The ZEB Laboratory: the development of a research tool for future climate adapted zero emission buildings

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Abstract. The building sector is responsible for approximately 40 % of the energy consumption and carbon emissions worldwide. Buildings of the future will have to comply not only with stricter energy regulations, but they will also have to face changing climate challenges. To increase the level of interdisciplinary knowledge and to develop and test innovative technology with users, new types of adaptive research facilities are needed. The development of the ZEB Laboratory replies to this need. Developing the building as a research tool has made us focus on 1) a flexible laboratory for tomorrow building design research and 2) making the building itself a climate adapted zero emission building. The laboratory building is realised following the Norwegian ZEB-COM ambition. The development of this research tool has called for an iterative approach with use of partnering and collaborative elements for planning and production. Connected challenges related to e.g. research facility needs, building process, building physics, flexibility of use, energy supply and indoor environment had to be solved through iterations and co-creation processes. This paper presents a modern research tool for climate adaptation and mitigation measures for buildings including stormwater management at site and assesses the development and building process of the laboratory.

1. Introduction

The energy consumption associated to building construction and operation represents more than one third of the total annual energy balance in an industrialised country [1] . In particular, the UN Global Status Report stated in 2017 that buildings and the construction process account for 36 percent of global energy use and 39 percent of energy-related carbon emissions [2].

New materials and technologies are used more widely in the building industry to increase the efficiency and to reduce the environmental impact. Nevertheless, this innovation encounters some barriers. New solutions find it often difficult to penetrate the market. In fact, most solutions are immature when they are adopted in commercial construction projects and, once integrated, they will stay in place disregarding their effectiveness. A second problem is the fact that every solution adopted in a building must not only perform well from the purely technical point of view, but it must be accepted and work well from the point of view of the occupants/users. Building occupants act as a sensor and a stochastic disturbance for the performance of the building components. Another challenge is represented by the climatic change. According to models, the climate that new buildings will have to face will change within their life. Due to this, we must be able to test and assess new solutions with an eye to both climate adaptation and mitigation measures for buildings.

The ZEB Laboratory [3] was designed and realised with the aim to be a test and research facility able to respond to these requirements, as a pilot building to facilitate the diffusion of new environmentally friendly building components, solutions and processes and as an arena for national and international research cooperation.

Figure 1. The ZEB Laboratory: Southern and Western façade. (© Photo: M. Herzog / www.visualis-images.com).

2. Building design process

2.1. Ambitions and project delivery

The research organisations in charge of the project (NTNU and SINTEF) had a vision [4] and very high ambitions in terms of scale, flexibility and innovation, in addition to making the initial building a relevant research case, with regard to energy performance, climate mitigation and adaptation and mutual interaction with users [4]. The ambitions and complexity of the laboratory and building went beyond a mere optimisation in terms of time, costs, and quality required in a traditional construction project. The research groups had high ambitions for the functions of the building and laboratory and decided to work with external companies used to design and construction of complex building projects.

An innovative approach to project delivery needed to be adopted [5]. The chosen method was an Integrated Project Delivery (IPD) [6] where all the key actors share an early involvement in the project, set common targets and can benefit from each other's expertise while reducing the liability among team members and reduce the risk. The ZEB design method [7] was unified in an Integrated Project Delivery (IPD) for the first time ever.

2.2. ZEB-COM level

The EU Commission [8] has encouraged each Member State to set its own indicator for nearly zero energy buildings. Norway has defined, through the work of the ZEB Research Centre [7], five levels of ambition as shown in Figure 2. The process to achieve a ZEB-COM level of a building requires a different approach from the beginning of the design phase and requires a highly skilled group that works in strict connection and with a detailed and continuous communication across disciplines. A collaborative positive engagement is needed and developed collaborative skills among the people in the group are necessary. If this is not the case, changes in personnel should be done, this was also the case in this project.

2.3. Lessons learnt

It was crucial to bring all the actors together at an early stage and to create a professional and social competent team with little replacement of people. ZEB workshops for the whole team were a success. The focus was set on improvements and a system for mutual evaluation between the parties in the project

was used. Continuous measurements of process and progresses should keep the team members accountable. Engebø et al. [9] studied the design process of the ZEB Laboratory and concluded that trust was essential as the participants were able to rely on each other's expertise and work interdependently towards a common goal. They further conclude that the most prominent elements that affected trust were the start-up seminar, team composition, shared interest, support from management, common problem solving, and the use of integrated concurrent engineering. These elements built and sustained trust thanks to their ability to create and to positively impact the experiences, problem-solving, shared goals, reciprocity, and reasonable behaviour of the project team [9].
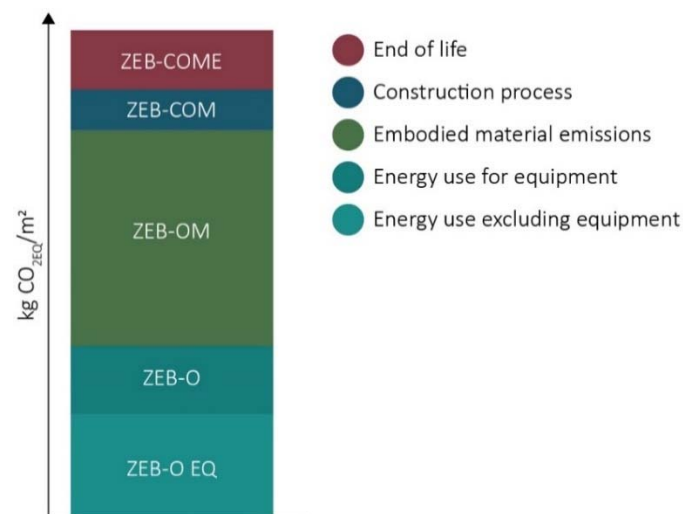

Figure 2. The ZEB (Zero Emission Building) ambition levels. The illustration shows what is included in the climate gas emission calculation (Original in [10]). Local renewable energy production should compensate for emissions related to materials/equipment, construction and use.

3. Anatomy of the laboratory

Figure 3. Plant view of the 2nd floor. Illustration: LINK Arkitektur.

The ZEB Laboratory is a 4-storey office building with a total surface of nearly 2000 m^3. Together with the ZEB Test Cell [11] and the ZEB Living Lab [12] it completes the collection of full scale outdoor research facilities at NTNU/SINTEF for the study of modern building performance.

Of the four floors, two are used as an office space and two as an educational space with lecture rooms, and spaces for study and cooperation. The second floor is equipped with two identical rooms (twin-rooms) whose façades can be reconstructed and that work as two 11 people office test cells.

3.1. Building Envelope and loadbearing structure

The loadbearing structure of the building consists of glued laminated timber (gluelam) columns, Cross-Laminated Timber (CLT) floors, some stiffening inner walls and traditional insulated wooden framework in outer walls. The roof is realised with an innovative wooden compact construction made of framework with a smart vapour barrier as presented in [13]. The U-values [W/m^{2}K] of the building components are: 0.15 (wall), 0.09 (roof), 0.10 (floor on ground) and 0.77 (windows) and the air leakage number measured by the contractor is 0.3 ACH (at 50 Pa). Relative humidity and temperature sensors are installed in the roof construction, see [13]. Moisture and temperature measurement sensors are mounted in a north-facing CLT wall (second floor) and in the air layers behind the PV on the roof and walls.
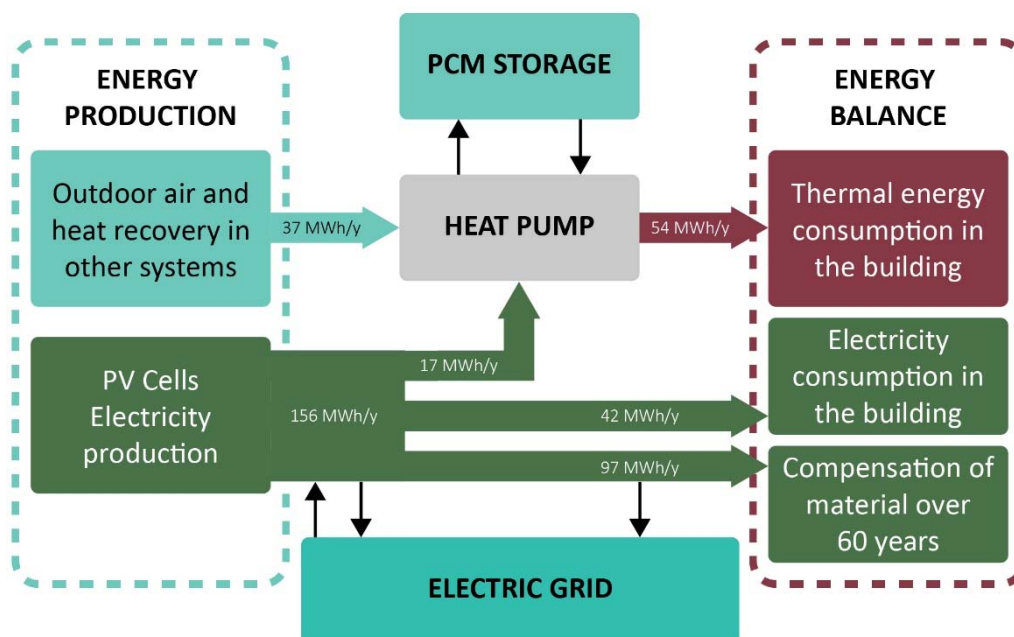
3.2 Energy Production

Figure 4. Sketch of the overall energy balance.

The whole renewable energy production of the building is achieved by harvesting solar power with building integrated photovoltaic panels (BIPV). The entire roof is cladded by BIPV panels as most of the East and South façade and the upper part of the North façade. The whole surface of the pergola that screens the largely glazed part of the façade of the ground floor is built with BIPV elements. In this case the system needs to have a certain transparency to allow the natural lighting of the ground floor. The solution is based on a chessboard distribution of opaque and semi-transparent PV panels. The latter are double-sided, thus being able to extract power from the reflected and diffuse radiation present in the space below the pergola. The West and North façade are only partially covered with BIPV. This choice was taken by cost-benefit consideration related to the ZEB-goal. The total number of panels installed is 701, corresponding to an area of 963.4 m^2. All the panels are based on mono-Si cells, but different types

from different producers are installed to optimise the size, the distribution and especially to be able to accommodate custom made PV-panels (triangular or trapezoidal) to cover the most available surface on the East and West façade. All the panels are covered with an anti-reflex paint, this contributes to the uniformity of colour. The total installed PV power is 181 kW_p. The solar panels are organised in strings optimised to maximise the power conversion. Three multistring inverters are installed with a rated power of 110 kW, 50 kW and 10 kW, respectively. The AC power is transferred to the power grid at 400 V. Through solar power simulations run on this configuration, it was calculated a net electric work contribution of 156 MWh per year.
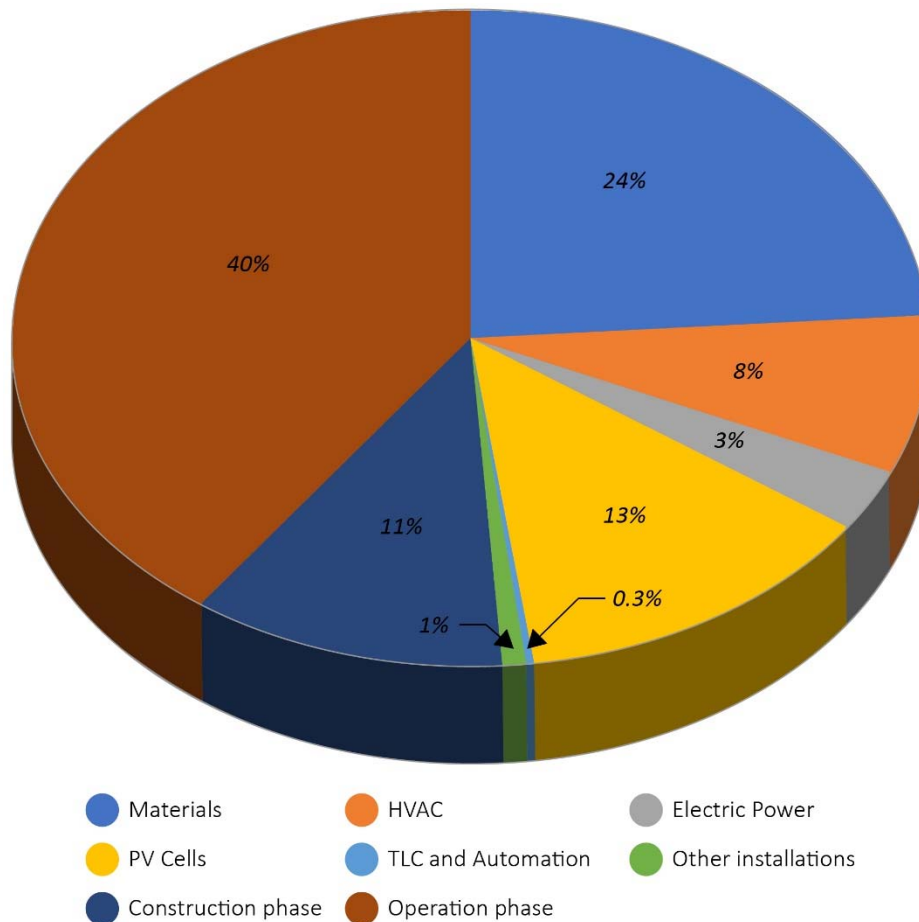

Figure 5. The total CO2 emission contributions from the different phases of the life cycle and embodied emissions from different parts of the building. The generated renewable energy over the expected lifespan of the building (60 years) compensates fully for the emissions related to the materials (49%), to the construction (11%) and for use/operation. Calculations performed according to [10,14].

3.3. Energy systems

The heating and the DHW systems of the building are based on two air-to-air heat pumps. The machines make use of natural coolant R-290 and absorb a peak power 16 kW from a 3-phase 400V AC line. The facility is also equipped with another heat pump, only used as a refrigeration machine for technical systems when needed. The technology of this machine is the same, but it has a smaller size with a peak power absorption of 14 kW.

The heating systems is equipped with an innovative, first of a kind, large heat storage tank based on Phase Changing Material (PCM) and developed as a prototype for this laboratory. The storage is meant to have a peak shaving effect for the heating requests. This is particularly important when the heating is entirely based on heat pumps, since it allows the machines to work at their best efficiency. The PCM heat storage also allows the heat recovery from other sources. The system is constituted of a 5 m^3 insulated tank with a bank of metal pillow plates immersed in the PCM material. The latter is an organic wax with a melting point measured peak of 36.5°C. The density of the material is circa 840 kg/m3 and the measured latent heat is 197 kJ/kg. This design makes the system 4 times more compact if compared to traditional hot water storage. In terms of energy, the heat storage capacity is calculated around 200 kWh.

The building is not equipped with a cooling system. Ambition of the project is also to evaluate to what extent the building can be cooled only using passive means and ventilation strategies. This will also represent an interesting research area.

3.4. Ventilation

The building can be ventilated naturally, mechanically or by a combination of the two (hybrid). It is equipped with a centralised mechanical ventilation system, and all the air distribution systems (four different in total) rely on the principle of displacement ventilation. To recover the heat contained in the exhaust air, the air handling units are fitted with rotary heat exchangers. The twin rooms are especially equipped both with independent HVAC systems and the possibility to apply both heating and cooling via heating/cooling coils connected to the central hydronic system. Some windows in the building can be opened manually while others are motorised. The windows' positions are designed to facilitate cross and buoyancy driven ventilation. The main staircase works as an extract for both mechanical and natural ventilation. Further information about the ventilation systems and strategies can be found in [15].

3.5. Stormwater handling

The ZEB laboratory has a combination of many stormwater handling solutions, where the run-off of the various solutions is collected in a large reservoir/tank that controls joined discharge to the pipe network. The roof water is collected and led into a separate pipeline to the reservoir/tank. A permeable cover, two rain beds and other green areas, provide stormwater management with its own runoff characteristics. The water from each of these solutions is led in separate pipelines into the reservoir/tank. Measuring instruments that allow to measure the runoff flow from each of these solutions will be installed. This will consent the study and the comparison of the solutions and it will favour valuable information on future different combinations with different runoff profiles adapted to local conditions and requirements. The reservoir/tank is split into two parts, making water from one part being suitable to be reused for irrigation and other uses. The tank can also be equipped with a heat exchanger. This way the heat contained can be used or the whole water mass can be used as an additional heat storage.

4. Control systems

4.1. Monitoring and control

As both a workplace and a laboratory, the ZEB Laboratory requires an advanced control system and an accurate acquisition and storage of all the data that can be useful both for the control and research analysis. The control platform is based on Building Energy Management System (BEMS). All the sensors and actuators present in the building are connected to a controller via a serial digital signal. The controller communicates with the BEMS and a research server. Data are written in a time series database and are available for analysis and control.

The building is mainly operated by NTNU Campus Service and follows a typical routine. Nevertheless, the control system provides a "Research Mode". In this mode researchers can edit the data

protocol string and take control of the building or part of it to test new control strategies or to provide specific condition needed for research (i.e. induce discomfort).

4.2. Indoor positioning system

An Indoor Positioning System (IPS) works in strict connection with the BEMS. The presence in time and space of the occupants is acquired real time and in anonymous data through the wireless communication between the IPS and the smartphones of the occupant or the smart access cards. Both guarantee the access to the facility or the office space according to the privilege each user has.

The IPS communicates with the simulation server and writes data on the time series database. The use of a single data structure for the sensors and the occupancy is an added value for researchers. In fact, together with the more traditionally building physics related investigation topics, this opens the way to a series of analysis on the response of the building to external condition, actual, potential, or future, and makes the laboratory an important infrastructure for the study of Artificial Intelligence and Machine Learning based control strategies, as well as an interesting test arena for all new IoT solution for building and office management.
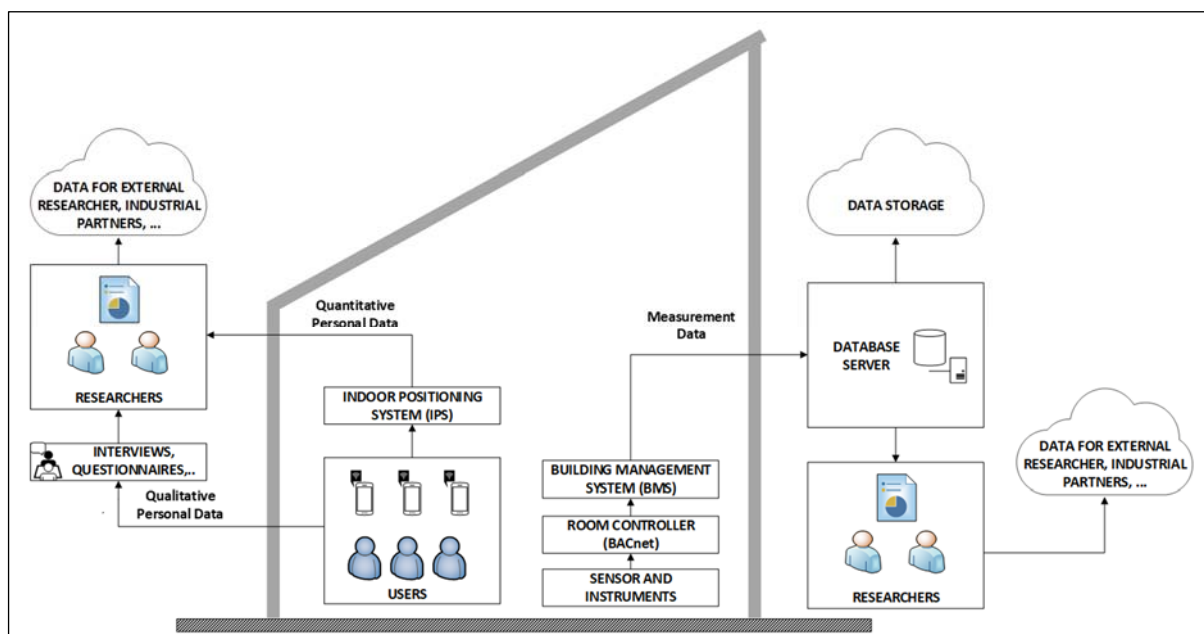

Figure 6. Schematic illustration of the data flow in the ZEB Laboratory.

5. Conclusions

The ZEB Laboratory was developed, and it now serves as a multipurpose investigation facility for building management, technology, and low environmental impact building/energy system. The structure is a living laboratory for the personnel of NTNU and SINTEF, both employees and students. It represents an arena for national and international cooperation in the investigation of innovative building technology, performance, and integration with users. The common effort of researchers and the continuous feedback from systems, sensors and occupants will represent a valuable contribution towards

the research on innovative building components and performance towards a deeper integration of the building management strategies and the latter advancements in data driven system (AI, ML, etc.).

The building has been partly operative since January 2021, has nearly completed the commissioning period and is today in the phase of trial operation. It is used as office and lecture space by NTNU and SINTEF in addition to being a laboratory.

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