ZEB Project report 35– 2017

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Pilot Building Powerhouse Kjørbo As Built Report

The Research Centre on Zero Emission Buildings

SINTEF Academic Press

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Abstract

Powerhouse Kjørbo, located in Sandvika near Oslo, consists of two office blocks from the 1980´s that have been upgraded to energy-efficient and modern offices. The Powerhouse goal is that the refurbished buildings over their lifetime generate more energy than they consumes. This implies that the building shall produce and export energy that compensates for the energy used for production of materials, construction, renovation, operation and end of life. Energy consumption related to technical appliances is not included.

In regards of ZEB emission goals, the Powerhouse goal can be translated to the ZEB emission ambition ZEB-COM÷EQ. This means that emissions related to all energy use in Construction "C", operation "O" except energy use for equipment/appliances (EQ) and embodied emissions from materials "M" shall be compensated with on-site renewable energy generation. In this report, also energy use for equipment (EQ) and the end of life "E" are shown in the GHG emissions account, which then includes all the ZEB-COME ambition levels.

Energy efficiency measures and materials with low embodied energy have been crucial for obtaining the energy goal at Powerhouse Kjørbo. An efficient ventilation concept has been developed, to reduce the overall energy demand for operation. Also other parameters were important during the design, such as daylight utilization, using thermal mass to regulate the indoor climate, acoustic conditions and the use of low VOC emitting products. The energy need is covered by a heat pump and a photovoltaic system.

As the Powerhouse and ZEB definitions state that the fulfilment of the definition should be documented by measured results, the energy use at Powerhouse Kjørbo was followed up closely. Operation and measurements started in April 2014, and results for the two first year of operation are available. The average operational energy use for the first two years was predicted to be 21.6 kWh/m^2 and measured to be 25.1 kWh/m^2. For the production of energy, the predicted average is 44.1 kWh/m^2 while the measured electricity production during the second year is 43.1 kWh/m^2.

For materials, both primary energy and GHG emissions calculations are presented. The GHG emissions results from materials (A1-A3, B4) is 5.59 kg $CO_{2\text{-eq}}$/(m^2 year), construction installation process (A4-A5) is 0.25 kg $CO_{2\text{-eq}}$/(m^2 year) and end of life stages (C1-C4) is 0.74 kg $CO_{2\text{-eq}}$/(m^2 year).

The Powerhouse goals has been the governing goals in the planning and construction process at Kjørbo. The energy balance to achieve the Powerhouse goal was achieved the second year, with a margin of 3.5 kWh/m^2. The energy balance for the first year was not reached, since the solar energy plant was not yet fully in operation.

In regards to the ZEB ambition, the results shows that 62% of the ZEB-COM÷EQ emissions are compensated for with renewable energy production. The results for the ZEB-COME account show that the product and construction phase (A1-A5) make up 32% of the lifecycle GHG emissions, the replacement of components (B4) 15%, the average measured operational energy use including equipment (B6) 47% and the end of life phase (C1-C4) 6%.

Powerhouse Kjørbo has received national and international attention, and the building has been nominated for a number of awards. Powerhouse Kjørbo demonstrates that it is possible to renovate existing properties into energy-plus buildings in cold climates, and that such renovations make commercial and environmental sense to the parties involved. A holistic approach to the project that simultaneously considered materials and embodied energy, technical systems, architecture, and energy efficiency and generation over the lifespan of the buildings was crucial to achieving the project's ambitious objectives.

Contents

1. Introduction

1.1 Powerhouse Kjørbo and the Powerhouse ambitions

Powerhouse Kjørbo, located in Sandvika near Oslo, consists of two office blocks from the 1980´s that have been upgraded to energy-efficient and modern offices.

The main definition of Powerhouse is “a building that during its lifecycle produces more renewable energy than it consumes for production of building materials, construction, operation and demolition of the building". In addition, the building shall be built within commercial conditions (Thyholt et al., 2012).

The goal of the Powerhouse Kjørbo project is to make a so called “energy positive building” or a “plus energy building”. This was defined as a building that generates at least the same amount of energy from on-site renewables as the energy used for production of building materials, the construction and installation process, maintenance and replacement, and operation of the building. Energy used for equipment in the operational phase, such as PCs and coffee machines, and also energy used for the building end-of-life phase was excluded from the energy goal. The fulfilment of the goal should be calculated theoretically during the construction phase. In addition, the fulfilment should be documented by measured results of the energy production and use during the operation period.

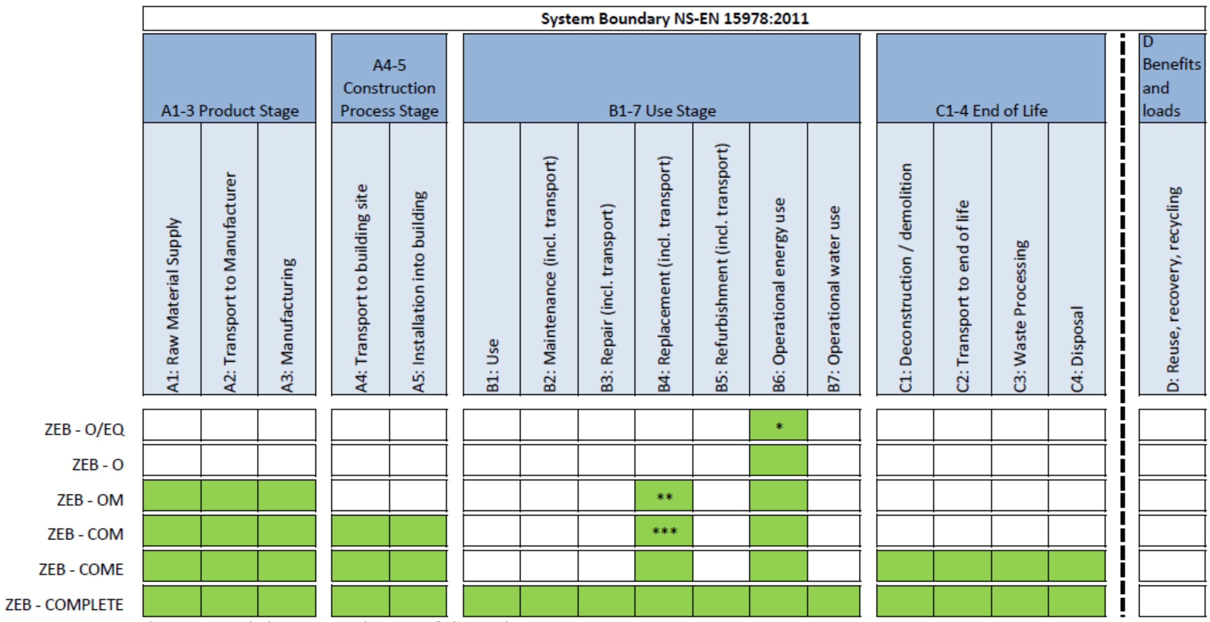
The background for this work was the establishment of the Powerhouse alliance and their goal to create buildings in Nordic climates that have a positive lifecycle primary energy balance. The Powerhouse alliance consists of the real estate company Entra, the construction company Skanska, Snøhetta architects, the environmental non-governmental organization ZERO, the aluminium company Hydro, the aluminium profile company Sapa and the consulting firm Asplan Viak. Four of the Powerhouse partners are also ZEB-partners and the first Powerhouse projects were developed in close cooperation with ZEB. In the future, the consortium plans to build on its experience and construct more energy-positive buildings, both in Norway and abroad (Skanska, 2014).

Figure 1.1 Building before renovation. Photo: Skanska.

Figure 1.2 Building after renovation (right). Photo: Chris Aadland / Asplan Viak.

1.2 Powerhouse Kjørbo ZEB-ambition level

The Norwegian Research Centre on Zero Emission Buildings (ZEB research centre) has been revising the Norwegian ZEB definition based on the relevant national and international work and experiences gained from the ZEB pilot building projects. The ZEB research centre measured the net ZEB balance in terms of greenhouse gas equivalent emissions (CO_{2eq}) as an indicator during the lifetime of a building (60 years) instead of on direct energy demand and generation (Fufa et al., 2016). The system boundary, in which the emissions are accounted for, has been defined in a range of ambition levels. The scope of the ambition levels have been standardised in accordance with the life cycle modularity principle defined in EN 15978 (see Figure 1.3).



* 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

Figure 1.3 Description of ZEB ambition levels according to NS-EN15978: 2011. (Fufa et al., 2016).

The lowest ZEB ambition level is ZEB-O÷EQ, which is equivalent to all emissions related to energy use for the operation of a building (O), excluding the energy use for appliances and equipment (EQ), shall be compensated for with on-site renewable energy generation. ZEB-COMPLETE is the highest ambition level whereby all emissions related to the entire life cycle of a building shall be compensated for with on-site renewable energy generation. That means, C (Construction) corresponds to life cycle modules A4 and A5 and represent transport of building materials from the factory to the construction site and the installation of building materials and other construction site activities. O (Operational energy use) corresponds to life cycle module B6 for operational energy use. M (Materials) correspond to life cycle modules A1 – A3 for the production of building materials and life cycle module B4 for the replacement of building materials. PLET corresponds to B1-B3, B5 and B7 life cycle stages for use, maintenance, repair, refurbishment and operational water use, and E (end-of-life) corresponds to end of life cycle modules C1 – C4 which include the deconstruction/demolition, transport of waste-to-waste processing site, waste processing and final disposal of the building materials.

The ZEB ambition levels were still under development when Powerhouse Kjørbo was designed and constructed. Furthermore, primary energy was considered as zero energy balance indicator in Powerhouse. Thus, the design project report in 2012 (Thyholt et al., 2012) described that Powerhouse shall fulfil the following ZEB requirements:

1. *Documentation of "zero energy" regarding the operation of the building over 60-year life-time perspective. CO_2-factors should be used in accordance with values defined by ZEB*.
2. *A greenhouse gas emissions account shall be carried out, and which includes transport of materials, construction of the building, maintenance and in case also renovation, and demolition of the building*. In 2012, methods for the calculations were still under development in ZEB, and quantifiable requirements for emissions were too early to define. However, a goal was set *to minimise the greenhouse gas (GHG) emissions associated with these activities*.

When translating these ambitions to the ZEB-ambition levels described by the Norwegian ZEB Definition Guideline (Fufa et al., 2016), the Powerhouse goal can be translated to the ZEB emission goals ZEB-COM÷EQ. This means that emissions related to all energy use in Construction "C", operation "O" except energy use for equipment/appliances (EQ) and embodied emissions from materials "M" shall be compensated with on-site renewable energy generation.

In this report, energy use for equipment (EQ) and the end of life "E" are also included in the GHG emissions account. GHG emissions account for all the ZEB-COME stages are thereby carried out, and a share of these emissions are covered.

Table 1.1 summarizes powerhouse goals and equivalent ZEB requirements, and life cycle stages covered. The Powerhouse goals are related to energy while the ZEB ambition levels are related to GHG emissions. This is further described in Chapter 5, 6 and 7.

Table 1.1 Comparison of the ZEB ambition levels and the Powerhouse goal. The Powerhouse goal are related to energy while the ZEB ambition levels are related to GHG emissions.

Life cycle stages	ZEB requirements		Powerhouse goals
	ZEB-COM÷EQ: **GHG** emissions from construction and installation process, operational energy use, except energy use for equipment / appliances and emissions from materials should be compensated with on-site renewable energy production	**ZEB-COME:** GHG emissions from construction and installation process, operational energy use, emissions from materials and end-of life phase shall be compensated with on-site renewable energy production	Generates at least the same amount of energy from on-site renewables as the energy used for construction and installation process, operation of the building (except energy use for equipment/appliances) and energy used for production of building materials.
A1-A3 Product stage	A1-A3	A1-A3	Embodied energy in materials should be compensated for
A4-A5 Construction process stage	A4-A5	A4-A5	
B1-B7 Use stage	B4, B6*	B4, B6	Energy use/production, except energy for equipment
C1-C4 End of life stage	-	C1-C4	Calculated and minimized, but not compensated for

1.3 Renovation of the Kjørbo office buildings

Before the renovation, the delivered energy to the two office buildings was about 240 kWh/m^2 per year, including energy for equipment. The delivered energy was divided on electricity (125 kWh/m^2), district heating (75 kWh/m^2) and district cooling (40 kWh/m^2) (Bernhard and Bugge, 2014). Heat losses for windows, ventilation, infiltration and thermal bridges were high. The façades were mainly covered by glass and black aluminium profiles. The black façade combined with lack of solar shading gave a high temperature inside and non-acceptable indoor climate conditions.

Energy efficiency measures and use of materials with low embodied energy have been crucial for obtaining the energy goal (Fjeldheim et al., 2015). An efficient ventilation concept has been developed, to reduce the overall energy demand for operation. The energy demand is covered by a heat pump and solar cells.

Key Data	
Name and address	Powerhouse Kjørbo, Kjørboveien 18-20, 1307 Sandvika, Norway.
Location data	Latitude 59°N, Longitude 10°E. Annual ambient temperature: 6.3°C, Annual solar horizontal radiation: 962 kWh/m^2
Building type	Two office building blocks (3 and 4 floors) connected by a common stairway. Originally constructed in 1979.
Heated floor area	5 180 m^2
Project type and ambition level	Renovation, Powerhouse Plus Energy (translated to ZEB-COM÷EQ), BREEAM Outstanding
Building owner / Tenant	Entra Eiendom AS / Asplan Viak
Design team	Snøhetta (architect), Skanska (contractor, energy advisor and BREAAM AP), Hydro/Sapa (PV and windows), Asplan Viak (technical consultants), ZERO (NGO) and the ZEB Research Centre (energy and GHG emissions).
Design phase	2009-2012 / 2012-2014
Construction phase	March 2013 – February 2014
Opening	March 2014

2. Building Design

2.1 Final Building design

2.1.1 Building location and form

Powerhouse Kjørbo is located by the river in Sandvika, Norway, 15 km from Oslo. The two buildings renovated in 2013/2014 were originally constructed in 1979. The buildings are part of a 9 building business park and are known as Building 4, with four floors, and Building 5, with three floors. The renovated buildings have a total heated floor area of 5.180 m^2. Figure 2.1 show the building location.

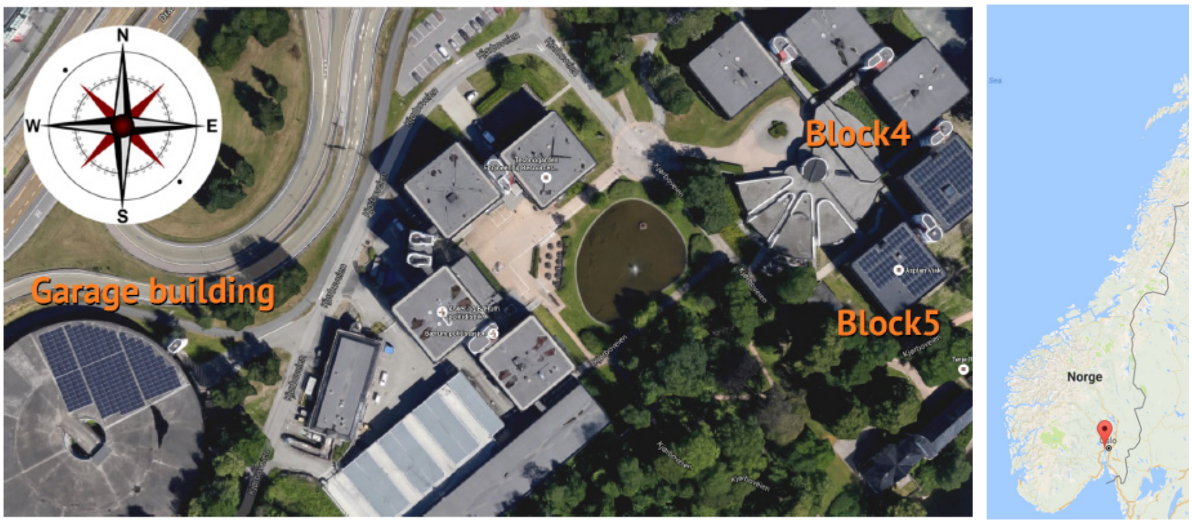


Figure 2.1 Blocks 4 and 5 are the renovated Powerhouse office blocks. Some PV panels are also placed on the roof of the garage building to the left. Screenshots from GoogleMaps

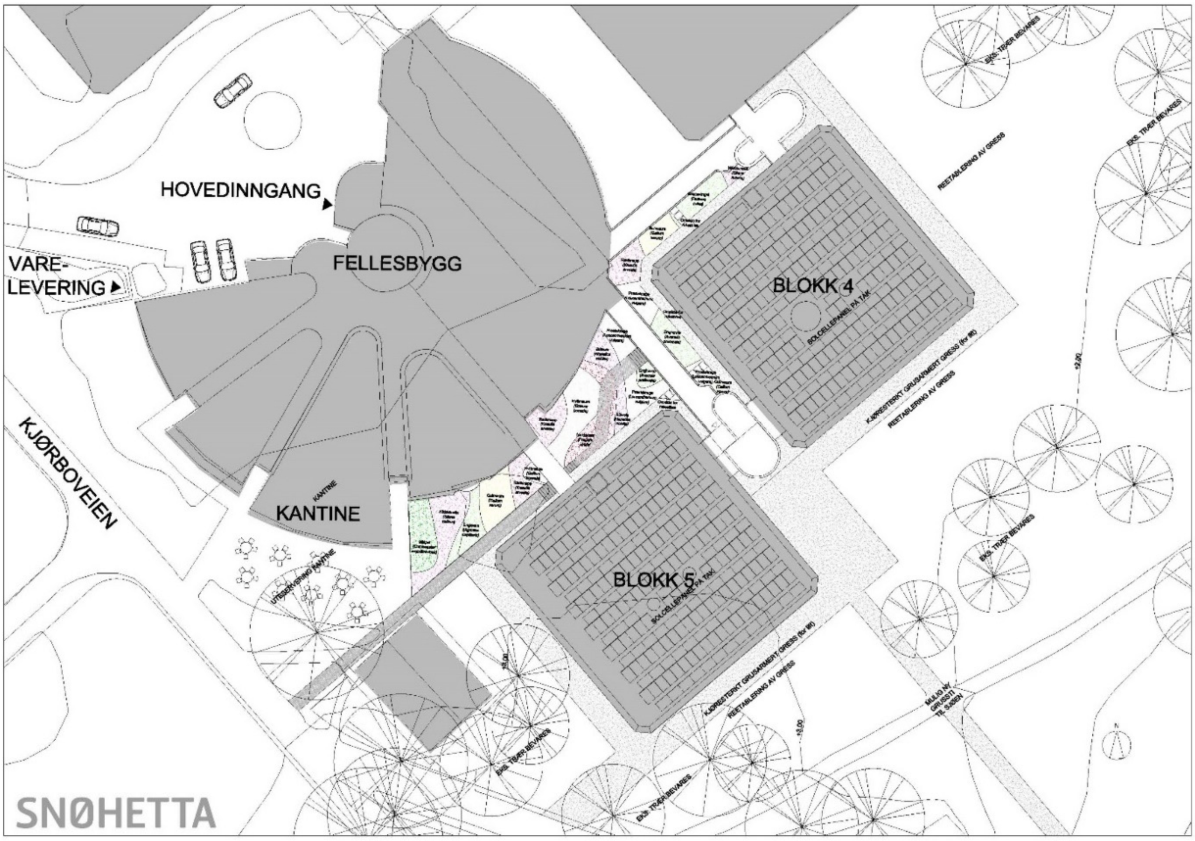


Figure 2.2 Sketch of the renovated Powerhouse office blocks 4 and 5. Illustration: Snøhetta.

A Powerhouse goal related to the building form is that "The energy goal must not be reached at the sacrifice of good architecture and indoor climate, or other central environmental qualities" (Chapter 2.1 (Thyholt) in Snøhetta et al. (2012)). During the design process, it was a focus on achieving such qualities. For example, to achieve interactions with the park, light, weather and seasons have been important in the development of the office environment in the Powerhouse Kjørbo project.

For the office area, the distribution between open landscape and cell offices is in the range of 30 / 70 % (Snøhetta et al., 2012). The two buildings are programmed for approximately 240 people, corresponding to an average area of 22 m^2 per person (Bernhard and Bugge, 2014).

Figure 2.3 and Figure 2.4 illustrate a typical floor plan of Powerhouse Kjørbo and section of the two office blocks, which are connected by a shared stairway.

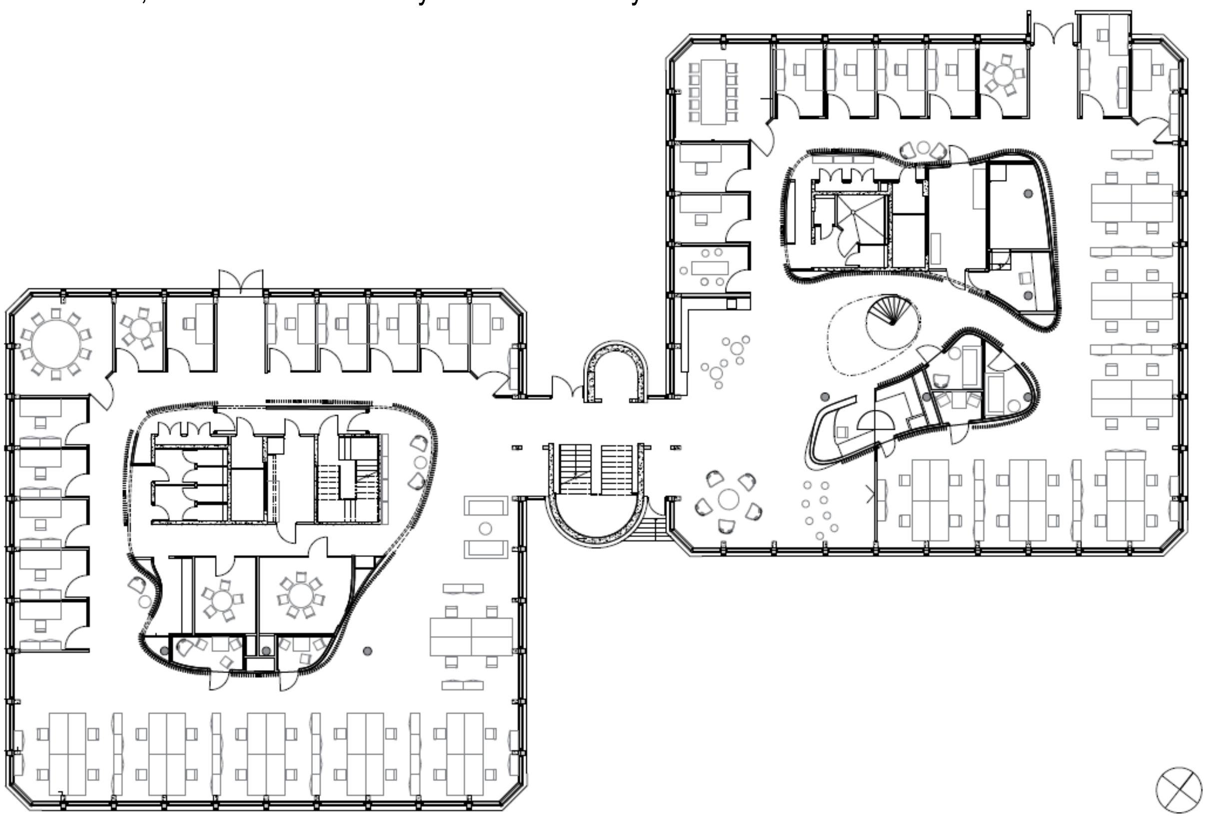


Figure 2.3 Typical floor plan. Illustration: Snøhetta.

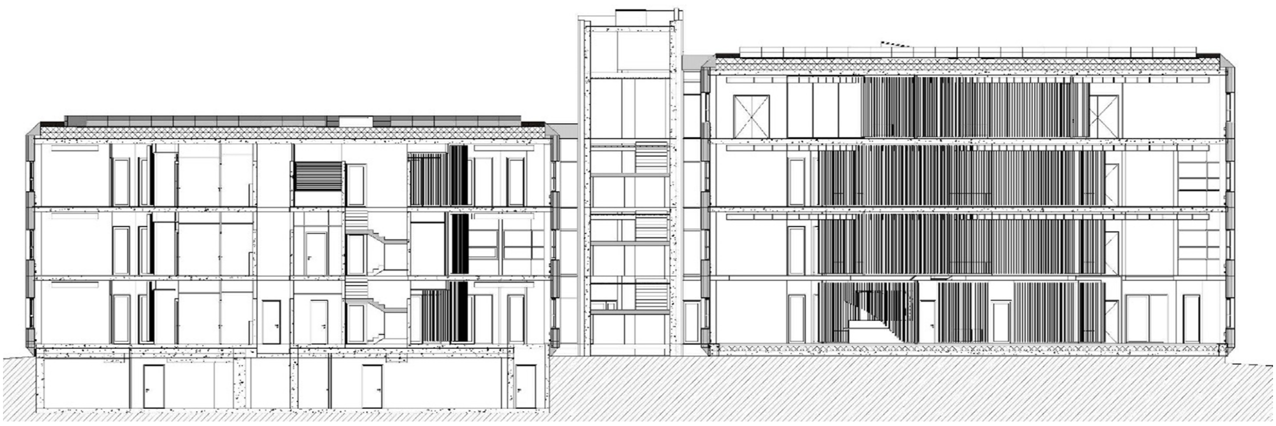


Figure 2.4 Section of the two office blocks. Illustration: Snøhetta.

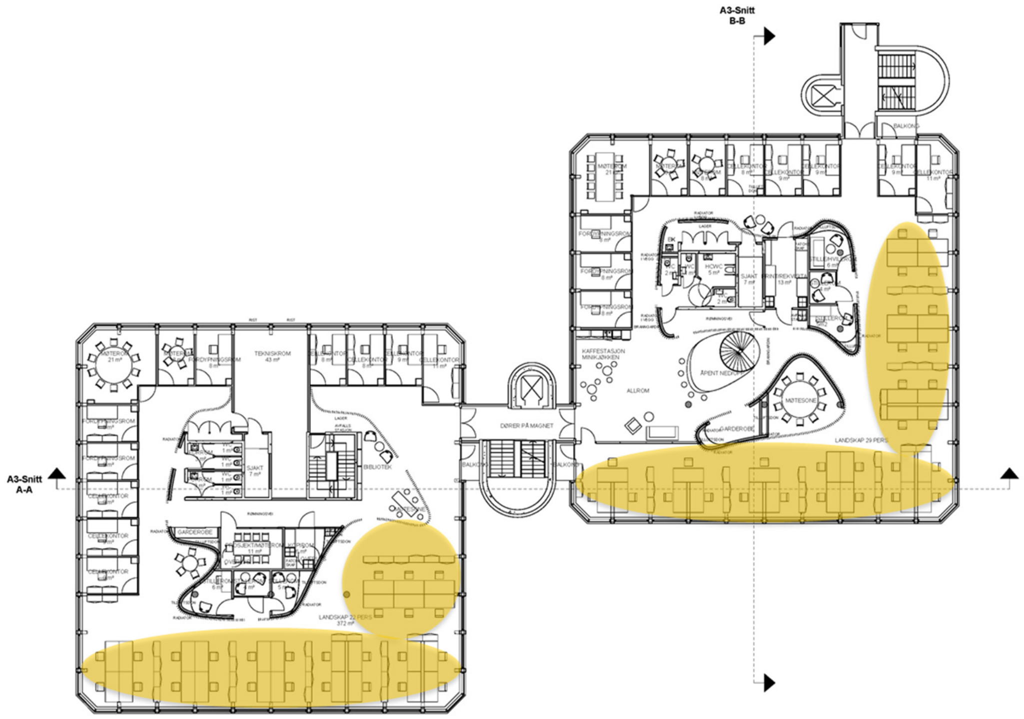


Figure 2.5 Illustration of how the office landscape areas are located at the most attractive areas (scenic view). Large open areas located along the southern facade also makes the indoor climate more robust against overheating. Illustration: Snøhetta.

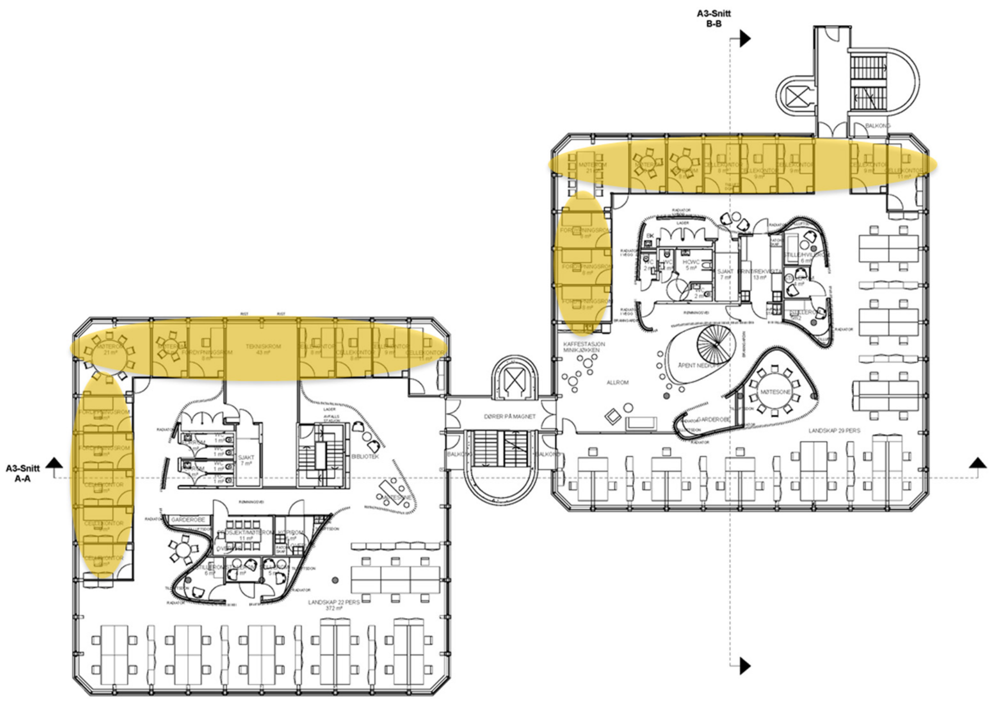


Figure 2.6 Illustration of how the cubicles are located along the northern and western parts to avoid high temperatures. Open doors to the cubicles are utilized as part of the ventilation strategy, with open doors when the offices are not in use. Illustration: Snøhetta.

2.1.2 Building envelope

The energy concept is based on the principle of first reducing the lifecycle primary energy demand, including both embodied and operational energy. This is further described in Chapter 2.2 Design choices.

Powerhouse goals related to the building envelope (Chapter 2.1 (Thyholt) in Snøhetta et al. (2012)) state that the building shall as a minimum fulfil the Passive House standard NS 3701. 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, sun shading, embodied energy and the possibility of natural ventilation (Jenssen, 2016).

Figure 2.7 The roof of Powerhouse Kjørbo prepared for improved insulation (left), and work on improving the insulation on the external wall (right). Photos from Jenssen (2016).

During the renovation, the original concrete structure was kept, including the stairs, shafts and the core. There was a need to change all the technical equipment and indoor materials (Hegli, 2016). The thermal properties for the building envelope are summarized in Table 2.1, before and after renovation.

Table 2.1 Thermal properties of the building envelope after and before refurbishment (Skanska Teknikk, 2012), (Brager-Larsen, 2014), (Overøye, 2012)

Properties	Before renovation	After renovation
U-value external walls	0.29 W/m²K	0.13 W/m²K
U-value roof	0.16 W/m²K	0.08 W/m²K
U-value floor on ground	0.16 W/m²K	0.12 W/m²K
U-value windows and doors	2.8 W/m²K	0.80 W/m²K
“Normalized” thermal bridge value (per m² heated floor area)	0.11 W/m²K	0.02 W/m²K
Air tightness, air changes per hour (at 50 Pa)	2.0	0.24

The facades were rebuilt with a 30 cm thick, insulated timber frame construction. External solar shading consisting of dark grey textile screens were fitted behind the wood cladding. The windows were slightly enlarged compared to the old building, to allow more daylight into the office space. The roof was upgraded with 40 cm rigid mineral wool insulation, and the basement exterior walls were insulated – where possible from the outside and, where not possible, from within.

Special care was taken to make the envelope as air-tight as possible. This was done by thorough detailing and a careful construction process. During the planning phase, at test wall was built for studying details for insertion and sealing around windows (Jenssen, 2016). The air leakage number was measured to be 0.24 ACH (Blower Door test at 50 Pa over/under-pressure) for the finished building, which is well below the passive house standard of 0.6 ACH. The thermographic pictures show no more thermal bridges than one would expect of this type of construction (Brager-Larsen, 2014).

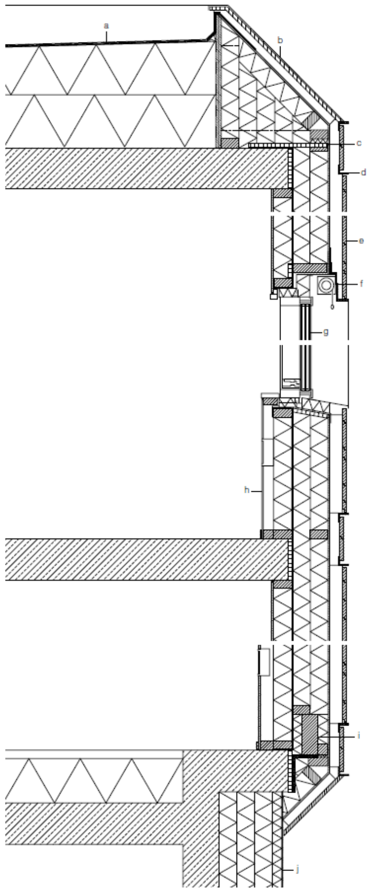


Figure 2.8 Section through exterior wall. Illustration from DetailGreen (2015).

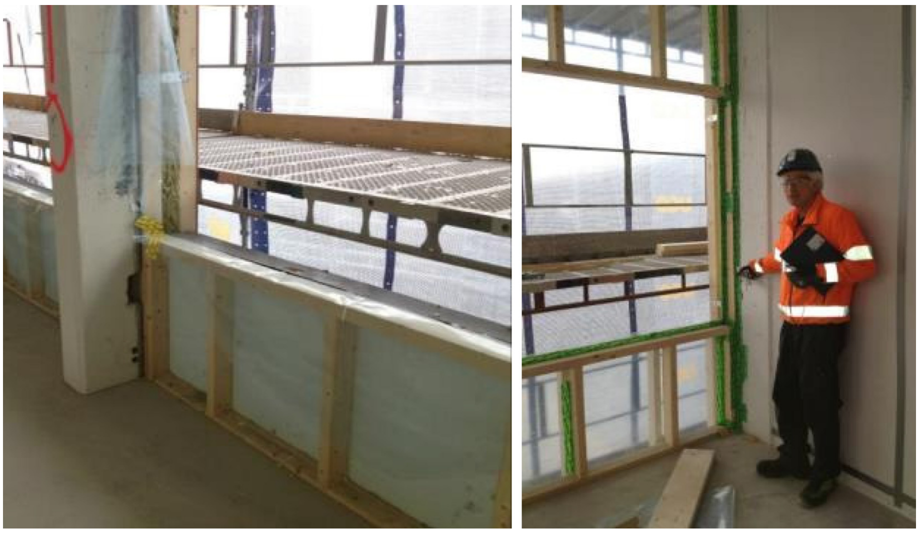


Figure 2.9 Thermal insulation on external walls of Powerhouse Kjørbo Block 5 (left), and sealing around windows (right). Photos from Jenssen (2016).

The windows were the part of the building envelope that were considered to have the highest improvement potential. The average total U-value has been calculated to 0.80 W/m^{2}K (Jenssen, 2016).

Technical details of windows in Block 4 and 5 is available in Annex 1.

The windows can be opened. However, the top-hinged ventilation windows conflicted with the sunscreens, which restrict the opening of some windows (Jenssen, 2016).

There are also windows in the common stairway, which open and close automatically. These windows are the most important windows for ventilation.

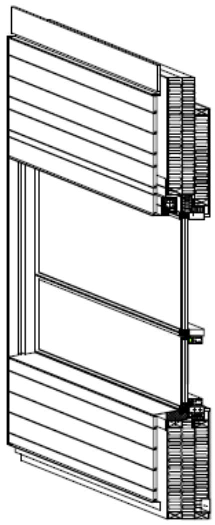


Figure 2.10 The windows. Illustration: Snøhetta

2.1.3 Building details

Building details for the windows and walls are shown in Figure 2.11 to Figure 2-14.

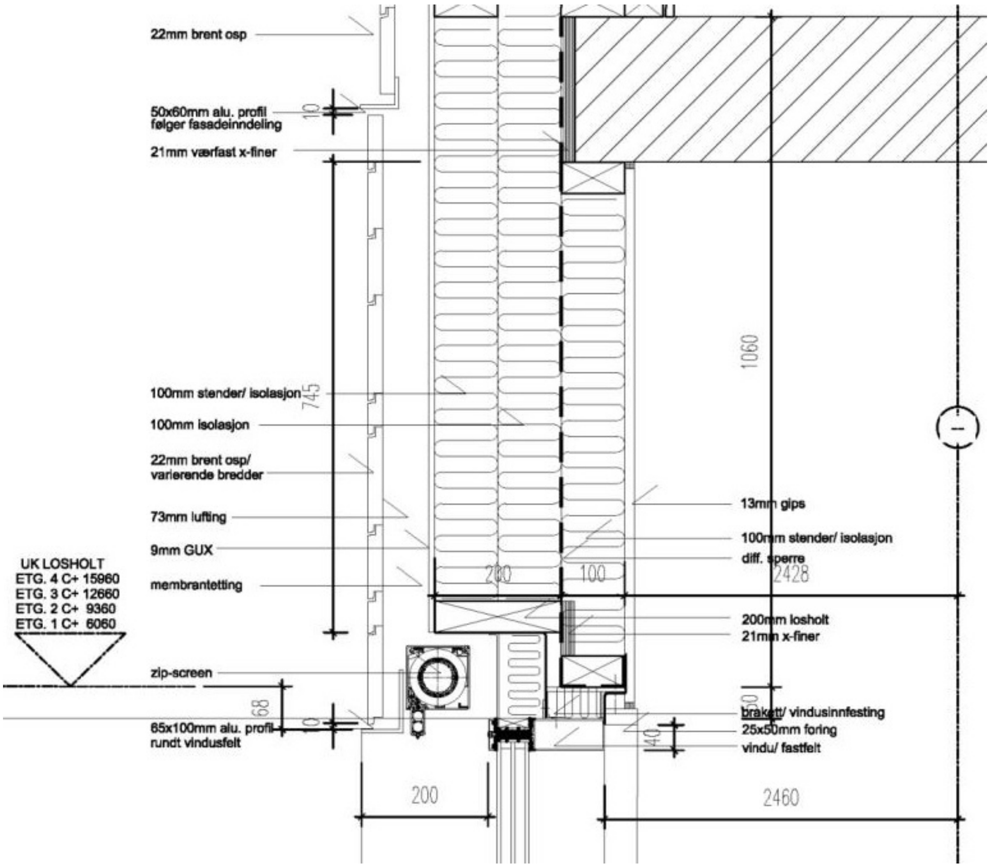


Figure 2.11 Vertical details above the window. Illustration: Snøhetta.

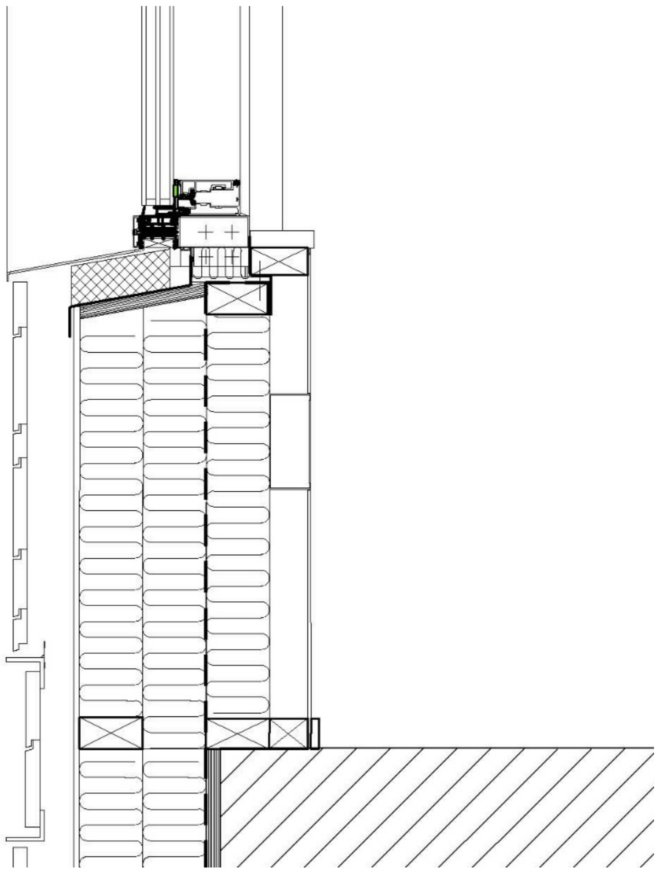


Figure 2.12 Vertical details under the window. Illustration: Snøhetta.

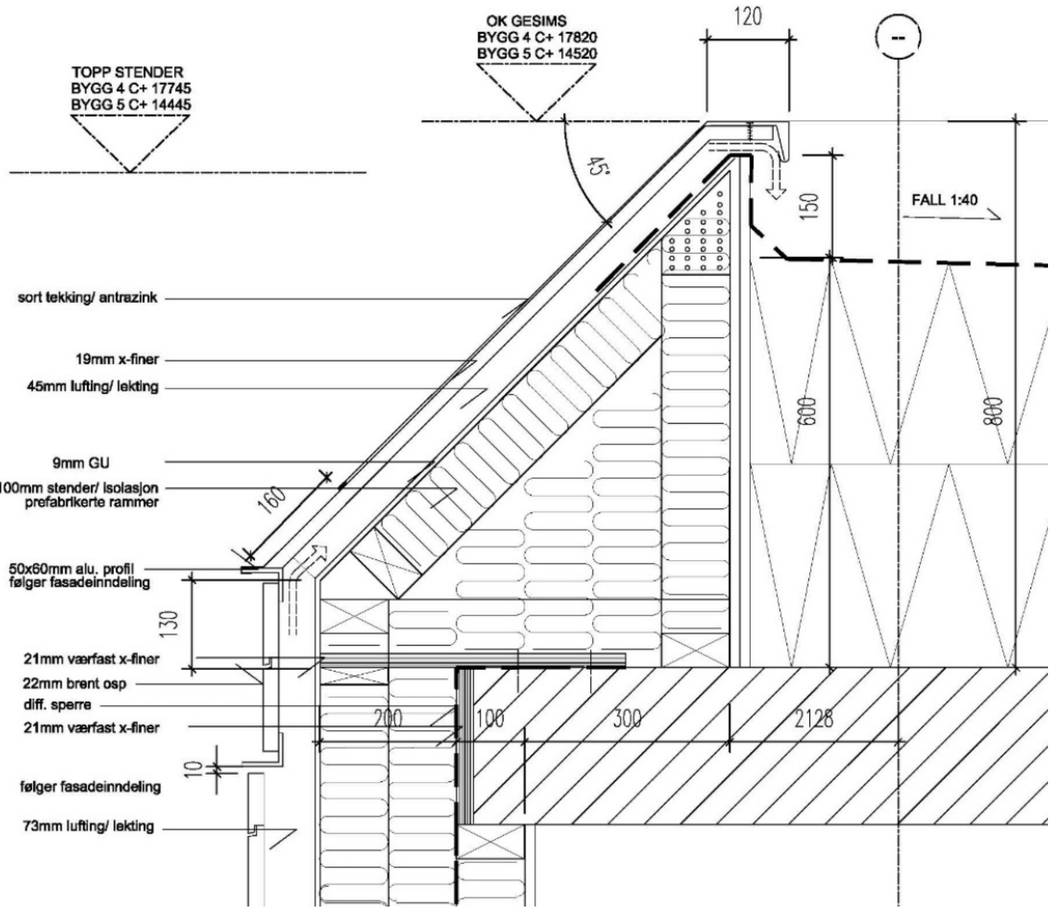


Figure 2.13 Vertical detail of the parapet. Illustration: Snøhetta.

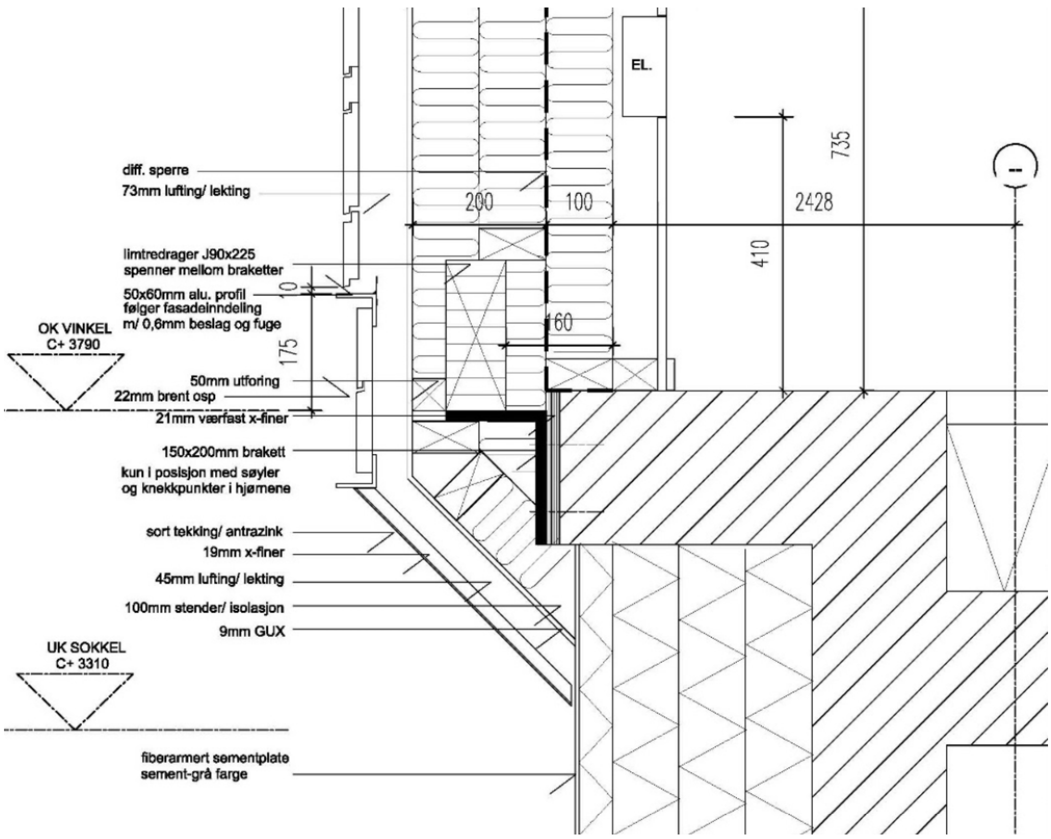


Figure 2.14 Vertical detail of the base. Illustration: Snøhetta.

2.2 Design choices

2.2.1 Design choices based on emission drivers

To reduce the embodied energy of the materials and components, all existing reinforcing steel and concrete constructions were maintained and reused in the refurbished building.

The existing glass facade panels were reused as interior office fronts in the refurbished buildings, as illustrated in Figure 2.15.

For the façade cladding, charred wood was chosen to minimize the energy for production, while achieving a relatively long service life and minimize maintenance frequencies. Charred wood is a technique the Japanese invented centuries ago for preserving/antiquing wood, calling it "shou sugi ban" or "yakisugi". In this method, the wood is burned enough to create a layer of char on the outside, which makes it significantly more fire-resistant as well as more resistant to rot and bugs.

Figure 2.15 Interior office fronts with reused glass facade panels. Photo: Skanska.

Figure 2.16 Charred wood in the façade. Photo: Snøhetta.

Figure 2.17 Charred wood in the façade. Photo: Skanska.

The team used the www.klimagassregnskap.no foot printing tool to help minimize embodied carbon emissions (Skanska, 2014). Technical conduits and pipes are attempted optimized to minimize material use, to reduce embodied energy. The photovoltaic modules were selected based on an evaluation of the overall balance between embodied energy and efficiency.

More sustainable modes of transport were promoted during construction, such as by distributing information about public transport to the workforce. The buildings are equipped with safe bicycle parking and good shower and changing facilities to encourage occupants to cycle to work. The buildings also have priority parking spaces for electric vehicles (Skanska, 2014).

2.2.2 Energy efficiency concept

There has been a particularly high focus on reducing the energy need for ventilation in the building, which is further described in Chapter 3.1. Furthermore, the energy efficient building envelope is combined with daylight utilization, a lighting control system suiting different user needs, energy efficient equipment and a ground source heat pump, which reduces the electricity demand for operation. (Fufa et al., 2016)

In the interior spaces, about 80% of all concrete ceilings are exposed (Rådstoga, 2017), so that the concrete slabs can be utilized as thermal mass to regulate the indoor temperature fluctuations and thus reduce cooling (and heating) loads. The exposed concrete surfaces requested a special focus on acoustics, which is further described in Chapter 3.3.

The floor layouts are designed to allow for efficient ventilation concepts and utilization of overflow to reduce the ventilation demand, and thereby the energy consumption. The workstations are located along the facades to utilize daylight and reduce the need for artificial lighting (Jenssen, 2016).

2.2.3 Energy generation concept

Heating is provided by a heat pump system which is connected to ten thermal 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 is circulated around the buildings by ensuring internal doors to the offices are kept open when the rooms are not in use (Skanska, 2014). The heat pump is also used to pre-heat the supply air and to heat domestic hot water. The buildings are also connected to district heating for backup. (Fufa et al., 2016)

“Free cooling” is provided by circulating the brine from the boreholes through a heat exchanger in the ventilation system. The need for cooling is reduced by solar shading, low heat loads from the lighting system and exposed concrete thermal mass in the ceilings to absorb excess heat (Skanska, 2014).

Electricity is generated by solar cells on the roofs of the two office buildings as well as on the neighbouring garage. The solar cell system has a total module area of 1556 m^2 and a total peak power of 312 kW_p. Only a fair share of the garage roof is used, so also the other office buildings on-site has available space for solar cells on the garage, if becoming Powerhouse-buildings later.

Chapter 4 provides more information on the energy supply system.

3. Building Services

3.1 Ventilation

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 for Powerhouse Kjørbo. This includes using low emitting materials to reduce the ventilation demand, demand control of ventilation supply, displacement ventilation, low pressure design to minimize fan energy, and heat recovery. The average ventilation air volume is about 3 $m^3/(m^2h)$ in wintertime with a maximum rate of about 6 $m^3/(m^2h)$ during warm days in the summer. The specific fan power varies between 0.5 and 0.8 [kW/m^3/s] during operation hours (Rådstoga, 2017).

The air intake is in the façade and the air-handling unit is located in a technical room below the roof of each building. Vertical supply ducts are integrated in the building core channel to the different floors. The air is supplied to single offices and the open area through diffusers. The VAV wall diffusers in the office landscape has a capacity of 800 m^3/h (Sangnes, 2016). The external pressure drop from the air-handling unit to the rooms is very low (~20Pa), due to the large volume of the channels and the low air velocity.

The cellular office diffusers were originally designed to supply air at a maximum ventilation rate of 100 m^3/h into each office, but the air flow rate through these diffusers has later been adjusted to 60 m^3/h (Sangnes, 2016). The return air is transferred to the corridor by means of overflow outlets and the staircases are used as the main exhaust duct. In addition, there are separate exhaust from copy rooms and bathrooms.

Figure 3.1 Ventilation air is supplied to the cellular offices and meeting rooms. The outlet goes through transmitting vents to the corridor and the main staircases. Photos: Jenssen (2016)

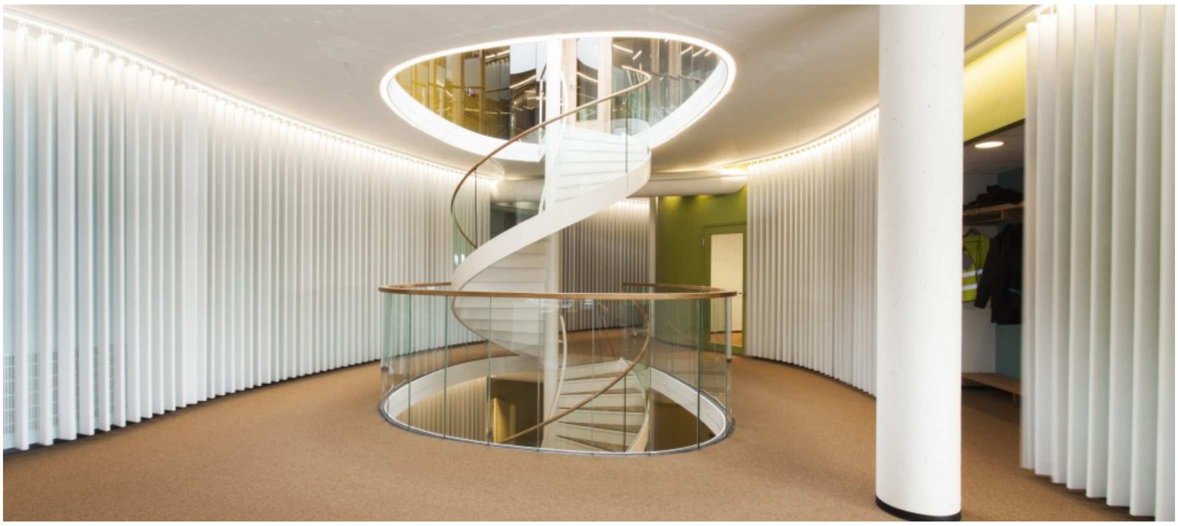


Figure 3.2 Picture showing exposed thermal mass in ceiling, vertical acoustic baffles on interior walls, and the central stairway that functions as a return air duct. A supply air diffuser is barely visible in the lower left corner of the picture. Photo: Chris Aadland / Asplan Viak.

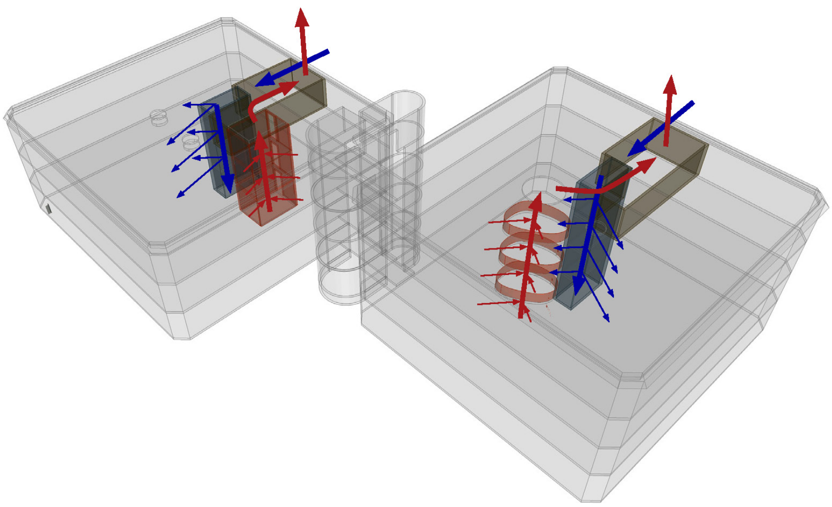


Figure 3.3 Ventilation principle, using stairways for the vertical return air channels. Illustration: Snøhetta.

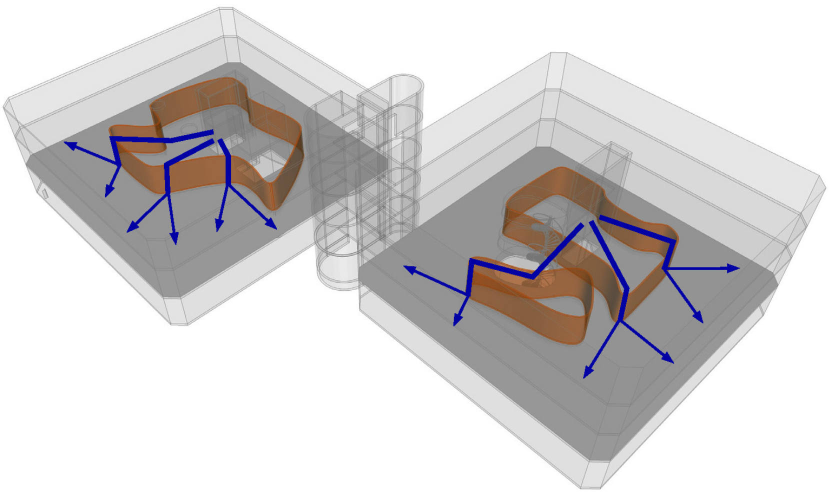


Figure 3.4 Ventilation principle, showing the horizontal distribution of supply air. Illustration: Snøhetta.

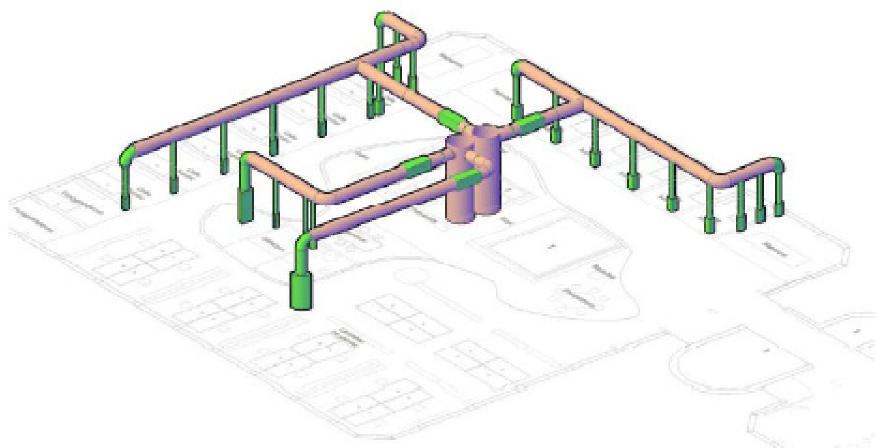


Figure 3.5 Illustration of typical air supply to a floor level. Illustration: Asplan Viak.

A heat recovery wheel is used to recover the heat from ventilation. Each unit was expected to recover approximately 87% of the heat from the exhaust air during the heating season, however, the measured efficiency during operation turned out to be somewhat lower, about 76% (Nordang, 2015). The main reason for this is believed to be a drop in heat recovery when the front air velocity is below 1 m/s through the rotating wheel. The heat recovery for Kjørbo is studied in more detail by Maria Justo-Alonso et al and by Peng et al (to be published in 2017).

Figure 3.6 shows a technical drawing of the ventilation units as built at Powerhouse Kjørbo (Søgnen (2015), from Asplan Viak).

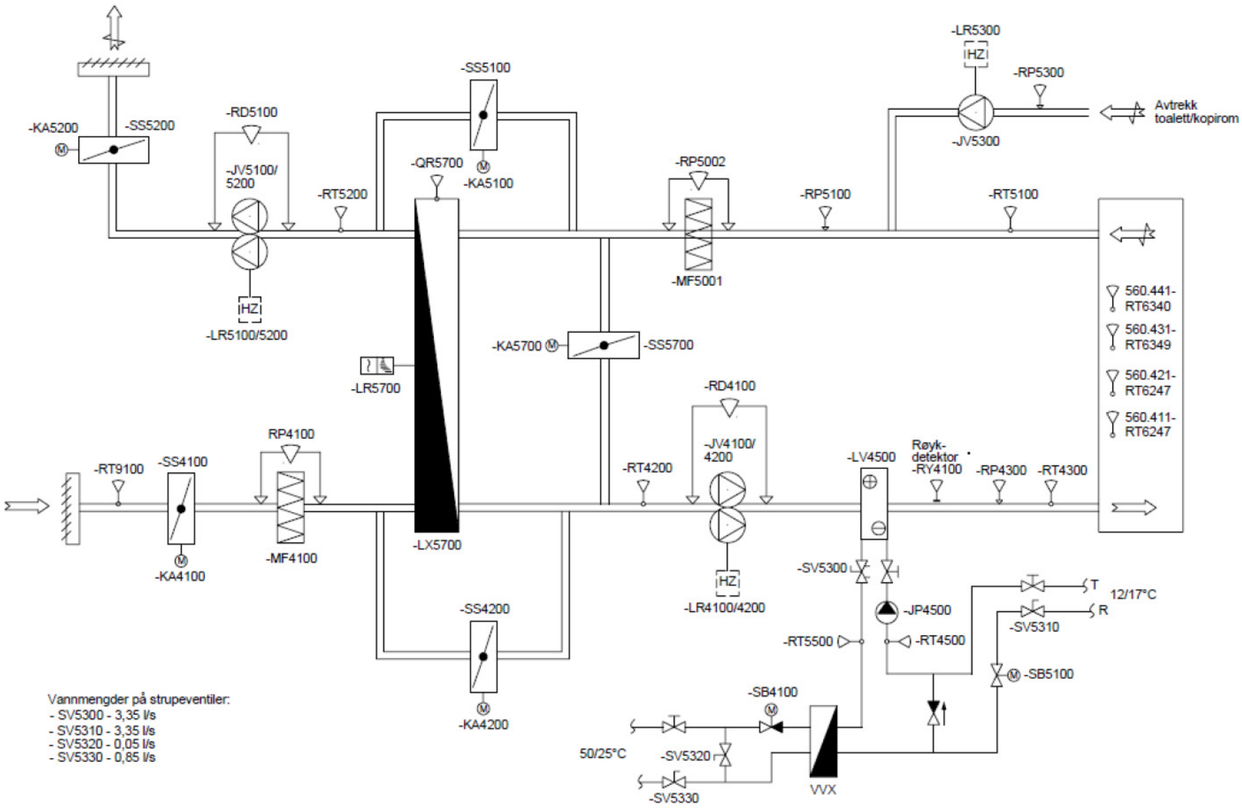


Figure 3.6 A technical drawing of the ventilation units as built at Powerhouse Kjørbo (Søgnen (2015), from Asplan Viak).

3.2 Lighting

The daylight level was analysed during the planning phase in 2012. The new windows were designed to allow a high level of daylight transmission and distribution in the rooms to reduce the need for artificial light (Skanska, 2014).

The lighting system is based on a combination of T8 fluorescent tubes in the office areas and LEDs in the common areas and the corridors. The general lighting level in the office areas is kept relatively low, at 300 lux, while desk lamps are provided for individual task lighting. The lighting is controlled by DALI (Digital Addressable Lighting Interface) according to occupancy and daylight level. The workstations are placed along the facades while the interior has open landscapes. The floor to ceiling height is larger and the glazed area has been increased by around 15% compared to the area before renovation.

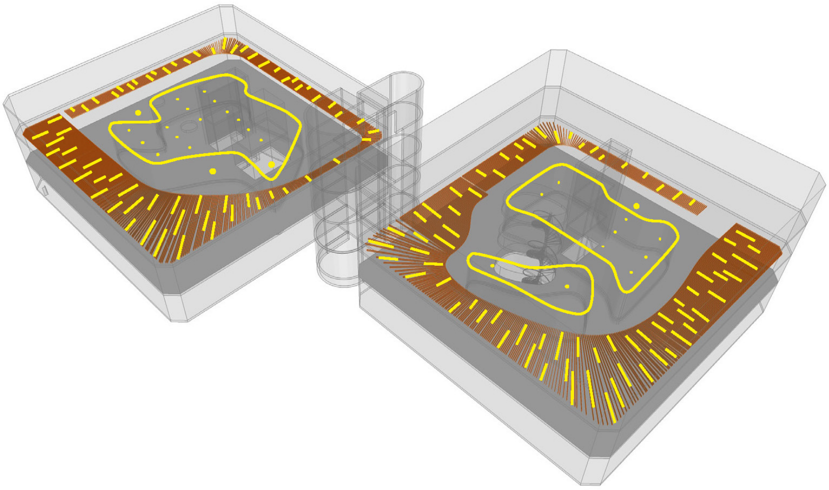


Figure 3.7 Illustration of the lighting system layout. Illustration: Snøhetta.

Figure 3.8 Lighting in Powerhouse Kjørbo. Photo: Chris Aadland / Snøhetta.

Figure 3.9 Lighting in Powerhouse Kjørbo. Photo: Snøhetta.

Figure 3.10 Lighting in Powerhouse Kjørbo. Photo: Chris Aadland / Snøhetta.

3.3 Acoustics

At Powerhouse Kjørbo, exposed concrete surfaces are used to reduce temperature fluctuations and avoid the need for mechanical cooling. However, this hinders the use of traditional acoustic ceilings. Other measures was therefore necessary to obtain satisfactory acoustic conditions (Jenssen, 2016).

Good acoustic conditions are reached by the use of proper zoning and material use. The wavy wall structures are designed for optimal zoning and sound attenuation in the open areas. The open office areas are not used as traffic zones for meeting rooms, offices or printer rooms etc. (Hegli, 2016).

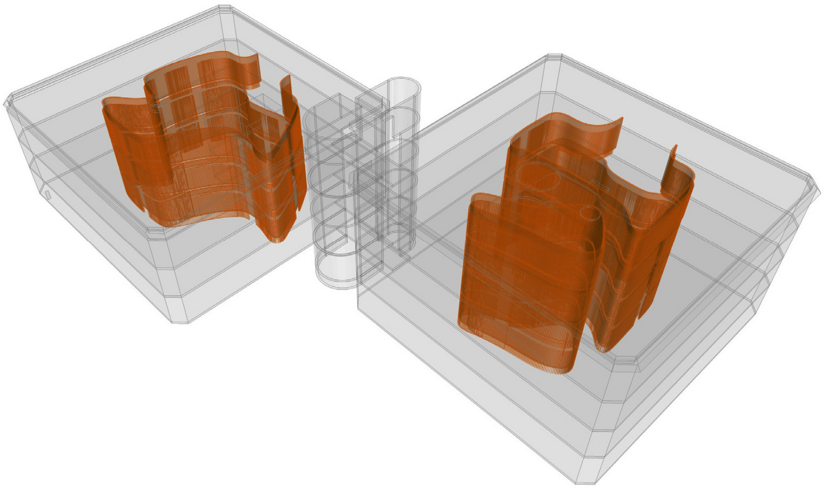


Figure 3.11 Illustration of the wavy wall structure. Source: Snøhetta.

Due to the open plan, it was also important to reduce acoustic resonance as far as possible. The architect therefore designed a system of sound absorbing baffles, which are suspended from the ceiling and/or the walls. The acoustic baffles consist of a fibrous insulation material manufactured from recycled plastic bottles, to lower the embodied energy of the insulation material.

Experiences from the construction phase was that the acoustic baffles were complex to mount. There was challenges with the plastic material loosening from the surfaces and the baffles had to be dust bonded after mounting. This solution proved to be relatively costly, but it resulted in the desired acoustic effect. The solution therefore demonstrates that it is possible to combine good acoustic conditions, with exposed thermal mass (Jenssen, 2016).

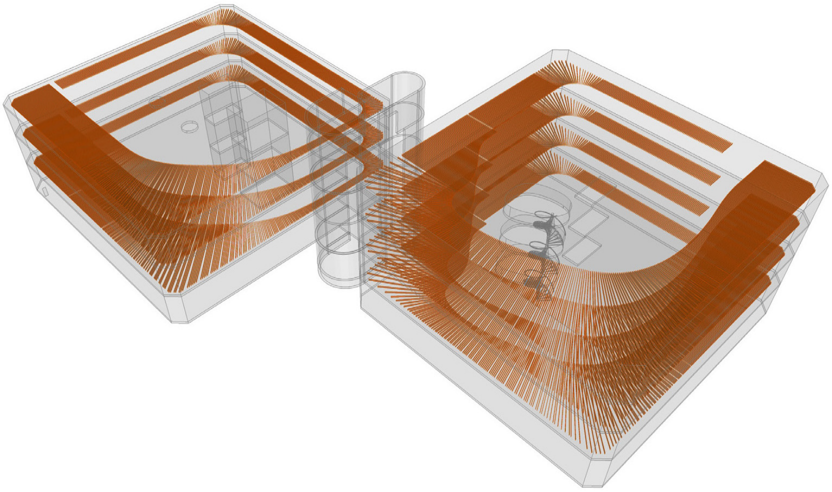


Figure 3.12 Illustration of acoustic baffles. Source: Snøhetta.

Figure 3.13 The acoustic baffles in Powerhouse Kjørbo. Photo: Ketil Jacobsen / Snøhetta.

4. Energy Supply Systems

4.1 Energy need and delivered energy

4.1.1 Powerhouse goal – Energy positive building

The Powerhouse goal is that during the building's life-time the building shall be a so called "energy positive building" or a "plus energy building". This implies that the building shall produce and export energy that compensates for energy used for production of materials[1], construction, renovation, operation and demolition ("embodied energy"). Exported energy must as a minimum be as high as the total energy used in a defined life-time perspective (Thyholt / Snøhetta et al. (2012)).

Energy consumption related to technical appliances (elevators, kitchen, IT, infrastructure, etc.) which belong to the users or are mainly influenced by the users and are likely to be changed during 60 years life time of the building won't be compensated with energy production. After more detailed information about the first tenants a separate energy goal (percentage of energy contribution or degree of autonomy) shall be defined. Furthermore, in order to ensure good interaction between the users and the building, this goal shall be followed up with separate measurements (Thyholt / Snøhetta et al. (2012)).

The geographic boundary of the project is the site on which the building is located. The Powerhouse boundary is similar to the Boundary II (On site generation from on-site renewable) shown in Figure 4.1 (Thyholt / Snøhetta et al. (2012)).

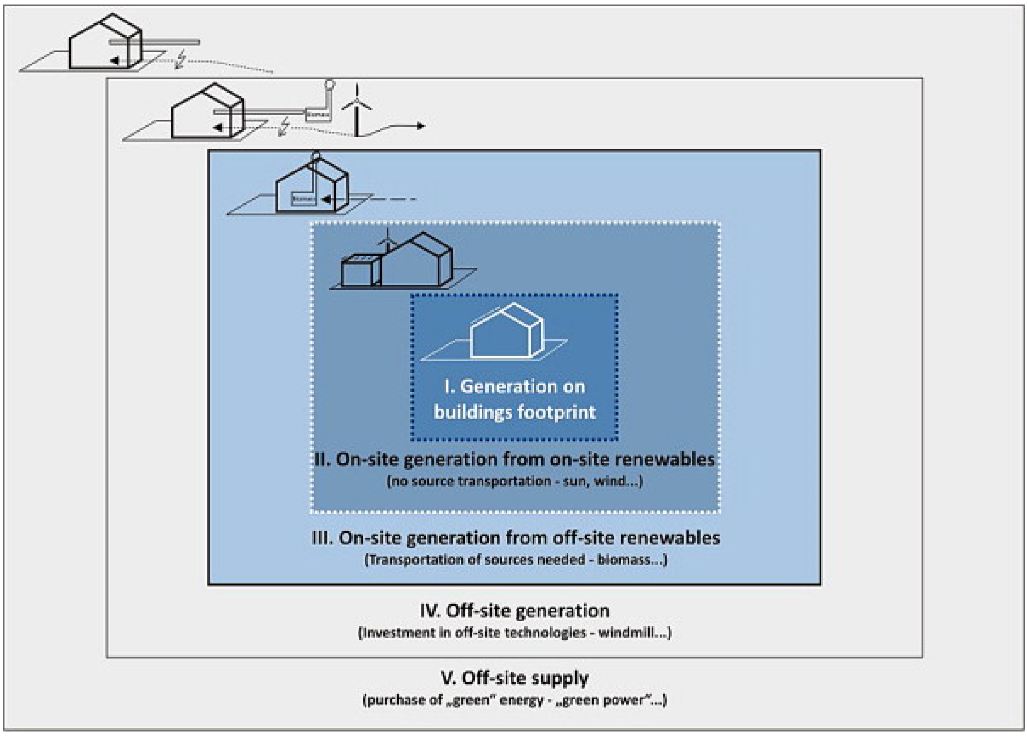


Figure 4.1 The Powerhouse boundary is similar to the Boundary II (On site generation from on-site renewable). Illustration from Marszal et al. (2011)

[1] For a renovation project, embodied energy in materials that are re-used, shall not be added to the energy account. To avoid double counting related to recycled materials, embodied energy related to demolition materials, which will be recycled, shall not be included as a deduction in the energy account. This embodied energy is to be taken into consideration in new projects (as for Powerhouse).

Other Powerhouse goals related to the energy systems (Chapter 2.1 (Thyholt) in Snøhetta et al. (2012)):

- The excess energy from electricity production can be exported to the grid, neighbour buildings or electric cars.
- Excess energy from heat production or from cooling, can be exported to the district heating grid or neighbouring buildings. If export to the district heating grid causes that heat from garbage incineration or waste heat from industry cannot be utilized in the district heat production, the exported energy cannot be included in the energy balance of the buildings.
- It is required that neighbour buildings which imports energy from Powerhouse fulfils the energy supply requirements given in TEK (technical regulations) or voluntary standards as passive house standard etc. If exported energy to neighbouring buildings replaces already "required" renewable energy, the exported energy cannot be included in the energy balance of the buildings.
- The energy balance for the operation period can be calculated for a period of up to one year, while the calculation period for the whole life cycle is to be set to 60 years.
- Powerhouse shall fulfil the ZEB requirements:
  1. Documentation of "zero energy" regarding the operation of the building, seen in a 60-year life-time perspective. CO_2-factors should be used in accordance with values defined by ZEB.
  2. A greenhouse gas emission account shall be carried out, and which includes transport of materials, construction of the building, maintenance and in some cases also renovation, and demolition of the building.

  When Powerhouse Kjørbo was planned, the methods for the calculations were still under development in ZEB.

4.1.2 Simulated operational energy performance

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

To allow for improvements during the initial operational period, the energy need during the first operational year was set to be 20% higher than the following "standard years".

The specific energy need for a standard year was calculated to be 78.9 kWh/m^2 heated floor area, or 53.5 kWh/m^2 without the energy use of appliances and server room.

If comparing the specific energy need with the energy frame for offices in the building code TEK10, standard values from NS3031 need to be used for operation time schedules, lighting, equipment and domestic hot water. If leaving all other parameters as in the SIMIEN-calculation, this gives an energy need of app. 106 kWh/m^2, which is below the energy frame for offices in new TEK of 115 kWh/m^2 (new TEK-rules from 2017).

The need for delivered energy is calculated to be 45.0 kWh/m^2, or 19.6 kWh/m^2 without appliances and server room. To qualify an office building for energy performance certificate grade A, the need for delivered energy has to be below 90 kWh/m^2. This is the case for Kjørbo, also when using NS3031-values for operation time schedules, lighting, equipment and domestic hot water.

Table 4.1 Predicted energy need and delivered energy for the first operational year and for the following years (Based on Jenssen (2016))

5180 m^2 heated area	Predicted, 1st year only				
	Energy need	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**kWh**	**COP**	**kWh/m^2**	**kWh/m^2**
Space heating	107 921	33 725	3,2	20,8	6,5
Ventilation heating	10 625	3 320	3,2	2,1	0,6
Domestic hot water	29 726	9 290	3,2	5,7	1,8
Fans	15 475	15 475		3,0	3,0
Pumps	11 300	11 300		2,2	2,2
Lighting	41 074	41 074		7,9	7,9
Appliances	52 912	52 912		10,2	10,2
Server room (IT)	105 120	105 120		20,3	20,3
Space cooling	0,00	0,00		0,0	0,0
Server room cooling	105 120	7 008	15,0	20,3	1,4
Ventilation cooling	11 322	755	15,0	2,2	0,1
Total	**490 595**	**279 979**		**94,7**	**54,0**
Without appliances + server room	**332 563**	**121 947**		**64,2**	**23,5**

5180 m^2 heated area	Predicted, standard year 2-60				
	Energy need	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**kWh**	**COP**	**kWh/m^2**	**kWh/m^2**
Space heating	89 934	28 104	3,2	17,4	5,4
Ventilation heating	8 854	2 767	3,2	1,7	0,5
Domestic hot water	24 772	7 741	3,2	4,8	1,5
Fans	12 896	12 896		2,5	2,5
Pumps	9 417	9 417		1,8	1,8
Lighting	34 228	34 228		6,6	6,6
Appliances	44 093	44 093		8,5	8,5
Server room (IT)	87 600	87 600		16,9	16,9
Space cooling	0,00	0,00		0,0	0,0
Server room cooling	87 600	5 840	15,0	16,9	1,1
Ventilation cooling	9 435	629	15,0	1,8	0,1
Total	**408 829**	**233 316**		**78,9**	**45,0**
Without appliances + server room	**277 136**	**101 623**		**53,5**	**19,6**

The predicted monthly distribution of delivered energy is shown in Figure 4.2. The prediction is valid for years 2-60 and is divided on the various energy posts.

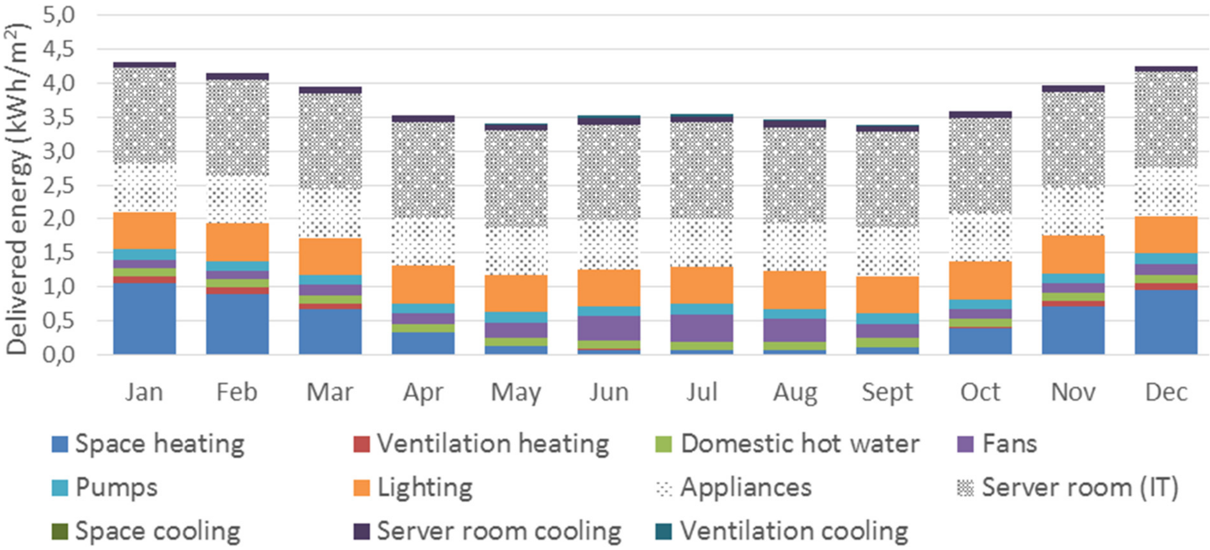


Figure 4.2 Predicted monthly delivered energy to Powerhouse Kjørbo, divided on the various energy posts.

When it comes to delivered electricity, the total yearly energy yield from the PV system was calculated to be 229 360 kWh during the initial year and 227 499 kWh during the second year, including all losses.

When calculating the solar energy production over 60 years, it is assumed a linear reduction of efficiency of the photovoltaic system totalling 20% at the end of the life cycle of 30 years (Jenssen / Skanska et al., 2015). The photovoltaic system is replaced after 30 year and it is assumed that the new photovoltaic system has an efficiency of 40% above current levels. The annual estimated solar energy production is illustrated in Figure 4.3.

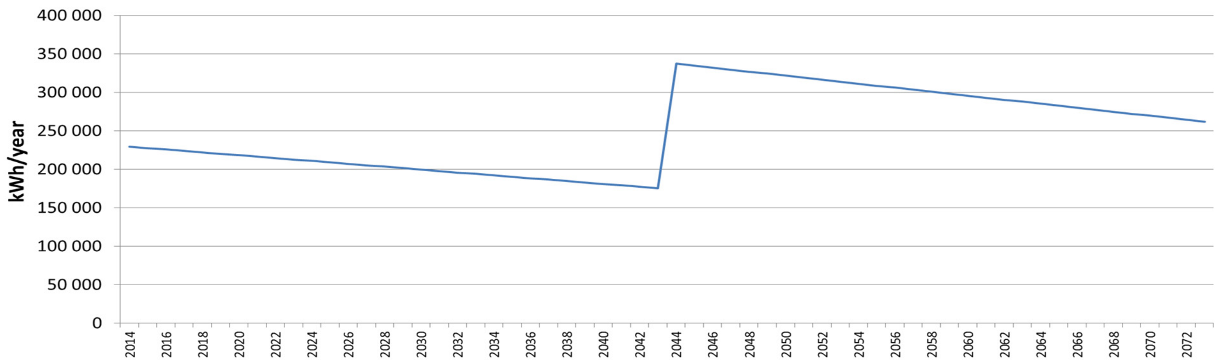


Figure 4.3 Annual estimated solar energy production at Powerhouse Kjørbo (Jenssen / Skanska et al., 2015)

Prior to construction, a simulation analysis of the PV system was performed using the software PVsyst (www.PVsyst.no) by the installers Solkompaniet Sverige AB (at that time named Direct Energy AB). Solkompaniet performed a simplified simulation of the three rooftops separately, with some differences from the design that was actually built (Ødegården, 2016).

The simulation was run with 936 modules, at 0± tilt and 100 % power loss due to snow from December to March. No other shadings was included in the model, but "near shading losses" was specified to be 2.4% for Block 4 and 1.1% for Block 5. The result was a theoretical electricity production of 229 000 kWh/year, with an average production of 210 000 kWh/year during their lifetime of 30 years. To compensate for degradation of approximately 0.5 % per year, the final installed system included 18 modules more than the simulated case (Ødegården, 2016).

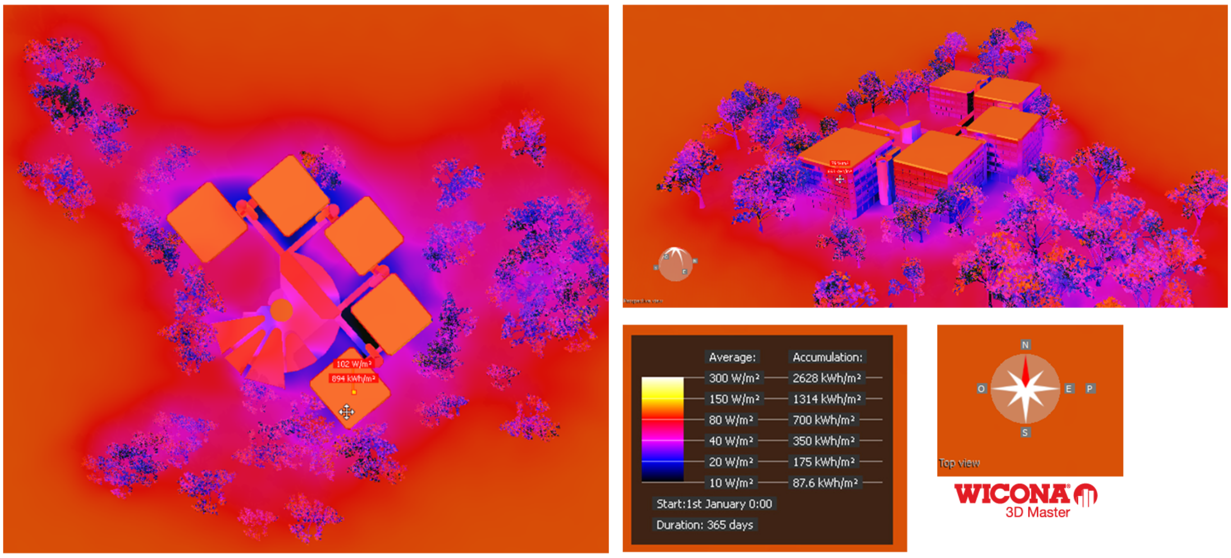


Figure 4.4 Calculation of the solar energy potential for the flat roof and the facades. Illustration: Hydro/SAPA.

4.2 Heating and cooling system

4.2.1 Overview of the heating and cooling system at Powerhouse Kjørbo

The heating system at Powerhouse Kjørbo is based on two brine-to-water heat pumps connected to boreholes for base heat load supply and domestic hot water. District heating is used as peak load and backup. Heating of the office spaces is provided primarily by radiators, which are attached to the core walls of the building. Cooling is mainly supplied with free cooling from the bore holes, with the possibility to utilize one of the heat pumps as chiller. The borehole park is dimensioned to cover the whole need for cooling, and the chiller has not been needed for the first three summers. Figure 4.5 shows a simplified sketch of the thermal energy system.

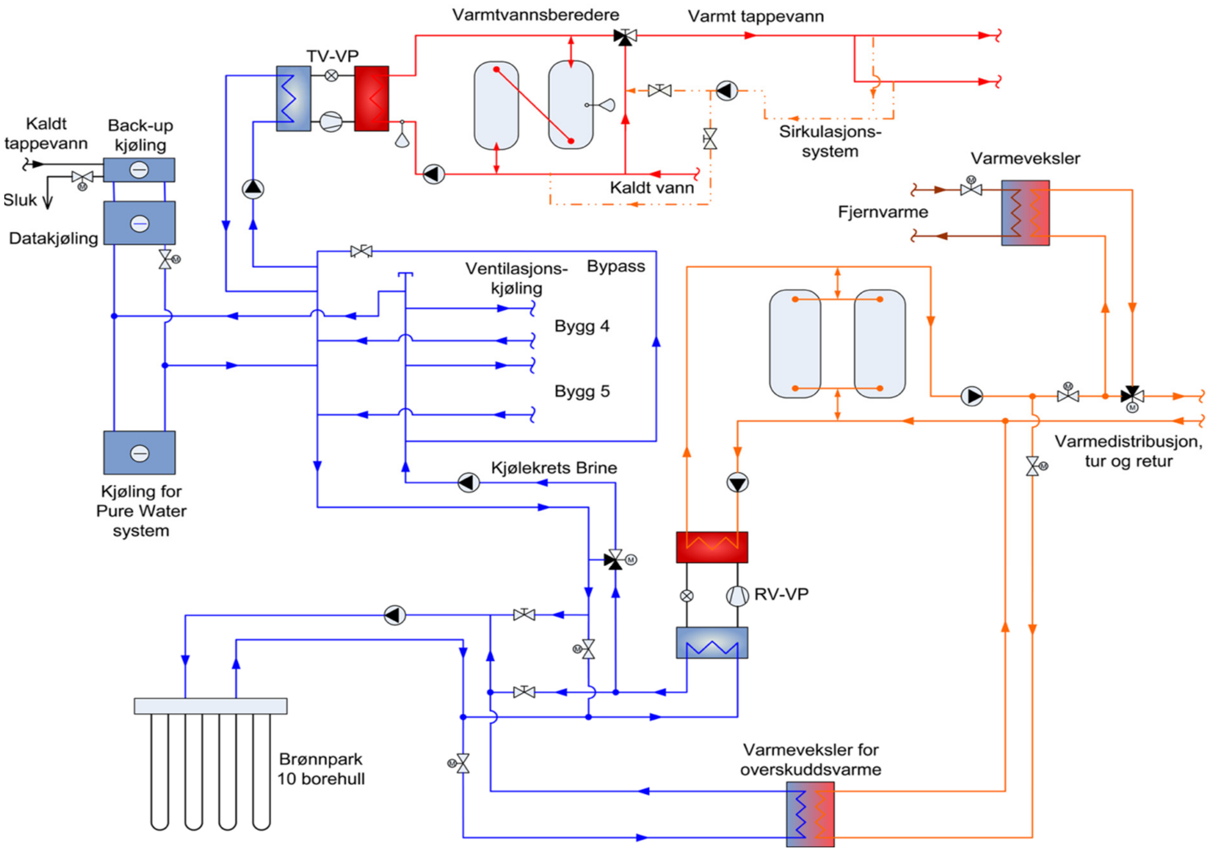


Figure 4.5 Simplified sketch of the thermal energy system – heat pump and liquid chiller, DHW heat pump and district heating heat exchanger – for space heating, heating of ventilation air, domestic hot water (DHW) heating, space cooling, and process cooling at Powerhouse Kjørbo (Nordang, 2014, Nordang, 2015)

The following subchapters describe the heating and cooling systems in more detail. More information can also be found in the master theses "Analysis of the Thermal Energy Supply System at Powerhouse Kjørbo" (Nordang, 2014) and (Nordang, 2015). Nordang (2015) is also discussing suggestions for improvement of the system design or operation of the current heating and cooling system, to make it more profitable. (Stene and Alonso, 2016) and (Alonso et al., 2017) are also describing and analysing the heating and cooling system, with focus on the heat pumps.

4.2.2 The heat distribution system

The heat distribution system utilizes centrally placed radiators and combined heating and cooling coils in the air handling units. The design temperature levels are 50/40°C for the radiators, and 50/25°C for the air handling units (Nordang, 2015).

The heating need in the office cubicles is marginal during working hours, even at the coldest days. Simulations showed that the temperatures would be satisfactory as long as the office doors are kept open when the offices are unoccupied and the temperature in the office landscape was increased to 22°C. Based on this, it was decided not to use separate radiators for each office. This simplified the radiator system and reduced pipelines, heat losses, pump work, number of components and thereby reduced the embodied energy and cost (Jenssen, 2016).

Outside the operating hours, the ventilation system can be run in "recirculation mode" (*omluftsfunksjon*) if additional heat is needed.

Operational experience and measurements seem to comply relatively well with the simulations, but with a lower need for space heating (radiators) than predicted and a higher need for ventilation heating. Some comments from occupants on cold offices and meeting rooms have been registered. More details on the energy measurements can be found in chapter 5.1.2 and indoor climate in chapter 5.2.

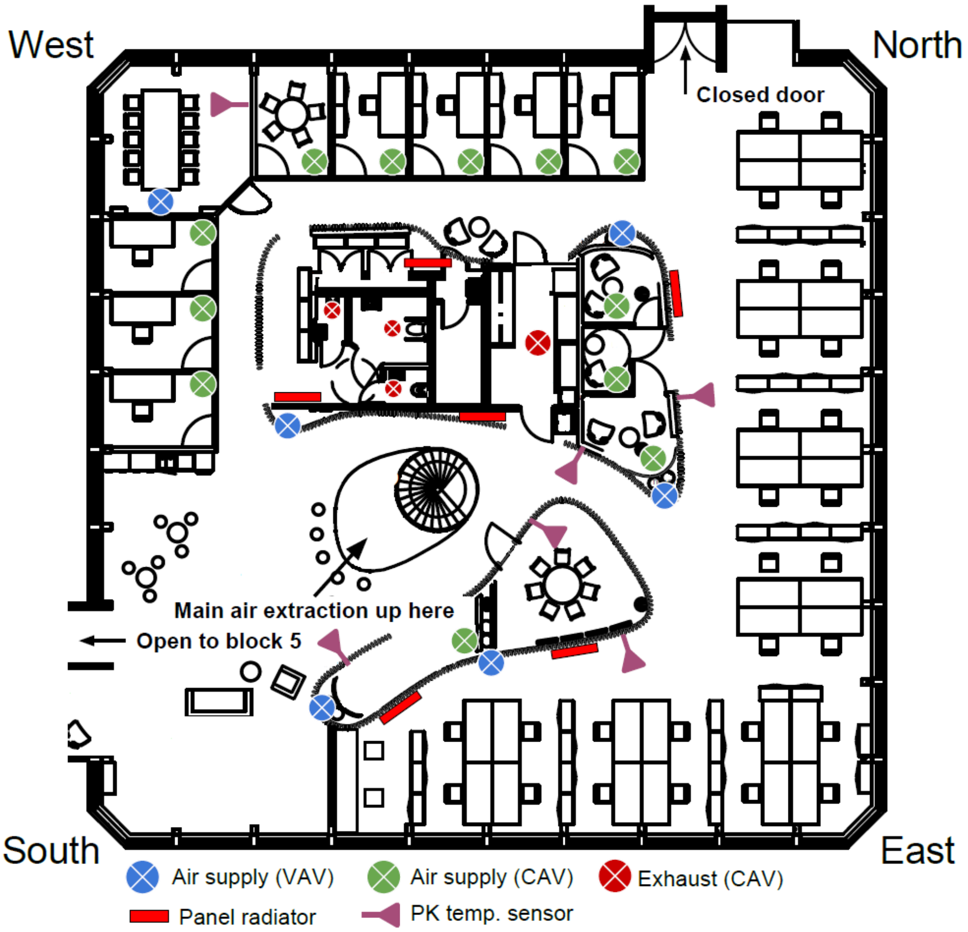


Figure 4.6 Building plan of the 2nd floor in block 4, illustrating the placement of the panel radiators as well as the air supply, exhaust and the temperature sensors. Illustration: Entra, from (Søgnen, 2015)

4.2.3 The borehole system

Two ground-source heat pump units are installed at Powerhouse Kjørbo (Stene and Alonso, 2016):

- A brine-to-water heat pump and liquid chiller unit for space heating and heating of ventilation air as well as back up for space cooling (described in Chapter 4.2.4),
- A brine-to-water heat pump for DHW heating (described in Chapter 4.2.5).

The heat pump units are connected to a common ground-source system comprising 10 boreholes, each approximately 200 m deep. The borehole system was designed to cover the entire space and process cooling need in the building (65 kW) by free cooling at 12/17 °C supply/return temperature in the distribution system.

I.e. the outlet brine temperature from the boreholes cannot exceed the required set-point temperature in the cooling system. In standard ground-source heat pump systems the heat pump is utilized as a liquid chiller that covers the peak load space cooling need in the building, and the excess condenser heat is rejected to the boreholes at a temperature level between 25-30 °C. The conventional system design requires fewer boreholes than a system based entirely on free cooling, but the annual energy consumption will be slightly higher due to occasional chiller operation during the summer. (Stene and Alonso, 2016) The solution at Powerhouse Kjørbo was chosen to reduce the electricity demand, which again reduces the needed area for solar cells (PV).

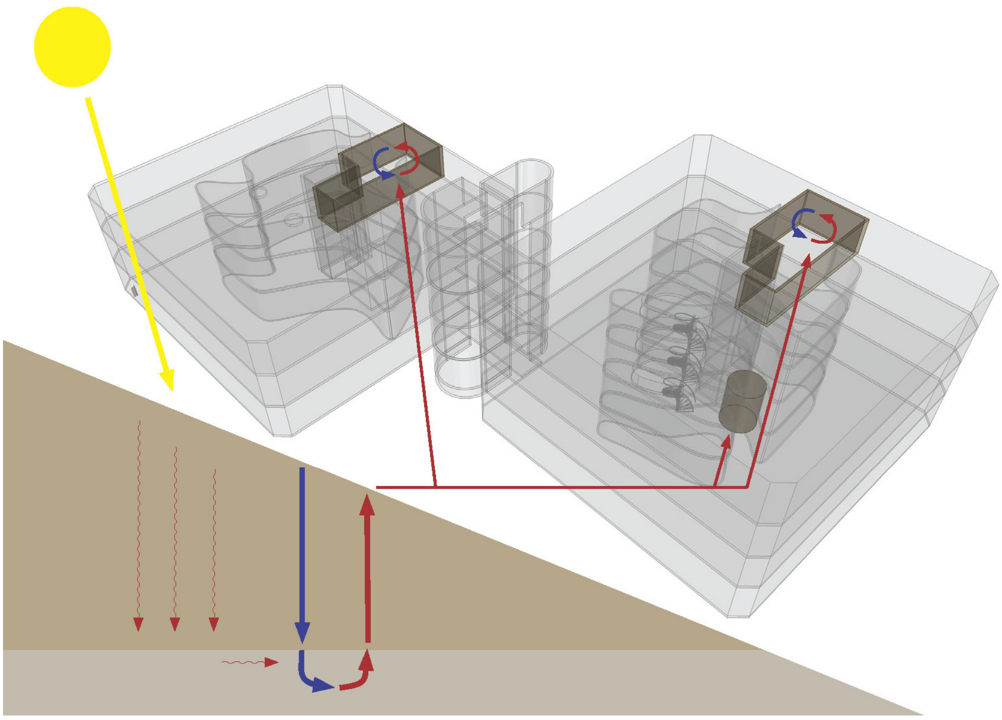


Figure 4.7 Illustration of the heat pump system. Source: Snøhetta.

The ground-source simulation programme Earth Energy Designer (EED) was used to calculate the average brine temperatures and thermal energy balance for the borehole system during several years of operation. Figure 4.8 shows the simulated and measured mean brine temperatures at max. power (capacity) and part load operation in heating and cooling mode.

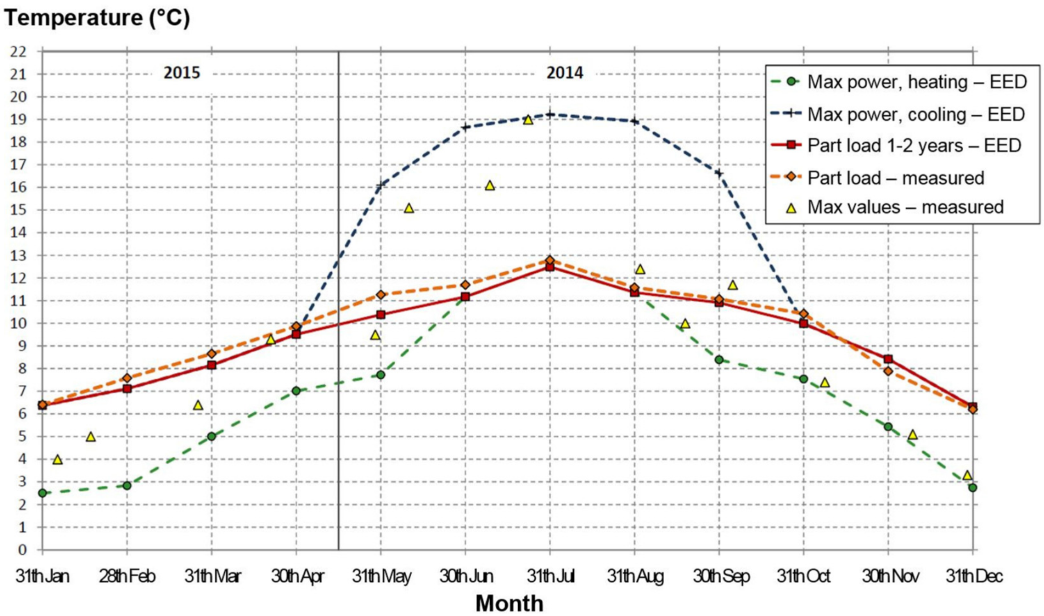


Figure 4.8 Simulated (EED) and measured average brine temperatures for the ground-source (borehole) system at max. power and part load in heating and cooling mode (Nordang, 2015), (Stene and Alonso, 2016)

Stene and Alonso (2016) describe that:

- The measured values corresponds rather well with the simulated values.
- The measured average brine temperatures during the heating season (space heating and heating of ventilation air) ranges from about 3 to 10 °C. The relatively high temperature level provided excellent operating conditions for the heat pump units.
- The measured minimum mean temperature during heating mode was as high as 3 °C.
- The measured maximum average brine temperature in cooling mode was approx. 19 °C.
- If standard design rules for the boreholes system had been applied, the number of boreholes could have been be reduced from 10 to 5 or 6, thus reducing the investment costs by approx. 40-50 % for the boreholes.

4.2.4 The heat pump and liquid chiller unit

The heat pump unit for space heating, heating of ventilation air and back-up space cooling (SH-HP) was designed to cover the gross power demand for heating. District heating is used as peak load and back-up only. (Stene and Alonso, 2016)

Two 900 litres accumulation tanks are connected to radiators and heating batteries in the air-handling/ventilation units, with design temperatures of 50/40 °C and 50/25 °C, respectively.

Table 4.2 Specifications of the heat pump unit for space heating, heating of ventilation air and back-up space cooling (Stene and Alonso, 2016), (Rådstoga, 2017)

Type:	Standard brine-to-water heat pump/chiller unit	
Heating capacity:	64 kW at 0/45°C	
Working fluid:	R410A	
Compressors:	2 scroll compressors, intermittent (on/off) operation. Max. 3 start/stops per hour	
Expansion valve:	Electronic type	
Max. outlet water temp.:	60°C	
COP:	4.2 at 0/35°C – data from manufacturer 3.4 at 0/45°C – data from manufacturer	Photo from (Jenssen, 2016)

The supply water temperature in the heat distribution system is controlled according to an ambient temperature compensation curve (control curve). This means that the supply temperature from the heat pump is reduced when the ambient temperature (i.e. the space heating demand) increases and vice versa. This maximizes the COP for the heat pump (Stene and Alonso, 2016).

The most important factors leading to a high SPF (seasonal performance factor of 3.9 (Alonso et al., 2017)) was the application of a low-temperature heat distribution system (50/40°C) and the oversized ground-source system with a relatively high average brine temperature. The use of a separate domestic hot water heat pump allows the space heating heat pump to operate at lower temperatures.

4.2.5 The heat pump for domestic hot water heating

The heat pump for domestic hot water heating (DHW-HP) is a standard R407C brine-to-water heat pump unit. The heat pump recovers heat from the computer cooling (Nordang, 2015). There are two storage tanks for domestic hot water of 550 litres each.

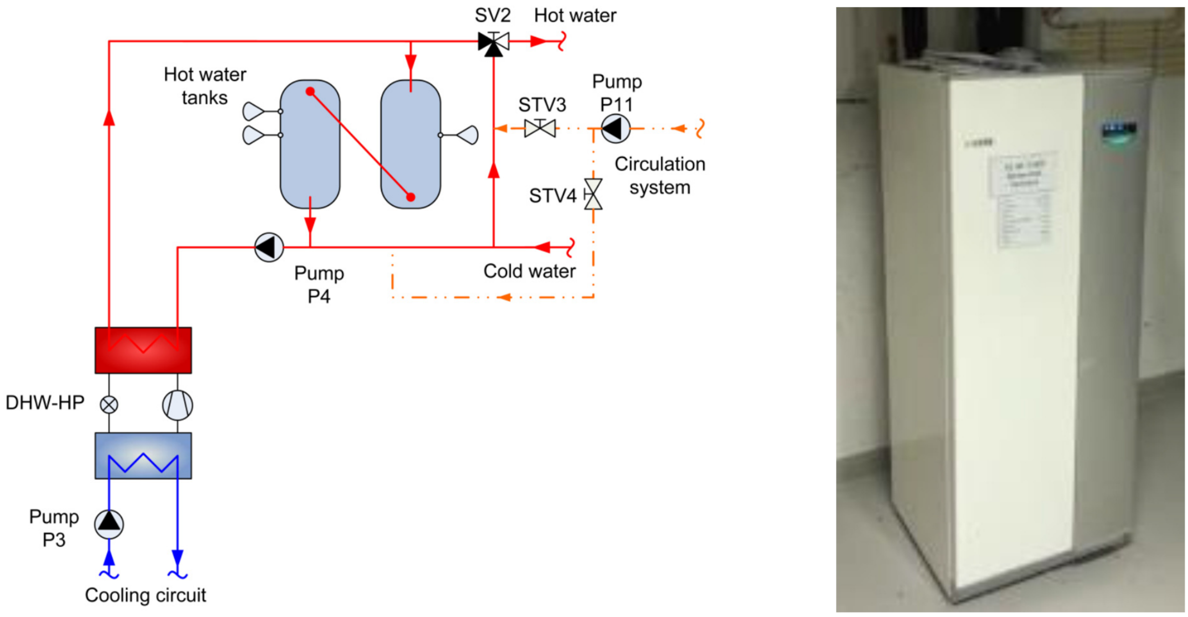


Figure 4.9 Left: Design of the DHW system (Nordang, 2014). Right: The heat pump DHW heater at Powerhouse Kjørbo. Photo from (Jenssen, 2016)

Table 4.3 Specifications of the heat pump unit for domestic hot water (Stene and Alonso, 2016)

Type:	Standard R407C brine-to-water heat pump unit
Heating capacity:	8.5 kW at 0/45 °C – residential unit
Working fluid:	R407C
Compressors:	1 piston compressor, intermittent (on/off) operation Max. 3 start/stops per hour
Expansion valve:	Thermostatic type
Max. outlet water temp.:	65 °C
COP:	4.8 at 0/35 °C – data from manufacturer 3.8 at 0/45 °C – data from manufacturer

The two storage tanks for domestic hot water (Oso Hotwater) are connected to the DHW-HP in series. Temperature sensors send signals to the central control system and the DHW-HP. One of the tanks has an electrical immersion heater for back-up (Nordang, 2014).

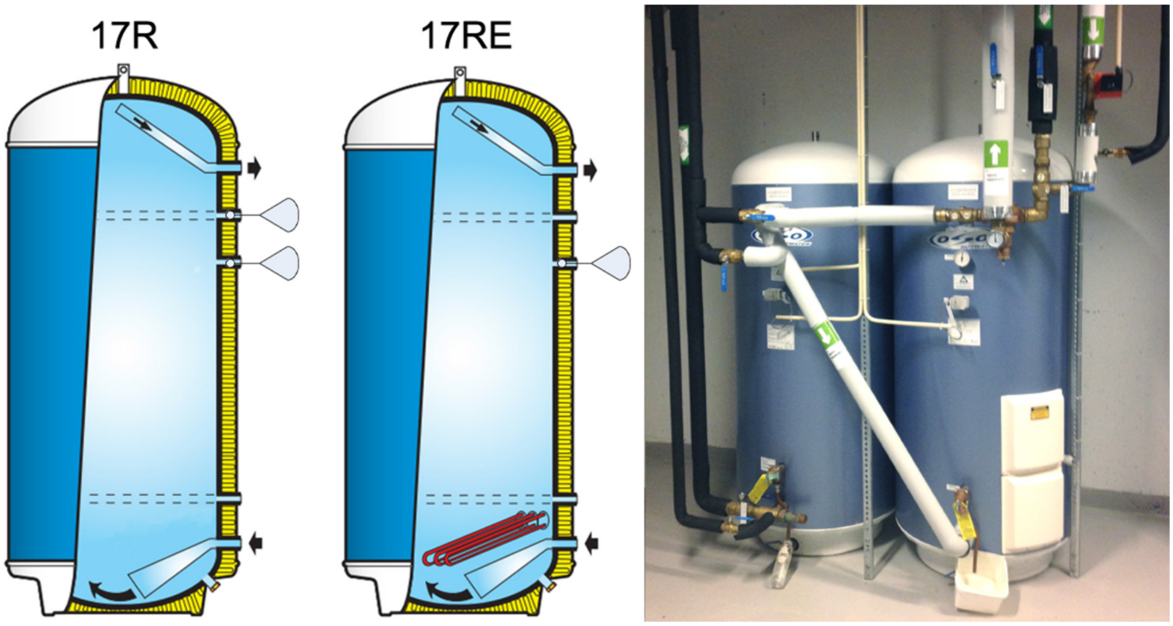


Figure 4.10 The DHW storage tanks. Foto to the left: (Oso Hotwater, 2014b), modified picture. (Nordang, 2014)

4.2.6 Heating and cooling operating modes

The heat pump and liquid chiller system is operated in "Heating Mode" or "Cooling Mode". The details of the two modes are described by Stene and Alonso (2016).

In heating mode, the space and DHW heating needs are the dominating thermal loads. There is no space cooling need, but a small process cooling need. In cooling mode, the demand for process cooling and space cooling are the dominating thermal loads. There is no space heating need, but a DHW heating need.

“Free cooling” is provided by circulating the brine from the boreholes through a heat exchanger in the ventilation system. The brine temperature is about 8-10°C. During the first three summers, this was sufficient to cool the building, and there was no need to switch the heat pump on as chiller (Rådstoga, 2017).

For the server room, a cooling system of 15 kW was installed. Experiences from the first two years show that only a capacity of 5 kW was needed, however. The installed capacity of data servers are also somehow smaller than planned. During winter, the excess heat from the server room is used for preheating of domestic hot water and for space heating.

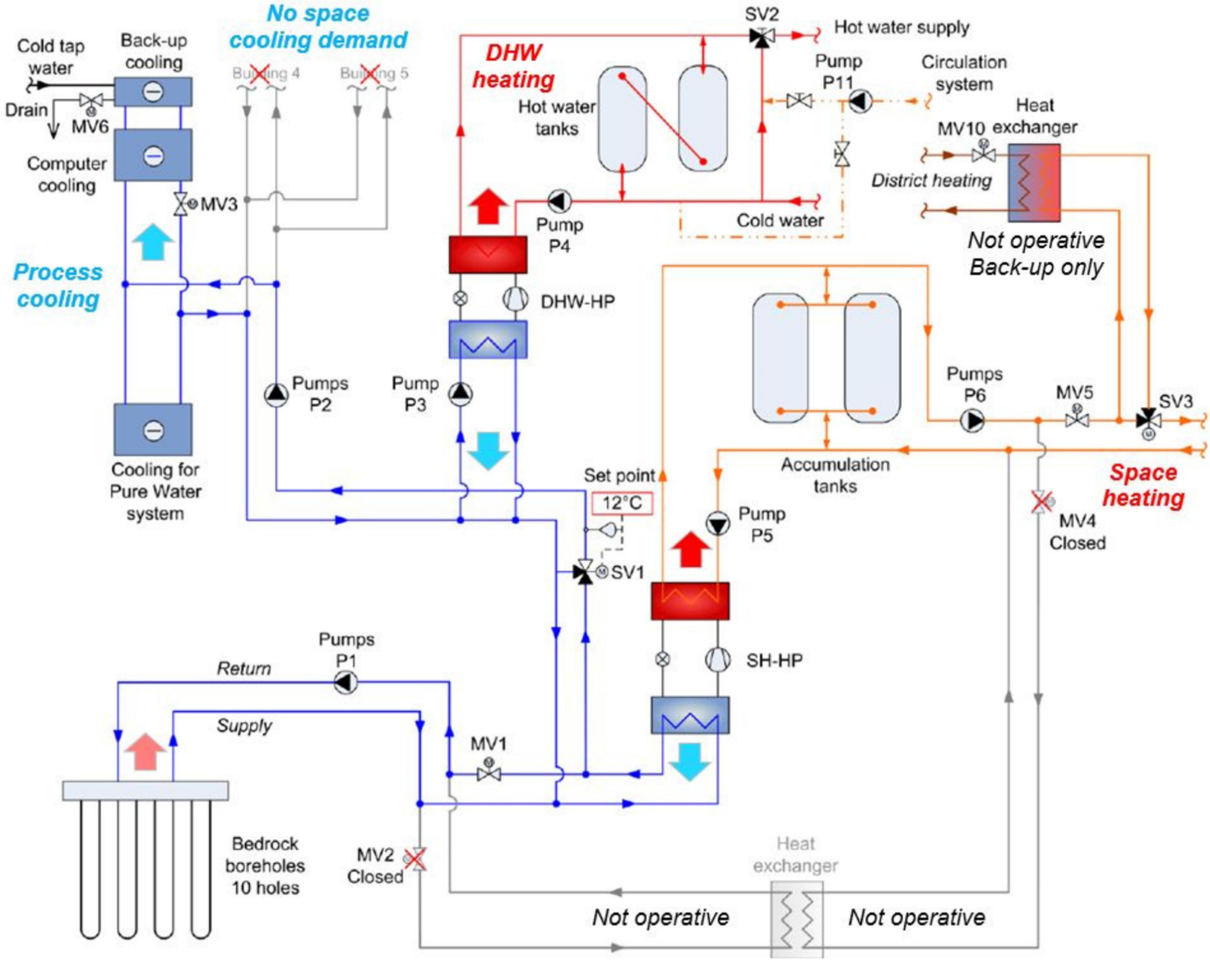


Figure 4.11 The thermal energy system operating in "Heating Mode – heat pump mode". Both space heating and DHW heating – process cooling but no space cooling (Nordang, 2014, Nordang, 2015)

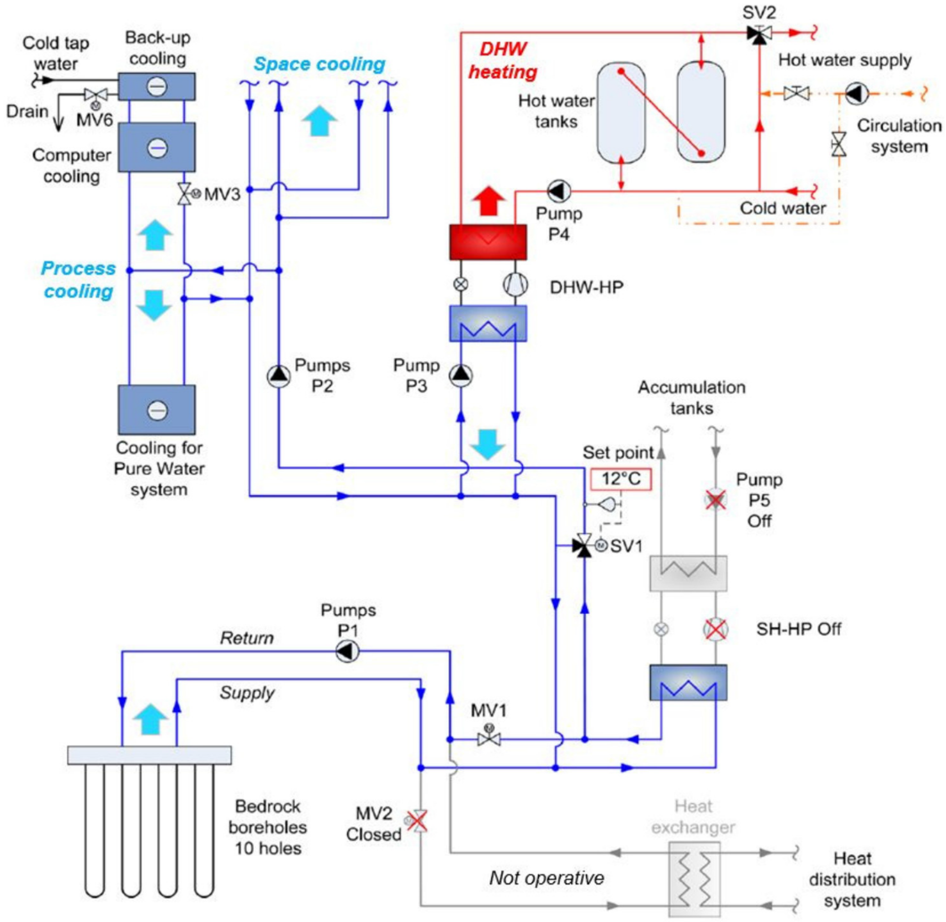


Figure 4.12 Thermal energy system operating in "Cooling Mode, free cooling only". DHW heating but no space heating. Process cooling and space cooling (Nordang, 2014, Nordang, 2015)

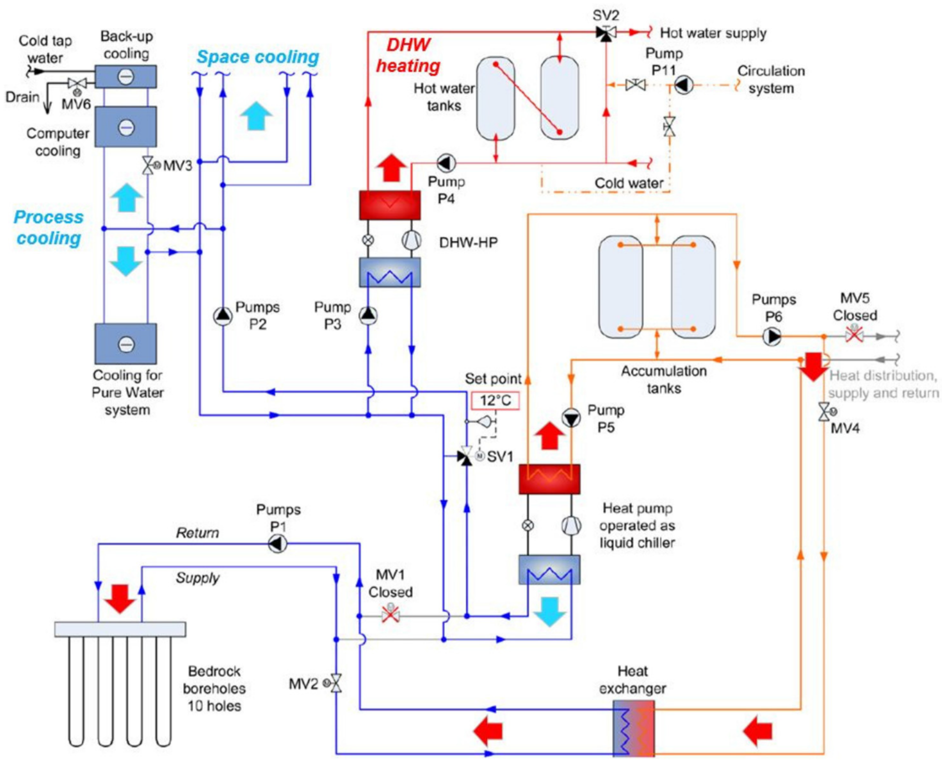


Figure 4.13 Thermal energy system operating in "Cooling Mode, liquid chiller operation". DHW heating but no space heating. Process cooling and space cooling (Nordang, 2014, Nordang, 2015)

4.3 Photovoltaic System

4.3.1 Technical information of the PV system

Photovoltaic modules (PV, solar cells) are placed on the roofs of the two office buildings as well as on part of the neighbouring garage. It consists of 954 modules with a total module area of 1556 m^2 and a total peak power of 312 kWp (Bernhard and Bugge, 2014). The PV modules are of the type *Sunpower E20*, which consists of high-performance monocrystalline cells. There are 16 multistring inverters with a total capacity of 244 kW, of the inverter type *Synny Tripower 17000 TL* from SMA Solar Technology. The vendor of the mounting system was Knubix GmbH.

Table 4.4 summarizes the distribution of PV modules, installed power and orientation of the PV-system installed. The azimuth angles given in the table are approximations done by Ødegården (2016), where the reference is South with positive direction clockwise.

Table 4.4 Distribution of PV modules at Powerhouse Kjørbo (Ødegården, 2016)

	No. of modules	P_{peak}	**Azimuth**
Block 4	212	69.3 kW_p	-35° (SE) / +145 ° (NW)
Block 5	180	58.9 kW_p	-35° (SE) / +145 ° (NW)
Garage	562	183.8 kW_p	-110° (NE) / +70 ° (SW)
Total	**954**	**312 kW_p**	

All the PV modules are mounted with a tilt angle of 10° facing east/west, as shown in Figure 4.14. This was done to optimize the amount of panels fitted on the roof in order to get as much energy output as possible per square meter of roof area. Compared to PV-panels facing east or west, a south-faced PV-panel would produce more energy. However, the panels facing east or west have a flatter production profile of electricity, with a higher share of the electricity early or late in the day. This can be an advantage when it comes to self-consumption.

Figure 4.14 Photos showing the placement of the PV panels on the roof. Photo: Skanska.

One main challenge in designing the PV-system was the limited roof space available, and that the façade was not suitable for BIPV (building integrated photovoltaics), due to shading. On this background, the criteria for selecting the modules were (Bernhard and Bugge, 2014):

1. Highest possible system performance (expected annual production)
2. Embodied energy balance
3. Mounting solutions
4. Costs

Relevant data for the PV modules are presented in Table 4.5. More detailed specifications are provided in the module's data sheet in Annex 4. The module efficiency is 20.4%, which is well above average for mono-crystalline cells (Ødegården, 2016).

Table 4.5 Data for the SunPower E20-327 PV modules (Ødegården, 2016).

Peak power per module (P_{max})	327 W_p
Module efficiency (at standard conditions)	20.4%
Module area	1.63 m^2

Each module has three bypass diodes. The bypass diodes are activated in case of severe shading and thus minimizing the maximum power loss (Ødegården, 2016). The modules have a horizontal positioning, which ensures less lost power due to snow covering the modules (Ødegården, 2016). This is shown in Figure 4.15.

Figure 4.15 The roof of Block 4 from March 10th, with snow on the modules. Photo: L. Ødegården.

Ødegården (2016) has analysed the cast shadows that affect the PV modules at Powerhouse Kjørbo. Figure 4.16 illustrates the cast shading observed in May. Block 4 and 5 both had multiple sources for cast shadows causing partial shading of modules, while no such shades were observed at the garage. Figure 4.16 also present the string configurations where each string is coloured and given a label. Further information on how cast shadows and soiling of the modules can affect the energy production can be found in the MSc thesis Ødegården (2016).

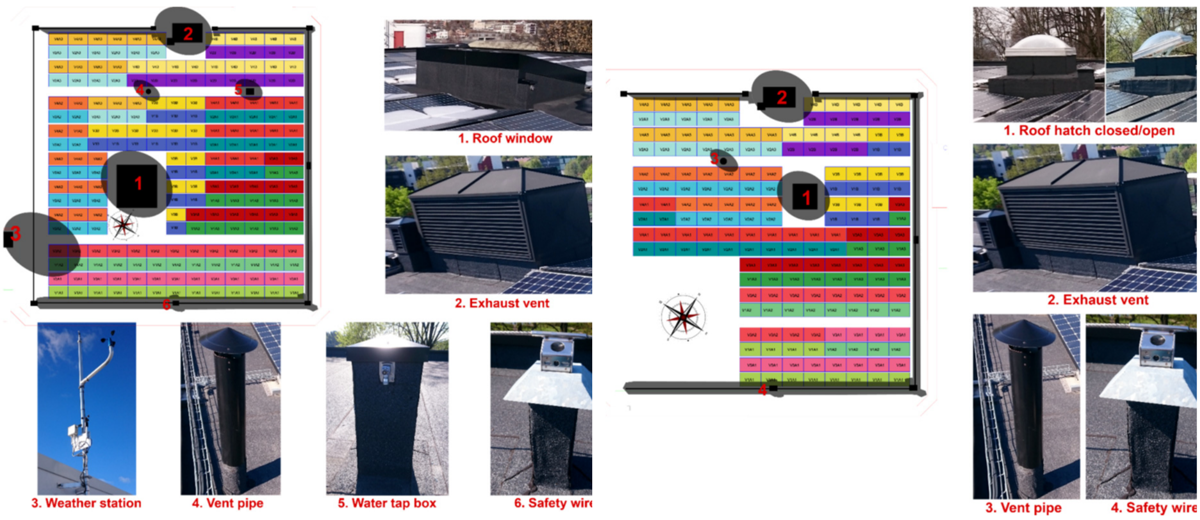


Figure 4.16 Identification of cast shadows at Block 4 (left) and Block 5 (right). (Drawing from Entra, Asplan Viak, photos by L. Ødegården) (Ødegården, 2016)

4.3.2 Framework conditions for the electricity sale

At surplus production from the PV system, electricity is distributed to neighbouring buildings in the area or delivered to the local grid. Powerhouse Kjørbo is a prosumer (Plusskunde) with the grid company Hafslund (Jenssen, 2016).

Financially, electricity bought from the grid is more expensive than the selling price for electricity. This situation has initiated the idea of local production of hydrogen from the solar electricity. In 2016, a hydrogen station was built close to Powerhouse Kjørbo. Hydrogen is produced from the surplus solar electricity as well as from grid electricity.

Figure 4.17 Hydrogen sale by Kjørbo. Photo: naturpress.no

4.4 Control system

The energy systems (heating, cooling, ventilation and lighting) was planned with focus on demand control, at the same time as the number of sensors and control units were limited to a minimum (Jenssen et al., 2015). Sensors for presence, daylight and temperature at appropriate locations control the ventilation rate, lighting, and temperature, according to the demand.

4.4.1 Control system for the thermal energy system

Figure 4.18 provides an overview of the temperature sensors, pressure sensors, electricity meters, and thermal energy meters, which are installed in the heating and cooling circuits. All the sensors are linked to a centralized monitoring system (Nordang, 2014, Nordang, 2015), (Stene and Alonso, 2016).

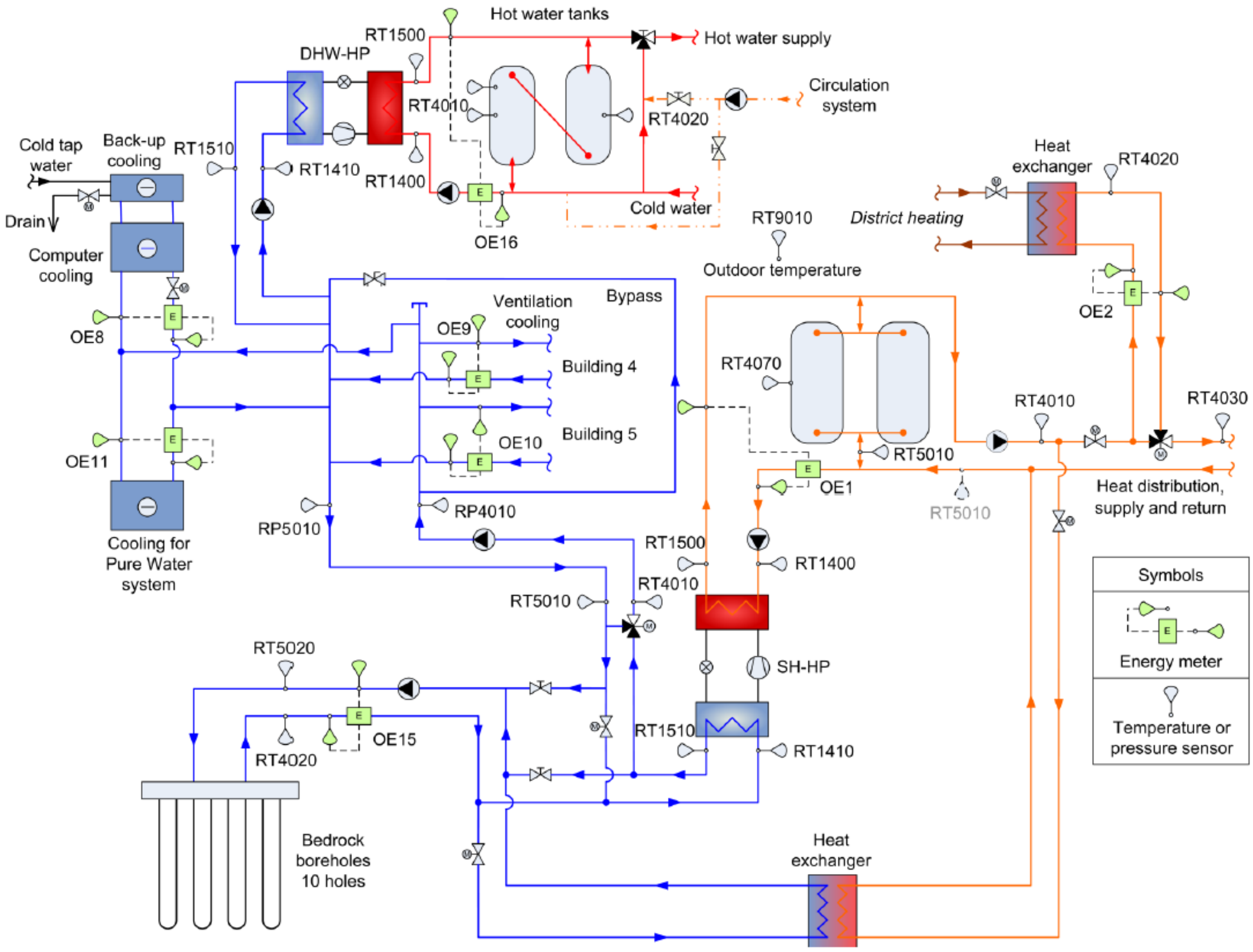
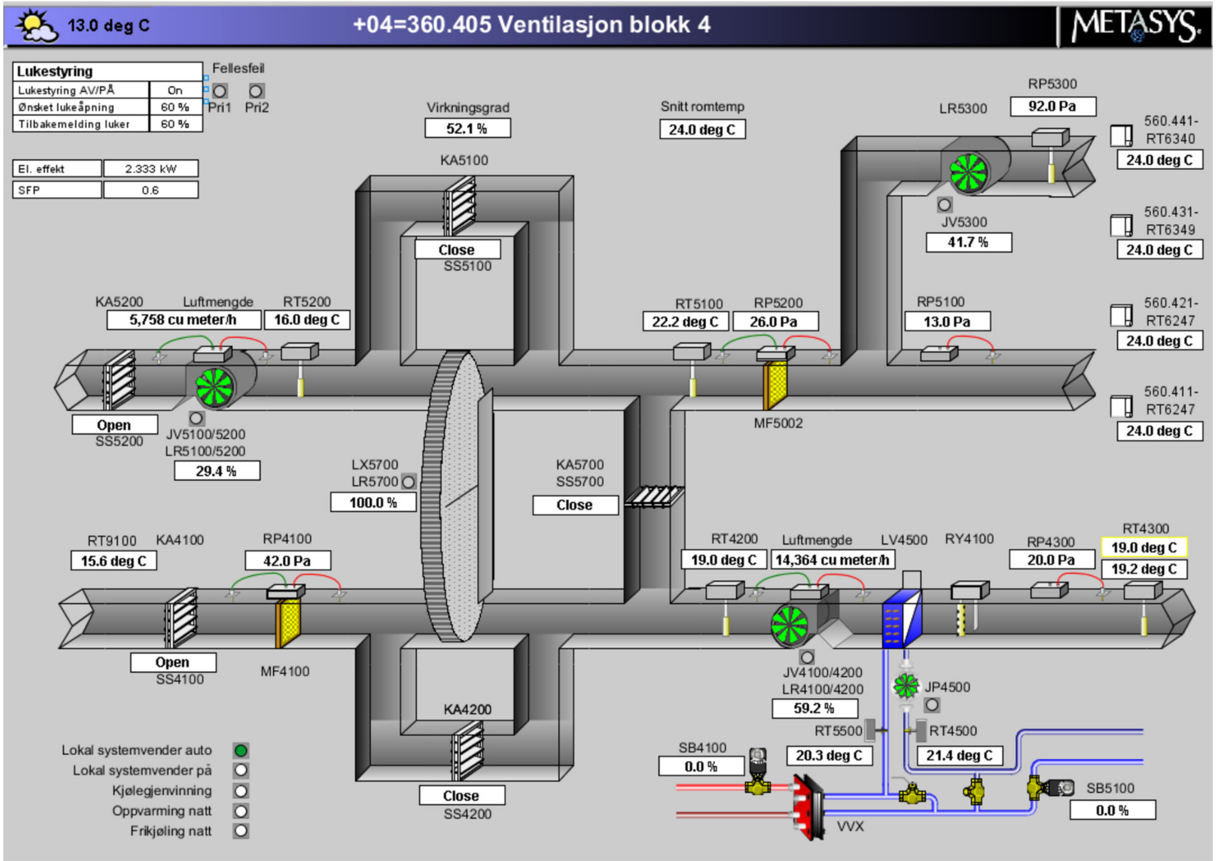
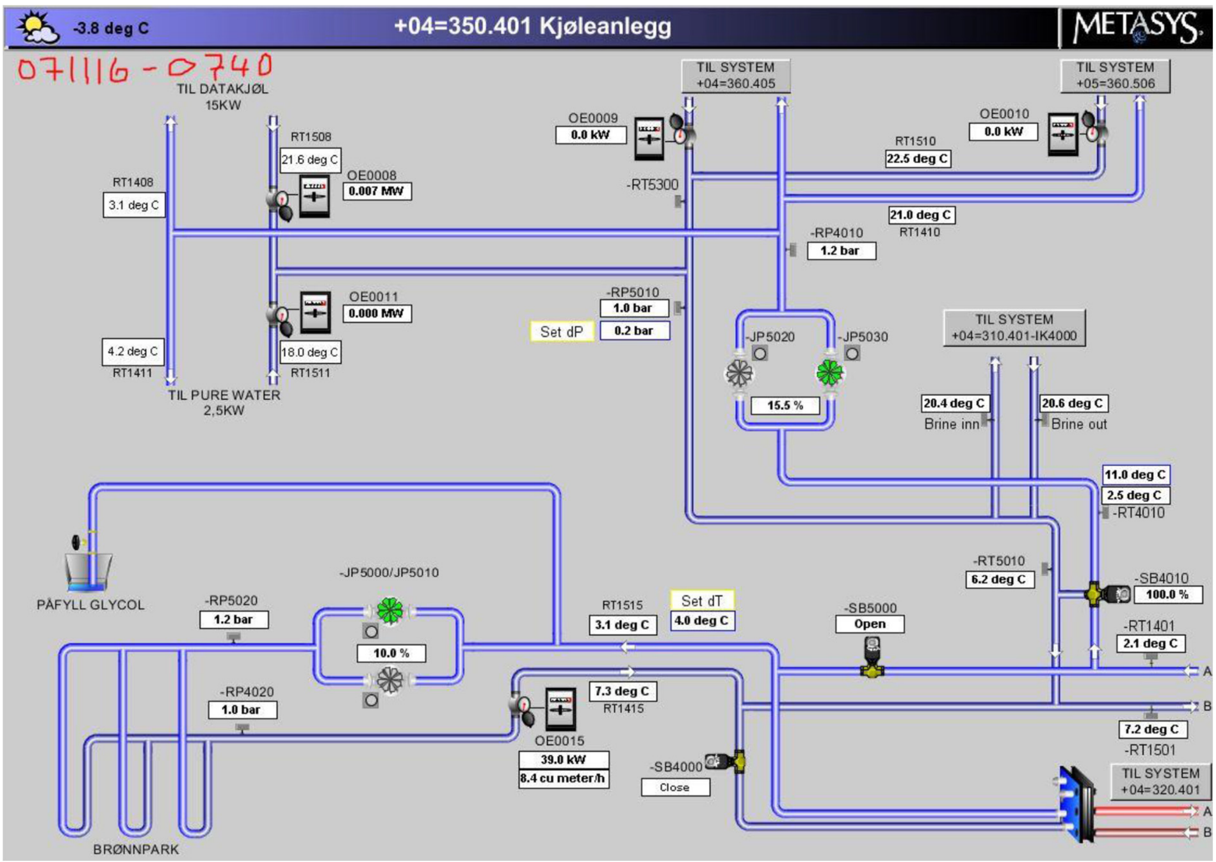
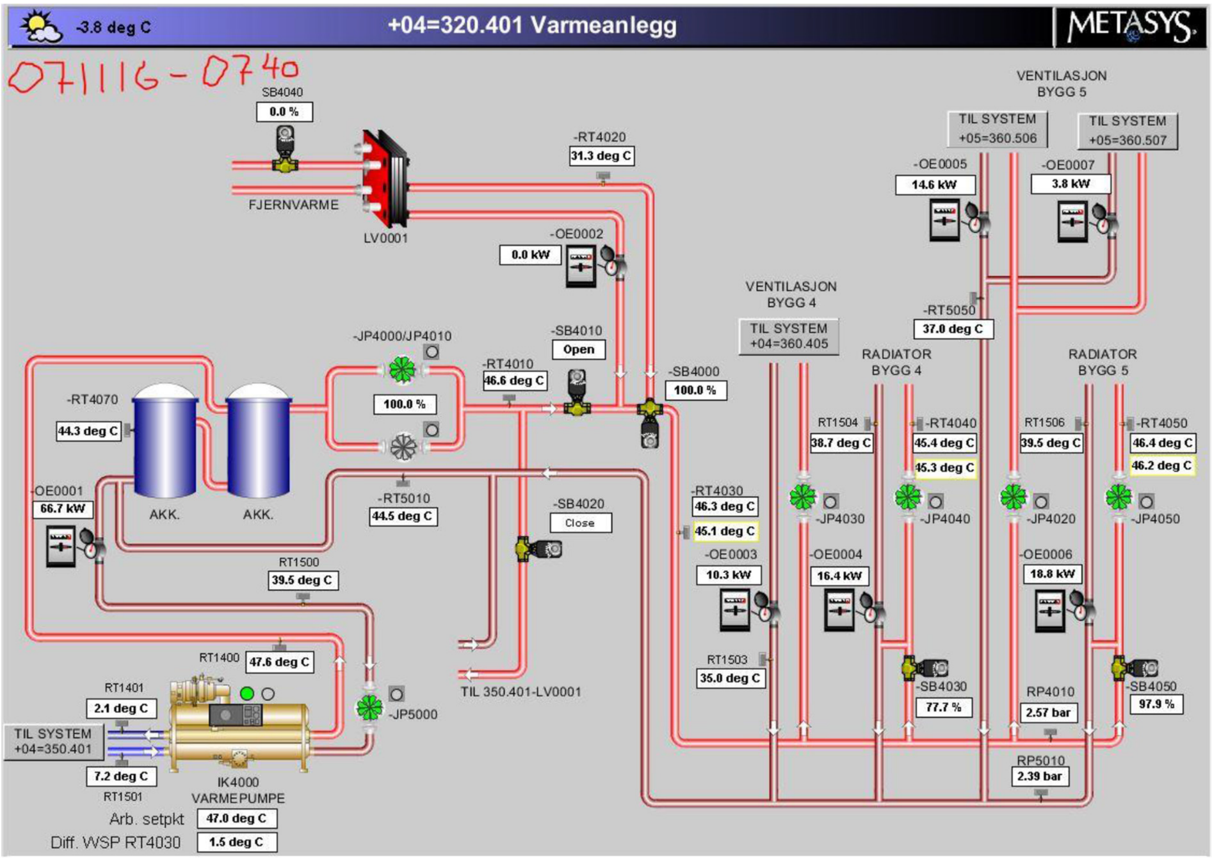


Figure 4.18 Instrumentation for the thermal energy plant with temperature sensors, pressure sensors, electrical power/energy meters, and thermal power/energy meters (Nordang, 2014)

Figure 4.19 shows four examples of screen-shots from the extensive monitoring system.


13.0 deg C
+04=360.405 Ventilasjon blokk 4
METASYS
Lukestyring
Lukestyring AV/PÅ On
Ønsket lukeåpning 60 %
Tilbakemelding luker 60 %
Fellesfeil
Pri1 Pri2
El. effekt 2.333 kW
SFP 0.6
Virkningsgrad 52.1 %
Snitt romtemp 24.0 deg C
KA5100
Close SS5100
LR5300
RP5300 92.0 Pa
JV5300 41.7 %
560.441-RT6340 24.0 deg C
560.431-RT6349 24.0 deg C
560.421-RT6247 24.0 deg C
560.411-RT6247 24.0 deg C
KA5200
Luftmengde 5,758 cu meter/h
RT5200 16.0 deg C
RT5100 22.2 deg C
RP5200 26.0 Pa
RP5100 13.0 Pa
MF5002
Open SS5200
JV5100/5200
LR5100/5200 29.4 %
LX5700
LR5700 100.0 %
KA5700
SS5700 Close
RT9100 15.6 deg C
KA4100
RP4100 42.0 Pa
RT4200 19.0 deg C
Luftmengde 14,364 cu meter/h
LV4500
RY4100
RP4300 20.0 Pa
RT4300 19.0 deg C 19.2 deg C
Open SS4100
MF4100
JV4100/4200
LR4100/4200 59.2 %
JP4500
KA4200
RT5500 20.3 deg C
RT4500 21.4 deg C
SB4100 0.0 %
SB5100 0.0 %
VVX
Close SS4200
Lokal systemvender auto
Lokal systemvender på
Kjølegjenvinning
Oppvarming natt
Frikjøling natt


-3.8 deg C
+04=350.401 Kjøleanlegg
METASYS
071116-0740
TIL DATAKJØL 15KW
TIL SYSTEM +04=360.405
TIL SYSTEM +05=360.506
RT1508 21.6 deg C
OE0008 0.007 MW
RT1408 3.1 deg C
OE0009 0.0 kW
-RT5300
OE0010 0.0 kW
RT1510 22.5 deg C
21.0 deg C RT1410
-RP4010 1.2 bar
OE0011 0.000 MW
-RP5010 1.0 bar
Set dP 0.2 bar
-JP5020
-JP5030
15.5 %
TIL SYSTEM +04=310.401-IK4000
20.4 deg C Brine inn
20.6 deg C Brine out
4.2 deg C RT1411
18.0 deg C RT1511
TIL PURE WATER 2,5KW
11.0 deg C
2.5 deg C
-RT4010
PÅFYLL GLYCOL
-JP5000/JP5010
-RP5020 1.2 bar
10.0 %
RT1515 3.1 deg C
Set dT 4.0 deg C
-SB5000 Open
-RT5010 6.2 deg C
-SB4010 100.0 %
-RT1401 2.1 deg C
-RP4020 1.0 bar
7.3 deg C RT1415
OE0015 39.0 kW 8.4 cu meter/h
-SB4000 Close
7.2 deg C -RT1501
TIL SYSTEM +04=320.401
A
B
A
B
BRØNNPARK



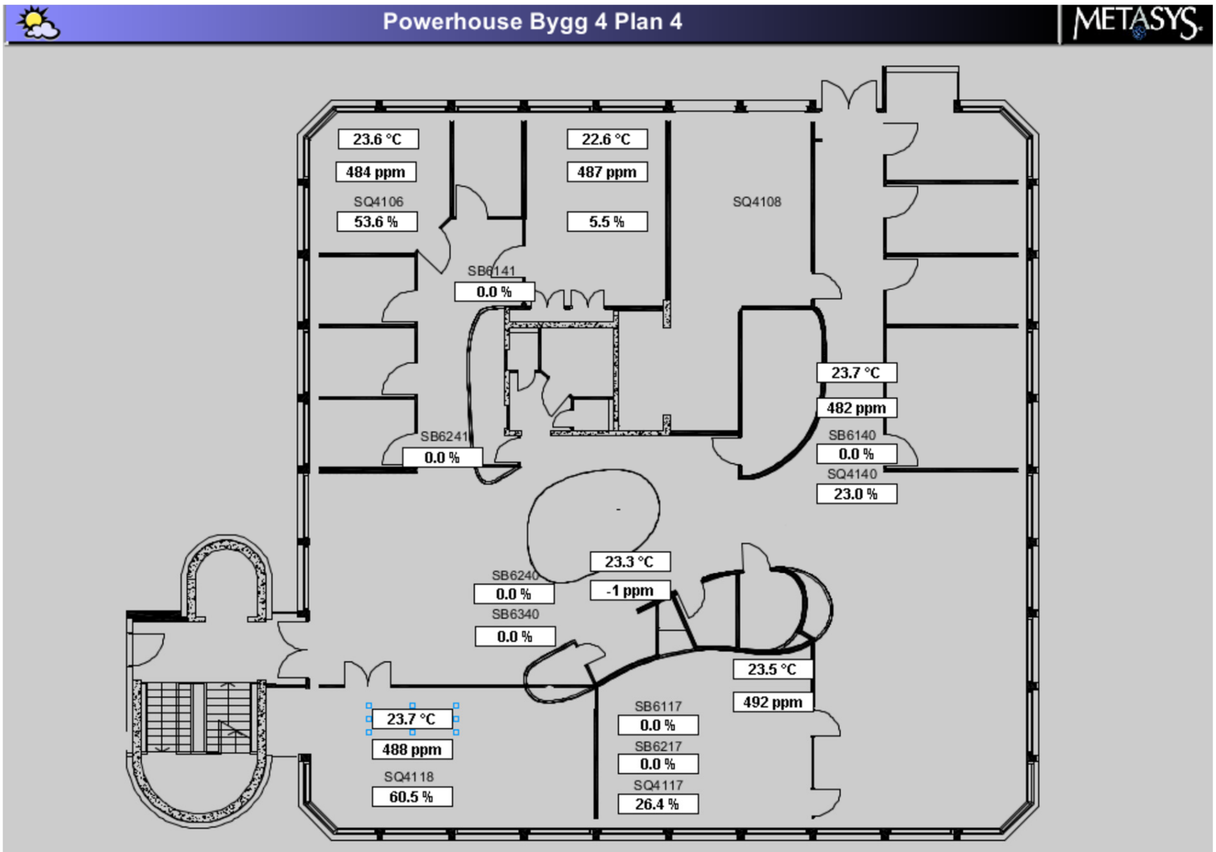


Figure 4.19 Example of screen shots from the monitoring system (Rådstoga/Asplan Viak, 2016)

4.4.2 Control system for lighting and sun shading screens

The lighting is controlled individually for different zones. In the open office plan, the zones are typically 15 m^2, and serves about four persons. The lighting control's objective is to only light up areas that are in use. The system controls lighting via the three components daylight, constant light and presence (ITECH AS, 2013).

To avoid overheating in the summer, exterior sun shading screens are automatically activated. The sun shading screens are semi-transparent so that the view is not obstructed.

The main challenge with the demand control system has been the control of the sun shading screens coupled with the artificial lighting. Initially, the sun screens where brought all the way down by the sun sensor, which caused too little light to enter into the office areas. This control was modified to stop the sun shading screens above the lower window field. This improved the daylight conditions, the scenic view and the general user satisfaction (Jenssen, 2016). In addition, the control system has been sensitive to local reflections from e.g. table lamps or white papers on the work surface.

Based on experiences from the first two years, it is estimated that about 40% of the lighting demand is outside office hours. During this period, lighting was activated even when there was only a few people in the offices. It was therefore decided to introduce a specific lighting modus for presence in the office area outside working hours. This will reduce the need for lighting.

4.4.3 Control system for equipment

The energy use for equipment influences the building energy use both directly and indirectly, especially through increased cooling need. Selection of modern and energy effective equipment has therefore been important (Jenssen, 2016).

Power sockets used for screens, lamps, tables and chargers are controlled by the same presence sensors as the lighting.

However, energy use for equipment is not included in the "plus energy building" calculation, since it is largely influenced by the end user.

4.4.4 Control system for solar energy production

During March 2016, the inverters at Powerhouse Kjørbo were connected to the *Sunny Portal* made by SMA Solar Technology AG (Ødegården, 2016). Sunny Portal is an Internet portal set up by SMA Solar Technology, where PV system owners can monitor and download information and data (sunnyportal.com). Available data are available on a 15-minute basis, e.g. the PV system's power and energy production, irradiance, temperature and performance ratio. Temperature and global irradiance sensors are installed at the garage building with the same orientation as the PV modules – one for each direction.

4.4.5 Publicly available Energy Dashboard

Some of the measurements are available on an open homepage, displaying real time electricity consumption and production, geothermal heating and cooling, etc. (Asplan Viak, 2016). The Energy Dashboard is available on http://buildingdashboard.com/clients/powerhouse/kjorbo and is shown in Figure 4.20.

Figure 4.20 Screenshot of the open homepage with energy measurements (Asplan Viak, 2016)

5. Operational Building Performance

5.1 Energy measurements

5.1.1 Introduction to the energy measurements

As the Powerhouse definition states that the fulfilment of the definition should be documented by measured results, the Powerhouse Kjørbo is instrumented for detailed energy metering and energy use was followed up closely. The detailed follow-up was also used to optimize the operation, map potential errors or weaknesses and evaluate the performance versus the project goals.

Since the energy need and production can vary from year to year, a certain operation time is needed before it can be concluded whether or not the energy goals are achieved.

Operation and measurements started in April 2014, and results for the two first year of operation are presented here, mainly based on Jenssen (2016). The building owner Entra has signed an agreement with Skanska, which is taking the responsibility of the operation of the buildings. Skanska is analysing the energy measurements each month and is subsequently suggesting improvements. Especially energy posts with significant negative deviations are devoted special attention.

The building is in a two year test phase and undergoing adjustments to optimize the energy use. Several adjustments have already been made, for example:

- 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.

In addition, some points for improvements related to the design of the technical system were identified, e.g.:

- 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 was 85%, while measurements during the 1st year showed 70-75%. This fact was previously unknown to the manufacturer.

Figure 5.1 The technical room at Powerhouse Kjørbo. Photo: Asplan Viak.

5.1.2 Energy performance

Table 5.1 shows predicted and measured energy use (net energy need and delivered energy) in kWh and kWh/m² heated floor area (Jenssen, 2016), using terms from prEN 15603 (European committee for standardization, 2013) and NS3031. The results shown in the table have not been corrected for climate variations and user variations. The building is in a two-year test phase and is continuously undergoing adjustments to optimize energy use, as described in Chapter 5.1.1.

Total delivered energy, including server room and appliances, is measured to 221 654 kWh (42.9 kWh/m²) during the first year of operation and 232 454 kWh (45.2 kWh/m²) during the second year (Jenssen, 2016).

If not including appliances and server room, the need for delivered energy was 23.7 kWh/m² during the first year and 26.6 kWh/m² during the second year. This average delivered energy after two year is therefore 25.1 kWh/m², and this value is used when evaluating the achievement of the Powerhouse and ZEB goals in Chapter 7. The *predicted* average for the two years were 21.6 kWh/m². Figure 5.1 shows delivered energy to Powerhouse Kjørbo, divided on the various energy posts. The values for predicted and measured energy need and delivered energy is shown in Table 5.1, both for the building in total (kWh) and specific energy divided on heated floor area (kWh/m²).

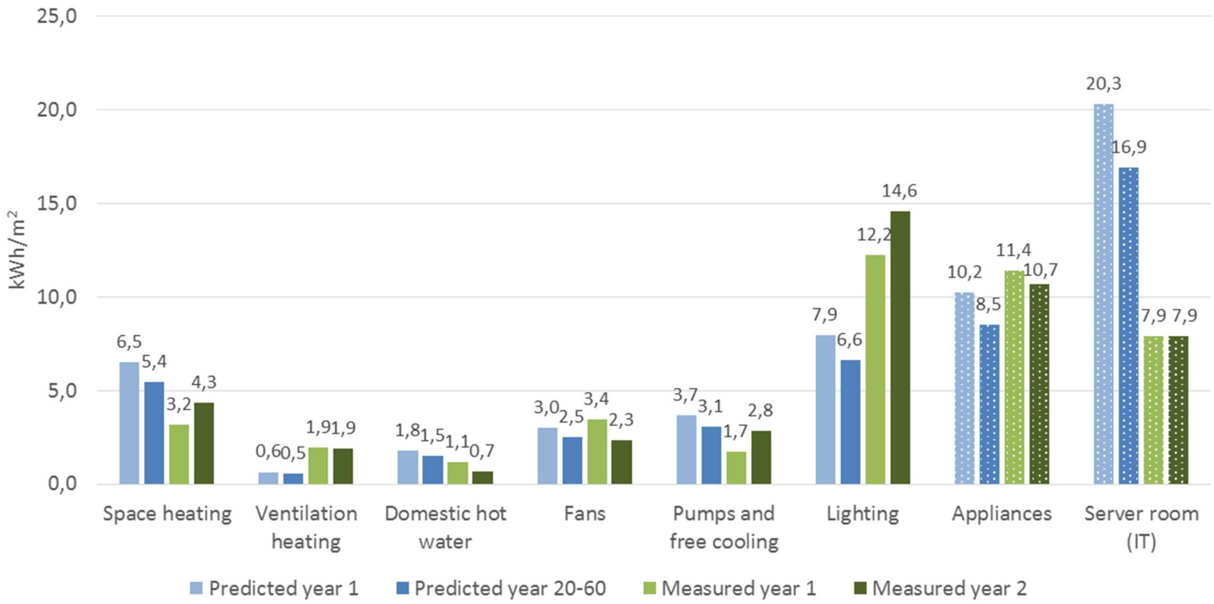


Figure 5.2 Delivered energy to Powerhouse Kjørbo, divided on the various energy posts. Predicted values for year 1 and year 2-60 as well as measured values for year 1 and 2 is shown.

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

- Space heating and ventilation heating:
    - If combining the need for space heating and ventilation heating, this need was 20.8 kWh/m² during the first year and 20.9 kWh/m² during the second year. This corresponds well with the calculated heat need, which was 22.9 kWh/m² for the initial year and 19.1 kWh/m² for the second year. The need for space heating (radiators) was lower than predicted. The need for ventilation heating was higher than predicted, probably because of a lower efficiency than expected in the heat recovery unit.

- For the first two years, the actual Seasonal Coefficient of Performance (SCOP) for the heat pump (4.2 year 1 and 3.5 year 2) has been 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. The second year it is 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 need 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 is close to the calculated values. The energy need 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 where 2.8 kWh/m^2 measured and 3.0 kWh/m^2 calculated.
- Lighting:
  - Electricity for lighting is 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 accounted for more than half of the buildings' total energy use, if not including the appliances and server room.
  - Towards the end of the second year of operation, in February 2016, a number of measures have been implemented to reduce the energy need for lighting. If comparing March 2016 (after the measures) with March 2015, the energy need in 2016 is 24 % lower than in 2015.
- Appliances and server room (IT):
  - To reduce 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 need for the first two years has been covered by free cooling from the borehole system.
  - During the first year, the cooling need of the building was 9.6 kWh/m^2 and the second year the need was 8.0 kWh/m^2. The delivered energy is measured as part of the energy for the pumps, where around 30 % is assumed to be connected to the cooling need.

In total, there is an increase of about 12 % delivered energy from the first to the second year of operation. In the planning phase it was estimated a 20% reduction in energy use from the first to the second year.

Table 5.1 Predicted and measured energy use (net energy need and delivered energy) in kWh and kWh/m2 heated floor area (Based on Jenssen (2016))

5180	Predicted, 1st year only				
m2 heated area	Energy need	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**kWh**	**COP**	**kWh/m2**	**kWh/m2**
Space heating	107 921	33 725	3,2	20,8	6,5
Ventilation heating	10 625	3 320	3,2	2,1	0,6
Domestic hot water	29 726	9 290	3,2	5,7	1,8
Fans	15 475	15 475		3,0	3,0
Pumps	11 300	11 300		2,2	2,2
Lighting	41 074	41 074		7,9	7,9
Appliances	52 912	52 912		10,2	10,2
Server room (IT)	105 120	105 120		20,3	20,3
Space cooling	0,00	0,00		0,0	0,0
Server room cooling	105 120	7 008	15,0	20,3	1,4
Ventilation cooling	11 322	755	15,0	2,2	0,1
Total	**490 595**	**279 979**		**94,7**	**54,0**
Without appliances + server room	**332 563**	**121 947**		**64,2**	**23,5**

	Measured, 1st year of operation (Apr 14-Mar 15)					
	Energy need	Delivered	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**El, kWh**	**DH, kWh**		**kWh/m2**	**kWh/m2**
Space heating	66 782	16 136	277		12,9	3,2
Ventilation heating	40 853	9 621	402		7,9	1,9
Domestic hot water	11 626	5 957	0		2,2	1,1
Fans	17 764	17 764			3,4	3,4
Pumps	8 993	8 993			1,7	1,7
Lighting	63 375	63 375			12,2	12,2
Appliances	58 973	58 973			11,4	11,4
Server room (IT)	40 836	40 836			7,9	7,9
Space cooling	0,00	0,00			0,0	0,0
Server room cooling	39 200	0*			7,6	0*
Ventilation cooling	10 211	0*			2,0	0*
Total	**358 612**	**221 654**	**679**		**69,2**	**42,9**
Without appliances + server room	**258 803**	**121 845**	**679**		**50,0**	**23,7**

* included in the energy for pumps

Measured	**El need**	**El delivered**		**SCOP**
Heatpump DHW	8 285	2 720		3,0
Heatpump heating	106 956	25 757		4,2
Total, both HPs	**115 241**	**28 477**		**4,0**

5180	Predicted, standard year 2-60				
m2 heated area	Energy need	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**kWh**	**COP**	**kWh/m2**	**kWh/m2**
Space heating	89 934	28 104	3,2	17,4	5,4
Ventilation heating	8 854	2 767	3,2	1,7	0,5
Domestic hot water	24 772	7 741	3,2	4,8	1,5
Fans	12 896	12 896		2,5	2,5
Pumps	9 417	9 417		1,8	1,8
Lighting	34 228	34 228		6,6	6,6
Appliances	44 093	44 093		8,5	8,5
Server room (IT)	87 600	87 600		16,9	16,9
Space cooling	0,00	0,00		0,0	0,0
Server room cooling	87 600	5 840	15,0	16,9	1,1
Ventilation cooling	9 435	629	15,0	1,8	0,1
Total	**408 829**	**233 316**		**78,9**	**45,0**
Without appliances + server room	**277 136**	**101 623**		**53,5**	**19,6**

	Measured, 2nd year of operation (Apr 15-Mar 16)					
	Energy need	Delivered	Delivered		Energy need	Delivered
Powerhouse Kjørbo	**kWh**	**El, kWh**	**DH, kWh**		**kWh/m2**	**kWh/m2**
Space heating	75 546	21 454	1 066		14,6	4,3
Ventilation heating	32 859	9 332	464		6,3	1,9
Domestic hot water	11 685	3 431	0		2,3	0,7
Fans	12 037	12 037			2,3	2,3
Pumps	14 682	14 682			2,8	2,8
Lighting	75 383	75 383			14,6	14,6
Appliances	55 248	55 248			10,7	10,7
Server room (IT)	40 887	40 887			7,9	7,9
Space cooling	0,00	0,00			0,0	0,0
Server room cooling	38 100	0*			7,4	0*
Ventilation cooling	3 103	0*			0,6	0*
Total	**359 530**	**232 454**	**1 530**		**69,4**	**45,2**
Without appliances + server room	**263 395**	**136 319**	**1 530**		**50,8**	**26,6**

* included in the energy for pumps

Measured	**El need**	**El delivered**		**SCOP**
Heatpump DHW	11 685	3 431		3,4
Heatpump heating	108 405	30 786		3,5
Total, both HPs	**120 090**	**34 217**		**3,5**

The measured monthly distribution of delivered energy for the first year is shown in Figure 5.3. The Figure can be compared with the predictions in Figure 4.1.

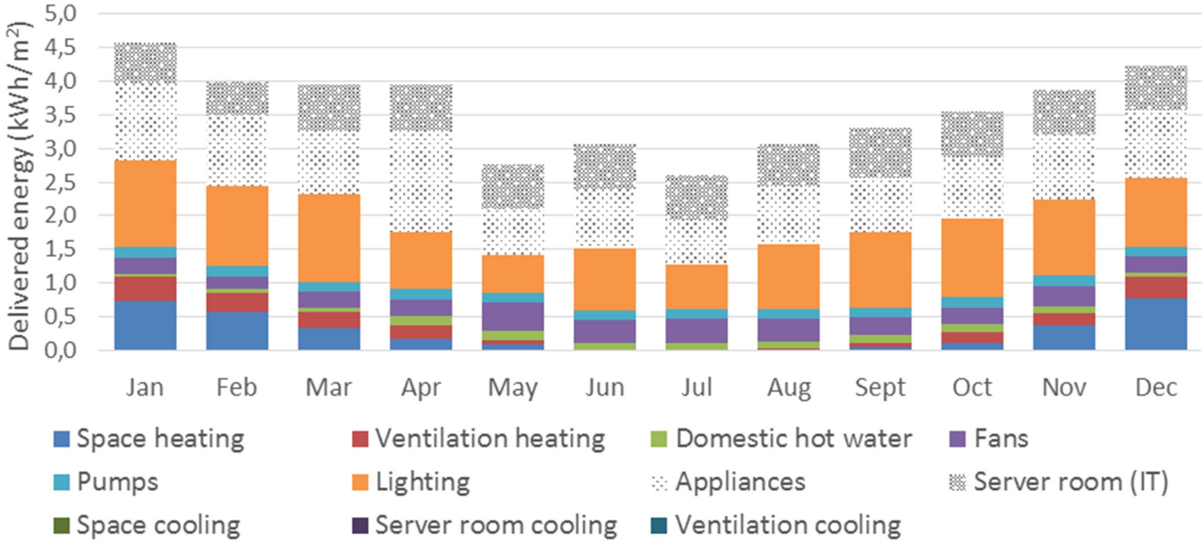


Figure 5.3 Measured monthly delivered energy to Powerhouse Kjørbo from April 2014 to March 2015, divided on the various energy posts.

5.1.3 Produced electricity

Measurements from the 2nd year of operation showed a yield of 223 501 kWh (Jenssen, 2016).This production is close to the predicted production, as shown in Table 5.2. During the first year, the energy production was 133 568 kWh. The main reason for the lower production the first year is that the solar energy plant on the garage started delivering energy in August, four months after the measurement period started.

When evaluating the achievement of the Powerhouse and ZEB goals in Chapter 7, the electricity production during the second year is used: 43.1 kWh/m^2. The predicted average for the two years were 44.1 kWh/m^2. Table 5.2 show the monthly predicted and measured energy production from the photovoltaic system at Powerhouse Kjørbo.

Ødegården (2016) states that due to a technical error, approximately 6000 kWh were lost between May and June 2015. This energy production is not included in Table 5.2 and the electricity production for the second year of 43.1 kWh/m^2, but would increase the production to 44.3 kWh/m^2.

Table 5.2 Predicted and measured energy production from the solar cells at Powerhouse Kjørbo (based on Jenssen (2016))

	Predicted year 1					**Measured year 1** (Apr 14-Mar 15)				
	Building 4	Building 5	Garage	Total		Building 4	Building 5	Garage	Total	
Apr-14	6 054	5 338	17 090	28 482		(incl in b5)	13 000	not in operation	13 000	
May-14	9 548	8 446	27 300	45 294		8 700	7 500	not in operation	16 200	
Jun-14	9 263	8 083	26 210	43 556		10 000	8 750	not in operation	18 750	
Jul-14	9 218	8 083	26 180	43 481		10 100	8 800	not in operation	18 900	
Aug-14	7 147	6 302	20 240	33 689		6 500	5 800	10 200	22 500	
Sep-14	4 290	3 793	12 190	20 273		5 000	3 900	14 000	22 900	
Oct-14	1 967	1 717	5 760	9 444		1 300	1 000	4 000	6 300	
Nov-14	727	610	2 200	3 537		232	300	673	1 205	
Dec-14	335	269	1 000	1 604		90	77	162	329	
Jan-15	0	0	0	0		0	0	0	0	
Feb-15	0	0	0	0		505	357	0	862	
Mar-15	0	0	0	0	kWh/m²	3 001	2 364	7 257	12 622	kWh/m²
kWh	**48 549**	**42 641**	**138 170**	**229 360**	**44,3**	**45 428**	**51 848**	**36 292**	**133 568**	**25,8**

	Predicted year 2				kWh/m²	**Measured year 2** (Apr 15-Mar 16)				kWh/m²
kWh	**48 155**	**42 295**	**137 049**	**227 499**	**43,9**	**50 902**	**41 855**	**130 745**	**223 502**	**43,1**

Figure 5.4 shows the monthly solar electricity production for 2015, separating between the three rooftop PV systems (Ødegården, 2016). During January, February and December, the total energy yield was only 1570 kWh, which is due to snow covering the rooftops. For April to August, the solar energy production is larger than the total consumption of the building.

Experiences from the first two years in operation is that there is little maintenance concerned with the PV system (Jenssen, 2016). Even though the panels are exposed to dust and seagull droppings, the impurities are washed off by the rain.

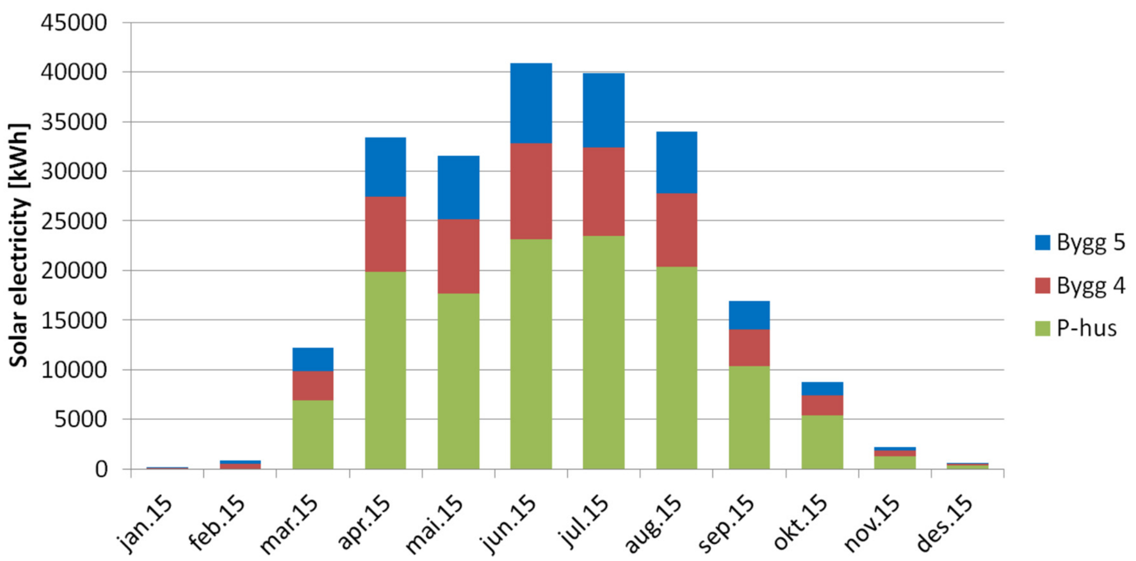


Figure 5.4 Monthly solar electricity production at Powerhouse Kjørbo from 2015 (Ødegården, 2016).

5.2 Indoor Climate Performance

The indoor climate of Powerhouse Kjørbo has been examined through both measurements and surveys during the first years of operation.

5.2.1 Measured indoor climate

The standard set point temperature of an office building is 21°C during operation, according to Norwegian standard NS3031:2014. In general, the occupants at Powerhouse Kjørbo were not satisfied with an indoor temperature of 21°C and the set point for the temperature was increased.

The first summer of operation at Powerhouse Kjørbo, was a hot summer with several consecutive days with temperatures approaching 30°C during working hours. During these days the indoor temperature never reached above 25°C, even without mechanical cooling (Jenssen, 2016).

Detailed indoor climate measurements at Powerhouse Kjørbo were performed by (Søgnen, 2015). He states that the heating strategy at Powerhouse Kjørbo is dependent on the heat distribution among the open area and other rooms in the building, since there are no dedicated heat sources outside the centre of each floor. The heating and cooling systems are based on a heating strategy by waterborne panel radiators at each floor and free cooling through the ventilation system.

The measured ventilation efficiency indicates that the strategy works more like mixing ventilation than displacement ventilation in terms of removing pollutants and air exchange. However, this is not a final conclusion and the ventilation and temperature distribution is being studied in more detail by Maria Justo-Alonso et al (to be published in 2017).

Operational experience shows that the ventilation control in general has worked well. There were some initial trouble with ventilation cooling provoking radiator heating. This was solved by altering the control system to not allowing heating when temperature sensors called for ventilation cooling. (Jenssen, 2016)

5.2.2 Perceived indoor climate

The ventilation system was allowed to let temperatures drift between 20-25 °C to benefit from the exposed thermal mass. This drift was found to be acceptable by the occupants (Throndsen et al., 2015).

A survey about the perception of the indoor climate has been conducted for the employees at Powerhouse Kjørbo (PK) and an architecturally similar office building (ROB), which has been renovated to a less ambitious energy standard. Results indicate that employees are generally more satisfied with both the thermal environment and the indoor air quality at Powerhouse Kjørbo compared to the other building. Complaints about occasionally low temperatures in the building and poor air quality in meeting rooms have been reported, but apart from that, the satisfaction with thermal environment and air quality is high (Søgnen, 2015).

Figure 5.5 shows the general perception of respondents to the indoor climate, including acoustic, visual comfort, air quality and room temperature. The results indicate that the general perceptions of respondents to indoor climate were positive, with a few exceptions (Guan et al., 2016).

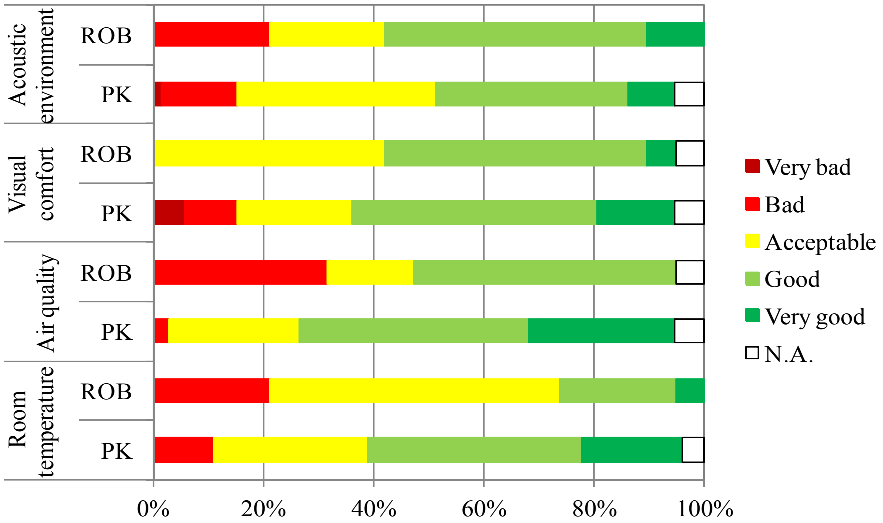


Figure 5.5 General perceptions of respondents to indoor climate. PK = Powerhouse Kjørbo, ROB = renovated office building to less ambitious energy standard (Guan et al., 2016)

It was found that employees of Powerhouse Kjørbo complained more about the indoor temperature being too cold in the winter than too warm in the summer. This is particularly pointed out in Figure 5.6, where 40% state that they experience low temperatures sometimes, and 7.5% experience it often. The most frequent complaints on the indoor environment at Powerhouse Kjørbo are related to the thermal environment, and around 75% of those who complain on the thermal environment are located close to the external walls (Søgnen, 2015). Also, visual comfort has been an issue. Initial challenges and modifications in the control system for lighting and sun shading screens are further described in Chapter 4.4.2.

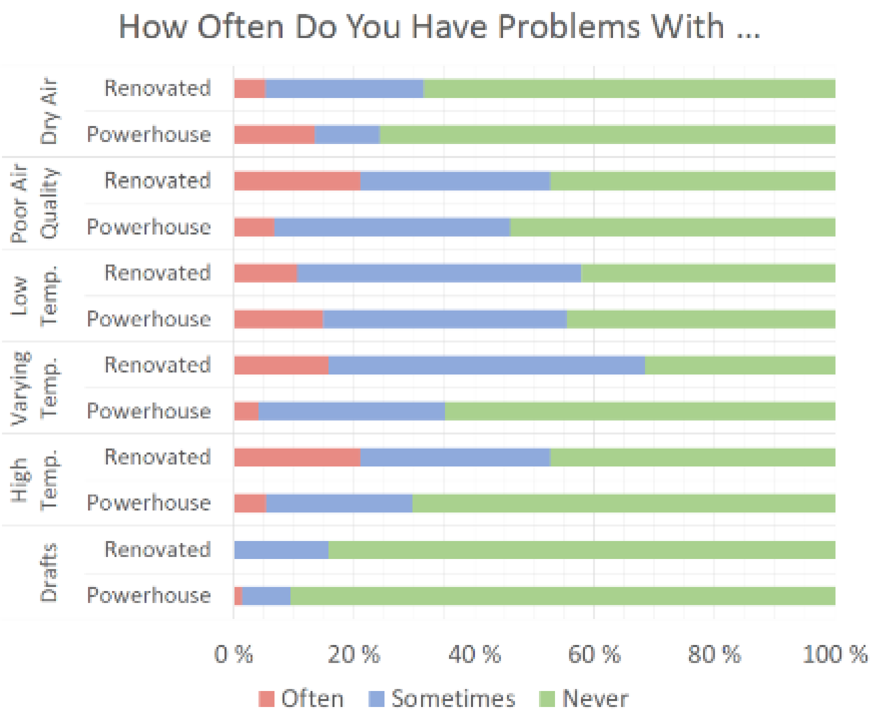


Figure 5.6 Reported problems with indoor climate at Powerhouse Kjørbo and adjacent office blocks renovated to less ambitious energy standard (Søgnen, 2015)

Further details on the thermal indoor climate and air quality can be found in (Guan et al., 2016, Søgnen, 2015). The issues are also studied in more detail by Maria Justo-Alonso et al (to be published in 2017).

6. Embodied energy and GHG Emissions

6.1 Methods and Tools

As described in Chapter 1, embodied energy and GHG emissions are calculated to evaluate the Powerhouse goal and ZEB ambition levels. The Powerhouse goals are related to energy while the ZEB ambition levels are related to GHG emissions.

Thyholt et al. (2012) state that a life cycle primary energy and greenhouse gas emission account shall be carried out. This report therefore includes energy and GHG emissions account for all the ZEB-COME stages: Construction "C", operation "O", materials "M" and end of life "E". A share of these emissions are compensated for by the production of on-site renewable electricity, as described in Chapter 7.

This chapter summarizes the methodologies used to calculate the primary energy use and CO_{2eq} emissions results from Materials (A1-A3, B4), construction installation process (A4-A5) and end of life (C1-C4) life stages of Powerhouse Kjørbo based on Fjeldheim et al. (2015) and (Fufa et al., 2016a). The primary energy use, energy production, and emissions from operational energy is discussed in Chapter 5.1.

A functional unit of 1 m^2 of a refurbished heated floor area of over an estimated 60-year service life of the building was considered. The calculation was performed for a total refurbished heated floor area of 5180 m^2.

The analysis included the environmental impact categories global warming potential, based on the IPCC 100 year method (Solomon et al., 2007) and primary energy use, based on the cumulative energy demand method (Frischknecht et al., 2007). The cumulative energy demand (CED) comprise the entire demand valued as primary energy, which arises in connection with the production, use and disposal of an economic good (product or service) or which may be attributed respectively to it in a causal relation (Althaus et al., 2010). Thus, CED calculates the total primary energy use, both for raw materials energy use (feedstock) and direct energy use.

The system boundary has been defined in accordance with the modular system of life cycle stages as defined in EN 15978. Product stage (A1-A3), construction process stage (A4-A5), replacement in use stage (B4) and end-of-life (C1-C4) life cycle stages are considered for both primary energy use and CO_{2eq} emissions calculations.

6.2 Inventory analysis

This chapter describes the inventory gathered for the different life cycle phases and scenarios used for the calculations, based on (Fufa et al., 2016) and Fjeldheim et al. (2015). The inventory analysis for the construction materials is structured according to the Norwegian standard NS 3451:2009 Table of Building Elements (Standard Norway, 2009), in order to get an overview of the building elements included and make comparisons with other projects.

The material inventory analysis included the following construction parts based on the inventory suggested by Wittstock et al. (2011) (Fjeldheim et al., 2015):

- Foundation and load bearing structure
- Basement walls
- Exterior walls
- Structural vertical elements
- Surface coating
- Floor structure and slabs
- Coverings and tightness elements
- Roof framework
- Partitioning walls
- Internal doors
- Suspended sealing
- Windows and joinery work
- Exterior doors
- Floors
- Painting and wallpaper coverings
- Heating and ventilations systems
- Electricity wiring (high and low voltage)
- Communication and network
- Elevator
- Photovoltaic systems with inverters

Materials for infrastructure related to water and drain were not included. Biogenic CO_2 uptake of wood and absorption of CO_2 by carbonation of the concrete used in the construction were not accounted for in the analysis.

The material quantities were gathered from the Revit BIM (Building information model) and from MagiCad for the ventilation system. During the construction phase, the quantities were updated if changes were made from the design phase. The primary energy and GHG emissions were based on data gathered and analysed directly from producers, type III environmental product declarations (EPDs), Ecoinvent v2.2 database (Swiss Center for Life Cycle Inventories, 2010) and scientific articles. The analysis by (Fthenakis, 2011) provided inputs into the embodied energy in the PV modules.

The material replacement intervals (B4) were based on service lifetimes available from EPDs or from SINTEF Building and Infrastructure's guidelines for building component replacement intervals (SINTEF Building and Infrastructure, 2010). The equations presented in EN15978 (CEN, 2011) were applied for the number of necessary replacements. In general, the replaced components were based on the same inventories as the initial inventories, assuming that no changes in the technical performance or production methods were applied. However, for the PV modules it was assumed an improvement in the production method and efficiency, as described in the next chapter. The service lifetime for the PV modules was based on Fthenakis (2011).

6.2.1 Product stage (A1-A3) and replacement (B4)

Primary energy and GHG emissions calculations from the product and replacement stages include primary energy and GHG emissions related to building material production and replacement of materials, including materials related to the PV system.

All reinforcement steel and concrete from the previous building has been adjusted and reused and the existing glass facade panels are reused as interior walls in the new building. According to NS-EN 15978:2011 Section 7.3, the environmental loads from components that are reused shall be allocated based on the remaining service life. In the Powerhouse Kjørbo project, embodied energy and emissions loads from the reused components were not accounted for into the analysis considering the embodied energy and emissions originating from the remaining service life of materials in an existing building as belonging to the previous life cycle of that building. This decision was made to encourage reuse of materials and based on an argument that the reused components were older than 30 years, had served more than 50% of their estimated service life, and that the remaining environmental impact should not be included. Analyses concluded that based on the calculation rules of EN 15978, 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.

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 (NREL, 2014). This is also in accordance with the optimistic scenario presented in Frischknecht et al. (2015).

6.2.2 Construction and installation (A4 –A5)

The transport of materials and components to the construction site (A4) was registered. The actual weight of materials and components for each means of transport was not known, therefore the total weight of materials and components used in the project has been evenly distributed over the total number of transports.

In 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. (Fjeldheim et al., 2015)

6.2.3 End of life (C1-C4)

The end-of-life phase includes the deconstruction (C1), transport to waste processing site (C2), waste processing (C3) and waste disposal (C4) phases. The following assumptions were used for end-of-life primary energy and GHG emissions calculations:

- C1: Due to lack of high quality data, the deconstruction phase was assumed to be equal to the construction installation process. Less heating will be needed for deconstruction since 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 out.
- C2: The transport of waste from construction site to waste treatment facility and disposal site were based on Erlandsen (2009) and supplemented with generic distances from Wittstock et al. (2011) and 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 (SSB, 2013).

6.3 Results

The results with respect to primary energy and GHG emissions are presented in Table 6.1. The GHG emissions from materials "M" (A1-A3, B4) is 5.59 kg $CO_{2\text{-eq}}/(m^2$ year); construction installation process "C" (A4-A5) is 0.25 kg $CO_{2\text{-eq}}/(m^2$ year) and end of life stages "E" (C1-C4) is 0.74 kg $CO_{2\text{-eq}}/(m^2$ year).

Table 6.1 Results of primary energy and GHG emissions from Fjeldheim et al. (2015)

Life cycle stage		**Primary energy** kWh/(m^2 year)	**GHG emissions** kg $CO_{2\text{-eq}}/(m^2$ year)
A1-A3	Raw materials supply, Transport and Manufacturing	20.11	3.77
A4	Transport to site	0.11	0.02
A5	Construction installation process	2.67	0.23
B4	Replacement	10.34	1.82
C1	Deconstruction	2.67	0.23
C2	Transport	0.27	0.06
C3	Waste process for reuse, recovery or/ and recycling	0.11	0.02
C4	Disposal	0.47	0.43
Sum		**36.75**	**6.58**

There are always significant uncertainties related to lifecycle counting of primary energy and GHG emissions (Fjeldheim et al., 2015). Scenarios are set based on probable outcomes, emission factors related to materials, energy and transport inputs are based on databases giving average production values, and scenarios for waste treatment is made on the basis of today's practice.

Figure 6.1 to Figure 6.4 show the distribution of the embodied energy and GHG emissions per building elements according to NS 3451:2009 and the major categories of materials, respectively.

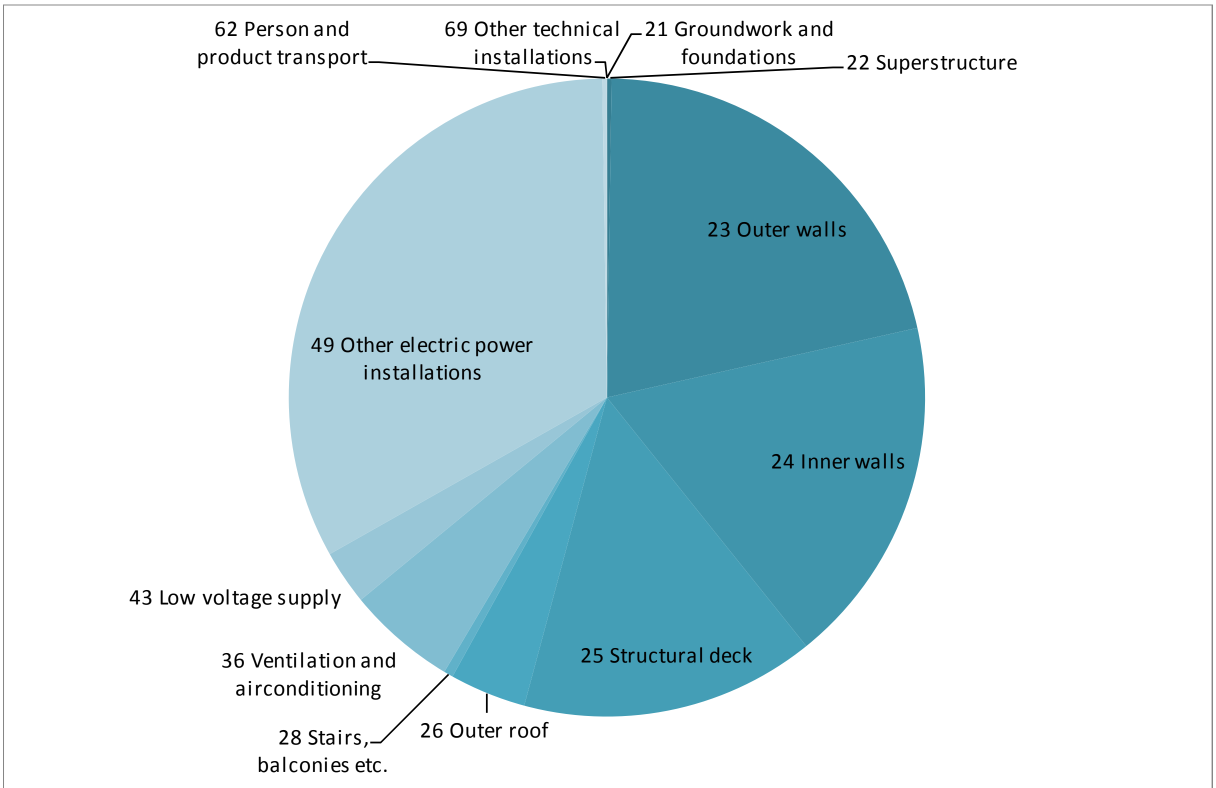


Figure 6.1 Total primary energy use of Powerhouse Kjørbo building per building parts according to NS 3451:2009 (Fjeldheim et al., 2015)

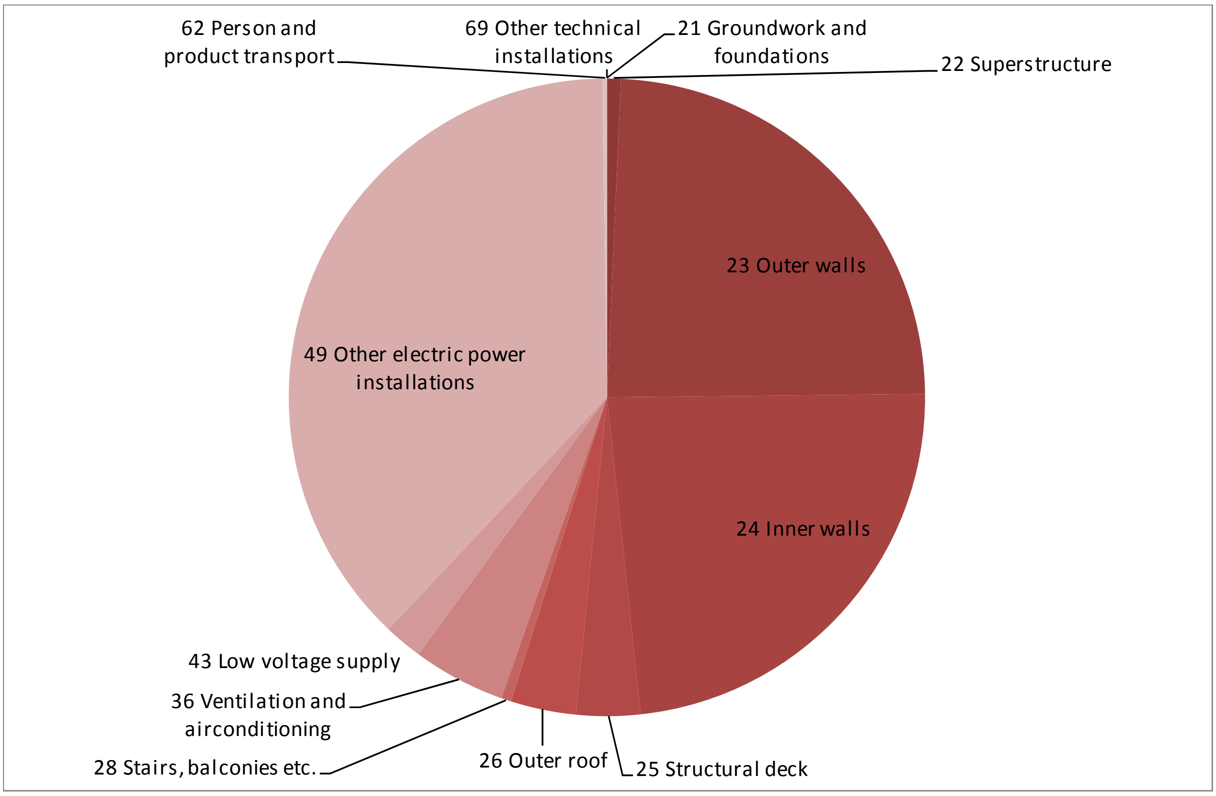


Figure 6.2 Total embodied GHG emissions of Powerhouse Kjørboper building partss according to NS 3451:2009 (Fjeldheim et al., 2015)

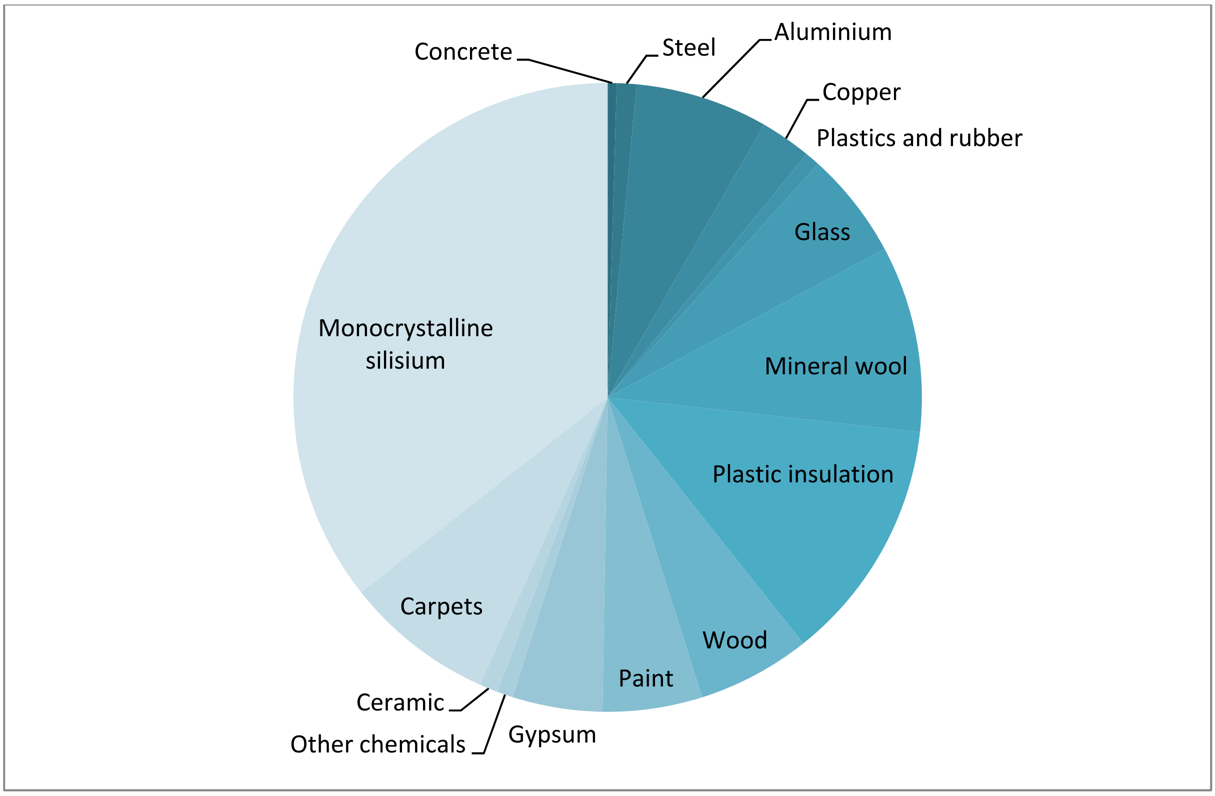


Figure 6.3 Total primary energy use distribution per major categories of materials (Fjeldheim et al., 2015)

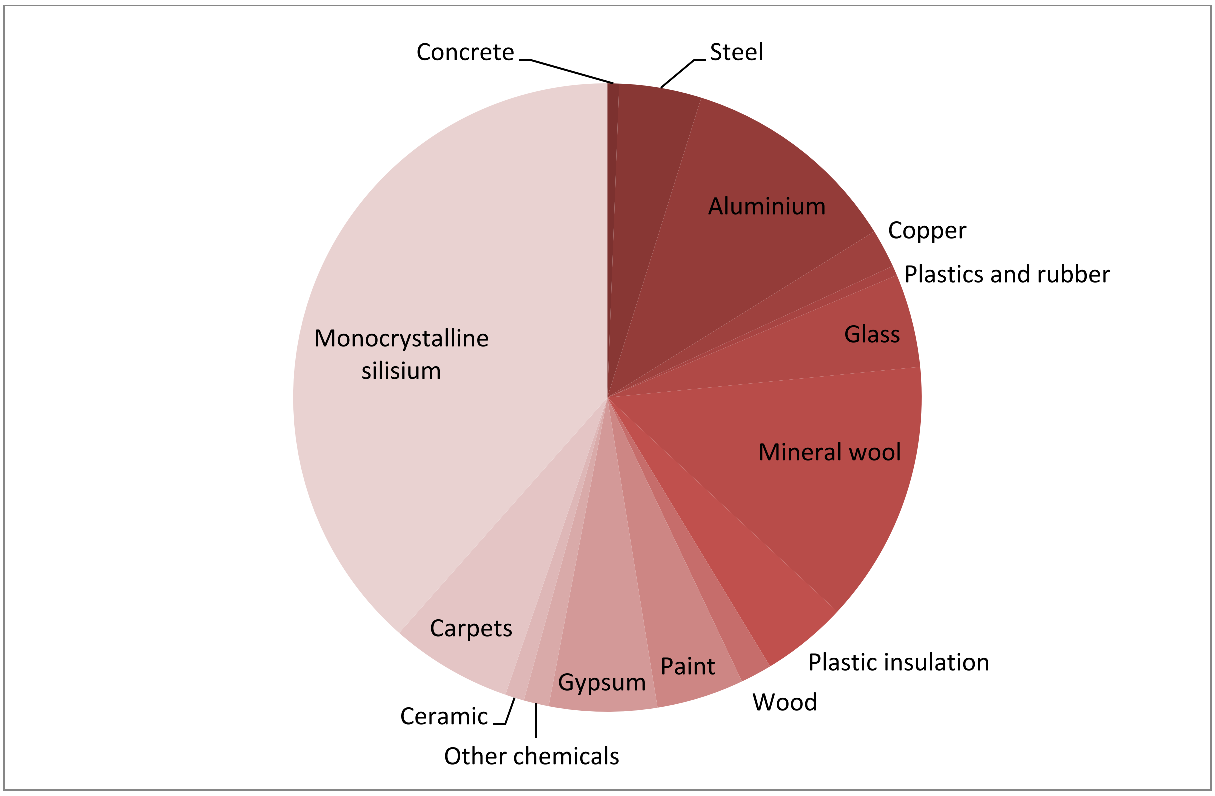


Figure 6.4 Total embodied GHG emissions distribution per major categories of materials (Fjeldheim et al., 2015)

7. The Powerhouse and ZEB goals

7.1 The difference between the Powerhouse and ZEB goals

This report describes both the Powerhouse goals and the ZEB ambition levels. As described in Chapter 1, the Powerhouse goals are related to energy while the ZEB ambition levels are related to GHG emissions.

Table 1.1 summarizes Powerhouse goals and equivalent ZEB requirements, as well as the life cycle stages covered. For Powerhouse Kjørbo, the Powerhouse goals has been the governing goals in the planning and construction process.

When evaluating the Powerhouse and ZEB goals, results from Fjeldheim et al. (2015) is used in both cases, when calculating the embodied energy or emissions in materials and construction. For the operational phase, both methods use measured results for energy production and consumption. The key difference in the methods is that for the Powerhouse goals, primary energy factors are used, while for the ZEB ambition levels emission factors are used.

For the Powerhouse goals, primary energy, embodied energy and primary energy factors are described by Thyholt et al. (2015):

- Primary energy is a unit for energy, which includes all consumption and losses of both renewable and non-renewable energy in the energy chain: From production of energy carriers, via conversion and distribution to consumption of energy. Primary energy is therefore not directly comparable to neither energy need in a building nor delivered energy to the building.
- If a given amount of electricity is produced from different energy carriers, also the consumption of primary energy will differ. A product produced by the same production method in similar factories can therefore still have different consumption of primary energy, depending on the energy carriers used and the energy systems.
- The Powerhouse definition of embodied energy for a product or material is the total sum of the energy needed in the manufacturing processes; From extraction of the raw material to the finished product as well as replacements. This embodied energy for a product or material is measured in primary energy.
- The primary energy factor for grid based electricity has been assumed to decrease linearly from 3.43 in 2010 to 2.38 (kWh primary energy/ kWh energy consumed) in 2050, according to Thyholt et al. (2015). This results in an average primary energy factor of 2.55 for the service life of Powerhouse Kjørbo.

For ZEB ambition levels, embodied emissions and emission factors are described by Fufa et al. (2016):

- Embodied emissions are included according to the ambition level for a building, e.g. emissions from the product stage (A1-3), construction process stage (A4-A5) and replacement (B4) in a ZEB-COM.
- The emission factor for electricity used for the ZEB projects is 0.132 kg CO_2 eq/kWh. The ZEB Research Centre considers Norway as part of the European power system. This yearly averaged factor is based on a future scenario assuming a fully decarbonised European grid by the end of 2050, according to EU policy goals.

Figure 7.1 illustrates the calculation of energy needed to compensate for material emissions ("M") when evaluating the ZEB ambition and the Powerhouse goal. The figure shows estimated material emissions/ embodied energy from Fjeldheim et al. (2015) and the described emission and primary energy factors. With these conditions, there is a need to produce about 3.5 times more energy from solar cells to achieve the ZEB ambition, compared to achieving the Powerhouse goal, to compensate for embodied emissions or energy in materials.

		Materials emissions/embodied energy (A1-A3, B4) (Fjeldheim 2015) *	Factors to use	Agreed factor **, ***	Energy to produce, if compensating for material
ZEB ambition	GHG emissions	5,59 kg CO_2-eq/(m^2 year)	Emission factor	0,132	**42,3 kWh/(m^2 year)**
		= comparable with			
Powerhouse goal	Primary energy	30,45 kWh/(m^2 year)	Primary energy factor	2,553	**11,9 kWh/(m^2 year)**

* The primary energy and GHG emissions are based on data gathered and analysed directly from producers, type III environmental product declarations (EPDs), ecoinvent database v2.2 (Swiss Center for Life Cycle Inventories, 2010) and scientific articles. The analysis by (Fthenakis, 2012) provided inputs into the embodied energy in the PV modules.

** The primary energy factor for grid based electricity has been assumed to decrease linearly from 3,43 in 2010 to 2,38 (kWh primary energy/ kWh energy consumed) in 2050 according to Kindem Thyholt et. al. (2015). This results in an average primary energy factor of 2,55 for the service life of Powerhouse Kjørbo. This scenario is in accordance with the guidelines from the ZEB centre and is based on the technological development scenario to meet the 2-degree target.

*** The emission factor for electricity is 0.132 kg CO_2 eq/kWh (Fufa et al., 2016). This yearly averaged factor is based on a future scenario assuming a fully decarbonised European grid by the end of 2050, according to EU policy goals.

Figure 7.1 Calculation of the energy needed to compensate for material emissions "M" and embodied energy in materials, when evaluating the ZEB ambition and the Powerhouse goal.

7.2 The energy balance to achieve the Powerhouse goal

The PV-system is the key to achieve the Powerhouse goal so that the refurbished building over its lifetime generates more energy than it consumes. Measured data of energy production and energy use during the operation period is the basis when analysing the fulfilment of the goal.

Embodied primary energy in materials and energy use in operating phase is calculated to be 30.5 kWh/m^2 per heated floor area, summarizing A1-A3 (Raw materials supply, Transport and Manufacturing) and B4 (Replacement) in Table 6.1 (Fjeldheim et al., 2015). Primary energy in the construction phase is 2.8 kWh/m^2, summarizing A4 and A5 (Transport to site and Construction installation process). To compensate for the embodied primary energy, 13 kWh/m^2 heated floor area needs to be produced by the photovoltaic system each year.

Table 7.1 shows the energy balance for Powerhouse Kjørbo, for both the calculated energy balance as well as the measured energy balance for year 1 and year 2. The predicted energy balance gives a margin of +7.8 kWh/m^2 during the first year and +11.3 kWh/m^2 the second year. The margin means that the goal can be achieved even if the real energy production is lower than the calculations, or the energy consumption is higher than the calculations.

Since the solar energy plant was not fully in operation the first year, the positive energy balance was not achieved for the first year. For the second year, the energy balance was achieved with a margin of +3.5 kWh/m^2. If looking at the second year energy production and the average measured operational energy use, the Powerhouse energy goal is achieved with a margin of +5.0 kWh/m^2. Even when including the End-of-life (E), the Powerhouse energy goal is achieved, but not when including energy use for equipment (EQ).

Table 7.1 Energy balance for Powerhouse Kjørbo, based on results from Fjeldheim et al. (2015) and operational data for the two initial years from Jenssen (2016). BRA is heated floor area.

	Primary energy	Primary energy	Predicted (kWh/m2 BRA)			Measured kWh/m2 BRA		Average 2 initial years
	kWh/m^2 BRA/y	factor	**Year 1**	**Year 2**	Average	**Year 1**	**Year 2**	kWh/m^2 BRA
Energy production solar cells, average			44,3	43,9	44,1	25,8 *	43,1	43,1
Embodied energy in materials (M)	-30,5	2,553	-11,9	-11,9	-11,9	-11,9	-11,9	-11,9
Energy use building phase (C)	-2,8	2,553	-1,1	-1,1	-1,1	-1,1	-1,1	-1,1
Energy use operational phase (O÷EQ)			-23,5	-19,6	-21,6	-23,7	-26,6	-25,1
Energy balance (COM÷EQ)			**7,8**	**11,3**	**9,5**	**-10,9**	**3,5**	**5,0**
Energy use equipment (EQ)			-30,5	-25,4	-28,0	-19,3	-18,6	-19,0
End of life (E)	-3,5	2,553	-1,4	-1,4	-1,4	-1,4	-1,4	-1,4
Energy balance (COME)			-24,1	-15,5	-19,8	-31,6	-16,5	-15,3

* Not in operation for the full year.
Average is therefore based on year 2

7.3 The ZEB balance to achieve the ZEB ambition

The ZEB ambition level for Powerhouse Kjørbo can be translated to ZEB-COM÷EQ, as described in Chapter 1.2. To fulfil the ambition, on-site renewable energy generation is needed to compensate for emissions related to Construction "C", operation "O" except energy use for equipment/appliances (EQ) and embodied emissions from materials "M". In this report, energy use for equipment (EQ) and the end of life "E" are also included in the GHG emissions account. GHG emissions account for all the ZEB-COME stages are thereby carried out, and a share of these emissions are covered.

Table 7.2 shows the ZEB balance for Powerhouse Kjørbo, based on results from Fjeldheim et al. (2015) and operational data from Jenssen (2016). The average predicted and measured operational energy use, except the energy use for equipment, for the first two years is 21.6 kWh/m^2 and 25.1 kWh/m^2, respectively. For equipment, the average predicted and measured energy use for the first two years is 28.0 kWh/m^2 and 19 kWh/m^2, respectively. For the average production of energy for the first two years, the predicted average is 44.1 kWh/m^2 while the measured electricity production is 43.1 kWh/m^2. The background for the ZEB balance is further described in Chapter 6 (Material Emissions) and Chapter 5.1 (Energy use and production).

Table 7.2 The ZEB balance for Powerhouse Kjørbo, based on results from Fjeldheim et al. (2015) and operational data for the two initial years from Jenssen (2016). The emission factor used for B6 is 0.132 kg CO_2 eq/kWh.

Life cycle stage		GHG emissions, ZEB-COME (kg $CO_{2\text{-eq}}/(m^2$ year)) Predicted	Measured *	GHG emissions ZEB COM÷EQ (kg $CO_{2\text{-eq}}/(m^2$ year))
A1-A3	Product phase: • Raw materials supply, Transport and Manufacturing	3,77	3,77	3,77
A4-A5	Construction phase: • Transport to site, Construction installation process	0,25	0,25	0,25
B4	Use phase: • Replacement of components	1,82	1,82	1,82
B6	• Operational energy use (excluding equipment)	2,85	3,32*	3,32*
	• Operational energy use, equipment	3,69	2,50*	-
	• Production of energy	-5,82	-5,70*	-5,70*
C1 –C4	End of life phase • Deconstruction, Transport, Waste process for reuse, recovery or/ and recycling and Disposal	0,74	0,74	-
Sum		**7,30**	**6,70**	**3,46**

* B6 is based on energy measurements from the first two years.

The GHG emissions from B6 is calculated by multiplying the specific energy use/production with an emission factor for electricity. 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.

The emission factor used for the ZEB projects is 0.132 kg CO_2 eq/kWh (Fufa et al., 2016). This yearly averaged factor is based on a future scenario assuming a fully decarbonised European grid by the end of 2050, according to EU policy goals. In Table 7.2, this emission factor is used when calculating the B6 stage.

In Fjeldheim et al. (2015), an emission factor of 0,17 kg CO_2eq/kWh was used when calculating the B6 stage. For comparison, the total GHG emissions in Fjeldheim et al. (2015) were 3.44 kg $CO_{2\text{-eq}}/(m^2$ year), with slightly different predictions for energy use and energy production.

The results for the ZEB-COME account show that the product and construction phase (A1-A5) make up 32% of the lifecycle GHG emissions, the replacement of components (B4) 15%, the average measured operational energy use including equipment (B6) 47% and the end of life phase (C1-C4) 6%.

Figure 7.2 shows the emission balance using measured operational energy used and GHG emission account for all the calculated life cycle stages for ZEB-pilot Kjørbo. The results shows that 62% of the ZEB-COM÷EQ emissions are compensated for with renewable energy production.

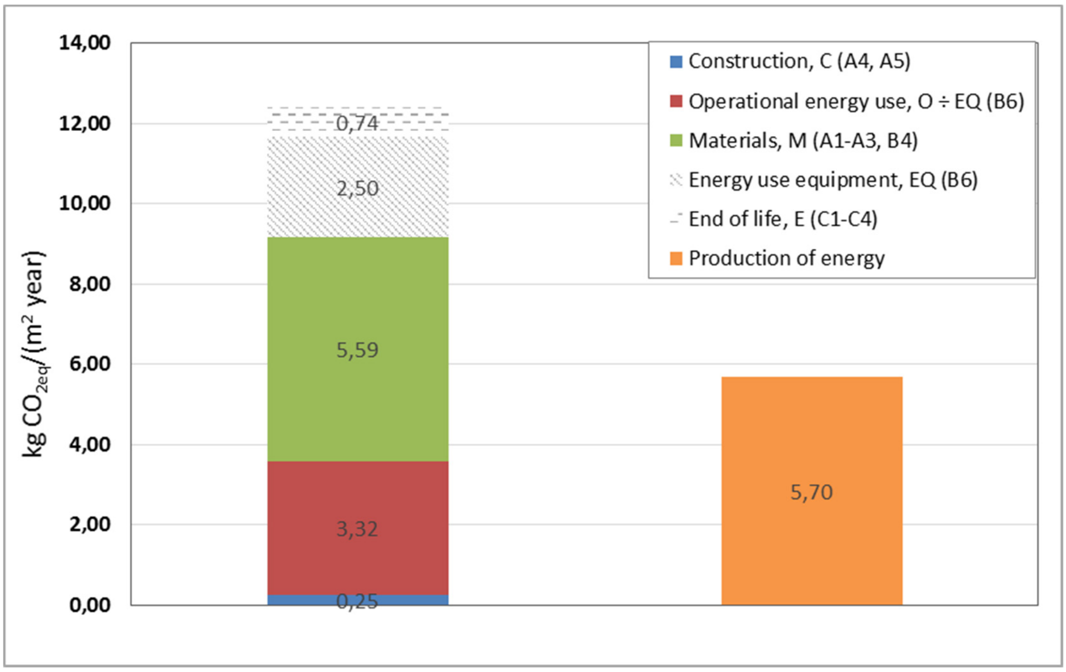


Figure 7.2 Calculated ZEB emission balance for ZEB-pilot Kjørbo ($kgCO_{2eq}/m^2$ year), with measured energy use (B6). To the left, the total GHG emissions/m^2/year per each COME life cycle stages (B6, A1-A5, B4, C1-C4). To the right, the on-site energy generation.

8. Design and Construction Process

The background for the project was the establishment of the Powerhouse alliance consisting of the real estate company Entra, the construction company Skanska, Snøhetta architects, the environmental non-governmental organization ZERO, the aluminium company Hydro, the aluminium profile company Sapa and the consultant company Asplan Viak. The Powerhouse alliance was established to cooperate towards the realization of energy positive buildings. It was also decided that the project should be a pilot project within the Research Centre on Zero Emission Buildings.

The main ambition and goal of the Powerhouse Allicance is to challenge and influence the existing planning processes, cooperation methods, technology, legislation, regulations, frameworks, vendors, contractors and consultants to establish the best possible foundation for plus energy buildings.

Gradually, several cooperation partners took part in the development of the Powerhouse concept, among others: Asplan Viak (consultant and tenant of the Powerhouse Kjørbo), Multiconsult (consultant with special expertise within solar power) and Systemair (ventilation vendor).

Subcontractors in the Powerhouse Kjørbo project were Direct Energy Sweden, Haaland Klima, Otera, C.M. Mathiesen, Basum Boring and Hunter Douglas Norge AS (Vental).

Important vendors were Systemair, Sunpower, Barum byggmontering, KlimaControl, Johnson Controls, Thermocontrol, Hubro, Sapa Building Systems and Stokkan Lys.

New projects will include new partners, which will contribute to dissemination of knowledge and further development of the solutions. However, the to ensure transfer of expertise, the Powerhouse collaboration agreement state that at least two partners must be involved in new projects.

Through cooperating in the Powerhouse alliance, the partners achieved better results than the sum of what the parties could have achieved individually (Jenssen et al., 2015). The Powerhouse alliance also forms the basis for new building projects, either within the Powerhouse alliance, or through other companies which have learned lessons from the Powerhouse alliance experiences and knowledge.

8.1 The Design Process

The design phase started out by establishing the Powerhouse definition; a clear and ambitious goal for the environmental standard of the building. The definition states that a Powerhouse must produce more renewable energy throughout its lifetime than it consumes for the production of materials, construction, operation, and disposal. The definition includes an assessment of measured energy, which means that its fulfilment must be documented through measurements.

The design concept phase was organized and led by a dedicated process leader from Snøhetta, and interdisciplinary workshops were held regularly. The team had a clear philosophy that the key factor for finding solutions to achieve the energy goal lay in an interdisciplinary design process. In addition to workshops, a number of workgroup meetings were carried out. The participants were divided into interdisciplinary workgroups, each with the responsibility for different specific tasks. Each workgroup had a designated leader, and a matrix was used to keep track of resources, tasks and responsibilities in the team. The design team conducted an iterative process of establishing alternative solutions, creating inventories and assessing these according to the defined methods. Figure 8.1 illustrates the Powerhouse design process and Figure 8.2 the structure of the deliverables and how responsibilities and roles were allocated across disciplines and organizations.

It is a consensus that the success of the project was due to a close cooperation between the various partners, the ability to find the most optimal solutions and the innovative combination of these solutions (Skanska, 2014). Working with all project stakeholders and the entire supply chain was an important part of the Powerhouse Kjørbo project due to its challenging demands on design, material uses and selections, energy efficient solutions and construction. No partner could undertake such a demanding project on their own, and the expertise and close cooperation of all partners was crucial to the project (Skanska, 2014).

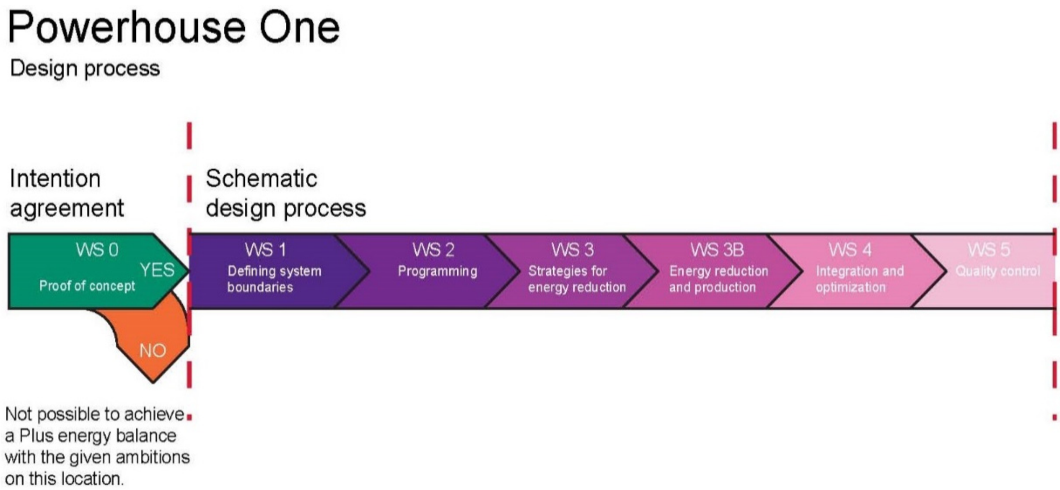


Figure 8.1 Illustration of the Powerhouse design process.

Powerhouse Kjørbo - Team and responsibilities

Participants	Company		Responsibilities																																
			Client representative (Entra)	Building manager (Entra)	User representative (Asplan Viak)	PH Alliance - PG/Communication	PH Alliance - PG/Framework	PH Alliance - PG/Consept	Projectplace (web)	BIM (Revit)	User & Indoor environment	PGL (Project Group Leader)	TEAM Process management	ARCH Project management	Quality program (MOP)	Environmental Coordinator (RIM/BREEAM)	Thermal energy supply system	Photo Voltaic	Ventilation Strategy	Embodied energy	Daylight studies	Building Envelope - windows/PV	Building envelope - opaque walls	Building automation	RIB (Structural engineer)	RIBr (Fire engineer)	RIE (Electrical)	RIV (Mechanical/Plumbing)	Acoustic engineer	Energy concept/Energy budget	3D-model (Revit)	Arch. drawings incl. interior and landscape	Cost Estimate / Time schedule	Risk analysis	Final report
Aasen, Thomas	HBS																																K		
Bernhard, Peter	Asplan Viak																H	K	K	U		K								U					U
Berulfsen, Halvor	Asplan Viak																												U						U
Bjørgum, Knut	SNØ																															U			U
Bøe, Torgeir	Skanska	PH Kjørbo PGL									K	H	K	K			K	K	K	K	K	K	K	H	H	H	H	H	K	K			K	K	U
Børve, Einar	Entra	Entra Project manager	H	H	H	K	K	K	K	K			K	K																			K	K	
Dahl, Camilla	Asplan Viak				K						K																								
Dokka, Tor Helge	ZEB	ZEB Project manager								K					K	K	K		K	H		K	K							U					U
Dæhli, Fredrik	Skanska																																U		
Eggertsen, Andreas	Snøhetta										K		K	K	H	K																U			U
Fjeldheim, Henning Olav	Skanska																			U															
Fløisbonn, Håkon	Skanska									H																					K				
Førlad-Larsen, Arne	Asplan Viak															U	U	K	U			K								U					
Gaarder, Hans Thomas	Skanska	PH Kjørbo Project manager (PGL)			K	K	K	K	K	K			K	K																			H	H	U
Haaland, Espen	Skanska																		U					K	K	K	K	K	K	U					U
Haug, Wenche Flø	Asplan Viak																									U									
Hegli, Tine	SNØ	PH Kjørbo Process coordinator				H	H	H	H	K			H	K	K																				H
Heier, Ellen	SNØ																					U										U			
Holman, Johannes	Multiconsult															U																			
Iversen, Per	Entra			K																															
Jennsen, Bjørn W.	Skanska																K	K	H	K	K	K	K							H					U
Jensen, Ole Mangor	Skanska																						U												
Klausen, Helge	Asplan Viak																								U										
Kristjansdottir, Torhildur	ZEB																			U															
Moneta, Camilla	SNØ	Snøhetta Project manager								K	H		K	H							K		H	K	K	K	K	K	H	K		H	K		U
Müller, Philipp	HBS																		K	U		H	U							K					U
Nermoen, Lars	HBS					K																													
Nygaard, Andreas	SNØ																					U	U									U			
Radt, Max	HBS																	H				U								U					U
Rådstoga, Olav																												U							
Sørnes, Kari	ZEB																			U															
Tyholt, Marit	Skanska	PH Kjørbo Environmental coord.						K					K		K	H	K				H	K	K												U
Vatn, Elin	SNØ									U	U									K											H	U			U
Vindal, Jon	Skanska																		K																
Widt, Einar	Asplan Viak																										U								
Wilhelmsen, Einar	Zero						K										K																		
	?	Økolog																																	
	?	Enova (Entra contact)																																	

Degree of participation: H=Responsible for coordination and decisions / U=Executing / K=to be consulted before decision / I=to be informed after decision. Responsible for coordination (H) is often also executing (U) - depending on the volume of work within the task. H is responsible for deliverances to the final report.

Figure 8.2 The matrix illustrating the structure of the deliverables and how responsibilities and roles were allocated across disciplines and organizations. The matrix was updated and changed during the course of the project. Illustration: Snøhetta.

Parallel to the concept phase an additional team started work on project development. This team had responsibility for further development and quality control of the ideas from the concept process and then lead the project development on to the general building permission. From this point on the project was organized as a traditional turnkey project, although a number of the key participants from the design phase also followed the project in this phase. Figure 8.3 illustrate the structure if the workgroups.

Powerhouse Kjørbo - Workgroups

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
User & Environment	**Thermal energy supply system (heatpump/cooling)**	**Active Building Envelope**	**Ventilation Strategy**	**Embodied Energy (Materials/Construction/ Demolition)**	**Cost Estimates / Risk analysis**
Moneta, Camilla	**Bernhard, Peter**	**Müller, Philipp**	**Jenssen, Bjørn W.**	**Dokka, Tor Helge**	**Gaarder, Hans Thomas**
Børve, Einar	Førland Larsen, Arne	Radt, Max	Haaland, Espen	Kristjansdottir, Torhildur	Bøe, Torgeir
Vatn, Elin	Rådstoga, Olav	Nygaard, Andreas	Førland Larsen, Arne	Fjeldheim, Henning Olav	Dæhli, Fredrik
Eggertsen, Andreas		Eggertsen, Andreas	Nome, Petter	Fløisbonn, Håkon	Haaland, Espen
Dahl, Camilla		Klausen, Helge	Rådstoga, Olav	Vatn, Elin	Aasen, Thomas
Førland Larsen, Arne		Widt, Einar	Dokka, Tor Helge	Eggertsen, Andreas	
Iversen, Per			Bøe, Torgeir		
Norén, Trond			Haug, Wenche Flø		
Klausen, Helge					
Berulfsen, Halvor					
Haug, Wenche Flø					
Widt, Einar					
Heier, Ellen					
Bjørgum, Knut					
Support					
Thyholt, Marit	Jennsen, Bjørn W.	Dokka, Tor Helge	Müller, Philipp	Muller, Philipp	Hegli, Tine
	Dokka, Tor helge	Jennsen, Bjørn W.	Ingebrigtsen, Sturla	Sørnes, Kari	Moneta, Camilla
	Müller, Philipp	Bernhard, Peter	Høseggen, Rasmus	ZEB, Sofie	Børve, Einar
	Radt, Max	Førland Larsen, Arne	Vatn, Elin		Asplan Viak
	Eggertsen, Andreas	Jensen, Ole Mangor	Eggertsen, Andreas		
	Zijdemans, David				
	Huus-Hansen, Wilhelm				

Figure 8.3 Illustration of the workgroups for Powerhouse Kjørbo. Illustration: Snøhetta (Hegli, 2016)

The consortium pioneered the use of BIM (Building Information Modeling)-based laser scanning on the Kjørbo project to map and model the exterior and interior of the building. The building's exterior façade and the surrounding trees were accurately modeled using laser scanning to enable detailed BIM solar studies to calculate the extent of shading from trees and to optimize the placement of roof-mounted solar panels. Laser scanning was also used to create an accurate as-built BIM model of the building's load bearing structure, which was retained and incorporated into the refurbishment. (Skanska, 2014)

8.2 The Construction Process

The dismantling started January 28th 2013. After ended dismantling, only the steel and concrete substructure was left standing. After the renovation works were finished, the buildings appeared as new, with highly insulated wood façades, new interior layout, new furnishing, and completely new technical solutions including ventilation system, heat pump systems and solar power (Jenssen et al., 2015).

Overall, more than 97% of the construction waste, including demolition waste, was diverted from landfill. The team worked with a comprehensive waste management plan to sort waste into 12 different streams. (Skanska, 2014)

Figure 8.4 The Construction process at Powerhouse Kjørbo. Photo: Snøhetta

Figure 8.5 The Construction process at Powerhouse Kjørbo, keeping the existing steel and concrete substructure. Photo: Snøhetta

Figure 8.6 The Construction process at Powerhouse Kjørbo; interior shafts for ventilation. Photo: Snøhetta

Figure 8.7 The Construction process at Powerhouse Kjørbo; fitting of wood cladding. Photo: Snøhetta

8.3 Evaluating the design and construction process

Throndsen et al. (2015) have evaluated the construction process and early use phase of Powerhouse Kjørbo. This Chapter is quoting their report.

As a tool for cross-disciplinary collaboration, energy and emissions calculations were central as a common reference point throughout the whole process. Considering only the design phase, it is clear that particularly the energy account was useful in defining both the necessary amount of work and the methods of the collaborative work. One of the merits was its ability to force each participant onto neutral ground based on shared information and work requirements. The energy account served as a boundary object (Star 2010) in this way as it provided “something” around which to collaborate across disciplinary boundaries and something that could translate different disciplinary specialities into a mutually comparable success criterion: the primary energy goal. The primary energy goal was both the what and the why of this collaboration, simultaneously a process of creation and a guiding force.

The effort that went into creating the energy account and collaboration in workshops, which were employed as a sort of management tool, were argued by some informants to have made the process ‘heavy on the nose’. This was largely due to design aspects and the signal effect, which was important for Powerhouse Kjørbo as a pilot project. As this was a pilot project, it has received a certain degree of special attention from all involved institutions. The participants describe the special requirements connected to this building as trust in the concept; broad participation in the project’s definition process; trust between partners; and high level decision making at the different partners’ companies to cater to an acceptable risk allocation for all parts.

According to the respondents, the design process benefited much from the oversight of a dedicated process manager, a role that was served by one of the project’s senior architects. In fact, many respondents noted the exact point in time when the process manager exited the project was also the point when the project encountered problems.

The participants agree 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. Failures accrued once the distance between actors increased due to their involvement in other projects. According to respondents, one important role for a process manager in the later stages could have been as a liaison between project management levels (contractor) and subcontractors. Some problems that appeared in this phase involved the sheer disbelief shared by the subcontractors when they first became acquainted with the calculations, the functional demands, and the specifications that had resulted from the design process - a process they knew little about. This constituted a failure on behalf of the Powerhouse collaboration to translate the concept to the hired hands, which complicated the execution phase.

Contract frameworks were also mentioned as a contributing source of errors as turnkey contract frameworks dis-incentivised subcontractors from making order changes also after they were clearly deemed necessary by consulting engineers. This is not an unusual mode of contracting in the construction business from a traditional viewpoint and could perhaps prove to work better in the future as the concept matures along with the market. A greater level of detailing in the design phase is one way to address this. However, in light of the experiences gathered at Powerhouse Kjørbo, the question is whether a more collaborative framework could have been applied to allow subcontractors to identify and share in the risk taking with the main contractors and/or project owner - or, in fact, to take part in the social learning that occurs as actors make the project ‘their own’. One way to incentivise junior contractors to join in more time-consuming, perhaps less profitable, contract arrangements could be to highlight the skill and knowledge development benefits available for participants in such projects. This would, however, require some proof of concept to be sufficiently translated into a clear added value for suppliers. At this juncture, the newly constructed Powerhouse is one such proof. In replicating elements of the Kjørbo project, it is likely that resources can be saved on design and parts of the pre-project phase. However, to avoid the amount of order changes seen in the execution of Powerhouse Kjørbo (especially for different projects), more resources must be spent on learning for junior contractors.

Finally, the symbolic value that was characteristic of Powerhouse Kjørbo contributed to both its ability to be realised and concrete benefits for actors involved in the time after completion. Many have drawn parallels between Powerhouse Kjørbo and Tesla, implying that Powerhouse Kjørbo is for the building industry what that electric car is for the automotive industry. As many of the respondents emphasised, the building is a statement that says “it’s possible.” The goal had never been accomplished, let alone attempted, before, and success hinged on the project participants’ belief in that final statement. A radically different approach combined with an ambitious goal made that belief possible, and it was reinforced by the interdisciplinary work that was the basis of the project. This extra effort was a necessity in this project, but it might not be in the next. Some of it can most likely be implemented in other projects. However, as this report also demonstrates, picking pieces out of the success story Powerhouse Kjørbo may not yield equally impressive results because there is a connection between the pieces that is important for the whole building to succeed.

8.4 BREEAM NOR certification

In a broader environmental perspective, an aim of this project was also to achieve the classification “Outstanding” in the BREEAM-NOR environmental certification scheme. Kjørbo was the first office building in Norway achieving the Outstanding-certification, which is the highest rating in BREEAM.

BREEAM-NOR is the Norwegian version of BREEAM (Building Establishments Environmental Assessment Method), which is an environmental classification system for the construction industry. BREEAM-NOR assesses buildings in the following areas: Energy and environmental performance; Healthy conditions for tenants; and Economic sustainability.

The project achieved in total 85.2 % in BREEAM (NGBC, 2016), where the best categories where energy (96%), Use of area and ecology (90%), Transportation (83%) and Waste (83%).

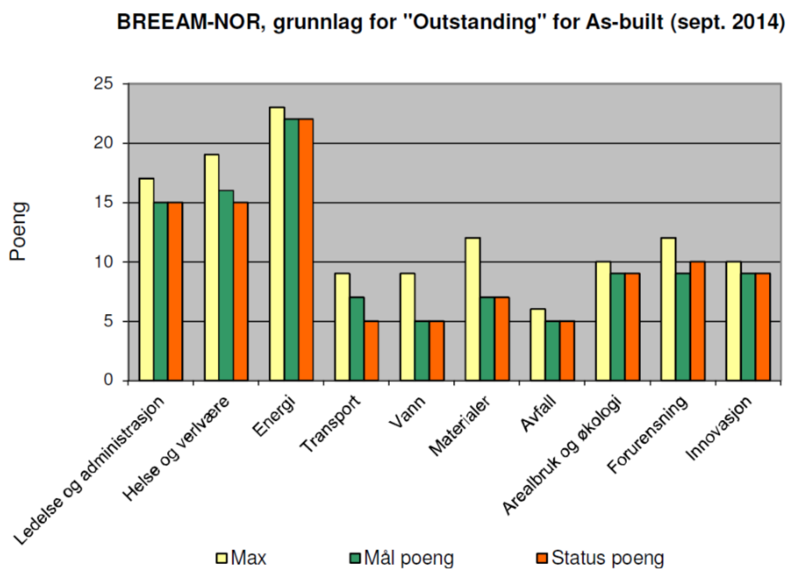


Figure 8.8 BREEAM-NOR basis for the achieved Outstanding certification, showing maximum possible points, planned points and achieved points for Kjørbo (Jenssen et al., 2015)

9. Design and Construction Costs

Entra Eiendom owns the buildings and its partner Skanska Norway was the contractor. The total costs for the redevelopment project was about 25 000 NOK/m^2. The added costs compared to refurbish the building to TEK-standard (energy label C) is estimated to 8 000 NOK/m^2. The enterprise Enova supported the project with in total about 3 000 NOK/m^2 through the program "New Technology in Buildings of the Future" and the Passive House program. (Jenssen et al., 2015)

The refurbished buildings will reduce energy costs by around 80 percent compared with a new building with the energy label C. When the generated electricity from the photovoltaic solar energy system is included, the reduction will be over 100 percent, through the buildings' energy-plus nature (including tenant equipment, but not energy for the data server). These savings promote profitability for the landlord and tenants. (Skanska, 2014)

10. Summary and Conclusions

Powerhouse Kjørbo, located in Sandvika near Oslo, consists of two office blocks from the 1980´s that have been upgraded to energy-efficient and modern offices. The Powerhouse goal is that the refurbished buildings over their lifetime generate more energy than they consumes. This implies that the building shall produce and export energy that compensates for the energy used for production of materials, construction, renovation, operation and end of life. Energy consumption related to technical appliances is not included.

In regards of ZEB emission goals, the ZEB ambition levels were still under development when Powerhouse Kjørbo was designed and constructed. However, the Powerhouse goal can be translated to the ZEB emission ambition ZEB-COM÷EQ. This means that emissions related to all energy use in Construction "C", operation "O" except energy use for equipment/appliances (EQ) and embodied emissions from materials "M" shall be compensated with on-site renewable energy generation (Fufa et al., 2016). In this report, also energy use for equipment (EQ) and the end of life "E" are shown in the GHG emissions account, which then includes all the ZEB-COME ambition levels

Energy efficiency measures and materials with low embodied energy have been crucial for obtaining the energy goal at Powerhouse Kjørbo. An efficient ventilation concept has been developed, to reduce the overall energy demand for operation. Also other parameters were important during the design, such as daylight utilization, using thermal mass to regulate the indoor climate, acoustic conditions and the use of low VOC emitting products. The energy need is covered by a heat pump and a photovoltaic system.

As the Powerhouse and ZEB definitions state that the fulfilment of the definition should be documented by measured results, the energy use at Powerhouse Kjørbo was followed up closely. Operation and measurements started in April 2014, and results for the two first year of operation are available. The average operational energy use for the first two years was predicted to be 21.6 kWh/m^2 and measured to be 25.1 kWh/m^2. For the production of energy, the predicted average is 44.1 kWh/m^2 while the measured electricity production during the second year is 43.1 kWh/m^2.

For materials, both primary energy and GHG emissions calculations are presented (from Fjeldheim et al. (2015)). The GHG emissions results from materials (A1-A3, B4) is 5.59 kg $CO_{2\text{-eq}}$/(m^2 year), construction installation process (A4-A5) is 0.25 kg $CO_{2\text{-eq}}$/(m^2 year) and end of life stages (C1-C4) is 0.74 kg $CO_{2\text{-eq}}$/(m^2 year).

The Powerhouse goals has been the governing goals in the planning and construction process at Kjørbo. The energy balance to achieve the Powerhouse goal was achieved the second year, with a margin of 3.5 kWh/m^2. The energy balance for the first year was not reached, since the solar energy plant was not yet fully in operation.

In regards to the ZEB ambition, the results shows that 62% of the ZEB-COM÷EQ emissions are compensated for with renewable energy production. The results for the ZEB-COME account show that the product and construction phase (A1-A5) make up 32% of the lifecycle GHG emissions, the replacement of components (B4) 15%, the average measured operational energy use including equipment (B6) 47% and the end of life phase (C1-C4) 6%.

Powerhouse Kjørbo has received national and international attention, and the building has been nominated for a number of awards. Powerhouse Kjørbo demonstrates that it is possible to renovate existing properties into energy-plus buildings in cold climates, and that such renovations make commercial and environmental sense to the parties involved. A holistic approach to the project that simultaneously considered materials and embodied energy, technical systems, architecture, and energy efficiency and generation over the lifespan of the buildings was crucial to achieving the project's ambitious objectives (Skanska, 2014).

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APPENDIX

A.1 Details of windows in Block 4 and 5
A.2 WWH R290 Varmepumpe
A.3 Solar energy inverters and strings
A.4 Data sheet Sunny Tripower Inverter

A.1 Details of windows in Block 4 and 5

AGC YourGlass

20-03-2013

Din sammensetning:

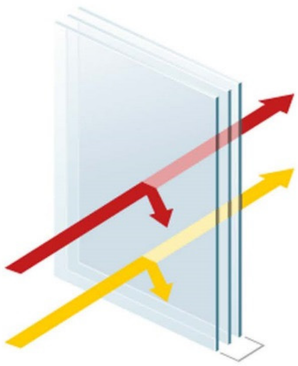
4 mm Planibel Low-e Top N+ pos.2 - 20 mm Argon 90% - 4 mm Planibel Clear - 20 mm Argon 90% - 4 mm Planibel Low-e Top N+ pos.5

Personlige notater:

Ug=0,52

Lys	
overføring	69
refleksjon	17

Energi	
g-verdi	47
Solenergirefleksjon	33



ISOLERINGSEGENSKAPER (EN 673)	EN 673
Ug-Verdi - W/(m².K)	0.5

LYSEGENSKAPER (EN 410)	EN 410
Lystransmisjon - τv (%)	69
Lysrefleksjon - ρv (%)	17
Fargegjengivelsesindeks-RD65 - Ra (%)	96

STRåLINGSEGENSKAPER	EN 410	ISO 9050
g-verdi - g (%)	47	44
Solenergirefleksjon - ρe (%)	33	35
Solenergitransmisjon - τe (%)	39	37
Absorbert solenergi i glass 1 - αe (%)	18	19
Absorbert solenergi i glass 2 - αe (%)	5	5
Absorbert solenergi i glass 3 - αe (%)	6	5
Totalt absorbert solenergi - αe (%)	29	29
Shading coefficient - SC	0.54	0.51
UV-transmisjon - UV (%)	9	
Schattenfaktor (DE) (b-Faktor) - b-Faktor		55.0

ANDRE EGENSKAPER	
Brannhemmende - EN 13501-2	NPD
Reaksjon mot brann - EN 13501-1	NPD
Skuddhemmende - EN 1063	NPD
Innbruddshemmende - EN 356	NPD
Pendultest (personsikkerhet) - EN 12600	NPD / NPD / NPD
Direkte luftbåren lydisolasjon(Rw (C;Ctr) - Anslått) - dB	32 (-1, -6)

The data are calculated using spectral measurements that are conform to standards EN 410, ISO 9050 (1990) and WIS/WINDAT.
The Ug-value (formerly k-value) is calculated according to standard EN 673. The emissivity measurement complies with standards EN 673 (Annex A) and EN 12898.
This document is no evaluation of the risk of glass breakage due to thermal stress. For tempered glass: the risk of spontaneous breakage due to Nickel-Sulfide is not covered by AGC Glass Europe. The Heat Soak Test is available on request.
Specifications, technical and other data are based on information available at the time of preparation of this document and are subject to change without notice. AGC Glass Europe can not be held responsible for any deviation between the data introduced and the conditions on site. This document is only informative, in no way it implies an acceptance of the order by AGC Glass Europe.
See also conditions of use.
These sound reduction indexes are estimated (no test).They correspond to glazings which are 1,23m. by 1,48 m. In-situ performances may vary according to the effective glazing dimensions, frame system, noise sources etc.
The accuracy of the given indexes is +/- 2dB.

www.yourglass.com

AGC GLASS UNLIMITED

Din sammensetning:

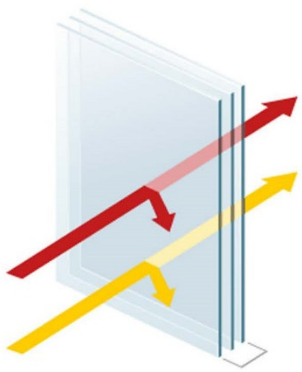
4 mm Planibel Low-e Top N+ pos.2 - 18 mm Argon 90% - 4 mm Planibel Clear - 20 mm Argon 90% - 6 mm Planibel Low-e Top N+ pos.5

Personlige notater:

Ug=0,53

Lys	
overføring	68
refleksjon	17

Energi	
g-verdi	47
Solenergirefleksjon	33



ISOLERINGSEGENSKAPER (EN 673)	EN 673
Ug-Verdi - W/(m².K)	0.5

LYSEGENSKAPER (EN 410)	EN 410
Lystransmisjon - τv (%)	68
Lysrefleksjon - ρv (%)	17
Fargegjengivelsesindeks-RD65 - Ra (%)	95

STRåLINGSEGENSKAPER	EN 410	ISO 9050
g-verdi - g (%)	47	44
Solenergirefleksjon - ρe (%)	33	35
Solenergitransmisjon - τe (%)	38	36
Absorbert solenergi i glass 1 - αe (%)	18	19
Absorbert solenergi i glass 2 - αe (%)	5	5
Absorbert solenergi i glass 3 - αe (%)	7	6
Totalt absorbert solenergi - αe (%)	30	30
Shading coefficient - SC	0.54	0.51
UV-transmisjon - UV (%)	9	
Schattenfaktor (DE) (b-Faktor) - b-Faktor		55.0

ANDRE EGENSKAPER	
Brannhemmende - EN 13501-2	NPD
Reaksjon mot brann - EN 13501-1	NPD
Skuddhemmende - EN 1063	NPD
Innbruddshemmende - EN 356	NPD
Pendultest (personsikkerhet) - EN 12600	NPD / NPD / NPD
Direkte luftbåren lydisolasjon(Rw (C;Ctr) - Anslått) - dB	36 (-2, -7)

The data are calculated using spectral measurements that are conform to standards EN 410, ISO 9050 (1990) and WIS/WINDAT.
The Ug-value (formerly k-value) is calculated according to standard EN 673. The emissivity measurement complies with standards EN 673 (Annex A) and EN 12898.
This document is no evaluation of the risk of glass breakage due to thermal stress. For tempered glass: the risk of spontaneous breakage due to Nickel-Sulfide is not covered by AGC Glass Europe. The Heat Soak Test is available on request.
Specifications, technical and other data are based on information available at the time of preparation of this document and are subject to change without notice. AGC Glass Europe can not be held responsible for any deviation between the data introduced and the conditions on site. This document is only informative, in no way it implies an acceptance of the order by AGC Glass Europe.
See also conditions of use.
These sound reduction indexes are estimated (no test).They correspond to glazings which are 1,23m. by 1,48 m. In-situ performances may vary according to the effective glazing dimensions, frame system, noise sources etc.
The accuracy of the given indexes is +/- 2dB.

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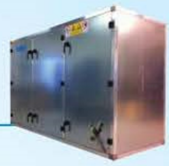
A.2 WWH R290 Varmepumpe

09 - 2012



WWH R290 Varmepumpe - 2 kredset

Miljøvenlig - Minimal lav kølemiddelfyldning - Højtydende - Kompakt design - Indendørs installation - Fremstillet i Danmark

Model		WWH30	WWH40	WWH60	WWH80	WWH100	WWH150	WWH180	WWH220	WWH260	WWH300	WWH330
Temp. +12/+7°C	KW køl	22,1	31,1	48,6	65,6	84,7	123,2	148,3	177,0	192,9	243,6	263,4
Temp. +0/-4°C	KW køl	20,2	27,5	41,5	57,8	73,0	105,2	129,2	151,2	171,2	208,5	224,0
Temp. +7/+12°C	KW varme	30,9	44,2	67,5	91,0	114,7	163,7	200,0	240,6	263,2	330,7	357,8
Temp. -4/+0°C	KW varme	26,7	36,9	55,4	78,7	95,8	137,3	168,1	197,9	226,8	276,1	298,0
Kompressor	antal	2	2	2	2	2	2	2	2	2	2	2
Kompressortype		Q5-21.1	Q7-28.1	S12-42	S20-56	V25-71	V35-103	Z40-126	Z50-154	W50-168	W60-187	W70-206
Driftstrøm	Amp.	17,8	27,8	35,8	60,6	63,4	77,6	98,6	124,8	139,6	178,4	192,4
Max Strøm Komp	Amp.	11,6	17,6	22,4	38,4	43,5	61,0	71,9	90,4	94,8	116,8	128,4
Optagen effekt	KW.	9,8	14,6	21,0	28,3	33,4	45,0	57,4	70,7	78,2	96,8	104,9
Startstrøm PW 3x400 V, 50 Hz	Amp.	72,0	101,2	77,0	117,8	150,0	183,3	208,5	251,0	327,8	479,2	513,2
Kølemiddel	kg, R290	2x2	2x3,5	2x4	2x4,5	2x5	2x6	2x2x7	2x7,5	2x9	2x11	2x13
Kap. trin	%	4*	4*	4*	4*	4*	4*	4**	4**	4*	4*	4*
Fordamper	type					FULDLODDET PLADEVARMEVEKSLER						
Flow v. ΔT 5K.	m3/h	2 x 2,07	2 x 2,89	2 x 4,53	2 x 6,11	2 x 7,88	2 x 11,48	2 x 13,89	2 x 16,49	2 x 17,97	2 x 22,7	2 x 24,55
Trykfald	kPa	23	26	28	29	21	24	23	21	20	16	17
Kondensator	type					FULDLODDET PLADEVARMEVEKSLER						
Flow v. ΔT 10K.	m3/h	2 x 1,34	2 x 1,93	2 x 2,95	2 x 3,97	2 x 5,00	2 x 7,14	2 x 8,73	2 x 10,5	2 x 11,49	2 x 14,44	2 x 15,62
Trykfald	kPa	16	17	20	20	16	17	17	17	17	14	14
Længde	mm	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Bredde****	mm	870	870	870	870	870	870	870	870	870	870	870
Højde	mm	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Vægt	kg	350	380	450	500	550	600	750	1000	1200	1300	1400
dB(A)	10 mtr	<45	<45	<45	<45	<45	<45	<45	<45	<45	<45	<45
COP varme		3,16	3,03	3,21	3,22	3,44	3,64	3,49	3,40	3,37	3,42	3,41
Ventilationsanlæg	180 m³/h pr. kW	5600	8000	12000	16400	20600	29400	36000	43300	47400	59600	64400

Low Noise modeller (LN) på forespørgsel

Data er opgivet ved væske temperatur på +50°C/+60°C på varm side, +12°C/+7°C på kold side (30% ethylenglycol)
Data med blå er opgivet ved væske temperatur på +35°C/+45°C på varm side, +0°C/-4°C på kold side (30% ethylenglycol)

* 25% - 50% - 75% - 100%
** 33% - 50% - 83% - 100%
*** Optaget effekt ved væsketemp. +12°C/+7°C
**** Bredde uden eltavle

Bundgaard

Bundgaard Køleteknik A/S Sadelmagervej 22, DK-7100 Vejle, Denmark - Tel. +45 75857311 • Naverland 14, DK-2600 Glostrup - Tel. +45 43457311 • www.coolcare.dk • administration@coolcare.dk

A.3 Solar energy inverters and strings

The tables below present the specifications for each of the inverters used at Powerhouse Kjørbo, from Ødegården (2016). They are named V1–V4 at Block 4 and 5, and V1–V8 at the garage building.

Table A.1: Specifications of the three inverter models installed at PK. [70]

Inverter model	STP 12000TL-10	STP 15000TL-10	STP 17000TL-10
Max DC power (PF = 1)	12.5 kW	15.6 kW	17.6 kW
Max DC voltage	1000 V	1000 V	1000 V
MPP voltage range	150–800 V	150–800 V	150–800 V
Max input current input B / input B	22 A / 11 A	33 A / 11 A	33 A / 11 A
No. of MPP trackers	2	2	2
Max no. of strings (input A / input B)	4 / 1	5 / 1	5 / 1
Max AC power output (230 V, 50 Hz)	12 kVA	15 kVA	17 kVA
Max. efficiency/ European efficiency	98 % / 97.5 %	98 % / 97.5 %	98 % / 97.5 %

Table A.2: Properties of the PV system of Block 4, "B4".

BUILDING 4 PV SYSTEM	
Number of modules per string (A / B)	13 / 14
Number of strings per input utilized (A / B)	3 / 1
Inverter model	STP 15000TL-10
Number of inverters	4
Rated PV power per inverter	17.331 kWp
Tilt angle	10°
Azimuth V1–V	-35° (SE)
Azimuth V3–V4	+145° (NW)
Rooftop area covered	345.56 m^2

Table A.3: Properties of the PV system of Block 5, "B5".

BUILDING 5 PV SYSTEM	
Number of modules per string (A / B)	12 / 9
Number of strings per input utilized (A / B)	3 / 1
Inverter model	STP 12000TL-10
Number of inverters	4
Rated power per inverter	14.715 kWp
Tilt angle	10°
Azimuth V1–V	-35° (SE)
Azimuth V3–V4	+145° (NW)
Rooftop area covered	293.40 m^2

Table A.4: Properties of the PV system of the garage building, "P".

GARAGE BUILDING PV SYSTEM	
Number of modules per string (A / B)	12 / 10 (11 for V4 and V8)
Number of strings per input utilized (A / B)	5 / 1
Inverter model	STP 17000TL-10
Number of inverters	8
Rated PV power per inverter	22.890 kWp (23.217 kWp for V4 and V8)
Tilt angle	10°
Azimuth angle V1–V4	+70° (SW)
Azimuth angle V5–V8	-110° (NE)
Rooftop area covered	293.40 m^2 916.06 m^2

In Figure A.1 to A.3, each string has its own color. Each module is labeled with the name of the string it belongs to (from Ødegården (2016).

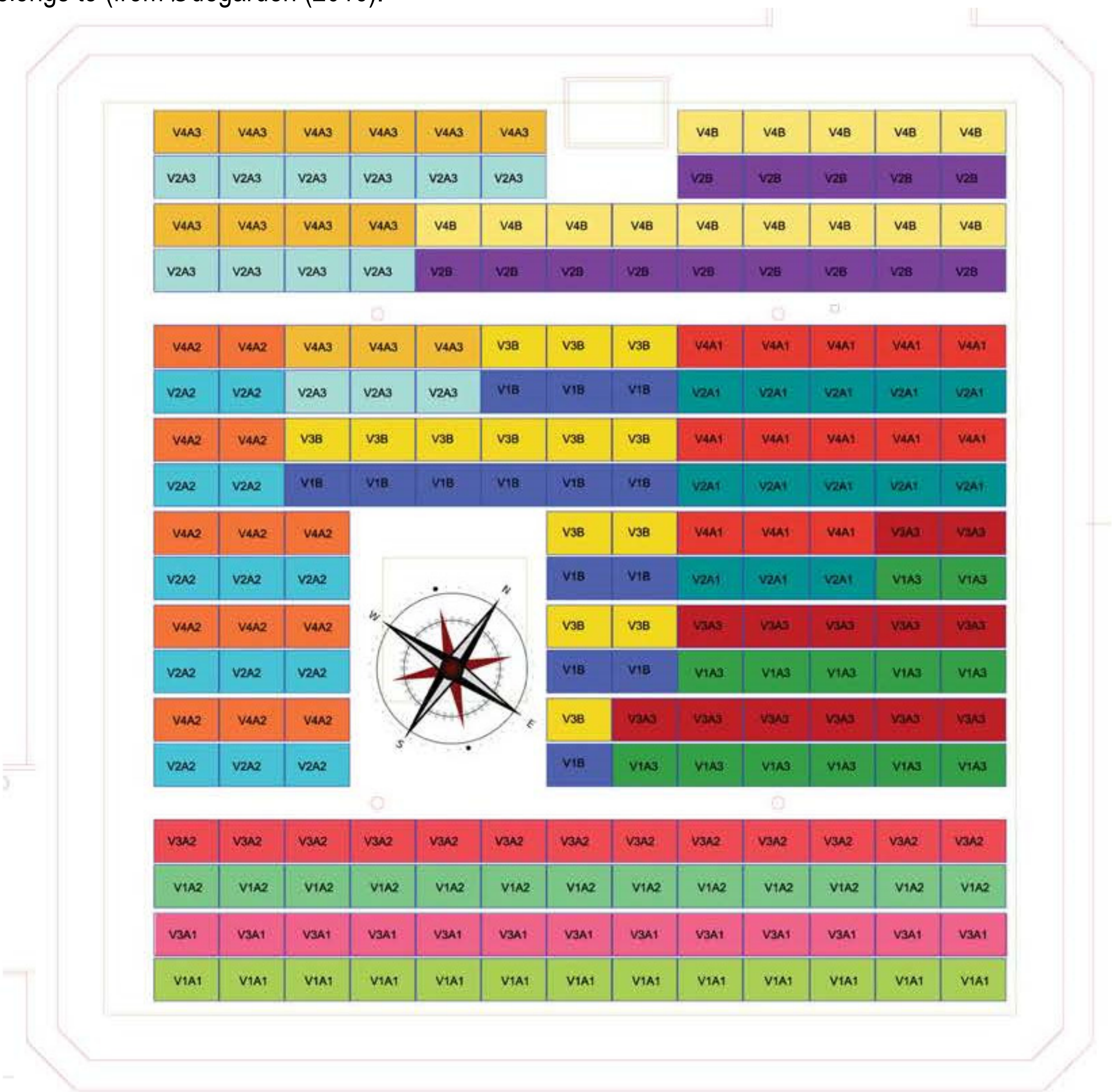


Figure A.1: Illustration showing the string configuration at Block 4. (Source: Asplan Viak, Skanska)

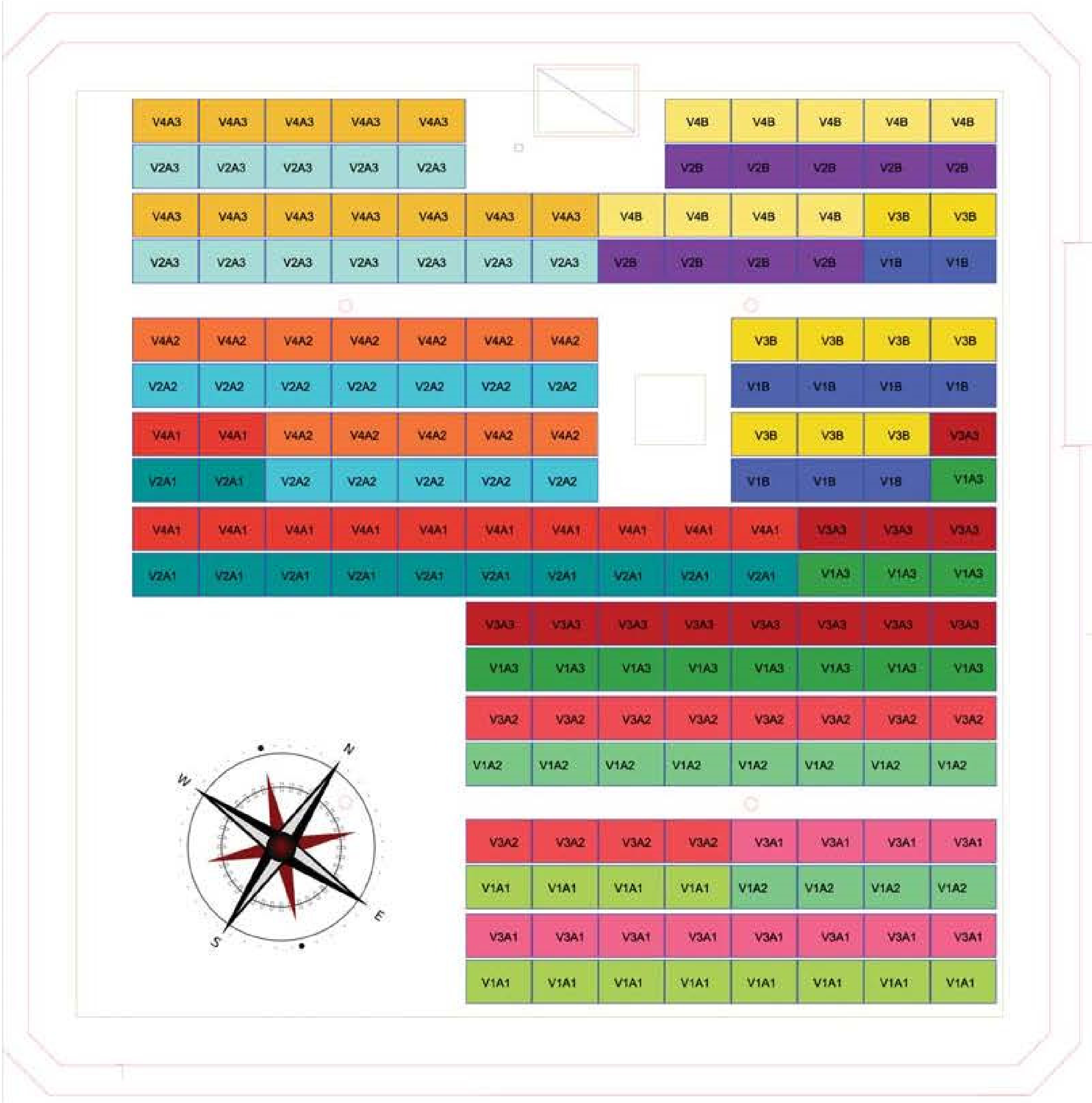


Figure A.2: Illustration showing the string configuration at Block 5. (Source: Asplan Viak, Skanska)

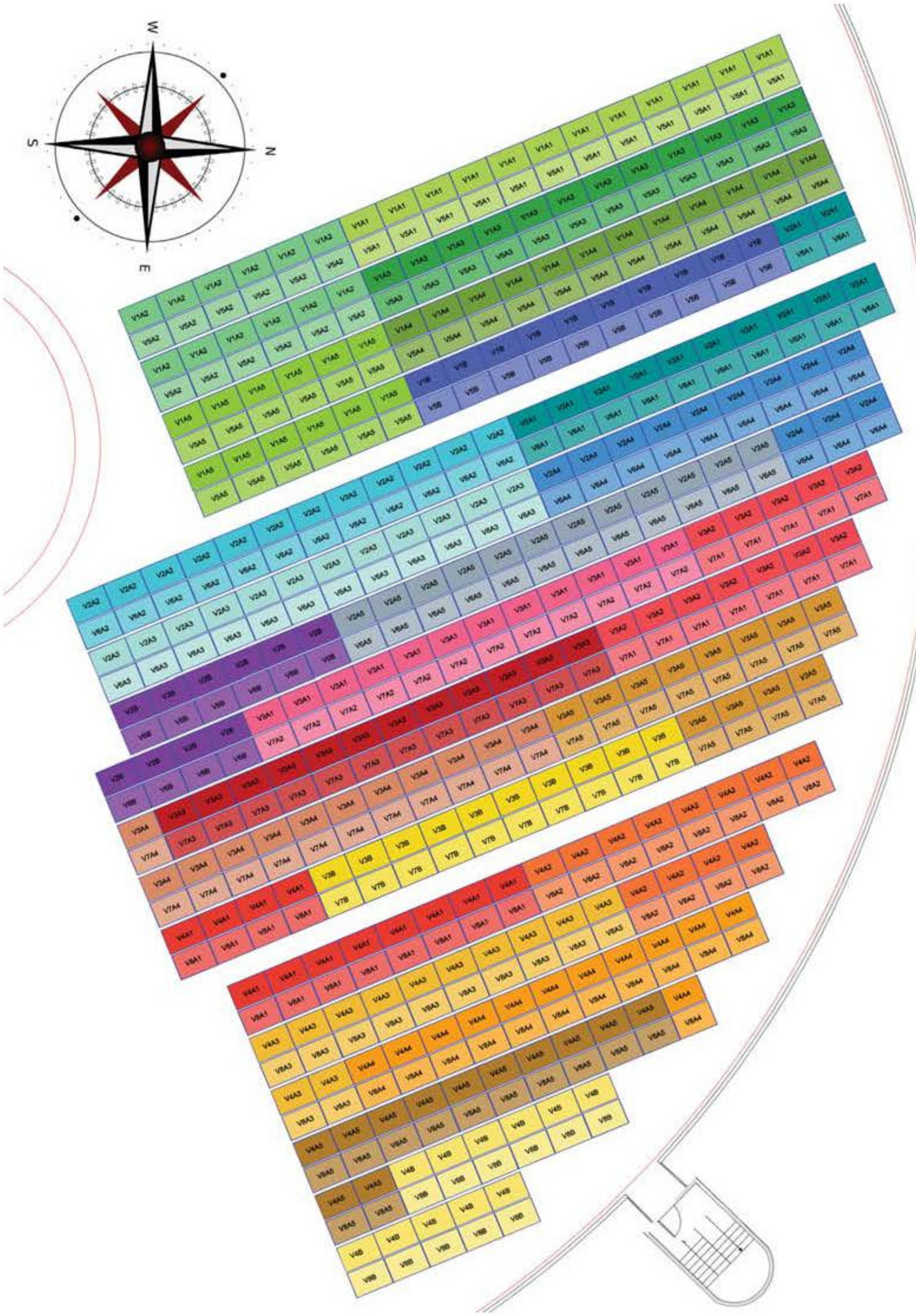


Figure A.3: Illustration showing the string configuration at the garage building. (Source: Asplan Viak, Skanska)

A.4 Data sheet Sunny Tripower Inverter

SUNNY TRIPOWER
10000TL / 12000TL / 15000TL / 17000TL

Efficient

- Maximum efficiency of 98.1 %
- OptiTrac Global Peak for best tracking efficiency*
- Bluetooth Communication

Safe

- Electronic string fuse and failure detection
- Integrable DC overvoltage protector [Type II]
- String current monitoring

Flexible

- DC input voltage up to 1,000 V
- Integrated grid management functions
- Tailor made plant design with Optiflex

Simple

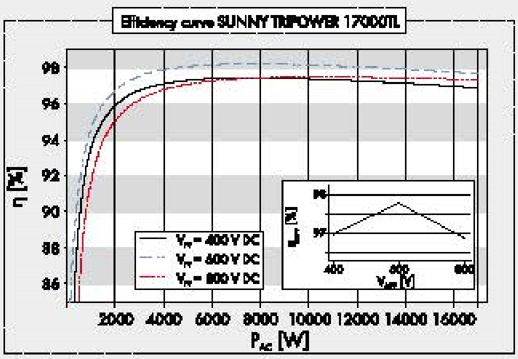
- Three-phase feed-in
- Cable connection without tools
- DC plug system SUNCLIX
- Easily accessible connection area

SUNNY TRIPOWER 10000TL / 12000TL / 15000TL / 17000TL

The three-phase inverter for easy system design

Packed full of pioneering technology: thanks to the new Optiflex technology with two MPP inputs and its very broad input voltage range, the three-phase Sunny Tripower is suited to almost any module configuration. In addition, it is highly flexible in terms of the plant design – right up to the megawatt range. The Sunny Tripower meets all the requirements for reactive power supply, utility interaction management and grid support, thus making a reliable contribution to grid management. The extensive Optiprotect safety concept, with its self-learning string failure detection, electronic string fuse and integrable DC overvoltage protector Type II, ensures maximum availability.

Technical data	Sunny Tripower 10000TL	Sunny Tripower 12000TL	Sunny Tripower 15000TL	Sunny Tripower 17000TL
Input (DC)				
Max. DC power (@ cos φ = 1)	10200 W	12250 W	15340 W	17410 W
Max. DC voltage	1000 V	1000 V	1000 V	1000 V
MPP voltage range	320 V – 800 V	380 V – 800 V	360 V – 800 V	400 V – 800 V
DC nominal voltage	600 V	600 V	600 V	600V
Min. DC voltage / start voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current / per string	A: 22 A, B: 11 A / 33 A	A: 22 A, B: 11 A / 33 A	A: 33 A, B: 11 A / 33 A	A: 33 A, B: 11 A / 33 A
Number of MPP trackers / strings per MPP tracker	2 / A: 4, B: 1	2 / A: 4, B: 1	2 / A: 5, B: 1	2 / A: 5, B: 1
Output (AC)				
AC nominal power (@ 230 V, 50 Hz)	10000 W	12000 W	15000 W	17000 W
Max. AC apparent power	10000 VA	12000 VA	15000 VA	17000 VA
Nominal AC voltage; range	3 / N / PE, 230 V / 400 V; 160 V – 280 V			
AC grid frequency; range	50, 60 Hz; –6 Hz, +5 Hz	50, 60 Hz; –6 Hz, +5 Hz	50, 60 Hz; –6 Hz, +5 Hz	50, 60 Hz; –6 Hz, +5 Hz
Max. output current	16 A	19.2 A	24 A	24.6 A
Power factor (cos φ)	0.8 leading ... 0.8 lagging			
Phase conductors / connection phases / power balancing	3 / 3 /–	3 / 3 /–	3 / 3 /–	3 / 3 /–
Efficiency				
Max. efficiency / Euro-eta	98.1 % / 97.7 %	98.1 % / 97.7 %	98.1 % / 97.7 %	98.1 % / 97.7 %
Protection devices				
DC reverse-polarity protection / reverse current protection	●/electronic	●/electronic	●/electronic	●/electronic
ESS switch-disconnector	●	●	●	●
AC short circuit protection	●	●	●	●
Ground fault monitoring	●	●	●	●
Grid monitoring (SMA Grid Guard)	●	●	●	●
Galvanically isolated / all-pole sensitive fault current monitoring unit	–/●	–/●	–/●	–/●
DC overvoltage protector type II	○	○	○	○
String failure detection	●	●	●	●
Protection class / overvoltage category	I / III	I / III	I / III	I / III
General data				
Dimensions (W / H / D) in mm	665 / 690 / 265	665 / 690 / 265	665 / 690 / 265	665 / 690 / 265
Weight	65 kg	65 kg	65 kg	65 kg
Operating temperature range	–25 °C ... +60 °C	–25 °C ... +60 °C	–25 °C ... +60 °C	–25 °C ... +60 °C
Noise emission (typical)	www.SMA-Solar.com	www.SMA-Solar.com	www.SMA-Solar.com	www.SMA-Solar.com
Internal consumption: (night)	1 W	1 W	1 W	1 W
Topology	transformerless	transformerless	transformerless	transformerless
Cooling concept	OptiCool	OptiCool	OptiCool	OptiCool
Electronics protection rating / connection area (as per IEC 60529)	IP65 / IP54	IP65 / IP54	IP65 / IP54	IP65 / IP54
Climatic category (per IEC 60721-3-4)	4K4H	4K4H	4K4H	4K4H
Features				
DC connection: SUNCLIX	●	●	●	●
AC connection: screw terminal / spring-type terminal	–/●	–/●	–/●	–/●
Display: text line / graphic	–/●	–/●	–/●	–/●
Interfaces: RS485 / Bluetooth	○/●	○/●	○/●	○/●
Warranty: 5 / 10 / 15 / 20 / 25 years	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○
Certificates and permits (more available on request)	CE, VDE 0126-1-1, EnelGUIDA, G83/1-1*, PPC, AS4777, EN 50438**, C10/C11, IEC 61727			
*In planning, ** Does not apply to all national deviations of EN 50438				
● Standard features ○ Optional features – Not available				
Provisional data, as of March 2010 – data at nominal conditions				
Type designation	STP 10000TL-10	STP 12000TL-10	STP 15000TL-10	STP 17000TL-10



Accessories

RS485 interface
DM-485CB-10

DC overvoltage protector
(type II), input A
DCSPD KIT1-10

DC overvoltage protector
(type II), inputs A and B
DCSPD KIT2-10

www.SMA-Solar.com SMA Solar Technology AG

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.

NTNU – Trondheim
Norwegian University of Science and Technology

SINTEF

ZEB The Research Centre on Zero Emission Buildings

FORSKNINGSSENTER FOR MILJØVENNLIG ENERGI

Partners

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Multiconsult
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Brødrene Dahl
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Snøhetta
www.snoarc.no

Forsvarsbygg
www.forsvarsbygg.no

Statsbygg
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