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The Norwegian ZEB definition and lessons learnt from nine pilot zero emission building projects

Inger Andresen^a, Marianne Kjendseth Wiik^b, Selamawit Mamo Fufa^b, Arild Gustavsen^a

^a Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

^b SINTEF Building and Infrastructure, Børrestuveien 3, 0373 Oslo, Norway

inger.andresen@ntnu.no

Abstract. In the frame of the Norwegian Research Centre on Zero Emission Buildings, nine real-life zero emission pilot building projects were initiated during the period of 2009 to 2017. Eight of the pilot building projects have been constructed and are currently in use, whilst one of them is still in the planning phase. All the pilot projects have been followed up by researchers during the design, construction, and operation phases, by e.g. analyses of construction documents, and post-occupancy surveys. The main lessons learnt from this work are presented in this paper. They include the importance of an integrated design process, having clear goals and associated assessment methods, following a strategy based on ‘trias energetica’, as well as choosing locally sourced materials with low embodied carbon and long service lives, and increasing the focus on the users.

1. Introduction

The Norwegian Research Centre on Zero Emission Buildings (the ZEB Centre) was established in 2009 with the aim to develop materials and solutions for new and existing buildings with net zero greenhouse gas (GHG) emissions over their lifetime (www.zeb.no). The centre was led by the Norwegian University of Science and Technology (NTNU) and SINTEF as research partners and encompassed 21 public and private partners from the Norwegian building and construction industry.

During the ZEB Centre, nine real-life zero emission pilot building projects were initiated in the period from 2009 to 2017. The pilot projects are listed in Table 1. Eight of the pilot building projects have been constructed and are currently in use, whilst one of them (Zero Village Bergen) is still in the planning phase. A summary of key data is also given in Table 1, and an illustration of each project is shown in Figure 1.

The pilot projects have been followed by researchers from the ZEB centre during the design, construction, and operation phases. Information has been gathered through participation in design workshops, analyses of construction documents, measurements, and interviews with participants in the design, construction, and operations phases.

This paper presents a summary of the main lessons learnt from the design, construction and operation of these zero emission pilot building projects. It will also discuss the definition of Zero Emission Buildings (ZEB), how the pilot projects have responded to the definition, and how the definition may be further applied in Norwegian building regulations.



Table 1. Key data from the zero emission pilot building projects.

Name of building	Type of building and heated floor area	Location and weather data	ZEB ambition level (see section 2)
Powerhouse Kjørbo	Office building, renovation HFA: 5000 m ²	Sandvika, Norway T _{amb} : 5.9°C I _{hor} : 960 kWh/m ²	ZEB-COM÷EQ
ZEB House Multikomfort	Single family house, demonstration building HFA: 200 m ²	Larvik, Norway T _{amb} : 7.6°C I _{hor} : 974 kWh/m ²	ZEB-OM
Visund Haakonvern	Office building HFA: 2000 m ²	Bergen, Norway T _{amb} : 7.5°C I _{hor} : 764 kWh/m ²	ZEB-O÷EQ
Skarpnes	5 single family houses HFA: 770 m ² (total)	Arendal, Norway T _{amb} : 7.5°C I _{hor} : 934 kWh/m ²	ZEB-O
ZEB Living Lab	Single family house, research test facility	Trondheim, Norway T _{amb} : 5.1°C I _{hor} : 890 kWh/m ²	ZEB-OM*
Powerhouse Brattørkaia	Office building HFA: 14000 m ²	Trondheim, Norway T _{amb} : 5.1°C I _{hor} : 890 kWh/m ²	ZEB-COM÷EQ
Heimdal School	High school HFA: 25000 m ²	Trondheim, Norway T _{amb} : 5.1°C I _{hor} : 890 kWh/m ²	ZEB-OM*
Campus Evenstad	Educational building HFA: 1100 m ²	Evenstad, Norway T _{amb} : 4.7°C I _{hor} : 663 kWh/m ²	ZEB-COM
Zero Village Bergen	800 dwellings, terraced houses and blocks HFA: 80 000 m ²	Bergen, Norway T _{amb} : 7.5°C I _{hor} : 764 kWh/m ²	ZEB-O

2. The ZEB Definition

The ZEB definition builds upon the framework for net zero energy buildings defined by Sartori et al. [1]. In this definition, the term *Net ZEB* is used to refer to buildings that are connected to the energy utility infrastructure, and the wording ‘Net’ underlines the fact that there is a balance between energy taken from and supplied back to the energy grid over time. The Net ZEB balance is calculated as in Eq. (1):

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

In a (net) zero *emission* building (ZEB), as defined by the Norwegian Research Centre on Zero Emission Buildings, 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 (GHG) emissions are calculated using CO₂ equivalent (CO_{2eq}) conversion factors for each energy carrier

(kgCO_{2eq}/kWh) or building materials (kgCO_{2eq}/m, kgCO_{2eq}/m², kgCO_{2eq}/m³, kgCO_{2eq}/kg or kgCO_{2eq}/pc). According to the definition, a ZEB can be achieved by offsetting greenhouse gas (GHG) emissions from the entire life cycle of the building through the generation of onsite renewable energy [2]. The ZEB Centre's definition is very ambitious; therefore, a stepwise approach with different ambition levels has been developed to allow flexibility for different types of buildings and local boundary conditions. The main ambition levels applied for the pilot projects in the ZEB Centre are as follows, starting with the lowest [2]:

ZEB-O÷EQ: Emissions relating to all energy use for operation "O", except energy use for appliances/equipment (EQ), shall be compensated for with renewable energy generation.

ZEB-O: Emissions relating to all operational energy "O" shall be compensated for with renewable energy generation.

ZEB-OM: Emissions relating to all operational energy "O" plus embodied emissions from materials "M" shall be compensated for with renewable energy generation.

ZEB-COM: This is the same as ZEB-OM, but it also considers emissions relating to the construction "C" phase. The additional phases included are transport of materials and products to the building site and the construction installation processes.

Some of the zero emission pilot building projects have used a variation of these ambition levels, e.g. the two Powerhouse projects have included emissions from construction, but not emissions from the energy use of electrical appliances during the operation phase. The ambition level for the Powerhouse projects has therefore been set to ZEB-COM÷EQ.



Figure 1. The ZEB Pilot building projects. From upper left to lower right: Powerhouse Kjørbo, ZEB house Multikomfort, Visund Haakonvern, Skarpnes, ZEB Living Lab, Powerhouse Brattørkaia, Heimdal School, Campus Evenstad, Zero Village Bergen.

3. Lessons learnt from the design process

3.1. Integrated design

All the zero emission pilot building projects have endeavoured to use an integrated design process, as described in [3]. Such a process involves establishing clear goals, employing multi-disciplinary cooperation from the early design stages, implementing a high level of energy integration and synergy of systems, and using modern performance prediction tools throughout the process to improve the environmental performance of a building.

Experiences show that having a well-defined goal for the environmental ambition is crucial for the success of zero emission building projects [3]. Moum et al [4] emphasise the importance of strong collaboration and involvement of stakeholders, through management style and the establishment of good meeting arenas. In the evaluated pilot projects, project participants seemed to have a shared understanding and acceptance of the purpose and need of a ZEB definition. The actors saw the possibility of learning and gaining new knowledge as highly useful for their own career and company competitiveness. There was a special focus on enabling good interdisciplinary collaboration for reaching the ZEB ambition.

To achieve a well-functioning ZEB, the different design concerns must be viewed as integral parts of the overall concept with all its differing requirements, e.g. minimized GHG emissions, excellent energy performance, high quality indoor and outdoor environments, and good architectural qualities. Each of the various technologies or strategies applied do not necessarily have to be new or innovative, but the whole concept will be. This was expressed as followed by one of the participants in the design of Powerhouse Kjørbo [5]:

It's not that we've invented new solutions; we've used known solutions [...]. It's mostly known solutions that have been combined and that have been dimensioned optimally. Instead of choosing installed systems in the design based on isolated performance criteria in each specialist area (e.g., HVAC, acoustics, electric installations), the approach emphasized the function of each part in view of the whole.

The underlying design strategy is based on the fact that passive energy design has a significant importance in achieving Zero Emission Buildings. A way of illustrating such a design strategy is through the *Trias Energetica* pyramid [6]. Trias Energetica is a three-step approach that gives priorities for realising an integrated sustainable energy solution, and consists of the following steps:

1) Reduce energy demand and related GHG emissions by applying energy reducing measures such as efficient building form, plan, orientation and facade layout, good thermal insulation, air tightness, and heat recovery. In a ZEB process, this step also includes designing for low GHG emissions from the construction and use of building materials by selecting local materials with low embodied emissions and long services lives. 2) Employ technologies for utilising local renewable energy sources, such as solar thermal systems and photovoltaics, heat pumps, biomass, waste and wind. In a ZEB process, this also includes properly integrating building services and renewable energy sources to avoid a double up of building materials, for example building integrated photovoltaics. 3) Finally, if there still is a need for some auxiliary energy, this takes place at the third level, using the least polluting fossil fuels in the most efficient way. In a ZEB process, one would of course seek to avoid the use of fossil fuels entirely.

The researchers of the ZEB Centre have developed a more detailed model consisting of 9 steps: 1) Location, orientation, and form, 2) daylight and sun, 3) material choices, 4) the building envelope – insulation and air tightness, 5) energy efficient lights and appliances, 6) efficient heating, ventilation, and air conditioning (HVAC) systems, 7) measurement and control, 8) renewable thermal energy, and 9) renewable electricity. However, the process of going through these steps should not be interpreted as a linear one. This is because the design process is so highly integrated. It is necessary to see the interrelations between the different passive and active measures and optimise the whole building concept. In the following, four of these aspects are addressed in light of the pilot building projects, namely energy reduction, efficient HVAC systems, local renewable energy production, and material use.

3.2. Reduce first

Across all of the zero emission pilot buildings, measures have been taken to reduce energy demand as much as possible. This involves implementing a well-insulated, air-tight building envelope, passive solar strategies, utilising daylight, and demand control. All of the pilot buildings are designed in accordance with the Norwegian passive house standard [7,8] or better. U-values for exterior walls are between 0.10 and 0.15 W/(m²K), whilst roofs have typically lower U-values. U-values for windows are lower than 0.8 W/(m²K). There has also been a strong emphasis on achieving continuous air and moisture barriers in the building envelopes. In places where the air and moisture barriers are perforated by ducts or pipes, cuffs and/or tape are used to avoid leakages. The air leakage number, n₅₀, has been designed to be below 0.6 air changes per hour (ACH) for all of the pilot buildings. Measurements with blower doors tests show that all projects except one (Campus Evenstad), achieved this goal. One project (Visund Haakonsvern) even obtained a value of 0.1 ACH, which is extremely low.

3.3. Efficient HVAC systems

All projects have focused on reducing the installation and running costs of HVAC systems, by employing efficient energy solutions. This is made possible by utilising passive and active measures to reduce the need for heating and cooling, such as solar shading, thermal mass, demand control, and installing glazing with low U-values. The heat distribution system may be much more compact than in a conventional building if the facades are very well insulated and the heating load is low. For example, in the ZEB residential buildings, there is only one radiator per floor, centrally located near the technical room, which allows for shorter distribution pipes and less technical installations. The energy use for fans is minimised through designing systems with low pressure drops, and includes demand control, short and spacious distribution channels, partly relying on using secondary spaces such as corridors as return air channels and taking advantage of thermal buoyancy when extracting air. Ventilation air volumes are reduced by activating thermal mass to avoid overheating, and by using low-emitting materials to minimise indoor air pollutants. Specific fan power (SFP) factors vary between 0.5 and 1.5 kW/(m³s) as design values across the ZEB pilot projects.

3.4. Utilising local renewable thermal energy and electricity

A wide range of on-site renewable energy systems were considered for the pilot projects, including different kinds of heat pumps, solar thermal collector systems, bio-energy systems, photovoltaic systems and wind power installations. In most cases, heat pumps with ground or sea water source systems were selected to cover 80-100% of the heating and cooling loads, due to their high cost-efficiency. Seven of the ZEB pilot buildings have heat pump systems. Two of the pilot projects, the ZEB House Multikomfort and ZEB Living Lab, have solar thermal systems in addition to heat pumps, mainly for demonstration and testing purposes. The building at Campus Evenstad is connected to a combined heat and power (CHP) plant based on gasification of wood chips, while Heimdal school uses a CHP system based on biogas. The ZEB House Multikomfort also has a grey water heat recovery system. Where district heating is available, this is used for auxiliary heating. Wind power was not selected in any of the projects because of low energy yields due to insufficient wind speeds on site. In all except one of the pilot projects (Campus Evenstad), photovoltaic systems have been chosen. All are based on crystalline silicon technologies with module efficiencies ranging from 16 to 21%. All are grid connected, and one has battery storage for electric car charging (ZEB House Multikomfort). The annual output of the PV systems has been calculated to range from 113 to 149 kWh per m² of PV module area [9].

3.5. Materials matter

Research from the ZEB Centre shows that the relative share of embodied GHG emissions in construction materials and technical installations may be significant for buildings where the operational energy demand has already been minimised [10], and that the production and replacement of building materials may contribute between 55-85% of total emissions across the Norwegian ZEB pilot projects. In the zero

emission pilot building projects, there have been efforts to reduce embodied GHG emissions in construction materials and in the construction phase.

The most efficient design strategies and material choices for achieving low embodied emissions identified through the pilot projects were; area and material reduction, application of reused and recycled materials, using materials with low embodied carbon, sourcing local materials, and adopting materials with high durability and a long service life [11, 12]. The ZEB case studies highlight that it may be challenging to keep up the focus on embodied emission reduction during a complex project process. This is because decisions regarding design and material alternatives are based on many criteria including technical properties such as load bearing capacity, fire safety, durability and sound proofing properties; as well as data availability, cost and time issues [12]. Challenges during the project also included unforeseen changes in the design and construction phases, such as unexpected ground conditions or new design requirements.

4. Lessons learnt from the construction process

Several of the issues addressed in section 3.1 on the integrated design process, may also be transferred to the construction process. Throndsen et al [5] conclude that in building projects with a high degree of innovation and development, it is extra important to focus on good communication between the design team and the executing part on the building site. In the ZEB pilot projects, there was often a need to adjust and improve solutions directly on the building site. This required an understanding of the intentions behind construction drawings. One criterion for success was found to be having enough time to go through all the challenges and issues with the construction manager and sub-contractors [4].

Participants in the pilot projects also agreed that “closeness”, in terms of frequent communication both face-to-face and by other means, between the central and defining actors in the project team was a key to success [4]. Failures increased once the distances between actors increased. A problem that appeared was a disbelief shared by the subcontractors when they first became acquainted with the functional demands and the specifications from the design process - a process they knew little about. According to respondents, one important role for a process manager in the later stages could have been to liaise between the project management level (construction manager and contractor) and the subcontractors.

Some of the participants in the pilot projects also mentioned that contract frameworks could be a contributing source of errors, as turnkey contract frameworks typically dis-incentivised subcontractors from making order changes, also after they were clearly deemed necessary by consulting engineers [4]. Moum et al [4] suggest that a more collaborative framework could have been applied to allow subcontractors to identify and share the risk taking with the main contractors and project owner. They further propose that one way to incentivise sub-contractors to join in more time-consuming contract arrangements could be to highlight the skills and knowledge development benefits available for participants in such projects.

One of the pilot projects, Campus Evenstad, was closely followed up by the researchers with respect to documentation of GHG emission in the construction phase [13]. Following up on this, ZEB researchers have investigated these themes further to ascertain measures for emission reduction. Some of these measures include using biofuels instead of fossil fuels in construction machinery, avoiding foundations and groundworks during the cold season, utilising district heating for drying and heating of construction works, and electrifying construction site machinery that would otherwise use fossil fuels [12,13].

5. Lessons learnt from the operation phase

5.1. Energy performance – measurement versus predicted

Three of the pilot building projects have been in operation long enough to achieve at least one year of actual energy measurements, namely; Powerhouse Kjørbo, Visund, and Skarpnes. The measurements show that overall, the total energy performance of the buildings is harmonious with the predicted

performance [14,15,16,17]. However, in the office building projects, the measured energy use for lighting was found to be somewhat higher than predicted values, whilst in the residential buildings, the heating energy use is higher than calculated. On the other hand, the measured output from the PV systems was higher than predicted across all three projects.

5.2. *Indoor environment*

The above-mentioned pilot buildings have also been evaluated with respect to indoor environment. After some running-in problems of some technical systems were resolved, the user evaluations showed that the buildings performed very well [4,5,14,15,16,17]. Also, physical measurements of indoor air temperatures and CO₂-levels, showed values that were within established comfort standards [14-17].

5.3. *Don't forget the users*

Berker [18] identifies three main practical/user issues that are central to address in ZEBs: 1) The level of end-user control, 2) the level of complexity of systems, and 3) the need for information about correct use. Users are much less satisfied when they cannot understand how things work or are unable to control temperature and ventilation. Moreover, the perception of personal control over an environment increases satisfaction. How much control the user gets over his or her environment is much more relevant in a building that is finely tuned to achieve an ambitious overall energy use. Furthermore, very energy efficient buildings tend to be more complex than traditional ones, and this makes it more difficult for users to make informed decisions about the operation. Thus, there is a need for good information about the use of the building. Such information, Berker claims, should ideally be given repeatedly and adapted to the users' needs.

6. Conclusions

The ZEB Centre's experiences with the pilot buildings show that ZEBs can be realised in Norway for different building typologies and locations. The ZEB definition may advance a Norwegian ZEB standard, where common traits include low-energy, well insulated, timber-framed buildings utilizing passive strategies with high-efficient HVAC systems, and local renewable energy systems. Realizing such buildings does not require new or unknown technologies, but the combination of known strategies, materials and technologies in new and smarter ways. Also, it requires increased investment in time and skills in the early design phases, new contracts for sharing the risk, and more consideration of users.

When considering Norwegian building regulations, a range of statutory frameworks and tools exist for aiding building professionals in achieving a ZEB-O ambition level. For example, the Norwegian technical specification SN/TS 3031 [19] provides energy performance calculation methodologies, whilst the Norwegian passive house standards NS 3700 [7] and NS 3701 [8] provide criteria to ensure buildings with low energy demand. However, more focus should be given to the other ZEB ambition levels, such as the materials in ZEB-OM and the construction processes in ZEB-COM. The new Norwegian standard for greenhouse gas calculations of buildings, NS 3720 [20], is a good starting point for evaluating the effect of material choices. Also, guidelines for zero emission construction sites have been developed based partly on the experiences from the ZEB pilot projects [21]. All together, these experiences and guidelines pave the way for the advancement of Zero Emission Buildings.

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