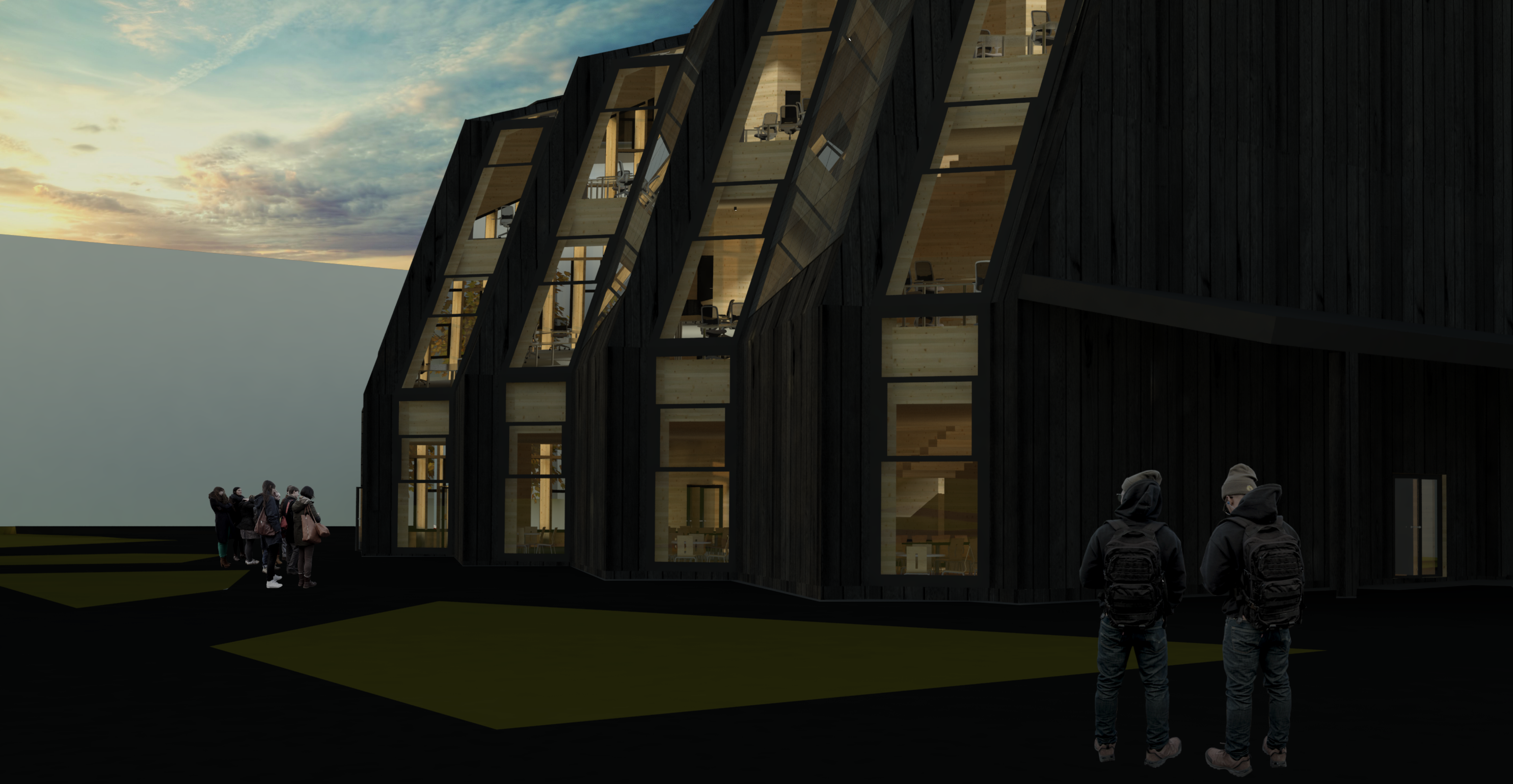

SENJA

| ABSTRACT

The ZEB Flexibility Lab focuses on integrated energy design to create a zero emission building through passive energy design, reduction of thermal losses, and production of renewable energy on the site, while maintaining a comfortable indoor environment. The ultimate challenge of a zero emission building is to develop a balance between a building's energy expenditure and the energy that can is produced on site. The design goal of this project is to create a laboratory that attains the status of ZEB-COM and provides a comfortable and flexible environment for the researchers and students that will be using the building. Upon analysis, it was determined that primary drivers of a building's energy consumption occur in the heating and ventilation of the building, while the most promising renewable energy resources available on the site are solar power and geothermal heating. During the design process, computer simulations were used to determine the thermal efficiency of the building, leading to an evolution of the shape, layout, and structure of the building, as energy production techniques were evaluated, analyzed, and optimized. We attempted to reduce the building's energy use by establishing an effective thermal envelope, implementing a hybrid ventilation system, and using a geothermal heat-pump for the generation of heat for the building; balancing the building's energy requirements with electricity produced by photovoltaic panels mounted on the facade of a building.

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| INTRODUCTION

The project group consists of four members, all students of MSc Sustainable Architecture but with different academic backgrounds:

Brisa Bøhle: Architecture and Urbanism
Janja Radivojevic: Architecture
Ida Hallebrand: Structural Engineering
Kari Tarnstrom: Architectural Engineering

As the task sets quite complex requirements, merging into one another, good communication between group members and insight in tasks are necessary to in order to provide time-efficient and good-quality design. The design process started with discussion about fields of expertise, time-management, communication tools and softwares and setting milestones. After individual analysis of requirements and boundary conditions and deeper understanding of the task, it was necessary to discuss priorities and find a common design key drivers in order to strive to the same goal. Further process until the submission is based on research and comparison of different concepts and group decision making based on pros and cons of each idea, in terms of both architectural quality and building =performance. During the process, the previous options were kept in mind and reevaluated as the design was progressing. The mapping helped keeping track of important interactions between different aspects.

The entire group worked together to establish general concepts and approaches, while specific tasks and responsibilities were distributed among members based on their skills sets and specialties. The floor plan layout and functional design of the building were the primary focus of Janja and Brisa, who both have Architectural backgrounds. They additionally took responsibility for the design the layout for the natural ventilation system due to its dependence on the building layout. The technical systems of the building were developed by Ida and Kari. Ida has a background in structural engineering led her to take responsibility for the construction techniques and to develop a plan for the building's structural system. Kari's background in architectural engineering and her experience with plumbing and mechanical systems led her to focus on the mechanical ventilation and heating distribution systems of the building.

Various software programs were used during different design stages of the project. During the initial site analysis, Meteonorm and Ecotect were used to collect data specific to the site, including climate and shadow studies. Polysun was used to estimate the energy production of the photovoltaic panels, while IDA ICE was used for interior daylight simulations throughout the project. Both SIMIEN and IDA ICE were used to track the building's energy demand and indoor comfort.

Brisa Bøhle, BA Architecture and Urbanism:
- site analysis
- drawings
- architecture
- furniture layout
- presentations and posters
- renders

Ida Hallebrand, BSc Structural Engineering, major Architecture:
- urban analysis
- resource analysis
- materials
- construction
- occupancy
- LCA

Janja Radivojevic, BSc Architecture:
- climate analysis
- resource analysis
- workplace design
- PV optimization
- daylight
- energy modeling
- booklet

Kari Tarnstrom, BS Architectural Engineering Technology and BS Civil & Environmental Engineering:
- requirements and goals
- models
- heating system
- HVAC system

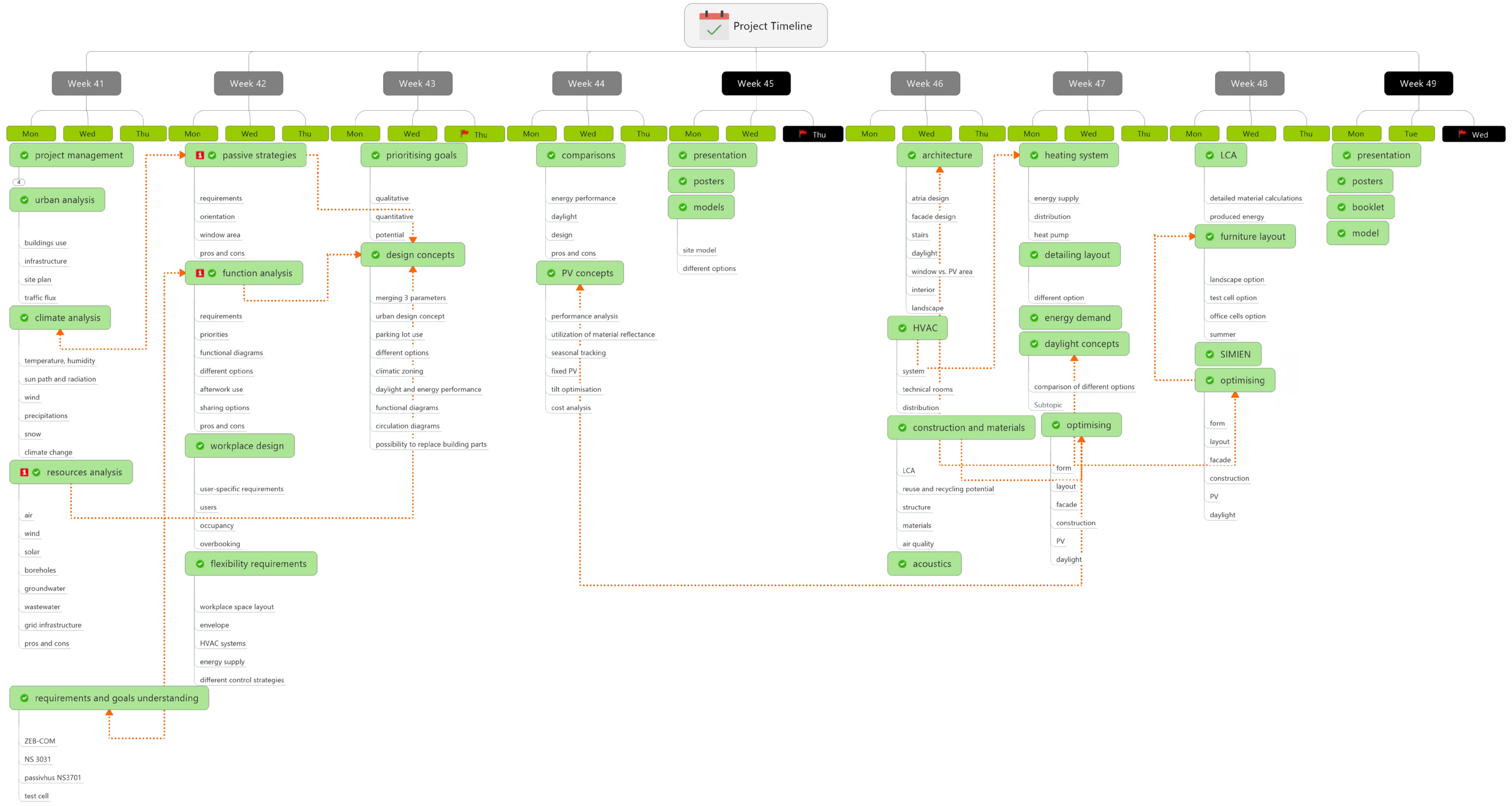


Figure 1: Weekly schedule [MindManager]

| REQUIREMENTS AND GOALS

The purpose of the ZEB Flexible Lab project is to develop a building on a site on the NTNU campus that will act as a laboratory space for research and development of Zero Emission Building technologies and methods. SINTEF wants to build a laboratory for a internationally competitive industry with the vision of generating knowledge at a high international standard, while acting as a national resource center for research within the field.

To incorporate ZEB technologies and address the desires of the client, two goals have been established for the design of this building: to create a lighthouse project and a research laboratory.

The first goal is to create a Lighthouse Project, fulfilling the criteria for a ZEB-COM building with an approach that combines high architectural quality with the use of future oriented material use and building technologies. The assumed emissions for the project will be 1,0 kg CO2-eq/m2 for construction and 4,0 kg CO2-eq/m2 for material use. Although the materials used from energy systems are not included in the used materials, they will be calculated and reported.

The second goal is to create a SINTEF research laboratory. Flexibility of use is a key feature of this space. In addition to a flexible design, energy systems and HVAC systems must incorporate passive strategies, such as incorporating natural forces and pressure drops, and be prepared to adapt and upgrade to new technologies and control strategies, while providing quantitative information on energy performance and indoor comfort.

The goal of creating a flexible building also extends to the design of the work space. A modern office system must be taken into account, considering the sharing of workstation areas, accommodation for working remotely, and the provision of different types of work areas. The focus of the workplace design will be based on the quality rather than the quantity of the space, with aims to use the available space more efficiently.

Figure 2: Flex Lab ambitions and Passivhus standard NS 3701

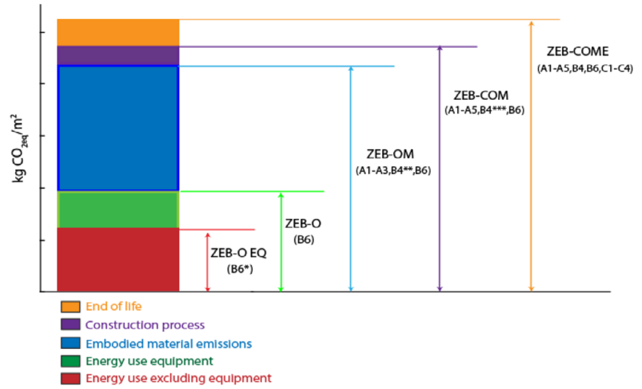


Figure 3: ZEB standards [1]

| CLIMATE ANALYSIS

The site is located in Trondheim (63°24′51′′N 10°24′31′′E), 37,5 m above the sea level.

The climate in Trondheim is temperate. It is classified as Dfc (continental subarctic climate) by the Köppen-Geiger system. It is characterized by long, usually cold winters, and short, cool to mild summers. The average annual temperature is 5,1 °C and the average rainfall is 884 mm. The coldest months are January and February when the average temperature is below 0°C, and the warmest months are July and August with around 14 °C average temperature.

Over a year, the average monthly temperatures are below the comfort levels and there is a heating demand at least from October to April.

The relative humidity levels are above the comfort levels almost throughout the whole year. It is the lowest in May (61 % in average), while the average values in winter are around 85 %. Annual average relative humidity is 77,2 % [2].

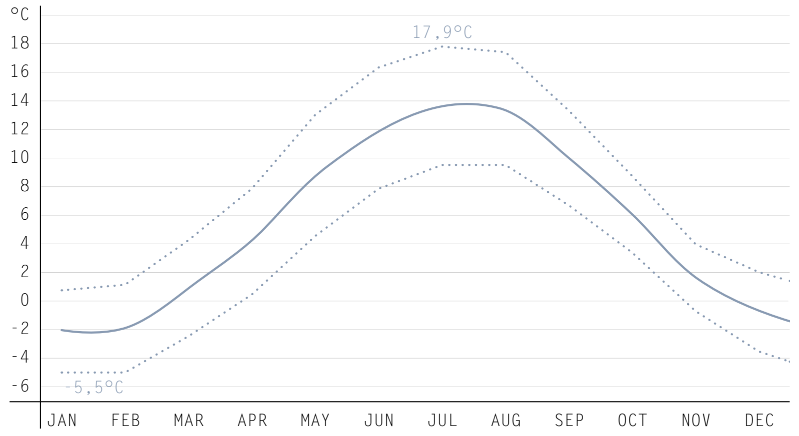


Figure 4: Monthly average temperature range [2]

Figure 5: Monthly average relative humidity [2]

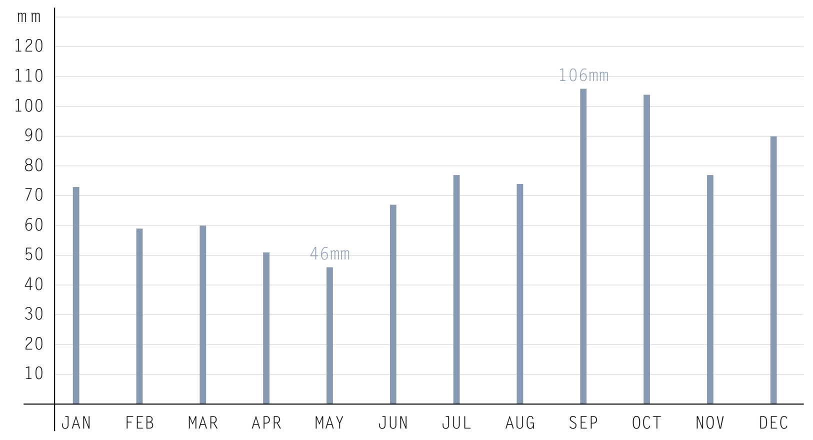


Figure 6: Average monthly precipitation [2]

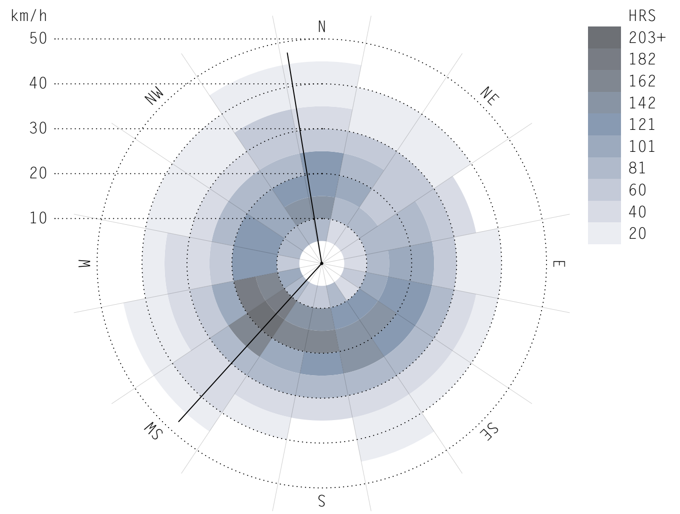


Figure 7: Prevailing winds over a year [Ecotect]

The precipitation in Trondheim is quite equally distributed throughout the year. The driest month is May, with 46 mm of rain. The greatest amount of precipitation occurs in September, with an average of 106 mm. There is only 60 mm difference between the driest and the wettest month.

In certain conditions, it takes a form as snow. The snowfall is moderate, from November to March. There are on average 14 days in winter with at least 25 cm snow cover on the ground. In winter 2016/17, measured at Trondheim (Voll observation station), snow depth higher than 0 cm was measured on around 30 days. The difference in annual maximum snowfall between the periods 1961-1990 and 2071-2100 is-80 % to-60 %. When it comes to the number of days with snow, it is predicted that in period 2071-2100 it will be from -80 % to -65 % in comparison to the period 1961-1990 [3].

The annual prevailing winds are coming from SW direction. The average wind speed varies each year but stays in a range between 2,5 and 4,5 m/s. The maximal wind speed reaches up to 15-20 m/s. Over a year, the wind speeds are almost constant, and in Summer it is slightly slower. In Spring the wind is blowing mostly from SW, in Summer rather from N, in Autumn SSE and eventually in Winter goes in SW direction. The wind data are not measured directly on the site and therefore might be different in reality.

Trondheim has around 1.084 kWh/m²a direct normal irradiation and around 441 kWh/m²a diffuse radiation. The values for sunshine duration and solar radiation have been interpolated by using Meteonorm 7.2.2 tool. The values for sunshine duration represent the average duration per day in a certain month. It is visible that the sunshine duration is less than 50 % of the astronomical sunshine duration. It varies from 0,7 h in December to 8,5 h in June. Accordingly to that, the global solar radiation in winter is very low and very high in summer, and because of cloudiness the most of it is rather diffuse than direct radiation. The best orientation of vertical surface based on average daily incident radiation is 175° (0°N), according to Ecotect weather tool.

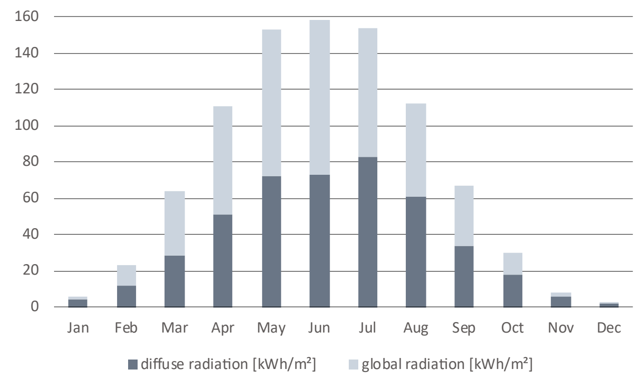


Figure 8: Diffuse solar radiation relative to global radiation [Meteonorm]

The number of sunny hours in Trondheim from 1961-90 was approximately 1346,5 h per year [4]. A new sun recorder was established in the city at Gløshaugen in late 2015, and recorded 1,592 sun-hours in 2016 [5].

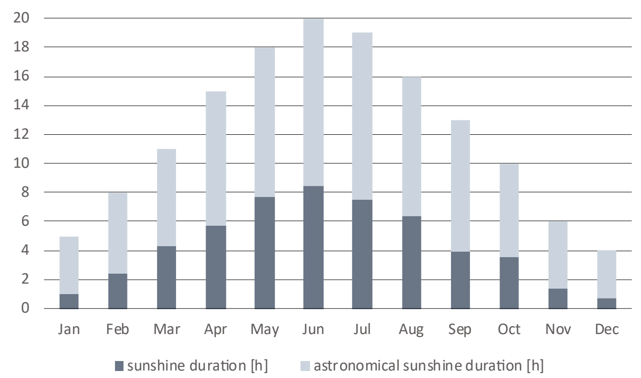


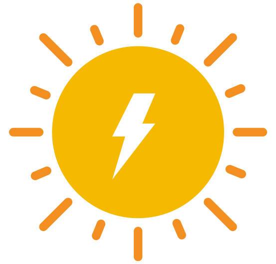
Figure 9: Average sunshine duration [Meteonorm]

In designing a project, one has to think over the entire building lifetime (50-100 years). One of the most important factors to consider are influences due to climate change. The climate is changing more rapidly than before and climate in the future has to be taken into consideration. In Norway, this reflects in hotter and wetter weather in the years ahead. Depending on emissions that can be cut, there are different scenarios for the future. It is expected that the temperature towards the end of the century could increase by about 4,5 °C if emissions continue to rise with this trend.

The rise of temperature would also have huge impact on precipitation and cloudiness resulting in less direct solar radiation. Studies suggest that the rainfall in Norway is going to increase by 10-20 % by the end of the century, but probably even more (20-25 %) [3]. The increase of precipitation is resulting rather in more rainy days than heavy rainfall. In coastal Norway, the rain intensity will be especially increased, which can lead to big damages to buildings.

The weather and warmer climate will increase the risk of fungal growth and a lot of buildings will be at risk of suffering big moisture and water damage. For this reason, it is extremely important to design buildings that will be able to withstand more rainy and humid climate.

| RESOURCES AVAILABILITY



If solar energy is to be utilized, the solar active area would be used for PV and not for solar thermal because of low domestic hot water demands of office buildings and the highest energy quality (electricity) which is more crucial for office buildings. Another advantage of PV electricity production is analogy between electricity production and electricity use in the building, resulting in less demand on storing the produced energy. On the other hand, there is a seasonal mismatch (the highest energy demand in the time of lowest energy production and vice versa.

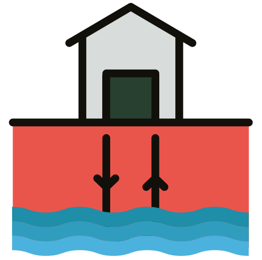
Nevertheless, the use of PV panels shows a lot of potential and therefore more thorough calculations are to be done later in the process.

There is also a big potential in utilizing neighboring buildings' area.

The wind utilization starting point for BIWT and BAWT is around 2 m/s. The wind speed in Trondheim is high enough- around 4m/s in average, according to weather data measurements. Depending on the characteristics of wind turbine, it is roughly estimated that it would be possible to produce up to around 21.000 kWh/a in an urban area in Trondheim with 3-blade rotor and high building augmentation with 24 m² turbine area [App. B]. But, because the performance of wind turbines depends on many aspects (axis height, surrounding surface roughness, wind channeling effect, turbine type, turbine area), it is necessary to do thorough assessment.

However, further research suggests that because of the terrain and the fact that the site is surrounded by hills, wind turbines could be utilized only after 50 m above the ground level. Therefore, wind power will not be utilized in this project.

Even though the ambient air is available everywhere in unlimited quantities and utilization of it has relatively low investment costs, heat pumps with ambient air as source is plausible to use only for low capacities or if they are operated in conjunction with a further heat exchanger. Taking the building heated area into consideration and regarding the type of climate with relatively high heating demand and long heating period because of very low outdoor temperatures, the system is rather inefficient and will not be applied on this building.

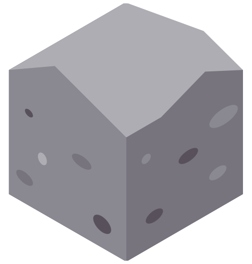


The location of the water table at the site was indicated to be at a quite shallow depth of about 0,2 – 1,4 meters from the surface, showing in geotechnical investigations in 1968 [6]. But today the water table have the at the level around 2 meters from the surface because of new buildings have been built at the site.

It is possible to utilize energy from the groundwater by drilling holes in the bedrock, as a source for a heat pump. The depth of drill holes varies between 50-200 m depending on the distribution of groundwater in the area [7].

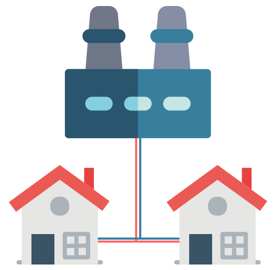
A large scale wastewater heat recovery system is not available at the site or in the Trondheim area. Such a system includes a heat pump and is generally installed in the wastewater treatment plant. This system is more efficient than a small scale system which is often installed inside the specific building construction or in the sewer. The small scale system is generally a heat exchanger where wastewater flows through the exchanger containing another fluid in addition to the wastewater. However the small scale system demands a certain wastewater flow through the system in order for it to work efficiently [32].

Since NTNU is a university building the wastewater flow is most likely not sufficient for the system to be efficient enough.



The bedrock at the site is located at a relatively low depth (8-18 meter) [8]. Due to geothermal activity the bedrock in Norway has in general a year round temperature of around 4°C.

Geothermal heating as a heat sources for heat pumps is a way to utilize the heat from the bed ground in the winter time and for cooling during the summer using the same technology [9].



District heating grid is available at the site and is used by Gløshaugen campus, NTNU.

District heating facilities with waste release are located in Heimdal and burns residual waste. The burning of residual waste generates heat, the heat is used for heating of water, which are transported in pipes to the grid. The district heating in Heimdal covers 30% of Trondheim's heating demand [10].

During the construction planning of the Sintef Byggforsk building, geotechnical investigations were performed at a large area which also covers the site. The geotechnical investigation was performed by Nybygg Bygningsingeniör avdelingen NTH and summarized in report O.669 published the 8th of May 1968. The report from the ground investigations has been gathered from the Government owned site NADAG where all ground investigations conducted for the Road Authority, The Railway Authority and municipalities in Norway are published [8].

The ground can be divided into different layers based on their characteristics. The top layer stretches from the surface down to 4-6 meter below the surface and is classified as a dry crust clay. Underneath this layer the ground in the area mainly consist of clay with a varying firmness, partly with intrusion of sand layers and organic materials. Slightly north of the site a layer of fast clay was identified just above the assumed level of bedrock.

The location of the water table was indicated to be at a quite shallow depth of about 0,2 – 1,4 meters from the surface. The bedrock was interpreted to be located between 8 to 18 meters below the surface and the frost free depth is located at 1,5 meter from the surface, which means that the ground is good to build on.

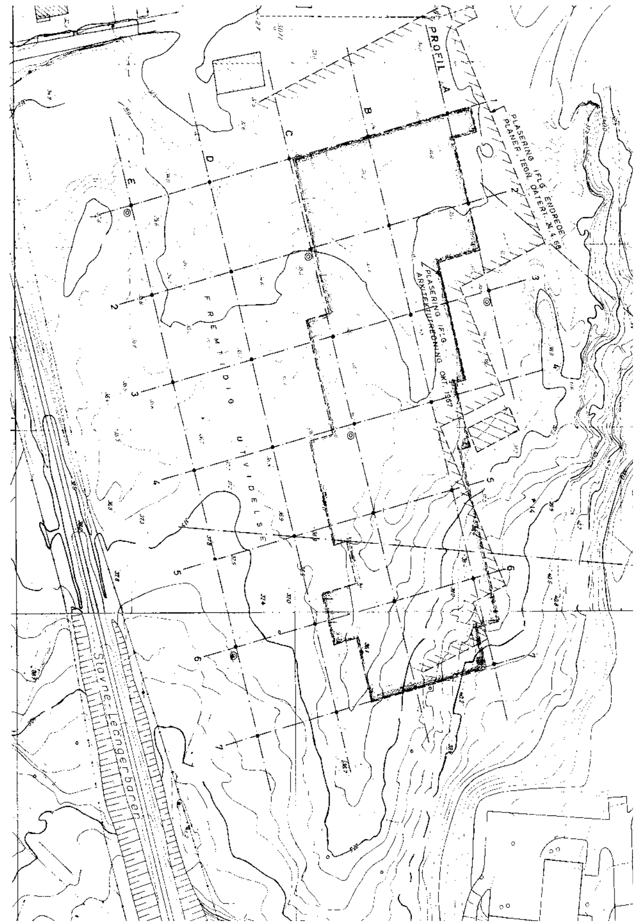


Figure 10: Site plan

The thorough analysis of the resources available on the site provided information about possible solutions for building energy supply. In further work, solar energy, bedrock sourced heat pump and district heating will be taken into consideration.

The general approach is to design the building as off the grid as possible by having highly efficient photovoltaics and ground sourced heat pump. It is taken into consideration the fact that the energy supply in Norway is very clean and therefore, it would still be considered sustainable to cover building peak loads from the grid instead of over-dimensioning the building's supply systems in the first place.

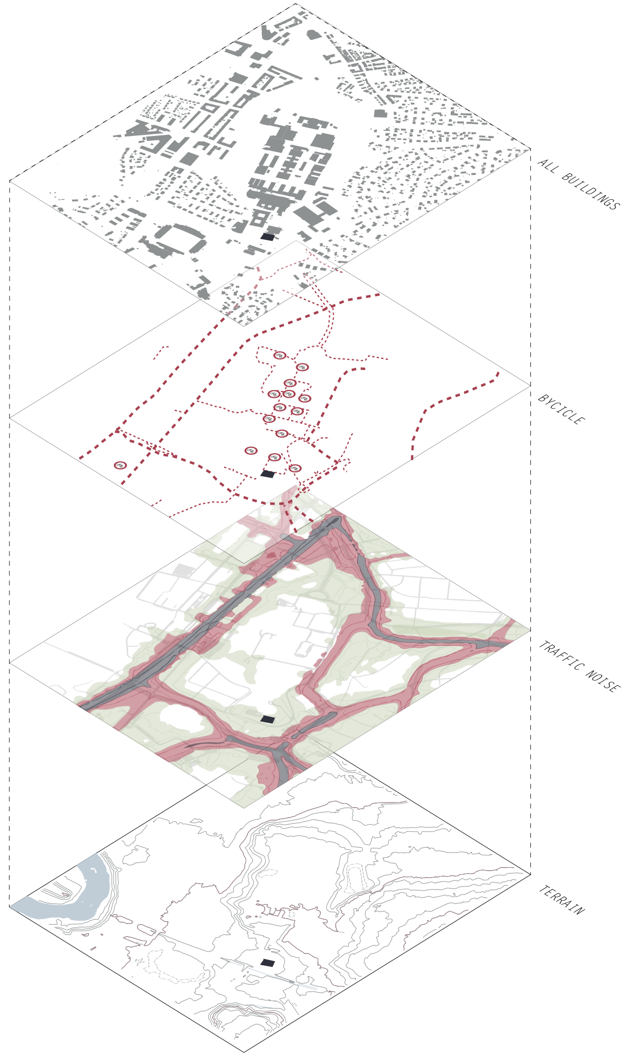


Figure 11: Site mapping

The site is located at Gløshaugen in Trondheim, approximately 2-3 km south east of Trondheim city center and are most known for the university area of Norwegian University of Science and Technology, NTNU.

The site is a part of the university area and are located south-east of the Gløshaugen campus. The area around the site dominates by residential buildings, university buildings and public areas. Just next to the site is Norwegian Institute of Natural research, NINA house and the science- and research institute SINTEF. It is also close to one of bigger roads on the area Strinadvegen and on the other side of Strindavegen is Lerkendal stadium and the hotel Scandic Lerkendal 0,4 km south of the site and Trondheim business School is 0,6 km west of the site. And several supermarkets are in the area of 0,5 km from the site.

The site is a little bit hidden behind Gløshaugen campus area and hidden from the other side of the elevated railway. Around the site it is a movement of people, passing by and no one really stops at the site. It is a lack of green spaces at the site even though it is close to larger parks at the university area. In daytime the area is lively and people are passing the site during the whole day due to the proximity of the university and the public areas. By night time the district is quiet and not many people are passing there.

The transportation in the area is good, there are several alternatives to travel to the site.

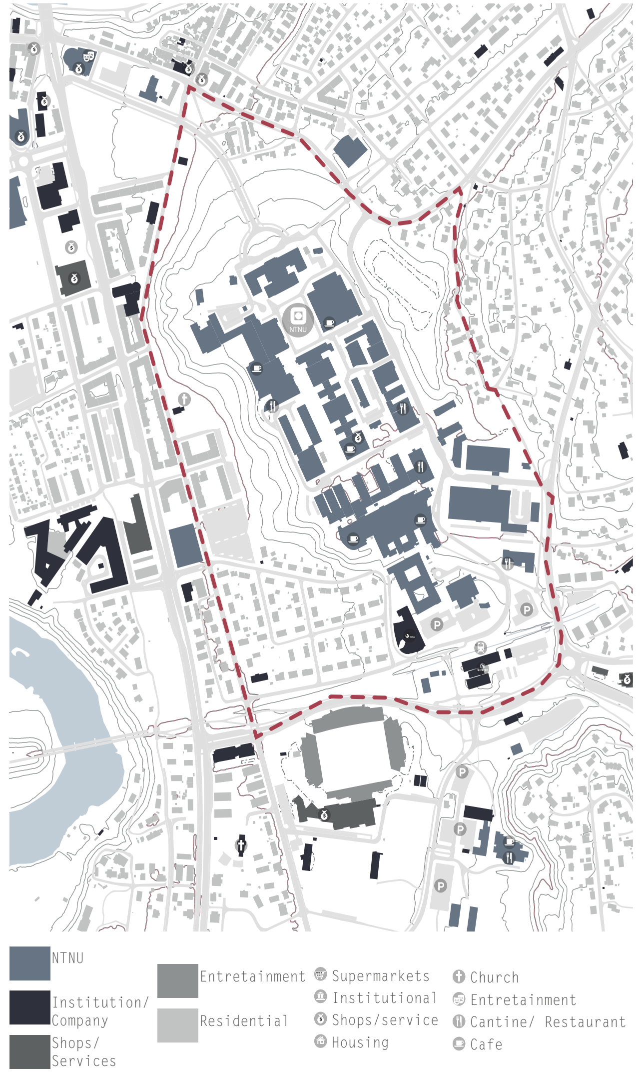


Figure 12: Urban analysis

Because of the close distance to Strindvegen and the railway the site is exposed for noises from the traffic at the road and from the trains. The noise from traffic at Strindvegen are from cars and buses that are passing there every day. The noise level from traffic are 50-55 db [11].

The noise from the railway Stevne-Leangenbanen where NSB passenger trains are stopping by. The passenger trains travels between Trondheim and Steinkjer and are stopping by a few times a day, in the morning and in the afternoon [12]. The noise level from the railway is 55-60 dB during the trains are passing [11].

Transportation	Distance (walk)
Train station Lerkendal	140 m
Bus stop Lerkendal Gård	300 m
Parking for students and employees of NTNU	400 m
Parking for public	50 m

Figure 13: Distance to transportation stations

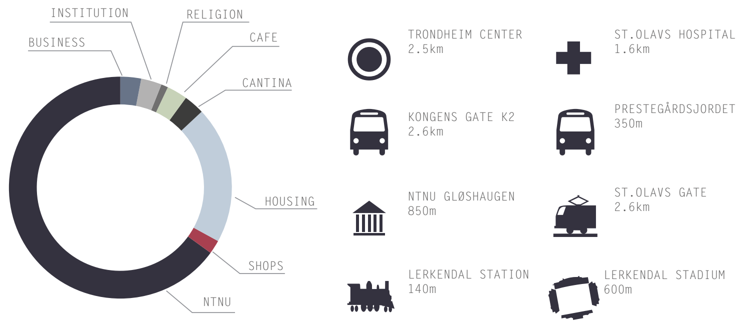


Figure 14: Transportation distances

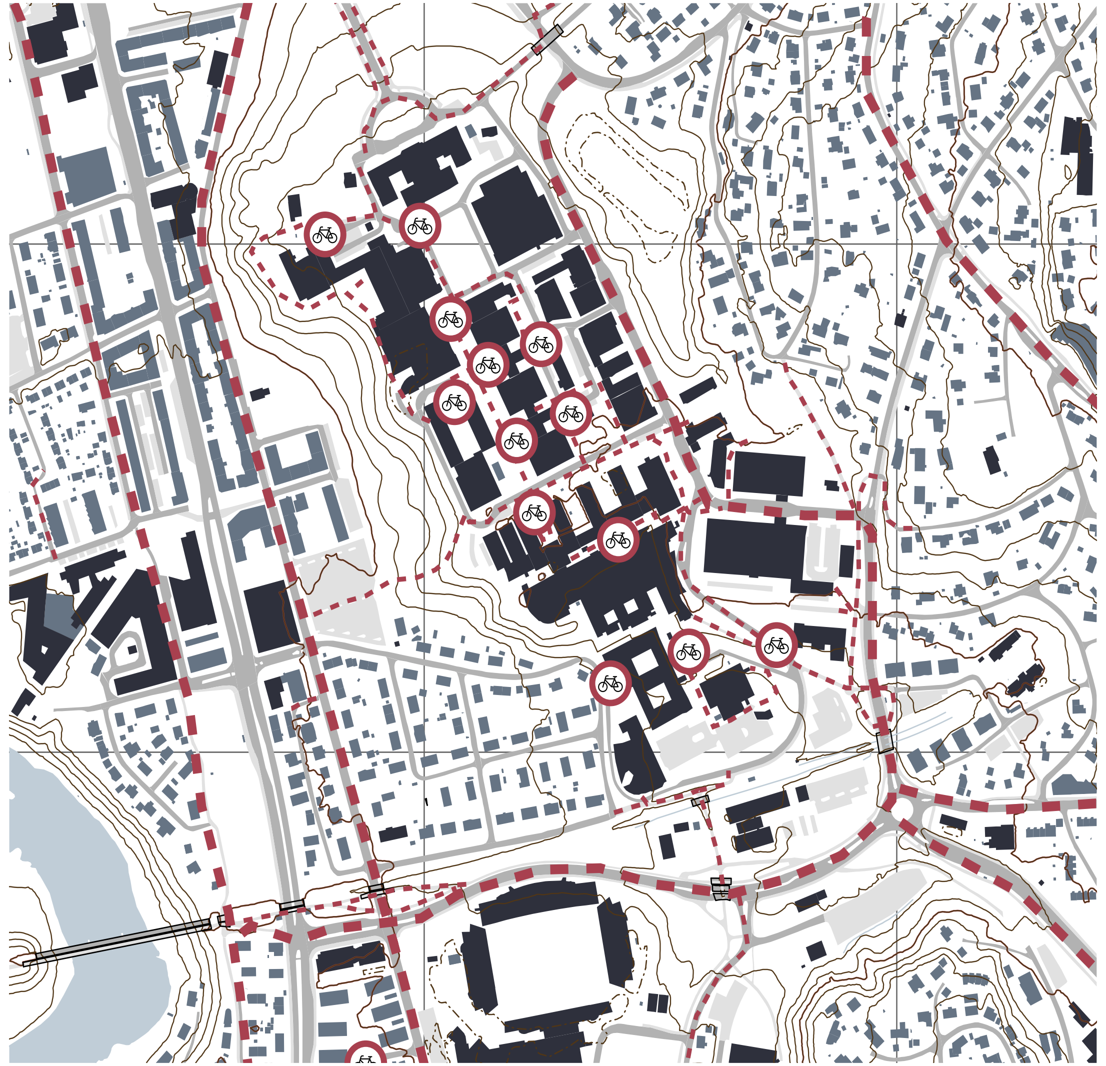


Figure 15: Bicycle tracks and bicycle parking spots

| SITE ANALYSIS

Figure 16: Site photo, October 23 14:00

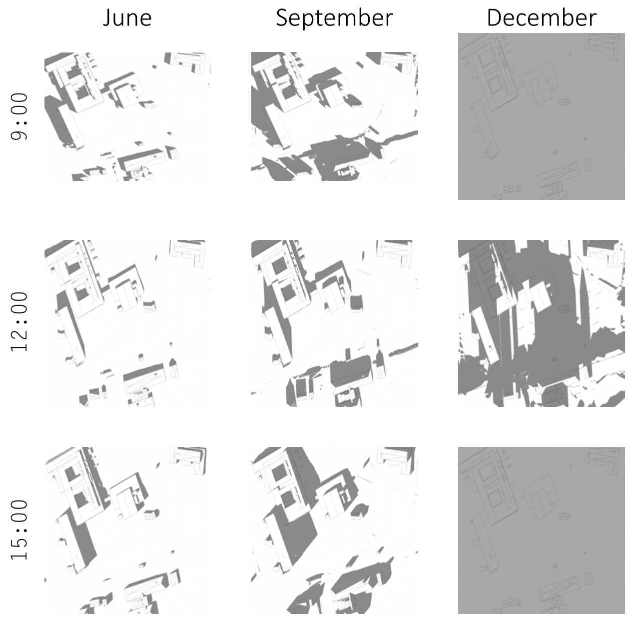


Figure 17: Solar shading analysis on site

Being on a parking lot, the site has a behind of the happening feeling. Surrounded by the research buildings, Nina Huset, SINTEF, ZEB TestCell and SINTEF Byggforsk, and Lerkendal train stop. In analysis of the site in relation with the urban contest, the train track close to it acts as an urban divider which gives the area manly local flux.

In analysis to the flux the cars that access the area are with parking propose, and building supply by small trucks. Once ZEB LAB takes place on one side of the parking area, it will result in fewer cars flux favors the pedestrians and bicycle flux.

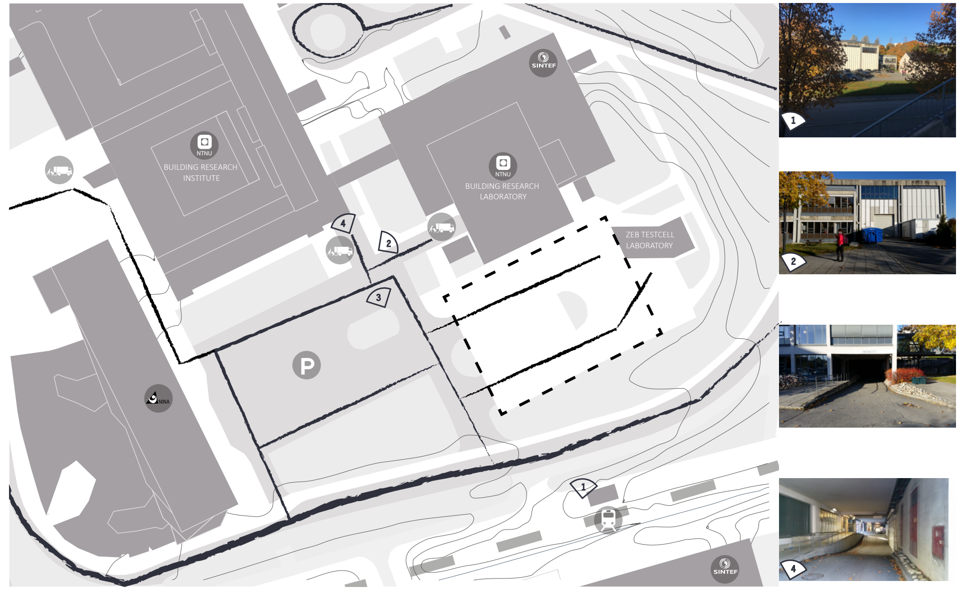


Figure 18: Traffic flux

There are a few bike racks close by the site and a medium to high flux a bicycle path and local pedestrian flux. the main access to SINTEF Byggforsk and ZEB TestCell are the closest to the site which was something to be considered for research interaction on process work.

The Solar analysis for the site during the year demonstrate the shadow from the neighbor buildings, and we can observe that later in the year the solar radiation is compromised on the ground level of the site. The photos were taken on October 23th around 14:00, there we can observe the shadow reaching the site. After the site analysis the design of the building took a different direction, even though the site area is big enough to achieve the square meters required in a single floor building, because of the solar radiation been affected by the lower terrain and neighbors, to attempt ZEB COM standard, the building needed to be taller.

Figure 19: Bicycle flux

Figure 20: Pedestrian flux

The building should provide 80 office workplaces (70-100 employees) on around 600 m² and teaching of 40 students on around 200 m². The design of the workplaces is based on kind of people, work they do and how often do they travel. If the number of employees is actually higher than 80, it is assumed that overbooking percentage has already been taken into account and the number shall not be reduced further.

The building should promote research in ZEB Flex Lab by both SINTEF researchers and NTNU professors and students. It can be assumed that there is a lot of different fields of expertise that need to communicate with each other and probably also interact with external experts. Possibility for students in building industry field to interact with workers and get familiar with research topics and environment should also be taken into account (e.g. NTNU students have a possibility to book an available office workplace). Therefore the focus of the design is to support the variety of activities that are to be performed, rather than traditional static workplaces. Spaces create opportunities for different activities, from intense, focused work and solo telephone calls to impromptu meetings or more formal collaborative work.

The workplace design and its flexibility focuses on variation, choice and control as the most important aspects for happiness. If designed carefully, activity based workplaces (ABW) can fulfill this kind of employees' requirements.

Leesman's studies of workplace effectiveness based on workplace impact and workplace activities shows that there are big improvements in staff collaboration, productivity, pride and effectiveness in ABW. Unfortunately, the benefits of ABW are seen only by workers with higher mobility profiles. The most of the people still belongs to low mobility profile (traditional offices), meaning that 71 % of staff never or rarely change their working location. This puts them in conflict with their new environment and this poor adoption to ABW represents a significant problem that limits widespread organizational benefits, resulting in decreased performance of employees. Also, it is interesting to note that the youngest employees (under 25 years), although showing great satisfaction with availability of various activity spaces, they are the ones the least likely to adopt to mobile behavior (84 % of them belongs to low mobility profiles) [App. C].

Still, the most mobile profile (10 % of employees) report the highest productivity, meaning that the more complex an employee's daily work profile, the more beneficial it is for them to work in a mobile way that utilizes multiple settings. In general, ABW concept makes overall improvement, and the aim is to be realistic and find the right portion of traditional to flexible spaces and satisfy both sides and provide enough possibilities for individual differences. The research provides information about which activities and features are considered to be the most important in workplaces [App. C].

With the knowledge from this research in mind, the most important activities in ABW are combined with the user-specific requirements (in this case researchers, professors and students). The brainstorming illustration gives a base for the layout of the building, activities, number of participants in each activity and the level of noise [Fig. 21]. Because the building layout is based on noise separation principle, in order to decrease problems with acoustics and necessary partitions and in that way provide higher space flexibility, the activities are assigned for each floor:

- 3rd floor- individual focused work
- 2nd floor- team work, presentations and lectures
- 1st floor- social activities

The design of the workplaces is very dynamic as a day of a typical researcher or student [Fig. 22]. In order to reach full use of the building, the design emphasizes this dynamic, interaction and circulation withing the building [Fig. 23]. It also provides a booking possibility for students and activities outside of the typical working hours (e.g. study desks for students, evening lectures and workshops, etc).

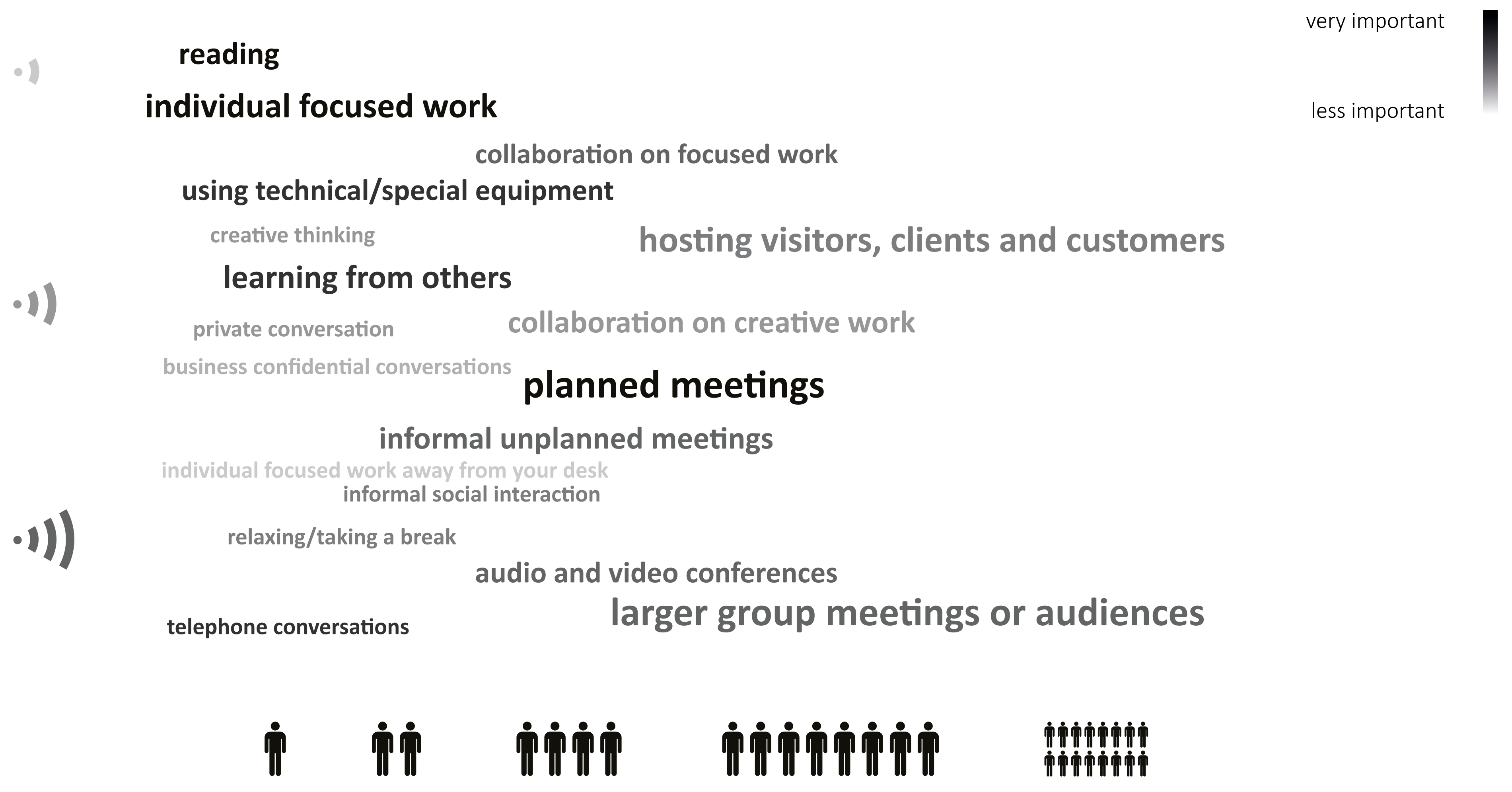


Figure 21: Mapping of the most important activities in office buildings based on Leesman's research on ABW [13]

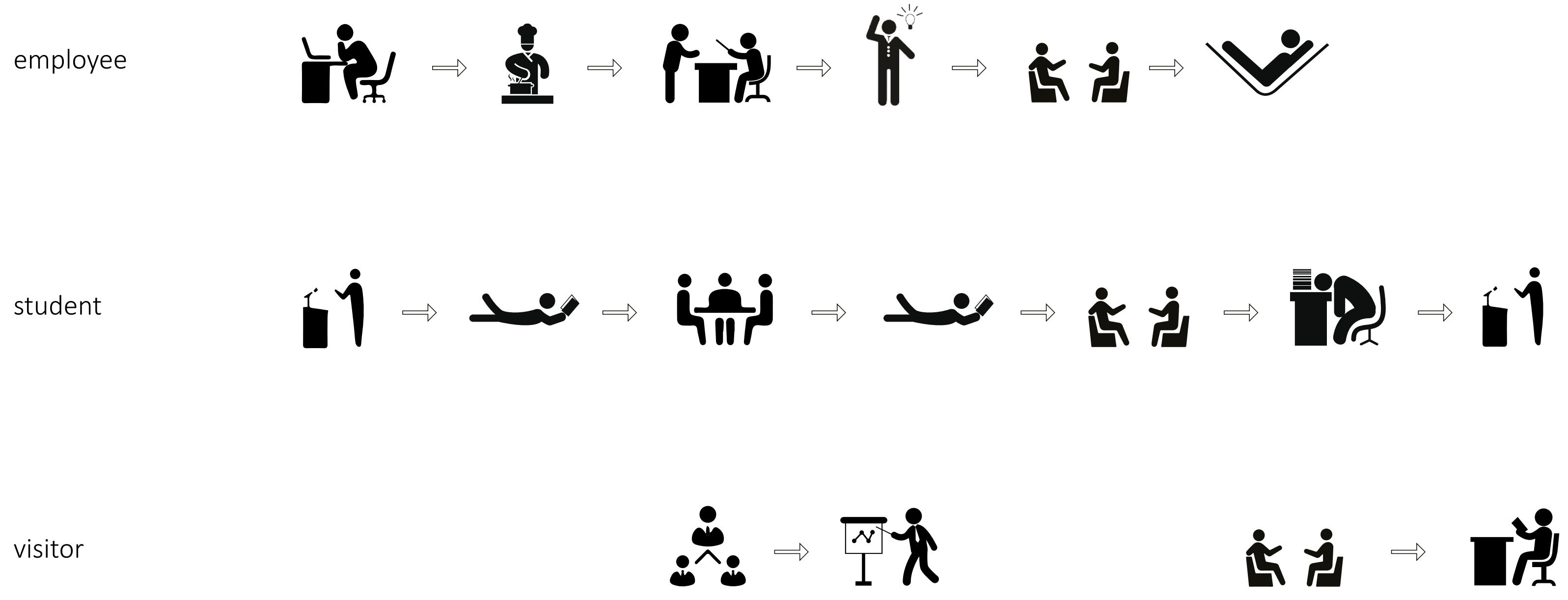


Figure 22: Activity scenarios for different occupants

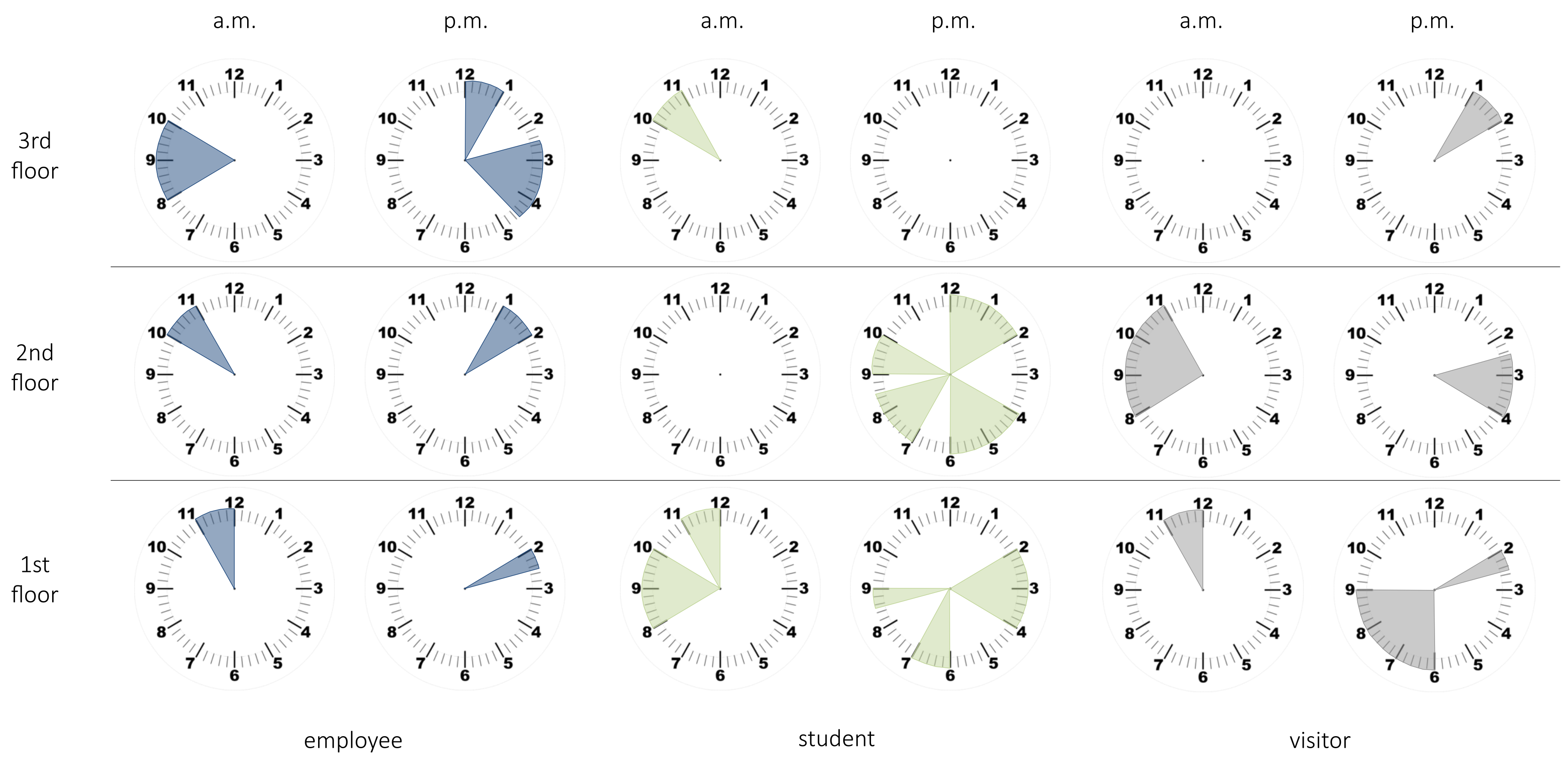
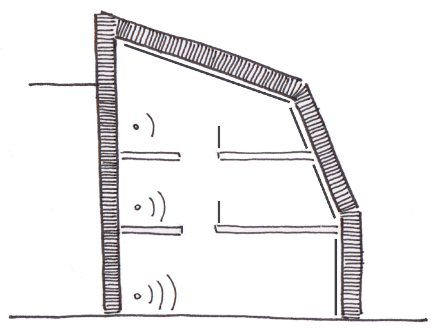
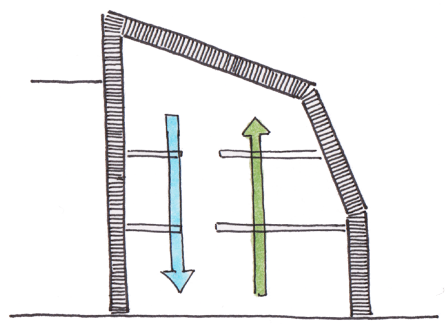


Figure 23: Occupancy scenarios



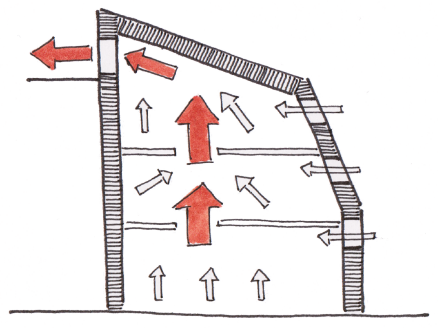
noise levels

At the very beginning, for many reasons the concept was going in a direction of multistorey building. One of them is reduction in material use for solving acoustic problems. One of the first concept solutions is having different floors based on activities provided on that floor. The idea is to have the loudest and the most active and social areas on the ground floor. Team work and cooperation along with lectures and presentations are mostly on the second zone, as a buffer betweens loud and silent. Finally, the third floor is planned for silent, focused work.



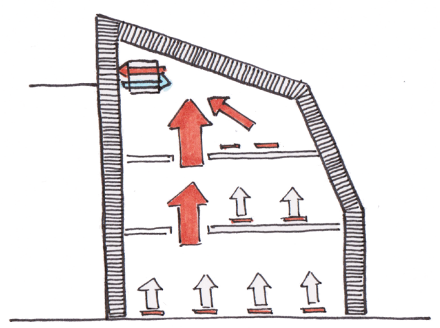
ABW dynamics

As the workplace design can be characterized as activity-based, the function distributions also takes into account the dynamics during a typical work day. The blue line suggests circulation of an employee, with focused work early in a day, team work after lunch and social activities later during the day. At the same time, the green line suggests a circulation of a student, who engages in lectures or in group work activities with fellow students at the beginning, moving towards the focused work and studying in the evenings.



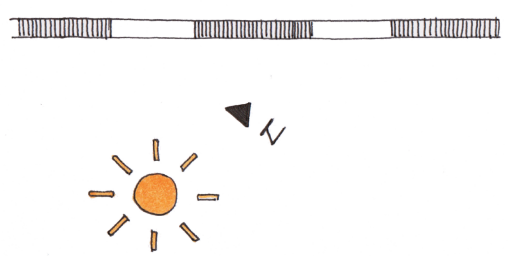
summer ventilation

In order to achieve less energy demanding building, there are different ventilation strategies for summer and winter. In periods where the ambient air does not need to be preheated (roughly from May until September), it is possible to use natural ventilation only. The ventilation uses thermal buoyancy and cross ventilation - the air enters on SE and SW facade, when it gets warmer it moves up through the staircase opening and goes out through the windows on the NW facade. The bigger room height on the 3rd floor allows stratification of warm, avoiding overheating.



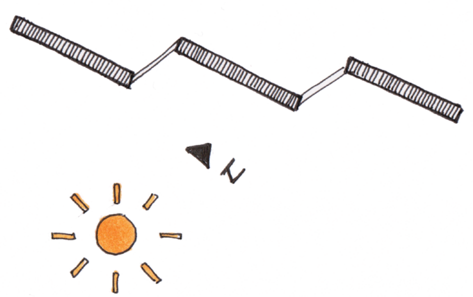
winter ventilation

In winter, the air needs to be preheated, therefore the ventilation needs to be mechanical. Nevertheless, some of the passive strategies can still be utilized, leading to less required fan power. As the thermal buoyancy effect works the same way in winter, the heat recovery unit can be placed under the building roof and reduce the fan energy demand.



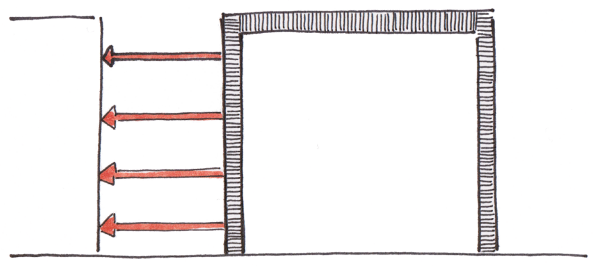
windows initially

The initial daylight concept assumed PV modules and window areas with the same orientation. This presented a conflict between electricity production and daylight situation in the building. Depending on required glazing area, it could have also presented a potential overheating problem in summertime.

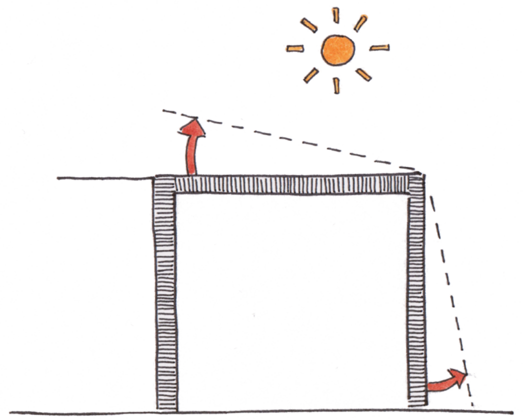


windows final design

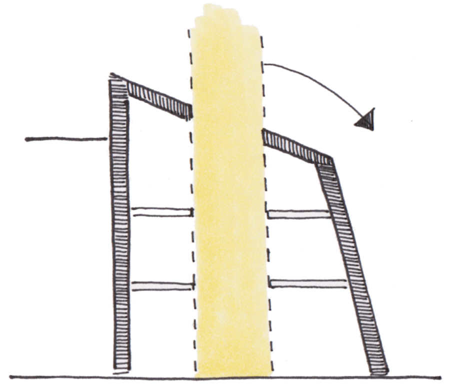
In order to solve the problems, both PV and window areas are rotated in opposite directions. The facade part covered with PV modules is then orientated almost completely towards south and the windows towards ESE, avoiding overheating in summer and utilizing solar gains in early mornings, preheating a space a bit after cold evenings.



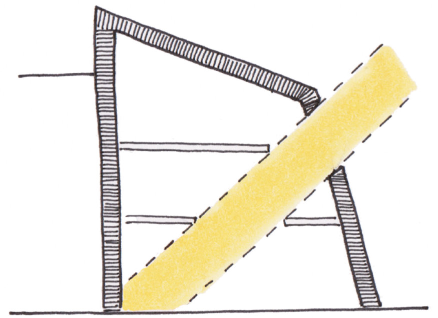
connection to Sintef Byggforsk



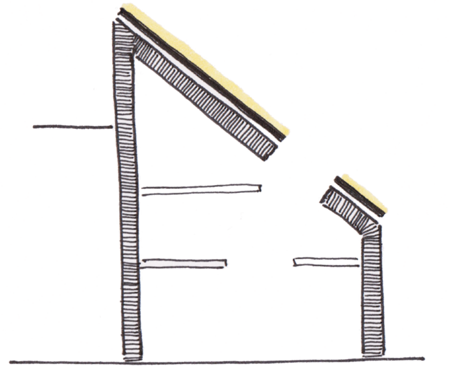
tilting of facade and roof



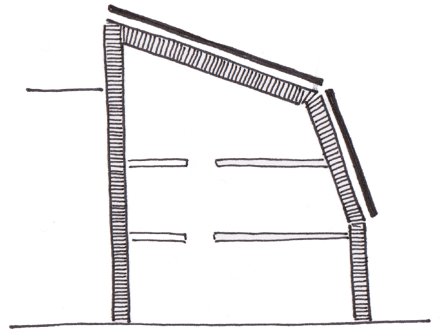
rooftop atria



tilting atria



45° roof tilt



atria to back

In this type of climate, undesirable thermal effects are reduced by building dense, well-insulated walls, backed up by thermal masses and designing building as compact as possible. A highly insulated building with high efficiency combined with these strategies provides indoor climate conditions inside the comfort area in summer and even reaches the comfort zone in winter [App. A].

The building is connected to the Sintef Byggforsk in order to minimize the heat losses and material use. It also makes it possible to shade the Test Cell less. For this reason and low daylight levels on the north side (due to orientation and neighboring building), ancillary spaces are to be positioned on the north side. Additionally, it enables the technical room of the Flex Lab and the Byggforsk to be merged together, and according to need of each building, offers a possibility of expanding technical area for testing of systems. Another advantage is space efficiency - it is not necessary to have access to the technical room from the outside because it is accessed through the byggforsk.

In the next design stage, both facade and roof are tilted in order to provide better performance of photovoltaic panel which are to be used in the project.

Next strategy is related to light inside the building. Window areas on the facade can provide plenty of daylight reducing artificial light demand, but glass has pour insulation properties resulting in heat losses, increasing heat demand. For having better daylight conditions with as least as possible window area, an atria is planned in the middle of the building .

The next step was tilting the atria in the way that the solar gains in summer are minimized, and in winter maximized. Even though this measure led to reduction in energy consumption and better daylight distribution, it also led to less PV active area, as the lower part of the facade is not highly efficient due to the neighboring building on the south and potential buildings on the south part of the site.

By changing the roof tilt to 45°, the building offered more efficient bigger potential PV area. The drawbacks such as problems with acoustics and space inefficiency (more circulation area necessary) and the necessary hight of the building (therefore more material use) due to the angle resulted in changing the approach in the later design process.

The final concept is a compromise between all the advantages of different concepts considered during the process. It solves the daylight problem, uses less material, less height and has big PV area. It is also very space-efficient and pleasant for the people working in it - the most attractive areas are now at the building's facades instead of the core. Equally important, its modular system provides areas suitable for testing of different systems on each floor and its construction offers a high level of workspace flexibility.

| CONCEPT

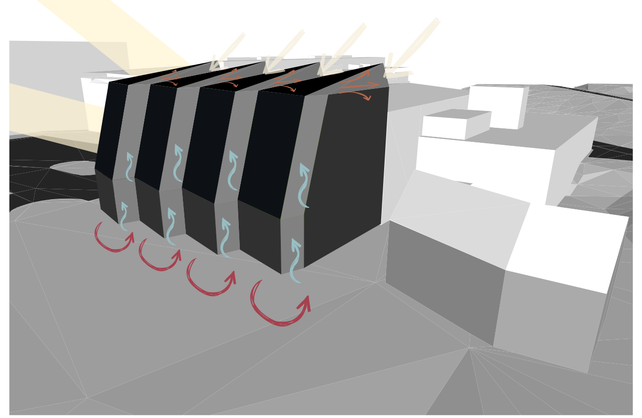


Figure 24: Concept

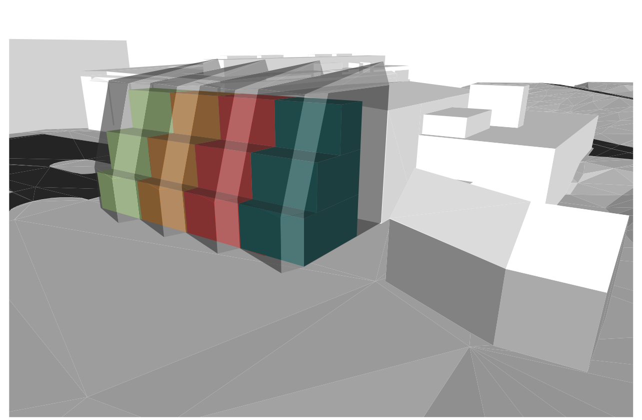


Figure 26: Testing zones

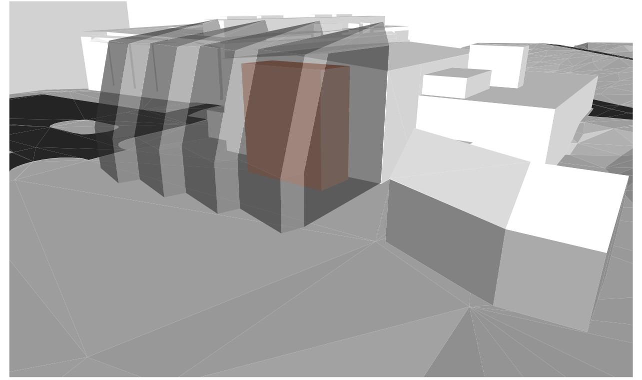


Figure 25: Technical core

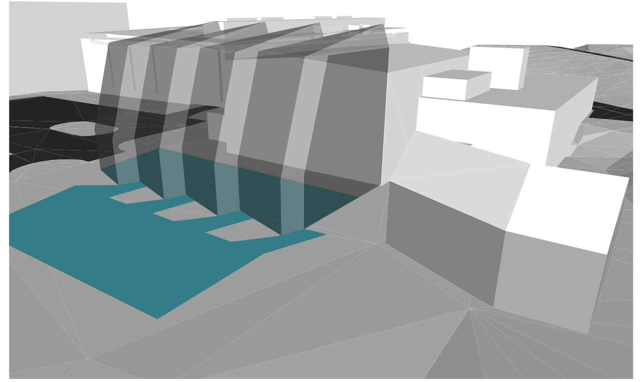


Figure 27: Social happenings/ Exhibition

The shape of the building needed to be vertical, and compact for photovoltaic panels on the main facade which conflicts with windows. The armadillo shape was the approach to increase surface area for windows for daylight and solar gains.

Thinking towards the future use for the building, the idea was to create flexible spaces with less partitions, and reduced floor plan, dividing the spaces into three main flexible spaces separated by slabs.

At the back of the building where the fixed technical core is, with the toilets, kitchen, bike workshop, and technical room on all three floors to supply the building and the testing zones also on all three floors.

Compacting the building frees up the first floor area in front that can be used as a give back to the city as space with nice landscape and possibility for social events, outdoors tests and exhibitions.

The goal was to meet all the ambitions and criteria, as well as improving urban space changing the "behind feeling".

Figure 28: Inspiration pictures [33]

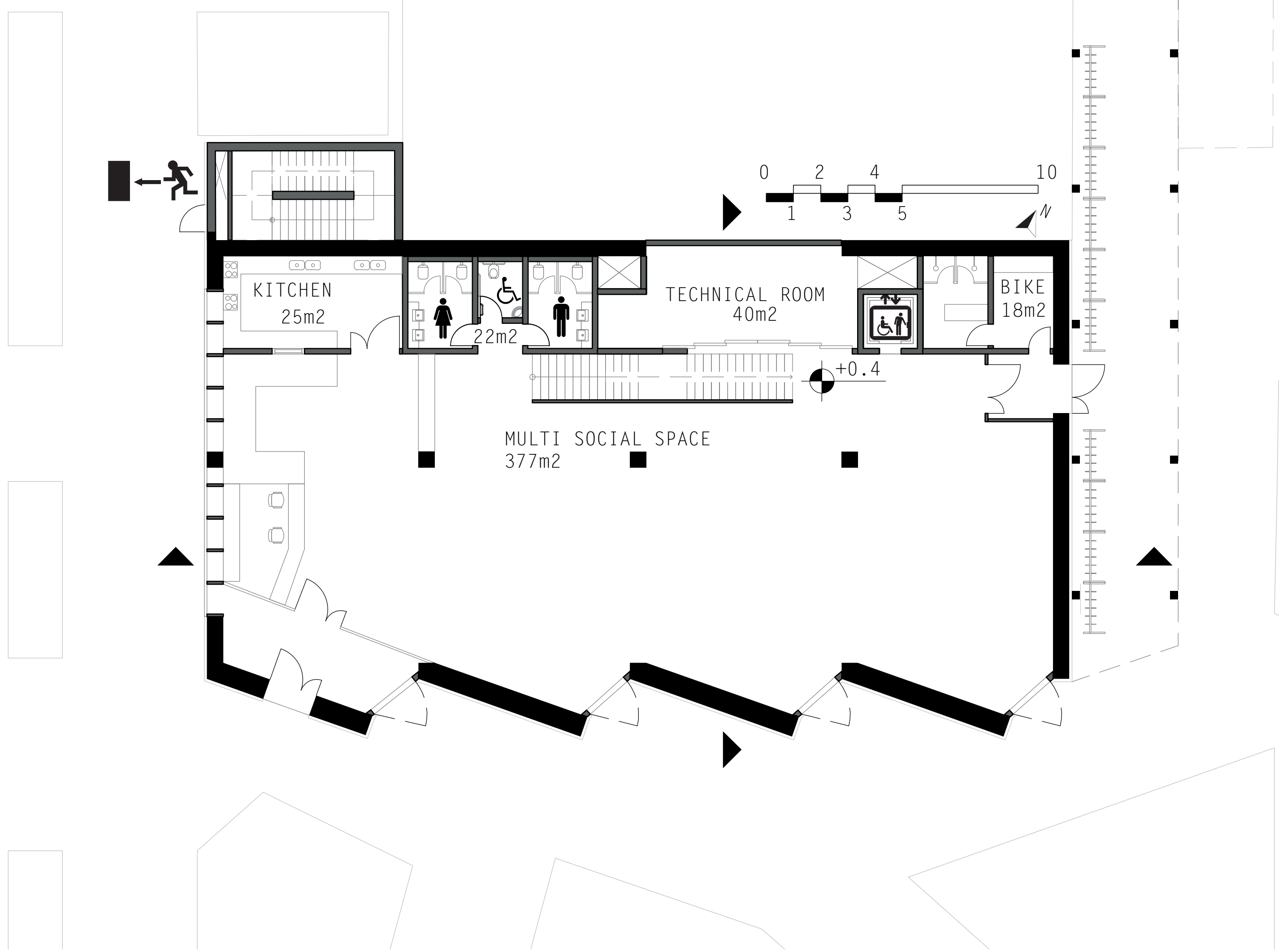


Figure 29: 1st floor plan 1:250

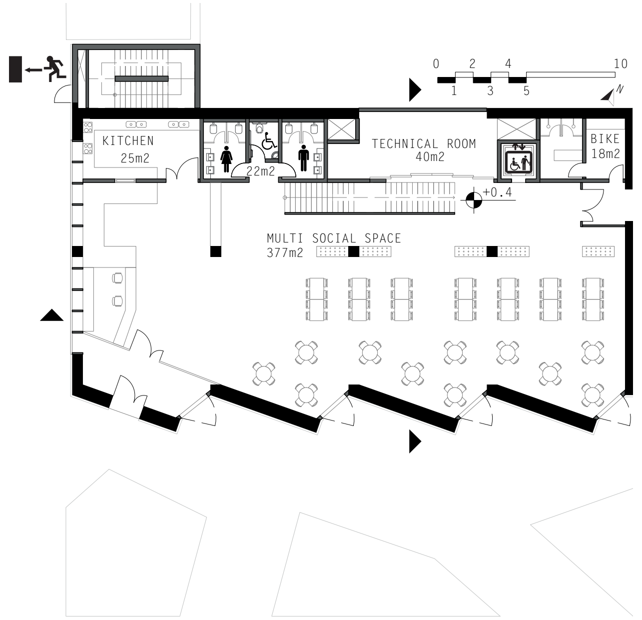


Figure 30: 1st floor plan open layout examples

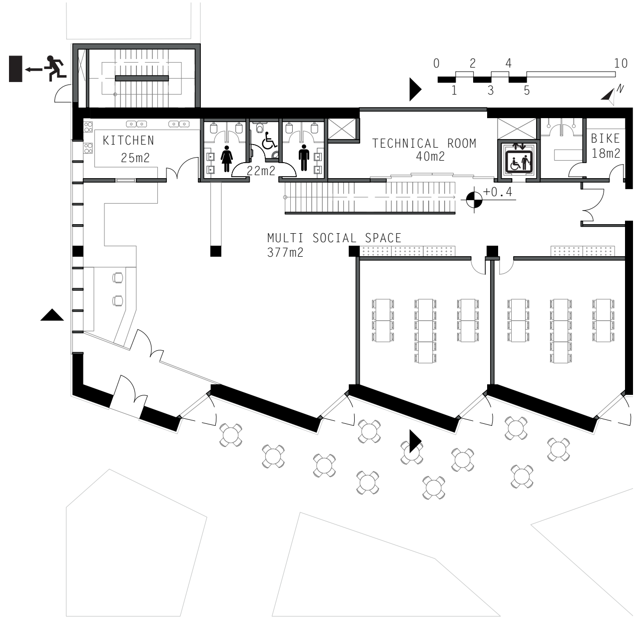


Figure 31: 1st floor plan layout examples- closed for testing

The main entrances are south and north east, and the vertical circulation on the fixed core of the building. The first floor is the main social area, second floor teaching combined with cooperation area, and at the top landscape office and focused work. The armadillo shape was modified to increase view and reduce shading on the photovoltaic panels. As demonstrated on the elevation of the main facade, the height of the building was so it could increase PV surface on facade and roof, giving high ceiling on each store, and raised floor for technical distribution and testing zones technical supply.

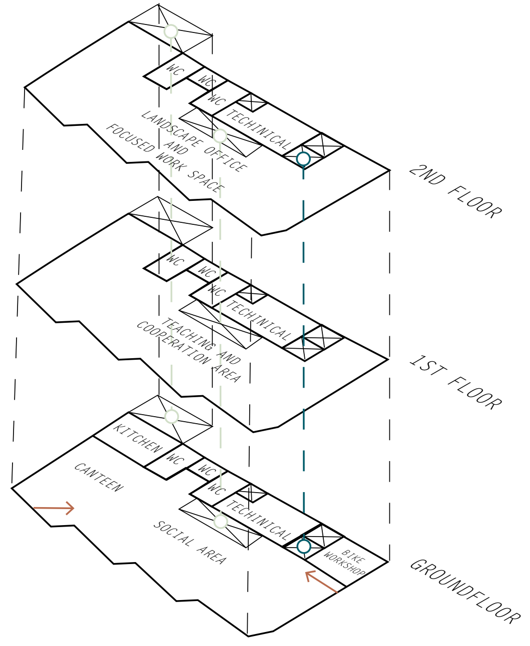


Figure 32: Layout and circulation concept

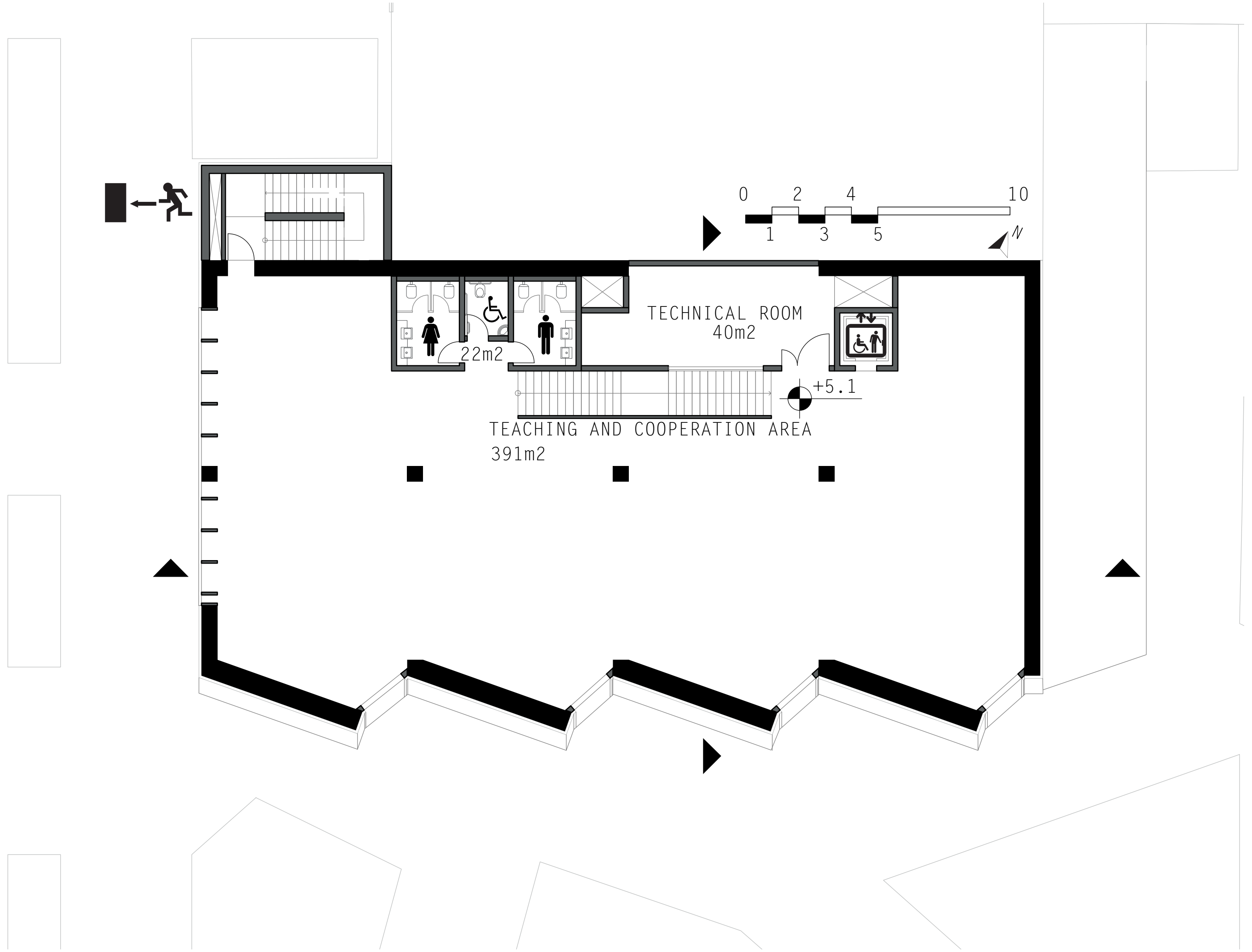


Figure 33: 2nd floor plan 1:250

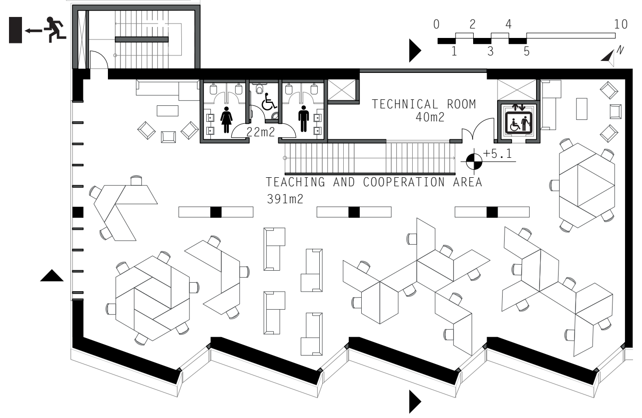


Figure 34: 2nd floor plan open layout examples

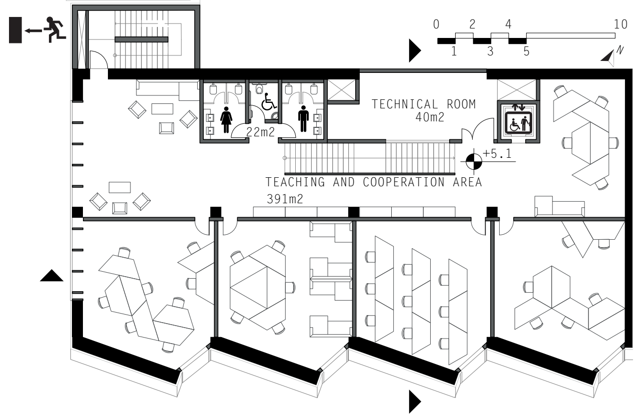


Figure 35: 2nd floor plan layout examples- closed for testing

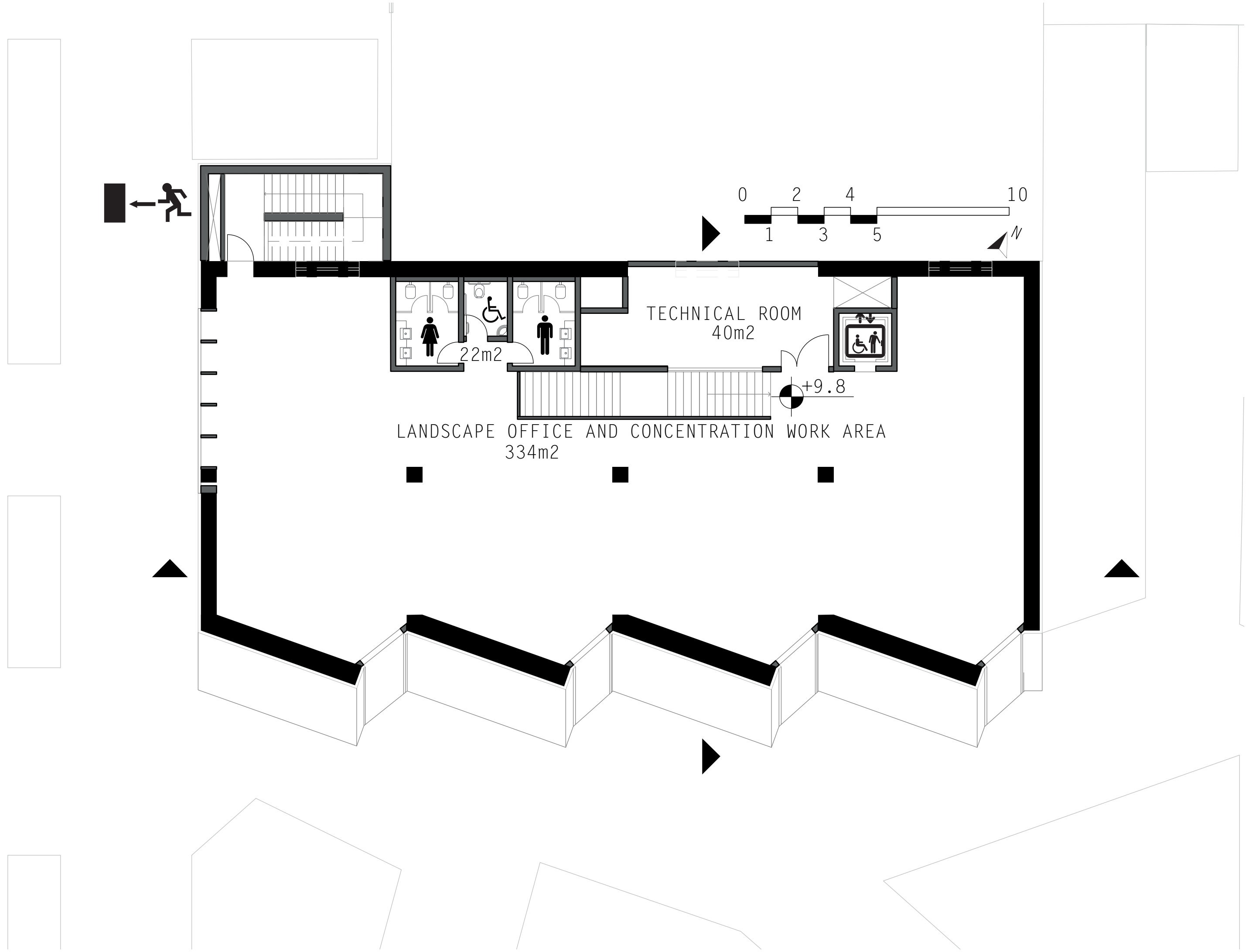


Figure 36: 3rd floor plan 1:250

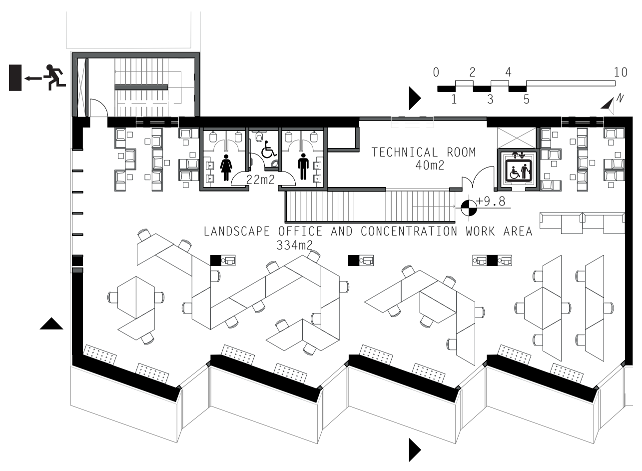


Figure 37: 3rd floor plan open layout examples

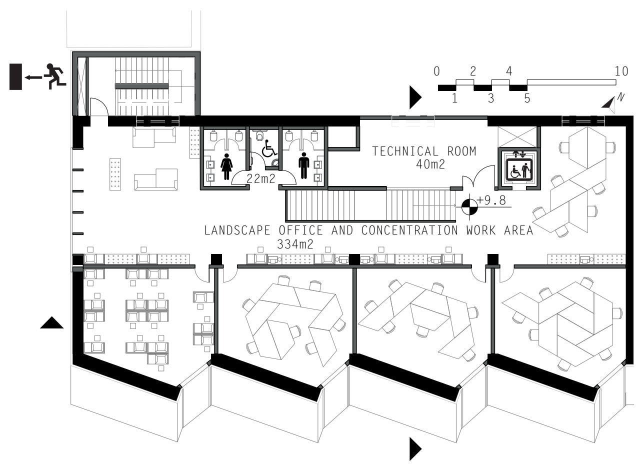


Figure 38: 3rd floor plan layout examples- closed for testing

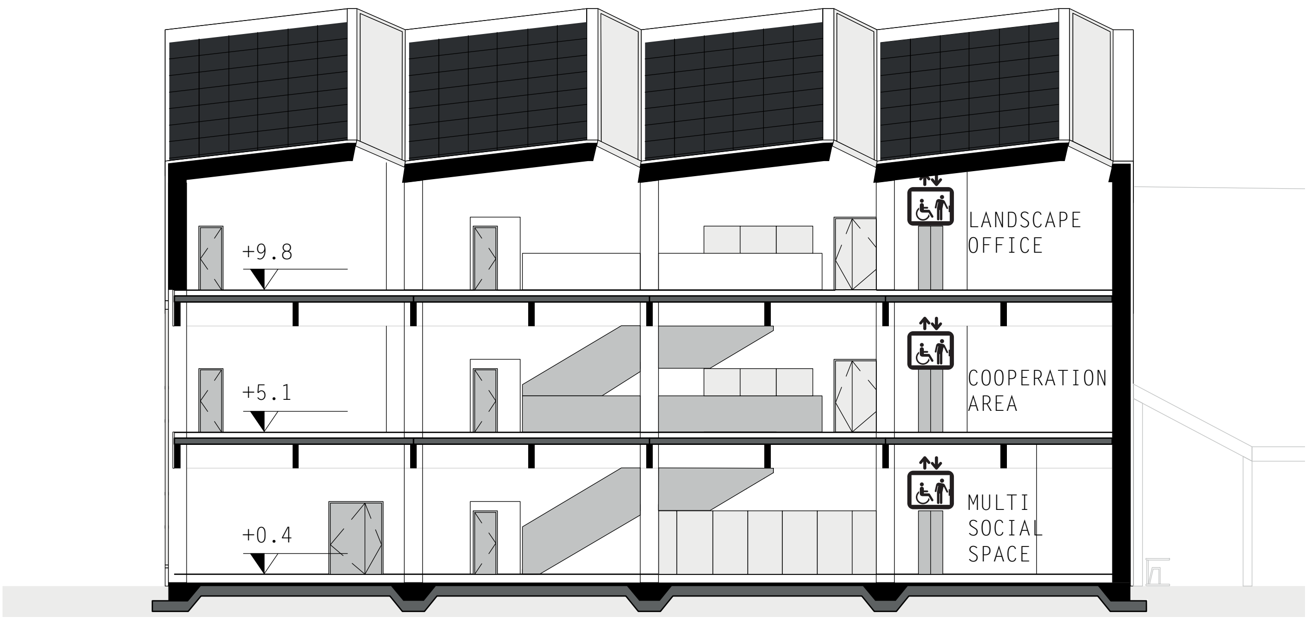
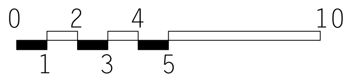


Figure 39: Section SW-NE 1:250



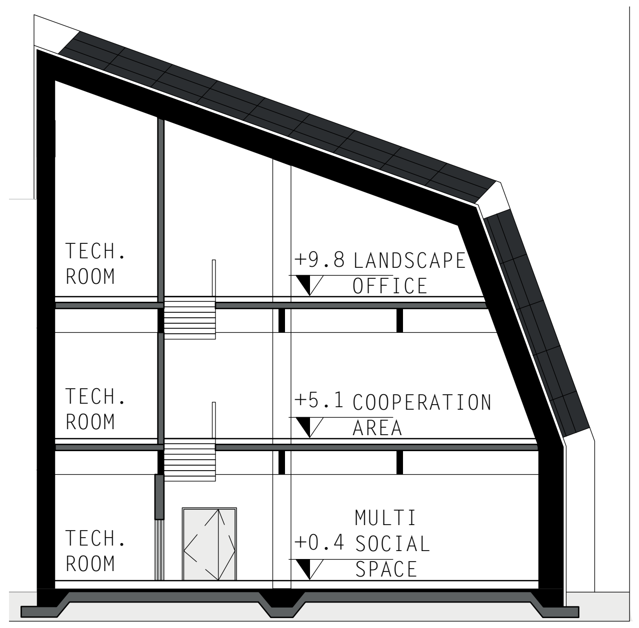


Figure 40: Section SE-NW 1:250

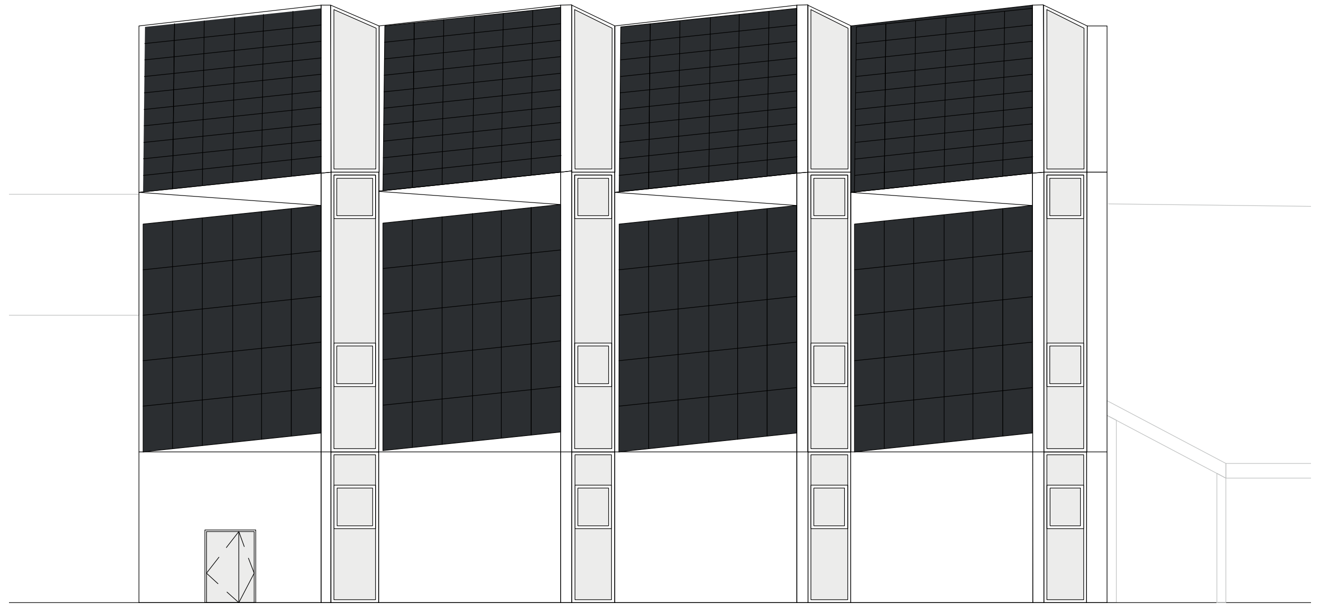


Figure 41: Elevation SE 1:250

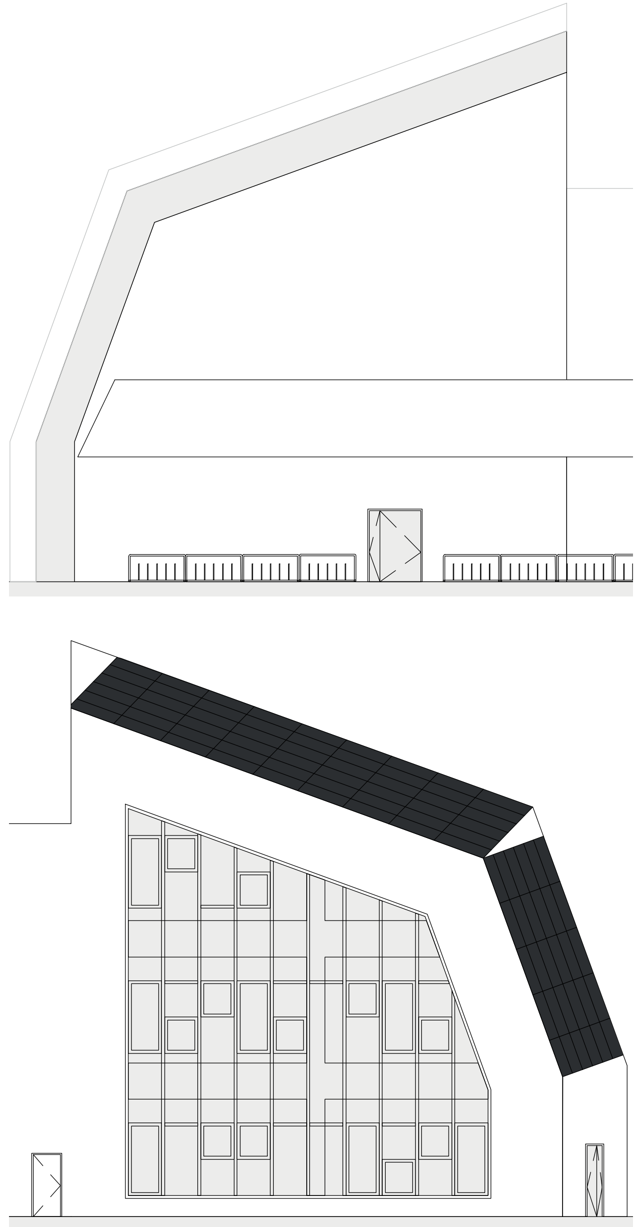


Figure 42: Elevation NE facade (up) SW facade (down) 1:250

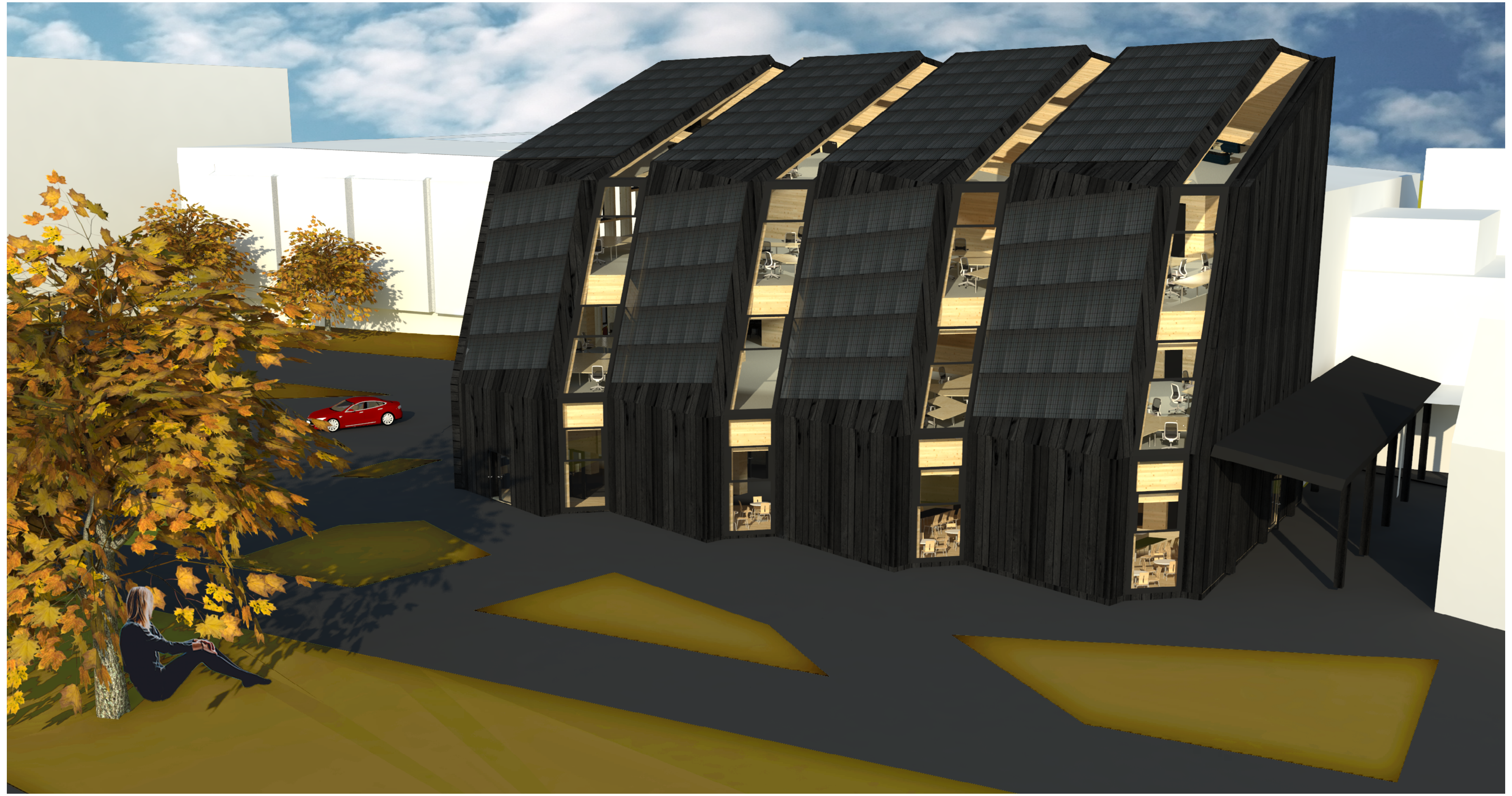


Figure 43: View from the walkway on Høgskoleringen

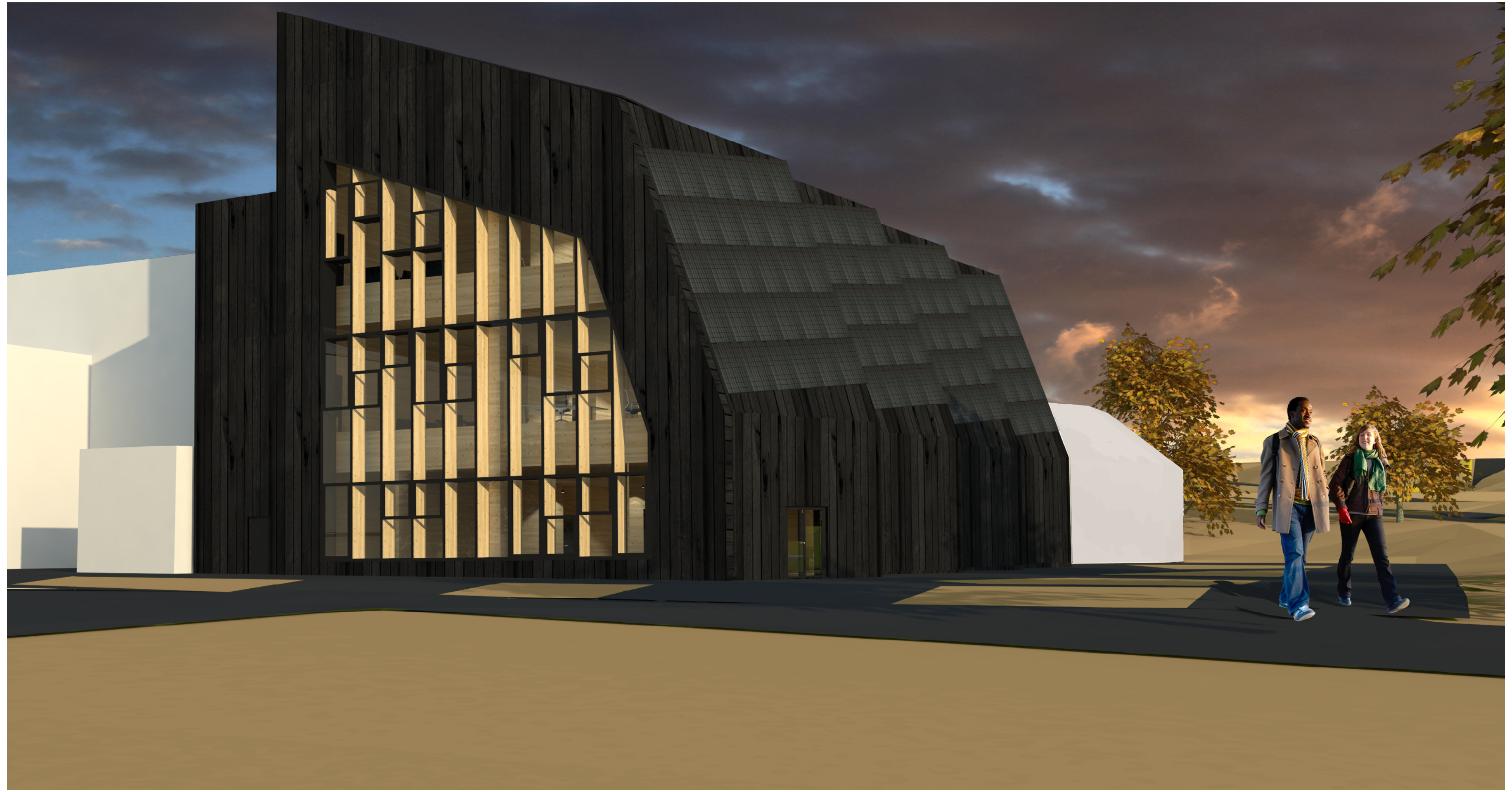


Figure 44: View from the parking lot by Nina Huset

Figure 45: Interior on the 3rd floor

| MATERIALS

Figure 46: Material palette

Figure 47: Acoustic panels on the walls

Figure 48: Acoustic panels on the ceiling

The indoor air quality in a building is an important part for the indoor environment for the employees, students and visitors in the building. The material choices and ventilation strategies are one of the key elements for good air quality. The materials used for the building is mostly wood materials. The super structure, roof, outer walls, inner walls and internal floors are all made of massive wood and are also insulated with wood fiber insulation. Wood provides a healthy and pleasant living environment. Wood have a moisture equalization capacity which means that during the month of the year when the humidity in the air is high, wood material can “store” humidity and in the dry month of the year the wood material can “give back” humidity. This results in that the humidity in the air inside the house will be balanced [34]. The wood fiber insulation is also a natural material, it does not scratch and it contains no harmful substances or additives that can affect the air quality [35].

The building is both natural ventilated and mechanical ventilated in order to optimize the air quality. During all the hours of a day the air is changed, the exhausted air is constantly flowing out of the building through the natural ventilation and the mechanical ventilation system make sure that new fresh supply air enters the building.

The acoustics in a building is an important part for the indoor environment and the acoustic has to be adapted for the employees, students and visitors in the building. To avoid problems with the acoustics inside the building some precautions have been made. The internal floors are made of wood, which in general has a high quality of acoustic performance, in addition to this a fabric carpet is placed on top of the raised floor in order to reduce footfall. Wooden acoustic panels are installed on the walls and under the ceiling in order to further absorb the noise in the building. Also the wood fiber insulation has good acoustic properties [14].

The structure of the house is made of massive wood combined with cross laminated timber panels and glue laminated pillars and beams.
The load bearing structure of the building is made out of the outer walls and internal pillars and beams. The structure is dimensioned to take both horizontal and vertical loads, the buildings own weight, snow loads and wind loads [15].

The building is constructed out of massive wood in order to reduce the carbon footprint. Massive wood is a natural material and by choosing a wood construction instead of other materials the CO_2 emissions is reduced, since a wood construction has a reduced embodied emission [16].

The glue laminated wood structure has been proven to have a high fire resistance of 40 mm /hour and the fire resistance can be further increased by increasing the dimensions of the structure [17]. The massive wood construction have a lifetime at least as long as the building itself, dependent of the right treatment. The massive wood construction is standing on a low carbon concrete slab. All the building elements of the house are designed to reach the Passive house standards.

Element	U-value [W/m^2 K]
Roof	0,1
Outer walls	0,13
Ground slab	0,08
Windows and doors	0,08

Figure 51: U-values of building elements

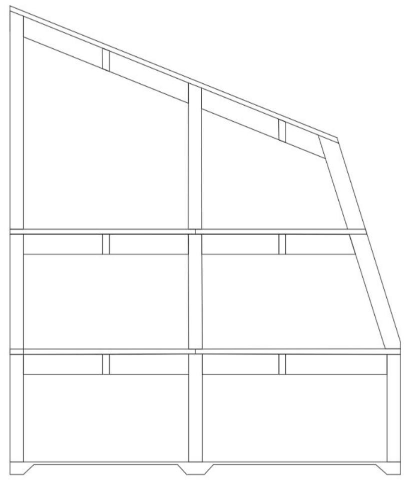


Figure 49: Construction section

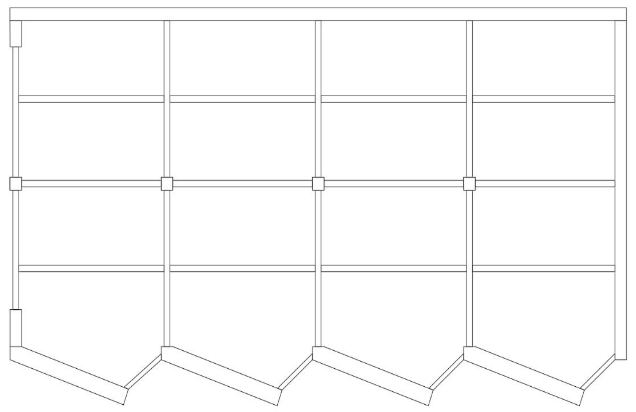


Figure 50: Construction plan

The roof is a well-insulated wood construction with a U-value of 0,1 W/m2 K. The material layer facing the inside of the building is the cross laminated panels which have a thickness of 120 mm and are part of the load bearing structure. The middle layer of the roof construction is the insulation layer. Between the cross laminated wood panels and the insulation layer is a vapor barrier in order to prevent the warm humid indoor air from entering the construction with the possible result of condensation in the colder layers [18].

The roof is insulated with a wood fiber insulation which has good insulation properties with a lambda value of 0,036 W/m K. There is an inner and outer insulation layer in order to minimize the thermal bridges in the construction.

The wood fiber insulation has also a good stability and come in the shape of plates in order to easily be placed between the studs in the roof construction. If any vapor should arise in the insulation the insulation is water vapor permeable for protection of the construction [19]. The installation of the wood fiber insulation can be done by hand because it is a natural material without any harmful substances or additives that will scratch the skin [20]. The insulation is treated with natural fire retardant in order to withstand a fire [20].

On top of the insulations is a wind barrier. The wind barrier makes the construction air tight but will has at the same time breathable properties so that moist air can be released through the ventilated air gaps between the counter batten and batten.

In order to make the whole building envelope air tight, all the joints of should be taped with anti-aging tape [20].
On top of the counter batten and batten is the water proof layer. It is a plywood with roofing felt in order to make the construction water proof.

On top of the roof are PV panels installed on a mounting system with a ventilated air gap. The PV panels are not integrated in the roof construction ensuring that they can be removed without and impact to the building physics.

The total thickness of the roof construction is 580 mm, without the PV panels. The calculations of the U-value are made according to the Norwegian standard.

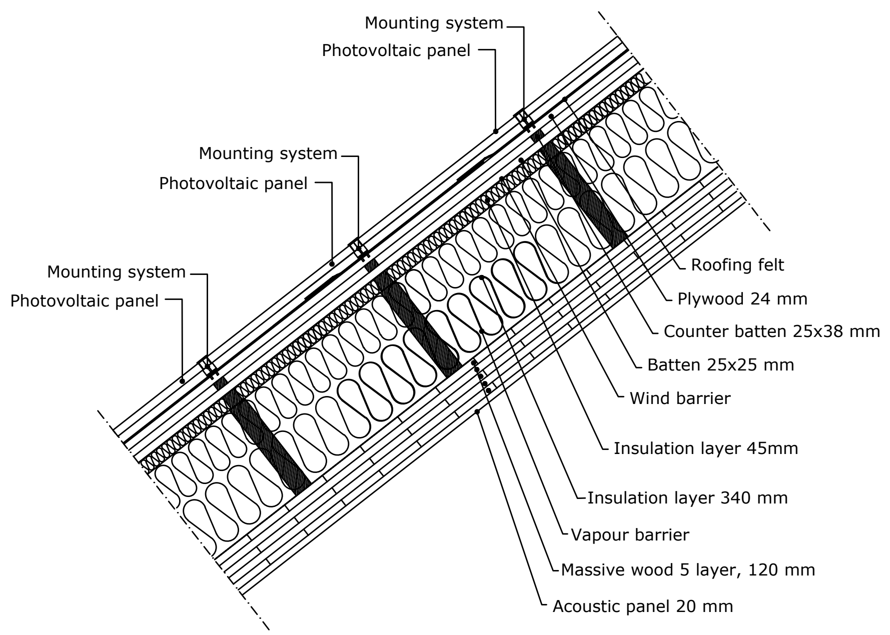


Figure 52: Detail-Roof

The outer walls are a well-insulated wood construction with a U-value of 0,13 W/m2 K.
The first layer closest to the internal side of the building is part of the load bearing structure and are made out of cross laminated wood panels with a thickness of 120 mm.

The outer walls are insulated with the same wood fiber insulation as in the roof construction and have the same properties with regards to lambda value, installation, stabilization, fire protection and water vapor permeability as described in the chapter about the roof construction. There is an inner and outer insulation layer to minimize the thermal bridges in the construction.

Between the cross laminated wood panels and the insulation layer is a vapor barrier in order to prevent the warm humid indoor air to enter the construction with the possible result of condensation in the colder layers [18].

On top of the insulations is a wind barrier. The wind barrier makes the construction air tight but will at the same time make the construction breathable in order to release any moist indoor air through the ventilated air gap under the wood cladding.

In order to make the whole building envelope air tight, all the joints of should be taped with anti-aging tape [21].

The outer layer of the outer wall construction is a wood cladding. The wood cladding have a burnt wood layer of a few millimeters on the outside of the cladding. The burning process draws out moisture, and results in a chemical compound protection of the wood resulting in a high durability of burnt wood cladding. For the burned wood cladding the quality of the wood can be of low quality wood, since it does not affect the cladding performance. The burned surface also gives the wood a high resistance to; rot, fire, insect attack and fading due to UV radiation. With the right maintenance the finish can last up to 80-100 years and even longer. This type of cladding is environmentally friendly since it is completely reusable, biodegradable and it contains very low amounts of embodied energy.

The total thickness of the outer wall construction is 535 mm. Calculations of the U-value are made according to the Norwegian standard.

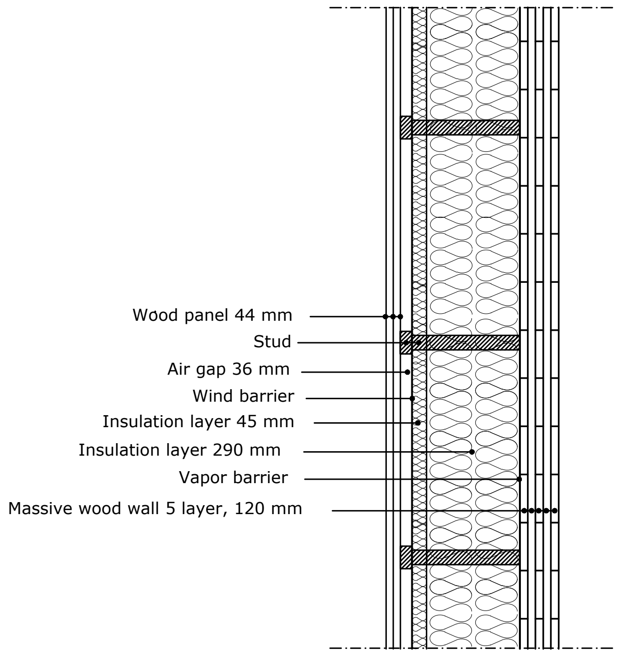


Figure 53: Detail-external wall

The internal floors are made out of cross laminated wood slabs, in order to reduce the carbon footprint.
The cross laminated wood slab has a thickness of 150 mm and is resting on the load bearing outer walls and beams and pillars.

Over the cross laminated slabs is a raised floor with an air gap of 228 mm, in this gap the technical installations are placed. The wooden raised floor covers the technical installations, but can easily be removed in order to access the technical installations.

The wooden floor is covered by a carpet in order to reduce the footfall and under the cross laminated wood slabs acoustic panels are installed in order to absorb noise.

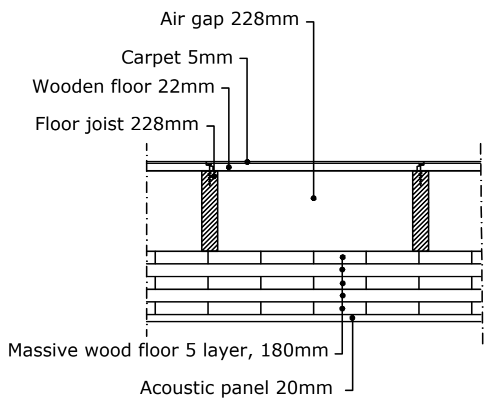


Figure 54: Detail-internal floor

The ground slab is a low carbon concrete slab insulated with EPS insulation. The result from previous geotechnical ground investigations shows that the ground conditions is a stable and solid surface crust of 4-6 meters and the frost free depth is located at 1,5 meter from the surface, which means that the ground is good to build on.

The low carbon concrete slab has a thickness of 100 mm and under the load bearing walls the thickness of the concrete slab footing is 500 mm in order to take the loads. The EPS insulation has a lambda value of 0,035 W/m K and a thickness of 350 mm. The EPS insulation is a material which is moisture resistant and serve as a capillary breaking layer [21]. The ground slab construction has a U-value of 0,08 W/m2 K.

Between the concrete slab and the EPS insulations is a radon membrane in order to protect the building from radon gas and other gases to leak inside the building [22]. The ground slab has a slab edge insulation to minimize the thermal bridges [23].

On top of the ground slab of low carbon concrete there is a layer of PE-foil to protect the building from moisture from the ground slab and ground. Above the layer of PE-foil is first an under floor made out of wood and above that there is a raised floor.

The ground slab including the low carbon concrete and EPS insulation, has a total thickness of 450 mm.

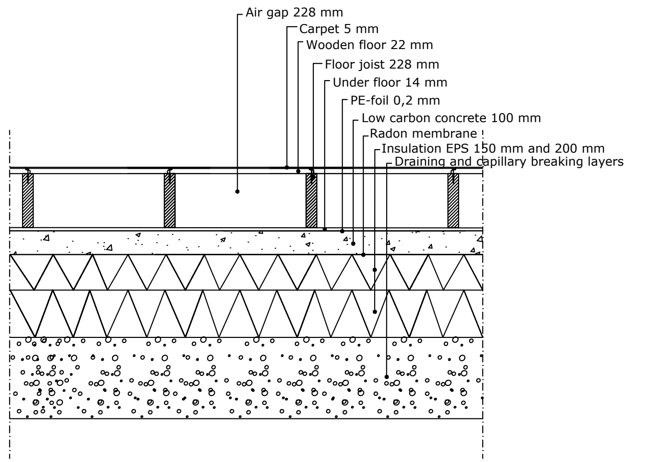


Figure 55: Detail-ground slab

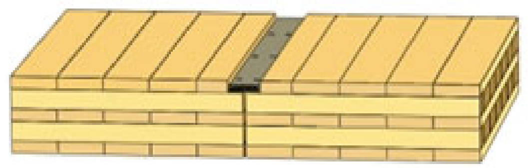


Figure 56: Connection slab and slab [17]

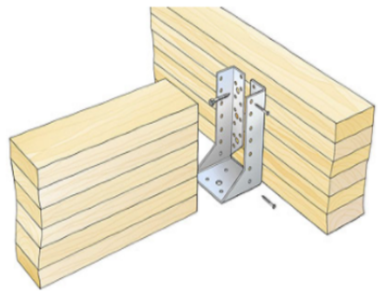


Figure 58: Connection beam and beam [17]

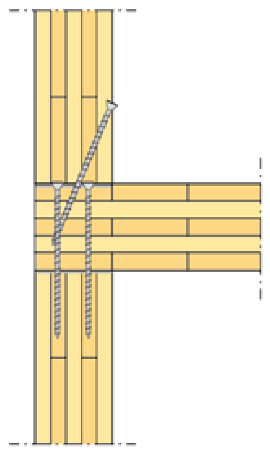


Figure 57: Connection wall and slab [17]

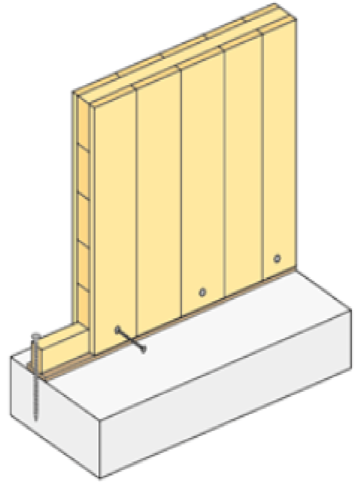


Figure 59: Connection concrete slab and wall [17]

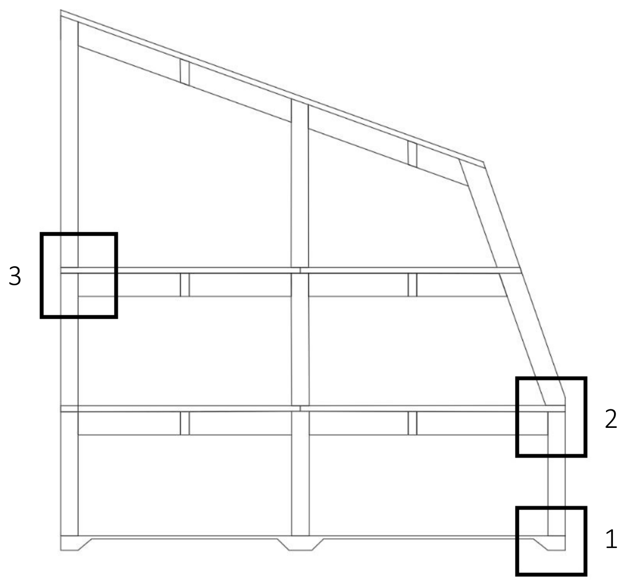


Figure 60: Construction section

1

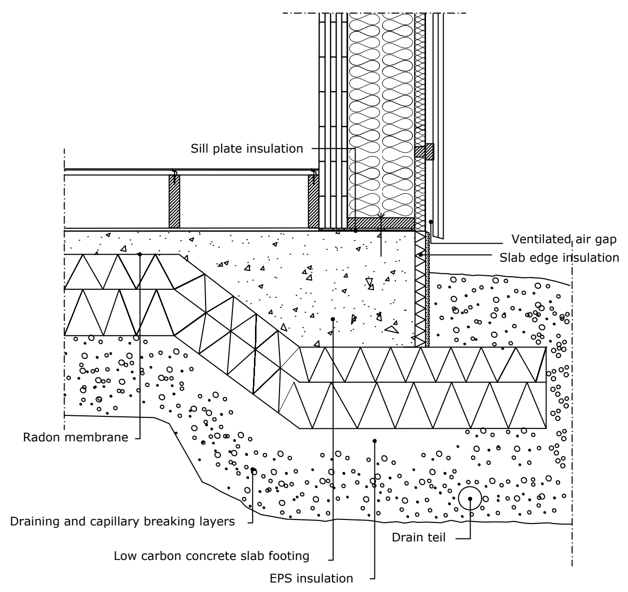


Figure 61: Detail-connection of ground slab and outer wall

2

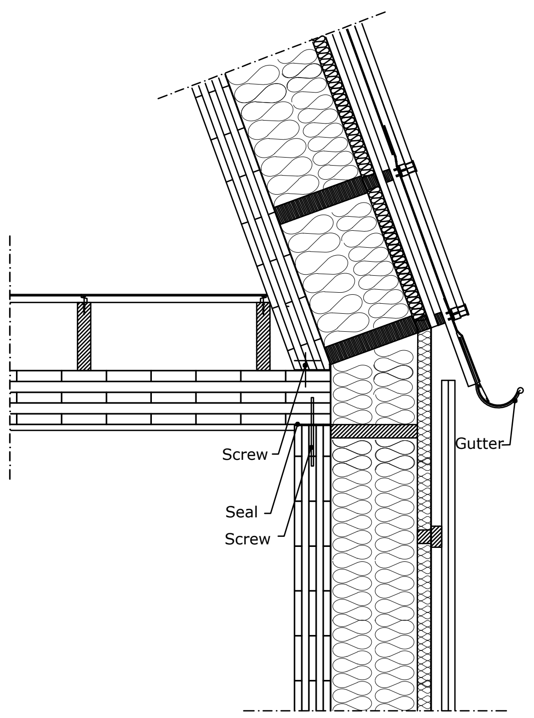


Figure 62: Detail-connection of outer wall, internal floor and roof

3

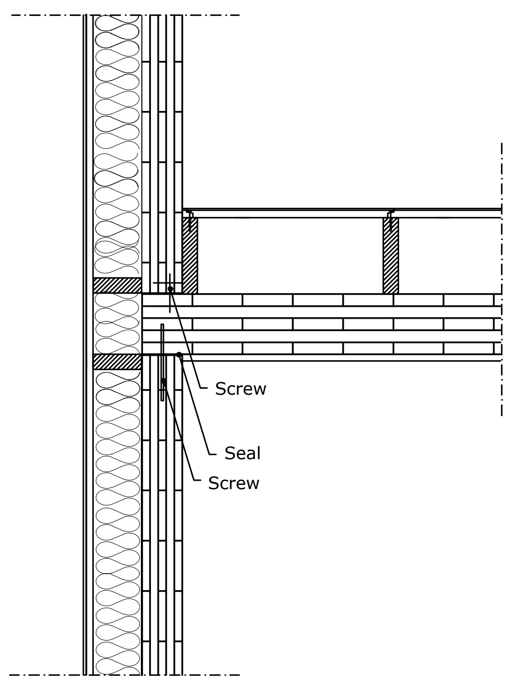


Figure 63: Detail-connection of wall towards Byggforsk and internal floor

| PHOTOVOLTAICS

The optimization of the building's electricity production was done by using Polysun software. In order to reach ZEB-COM level, the PV needs to be used very efficiently. Initially, the site analysis showed that there is overshadowing on the S and E due to the neighboring buildings and surrounding terrain [App. D]. Therefore it is assumed that it is plausible to use PV after 5 m above the site level.

The modules that are being used are PV-Modul-350W with 22,45 % STC efficiency, 104 cm wide and 155 cm long. The diagram represents the tilt optimization assuming 60.000 kWh of total consumption of G0 Trade and commerce profiles, based on self-consumption fraction as a guideline [Fig. 65].

The optimization included comparison of several options [Fig. 64] and optimization of the inverters and their layout:
1. seasonal tracking (winter and summer design)
2. fixed PV, 50° tilt
3. fixed PV (20° and 70° tilt)

The first option was dismissed due to very high costs and extensive maintenance of the tracking system. The second option was later also dismissed due to unused attractive space on the south side due to the steep tilt. The end design compromises with interior design, user comfort and space-efficiency and by tilting the roof up to 70°, it provides more attractive working space, better exposed to the natural daylight.

The roof is tilted 20° and in this way compromising architecture with highly efficient PV design [Fig. 65].

Even though the photovoltaics are not orientated exactly to the S (7° towards E), the performance of the modules is insignificantly lower compared to the performance of modules with south orientation.

Because the PV area is separated into 8 surfaces (4 surfaces with 20° tilt and 4 surfaces with 70°), with different number of modules, different string inverters are used for different layouts [App. D]. For 20° tilted roof (350 m²) NT10000 with 96,4 % efficiency and for 70° tilted roof (200 m²) SOLPLUS 80 inverter with 98,0 % efficiency are used.

The modules are only mounted and not integrated into the building in order to provide better performance due to better ventilation and in order to be exchangeable for testing in future [Fig. 66,67].

The all black panel design, combined with the dark charred wood facade lowers the contrast of PV to the cladding and emphasizes the contract between dark facade surfaces and window areas [Fig. 68].

Over a year, the PV modules the total of 336 modules produce 99.325 kWh AC (107.921,4 kWh DC), with 46,1 % self consumption fraction without using a battery [App. D].

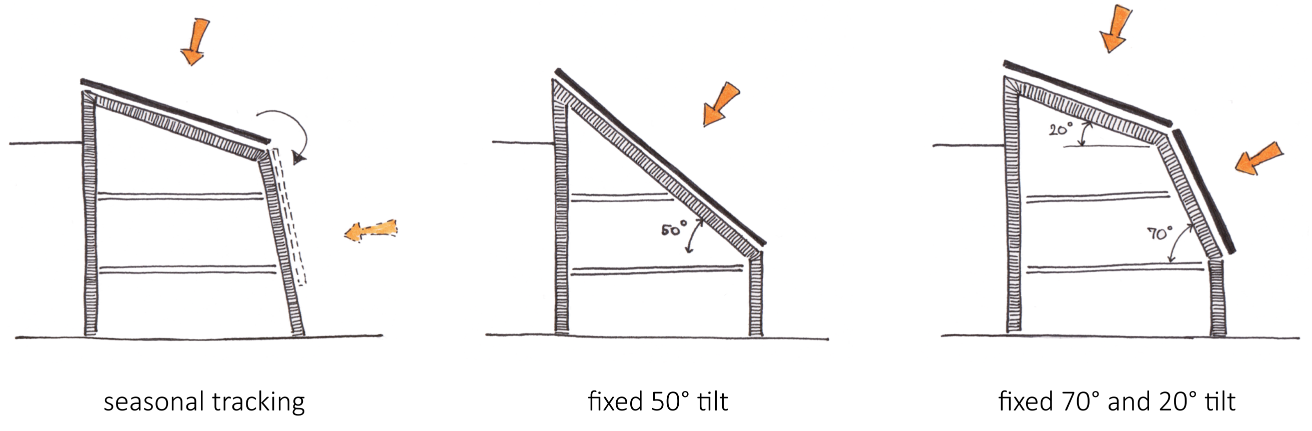


Figure 64: PV optimization- analyzed options

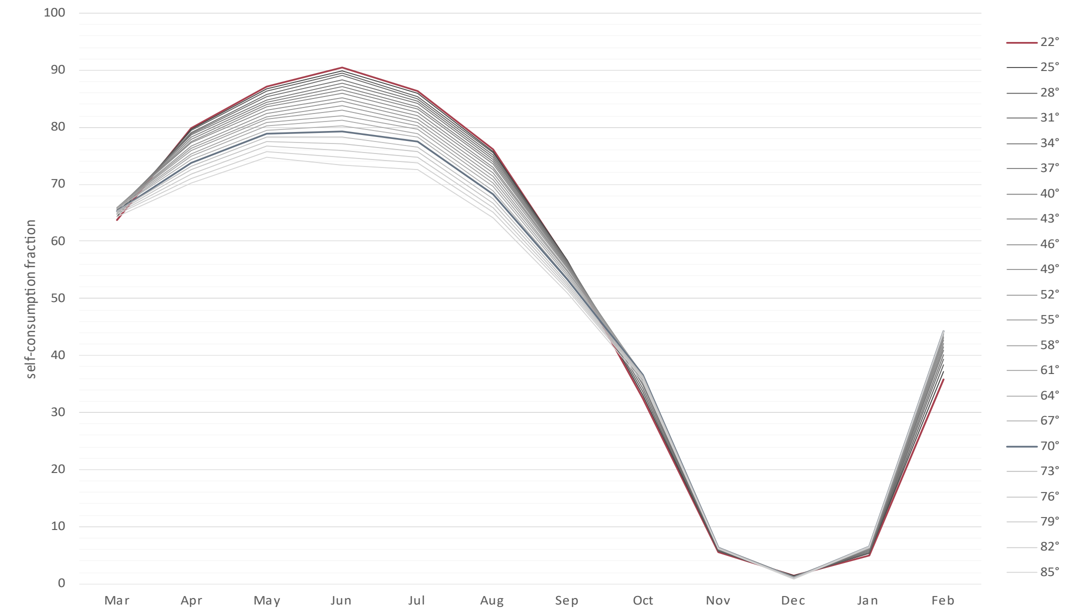


Figure 65: Optimization of self consumption fraction depending on tilt [Polysun]

The fact that electricity production of PV and loads in the building are matching provides high percentage of direct use of electricity. Therefore it is not necessary to have a battery. Nevertheless, by optimizing the battery capacity [App. D] it is possible to have more than 50 % higher self-consumption fraction (68,5 %) by using 100 kWh battery. But since there are no regulations for that, in terms of LCA it is better not to have it.

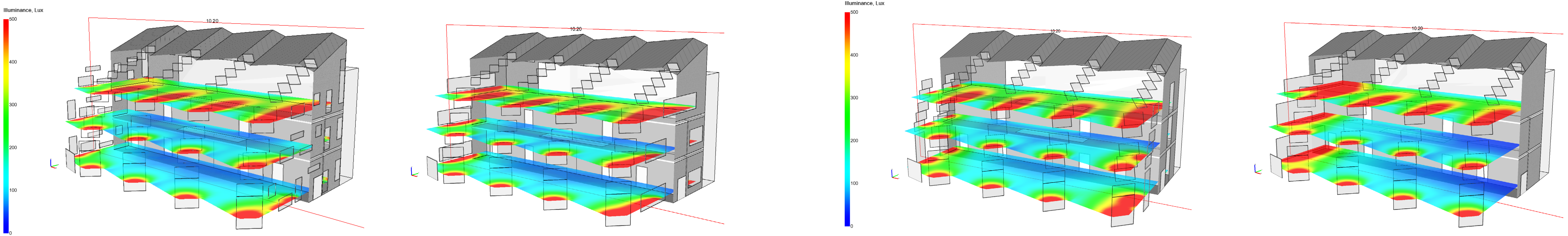
However the electricity can also be stored externally, for example in electric cars that would belong to SINTEF or NTNU. For example, the new Nissan Leaf coming out in 2018 will have a lithium-ion battery with 40 kWh capacity. By having a couple of those that would be charged by Flex-Lab photovoltaics, it would be possible to have higher self-consumption of produced energy [24].

Figure 66: Example of All-black PV

Figure 67: Example of all-black PV

Figure 68: Example of mounted PV surfaces

Figure 69: Nissan Leaf with 40 kWh battery [24]



option 1

lighting 3,29 kWh/m²

option 2

lighting 3,34 kWh/m²

option 3

lighting 3,27 kWh/m²

option 4

lighting 3,13 kWh/m²

Figure 70: Examples of different window distribution and its influence on lighting demand [IDA ICE]

The goal of the design is to maximize the daylight in the rooms, increase solar gains in winter but at the same time avoid overheating in summer. In the final design, the building is repeatedly cut in slices by window areas orientated towards ESE. In this way, solar gains are higher in morning hours when the building is starting to be occupied and passive solar heating is being utilized. Afterwards, when the sun is in the S, the solar gains are minimized due to facade covered with PV. Additionally, the spaces planned for work have been placed mostly on the SE facade and partially towards NE and SW. The rooms that do not require natural daylight (toilettes, technical rooms, storage and circulation) have been placed towards NW facade, connected to the SINTEF Byggforsk building.

Since the highest illuminance on workspace is required on the 3rd floor, there are additional skylights

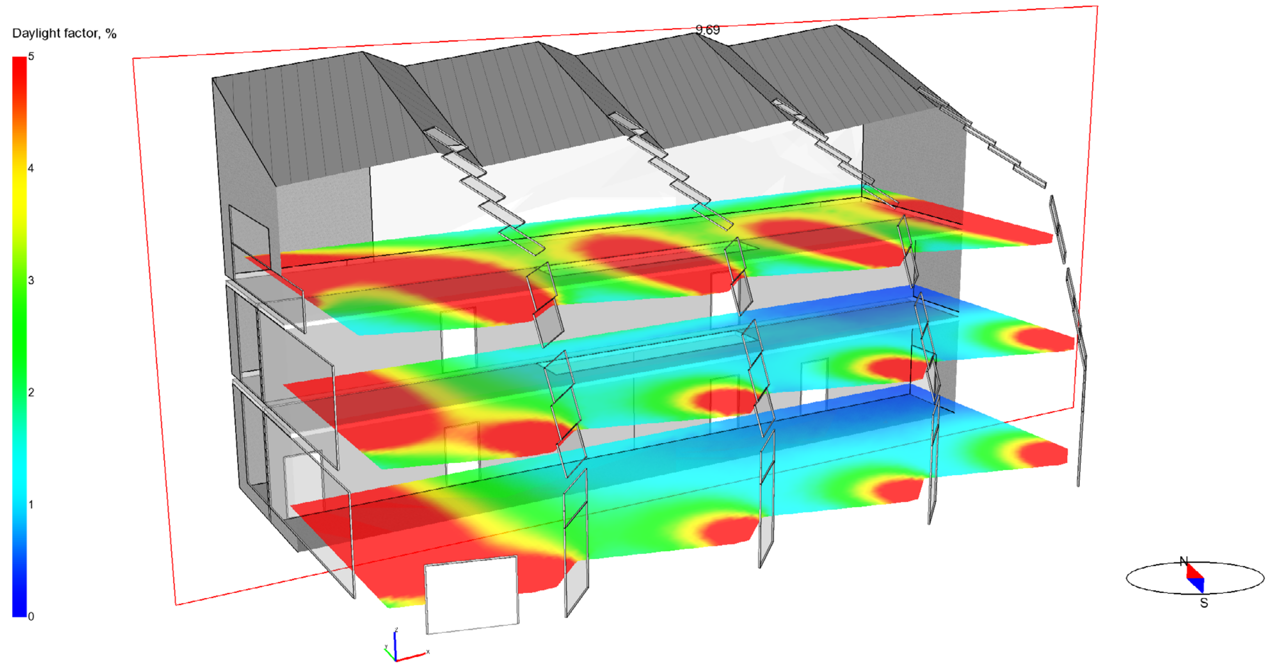


Figure 71: Daylight factor distribution on 0,8 m height above floor (21st September at 12 h) [IDA ICE]

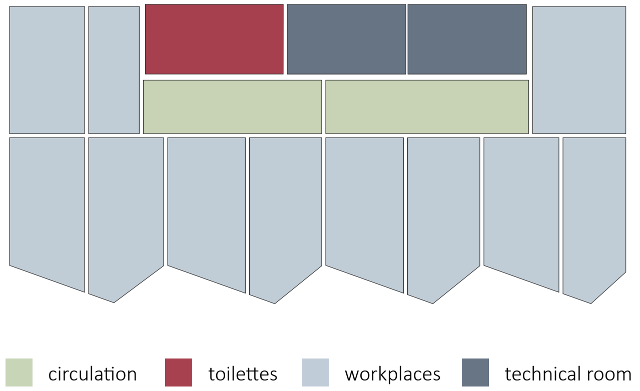


Figure 72: Lighting zoning control

providing better natural daylight. For the NE and SW facade different options have been taken into account [Fig. 70]. The chosen option is option 4 because of the lowest average lighting demand over the whole area and also because the big window area on the SW facade opens the building in that direction, providing workers with a nice view and people walking by the building with an insight.

The final design has 19,3 % window area. The average daylight factors (DF) for 21st September at 12 h:

- 1st floor - 3,25 %
- 2nd floor - 2,90 %
- 3rd floor - 4,25 %

Figure 73: Example of skylights

Figure 74: Example of skylights

Figure 75: Example of internal sunscreen roller blind

Average daylight autonomy (DA) calculated for requirements for tasks at given floors:

- 1st floor 80% of occupancy time above 200 lux
- 2nd floor 74 % of occupancy time above 400 lux
- 3rd floor 72 % of occupancy time above 500 lux

All the windows except sky-lighters are SGG Planitherm Ultra-N 3-panes, U-value 0,8 W/(m²K) and g-value 0,42. The skylights are made of SGG COOL_LITE KSN-174 3-panes, U-value 0,8 W/(m²K) and g-value 0,3. In this way, overheating in summer is prevented and passive solar gains in winter are still available.

For artificial lighting, the floor is subdivided in max. 30 m² control zones [Fig. 72] with LED, dimmable, luminaries with ''multi-sensor automatic control'' (presence detection and daylight availability). The dimming level is lower than 20 % of normal on, and the timing less than 15 min delay. The lighting energy demand simulations assume 50 W/m² in occupied areas.

When it comes to shading devices, according to indoor climate simulations, it is not necessary to have shading. But in terms of glare control on work surfaces, it is. There are many solutions that can be used, and can be tested on the building.

In order to avoid higher costs and maintenance of external shading systems, internal sunscreen roller blinds are planned.

On the SW facade, the part of the construction bearing the glazing is designed in a way to provide protection from direct sunlight.

MECHANICAL SYSTEMS

The primary mechanical systems of the building consist of hydronic heating, ventilation, and domestic water distribution. A single technical room contains these systems and is located along the north wall of the building, spanning three floors, with metal platforms dividing the floors. The kitchen, bike workshop, showers, and water closets are located along the north wall, to the east and west of the technical room, centralizing the rooms that require a large demand for water distribution and exhaust system on either side of the technical room.

The layout of the building's mechanical systems was designed to be flexible for both interchanging and testing different systems. The raised floor allows for flexible access and distribution of systems. The hydronic heat and ventilation air is distributed through the raised floor system. The distribution systems have been set up in underfloor grids, allowing for isolated heating and ventilation techniques to be applied to of different zones.

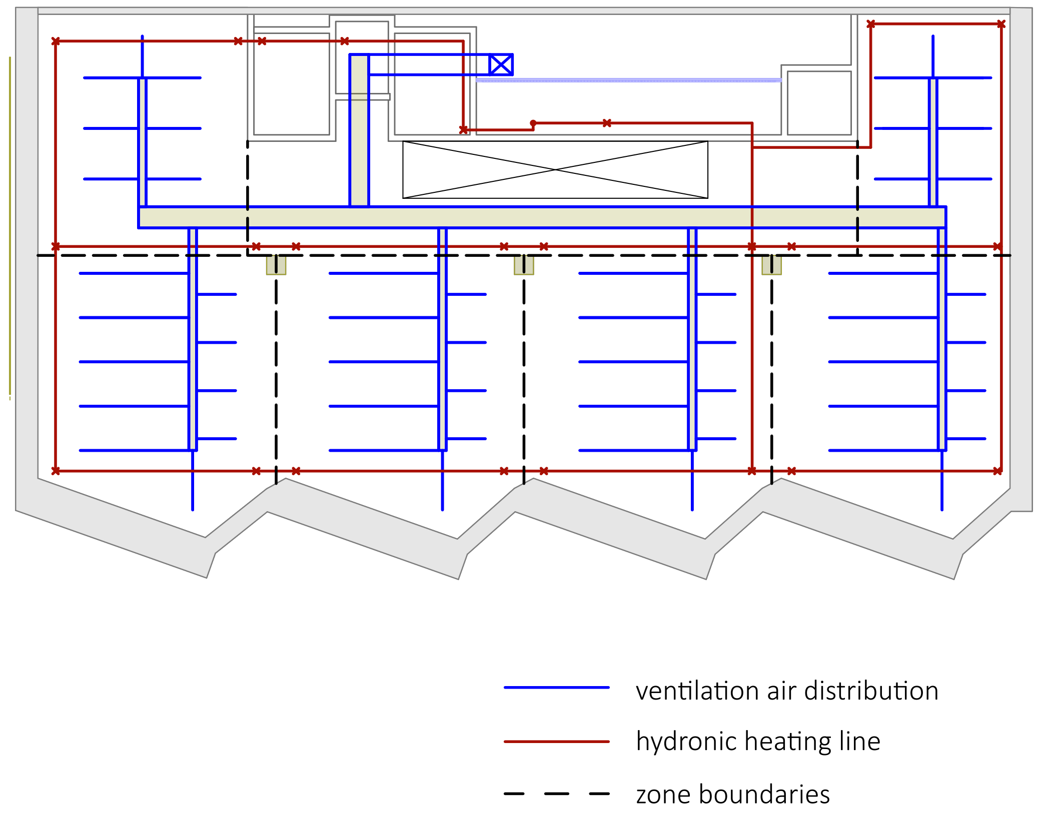


Figure 76: 2nd Floor Heating and Ventilation Distribution Systems

A heat pump is used to meet the main heating load for the building, with a connection to district heating as a backup heating source for any additional required loads. The heat pump uses bedrock as a heat source by means of three boreholes located along the west side of the building. The heating system gathers and distributes heat using water as a primary and secondary energy carrier; providing heat for the domestic hot water, ventilation, and space heating needs. Due to the cooler climate of Trondheim, a cooling load was incorporated into the design of the building.

The hydronic heating system consists of hot water pipes run beneath the raised floor, providing hot water access for appliances throughout the building. A main distribution line runs along the perimeter and central hallway of the building providing connection points for different types of hydronic heating distributors throughout the building. The individual connection points and the raised floor system allow for the interchange of different potential hydronic heating systems, including radiators, heated floor and wall systems.

The geothermal heat used to operate the heat pump provides a stable and steady heat source for the building. Although the initial cost of installing the system is high, the only energy demand, once the system has been installed, is the electricity that is required to run the pumps used for the circulation of the water. When temperatures drop and the heat load increases beyond the maximum heat load of the heat pump, district heating provides the heat needed for any surplus demand. This reduces the energy demand of the building's heating load to the electricity used to run the pumps used by the heat pump.

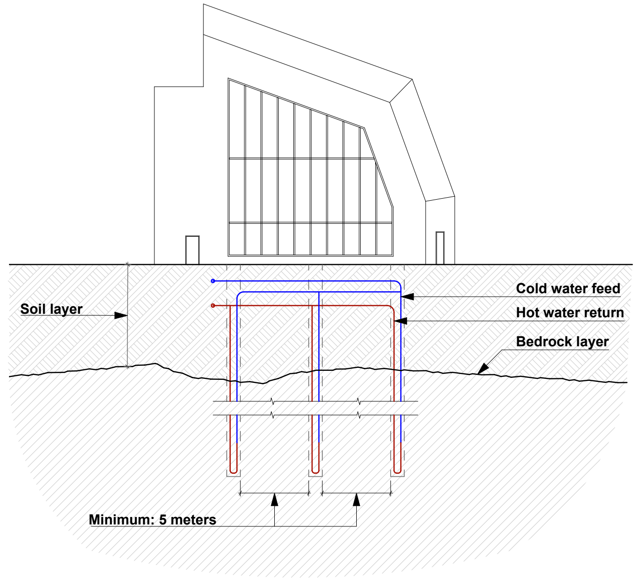


Figure 77: Geothermal borehole detail

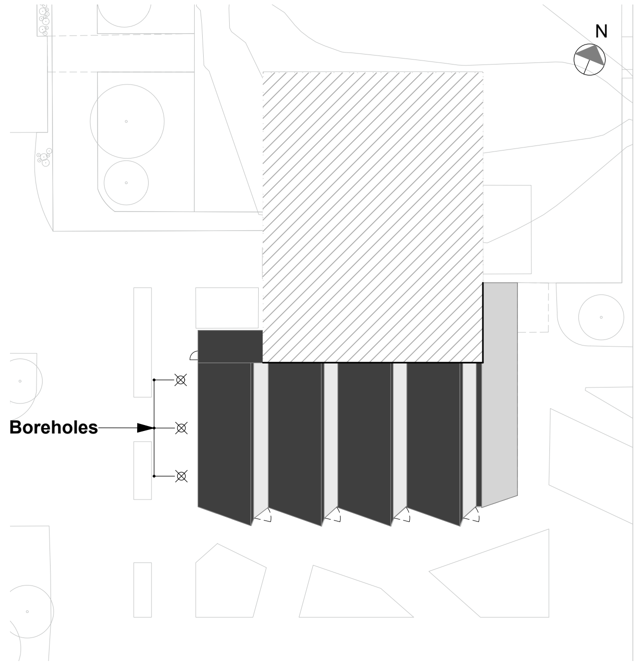


Figure 78: Geothermal borehole site plan

A hybrid ventilation system has been incorporated into the design of the building, combining natural and mechanical ventilation systems. During the warm summer months, the building is ventilated primarily with natural techniques, with a back-up mechanical system used to remove exhaust air from the kitchen, showers, and water closets when required. During the cold fall, spring, and winter months, the building utilizes the mechanical ventilation system.

The mechanical ventilation system uses the displacement method to ventilate the building. The high ceilings heights of the natural ventilation system, using buoyancy and stack effect to circulate the air, facilitates the use of displacement ventilation. Air is distributed and released through the raised floor system, and rises as internal heat loads slowly raise the air temperature, causing it to move upward. When the natural is not active, during colder outdoor air temperatures, the ventilation system collects air through vents along the high roof of the building, drawing it back into the exhaust system, allowing the warm air to be channeled through a heat exchanger before it is expelled from the building.

This hybrid ventilation system combines a natural ventilation system with a mechanical heat energy and reduces energy demands in warmer months by limiting the mechanical ventilation system to removing exhaust air from the kitchen, water closets, and showers. During the colder months, when natural ventilation would drastically increase the energy needed to heat the building, the mechanical ventilation system is primarily in use. Exhaust air is channeled through a heat exchanger, preheating the intake air before it is run through heating coils and distributed to the different floors. This reduces the energy demand needed to heat the ventilation air.

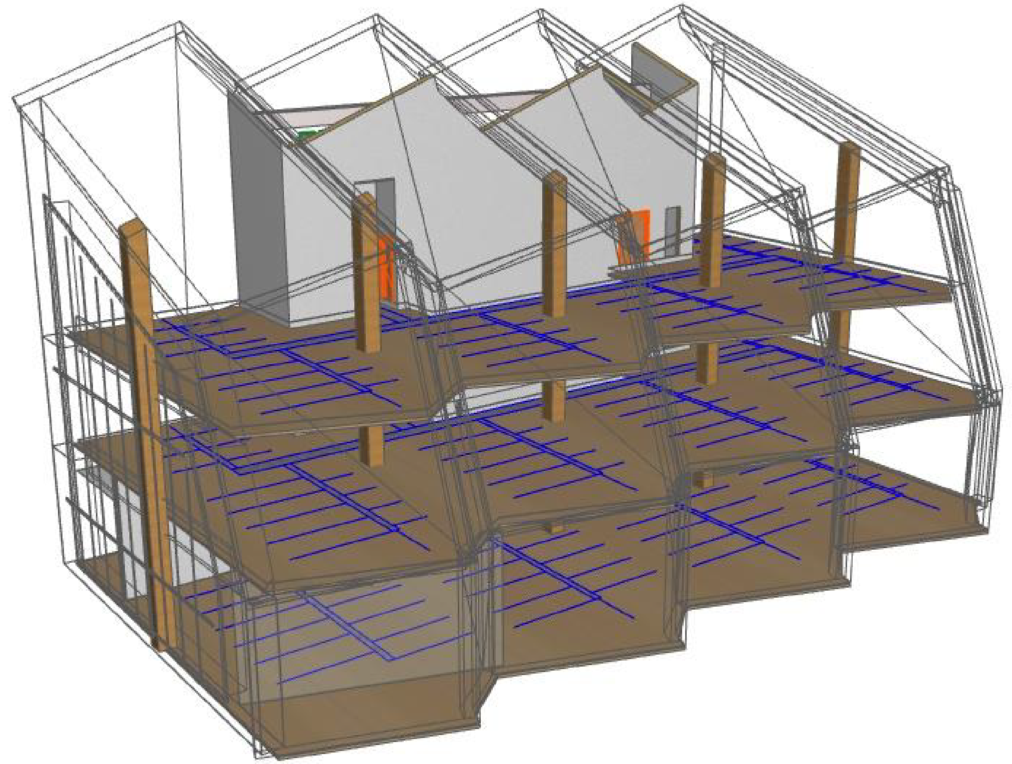


Figure 79: 2nd Floor Ventilation System

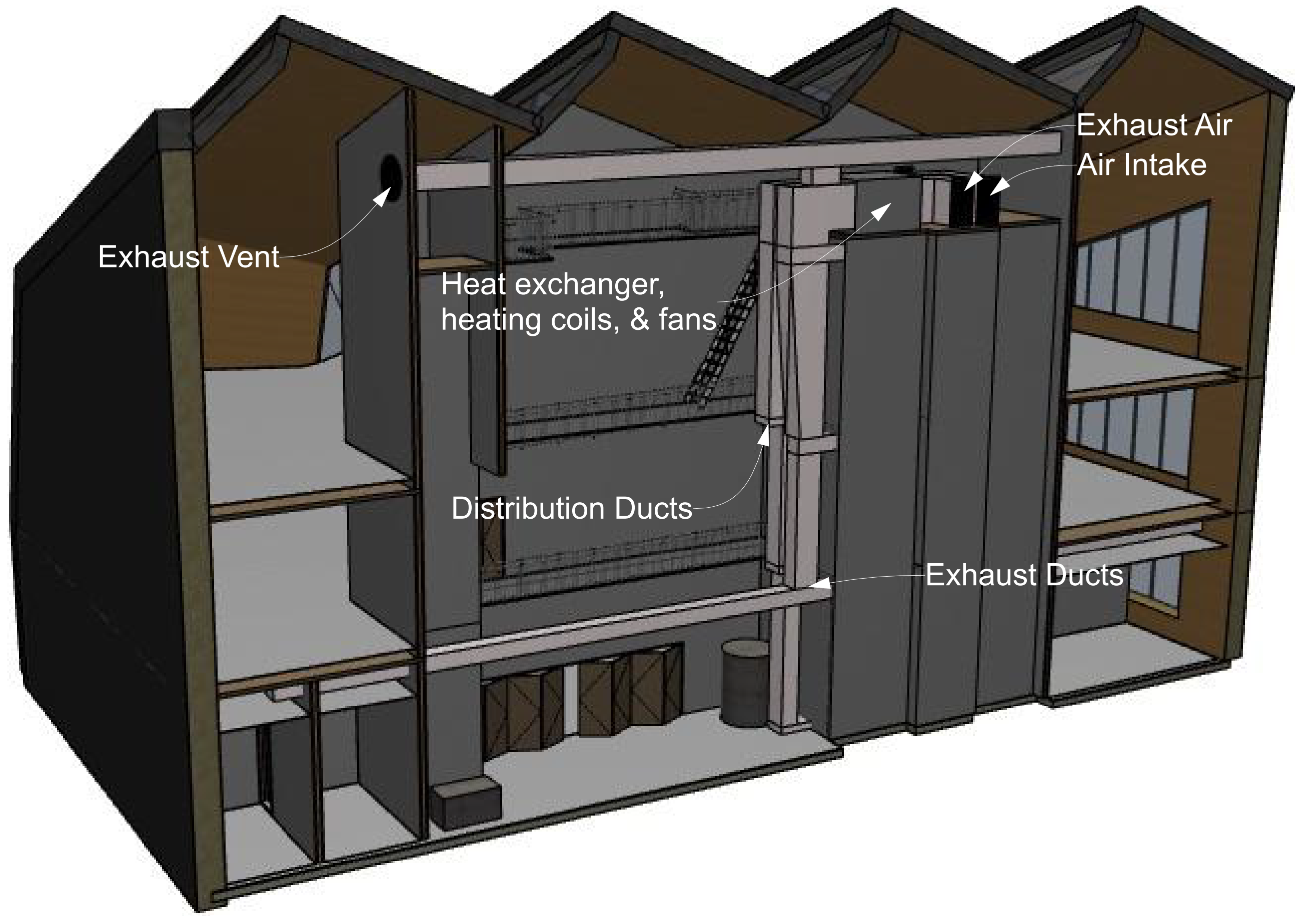


Figure 80: 3D Technical Room with Ventilation Ducts

| ENERGY DEMAND

General information about the building:

- A/V=0,31 m²/m³
- window area 19,3 %
- HVAC heat recovery system 85 %
- SFP 1,5 kW/(m³/s)
- infiltration n_{50}=0,5
- normalized thermal bridge value 0,03 W/m²K
- DHW demand 3l/person
- occupancy 7-18 h

For the calculation of the energy demand, two different softwares have been used - IDA ICE and SIMIEN. IDA ICE was used because it is very handy in early design phase and was immediately showing the impact of passive measures on energy demand. The figure 81 shows the reduction of energy demand by applying certain strategies during the early design phase. The initial design with atria on the rooftop was later changed to atria tilted towards the facade opening.

By having three floors with different activities and different requirements (more or less strict), it is possible to reduce the building's energy demand by about 12 kWh/m2. By having natural ventilation in summer, from 15th of May until 15th of September, the HVAC aux energy demand can be significantly reduced, resulting in 43,2 kWh/m² total energy demand.

Afterwards, the design has be changed to the final one and internal loads have been modified. The lighting input is 5 W/m² for LED lighting. The highest electricity demand is due to use of equipment. As buildings are becoming more efficient, when it comes to office buildings, it means that computers are an increasingly important source of energy use. Therefore it is of great importance to use energy efficient equipment and operate it as efficiently as possible. The IT equipment is getting more and more efficient rapidly. For this reason it is very difficult to predict its energy consumption in a period over the building's lifetime (100 years). The energy balance is based on a study of power demand of small equipment in office buildings [25] and the value of 30 W/occupant is taken as an input for equipment.

These changes resulted in total energy demand of 28,7 kWh/m². It is important to mention that this values do not fulfill the NS 3701 Norwegian standard, but are according to the indoor comfort requirements [App. F].

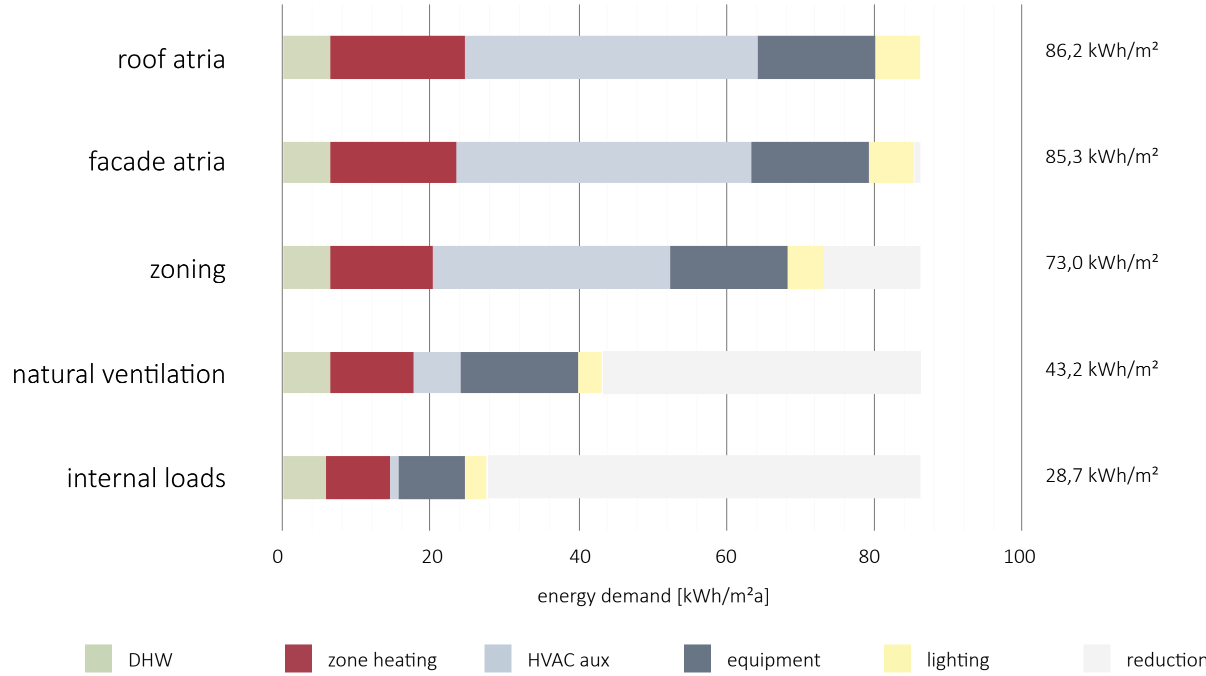


Figure 81: Energy demand reduction [IDA ICE]

SIMIEN was used in order to fulfill the Passivhus standard according to NS 3701 as a part of the project requirements [App. F].

The main input difference between these two are the mechanical ventilation volumes. In SIMIEN, according to the Passivhus standard for this type of the buildings, it has to be 7 m³/hm² and 1 m³/hm² when the building is not occupied (VAV).

Therefore the energy consumption is higher than in the other two simulations and is resulting in total of 59,7 kWh/m².

The second result represents the IDA ICE simulation of energy demand with the same ventilation strategy as SIMIEN. Nevertheless, because of dynamic simulation and fine tuning, the energy demand is significantly lower in comparison to the one from SIMIEN (almost 50 %). Furthermore, the IDA ICE VAV with CO_2 level control and automatic natural ventilation with temperature and CO_2 control provide the best results (28,7 kWh/m²). Even though the simulations show that the indoor climate is good, it is not according to standard [App. G]. Therefore, the second option can be taken as a reference for the LCA calculation.

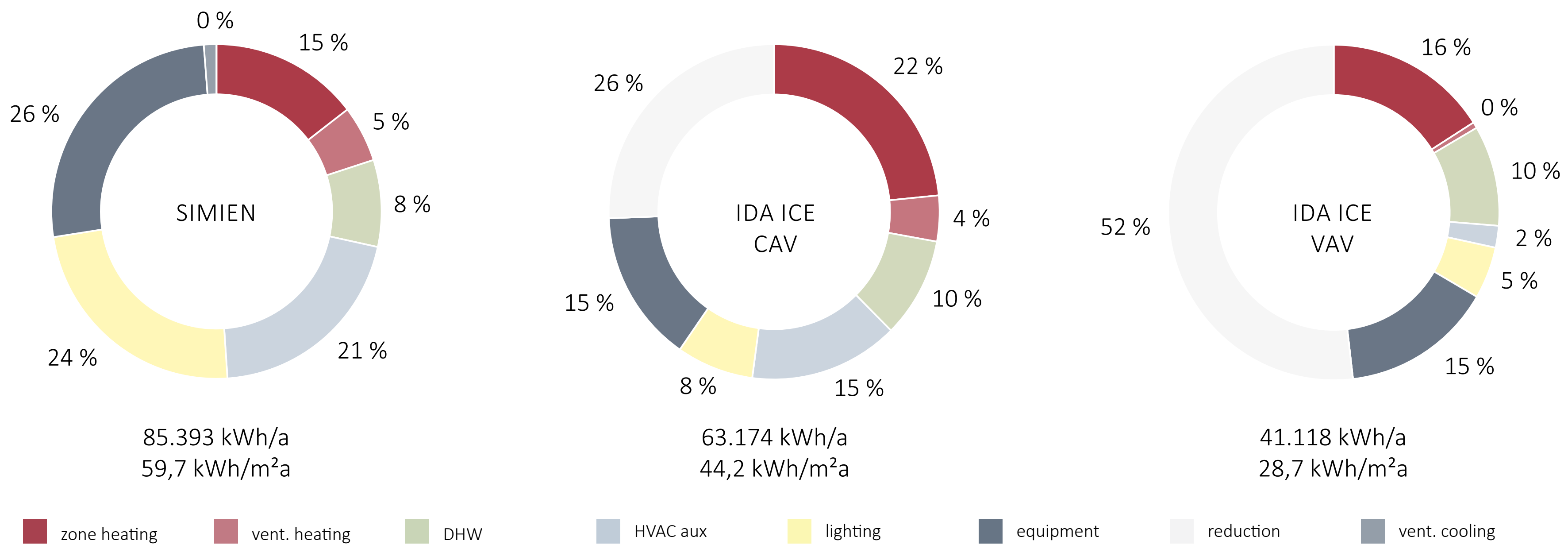


Figure 82: Energy demand - SIMIEN, IDA ICE CAV and IDA ICE VAV based on indoor comfort

In order to obtain the ZEB-COM standard, the PV panels need to compensate for the CO_2 emissions from the building construction process, building materials, operational time for the building and the embodied emission for energy supply i.e. PV and heat pump for this building.

The first calculations that have to be in count is the calculations for CO_2 emissions for the building construction process. The value are assumed to be 1.0 kg CO_2eq/m² per year. Careful consideration in the choice of materials for the building are a key factor in order to minimize the CO_2 emissions from the building.

Wood is a natural and renewable material and by choosing a wood construction instead of other materials the CO_2 emissions is reduced, since a wood construction has a reduced embodied emission. The building is constructed out of massive wood in order to reduce the CO_2 emissions. The building elements such as roof, outer walls, internal floor slabs and pillars and beams are made of cross laminated timber and glue laminated wood. The insulation in the roof and outer walls are also made of wood, in form of wood fiber insulation.

The only construction element that is not made out of wood is the ground slab, since a concrete ground slab has a good resistance against moisture and also provides a stable foundation for the building. The ground slab is made of concrete but in order to reduce CO emissions a low carbon concrete was chosen. The CO_2 emissions for the materials of the building are assumed to be 4 kg CO_2eq/m² per year.

The values of the PV panels and the heat pump are recalculated from the report [37]. The values from that report are used in order to be as close as possible to the PV used for the project. For more detailed calculations, see the App. H.

The roof area of the building is covered with 550 m² PV panels in order to produce electricity for the building. The electricity production of the PV panels is 99 325 kWh per year. The electrical grid factor of 132 g/kWh was used in the calculations. The PV panels that was chosen has an efficiency of 22,5 %.

The result of the calculations are the following:

Categories	$kgCO_2/m^2/year$
Construction process	1
Building materials	4
Building operational	3,48772
Embodied emission PV	1,9
Embodied emission heat pump	0,48
PV compensation	-9,16846

Figure 83: Calculated values for each category in $kgCO_2/m^2/year$

When calculating all the impact and compensation the result gives 1,715465 $kgCO_2/m^2$/year. This means that the compensations from the PV are not enough to cover all the impact of the building. But the value 1,715465 $kgCO_2$/m2/year is compensating for almost all the impact of the building.

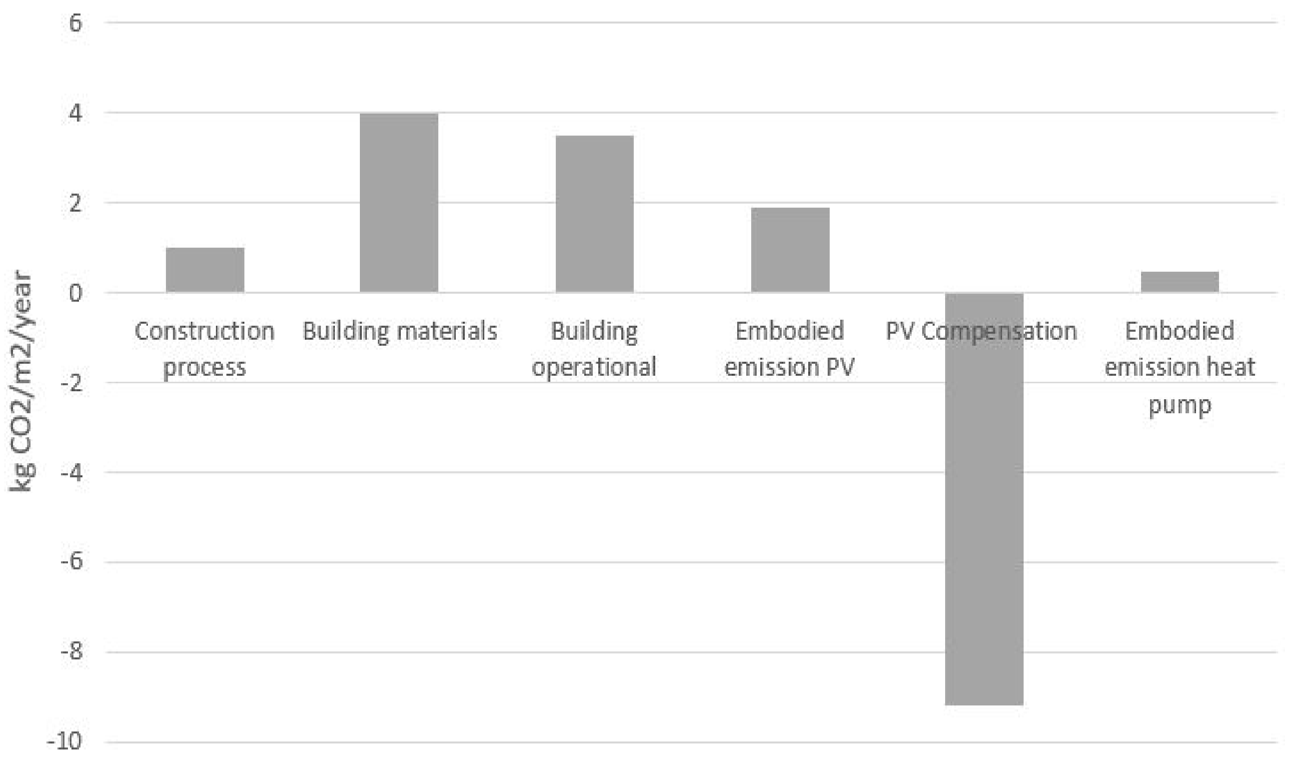


Figure 84: Life Cycle Assessment

| ABBREVIATIONS

ZEB	zero emission building
PV	photovoltaics
HP	heat pump
LCA	life cycle assessment
BIWT	building integrated wind turbines
BAWT	building augmented wind turbines
ABW	activity based workplace
DA	daylight autonomy
DF	daylight factor
SFP	specific fan power
DHW	domestic hot water
HVAC	heating, ventilation and air conditioning
STC	standard test conditions

| SOFTWARES

[1] Ecotect

[2] Meteonorm

[3] Polysun

[4] IDA ICE

[5] SIMIEN

[6] AutoCAD

[7] Adobe Creative Suite

[8] MindManager

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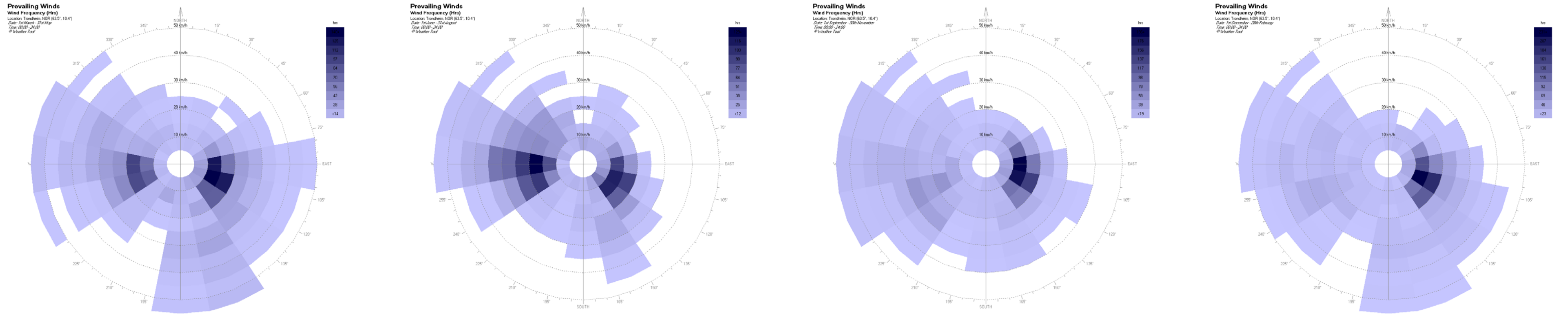
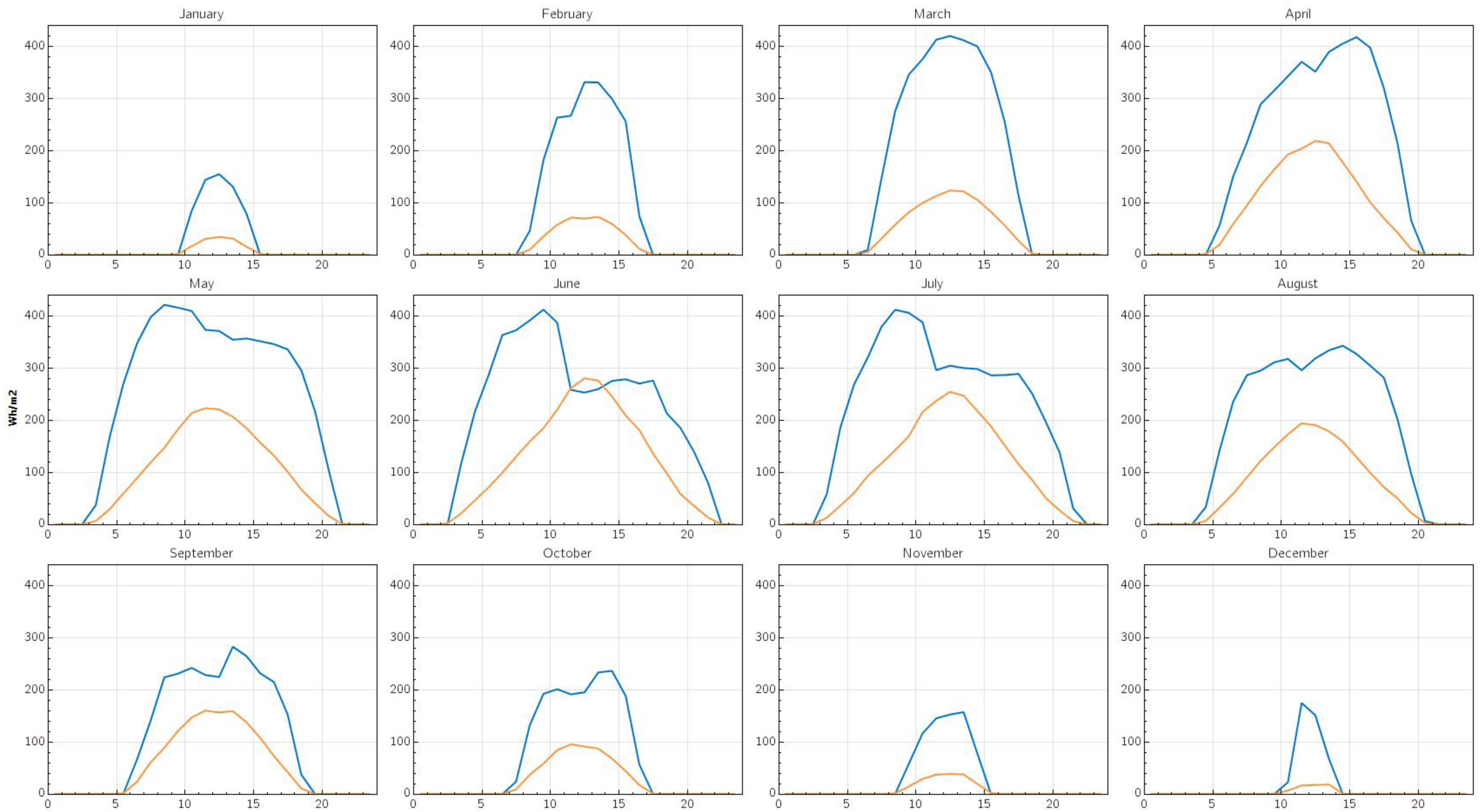
	Mean	Min	Max	Sum	Std Dev	Avg Daily Min	Avg Daily Max
All							
NOR_TrondheimSIMIENsolar.epw							
Trondheim_Vaernes-hour.epw							
Trondheim_NO-hour.epw							
Global Horizontal (Wh/m2)	101.264	0	808	887073	165.4154	0	309.3671
Direct Normal (Wh/m2)	123.7494	0	967	1084045	233.0876	0	403.6712
Diffuse (Wh/m2)	50.4298	0	381	441765	79.4916	0	153.137
Wind (m/s)	4.0871	0	16.2	35803	2.4739	1.9151	6.8145
Dry Temp ('C)	6.4926	-14.6	26.2	56875.4	7.2873	3.0792	9.8449
Wet Temp ('C)	1.681	-18.2	18.1	14725.5	6.5904	-0.3781	3.9847
Relative Humidity (%)	72.9877	32	100	639372	14.9265	55.589	91.0548
Pressure (mbar)	1012.4873	1005.6	1018.51	8869388.58	2.6514	1011.4292	1013.5142
WindDir (deg)	189.8372	0	360	1662974	99.5283	41.074	328.7397
Snow Depth (cm)	1.4668	0	19	12849	3.6164	1.2329	1.6548

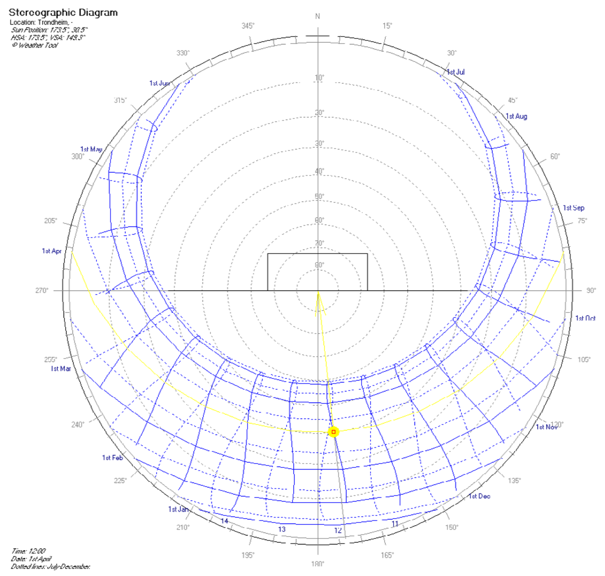
Climate statistics for the year 2005 (interpolated climate data for Trondheim) [Meteonorm]



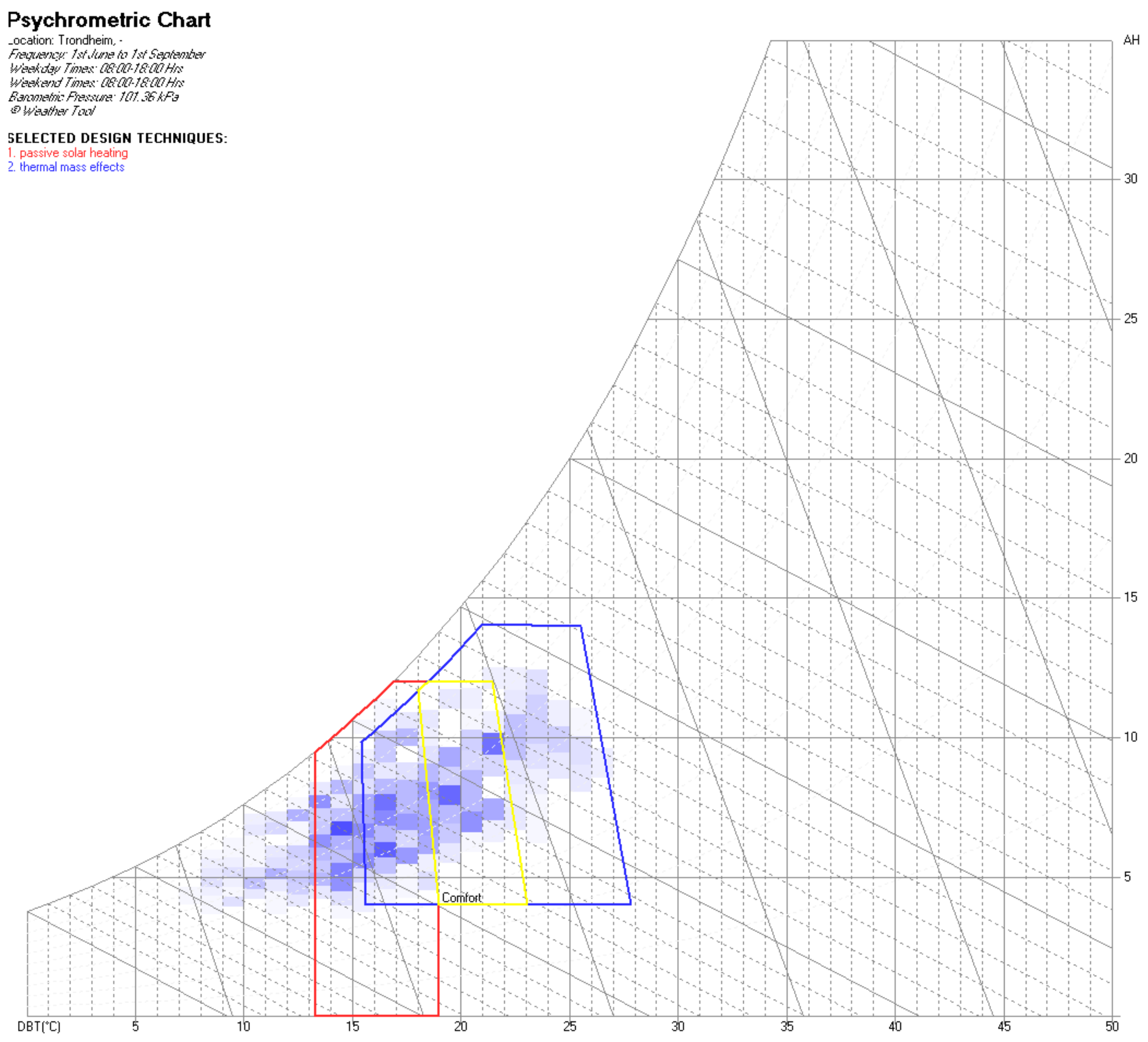
Monthly average temperature range [Ecotect]



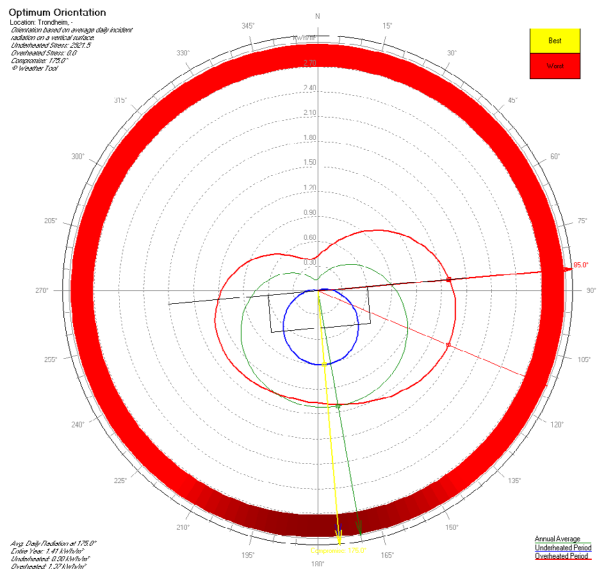
Monthly direct normal (blue) and diffuse solar irradiance (orange) profiles in Wh/m² (interpolated climate data for Trondheim) [Meteonorm]



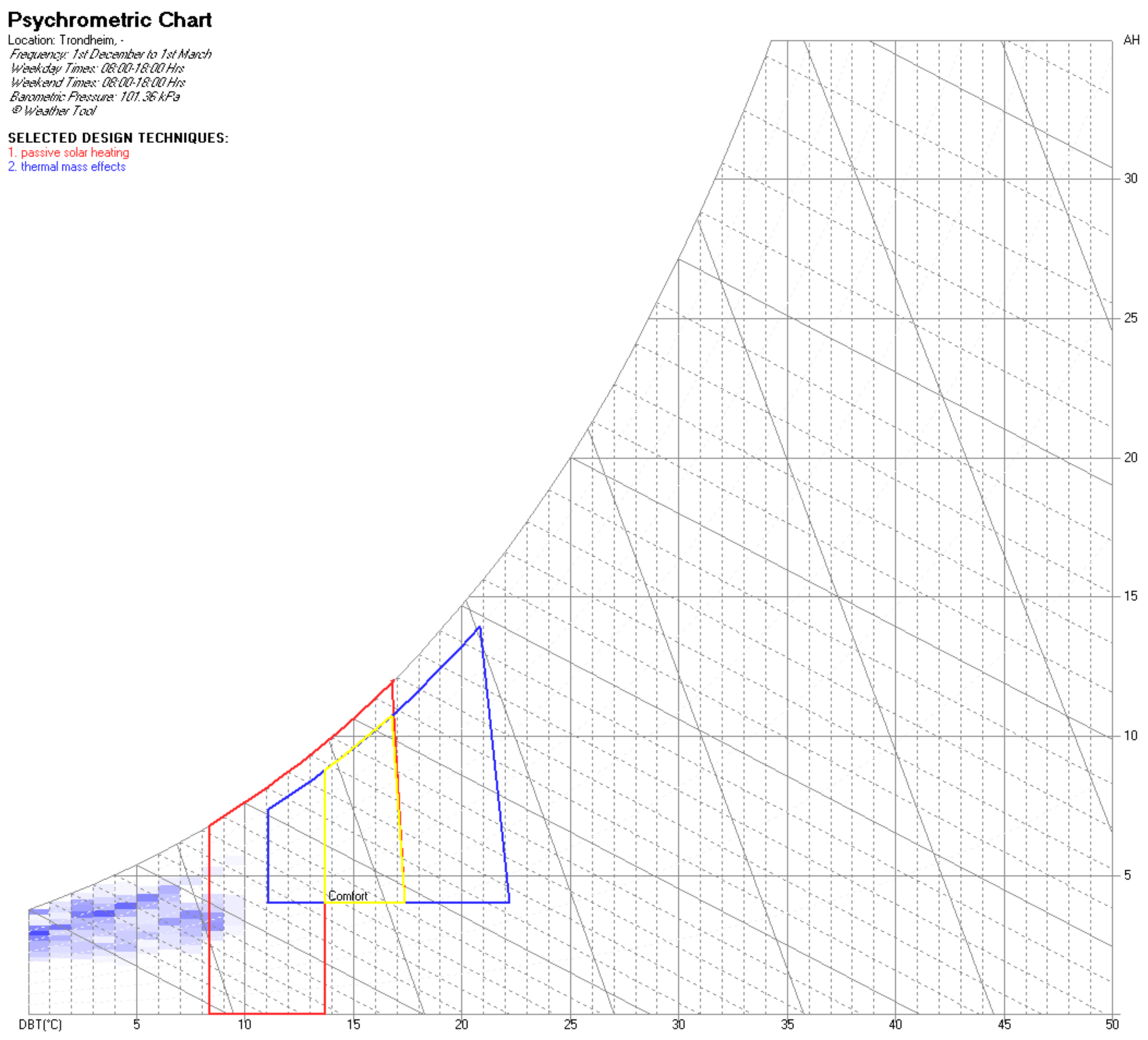
Sun path stereographic diagram [Ecotect]



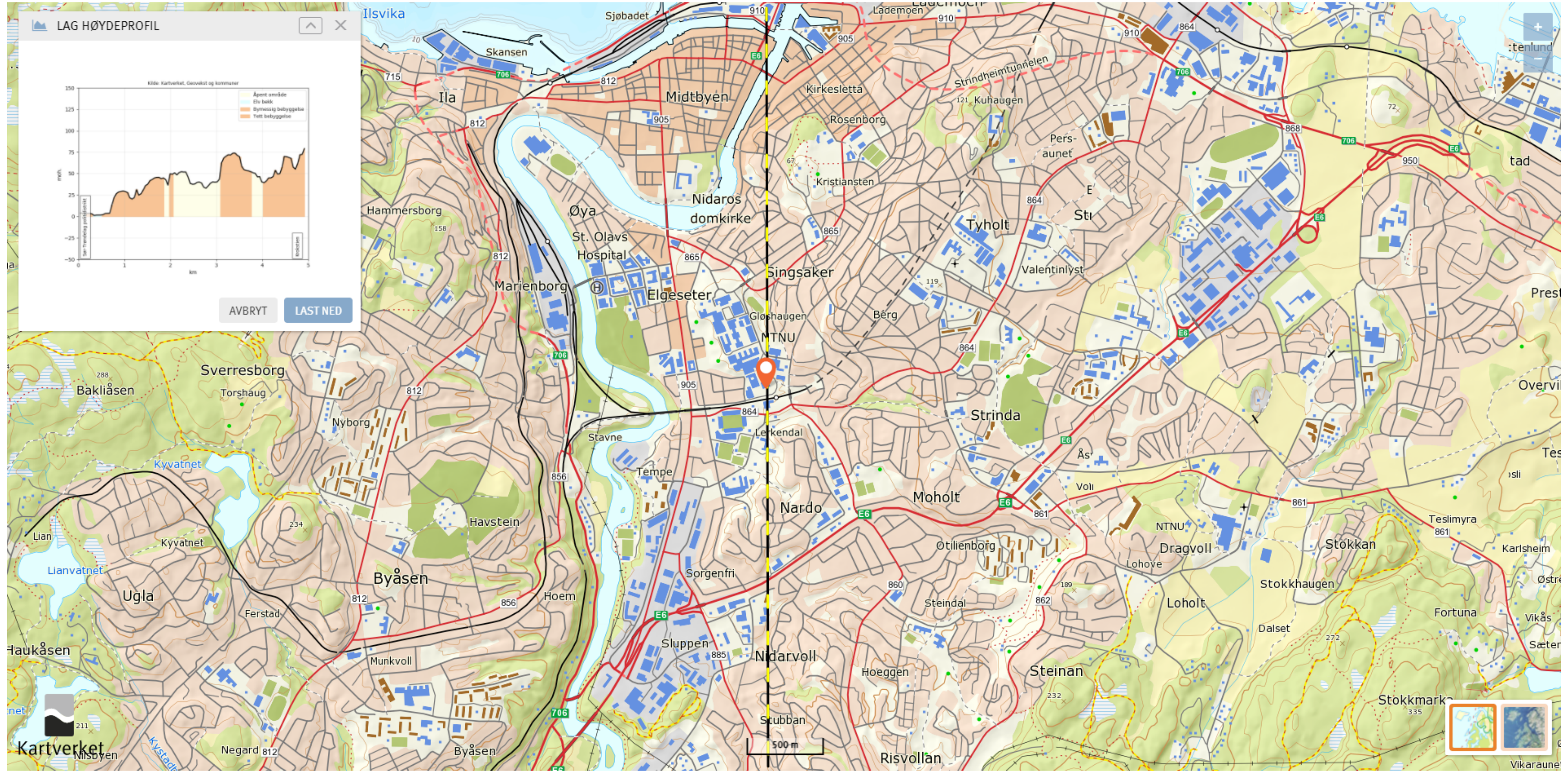
Influence of thermal mass effects and passive solar heating during the operating hours in Summer [Ecotect]



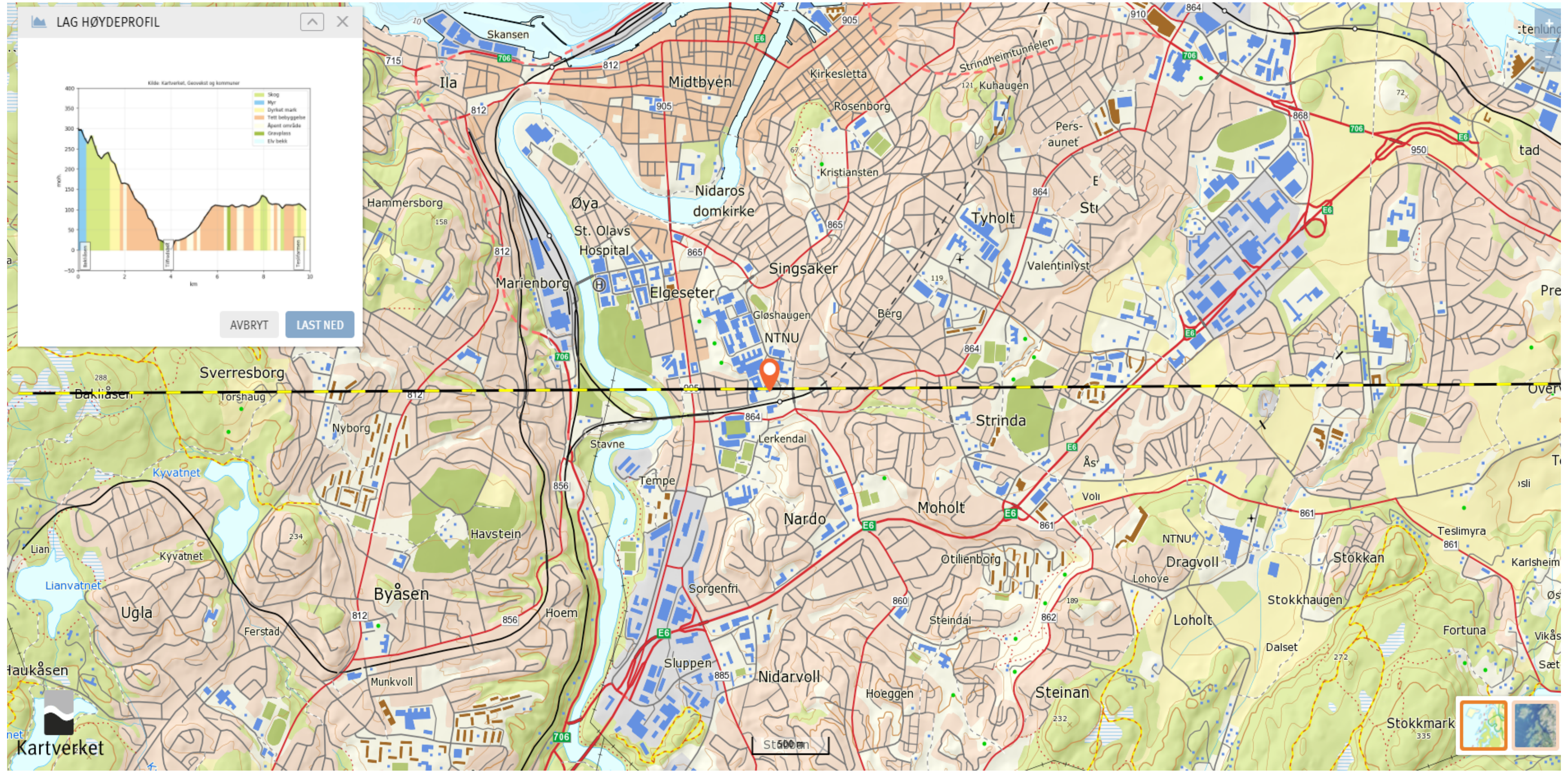
Optimum orientation base on average daily incident radiation on a vertical surface [Ecotect]



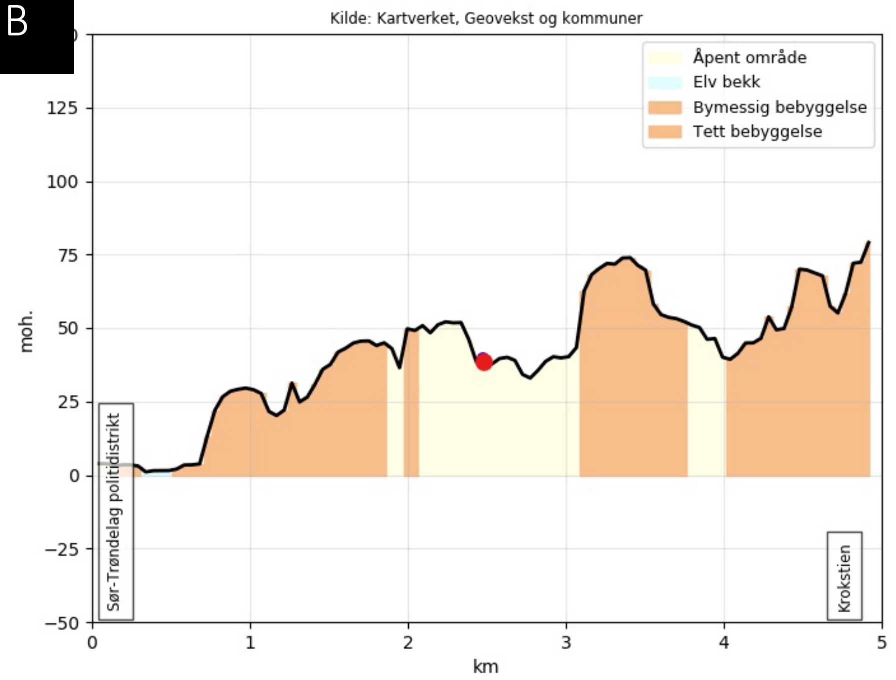
Influence of thermal mass effects and passive solar heating during the operating hours in Winter [Ecotect]



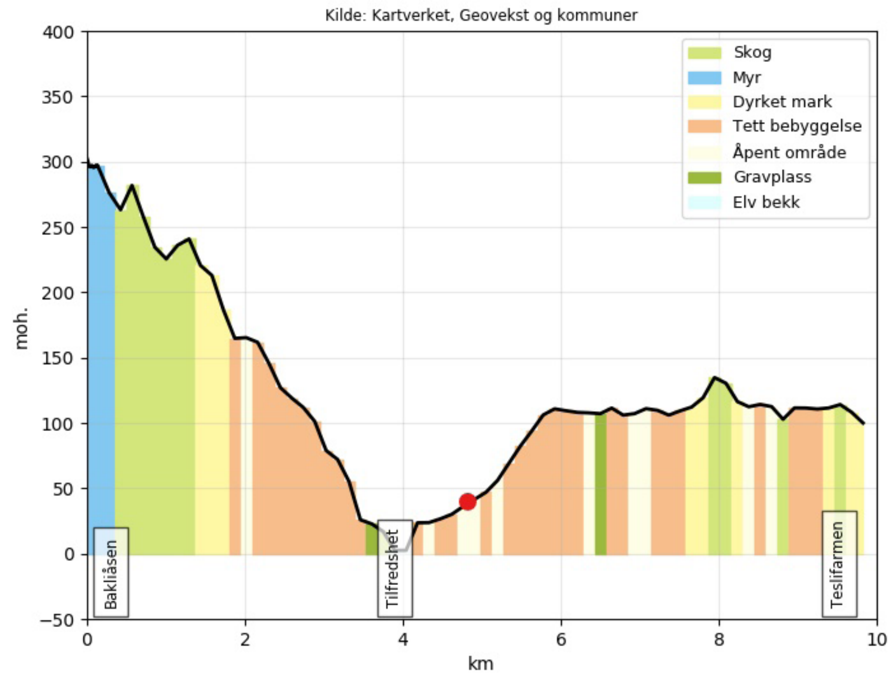
Height profile through the site in N-S direction [30]



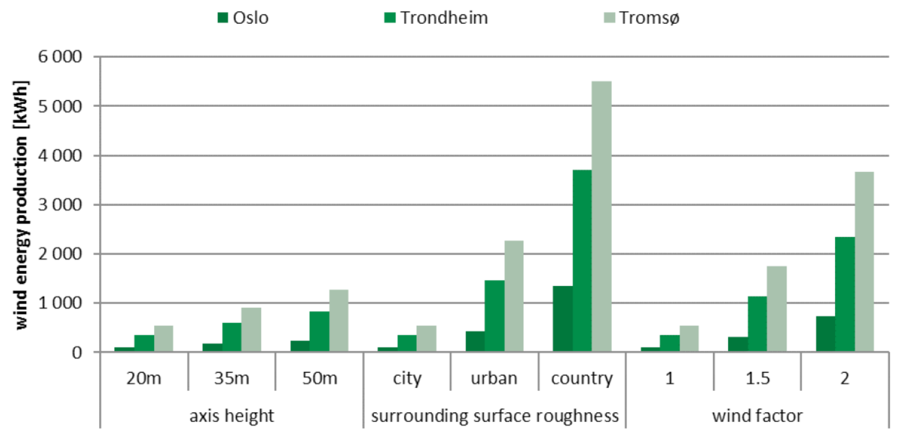
Height profile through the site in E-W direction [30]



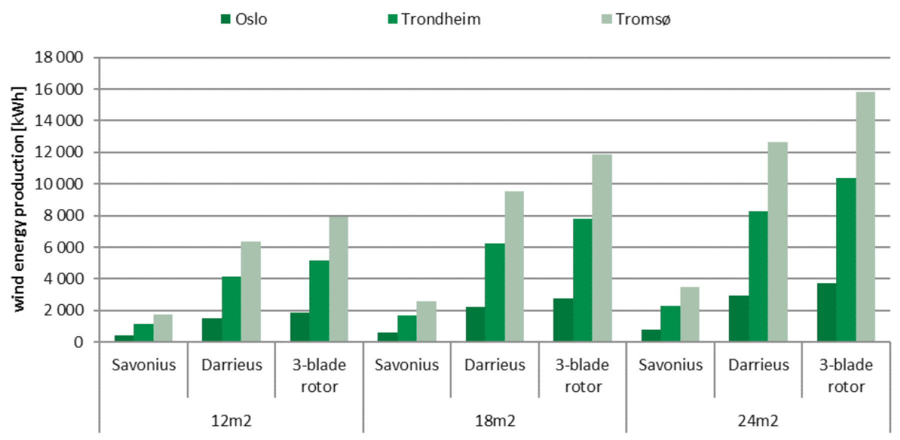
Height profile through the site in N-S direction [30]



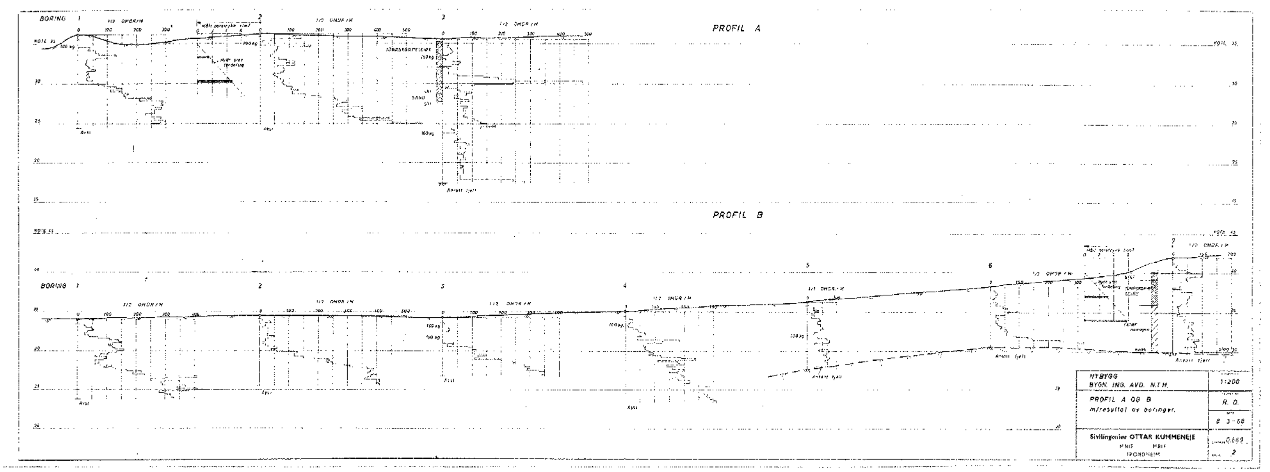
Height profile through the site in E-W direction [30]



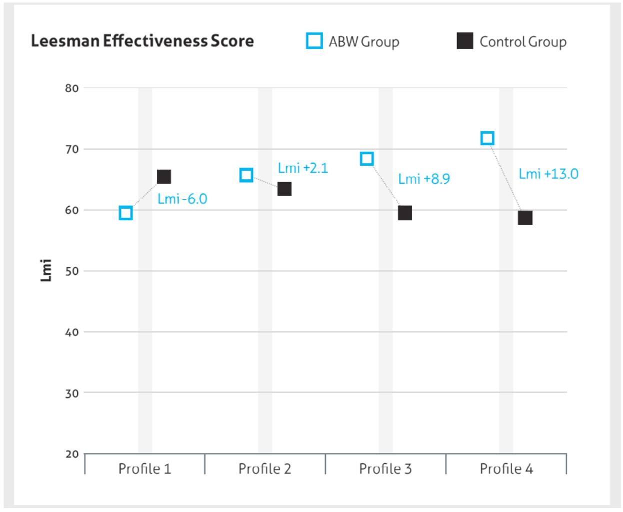
Influence of axis height, surrounding surface roughness and wind factor on wind energy production [31]



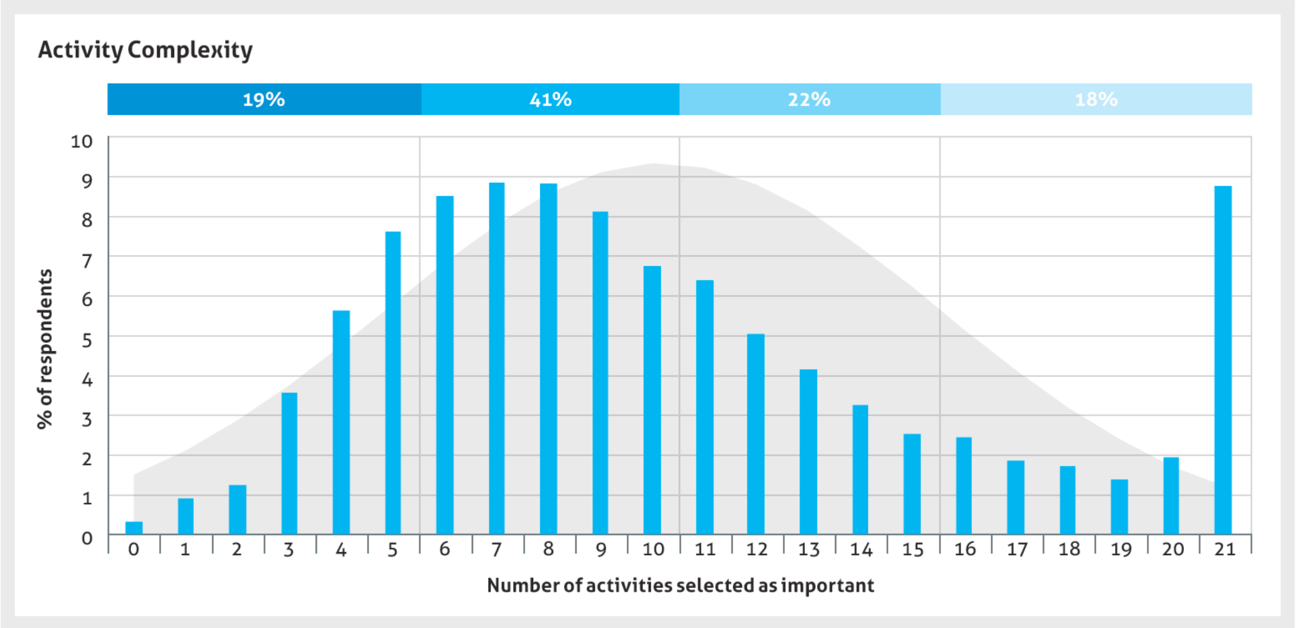
Influence of turbine type and area on wind energy production in Oslo, Trondheim and Tromsø [31]



Drilling profile



Comparison of Leesman's effectiveness score of ABW group to control group in ABW- Profile 1 the lowest mobility, Profile 4 the highest mobility [13]

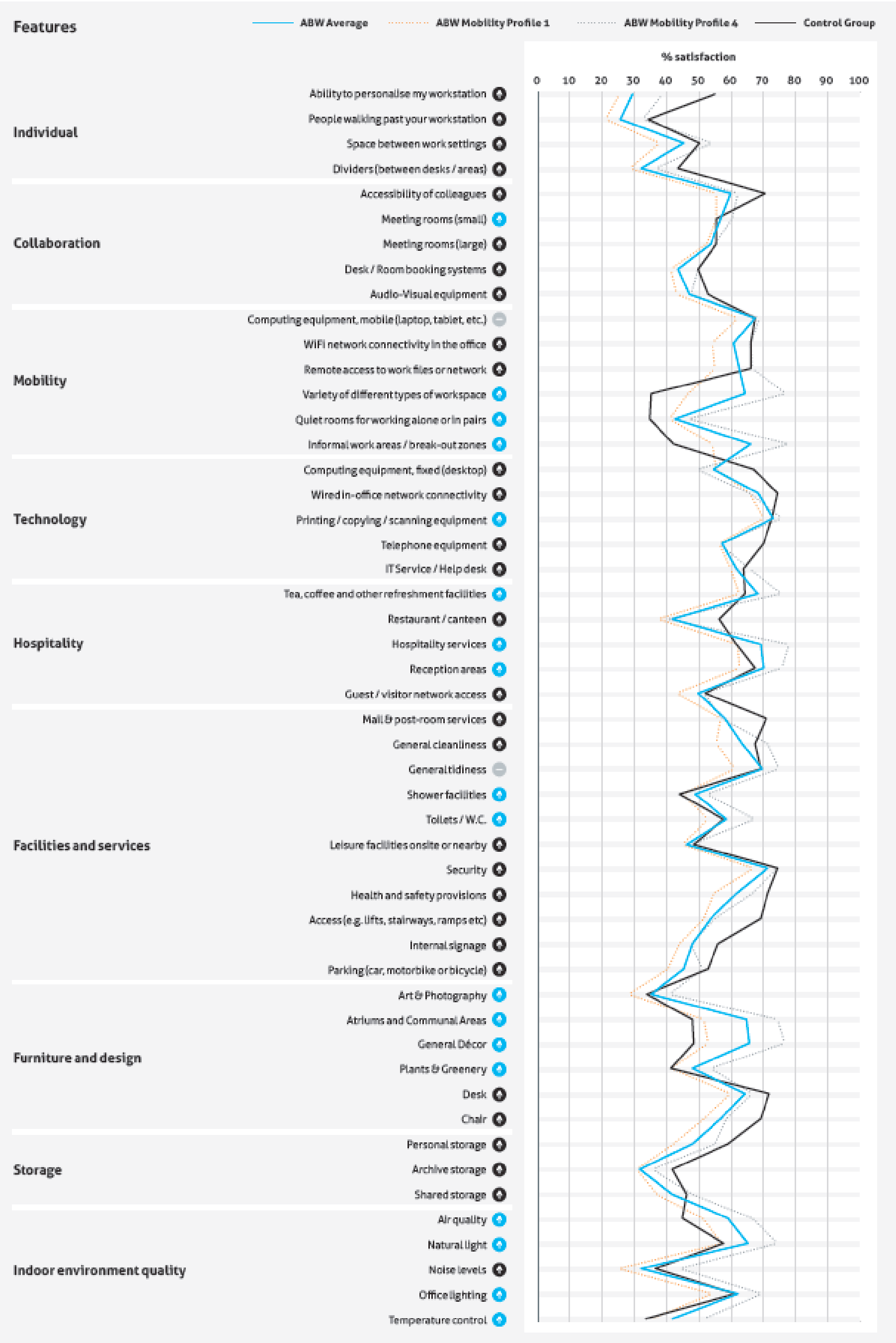


Preferred activity complexity in ABW [13]

Evaluation and rating of supported workplace activities and features in ABW [13]

Q3. Which activities do you feel are important in your work and how well is each supported?

		% Importance ABW	% Satisfaction ABW	% Importance Control group	% Satisfaction Control group	% Satisfaction Leesman+
1	Individual focused work, desk based	90.5	67.3	93.1	79.5	85.7
2	Planned meetings	80.8	77.6	76.2	80.4	82.7
3	Telephone conversations	73.0	59.3	73.0	65.6	77.8
4	Informal, un-planned meetings	67.0	72.5	61.6	63.9	81.8
5	Collaborating on focused work	58.9	74.5	57.5	74.1	86.4
6	Audio conferences	50.6	68.8	53.7	71.6	82.8
7	Relaxing / taking a break	49.1	76.8	53.6	65.5	80.9
8	Reading	49.0	56.6	50.4	62.4	75.1
9	Informal social interaction	48.7	84.7	47.2	75.6	87.4
10	Private conversations	43.5	54.9	46.4	51.7	63.6
11	Collaborating on creative work	43.4	73.1	40.5	64.0	78.9
12	Thinking / creative thinking	42.9	55.4	45.2	52.6	69.6
13	Business confidential discussions	42.3	56.7	43.3	57.8	68.8
14	Learning from others	41.5	76.8	43.4	78.6	84.9
15	Individual routine tasks	41.1	83.0	51.4	89.3	92.2
16	Video conferences	40.1	62.9	34.7	61.3	76.0
17	Hosting visitors, clients or customers	36.5	76.0	38.6	66.7	79.5
18	Larger group meetings or audiences	35.4	68.8	37.6	62.7	74.5
19	Individual focused work away from your desk	33.3	71.3	34.7	66.1	81.2
20	Spreading out paper or materials	29.7	45.8	37.3	65.0	65.7
21	Using technical / specialist equipment or materials	22.3	59.6	24.0	68.8	75.5



Q4. Which physical / service features do you consider to be an important part of an effective workspace and how satisfed are you with each?

		% Importance ABW	% Satisfaction ABW	% Importance Control group	% Satisfaction Control group	% Satisfaction Leesman+
1	Meeting rooms (small)	86.8	57.4	84.5	56.0	69.1
2	Desk	82.8	66.4	87.0	75.0	75.7
3	Chair	81.5	57.4	85.5	71.9	72.8
4	IT Service / Help desk	80.6	63.0	82.0	65.7	69.1
5	Tea, coffee and other refreshment facilities	79.0	71.0	82.4	66.0	78.3
6	Meeting rooms (large)	77.3	54.1	76.7	56.2	66.3
7	WiFi network connectivity in the office	77.0	62.1	75.1	68.2	64.1
8	General cleanliness	76.7	65.4	79.9	69.6	81.2
9	Temperature control	76.7	40.4	82.0	30.7	38.3
10	Noise levels	75.5	29.0	73.9	34.1	40.6
11	Personal storage	74.8	47.4	71.0	60.0	57.9
12	Toilets / W.C.	74.0	59.6	78.4	58.5	66.6
13	Natural light	71.8	67.3	74.2	58.6	73.4
14	General tidiness	71.4	72.4	73.3	71.8	82.5
15	Quiet rooms for working alone or in pairs	70.4	41.2	63.7	32.0	46.4
16	Air quality	69.9	60.0	73.5	43.7	56.2
17	Printing / copying / scanning equipment	69.5	76.4	75.8	76.1	78.4
18	Desk / Room booking systems	68.3	42.4	60.8	49.4	51.1
19	Computing equipment, mobile (laptop, tablet, etc.)	67.9	69.6	68.4	69.6	75.4
20	Restaurant / canteen	65.8	40.4	76.8	57.3	56.3
21	Office lighting	63.3	63.7	69.4	62.6	73.6
22	Access (e.g. lifts, stairways, ramps etc)	61.4	54.1	57.1	71.7	71.6
23	Accessibility of colleagues	60.8	61.0	56.1	73.3	76.4
24	Telephone equipment	58.7	58.3	67.7	72.8	78.0
25	Remote access to work files or network	55.6	64.3	60.1	68.3	66.9
26	General Décor	55.5	67.9	56.8	48.2	71.3
27	Informal work areas / break-out zones	53.2	68.5	57.0	40.7	69.2
28	Security	52.9	74.4	65.4	78.0	81.4
29	Ability to personalise my workstation	51.8	26.1	59.3	55.8	45.3
30	Plants & Greenery	49.6	47.3	53.6	39.6	47.3
31	Mail & post-room services	49.4	59.0	55.2	74.1	77.6
32	Wired in-office network connectivity	48.1	70.8	54.8	77.8	76.8
33	Hospitality services	47.3	72.0	42.1	63.0	68.9
34	People walking past your workstation	45.7	21.7	50.1	31.8	37.7
35	Variety of different types of workspace	45.6	66.2	37.5	32.6	61.0
36	Health and safety provisions	44.7	62.9	54.6	74.4	77.0
37	Space between work settings	44.5	44.6	51.2	49.9	58.0
38	Parking (car, motorbike or bicycle)	44.5	44.5	61.9	53.2	58.5
39	Leisure facilities onsite or nearby	43.3	45.3	48.8	47.7	50.9
40	Reception areas	42.3	72.8	47.9	69.9	81.3
41	Dividers (between desks / areas)	41.8	29.1	48.2	42.4	44.0
42	Atriums and Communal Areas	41.7	66.7	44.1	47.6	74.4
43	Audio-Visual equipment	38.1	46.5	40.6	52.8	63.7
44	Art & Photography	37.6	32.7	44.6	31.0	41.6
45	Shared storage	35.2	40.4	37.4	45.2	47.0
46	Internal signage	33.7	47.7	37.0	56.6	60.4
47	Guest / visitor network access	32.1	49.4	36.7	52.0	54.0
48	Shower facilities	32.1	48.5	37.4	42.8	46.4
49	Computing equipment, fixed (desktop)	30.2	55.0	45.1	69.3	74.8
50	Archive storage	24.9	28.6	30.3	40.5	39.2

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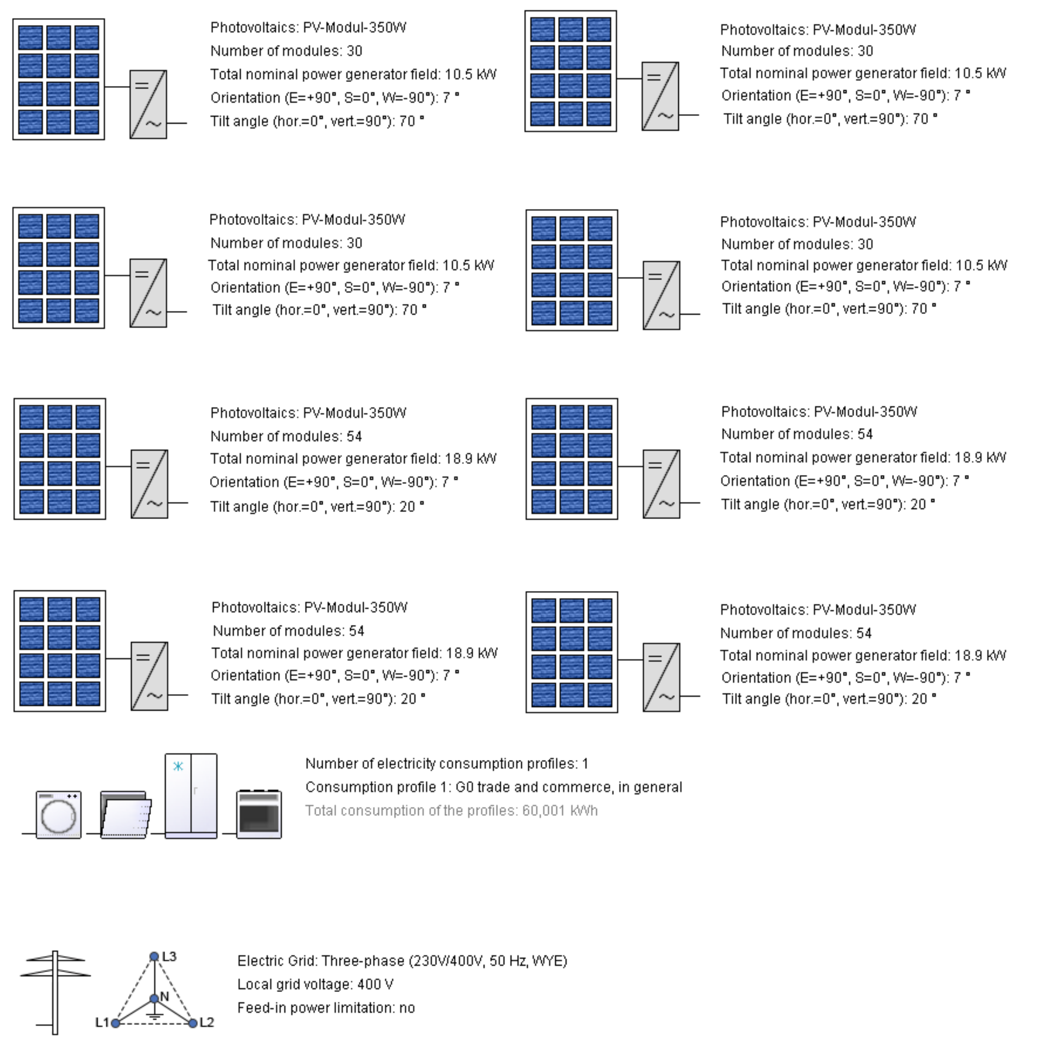
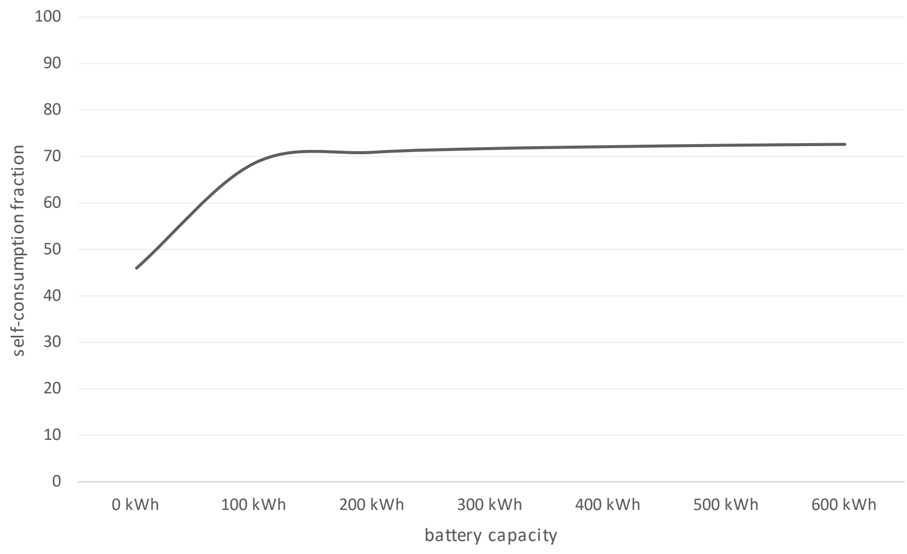
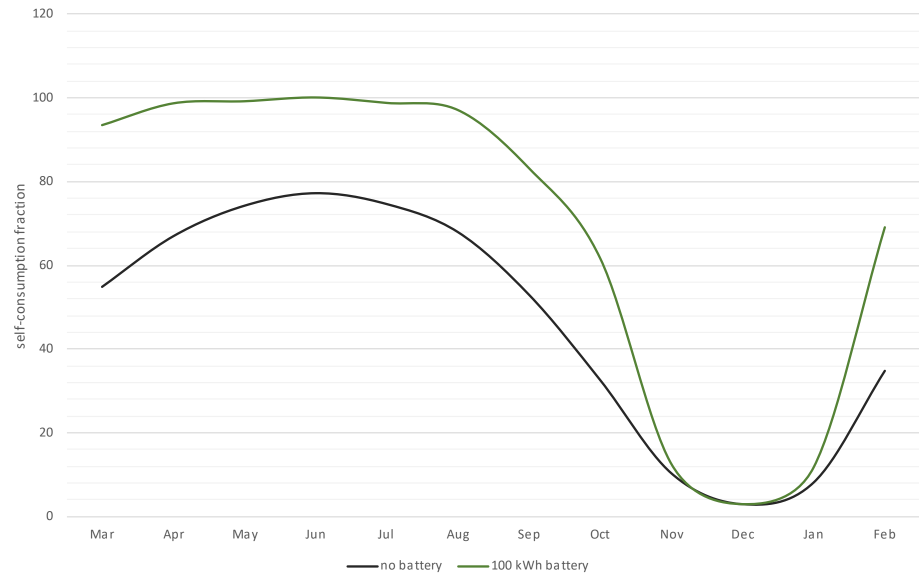


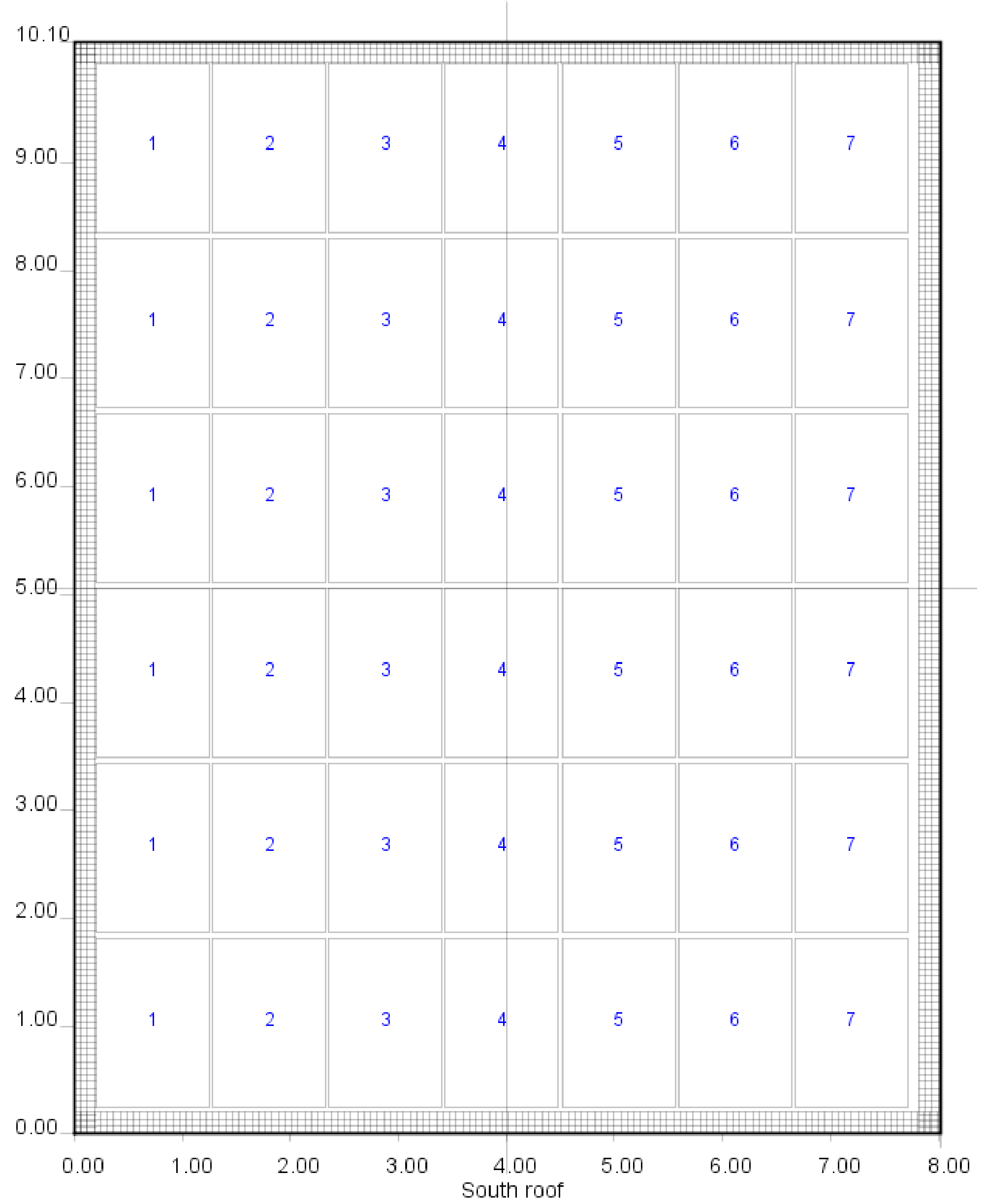
PV final design [Polysun]



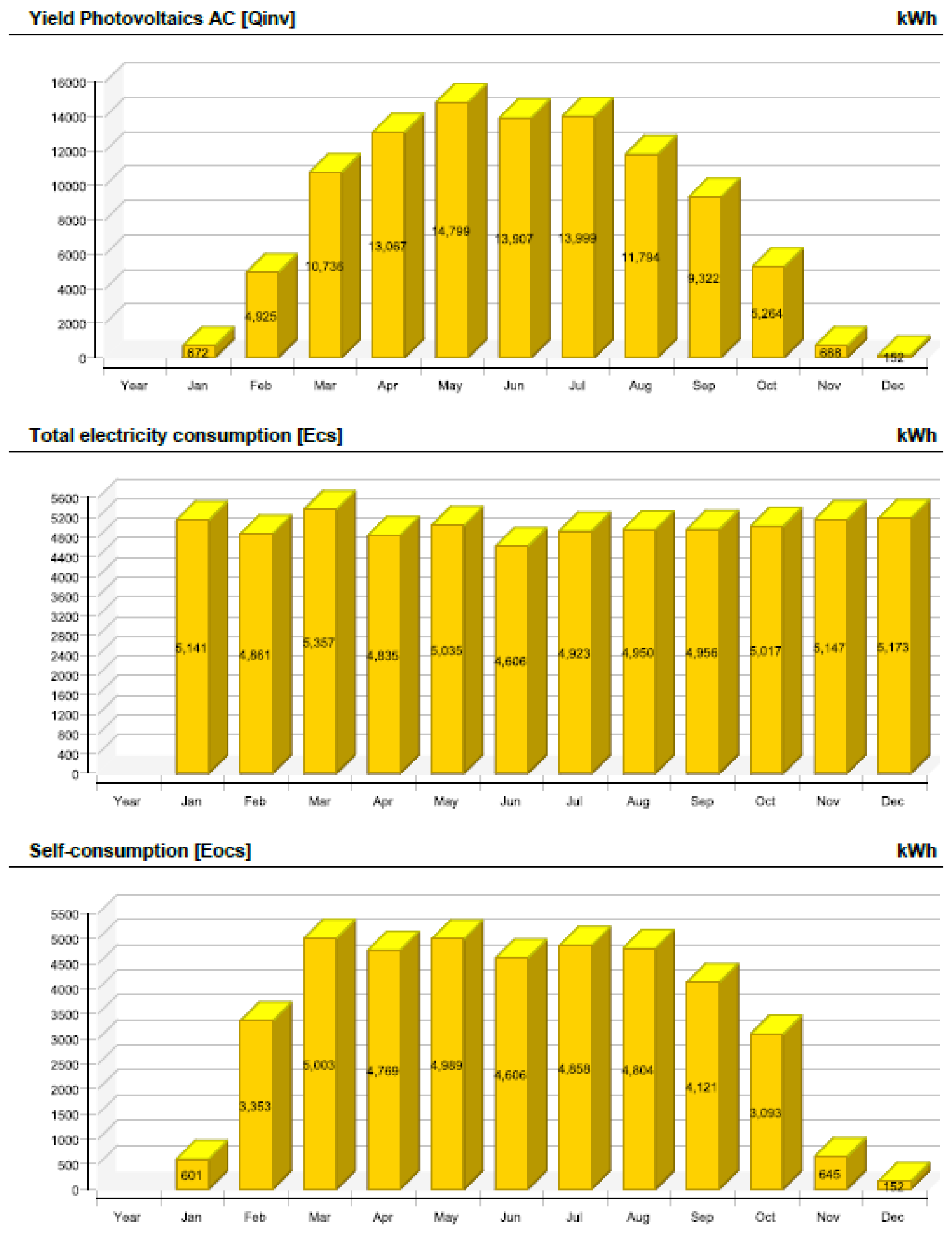
Optimization of battery capacity [Polysun]

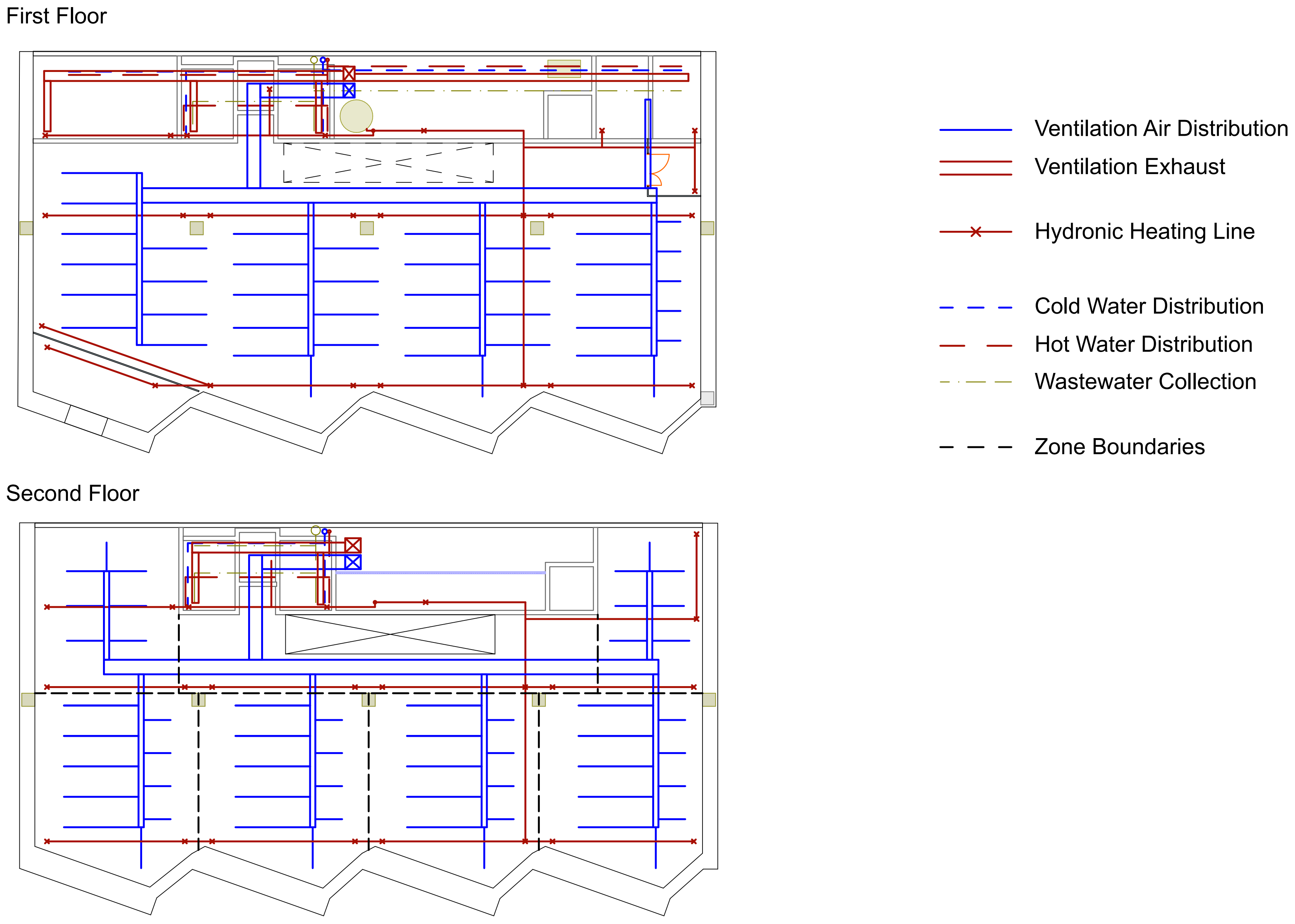


Monthly comparison of self-consumption fraction with and without a 100 kWh battery [Polysun]



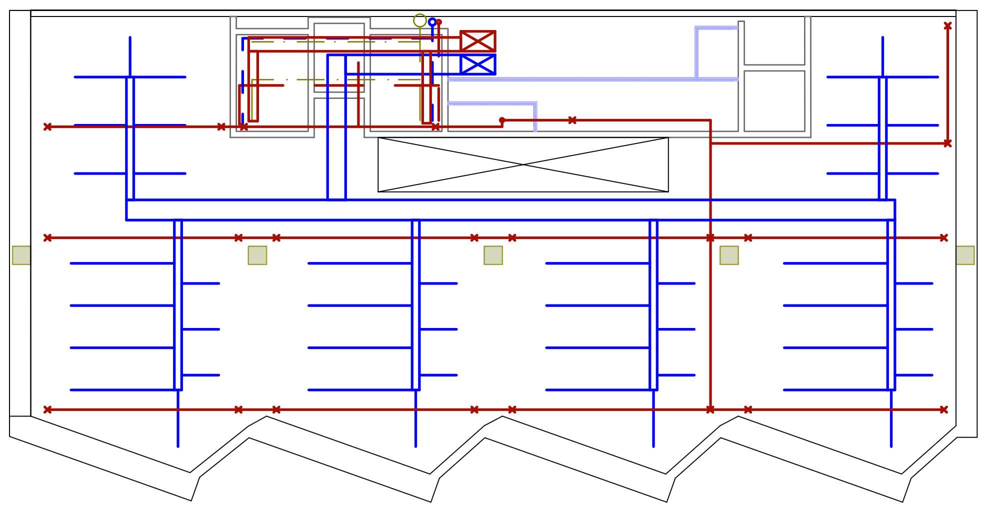
Inverter layout [Polysun]



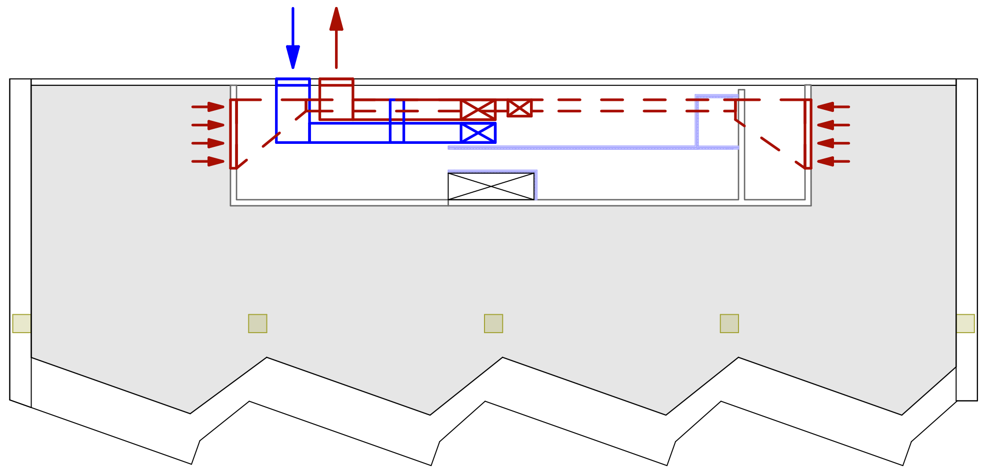


Mechanical systems distribution

Third Floor



Technical Room



Ventilation Air Distribution

Ventilation Exhaust

Hydronic Heating Line

Cold Water Distribution

Hot Water Distribution

Wastewater Collection

SIMIEN

Evaluering passivhus

Resultater av evalueringen	
Evaluering mot NS 3701	Beskrivelse
Varmetapsramme	Bygningen tilfredstiller kravet for varmetapstall
Energiytelse	Bygningen tilfredsstiller krav til energiytelse
Minstekrav	Bygningen tilfredsstiller minstekrav til enkeltkomponenter
Luftmengder ventilasjon	Luftmengdene tilfredsstiller minstekrav gitt i NS3701 (tabell A.2)
Samlet evaluering	Bygningen tilfredstiller alle krav til passivhus

Varmetapsbudsjett	
Beskrivelse	Verdi
Varmetapstall yttervegger	0,09
Varmetapstall tak	0,04
Varmetapstall gulv på grunn/mot det fri	0,03
Varmetapstall glass/vinduer/dører	0,15
Varmetapstall kuldebroer	0,03
Varmetapstall infiltrasjon	0,05
Totalt varmetapstall	0,39
Krav varmetapstall	0,40

Energiytelse		
Beskrivelse	Verdi	Krav
Netto oppvarmingsbehov	12,0 kWh/m²	24,3 kWh/m²
Netto kjølebehov	0,7 kWh/m²	6,6 kWh/m²
Gjennomsnittlig effektbehov belysning	4,5 W/m²	4,5 W/m²

Minstekrav enkeltkomponenter		
Beskrivelse	Verdi	Krav
U-verdi glass/vinduer/dører [W/m²K]	0,79	0,80
Normalisert kuldebroverdi [W/m²K]	0,03	0,03
Årsmidlere temperaturvirkningsgrad varmegjenvinner ventilasjon [%]	85	80
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,50	1,50
Lekkasjetall (lufttetthet ved 50 Pa trykkforskjell) [luftvekslinger pr time]	0,50	0,60

Documentation of the Passivhus requirements according to NS3701 [SIMIEN]

Energibudsjett (NS 3701)		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	12441 kWh	8,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	4653 kWh	3,3 kWh/m²
2 Varmtvann (tappevann)	7166 kWh	5,0 kWh/m²
3a Vifter	16418 kWh	11,5 kWh/m²
3b Pumper	1114 kWh	0,8 kWh/m²
4 Belysning	20155 kWh	14,1 kWh/m²
5 Teknisk utstyr	22398 kWh	15,7 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1048 kWh	0,7 kWh/m²
Totalt netto energibehov, sum 1-6	85393 kWh	59,7 kWh/m²

Levert energi til bygningen (NS 3701)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	0 kWh	0,0 kWh/m²
1b El. til varmepumpesystem	8189 kWh	5,7 kWh/m²
1c El. til solfangersystem	1776 kWh	1,2 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-34521 kWh	-24,1 kWh/m²
Totalt levert energi, sum 1-7	-24557 kWh	-17,2 kWh/m²
Solstrøm til eksport	-68420 kWh	-47,8 kWh/m²
Netto levert energi	-92977 kWh	-65,0 kWh/m²

Krav til energibehov belysning
Minst 60 % av installert effekt skal være underlagt dynamisk dagslys- og konstantlysstyring.
Alle rom skal ha dynamisk behovsstyring ved tilstedeværelse. Store rom skal ha minst en styringssone per 30 m2.
Energibehovet skal dokumenteres etter NS-EN 15193 basert på prosjektert eller installert effekt og styringssystemets innvirkning på energibehovet.
All belysning skal minst tilfredsstille kvalitetskravene for belysning gitt i NS-EN 12464-1.

Referanseinformasjon beregning	
Evaluering mot NS 3701	Beskrivelse
Beregning	Utført etter NS 3701:2012 med validert dynamisk timesberegning etter reglene i NS 3031:2007
Kommune, gårds- og bruksnummer	
Konstruksjon og plassering	
Tekniske installasjoner	
Soneinndeling	
Arealvurdering	

Dokumentasjon av sentrale inndata (1)

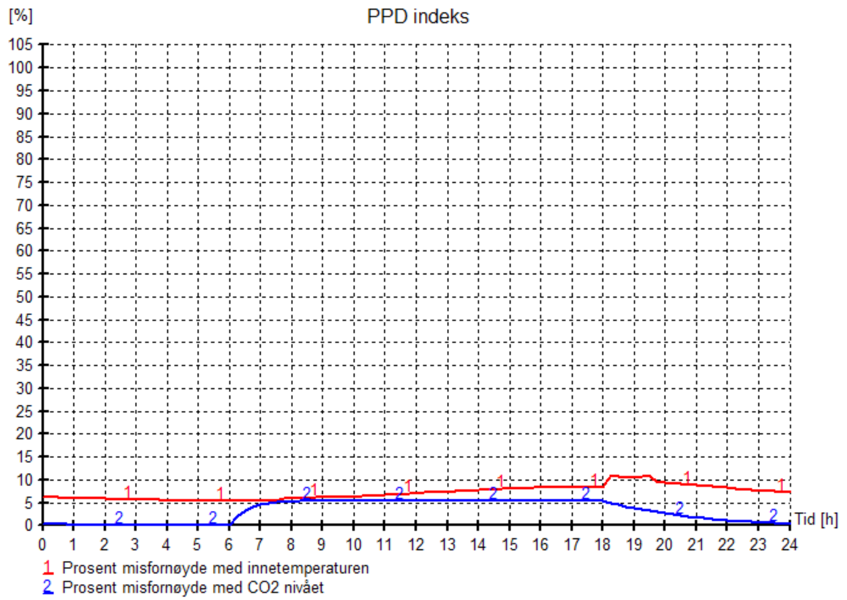
Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	957	
Areal tak [m²]:	574	
Areal gulv [m²]:	490	
Areal vinduer og ytterdører [m²]:	276	
Oppvarmet bruksareal (BRA) [m²]:	1430	
Oppvarmet luftvolum [m³]:	6050	
U-verdi yttervegger [W/m²K]	0,14	
U-verdi tak [W/m²K]	0,10	
U-verdi gulv [W/m²K]	0,08	
U-verdi vinduer og ytterdører [W/m²K]	0,79	
Areal vinduer og dører delt på bruksareal [%]	19,3	
Normalisert kuldebroverdi [W/m²K]:	0,03	
Normalisert varmekapasitet [Wh/m²K]	50	
Lekkasjetall (n50) [1/h]:	0,50	
Temperaturvirkningsgr. varmegjenvinner [%]:	85	

Dokumentasjon av sentrale inndata (2)

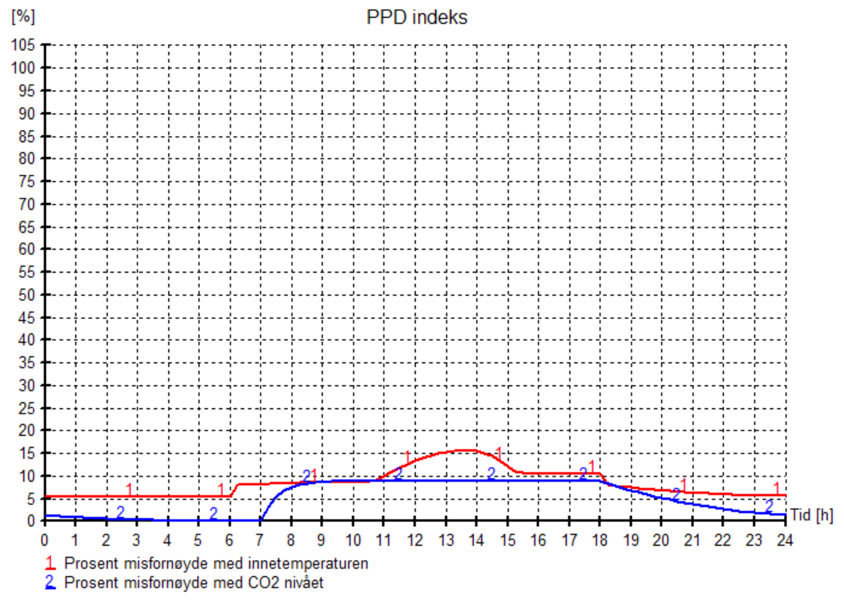
Beskrivelse	Verdi	Dokumentasjon
Estimert virkningsgrad gjenvinner justert for frostsikring [%]:	85,0	
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,50	
Luftmengde i driftstiden [m³/hm²]	7,00	
Luftmengde utenfor driftstiden [m³/hm²]	1,00	
Systemvirkningsgrad oppvarmingsanlegg:	3,13	
Installert effekt romoppv. og varmebatt. [W/m²]:	55	
Settpunkttemperatur for romoppvarming [°C]	20,0	
Systemeffektfaktor kjøling:	2,40	
Settpunkttemperatur for romkjøling [°C]	22,0	
Installert effekt romkjøling og kjølebatt. [W/m²]:	30	
Spesifikk pumpeeffekt romoppvarming [kW/(l/s)]:	0,50	
Spesifikk pumpeeffekt romkjøling [kW/(l/s)]:	0,00	
Spesifikk pumpeeffekt varmebatteri [kW/(l/s)]:	0,50	
Spesifikk pumpeeffekt kjølebatteri [kW/(l/s)]:	0,60	
Driftstid oppvarming (timer)	12,0	

Dokumentasjon av sentrale inndata (3)

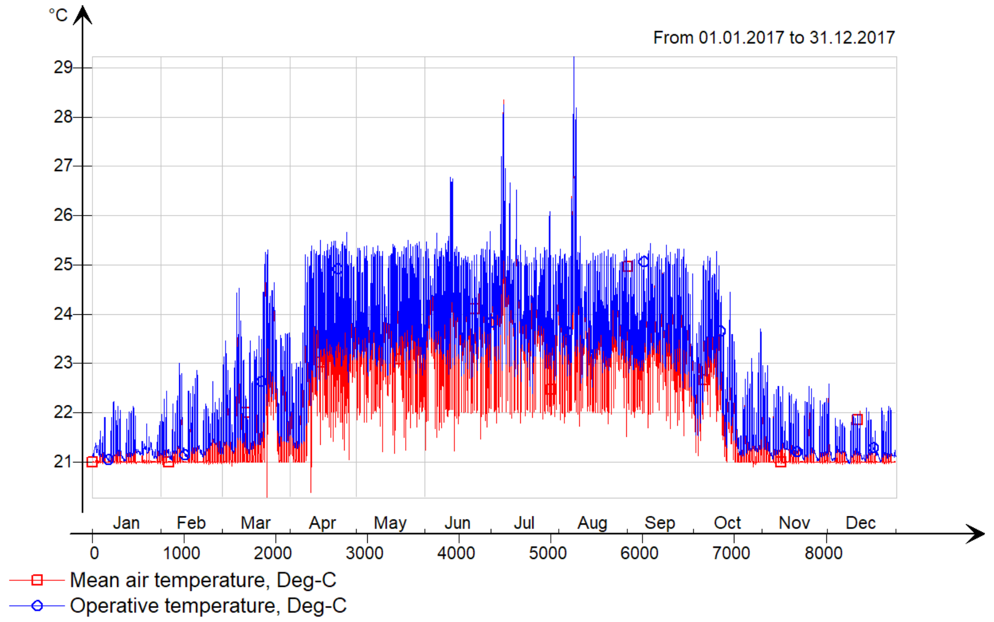
Beskrivelse	Verdi	Dokumentasjon
Driftstid kjøling (timer)	24,0	
Driftstid ventilasjon (timer)	12,0	
Driftstid belysning (timer)	12,0	
Driftstid utstyr (timer)	12,0	
Oppholdstid personer (timer)	12,0	
Effektbehov belysning i driftstiden [W/m²]	4,50	
Varmetilskudd belysning i driftstiden [W/m²]	4,50	
Effektbehov utstyr i driftstiden [W/m²]	5,00	
Varmetilskudd utstyr i driftstiden [W/m²]	5,00	
Effektbehov varmtvann på driftsdager [W/m²]	0,80	
Varmetilskudd varmtvann i driftstiden [W/m²]	0,00	
Varmetilskudd personer i oppholdstiden [W/m²]	6,00	
Total solfaktor for vindu og solskjerming:	0,72	
Gjennomsnittlig karmfaktor vinduer:	0,05	
Solskjermingsfaktor horisont/utspring (N/Ø/S/V):	1,00/1,00/1,00/1,00	



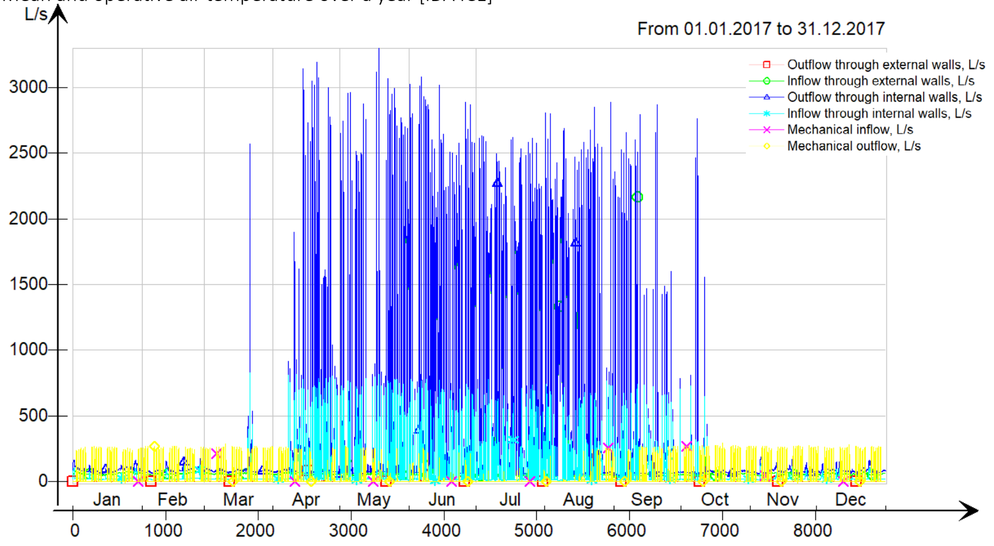
Predicted Percentage of Dissatisfied in summer [SIMIEN]



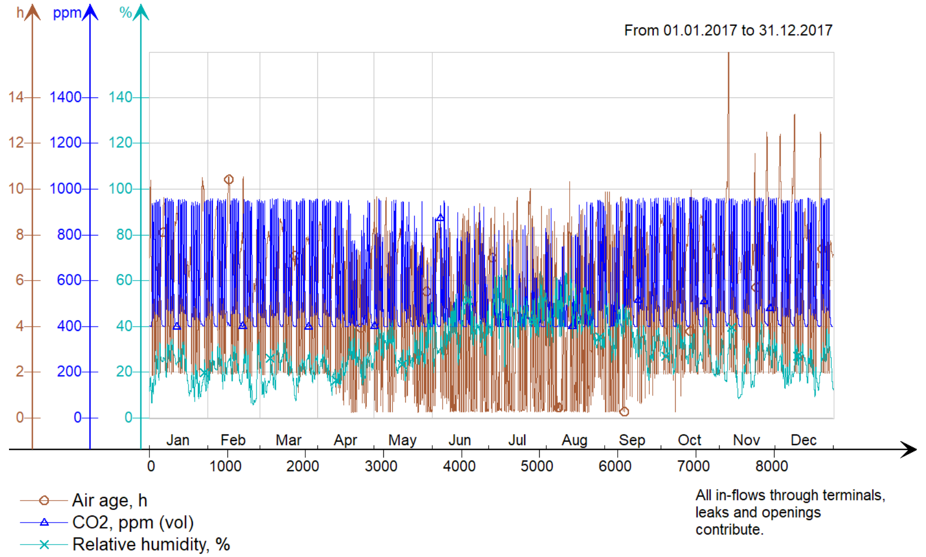
Predicted percentage of dissatisfied in winter [SIMIEN]



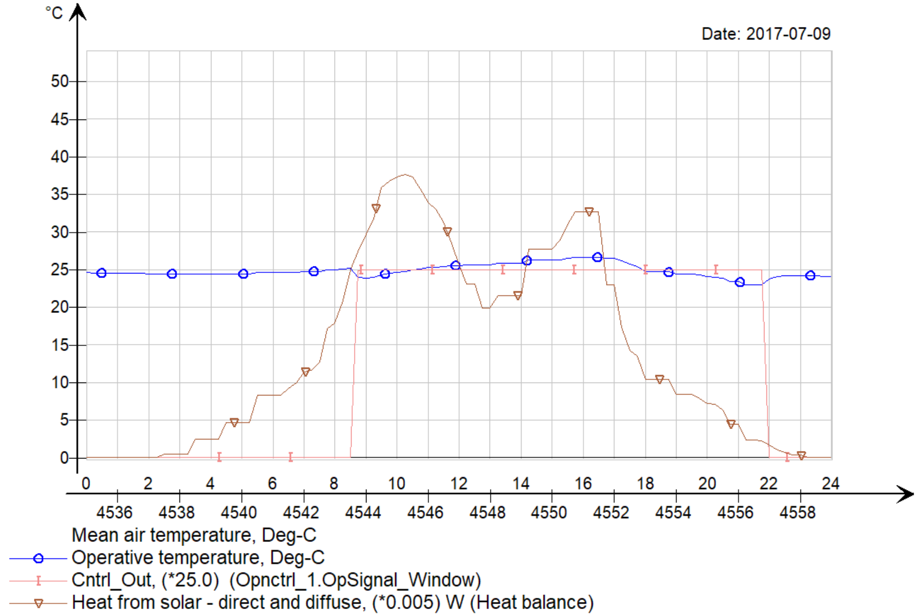
Mean and operative air temperature over a year [IDA ICE]



Air flow over a year [IDA ICE]



Indoor air quality over a year [IDA ICE]



Influence of window orientation and natural ventilation on indoor temperatures [IDA ICE]

Lifetime house	60	year	
Lifetime PV	30	year	
Lifttime heat pump	20	year	
Floor area	1430	m2	
PV area	550	m2	
PV embodid emission for 60 years	298,92	kg CO2 eq/m2	
PV embodid emission per year	4,982	kg CO2 eq	
PV el.production per year	99325	kWh/year	
PV el.production per year and m2 of the house	69,458	kwh/year per m2	
Heating demand	31095	kWh/year	
Electric grid factor	132	g CO2eq/kWh	
Eletricity demand	37784,2	kwh/yr	
Eletricity demand per m2	26,42252	kwh/yr	
Construction process emission	1	kg CO2eq/m2	
Material for the building	4	kg CO2eq/m2	
Calculations:			
Operational time for the building per year		3487,772	g CO2/m2/year
		3,487772	kg CO2/m2/year
PV embodied emission per year		1,916154	kg CO2eq/year
PV compensation		9168,462	g CO2eq/year
		9,168462	kg CO2eq/year
Compensation		-9,16846	kg CO2eq/year
Heat pump emissions		0,48	kg CO2eq/year
Result		1,715465	kg CO2eq/year

Renewable technology source	Number of case studies	References
1. Onshore wind	14	[10,21–23,118–129]
2. Offshore wind	5	[20,121–124]
3. Hydro-power	11	[10,14,34,35,122,123,128–130]
4. Marine technologies (Wave & tidal)	4	[36,37,131,132]
5. Geothermal	4	[10,46,123,129]
6. Photovoltaic	19	[10,47,51–54,59–61,122,123,128–130,133–138]
7. Solar thermal	6	[59–61,123]
8. Dedicated biomass	14	[62,65,66,105,123,129,139–142]
9. Waste treatment	4	[122,123,143,144]
10. Heat pumps	4	[97,99,100]
Total	85	

Overview of GHG emissions (gCO_{2eq}) of geothermal.

Study	gCO_{2eq}/kWh (Electricity)			Comments
	Mean	Min	Max	
[46]	53	39	78	For a 1.75 MW plant, extracting heat at different depth and efficiencies
[10]	15	11	26	Depends on lifetime and capacity factors
[123]	41			German estimates for hot dry rock system
[129]	18.9			

Overview of GHG emissions (gCO_{2eq}) of photovoltaic.

Study	gCO_{2eq}/kWh (electricity)			Comments
	Mean	Min	Max	
[10,47,51,52,54,145]	91.1	9.4	300	For c-Si systems
[51]	217			Only CO_2 emissions; based on 2.7 kWp generator
[53]		50	60	Only CO_2; current estimate
[53]		10	30	Only CO_2; future estimate
[10,47,53]	30.5	15.6	50	For a-Si systems
[122]		20	50	
[133]	88	75	116	UK estimates
[134]		22	49	Average estimates for US
[135]		20	55	Estimates for multi-, mono-Si, Ribbon, CdTe
[136]	38	21	45	
[10]	53	25	136	Rooftop 3 kW PV system (pc-Si) – base case. Depends on lifetime and capacity factors
[10]	43.9	20	111	Rooftop 3 kW PV system (pc-Si) – future case 1. Depends on lifetime and capacity factors
[10]	26	12	66	Rooftop 3 kW PV system (pc-Si) – future case 2. Depends on lifetime and capacity factors
[137]		31	67	Only C emission rate; based on very large scale generators
[130]	79	39	110	Based on LCA for small scale plants (3 kWp)
[123]	104			German estimates for a 3 kW pc-Si system
[138]		48	167	Estimates for pc-Si, CIS, CdTe
[128]	106	53	217	Australian estimates
[129]	49.2			

Overview of GHG emissions (gCO_{2eq}) from heat pumps.

Study	gCO_{2eq}/kWh (heat)			Comments
	Mean	Min	Max	
[100]	207	150	264	For ASHP using different efficiencies
[97]	276	138	276	ASHP. Lower values is for an electricity mix based on 80% contribution from renewables
[97]	189	90	189	GSHP and WSHP. Lower values is for an electricity mix based on 80% contribution from renewables
[99]		65	149	German estimates for GSHP for different electricity mix (national and regional)