Definitions, Targets, and Key Performance Indicators for New and Renovated Zero Emission Buildings

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Contents

Abstract

This article focuses on the definition, targets, and key performance indicators of Zero Emission Buildings (ZEBs), as defined by the Norwegian research center on Zero Emission Buildings. It also provides examples of the application of the definition in two pilot building projects: one new residential building and one renovated office building.

Keywords

Zero Emission Buildings · Pilot buildings · LCA

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Introduction

Different organizations around the world have developed, proposed, and applied various definitions, targets, and key performance indicators (KPIs) of (nearly) zero energy buildings [1–9].

In Norway, the Research Center on Zero Emission Buildings (hereafter called the ZEB Center) was established in 2009 with the primary objective to develop solutions for existing and new buildings in order to bring about a breakthrough for buildings with zero greenhouse gas (GHG) emissions associated with their construction, operation, and demolition (www.zeb.no). The ZEB Center has developed its ZEB definition, concepts, products, and full scale pilot building projects to test and demonstrate the strategies and solutions developed in the center.

This article provides a brief overview of different definitions, targets, and KPIs of ZEBs with a focus on the developments from the Norwegian ZEB Center.

Net Zero Energy Building Definition (Net ZEB)

Within the framework of the International Energy Agency, Marszal et al. [10] have presented a review of Zero Energy Building definitions with associated calculation methodologies. They found that the definitions were expressed with a wide range of terms and indicators, while the calculation methodologies were more consistent and had a common framework. In 2012, Sartori et al. [11] proposed a consistent definition framework for Net Zero Energy Buildings. In this definition, the term *Net ZEB* is used to refer to buildings that are connected to the energy utility infrastructure. The wording "Net" underlines the fact that there is a balance between energy taken from and supplied back to the energy grid over a period of time. The Net ZEB balance is calculated as in Eq. 1:

$$\text{Net ZEB balance} :|\text{ weighted supply }| - |\text{ weighted demand }| = 0 \qquad (1)$$

Figure 1 *(left)* gives an overview of the Net ZEB concept and relevant terminology addressing the energy use in buildings and the connection between buildings and energy grids, while Fig. 1 *(right)* shows the ZEB balance graphically, plotting the weighted demand on the *x*-axis and the weighted supply on the *y*-axis.

The weighting system converts the physical units of energy wares into a common metrics, such as primary energy or carbon equivalent emissions. The ZEB balance is a condition that is satisfied when weighted supply equals weighted demand over a period of time, normally a year. The ZEB balance can be determined either from the balance between delivered and exported energy or between load and generation.

The reference building represents the performance of a new building constructed according to the minimum requirements of the national building code, or the performance of an existing building prior to renovation. Starting from such a reference case, the pathway to a Net ZEB is given by two actions:

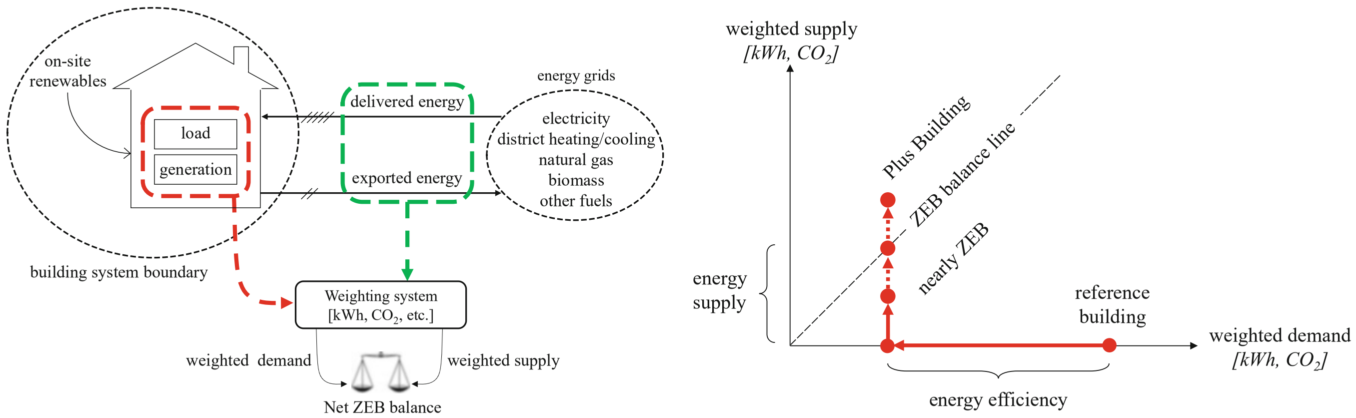


Fig. 1 (Left) Overview of the ZEB concept and relevant terminology; (right) graphical representation of the ZEB balance (From Sartori and Andresen [12])

1. Reducing energy demand (*x*-axis) by means of energy efficiency measures
2. Generating electricity as well as thermal energy by means of energy supply options to get enough credits (*y*-axis) to achieve the balance

Additionally, Sartori et al. [11] describe a set of associated criteria that should be included in the definition of a Net ZEB. Evaluation of the criteria and selection of the related options becomes a methodology for elaborating Net ZEB definitions in a systematic, comprehensive, and consistent way. The criteria include:

1. The building system boundary, including physical boundary, balance boundary, and boundary conditions such as local climate and indoor environment requirements
2. The weighting system, including metrics, symmetry of export and imports, and time-dependent accounting
3. The Net ZEB balance, including the balancing period, the type of balance, energy efficiency requirements, and eligible energy supply options (on-site or off-site)
4. The temporal energy match characteristics, including load matching and grid interaction issues
5. Measurement and verification system

In the following, the definition of Zero Emission Buildings of the ZEB center is described according to the above criteria.

Zero Emission Buildings (ZEB)

In energy efficient buildings, the reduced energy need during the operational phase is partly enabled by using more insulation and in general more materials for technical systems, thus increasing the relative importance of embodied energy. Studies have shown that for passive houses and nearly zero energy houses, the embodied energy may account for 20–50% of the life cycle energy use of a building [13, 14]. Moving towards full ZEBs, the embodied energy may account for an even larger share of the total life cycle energy use [15, 16]. Consequently, there is an increasing focus on life cycle-based zero emission buildings [17–20].

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

The greenhouse gas emissions is calculated 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

Table 1 Specific CO_2 factors employed by the ZEB Research Center [21]

Energy carrier	gCO_{2eq}/kWh	References
Electricity from the grid	130	[5, 22, 23]
Oil (fossil)	285	[5, 22]
Gas (fossil)	210	[5, 22]
Wood chips	4–15	[5, 24]
Pellets/briquettes	7–30	[5, 24]
Biogas from manure	25–30	[5, 24]
Bio-diesel and bio-oil	50	[5]
Bio-ethanol	85	[5]
Waste incineration (heat only)	185–211	[5, 24]

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.

Table 1 shows a summary of the default CO_2 factors that have been employed by the ZEB Research Center. The factors may vary depending on processes and system boundaries used. Furthermore, the center advices that other CO_2 factors may be used if the emissions are documented according to accredited methods and standards. When considering bio-fuels, the center advices that first-generation fuels should be avoided. Instead, second- or third-generation fuels that are certified and sustainably sourced should be used.

Within the ZEB Research Center, 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.

The approach adopted by the ZEB Research Center considers Norway as part of the European power system and takes into account that the power grid 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 [25]. Since buildings have a long lifetime, assumed 60 years at the ZEB Research Center for life cycle assessment purposes, it was deemed necessary to look at such future evolutions in the power sector.

The Ambition Levels and System Boundaries of Zero Emission Buildings

At the Norwegian Research Center on Zero Emission Buildings, the ZEB definition is characterized by a set of different ambition levels ranging from the lowest (ZEB-O÷EQ) to the highest (ZEB-COMPLETE) [21]:

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

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.

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.

ZEB-COM: This is the same as ZEB-OM, but also takes into account emissions relating to the construction "C" phase. The additional phases included 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 ZEB Definition also includes two higher ambition levels (ZEB-COME and ZEB-COMPLETE), but these levels have so far not been applied in any building projects in Norway. ZEB-COME is the same as ZEB-COM, but also taking into account emissions relating to the end-of-life phase (C1–C4). ZEB-COMPLETE takes into account all emissions related to all life cycle stages (A1–C4).

Figure 2 illustrates the five ZEB ambition levels that have been taken into account during the assessment of the different Norwegian ZEB pilot projects.

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

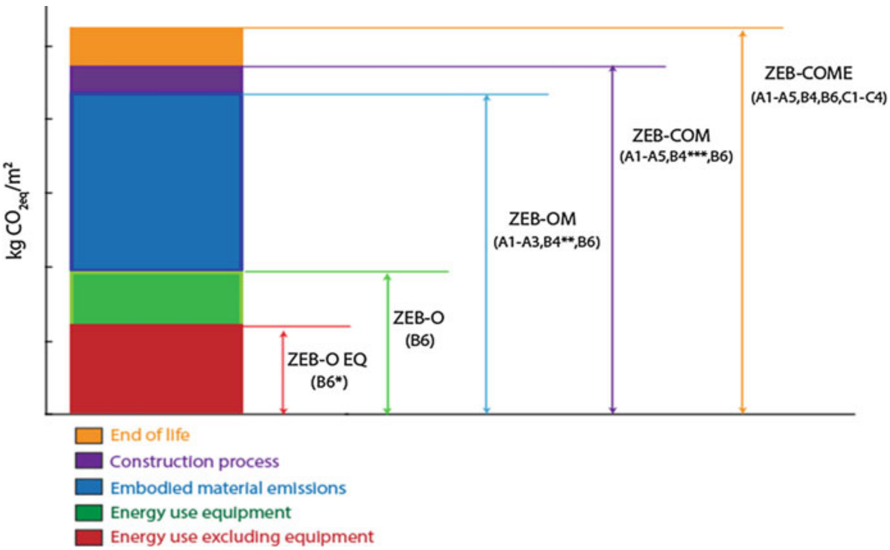


Fig. 2 ZEB ambition levels. See Table 2 for an explanation of the scope of the included life cycle stages, A1–A5, B4, B4**, B4***, B6, C1–C4 (From Fufa et al. [21])

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).

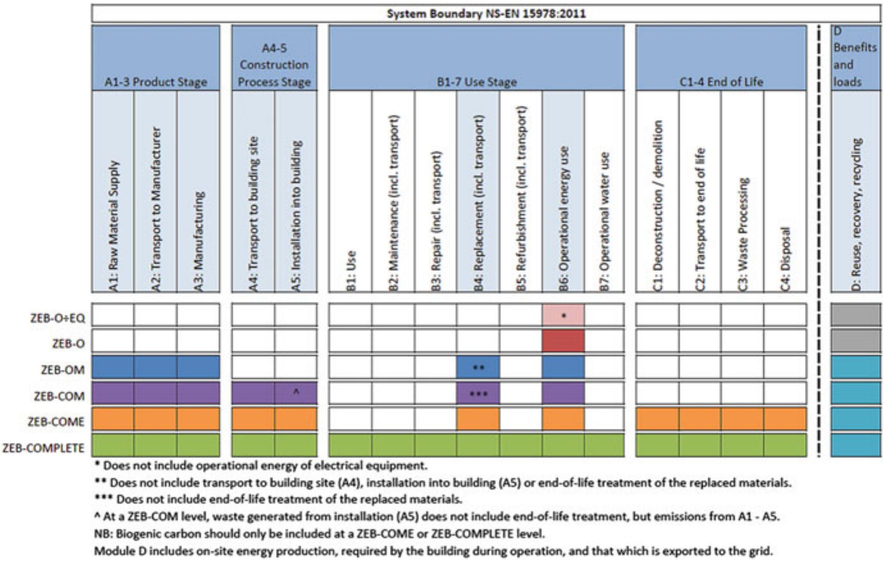
Use Stage (B1–B7): Use of construction products and services, related to building components (B1–B5) and operation of the building (B6–B7), during the entire lifetime of the building. The maintenance (B2) repair (B3) and replacement (B4) lifecycles are related to the product's estimated service life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

Table 2 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 Description of ZEB ambition levels according to NS-EN15978:2011 (From Fufa et al. [21])



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
– 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 Research Center has been to use a functional unit of 1 m^2 of heated floor area over a reference study period of 60 years when analyzing the emissions for the whole building [21]. 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 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.

Addressing Embodied Emissions at All Ambition Levels

For the two lowest definition levels, i.e., ZEB-O÷EQ and ZEB-O, emissions from materials are not included. Thus, in principle, such buildings may have relatively low greenhouse gas (GHG) emissions during operation, but higher embodied emissions overall due to suboptimized choices related to structures and materials. The ZEB center therefore recommends to have an emphasis on emissions from materials even at the ZEB-O÷EQ and ZEB-O ambition levels. In this case, qualitative measures may be used to identify significant contributors to GHG material emissions. This 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 [26].

Physical 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 [5]. The physical boundary is used to identify whether renewable energy sources are available on-site (within the boundary) or off-site. Figure 3 illustrates different options for system boundaries as defined by [10].

The Norwegian ZEB Research Center has employed the following boundaries for electricity and thermal energy generation [5]:

– For local renewable electricity generation, level III in Fig. 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 generation of electricity.
– For thermal energy generation, level IV in Fig. 3 has been chosen. Thus the thermal energy generation 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 generation 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 ZEB center has imposed a constraint that the exported thermal energy should not exceed imported energy (annually).

Energy Efficiency Requirements

The ZEB concept involves two design strategies; firstly, to minimize 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

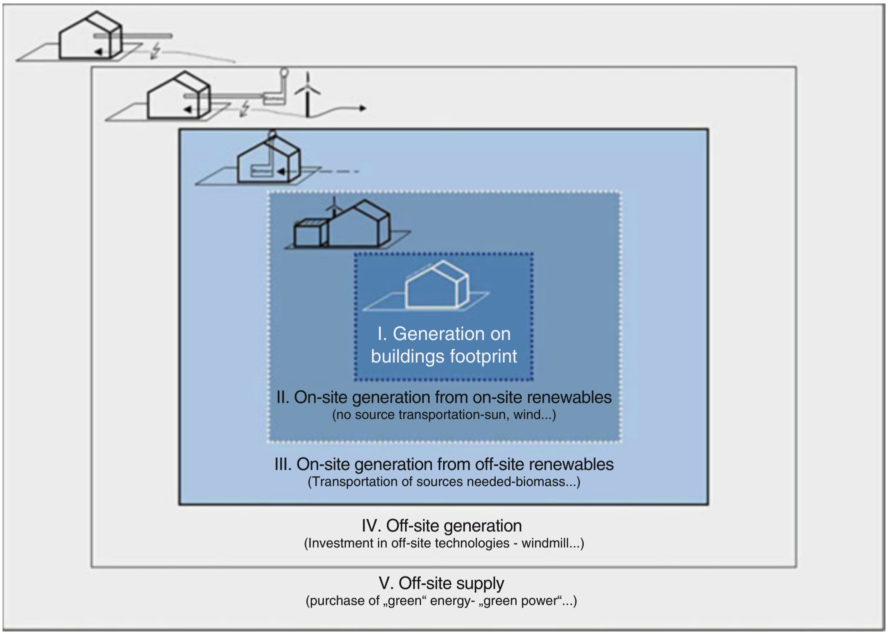


Fig. 3 Illustration of the different levels of possible system boundaries [10]

and materials, while active strategies typically involve technical systems or machinery to provide services to the building.

The minimum requirement for energy efficiency in the ZEB center is presented through the "low energy house standard" as compliant with Norwegian Standard NS 3700 for residential buildings [27] and NS 3701 for nonresidential buildings [28]. These standards set criteria for heating and cooling demand, maximum heat loss and thermal bridges, as well as air-tightness of the building envelope. Also, the standard requires that parts of the energy needs are covered by renewable energy supply.

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 [29, 30], and within International Energy Agency Annex 52 (http://www.iea-ebc.org/projects/completed-projects/ebc-annex-52/), see for example [31] and Annex 67 "Energy Flexible Buildings" (http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-67/).

Nevertheless, the Norwegian ZEB Research Center has chosen an approach which considers a constant yearly 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 [5]. Thus, the grid is regarded as an infinite capacity battery whereby surplus electricity is exported to the grid and reimported in periods of net demand. This approach has been taken to limit the complexity of the calculations. However, the ZEB center recommends 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).

Measurement and Verification

The ZEB Center recommends that the designed performance and calculations are 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 [32].
– **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 (Life Cycle Analyses) made for ZEBs are verified and quality assured by an independent, qualified third party [26].

Examples of Application of the ZEB Definition, Targets, and KPIS

This chapter provides examples of the application of the definition on pilot buildings in the ZEB Center: A new built single family residential building, and a renovated office building.

Pilot Building ZEB House Larvik

See Fig. 4.

Fig. 4 ZEB House Larvik. Photo: Jon Østgård

Key Data

Location and climate	Larvik, Norway, latitude 59°12′N, longitude 10°15′E. Annual ambient temperature: 7.6 °C, solar horizontal radiation: app. 950 kWh/m^2/year
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
Opening	2014

Energy Systems

The building envelope is well insulated and airtight, to reduce the need for heating, see Table 3. The house is designed to avoid the need for energy for cooling. There is solar protection on the bedroom windows, while other windows are placed so they are shaded from the sun.

The heating system is based on a ground-source-to-water heat pump (3 kW), which was estimated to cover 80% of the heating load with a seasonal COP (Coefficient Of Performance) of 5.17. In addition, 16 m^2 of solar thermal collectors was installed on the roof, which was estimated to cover the remaining 20% of the heating load.

The domestic hot water (DHW) system is supplied by two heat recovery systems that recovers heat from waste water (sink, shower, dishwasher, washing machine)

Table 3 U-values and other envelope specific input data used for the energy performance simulation of the ZEB pilot house Larvik [33]

Description	Value
U-value roof	0.084 [W/(m^{2}K)]
U-value ground floor	0.080 [W/(m^{2}K)]
U-value windows and doors	0.75 [W/(m^{2}K)] (average)
U-value exterior walls	0.111 [W/(m^{2}K)]
Normalized thermal bridge value[a]	0.03 [W/(m^{2}K)]
Total solar energy transmittance of windows	0.5
Sum of glass and door area related to heated floor area	29.2%

[a]The total of all thermal bridge values in a building, related to its heated floor area

Table 4 Energy budget: Calculated energy need for the ZEB pilot house Larvik [33]

Energy budget	Energy need (kWh/year)	Specific energy need (kWh/m^2/year)
Room heating	4,799	23.8
Ventilation heating	418	2.1
Domestic hot water	3,212 (6,424)[a]	15.9 (31.8)[a]
Fans	765	3.8
Lighting	1,765	8.8
Technical equipment	3,177	15.8
Total net energy need	**14,136 (17,348)[a]**	**70.2 (86.1)[a]**

[a]Due to the assumption that 50% of the energy in the gray water is recovered by the heat recovery system, only half of the energy need for domestic hot water is included

and preheats the water in the water tank. In addition, DHW is provided by the solar collectors, by an air-to-water heat pump (HP) in the exhaust of the ventilation shaft, and by the ground-source-to-water heat pump. Washing machines use hot water directly (hot-fill machines, no electricity for water heating needed).

The ventilation system is a balanced, mechanical ventilation system with constant air flows. The ventilation system is connected to a heat exchanger (87% efficiency) and an exhaust air heat pump. The heat pump can supply both heating and cooling to the ventilation inlet and is also used to heat domestic hot water. In addition, a heating and cooling battery is installed which uses energy directly from the boreholes.

The lighting system is designed to be based on LED and daylight utilization.

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 17,348 kWh per year, see Table 4. Including the heat pump system, the graywater system, and the solar collector system, the demand for delivered energy was calculated to 6,900 kWh per year.

The solar PV system consists of 91 modules installed on the roof. The photovoltaic modules have a rated efficiency of 15.5% and their peak power is 250 W_p, giving a total power output of 22.75 kW_p. The area of the installation is 150 m^2. Annual electricity yield from the PV system was calculated in the design phase to be

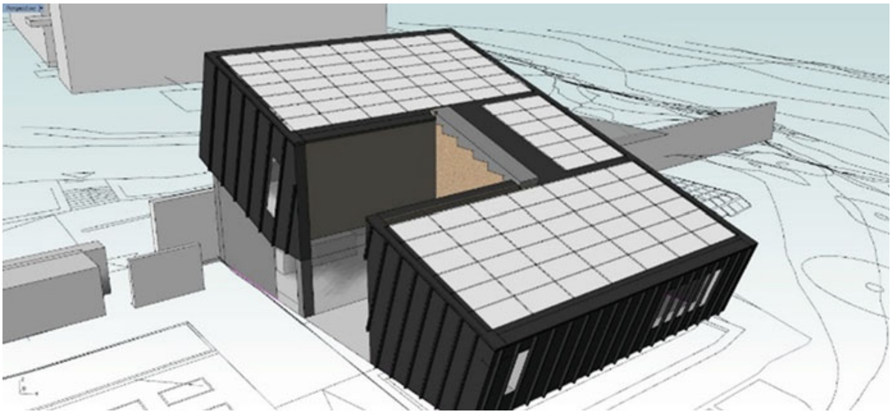


Fig. 5 The PV panels are placed on the upper and lower parts of the building. The middle part connecting the lower and upper parts is equipped with solar thermal collectors (illustration: Snøhetta)

19,200 kWh per year. The PV system is connected to the utility grid. The solar PV system also has a battery energy storage, with the aim to increase the economic output of the PV system (Fig. 5 and Table 5).

Materials

Service life, building:	60 years
Evaluated indicators:	Greenhouse gas emissions (kg CO_{2eq})
Year of assessment:	2014
LCA calculations:	ZEB/SINTEF building and infrastructure (for the analysis), Optimera (for product choices), Snøhetta (for the BIM inventory), Brødrene Dahl (for technical analysis)
Tools, 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 databases:	Environmental product declarations (EPDs), Ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories 2010). The analysis by [34] and EPD by Innotech provided information regarding embodied energy related to the PV modules.

The included system boundaries according to NS-EN 15978:2011 were A1–A3 and a simplified B4 life cycle stages. Transport and waste scenarios were not included in B4.

Table 5 Energy budget: Delivered energy (From Sørensen et al. [33])

Energy budget	Delivered energy (kWh/year)	Specific delivered energy (kWh/m^2/year)
Direct electricity	5,707	28.3
Electricity heat pump (ground-source HP)	1,014	5.0
Electricity solar energy	144	0.7
Other energy sources (HP in ventilation)	276	1.4
Total delivered energy	**7,142**	**35.4**

Table 6 Service lifetime scenarios (From Sørensen et al. [33])

Component	Service lifetime [years]	Component	Service lifetime [years]
Photovoltaic panels	30	Floor material	15
Heat pump	20	Interior wall surface	30
Ventilation ducts	60	Insulation	60
Solar thermal system	30	Steel	60
Concrete	60	Windows/doors	30
Batteries	20		

Construction parts included in the analysis were foundation, roof, inner walls, outer walls, floors, windows, doors, and interior stairs. Technical installations included were ventilation equipment, low voltage electrical equipment, materials use in floor heating system, solar electric panels, solar thermal collectors and not included were 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 were set mainly based on lifetimes set by relevant EPDs and estimated technical lifetimes based on information from producers (Table 6).

The following main material choices were done.

- 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.
- Recycled bricks were used in selected areas of the façade, timber claddings both in outer façade and selected inner walls.
- Ceramic tiles made of recycled material were used in the bathroom.
- Robust floor materials (parquet with 20 year lifetime).
- Solar cells based on recycled materials (Table 7 and Fig. 6).

Results

See Table 8.

Pilot Project Powerhouse Kjørbo

See Fig. 7.

Key Data

Location and climate	Sandvika (near Oslo), Norway, latitude 59°N, longitude 10°E. Annual ambient temperature: 6.3 °C, annual solar horizontal radiation: 962 kWh/m^2
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-COM÷EQ
Building owner/ tenant	Entra AS/Asplan Viak
Opening	April 2014

Table 7 Calculated emissions for different building parts (From Fufa et al. [21])

Construction parts (according to NS 3451:2009)	Pre-use phase[1] (kg CO_{2eq}/m^2 year)	Use phase[2] (kg CO_{2eq}/m^2 year)	Total (kg CO_{2eq}/m^2 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

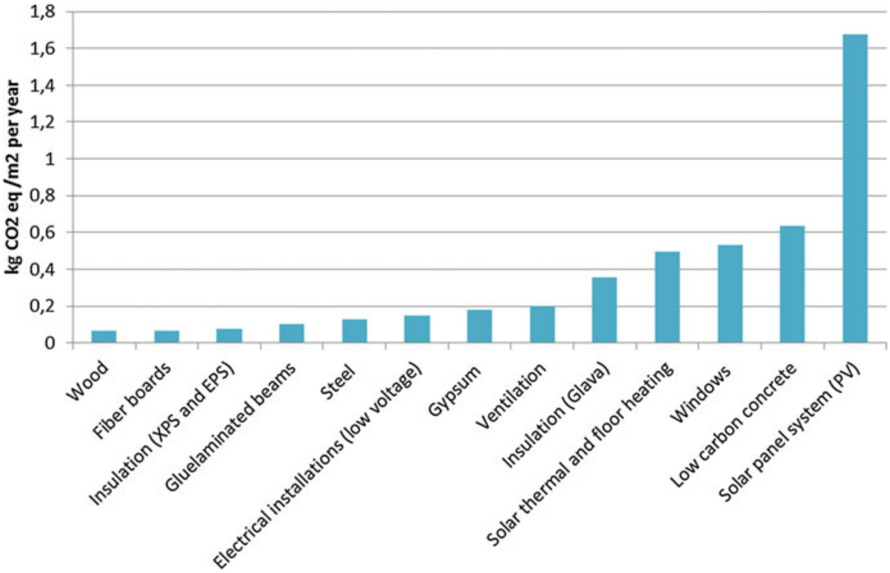


Fig. 6 Emissions related to materials and technical parts (From Fufa et al. [21]). *XPS* Extruded Polystyrene, *EPS* Expanded Polystyrene

Table 8 The ZEB balance for the ZEB House Larvik (From Fufa et al. [21])

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**

Energy Systems

The goals related to the building envelope state that the building should as a minimum fulfil the Norwegian Passive House standard NS 3701 [28]. The building envelope is well insulated with low infiltration losses and there are low U-values for windows and doors. Also other parameters were important during the design, such as daylight, solar shading, embodied energy, and the possibility of natural ventilation.

During the renovation, the original concrete structure was kept intact, including the stairs and the core. There was a need to change all the technical equipment and indoor materials. The thermal properties for the building envelope is summarized in Table 9.

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 (see Fig. 8), and highly efficient

Fig. 7 One of the office blocks of Powerhouse Kjørbo. Photo: Byggenytt.no

Table 9 Thermal properties of the building envelope after and before refurbishment [35]

Properties	Before renovation	After renovation
U-value external walls	0.29 W/(m^2 K)	0.13 W/(m^2 K)
U-value roof	0.16 W/(m^2 K)	0.08 W/(m^2 K)
U-value floor on ground	0.16 W/(m^2 K)	0.12 W/(m^2 K)
U-value windows and doors	2.8 W/(m^2 K)	0.80 W/(m^2 K)
"Normalized" thermal bridge value (per m^2 heated floor area)	0.11 W/(m^2 K)	0.02 W/(m^2 K)
Air tightness, air changes per hour (at 50 Pa)	2.0	0.24

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

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 were designed to 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.

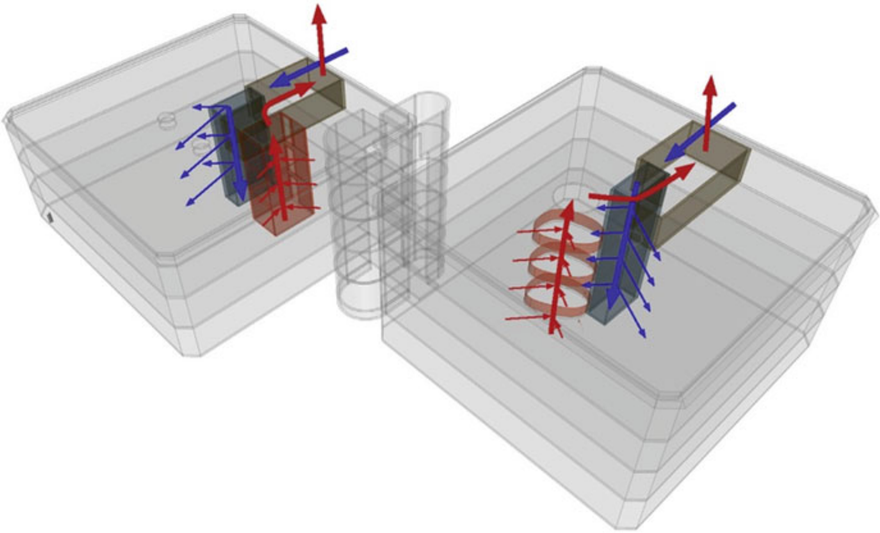


Fig. 8 Ventilation system using stairways for vertical supply and exhaust ventilation shafts. Illustration: Snøhetta/MIR

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 meters 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 preheat 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, and has a total peak power of 312 kW_p (Fig. 9).

As the ZEB 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. Table 10 shows predicted and measured energy use (demand and delivered energy) in kWh and kWh/m^2 heated floor area for the second year of operation. The results shown in the table have not been corrected for climate variations and user variations. The building is in a 2-year test phase and is continuously undergoing adjustments to optimize energy use.

Total delivered energy, including server room and appliances, is measured to 221 654 kWh (42.9 kWh/m^2) during the first year of operation and 232 454 kWh (45.2 kWh/m^2) during the second year.

Fig. 9 Photos showing the placement of the PV panels on the roof. Photos: Skanska

Table 10 Predicted and measured energy use (demand and delivered energy) in kWh and kWh/m^2 heated floor area (From Sørensen et al. [35])

5180 m² heated area	Predicted, standard year 2-60					Measured, 2nd year of operation (Apr 15-Mar 16)				
Powerhouse Kjørbo	Demand kWh	Delivered kWh	COP	Demand kWh/m²	Delivered kWh/m²	Demand kWh	Delivered El, kWh	Delivered DH, kWh	Demand kWh/m²	Delivered kWh/m²
Space heating	89 934	28 104	3,2	17,4	5,4	75 546	21 454	1 066	14,6	4,3
Ventilation heating	8 854	2 767	3,2	1,7	0,5	32 859	9 332	464	6,3	1,9
Domestic hot water	24 772	7 741	3,2	4,8	1,5	11 685	3 431	0	2,3	0,7
Fans	12 896	12 896		2,5	2,5	12 037	12 037		2,3	2,3
Pumps	9 417	9 417		1,8	1,8	14 682	14 682		2,8	2,8
Lighting	34 228	34 228		6,6	6,6	75 383	75 383		14,6	14,6
Appliances	44 093	44 093		8,5	8,5	55 248	55 248		10,7	10,7
Server room (IT)	87 600	87 600		16,9	16,9	40 887	40 887		7,9	7,9
Space cooling	0,00	0,00		0,0	0,0	0,00	0,00		0,0	0,0
Server room cooling	87 600	5 840	15,0	16,9	1,1	38 100	0*		7,4	0*
Ventilation cooling	9 435	629	15,0	1,8	0,1	3 103	0*		0,6	0*
Total	**408 829**	**233 316**		**78,9**	**45,0**	**359 530**	**232 454**	**1 530**	**69,4**	**45,2**

If not including appliances and server room, the need for delivered energy was 23.7 kWh/m^2 during the first year and 26.6 kWh/m^2 during the second year. This average delivered energy after 2 years is therefore 25.1 kWh/m^2, and this value is used when evaluating the achievement of the Powerhouse and ZEB goals. The *predicted* average for the 2 years was 21.6 kWh/m^2.

The measured performance shows a surprisingly high correspondence to the calculated energy performance. However, the results deviate somewhat when the different energy purposes are analyzed separately:

Space heating and ventilation heating:

- If combining the demand for space heating and ventilation heating, this demand was 20.8 kWh/m^2 during the first year and 20.9 kWh/m^2 during the second year. This corresponds well with the calculated heat demand, which was 22.9 kWh/m^2 for the initial year and 19.1 kWh/m^2 for the second year. The demand for space heating (radiators) was lower than predicted. The demand for ventilation heating was higher than predicted, probably due to a lower efficiency than expected in the heat recovery unit.

- For the first 2 years, the actual Seasonal Coefficient of Performance (SCOP) for the heat pump (4.2 year 1 and 3.5 year 2) was better than calculated (3.2). For the first year, the delivered energy for space and ventilation heating was 5.1 kWh/m^2, while the calculated delivered energy was 7.2 kWh/m^2. For the second year, there was almost a balance between actual delivered energy (6.2 kWh/m^2) and calculated delivered energy (6.0 kWh/m^2).

Domestic hot water (DHW):

- The demand for domestic hot water was lower than predicted both years.
- The SCOP for the DHW heat pump increased from year 1 to 2 (from 3.0 to 3.4), after implementing several measures to improve the operating conditions.

Fans:

- Measured energy use by the fans was close to the calculated values. The energy demand was reduced from the first to the second year, after measures to optimize the operation were implemented.

Pumps and cooling:

- The measured energy for pumps includes the server room cooling and ventilation cooling. For the first year, delivered energy for these purposes were 1.7 kWh/m^2, while calculated delivered energy for both pumps and cooling was 3.7 kWh/m^2. The second year the numbers were 2.8 kWh/m^2 measured and 3.0 kWh/m^2 calculated.

Lighting:

- Electricity for lighting was higher than predicted. For the first year, delivered energy for lighting was 12.2 kWh/m^2, while the calculated value was 7.9 kWh/m^2.
- For the second year, the measured energy use increased to 14.6 kWh/m^2, which is more than twice the calculated value of 6.6 kWh/m^2. For both years, lighting counted for more than half of the building's total energy use, not including the appliances and server room.
- Towards the end of the second year, in February 2016, several measures were implemented to reduce the energy need for lighting. Consequently, the energy need in 2016 was 24% lower than in 2015.

Appliances and server room (IT):

- Reducing the energy use for appliances and server room (IT) has been in focus, even though these are not included in the final energy balance. Measured values for electricity for servers are significantly lower than predicted.

Space cooling, server room cooling, and ventilation cooling:

- All the cooling needs for the first 2 years were covered by free cooling from the borehole system.
- During the first year, the cooling demand of the building was 9.6 kWh/m^2 and the second year the demand was 8.0 kWh/m^2.

When it comes to the generation of electricity from the PV system, measurements from the second year of operation showed a yield of 223 501 kWh. This production is close to the predicted production. During the first year, the energy production was

133 568 kWh. The main reason for the lower production in the first year is that the solar energy plant on the garage started delivering energy in August, 4 months after the measurement period started.

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
LCA calculations	ZEB, Skanska
Tools LCA	BIM (for the construction materials) + MagiCad (for the ventilation system) + Microsoft Excel + SimaPro
Background database	EPDs + Ecoinvent v2.2 + scientific articles
Construction Processes included	Impacts related to A4 and A5 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.

Notes Related to Product Stages A1–A3 and Replacement Stage B4 (Ref. Fig. 2)

- Emissions related to material extraction and production were included in the analysis, including materials related to the PV system.
- System boundaries: Materials for infrastructure related to water and drain was not included.
- B4 was based on service lifetimes available from PCR and SINTEF building and infrastructure's guidelines BKS 700.320 (Byggforskserien).
- Embodied energy and emissions loads from the reused components were 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 regarded as being counterintuitive, 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.

- It was assumed that the embodied energy and emissions from the production of the PV modules would be reduced with 50% in 30 years. This is of course uncertain; however, analyses presented by [36–38] support that there is a continuous improvement in the production of PV modules. The improvements are mainly related to increased material efficiency, improved production processes, and increased use of renewable energy in the production process. It was also assumed that the efficiency of the PV modules installed after 30 years would have an increased efficiency by about 40% from 20% to 28%. This is in accordance with the optimistic scenario presented in [36].

Notes Related to the Deconstruction Stages C1–C4 (Ref. Fig. 2)

- C1: Due to lack of good data, the deconstruction phase was 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 were assumed to balance each other.
- C2: The transport of waste from site to treatment facility and disposal were based on [39] and supplemented with generic distances from [40].
- C3 and C4: 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, aluminum, glass, gypsum, insulation, plastic, steel, wood, textile, bitumen, and generic waste between 2006 and 2011 [41].

Results

Table 11 shows the ZEB balance for Powerhouse Kjørbo. The average operational energy use for the first 2 years was predicted to be 21.6 kWh/m^2 and measured to be 25.1 kWh/m^2 per year. For the average production of energy for the first 2 years, the predicted average is 44.1 kWh/m^2 while the measured electricity production is 43.1 kWh/m^2.

The GHG emissions from B6 is calculated by multiplying the specific energy use/production with an emission factor for electricity. The emission factor used for grid electricity in the ZEB projects is 0.132 kg CO_{2eq}/kWh [21]. This yearly averaged factor is based on a future scenario assuming a fully decarbonized European grid by the end of 2050, according to EU policy goals. The same emission factor is used for the import and export of electricity to and from the building. The emission results are sensitive to changes in the emission factor. It is more difficult to achieve a ZEB balance with a low emission factor, and easier with a higher factor.

Conclusion and Future Directions

This article has provided a description of a definition framework for Zero Emission Buildings as developed in the ZEB research center. The definition framework includes a range of different targets for different ambition levels that may be used as a “staircase” for developers and property owners to “climb” according to the available resources and local conditions. The definition provides a systematic and

Table 11 The ZEB balance for Powerhouse Kjørbo [35]

Life cycle stage		GHG emissions kg $CO_{2eq}/(m^2\ year)$ Predicted	Measured[a]
A1–A3	Product phase: Raw materials supply, transport, and manufacturing	3.77	3.77
A4–A5	Construction phase: Transport to site, construction installation process	0.25	0.25
B4	The use phase: Replacement of components	1.82	1.82
B6	Operational energy use Production of energy	2.85 −5.82	3.32 −5.70
C1–C4	The end-of-life phase: Deconstruction, transport, waste process for reuse, recovery and/orrecycling, disposal	0.74	0.74
Sum		**3.61**	**4.20**

[a]B6 is based on energy measurements from the first 2 years

detailed description of KPIs and associated calculation methodologies, encompassing the entire life cycle of buildings.

It should be noted that by focusing only on the optimization of the performance of single buildings, one runs the risk of suboptimizing the energy supply system. This may for example imply that one is failing to take into account the synergy effects between energy consumption and production and not taking into account that it could be more cost-efficient to invest in off-site or nearby energy systems than on-site systems. As mentioned above, the ZEB balance is sensitive to the weighting factors for import and export of energy across system boundaries, which need to be carefully chosen. Hence, a shift towards encompassing Zero Energy or Zero Emission Neighborhoods (ZEN) is called for. In fact, a new Norwegian ZEN Center following up on the ZEB Center is currently under establishment.

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