Gabriela Menegat

THE BOXES: A ZERO-EMISSION INDUSTRIAL BUILDING

Master's thesis in Master of Science in Sustainable Architecture

Supervisors:
Niki Gaitani
Luca Finocchiaro

Trondheim, June 2021

MASTER'S THESIS

NTNU
Norwegian University of Sciency and Technology
Faculty of Design and Architecture
Department of Architecture and Technology

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ABSTRACT

The project is a zero-emission industrial building located in Malvik, Trøndelag. The building consists in a 1975m^2 space, divided in 1375m^2 for industrial area and 600m^2 for office area.

The design concept is functionality and logistics in the site, flexibility of design and balance between emissions.

The ambition level is a ZEB-OM, meaning that renewable energy should compensate for the emissions from the materials and operation of the building during a 60-year lifetime.

The design was developed by comparing different shapes to achieve the goal. The life cycle assessment (LCA) of the building was done to balance the embodies emissions. The structure system is made in massive wood, glulam and CLT.

Passive and active strategies were used to optimize the energy efficiency of the building. The renewable energy system design used photovoltaic panels to compensate for the emissions.

In total 1808.4m^2 of PV were installed in the roof and in the west, east and south fasade.

The embodied emissions considered the product manufacturing (A1-A3) and the replacement during the lifecycle (B4), resulting in 7.91 kgCO_{2eq}/m^2.yr. The operation emissions are 11.45 kgCO_{2eq}/m^2.yr.

The PVs procude energy enough to compensate for 17.39 kgCO_{2eq}/m^2.yr. The balance of emissions resulted in a plus of +1.96 kgCO_{2eq}/m^2.yr for a ZEB-OM. The renewable energy produced on site was not enough to achieve a ZEB-OM target. However, the system is suitable to achieve a ZEB-O goal.

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LIST OF ACRONYMS

BIPV	BUILDING-INTEGRATED PHOTOVOLTAICS
CLT	CROSS LAMINATED TIMBER
CO_2	CARBON DIOXIDE
CO_{2EQ}	CARBON DIOXIDE EQUIVALENT
DF	DAYLIGHT FACTOR
EPD	ENVIRONMENTAL PRODUCT DECLARATION
EPS	EXPANDED POLYSTYRENE
GAAS	GREEN ADVISERS AS
GHG	GREENHOUSE GAS
KW	KILOWATT
KWH	KILLOWATT-HOUR
LCA	LIFE CYCLE ASSESSMENT
PV	PHOTOVOLTAIC
U-VALUE	THERMAL TRANSMITTANCE
ZEB	ZERO EMISSION BUILDING
ZEB-O	ZERO EMISSION BUILDING IN OPERATION
ZEB-OM	ZERO EMISSION BUILDING IN OPERATION AND MATERIALS

CHAPTER I:

INTRODUCTION

INTRODUCTION

BACKGROUND

The construction sector is responsible for a considerable contribution of greenhouse gases (GHG) emissions into the atmosphere. According to the United Environmental Programe (UNEP), in 2019 the building industry related to construction and operation was responsible for 38% of the emissions. There is a worldwide interest in reducing the the negative impact of the sector. The European Comission have as target for 2030 reduce in GHG emissions with 40%. Another goal is to increase the shares of renewable energy with 32% and improve the energy efficiency with 32.5%.

Norway is facing a new phase in building industry, by developing research about sustainable construction. New concepts, as Zero Emission Buildings (ZEB) are being introduced in the sector and impacting construction techniques and strategies to enhence the building energy efficiency. The Powerhouse movement is taking place in the past decade, showing possibilities to build a building that generates more energy that it consumes.

In the past 3 years, 4000 new industrial facilities were built in Norway (Statistisk sentralbyrå, 2021). Many existing industrial buildings are fast becoming obsolete due to the economical and political changes in trading, as well as technology revolution. The industrial revolution is coming faster and new technologies developed constantly demand a change in the building system. As the way that the factories are changing, the physical space around it should adapt to meet the market's need.

Industrial buildings usually have a high energy demand, mainly related to operation of machinery and systems. It makes it more challenging to achieve a ZEB goal then residencial and office buildings.

A sustainable scenario in the building industry has to embrace all the sectors. There is potential to reduce the GHG emissions by changing the decision drivers to focus on sustainable and local producs, as well as implementation of strategies in buildings. Industrial buildings have a high energy demand. New solutions can be studied to reduce its negative impact in the environment.

This project is located in Malvik municipality, where there is a need for a commercial building with a storage room with 1975m². The warehouse/office has two production rooms that will be working independently. The office space is co-working. Offices are going to be used for the two different companies, sharing the common areas and meeting rooms.

The development of new practices toward the sustainable construction includes the analysis of the embodied emissions from materials. The life cycle assessment (LCA) is way to study the impact of materials in the project. The environmental analysis is a important point for this project and act as a decision driver when comes to materials.

This project was developed in cooperation with the company Green Advisers AS (GAAS), in which have been using the wood element system for 10 years. The company focus in a sustainable construction of passive houses, mainly commercial buildings. So far the company has not worked with renewable energy. However, recently there are more speculation from clients to have energy generation on site. The construction system used by GAAS is based on the use of glulam structure for beams and columns, and pre fabricated wall and roof elements placed in between the structure.

SCOPE

The scope of this project is to optimize the design of an industrial building to reach a ZEB-OM or ZEB-O target.

INTRODUCTION

The optimization is done by comparing different shapes and materials to check the best options available for the project, also meeting the client's expectations. The concerns related by the investor is to make a factory building that should be adaptable according to change of activity.

The idea of flexibility is that the internal area can be changed according to the economy, and in the future, the building can hold more companies, or even be hold by just one. This possibility of changing the internal layout is a request from the client.

The level target is ZEB-OM or ZEB-O. In the ZEB-OM level, the building should generate renewable energy enough to compensate the embodied emissions related to materials, replacement and the operation. This project is considering the emissions related to the material fabrication (A1-A3), excluding the transportation to the site and other machinery necessary in the construction phase. The operational lifetime of the building is considered to be 60 years.

The level ZEB-O considers only the emissions related to the operation of the building, not taking into account the materials.

The project uses passive and active strategies to reduce the energy demand of the building and increase its efficiency. The emissions are being compensated with the renewable energy generation by photovoltaic (PV) panels.

METHODOLOGY

The first step of this project was to understand the client need. A meeting with GAAS was made to understand the concerns related to the project and the client's expectations.

Further, a study about the area and surroundings were made. For the design process, since the beginning, it was important to understand about the construction system used by the company and its limitations. Guidance with the professors took place every second week to keep the work progress.

This project considered the integrated energy design (IED), which runs simulations and consider the energy generation into the process at an early stage. Since the early phase, simulations were done in order to make decisions about the building shape. The equilibrium between a good architectural space, flexibility and a low energy building was the goal by running the simulations.

The simulations performed in this project used the software Rhinocerus and SIMIEN. Rhinocerus is a 3D computer graphics and computer-aided design application, that is compatible with the plugins for programing and visualization grasshopper and DIVA. SIMIEN a Norwergian software for energy performance calculation in buildings.

The project was developed in the main phases:

1. Identification of the client needs. The early stage it was possible to have an idea of the client needs and expectations for the building.
2. Study of the building system. The elements system used by the company, the common sized used and how it impacts the design.
3. Understanding of the area and surroundings. The terrain mesh was modeled in Rhinocerus to check the shading analysis. A climate analysis was also performed.
4. Study of the building footprint in the site and logistics. Sketches were done in this phase to better understand the size of the building need and how it works in the building size.
5. Comparison between design concepts to choose the most suitable one. Three shapes and brainstorming of roof ideas were tried out to test the site limitations and the building size. The drawings were mainly sketched by hand, and later modeled in Rhinocerus for radiation analysis.

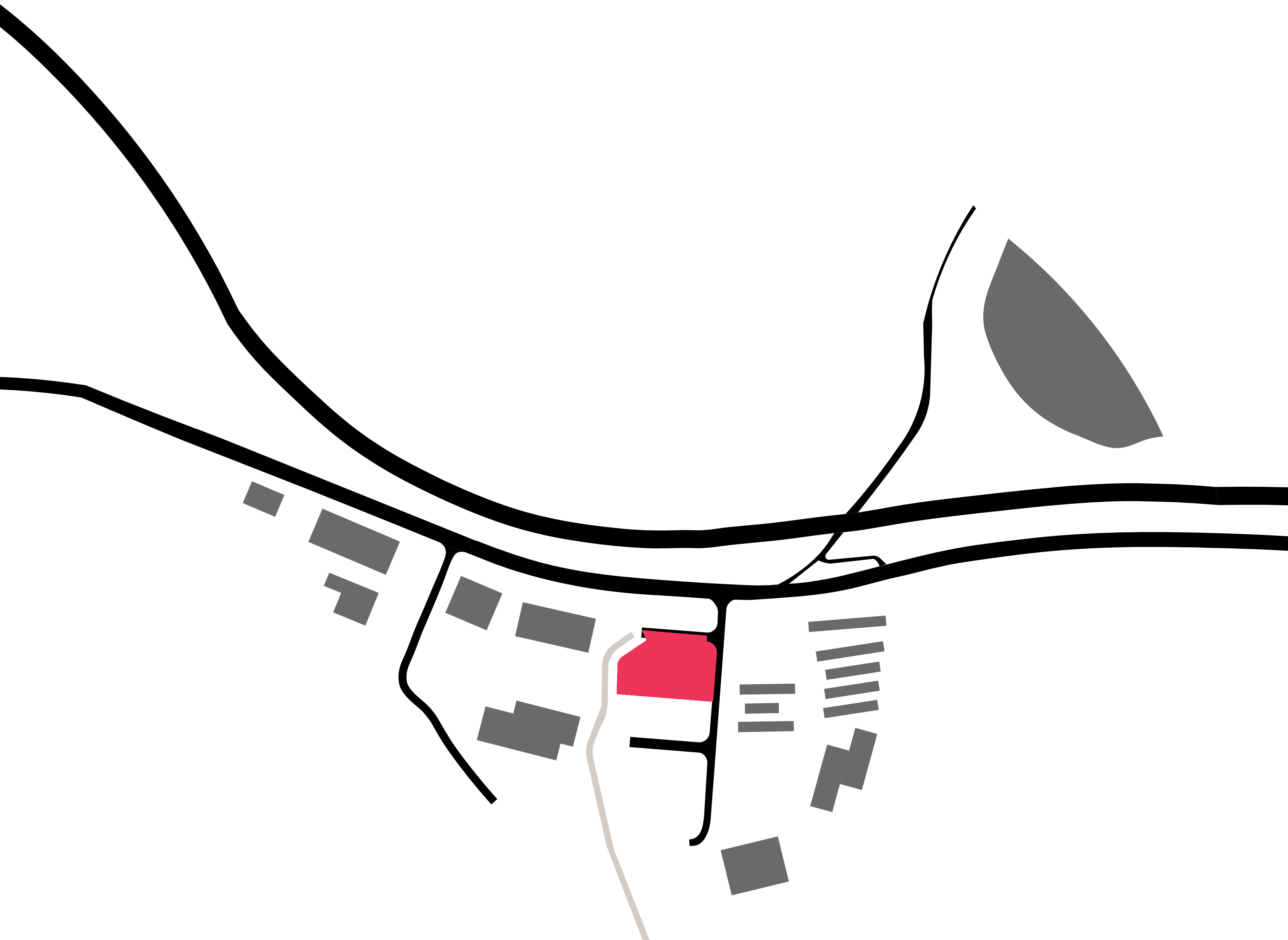
INTRODUCTION

In this stage SIMIEN simulations were performed for different shapes to analyse the energy performance and a simplified LCA to have an idea of the ZEB balance.

6. Deeper analysis of the chosen concept design to optimize the floor plan and roof shape. In this stage six shapes were compared regarding energy demand, energy production and space quality.
7. Development of floor plans of the chosen shape. The shape was modeled in ArchiCAD.
8. Integration of passive and active strategies. Many passive and active strategies were considered in this phase. SIMIEN was mainly used to check out the energy performance of the strategies. Daylight simulations were done using Rhinocerus – DIVA.
9. The building Life Cycle Assessment was developed to make decisions about the materials. The SINTEF Zeb Tool was used to check the emission balance. Most of the materials had EPD (Environmental Product Declaration) in Norway. Some materials were considered for neighbours' countries.
10. The detail drawings of the building were finalized in ArchiCAD. The 3D model was completed afterwards.
11. The report was done using inDesign.

CHAPTER II:

LOCATION AND CONTEXT



LOCATION AND CONTEXT

Malvik is a strategic town, located between Stjørdal airport and Trondheim, the third largest city in Norway. The current expansion plan done by Malvik municipality for 2050 divide the area in residential and commercial areas. The site is located in a commercial area to be expandable along the main highway through Norway.

Nowadays, there are 16 existing industrial buildings nearby, with approximately 10m of height.

The nearest point of the residential area is 700m away from the site. The site can be accessible by walking distance from a nearby residential area, or by bike or bus. From Malvik shopping center, the distance is 15 minutes walking. There are two bus stops nearby, approximately 8 minutes walking distance.

The site is accessed by the road E6. The main activity for access is about the trucks, that will be delivering materials, in which are coming from E6 and entering in the site.

The site is quite small for the area needed, having 4024.9m^2. It is surrounded by a local road against north and west. In the south there is a land, without any construction so far. On the west side there is a small stream, around 5 meters wide.

There is a hill surrounding the building on the south side. Shading simulations were performed to check the influence of the surroundings in the site. Figure 01 shows shading simulation using Rhinocerus plug in grashopper.

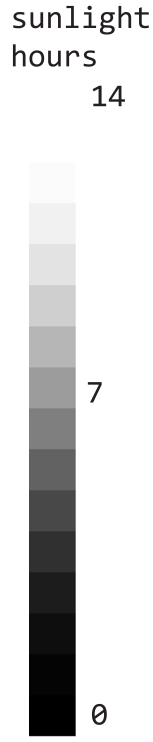
The simulations were performed for June 21, December 21, September 21 and March 21. Simulations for summer presents no shading, while simulation for winter time shows only a few hours of sun. During the fall, there is more shading in the east side, while in the spring there are more shading in the west side.

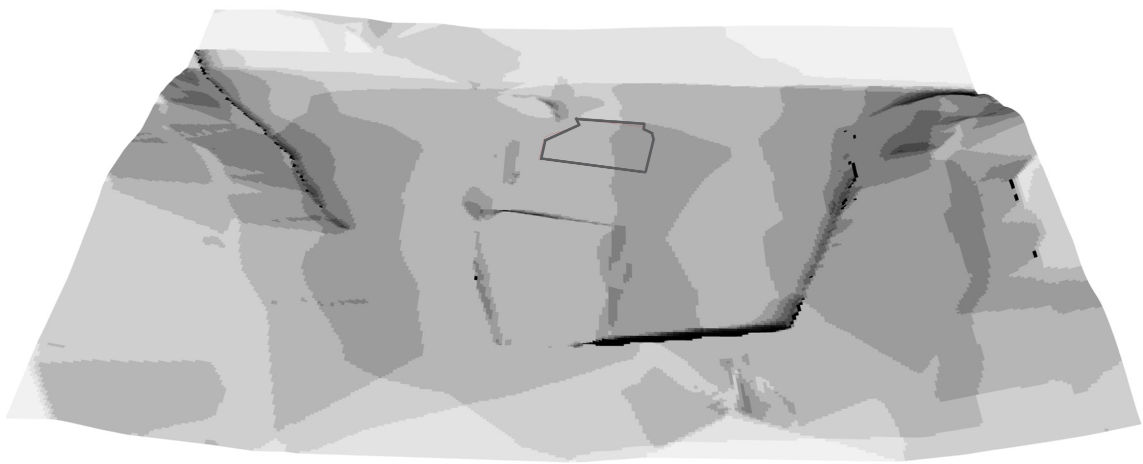
Regarding the radiation in the site for the generation of electricity in the solar panels, the hills influence in certain level. The simulation in Rhinoceros-grasshopper accounted a radiation on the site at 8.0m high (where the solar panels will be placed). The results are:

- Considering the hill and surroundings: 3603400 kWh/yr

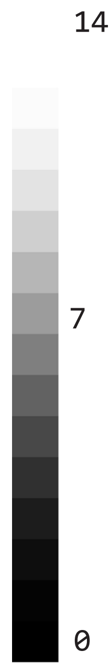
- Not considering hill and surroundings: 3676800 kWh/yr

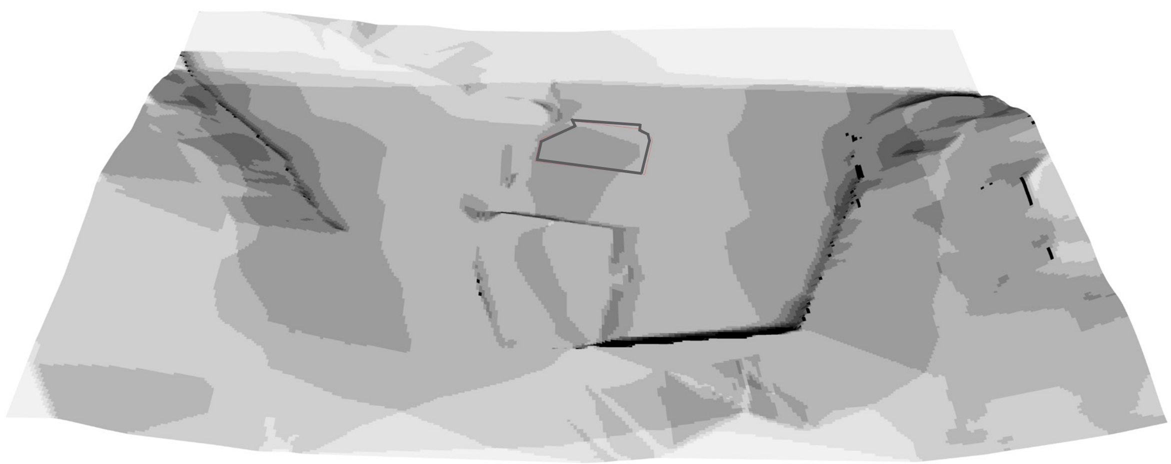
Figure 01: Shading analysis





September, 21





March, 21

LOCATION AND CONTEXT PLAN
1:2000

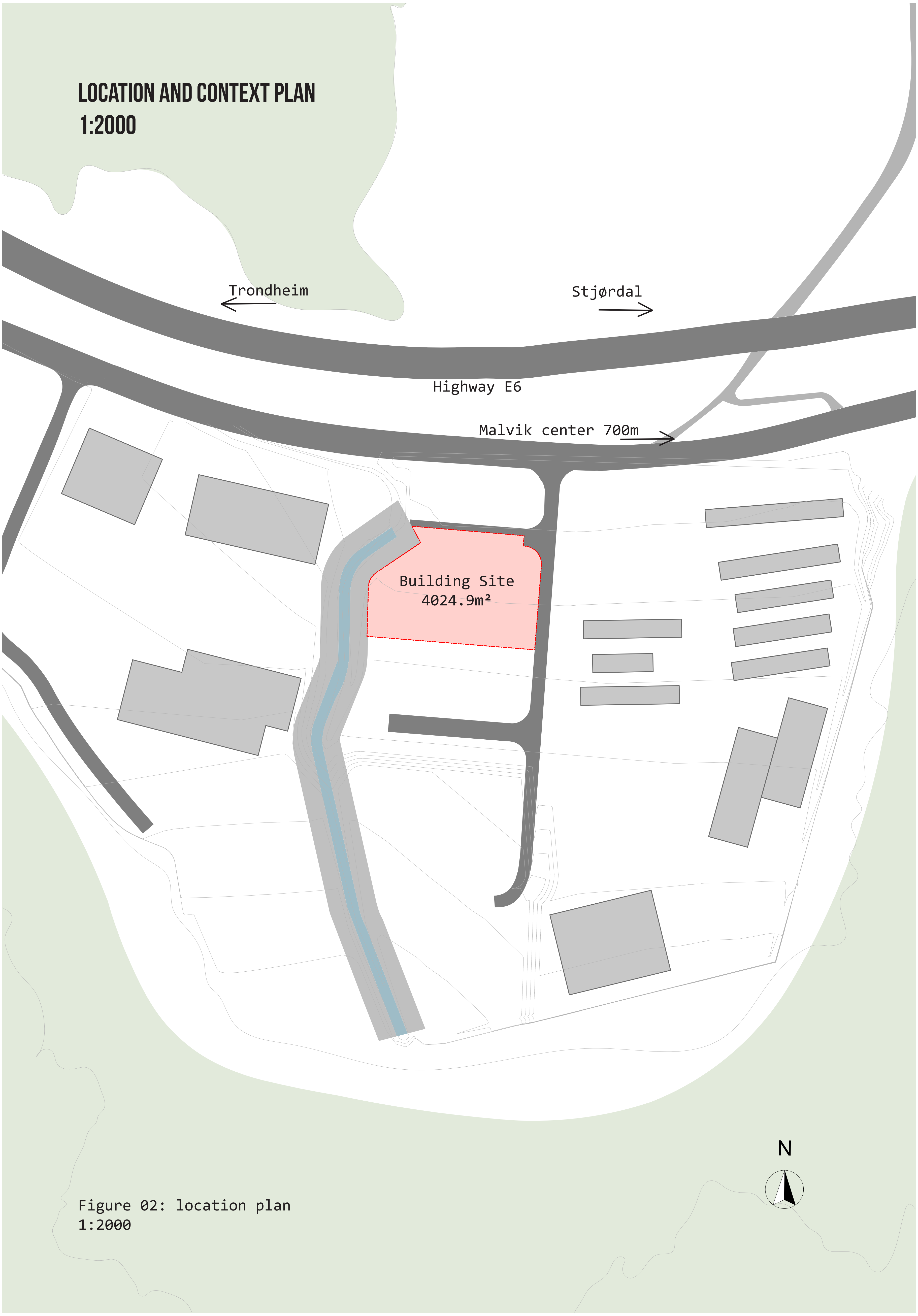
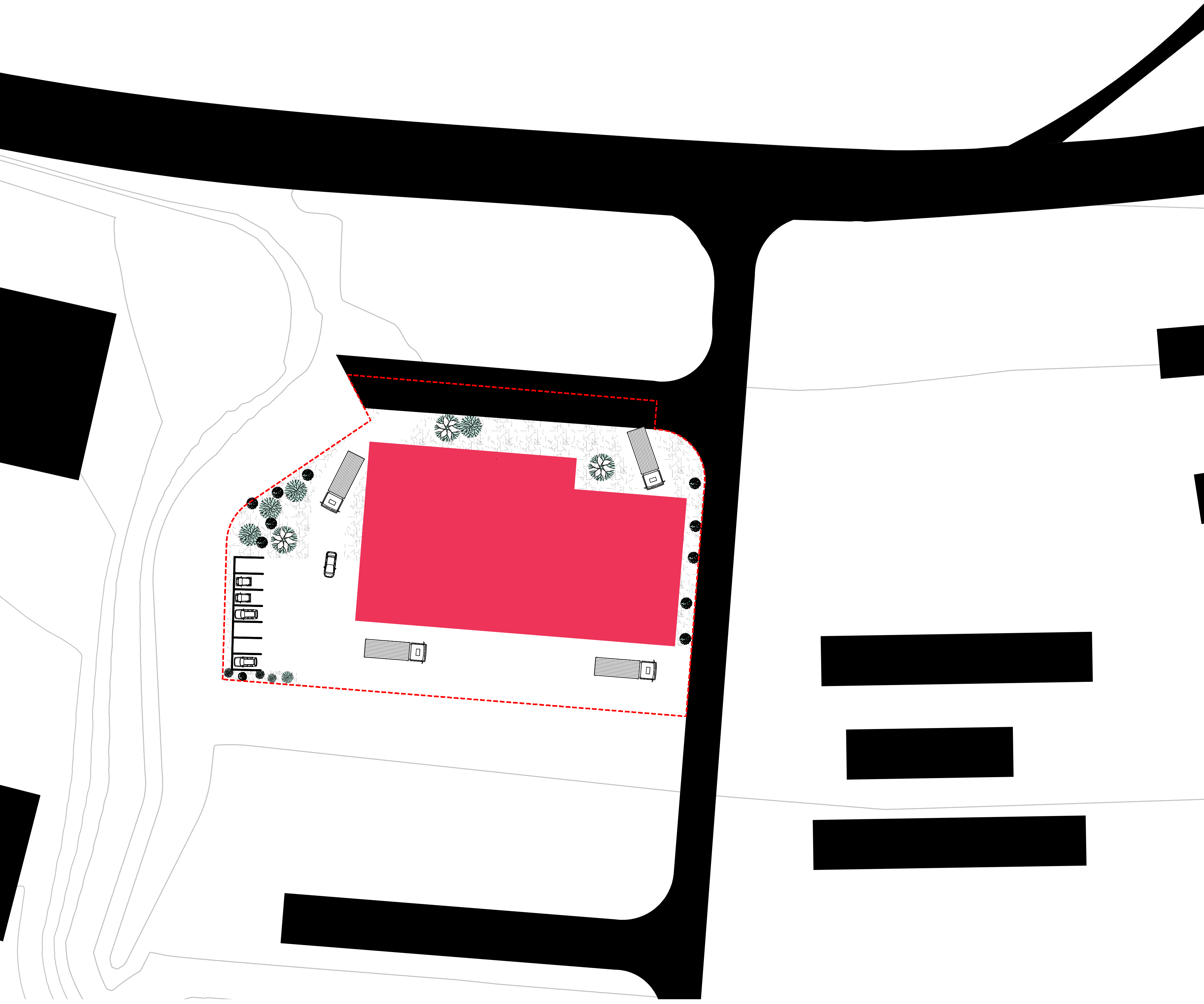


Figure 02: location plan
1:2000

CHAPTER III:

CONCEPT AND PLACEMENT



CONCEPT AND PLACEMENT

ROOM PROGRAM AND SITE CONSTRAINS

The project guidelines were adressed by the client (which is focusing in production area and offices). The expectation is a building that can be adaptable according to the economy in a way that the initial production areas can later be divided in smaller areas, or even become one big area.

The purpose is to have 1375m² for industry and 600m² for offices, including technical area and wardrobes.

The building footprint in the site is challenging, considering the amount of area needed and the area available.

The industrial area is not designed to fit many workers. The number of workers in the factory is estimated to be 10 people, in total.

Each industrial area has the garage door facing north and south, so then the vehicles flow is organized. The production space will have a crane that is shared between the occupants. A low-rise partition wall divides the areas.

The office space must fit at least the companies renting the industrial areas. The idea is to have a co-working space, instead of making isolated mezzanines in each industrial room.

Thus, all users can share the common areas (2 meeting rooms, wardrobe, canteen, and lounge). The balance point between private and common areas is a key for the project. Many factories receive clients and visitors, so it is also important to keep the company identity in each private room, while the common areas should be neutral.

CONCEPT DESIGN

The concept for this project is to create a rational architecture for the industrial space and office. The main points for the project are:

Functionality and logistics

Industrial buildings' priority is to produce an efficient product. For that, logistics are important. Vehicles should be able to enter and leave the site in a practical and effective way, optimizing time and cost.

Adaptability

Adaptability is requested by the client. The building should be able to adapt for changes in the companies renting it. The changes include size, activity and modernization.

BUILDING FACTS

Type of building:
1375m² Industry: 02 production areas
600m² Office space: Meeting rooms, office space, canteen, wardrobe, storage area.

Priorities: functionality, flexibility, quality of space, energy production.
Target energy demand: ZEB-O or ZEB-OM
Energy supply: PV and geothermal
Occupancy schedule: Office and industry 8 – 17, Monday - Friday
20 people office
10 people factory

CONCEPT AND PLACEMENT

The four gates opening to south and north fasade allows up to four production areas with private gates.

The design of the office and industry does not have load bearing walls, it is an open concept easy adaptable. In the industry, the internal division wall is a 2.8m high wall in CLT only. In the office space, division walls are mainly in glass.

Low carbon emission, high energy efficiency and renewable energy production

To meet the ZEB target, the building should balance the emissions. The renewable energy production should be as high as possible with low emissions. In this project the point is to have low embodied emissions from materials, low energy demand with high energy production. Passive and active strategies are considered to enhance the building's efficiency.

ORIENTATION

The building orientation purpose to fit the site better and to benefit the logistics and movement of trucks and vehicles.

The office space is desirable to be placed in the north side to avoid glare into the zone. Office buildings when exposed to glare need external solar shading devices, especially in summer months. The blinds outside result in increase of lighting demand, which also leads to higher energy demand for lighting. This effect happened in the Powerhouse Kjørbo, when studying the building performance after it was built, the research concluded that excess of glare increases the lighting demand (SØRENSEN et al, 2017). Offices facing north tend avoid overheating during summer.

ROOF

The use of PV in the roof to generate electricity is used to supply the emissions related to materials and operation of the building. In Norway, the best angle to have maximum efficiency in the PVs is 45 degrees facing south. However, as the building footprint is large due to the industrial areas, a slope would create a huge volume that is not needed for this case.

Many options were considered for the slope of the roof, also checking a mezzanine in the sloped area and reducing the angle size. The fact is that more slope angle, more is the area to be occupied in the loft.

The comparison considered two instalation systems in the roof: a mounting system and Building-integrated photovoltaics (BIPV).

Mounting systems are often used for solar farms, large roof areas and refurbishment. This system uses metal to tilt the panels in the roof.

Building integrated photovoltaics is being used in new buildings, replacing the conventional building materials, such as fasade cladding, roof cover, and windows.

COMPACTNESS LEVEL

The envelope is one the most contributors for emissions. A low ratio between the external surface and the volume heated is a desirable to achieve low emissions regarding materials and avoid heat losses.

For passive strategies, envelope is very important to achieve good indoor quality, being a driver to decrease need for heating in cold climates such as Norway (NESS et al, 2019).

The external walls have a good contribution for the embodied emissions. This is because in cold climates, it is needed to have high insulation to protect the building from the heat losses and wind (LECHNER, 2015).

The compactness level were considered in the project for the shape analysis. All the shapes had its surface measured from the interior wall.

SITE ACCESS AND VEHICLE FLOW

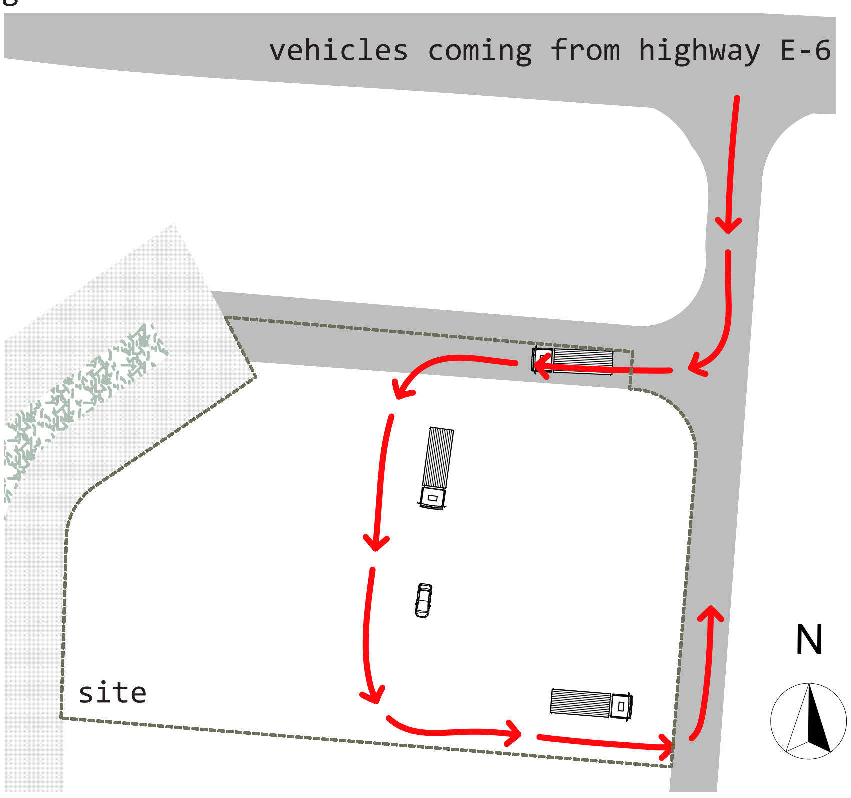
The access to the site is an important point in the project due to the vehicle flow. It is necessary that the trucks can enter in the site easily.

The analysis of the building site was done initially by checking the truck traffic, which takes a significant part of the buildable area. The curves done by the trucks need to have 12.0m of radius so then the trucks can make a turn in the site while entering and leaving the building.

For a better and safer traffic flow, one way road is the best option (figure 2). It is estimated that trucks type semitrailer will be accessing the site. This point shaped the site layout to keep good and safe access to the roads.

The shape of the site is irregular, which lead to use the regular area available to build. The remaining area on the west side is left to be used as parking space and storage.

Figure 03: Vehicle flow in the site



BUILDING VOLUME

The industry area is more critical regarding its depth and width. The area of 1375m^2 provides possibilities of a rectangle shape of different values for width and depth:

37m x 37m - not practical for structure
35m x 40m - not practical for structure
30m x 45m - possible
25m x 55m - possible
20m x 68m - possible

Shapes with span of 30m or more demand a special structure to make building with free plan (without columns in the middle). Moreover, can lead to daylight problems and need for skylights. Shapes with 20m or 25m are more practical.

PVs are more efficient at 45°. However, the issue is the amount of extra volume created by the roof slope. In large scale projects the extra height provokes can be impractical.

Table 02 presents values of increase in building height according to roof tilting. Analysing the office area of 600m^2, it is not practical to have a roof slope more than 20°.

The industrial area studied in this project will have dimentions of 30x45m and 25x55m, because it fits better in the site. New solutions were speculated to try to optimize the energy production for flat roofs. Some alternatives include:

- mounting system having tilted panels 15º east/west
- integrated roof design with PVs placed horizontally in a flat roof
- minimal tilting angle of maximum 10 degrees

Table 03 presents the efficiency of energy production accordint to the PVs orientation. The simulation took place with Trondheim climate database, and did not consider the site context.

Analysing the energy production per PV area, it is possible to check that placing the PVs horizontally in a flat roof is as efficient as having in a mounting system facing east/west. The advantage of placing east/west is that the tilting make it possible to assemble a larger area of panels.

Table 02: Study of building height

Span (m)	Angle	Height (m)
20	20°	7.6
20	30°	13.0
25	10°	4.4
25	20°	9.6
25	30°	16.3
30	20°	11.4
30	30°	19.5

Table 03: Orientation of PVs

Orientation	Total radiation roof kWh (grasshopper)	PV Energy output (kWh/m2) year
Horizontal - 0°	88657	146.8
South - 10°	98063	162.4
South - 20°	105572	174.8
South - 30°	110640	183.2
South - 40°	112969	187.1
West - 15°	87766	145.3
East - 15°	88202	146.1

BUILDING PLACEMENT ANALYSIS

Input values

For this analysis, three possibilities were studies for the building placement:

#1: building with flat roof in a box form
#2: separate the production area and the office area in two independent volumes
#3: moving the office space to a floor above the industrial area

The aproaches based the internal traffic with the trucks accessing the site by north and leaving at the south part.

To analyse the approaches, a initial SIMIEN simulation was done for the three conceps.

The production of energy was simulated in Rhinocerus with plug in grasshopper. It was calculated with efficiency of 23%, balance of the system of 80% and losses of 10%.

The energy simulation in SIMIEN used as input values based mainly on recommendations by Byggforsk. The air tightness of the building is based on the system used and tested by GAAS.

The internal gains were standard values from SIMIEN, except from the industry, which is based on the factory machinery assumption. The U-value for windows and doors are based on commercial available products.

The indoor temperature in the factory is designed to be 16 degrees. This is because of the high activity level to be performed by the employees.

- Activity level: medium-high activity (174W/m² ; 3 met)
- Clothing level of the workers: light work clothes (0,11 m².C/W ; 0,7 clo).

Both values were analysed in the optimal operative temperature and the optimal value is 16°C.

For the office space, the indoor temperature was set to be 21°C based on practical values used by GAAS.

The windows were distributed proportionally in the fasades and all of the shapes have the same window area.

The ventilation was set to be variable ventilation with indoor air quality of to keep the CO_2 level under a concentration of 800 parts per million.

Table 01 : SIMIEN inputs used in the simulations

Air tightness	0.4 l/h
Window/wall ratio*	0.2
U value external wall	external wall 0.11 W/(m²K) roof 0.08 W/(m²K) floor in terrain 0.17 W/(m²K) windows 0.59 W/(m²K) doors 1 W/(m²K)
Internal gains industry	lighting 6 W/m² technical equipment 25 W/m² hot water 1.6 W/m²
Internal gains office	lighting 4 W/m² technical equipment 6 W/m² hote water 1.6 W/m² people 2 W/m²

*proportionally distributed along the fasades

CONCEPT AND PLACEMENT

Approaches

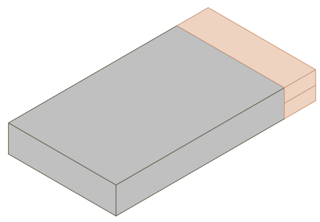
Shape #1 is a simple box, a cost-efficient way of building that is commonly used for industries. In this proposal the office space is located in the west part of the site with two stories. For the analysis, only flat roof was simulated, since a tilting roof would just create non usable area facing north. It was designed a mounted system with PVs tilted 15° towards east.

Shape #1 has a good potential for energy production, because the roof area is larger.

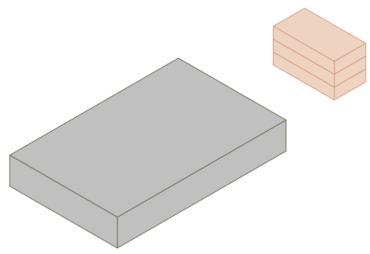
Shape #2 has the office separated from the industry. The office is placed in the west side of the site, using the irregular area of the land. The separation of the office and industrial is a good alternative for the site logistics. The noise pollution will be reduced in the office area. The negative point is that the building footprint is high, as wells as the building envelope. Moreover, it requires two technical systems.

Shape #3 propose that all the office space is located above the industrial area. This results in a smaller building footprint, what is beneficial in terms of logistic and flexibility. The PVs in this shape are placed along the roof, in a BIPV system.

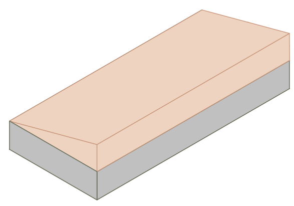
SHAPE #1



SHAPE #2



SHAPE #3



CONCEPT AND PLACEMENT

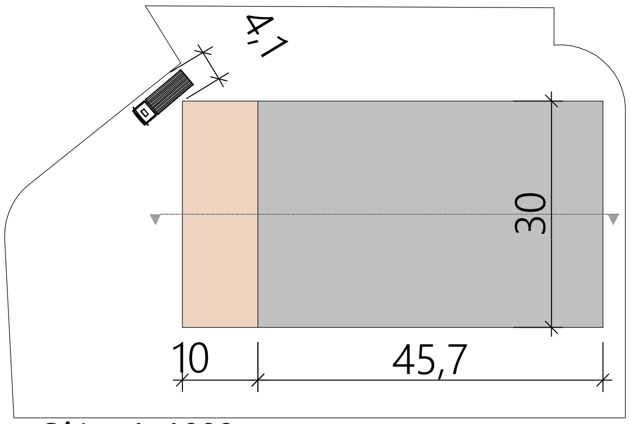
Figure 03: Buiding placement analysis

office

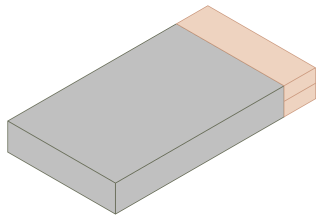
industry

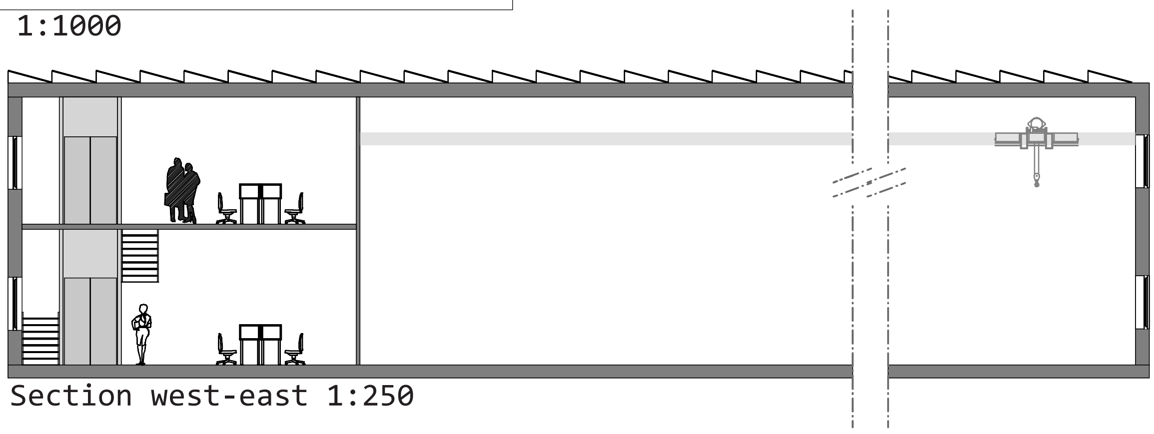
N

SHAPE #1



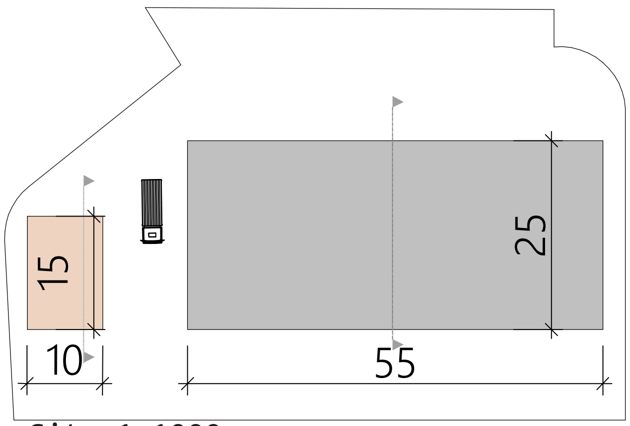
Site 1:1000



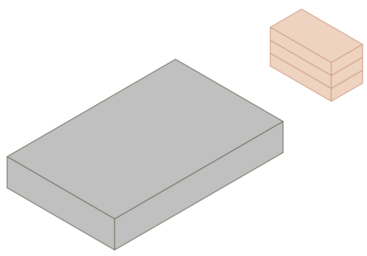


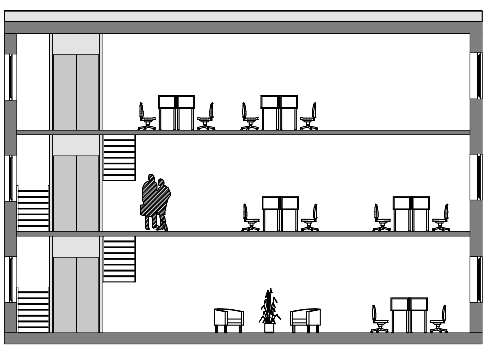
Section west-east 1:250

SHAPE #2

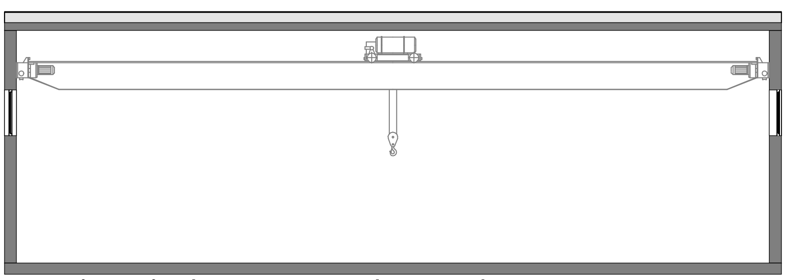


Site 1:1000





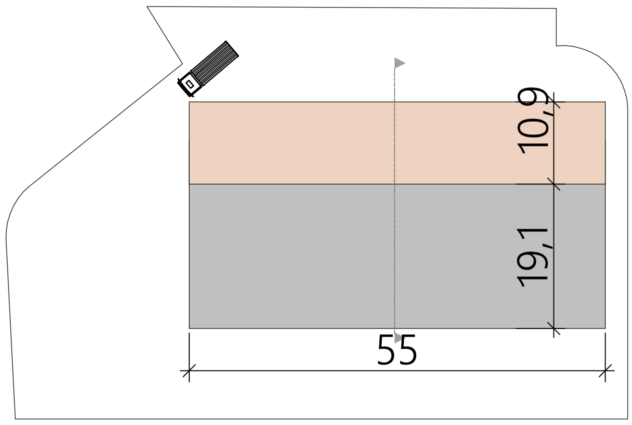
Section office north-south 1:250



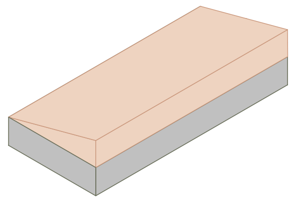
Section industry north-south 1:250

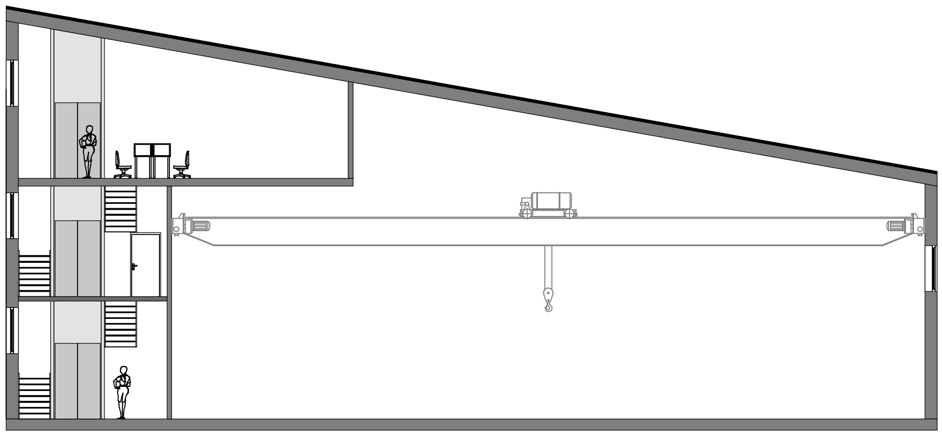
CONCEPT AND PLACEMENT

SHAPE #3



Site 1:1000





Section north-south 1:250

The three initial shapes were compared by checking its volume and surface area, the energy demand, and the energy production.

The best option regarding the building footprint is shape #3, which is the minimum footprint because only the industry is located on the first floor.

In general, the energy demand for those shapes is mainly affected by the internal loads for the appliances. In average, 48% of the energy demand is consumed by the technical equipment installed in the factory and in the office. All the shapes have the same load for equipment, the difference in the energy demand is due the volume difference and envelope (external walls and glazing).

The lowest energy demand is achieved by building two separated volumes (shape #2). This is mostly because the office space has a compact volume. The distribution of the glazing area also had influence. Since it is a box, the glazing was equally distributed. By the other hand, this shape has the highest building envelope, resulting in more embodied emissions.

The shape #3 has the higher energy demand. This is an outcome from the extra volume to be heated caused by the roof slope in both industrial and office spaces.

The warm air tends to rise upwards according to the law of thermodynamics. Locating the office above the industry affect the energy demand for heating space. This is not considered in the SIMIEN simulation due to software limitations. The energy demand of shaping #3 in practice tend to be lower then the one simulated.

The office space have a higher indoor temperature (21°C). Thus, the impact of the heated volume is more considerable than in the industrial space, where the operative temperature is only 16°C.

The total energy production is best in the shape #1. This is because the roof area is larger than shapes #2 and #3.

Both shapes #1 and #2 have the same energy production per PV area due to the similarities in the mountain system. Shading in the PVs were avoided in the shape design. The radiation simulation considered as context the surrounding hills, the building and the PVs.

The production of energy per PV area is higher for shape #3, since the roof is tilted to south. The high efficiency of PVs leads to less embodied emissions and lower GHG emissions payback time for the PV system.

Table 04: Building concept analysis

Shape	Floor area	Building footprint	Annual solar radiation on roof	PV area	Production of energy	Production of energy per heated area	Exterior surface*	Volume	Exterior surface / heated volume	Exterior surface / heated area	Heated area / volume	Energy demand per heated area
	m²	m²	kwh/yr	m²	kwh/yr	kwh/m² yr	m²	m³	-	-	-	kWh/m².yr
1	1975	1675	1571400	1795	260223	131.7	4820	13351	0.36	2.4	0.15	95.4
2	1975	1575	1410000	1618	233496	118.2	4958	12507	0.40	2.5	0.16	94.6
3	1975	1375	1374600	1410	227633	115.3	4471	14490	0.31	2.2	0.14	95.5

* internal area

Table 05 presents a simplified ZEB balance for each shape, taking into account only emissions from materials (A1-A3), replacement of PVs (B4) and operation (B6).

The PV system is one the most GHG emission sources in a construction. The emission for the PV panels used in this analysis is 250kg.CO_{2eq} per PV area, according to studies conducted by Kristjansdottir, 2016.

The emissions for the materials are higher for the shapes #1 and #2 due the larger surface area. Shape #2 have the higher emissions related to envelope.

The shape #3 has a tilted roof that reduces the superficial area and makes it the most compacted envelope in relation to surface area and volume, resulting in lower embodied emissions from materials.

The shape #1 has the largest roof area. It is possible to install more PVs, leading to a higher potential for emission compensation. Even tough, the balance between the emissions is higher for the building separate shape.

The emissions from operation (B6) are lower for the shape #2 since it has the lowest energy demand. However, the high envelope of the building result in a high number for the emissions balance.

The shape #3 result in the best compromise between energy demand, energy production and building footprint. Analysing the ZEB balance, it presents the lowest emission balance, meaning that is the closest to achieve the ZEB target. This is a result of a lower envelope, especially in the groundwork phase, avoiding emissions from concrete work. There are also advantages related to the logistics in the site. The space available in the site is limited, so it is preferable to have a minimal building footprint as possible.

Emissions included in this analysis:
Ground: concrete, steel for reinforcement
Walls: cladding, insulation, windbarrier, vapours barrier, wood frame
Roof: bitumen, insulation, wood frame
PV: Photovoltaic panels and mounting system

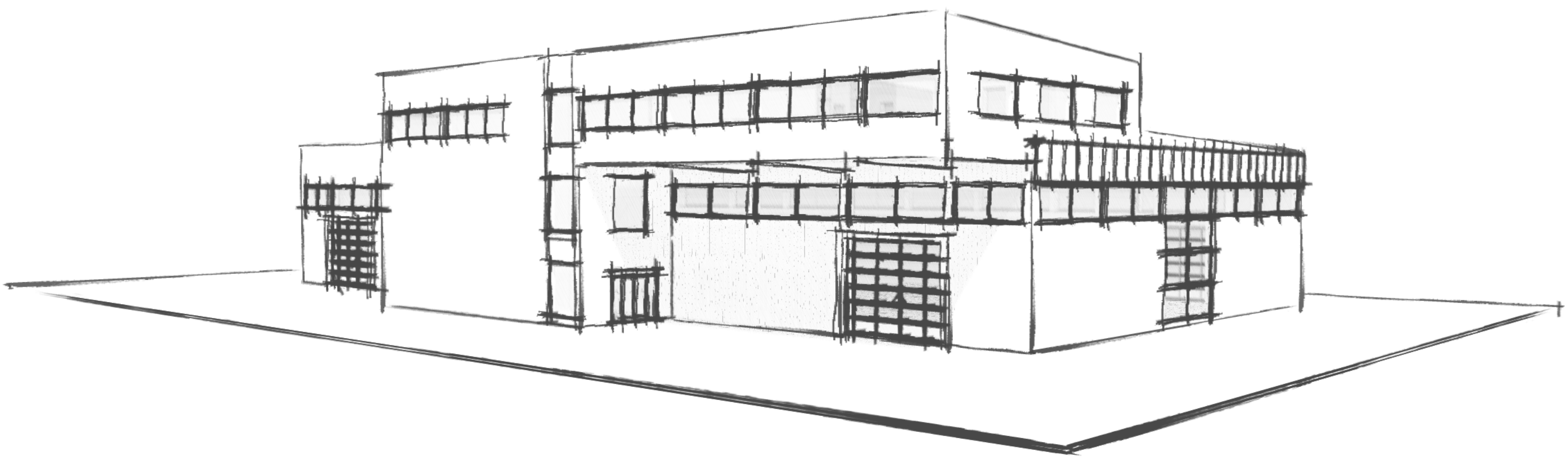
Table 05: Simplified LCA analysis

Emissions in $kgCO_{2eq}/m^2$ lifetime of 60 years.

Emissions A1 - A3 ($kgCO_{2eq}/m^2$)									
Shape	Ground	Walls	Roof	PV	A1 A3	B4 PV replacement	B6 +	B6 -	ZEB balance
#1	1.63	0.37	0.4	3.2	7.3	3.2	10.9	17.4	-4.0
#2	1.54	0.45	0.38	2.9	6.8	2.9	10.8	14.6	-5.9
#3	1.37	0.41	0.34	2.5	5.0	2.5	10.9	14.8	-3.6

CHAPTER IV:

SHAPE DESIGN



SHAPE DESIGN

After deciding on following the approach to have the office in a loft above the industrial area, some other alternatives were studied to optimize the internal area in the building. For this analysis, six shapes with variation in roof shape and office floor plan were compared.

The priorities in the design are:
1. Functionality/logistics
2. Quality of indoor space
3. Balance between emissions (ZEB)

Industrial buildings generally have a large footprint. A practical depth of the is around 25m to achieve area of 1375m². A span with 20m would result in a large length. More then 25m can lead to daylight problems. So, 25m of span was chosen for the industrial area.

SHAPE

The concept is based on the idea of having all the office spaces in the 3rd floor. The first floor then would have as minimal area as possible. Therefore achieving a minimum footprint beyond the production area.

The room program is presented below and is the same for all the shapes.
1st floor: stairs, wardrobes
2nd floor: stairs, technical room
3rd floor: office space, wardrobes, canteen, meeting rooms, lounge and office storage.

The first floor locate the stairs and one elevator, designed for acessibility. The wardrobes are also have one bathroom for persons with disabilities. There are two wardrobes separated by gender. The idea is to keep the facilities in the middle, so it is not far from none point of the industry.

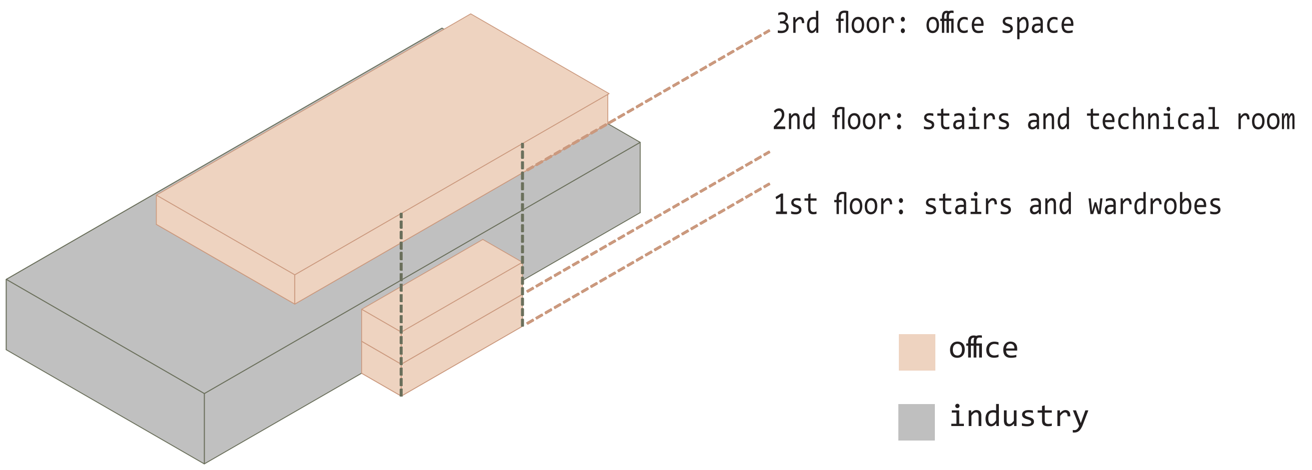
Shape A, B and C have the same floor plan, with different roof options. All have the functional areas in the central area and all of the rest in the loft space. The width of the office space for those shapes is 6.8m, with a one side corridor. One side corridors take usable space and are not desirable.

The shape D is a trial to compact the office space to avoid large area of corridors. For this shape, one part of the office is placed overhanging in the west side of the building.

A compact office space is more desirable to avoid large corridors area. Then the office space were compacted in a rectangle box in shape E to make the space more usable.

The shape E considered bringing together all the area in the west side of the building, making an office box over an industrial box. This shape makes the interior space in the office more usable, with less corridor spaces. The roof is flat, and the PVs are placed in a mounted system facing east at 15°.

Figure 05: Room program concept distribution



SHAPE DESIGN

It is desirable to have a BIPV system than a mounted system. Mounted systems need steel to tilt the PVs. Therefore, shape F is a proposal to have a minimal angle of PVs (2° for industry and 3° for office).

The results by the simulations shows that PV production per area is higher when tilting the PV towards south instead using a mounting system facing east.

The energy demand for all the shapes varies from 95.8 to 97.7 kWh per heated area. The average is 96.38 kWh/m², and the variance is 0.501. The lower energy demand is achieved by shape B, probably due the compactness of the shape.

Shape D had the highest energy demand, and it is the least compact shape.

Shape E and F have an overhang in west side, increasing the energy demand in comparison to shapes A, B and C. Shape F have 0.8 kWh/m² more then shape B.

The renewable energy production is higher for shapes A and F. Both shapes use sloped roofs with BIPV system and best results per heated area.

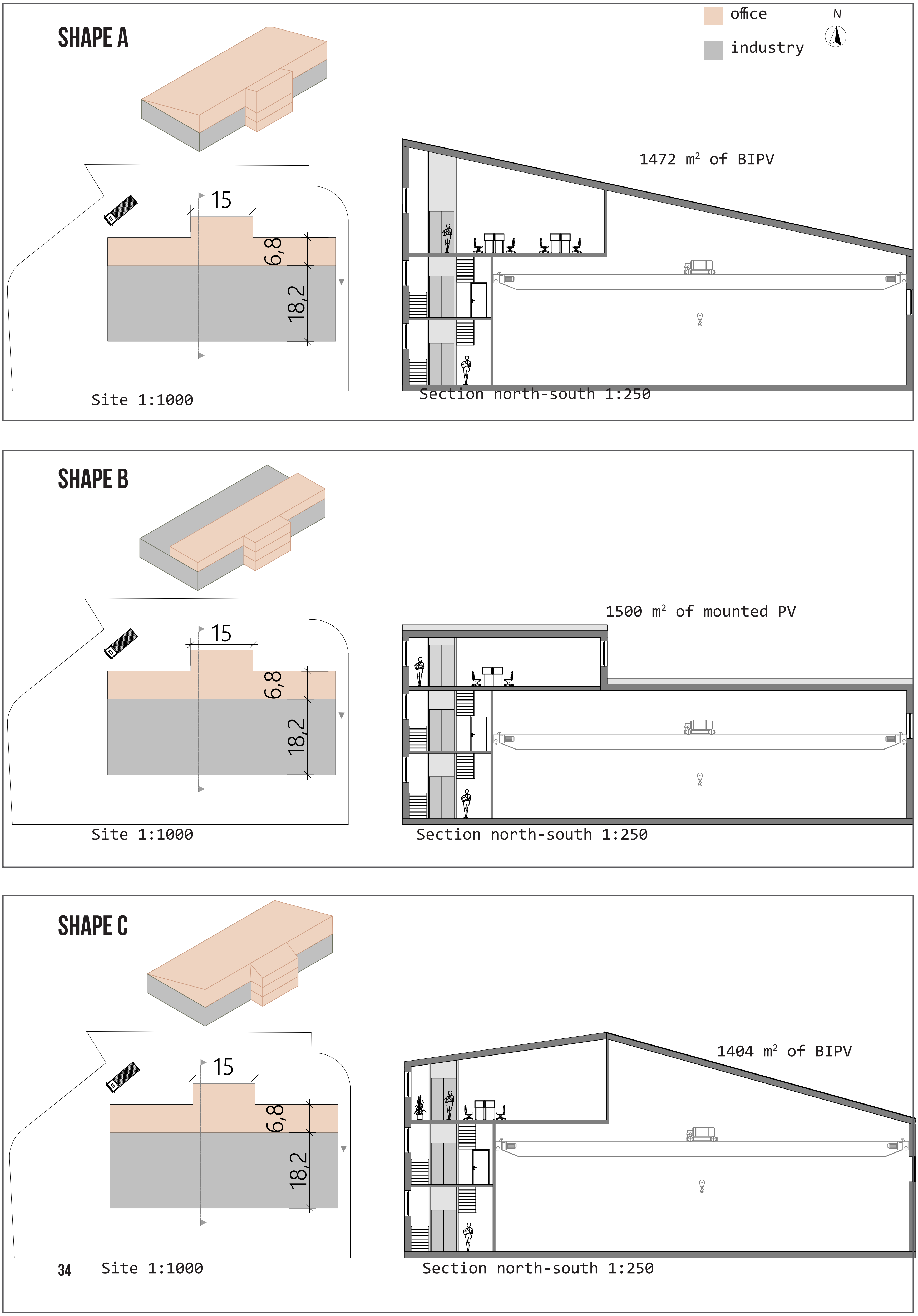
For shape E, 1612m² of PV panels would be placed on top generating 230697kWh. The shape F has 1555m² pf PV on the roof and generate 231840kWh. The efficiency of the panels is higher for roof F and the energy consumption is similar.

Analysing the shapes, shape F is the best compromise between renewable energy production, energy demand and quality of space. The energy production is high in comparison to the other shapes. The office space in a box form provides a good quality of indoor space and compactness.

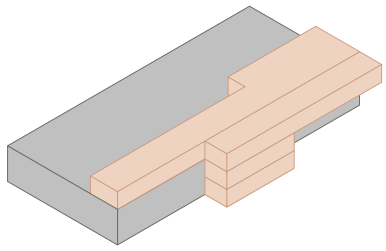
Table 06: Roof shape analysis

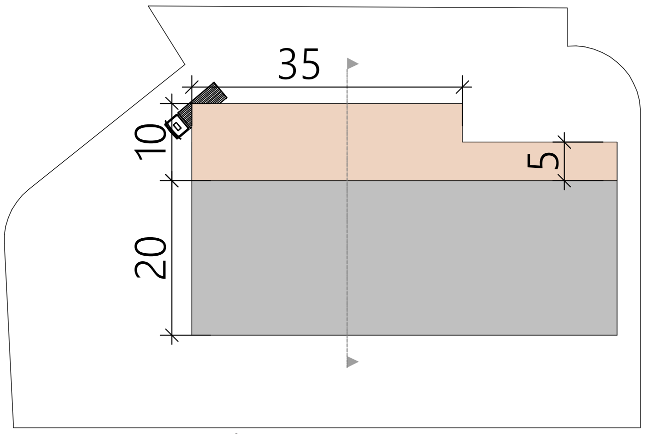
Building shape	Floor area BRA	Building footprint	Annual solar radiation on roof	PV area	Production of energy	Production of energy/m² heated	Exterior surface including floor	Volume	Exterior surface / heated volume	Exterior surface / heated area	Area/volume	Energy demand per heated m²
	m²	m²	kwh/yr	m²	kwh/yr	kwh/m² yr	m²	m³	-	-	-	kWh/m².yr
A	1975	1450	1404700	1472	232618	117.78	4644.8	14552.9	0.32	2.35	0.14	96.0
B	1975	1450	1268000	1500	209981	106.32	4636.6	12604.9	0.37	2.35	0.16	95.8
C	1975	1450	1349100	1404	223411	113.12	4672.2	15055.0	0.31	2.37	0.13	95.9
D	1975	1450	1324100	1603	219271	111.02	4940.8	12604.2	0.39	2.50	0.16	97.7
E	1975	1450	1393100	1612	230697	116.81	4830.8	12604.9	0.38	2.45	0.16	96.2
F	1975	1450	1400000	1555	231840	117.39	4919.5	13626.0	0.36	2.49	0.14	96.6

Figure 06: Shapes analysis



SHAPE D





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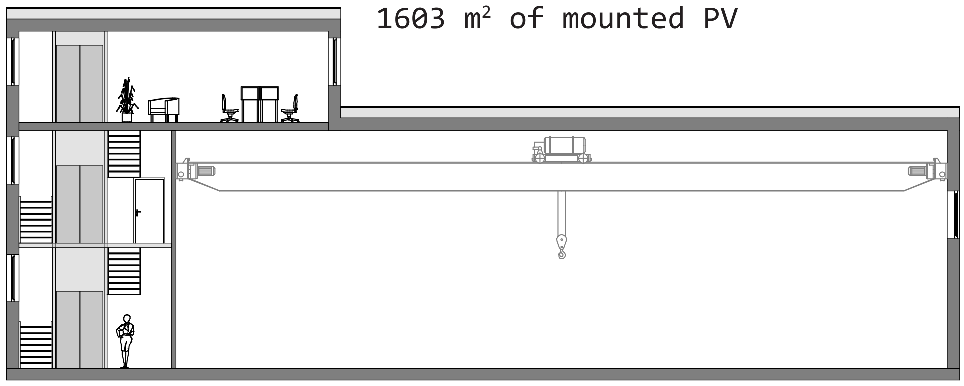
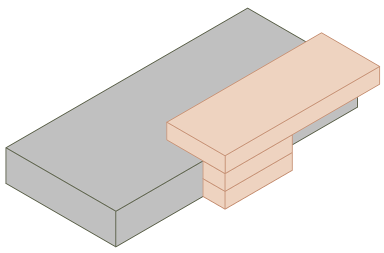
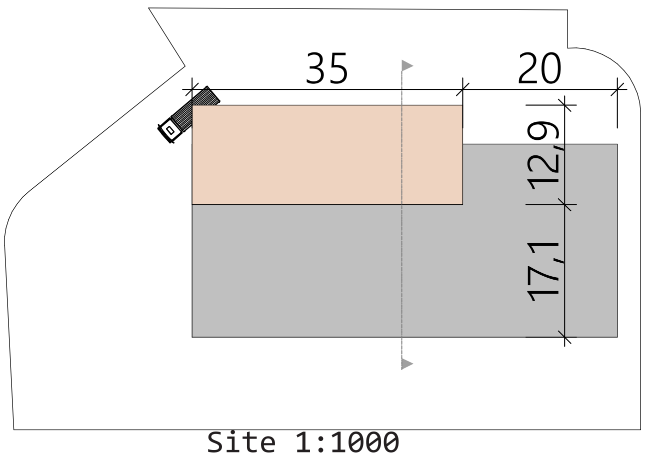


Section north-south

SHAPE E



1612 m² of mounted PV



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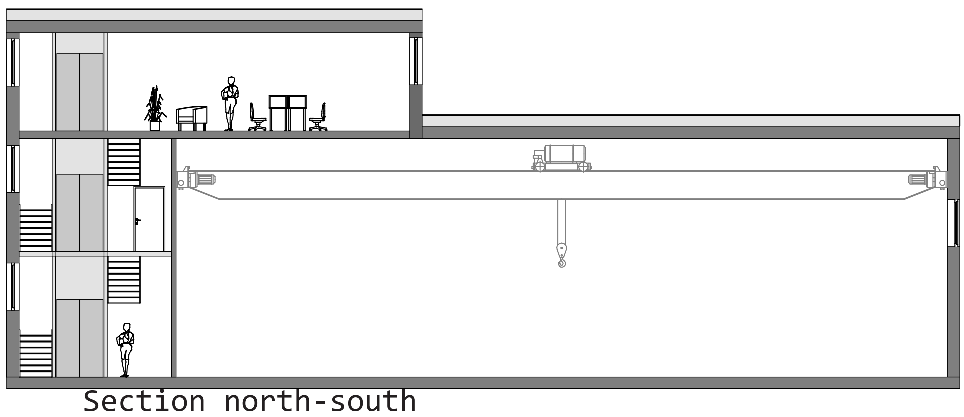
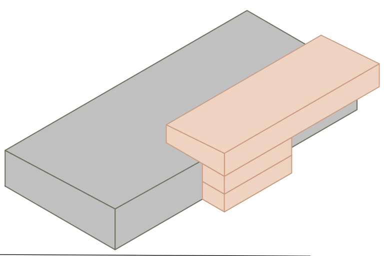
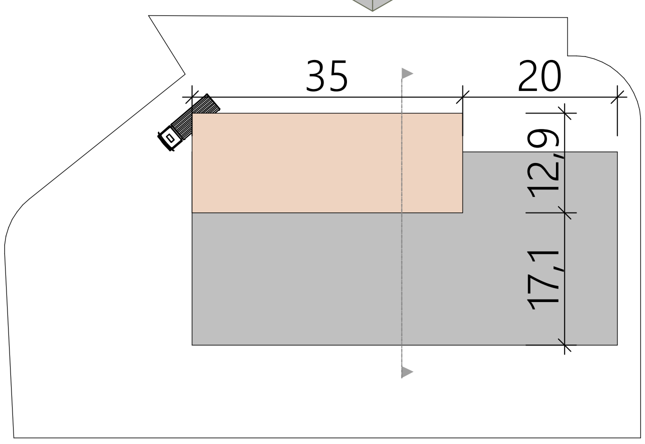


Section north-south

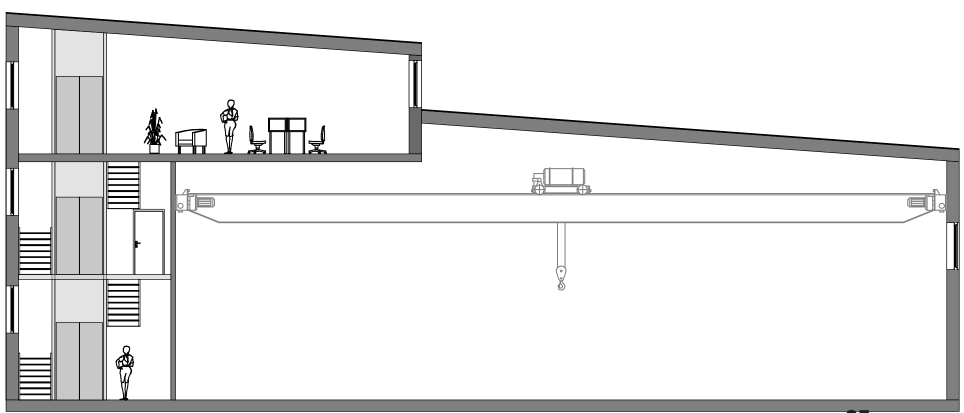
SHAPE F



1555 m² of BIPV



Site 1:1000



Section north-south

RENEWABLE ENERGY PRODUCTION AND BUILDING SHAPE

The roof optimization was done after choosing the shape. A simulation was performed to check the higher radiance value with minimal tilting options.

Table 07 presents values for different roof options for the chosen shape. The simulation takes in consideration shading from the surrounding hills and the building itself.

The option using a mounted PV system was not the best for this case, even though the total production is higher. The fact is that the mounted system allows a higher area for PVs, however, some area should be kept for maintenance of the roof. Moreover, the metal used in mounted structures has high embodied emissions. By using the roof with the PV cladding, it is possible to avoid emissions from bitumen roof covering.

Table 07: PV production on roof

PV direction	Energy production per PV area (kWh/m^2)
BIPV Horizontal	140,8
BIPV South 3°	149
BIPV West 3°	140,5
BIPV East 3°	142,2
mounted East 15°	139,9
mounted West East 15°	136,6

SHAPE DESIGN

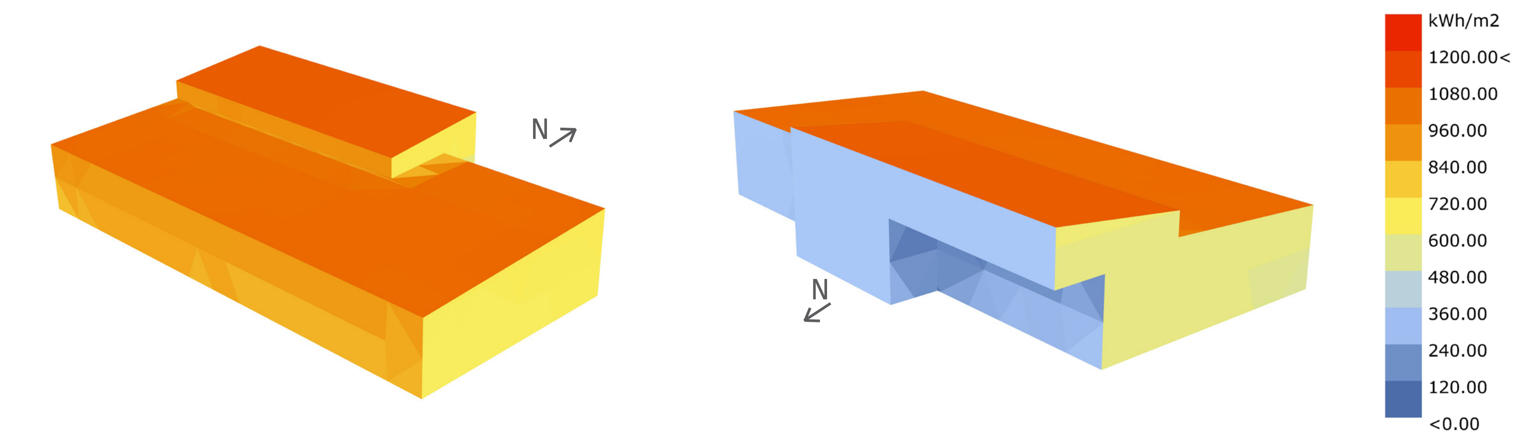
By checking the building radiation at figure 07, the roof have shown the best radiation value, followed by the south fasade, east, west, and north.

The south fasade is the most efficient regarding energy production. It is possible to observe that the lower area of the south fasade has shading. The PVs will be placed on the upper part of the fasade, where the radiation is higher.

The efficiency of energy production on the fasades is shown on table 08. The north fasade has the lower PV production and is not considered for this project. All other fasades are have PVs.

The final roof shape is a minimum roof with 2° for the industrial area and 3° for the office area.

Figure 07: Radiation analysis of shape



south and east fasades

north and west fasades

Table 08: PV production on fasades

Fasade	Energy production per PV area (kWh/m²)
North	51,9
East	90,3
South	126,0
West	73,9

SITE PLAN
1:1000

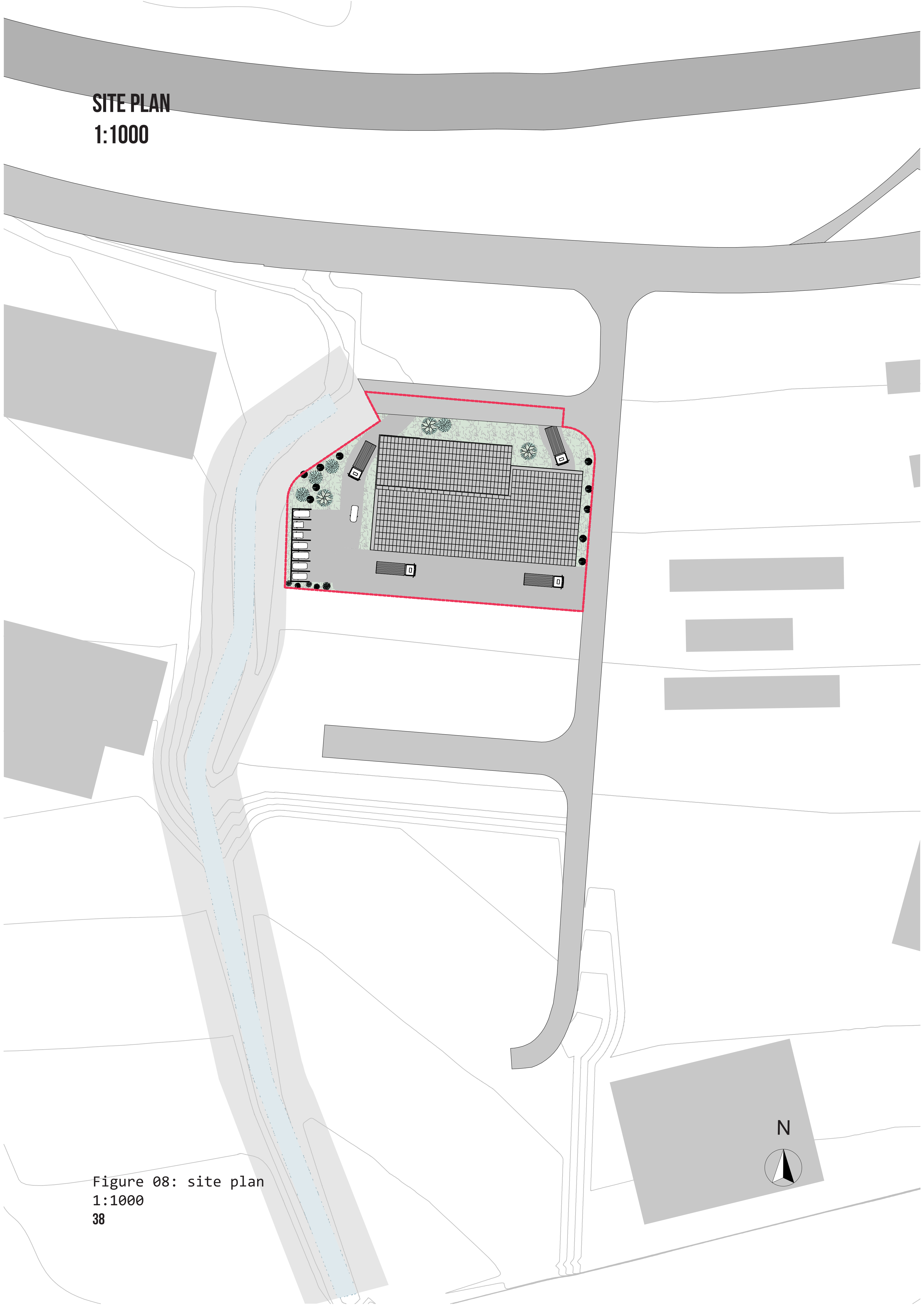


Figure 08: site plan
1:1000

FLOOR PLAN 1ST FLOOR
1:200

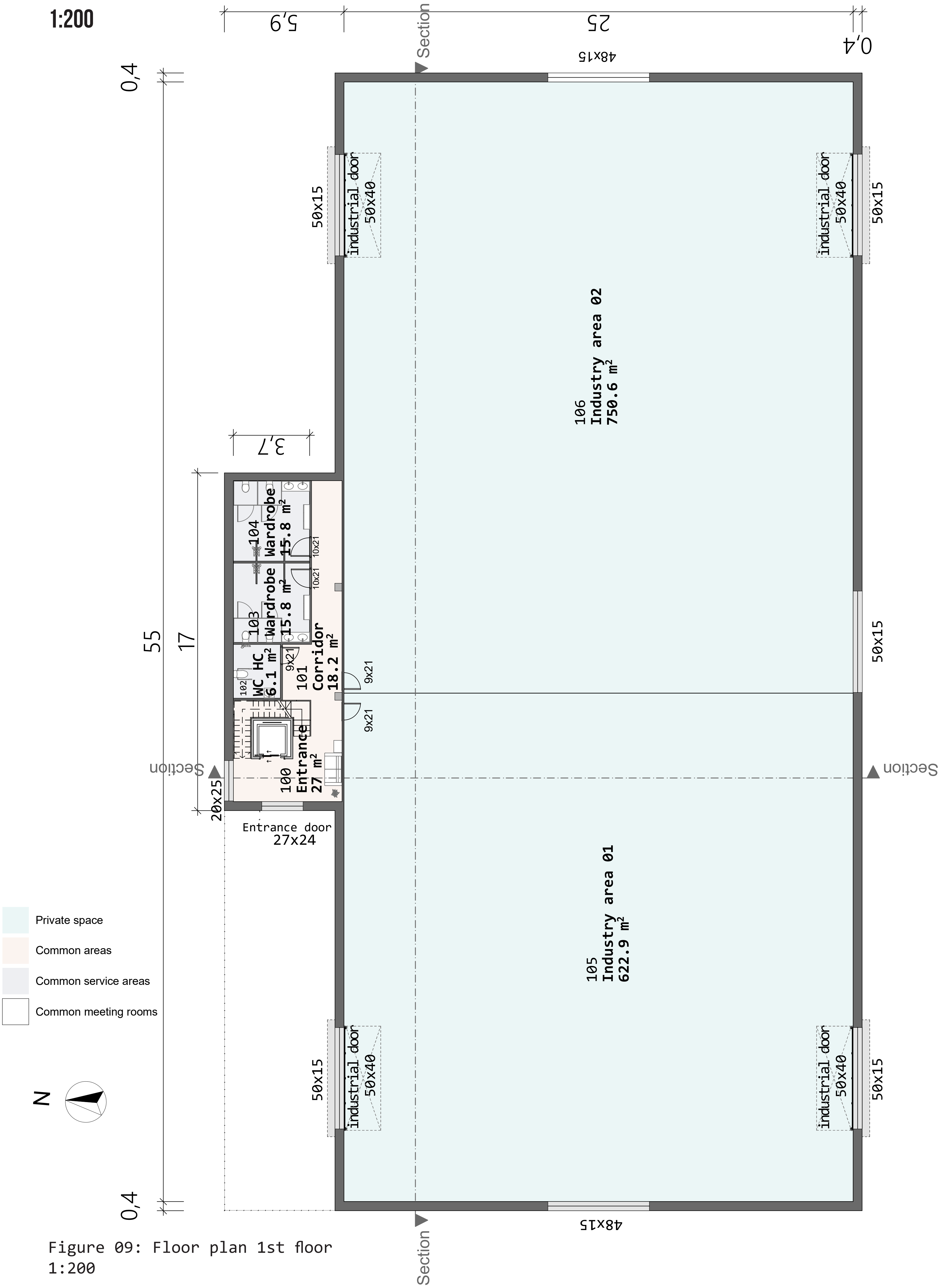


Figure 09: Floor plan 1st floor
1:200

FLOOR PLAN 2ND FLOOR
1:200

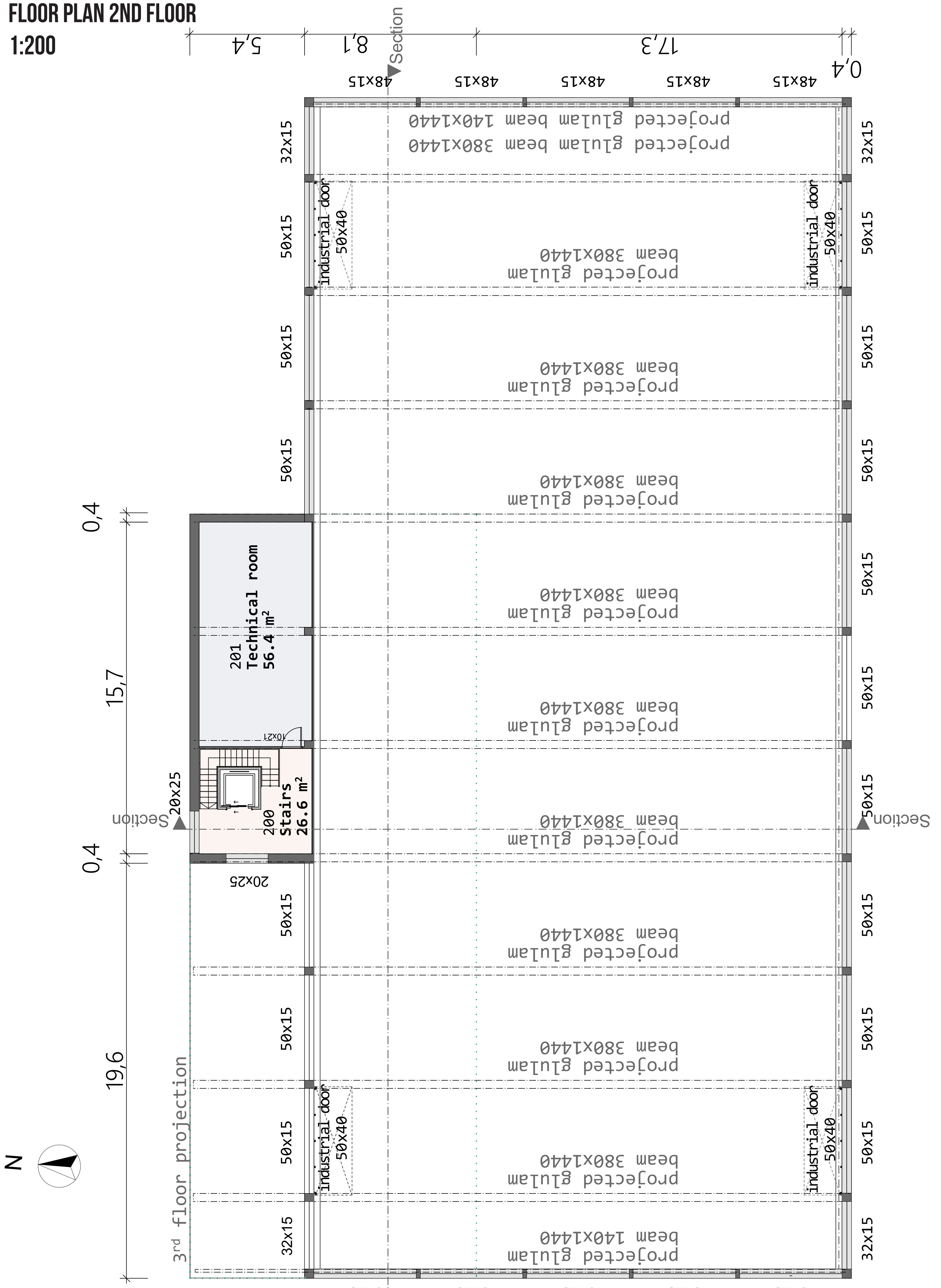


Figure 10: Floor plan 2nd floor
1:200

FLOOR PLAN 3RD FLOOR
1:200

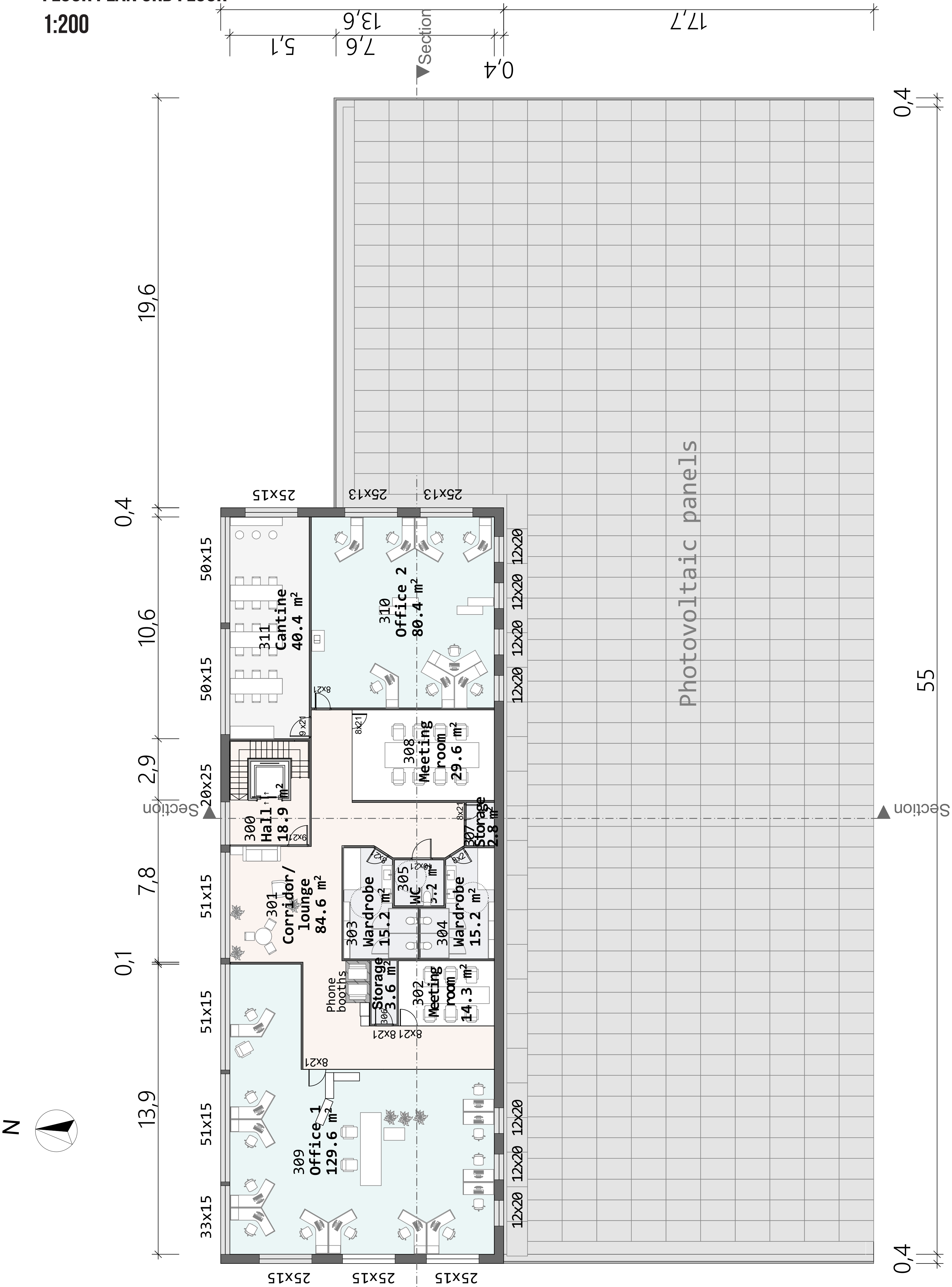


Figure 11: floor plan 3rd floor
1:200

SECTIONS 1:200

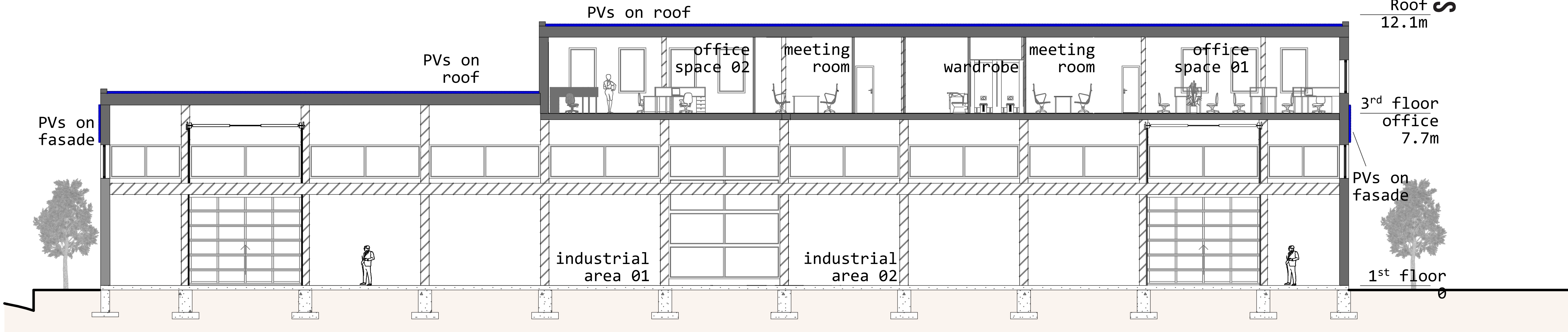


Figure 12: Section east-west 1:200

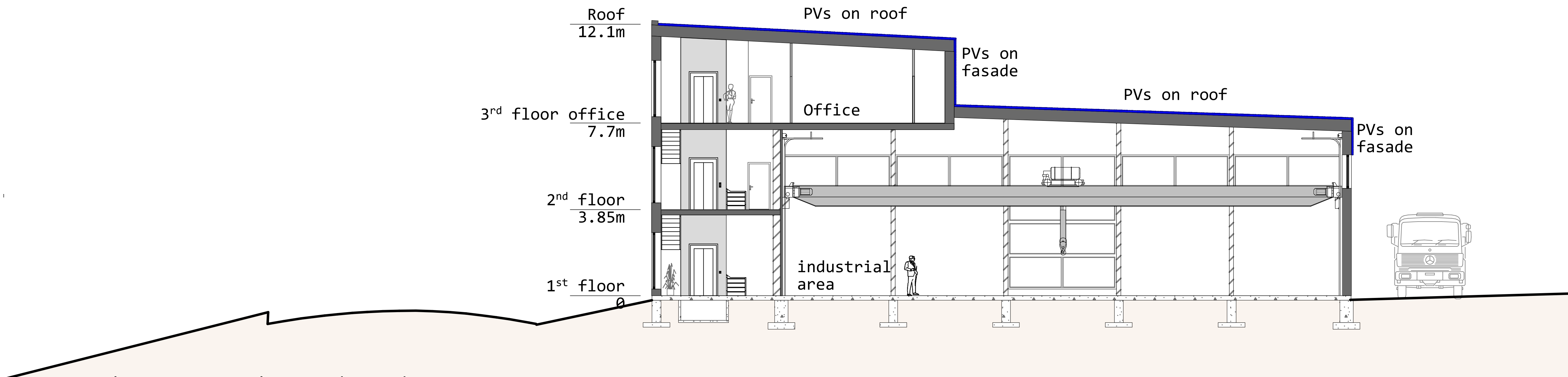
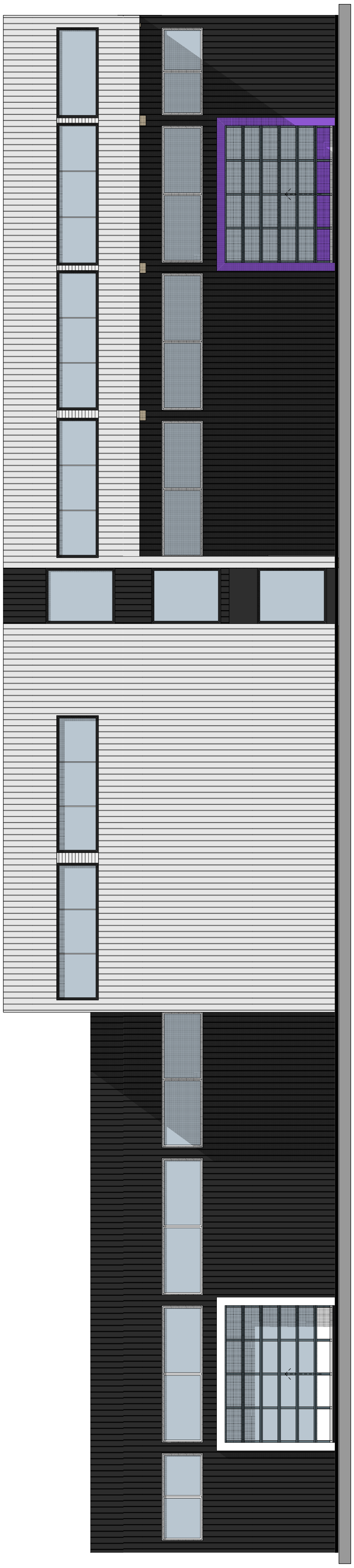


Figure 13: Section north-south 1:200

ELEVATIONS
1:200



1:Figure 14: South fasade
1:200

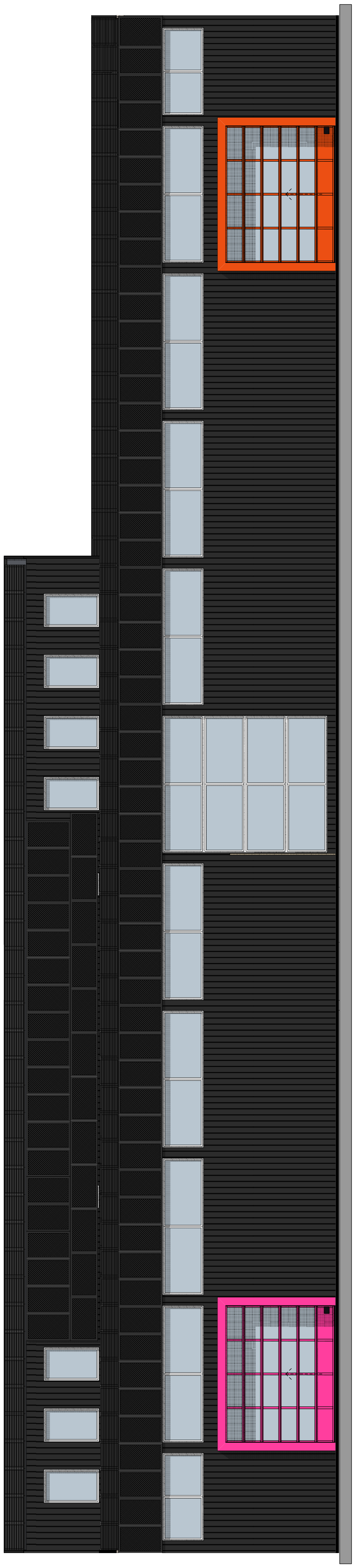


Figure 15: North fasade
1:200

ELEVATIONS
1:200

Figure 16: East fasade
1:200

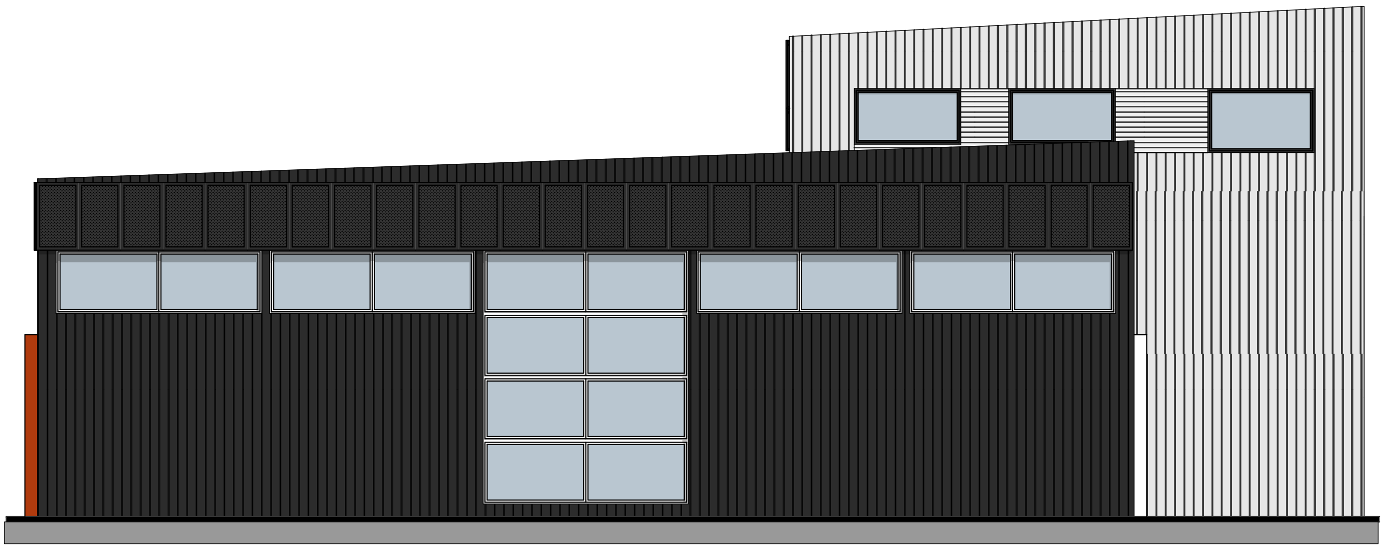


Figure 17: West fasade
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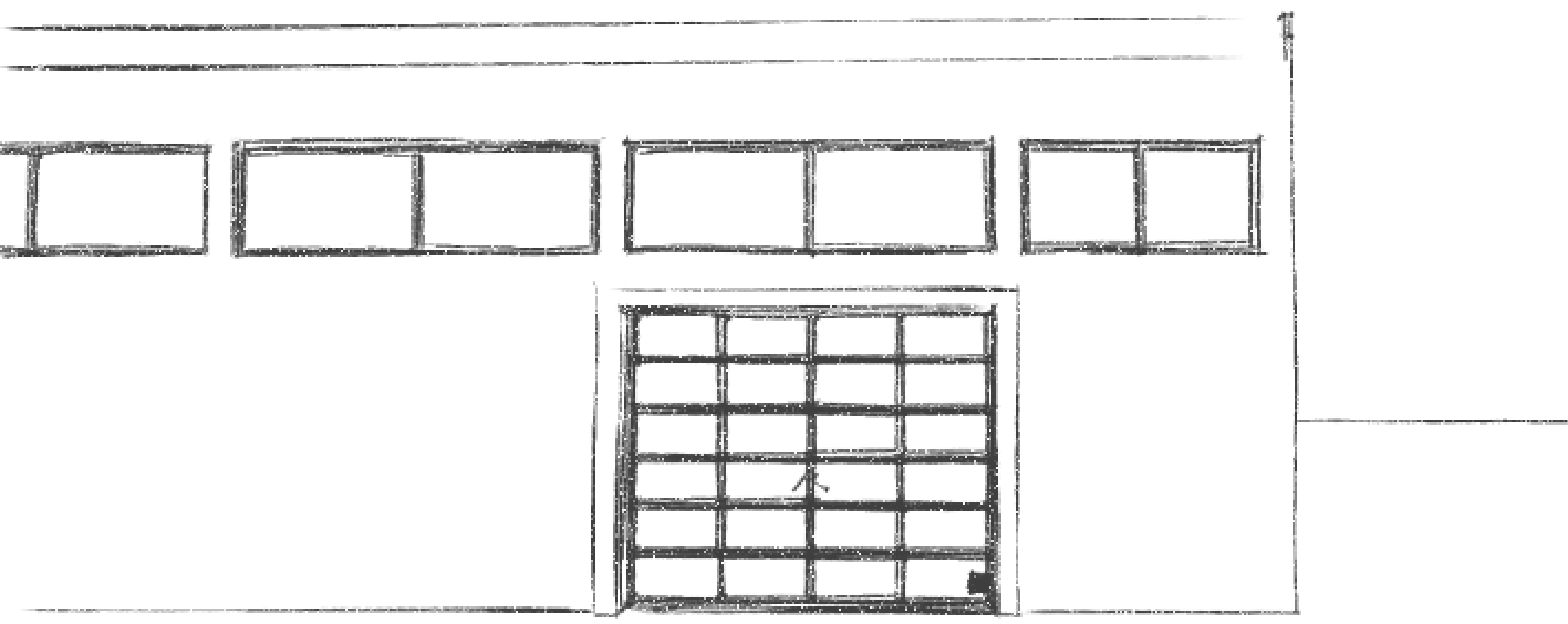
CHAPTER V:

PASSIVE AND ACTIVE STRATEGIES



PASSIVE AND ACTIVE STRATEGIES

Passive and active strategies are used in this project to enhance the efficiency. The local climate influences the strategies to be applied. This project studied solutions applied to cold climates.

PASSIVE STRATEGIES

Daylight

Recommendation by Byggforsk and building regulation in the Norwegian law sets that DF should be higher than 2% in rooms for workplace. All the spaces were tried to present a daylight distribution evenly, reaching the most points in the space. The daylight analysis is more focused on the industrial part since the office area has the workspace in a satisfactory distance from the windows.

The industry has a depth of 25m. The middle area behind the entrance lacks daylight. Stojkovic et al (2016), studied daylight for existent industrial buildings. The studied shows that industrial buildings with window/wall ratio between 10% and 20% and depth above 15m are challenging to have a good daylight. The author suggests increase of material reflectance and use of skylights. Skylights are not considered in this project since the mean DF achieve the target.

The materials considered for this project has a medium reflectance. The floor in the industry is concrete and the walls in CLT. In the office space, the walls have light wood cladding. The internal wall is white (high reflectancy) to increase the DF in that area.

The window proposed in this project is triple glazing with argon gas filling. The U-value is set at 0.59 W/(m².K)

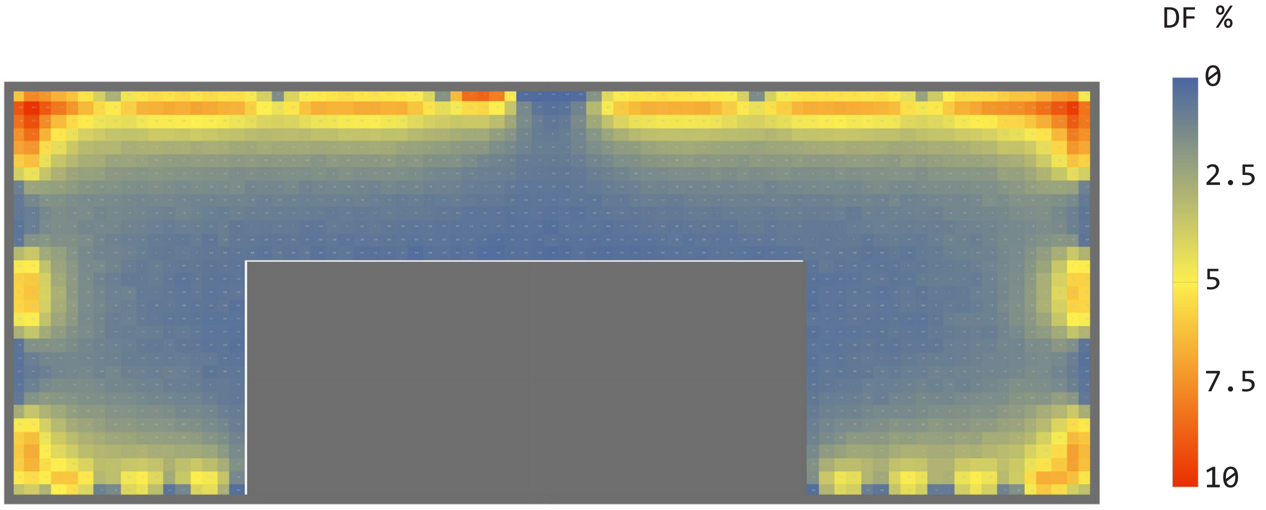
The simulations to check the daylight factor used Rhinocherus, plugin DIVA. The plane for all analysis was 0.78m above the floor, an approximate height of office tables in a workspace.

The office area considered windows with high of 1.5m, 0,9m above the floor. The north fasade has windows along the whole wall in the workspace, creating a comfortable indoor environment for the users. In the east and west fasade, smaller windows were placed to avoid glare. The south fasade has in total seven windows 1.5x2.0m. The mean DF in the workspace area is 3.01%.

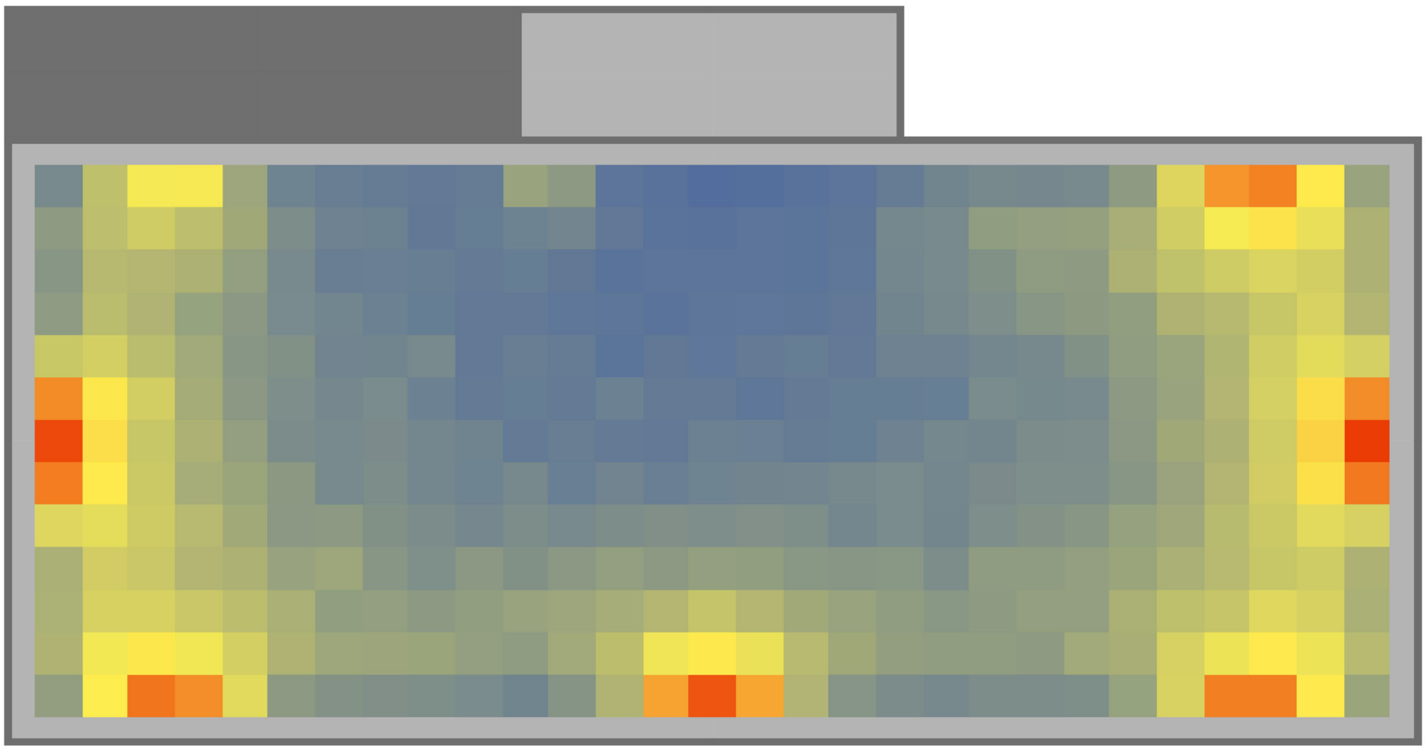
For the industry, the initial simulation (A) studied windows placed in the last element system, with glazing 1,5m high along the perimeter. In total 161m^2 of glazing were placed 4.5m above the floor. The mean DF was 1.33, not sufficient.

Most windows were placed in the upper part of the wall to guarantee a deeper daylight in the production area. Even so, in the middle, there were points with mean DF < 1. Another portion of the windows were placed in a vertical axis. As thermal mass is being explored as a passive strategy, it was important in this project to have a sun hitting the exposed concrete floor.

Figure 18: Daylight analysis



Office space



Industrial space

The following simulation (B) considered the garage door with glazing. The garage door has a significant area, being 4.8mx4m and it is facing south and north. This also enhance the possibility to place more PVs in the south fasade.

The simulation C added a vertical window in the south fasade, with 27.75m². The DF increased but still not sufficient.

The final simulation (D), added two more vertical windows, one in the east and other on west fasade. The final window sizes resulted in a mean DF = 2.28 for the industrial area (figure 18).

In general, the energy demand increases with the increase of glazing area. The U-value of the walls is smaller compared to the U-value of the glazing, leading to heat losses. By the other hand, solar gains can reduce the heating demand (LECHNER, 2015), in special if the windows are facing south.

The simulation B added only windows in the south fasade as a replacement of the industrial doors (U-value 1). The industrial doors are mainly produced with steel sandwish system and the heat losses are high. The glazing has a lower U-value. As a consequence, the energy demand is lower. Furthermore, glazing facing south increase the solar gains.

The final energy demand in the building is 187986 kWh/year, or 95.2kWh/m².

Table 09: Daylight analysis

Simulation	Industry glazing area (m²)	Industry mean DF (%)	Office glazing area (m²)	Office mean DF (%)	Energy demand (kWh/m²)
A	188.25	1.33	82.8	3.01	95.3
B	261.85	1.79	82.8	3.01	94.9
C	311.35	1.92	82.8	3.01	95.0
D	360.1	2.28	82.8	3.01	95.2

Natural ventilation

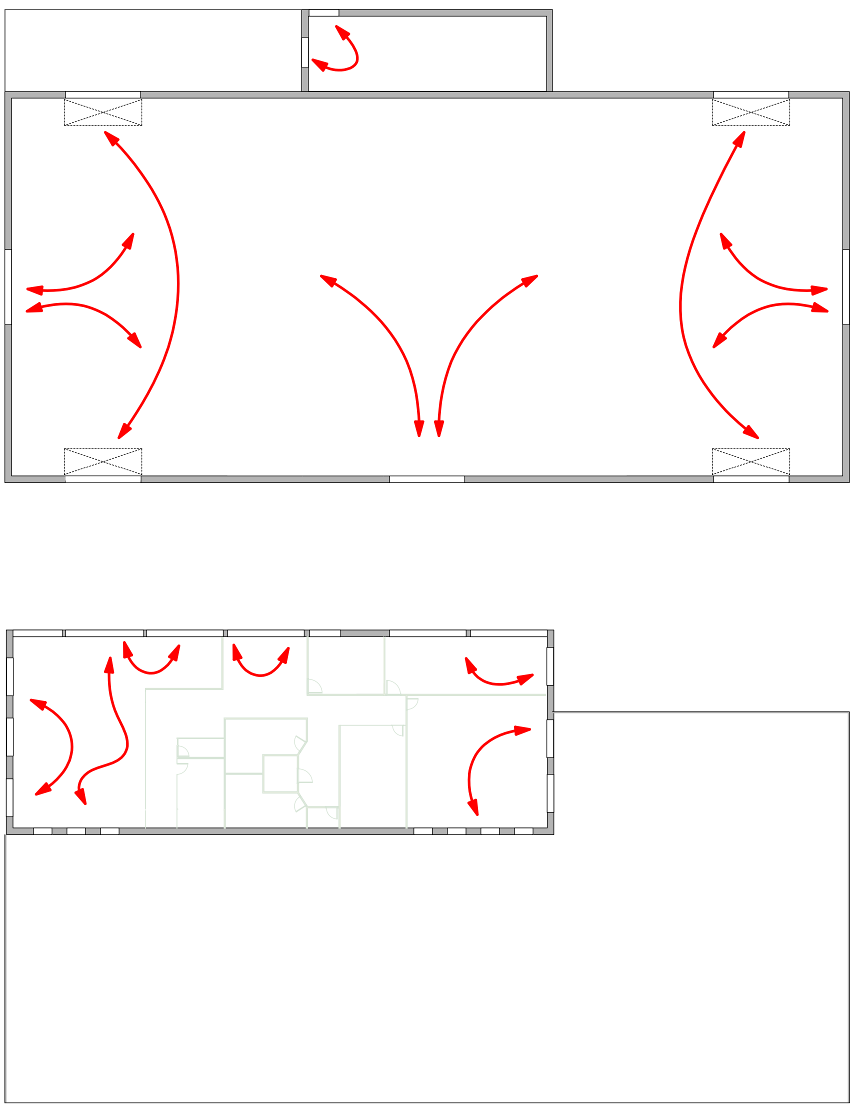
All the windows in the office space have the possibility to be opened. The cross ventilation in the area is a advantage in the summer to avoid overheating.

After simulations in SIMIEN, the maximum operative temperature for the industry is 28.4°C in July. In the summer months, it is possible that the gates can be kept open, as they are placed in opposite sides, they will guarantee natural cross-ventilation along the room. The upper windows are fixed glass frames, but the lowest windows are designed to be open in the summer period.

During the winter period, the windows and doors in the factory and in the office should remain closed to avoid heat losses through the openings.

Although the garage doors will be frequently open to receive and deliver materials, the industrial doors technology provides high speed doors. The doors can be opened and closed in a few seconds, avoiding huge air exchange from outside to inside.

Figure 19: Natural ventilation in the building



Thermal mass

The concrete slab in the first floor act as a thermal mass. As it is possible to check in the daylight analysis, there is going to be sun coming through the glazing, heating up the concrete slab.

The concrete slab is an efficient thermal mass when exposed to sunlight. According to LECHNER (2001), the beneficial effect of thermal mass depends on the insulation quality. The author also suggest that the mass should be placed in the indoor side of the insulation. About the materials, the author propose that the use of concrete should be justified by as many benefits as possible, to compensate for its high embodied emissions.

The walls made in exposed CLT also present a thermal mass effect. The time lag for 30cm tick wall of concrete is 8 h, against 20h for wood (LECHNER, 2001). Even though wood present a small thermal mass effect in comparison to concrete, in the internal CLT walls in the factory lead to thermal effects.

The floor in the factory is exposed, letting the sun in during summer months mainly. Also, it is considered that in sunny days, the doors in the factory are going to remain opened, exposing more the concrete slab to sunlight.

A simulation in SIMIEN for three different types of floors in terrain shows how thermal mass affects the energy performance. The results present that the use of thermal mass saves 1.19kWh/m² in comparison to a light floor.

Based on the comparison, it is worth to use exposed concrete floor in the industrial area. Concrete was already the option for the industry floor due to its properties. Using it as a thermal mass is a good alternative to make the best out of this material, since its embodied emissions are high.

The thermal mass storage is desirable for the project. For that, it is necessary to avoid hear losses through the ground. It can be don with the use of insulation under the slab and/or around the concrete foundation.

Brinks et al (2016) reserched nearZEB for industrial sector and describe the types of insulation in the floor slabs and its effects. A building with vertical insulation 1,0m deep is capable of store energy from the summer and use it in the wintertime. This effect is beneficial in this type of construction due the large size of the slab, made of concrete, a material that have a good energy storage. The effects were studied for steel construction and concrete slab.

A common practice was already done by the company, insulating around the building more then the slab. The results from constructions built a few years ago reported lower heating demand along the years. This effect corroborates with the results from Brinks et al (2016). The ground takes around 4 years to warm and present a steady condition regarding the energy losses through it. It is expected that the heating demand decreases after four years of construction.

Table 10: Effect of thermal mass in energy demand

Floor type	Energy performance	Heat capacity
	kWh/m²	Wh/m²k
concrete floor with thickness over 100mm	95.2	63
concrete floor with thickness below 100mm	96.0	13
light floor	96.4	3

Simulations in SIMIEN were done to check the effect of insulation in the storage of thermal mass (table 11). The results shows that the insulation around the building does not affect the heating demand in a significative way. This is probably due to SIMIEN limitation, that do not consider the effect of storage of thermal mass in the slab.

Furthermore, SIMIEN simulates the energy demand along the year and would not be able to calculate the storage after four years.

Table 11: Effect of ground insulation in energy demand

thickness of EPS insulation under slab (mm)	U-value	Width EPS insulation around foundation (mm)	Emissions (CO_2 factor 2,9 m²)	Energy demand kWh/m2	Emissions kWh/m2
200	0.17	-	16820	95.2	8.5
150	0.23	-	12615	95.4	6.4
300	0.12	-	25230	94.9	12.8
200	0.17	60 - vertical	16922	95.1	8.6
200	0.17	60 - horizontal	16922	95.2	8.6

ACTIVE STRATEGIES

Geothermal energy

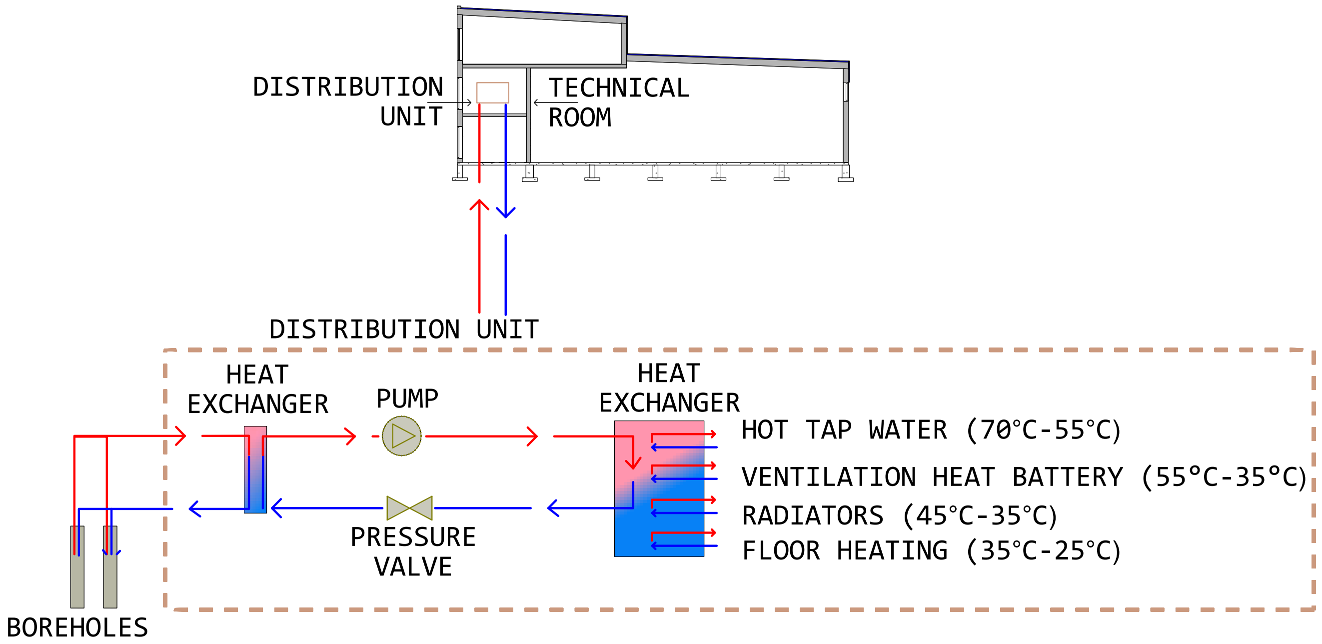
The heat pumps system consists in a system that transfer thermal energy from a source cooler to a warmer space using the refrigerator cycle and vice-versa. It is efficient and recommended for cold climates (LECHNER, 2001). Many ZEB in Norway and Sweden have been using this technique as a active strategy to reach a ZEB goal (DOKKA et al, 2015).

The use of heat pumps with a geo-exchange is a good alternative to supply the heating demand of the building. It is also a sustainable solution. The location of the building could make it possible to install an air-water system or all air system.

The heat pump for this project has a efficiency of 2.91, according to available commercial systems. The industry and the office will be heated and cooled by the heat pumps. The HP will also supply 80% of the hot water.

The gases working in the unit is a CO_2 liquid, that works with high pressure and is able to deliver high temperatures to the water tank. The water tank should have a temperature of 70°C to avoid bacteria growth.

Figure 20: Ground source heat pump scheme



Renewable energy

PV systems are being used in the roof to generate electricity and it is a common strategie to compensate the building's emissions in ZEB (DOKKA et al, 2015).

The technology for photovoltaic cells is in constant development. Nowadays, there are many types of commercial PVs. It includes glass panels, colorful, flexible, and so on. The negative point of the new technologies is the low efficiency compared to the emissions. To achieve a ZEB goal, the emissions from the PV system should be as low as possible with the best efficiency.

Emissions from PVs are studied for Kristjansdottir et al, 2016. In the study, it is presented estimation around existing PVs installed in Scandinavia. Most PVs are fabricated in other countries or have the raw material coming from many different places, making it difficult to estipulate an accurate number. The author considered that the emissions can vary from 150 to 350kgCO_{2EQ}/m^2.

For this project, it is proposed PV models coming from REC, with emissions of 210kgCO_{2EQ} per area of module. The modules have a size of 1665 x 991 cm.

The PVs are installed integrated in the roof, which as a tilting angle of 2 degrees only in the factory and 3 degrees in the office space. The PV considered for this project is a module of efficiency of 23%. The efficiency of solar panels tends to increase along the years, according to Bergensen 2015. This detail is however not considered for the emission calculation.

Figure 21: PV produced by REC

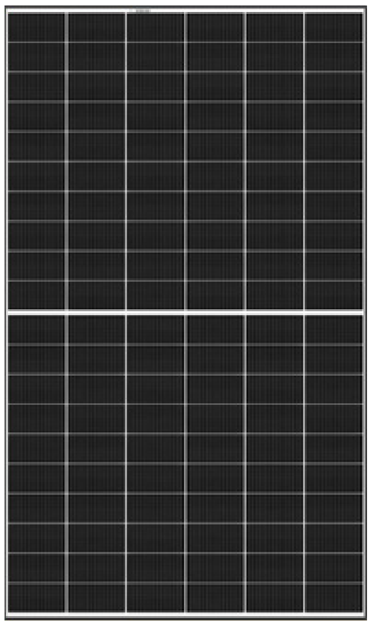
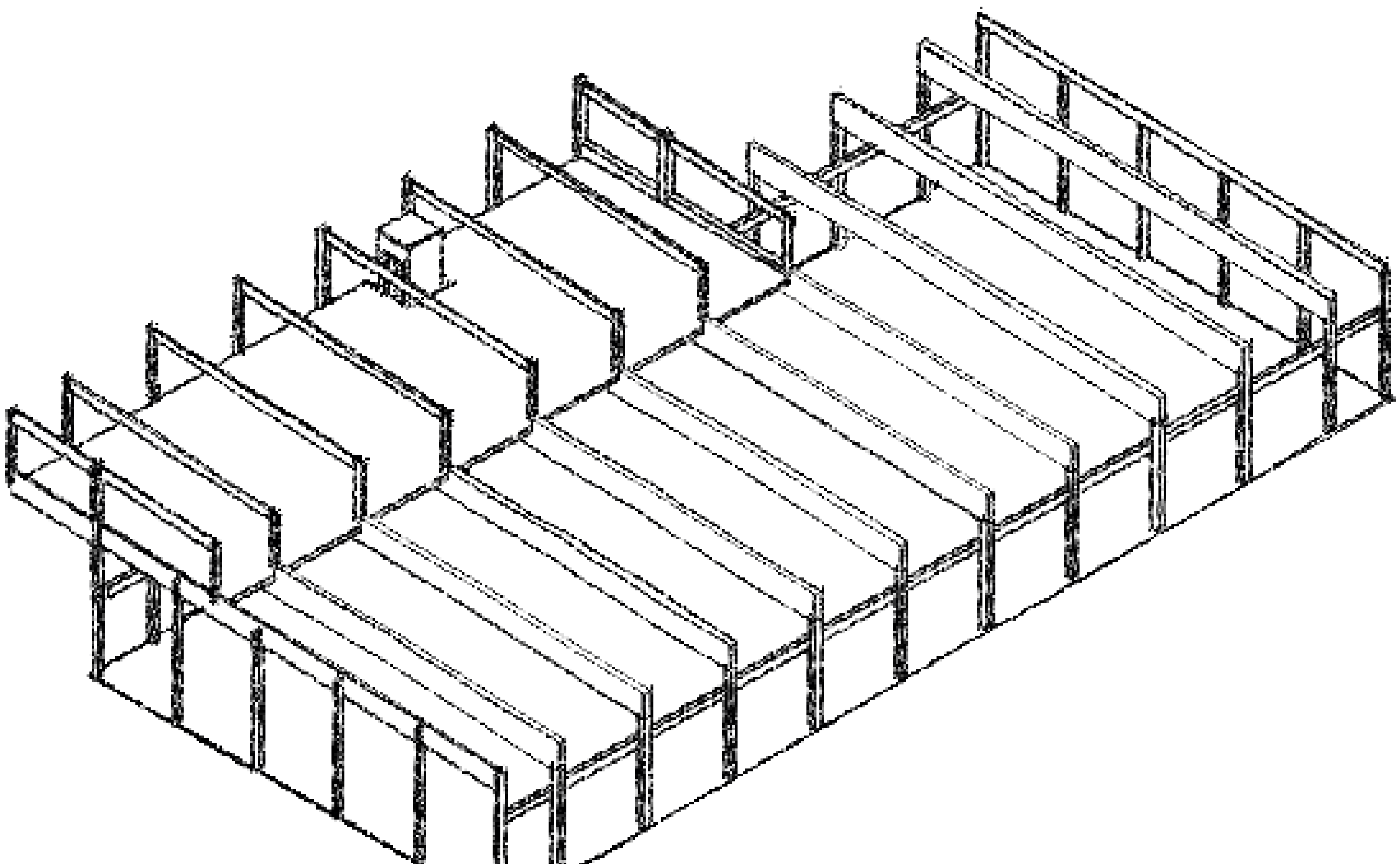


Table 11: Amount of PVs in the building

Location	Amount of panels	Effective area of PVs (m^2)	Total energy production (kWh/yr)
Roof	957	1579	235235
East fasade	26	42.9	3873
South fasade	87	143.5	17951
West fasade	26	42.9	3168
Total	**1096**	**1808**	**260227**

CHAPTER VI:

BUILDING TECHNIQUE AND DETAILS



BUILDING SYSTEM

Wood is an available product used in Scandinavia. Recently, the use of wood structure for large buildings is becoming more common, with the development of Engineering Wood Products (EWP).

Wooden columns and beams are made using glulam and CLT. It is a solution to replace steel and concrete in small and large scale constructions. The beams are placed in a grid system.

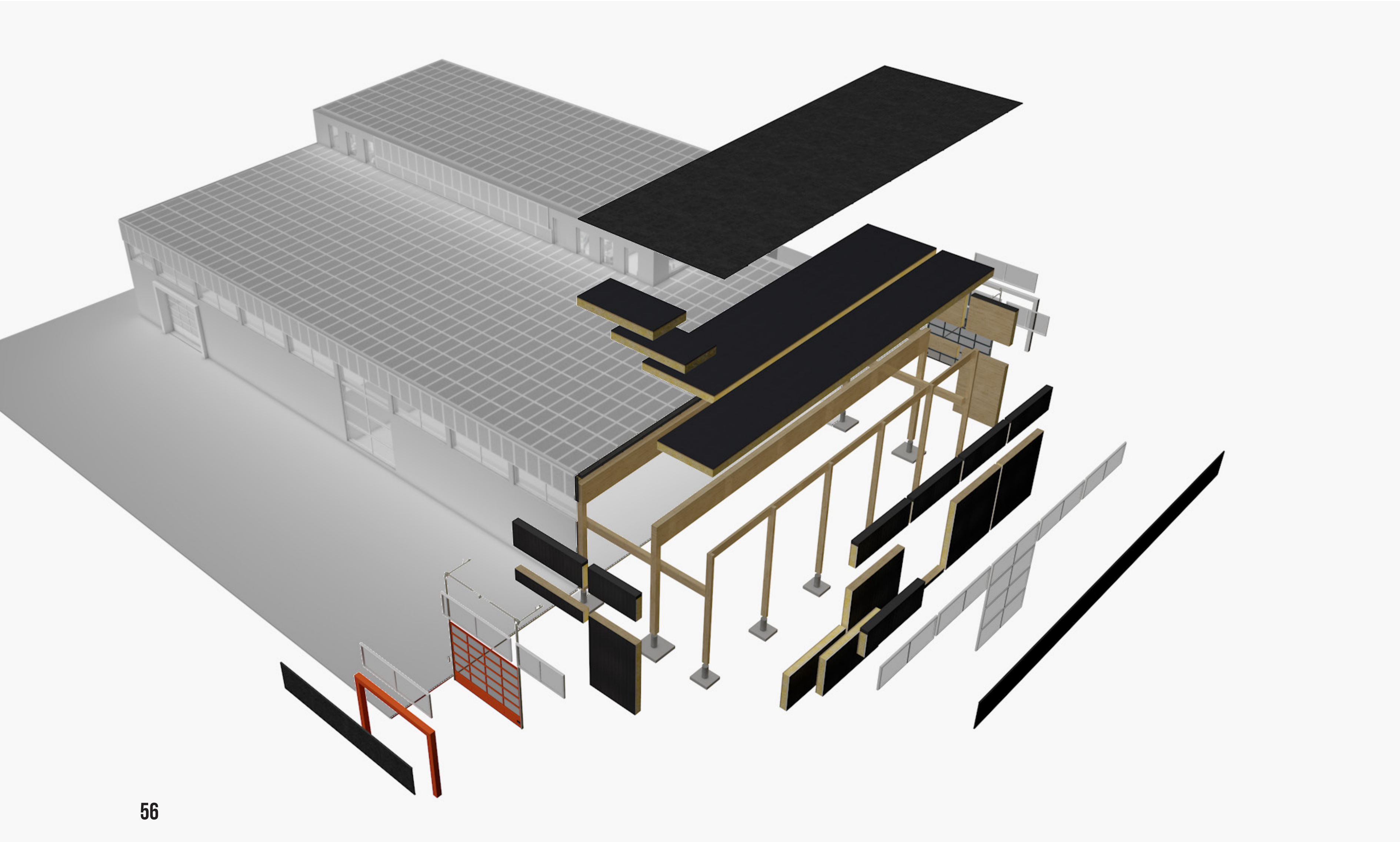
The size of the beams in this project are 380x1440mm, and guarantee a span of 25m in the production area.

The columns are 360x380mm and the distance between each other of 5m, in average.

The modular system used by GAAS consists in a sandwich element that is going to be placed in between the columns. Figure 22 shows a scheme of the external elements placement.

The technique makes the construction faster, because the elements are made in a warehouse and transported to the building site in a size that vary according to the project needs.

Figure 22: Building assembly system



The element size has a practical limitation nowadays of 4,8mx2,4m. This is a result of the CLT size available in the market. The control of the elements is more precise and makes the construction with less waste.

The external wall elements have the internal CLT, the insulation and the cladding already from the mounted. The panels that are going to receive solar panels will be finalized on site.

The placement of the vapour barrier and wind barrier have influence in building air leakage. According to Brinks et al (2015), leakages in vapour barrier connections are responsible for 44% of total leakages in light steel buildings.

The vapour barrier is placed between the CLT and the insulation. The elements are made with vapour barrier to be connected in the windows and in the columns. This practice decrease the air leakages in the building.

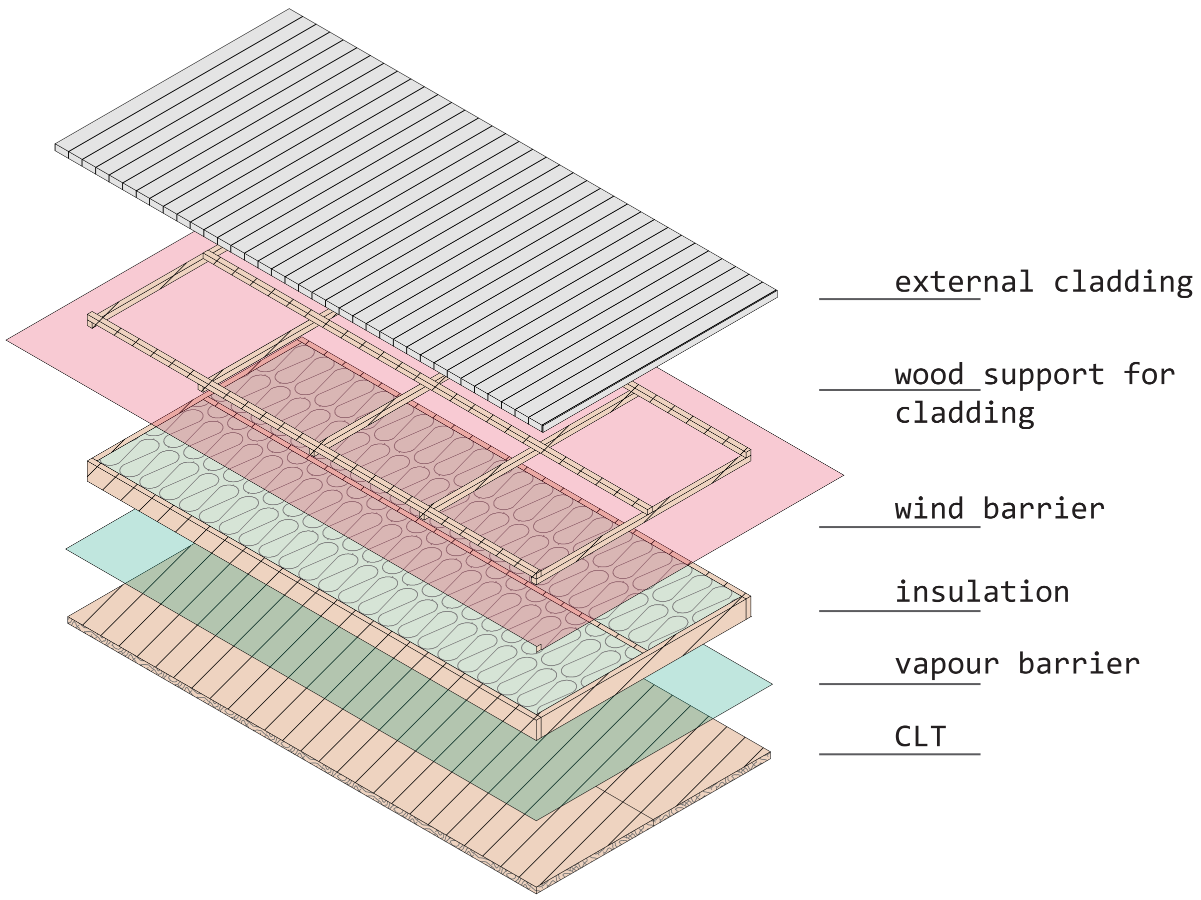
The wind barrier is placed between the insulation and the external cladding and protects the insulation againts external weather conditions.

The sequence of construction is starting by the reinforced concrete foundation and slab, followed by the placement of the columns and beams. After the structure is set, the slabs in between the floors are placed. It is a common practice by GAAS to use a layer of concrete in the floor slabs to provide weight to the structure and stability. For this project concrete is not considered in the slabs betweenn floors, to avoid emissions.

Subsequently, external walls and roof elements are placed in between the columns, followed by the technical installation, and windows, and, finally, the covering and finishing layers.

The roof elements are placed over the beam system and are mounted with the insulation and the PVs on top.

Figure 23: Exteral wall element



BUILDING TECHNIQUE AND DETAILS

DETAILS OFFICE AREA 1:50

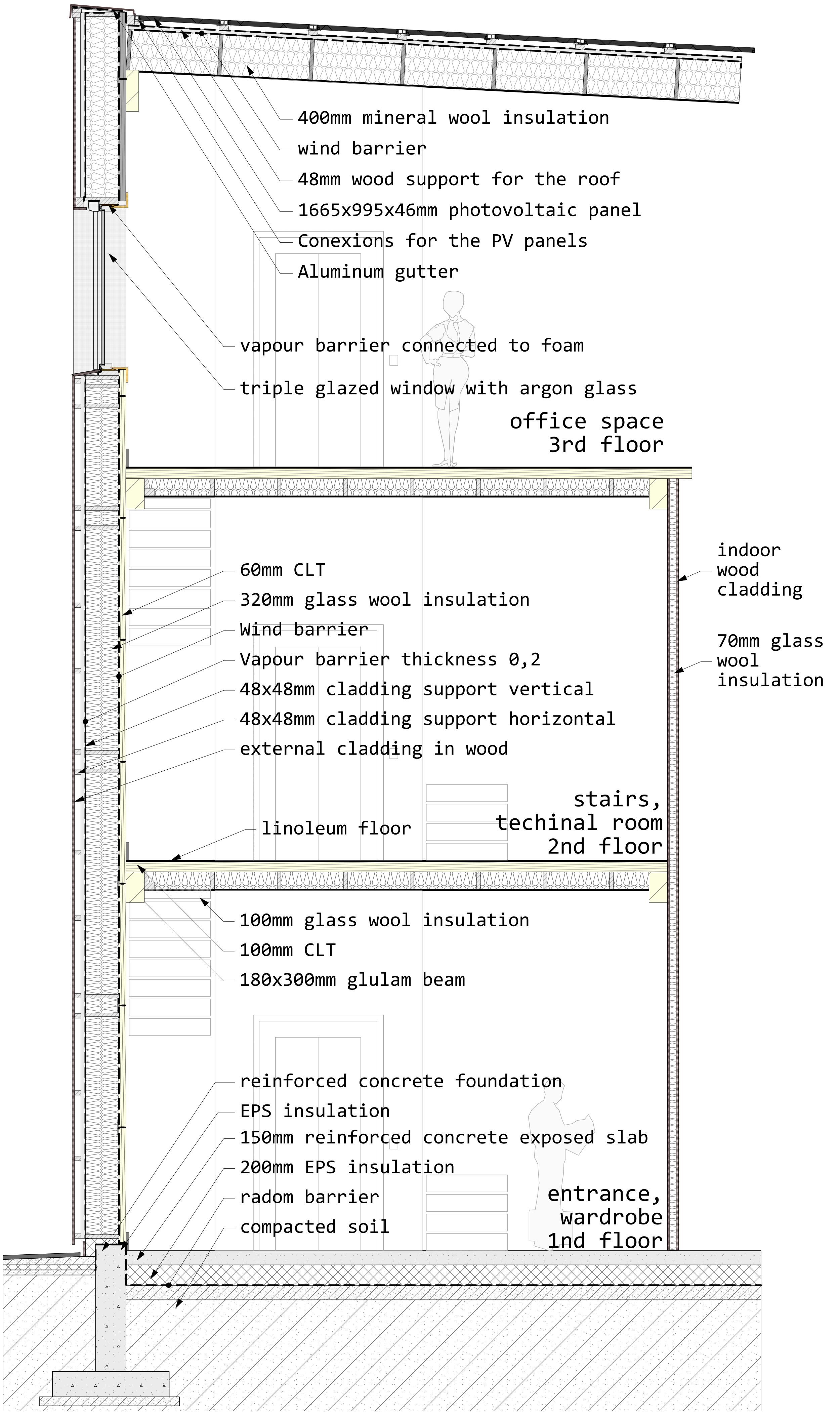


Figure 24: Details office area
1:50

DETAILS INDUSTRIAL AREA 1:50

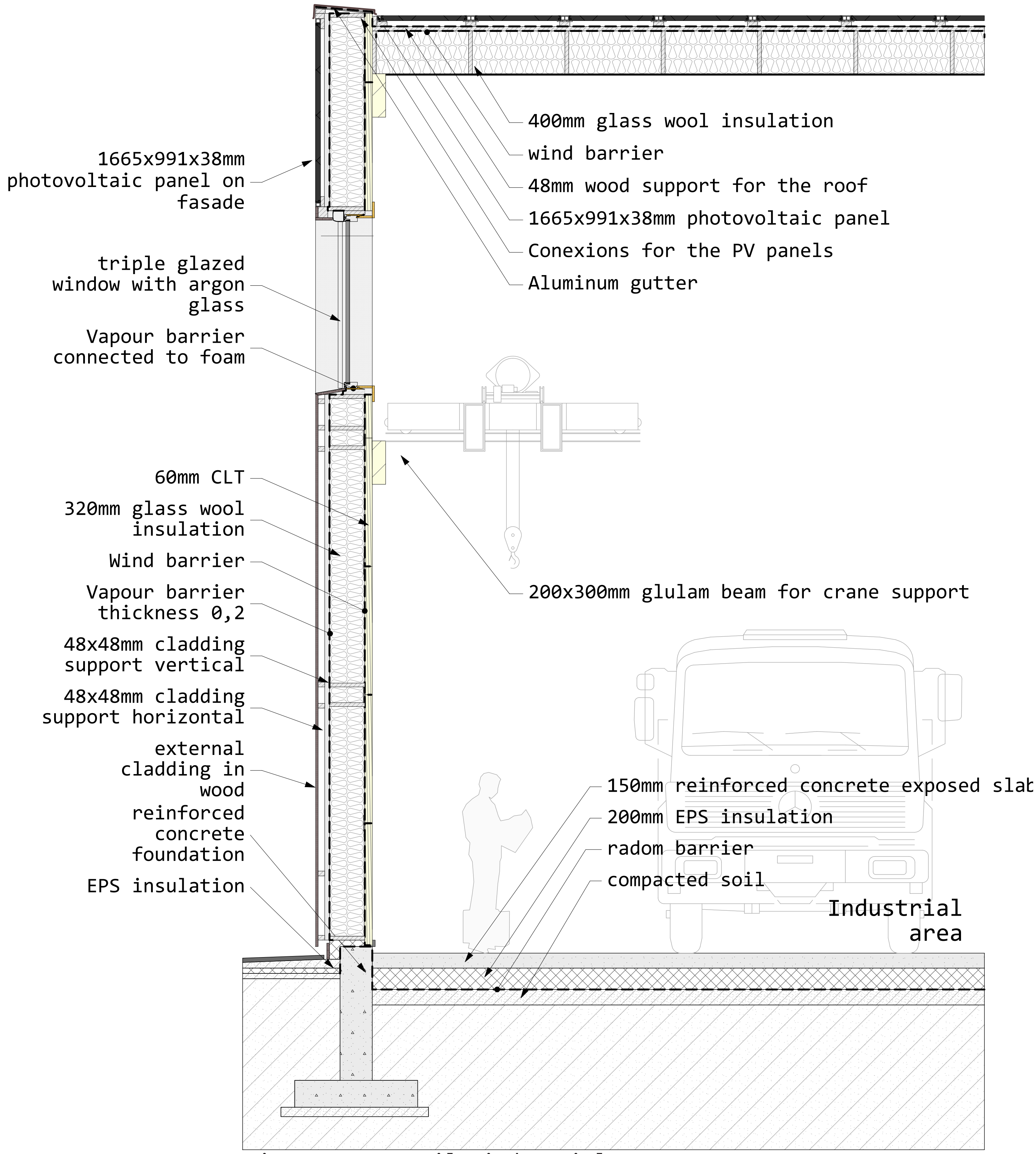
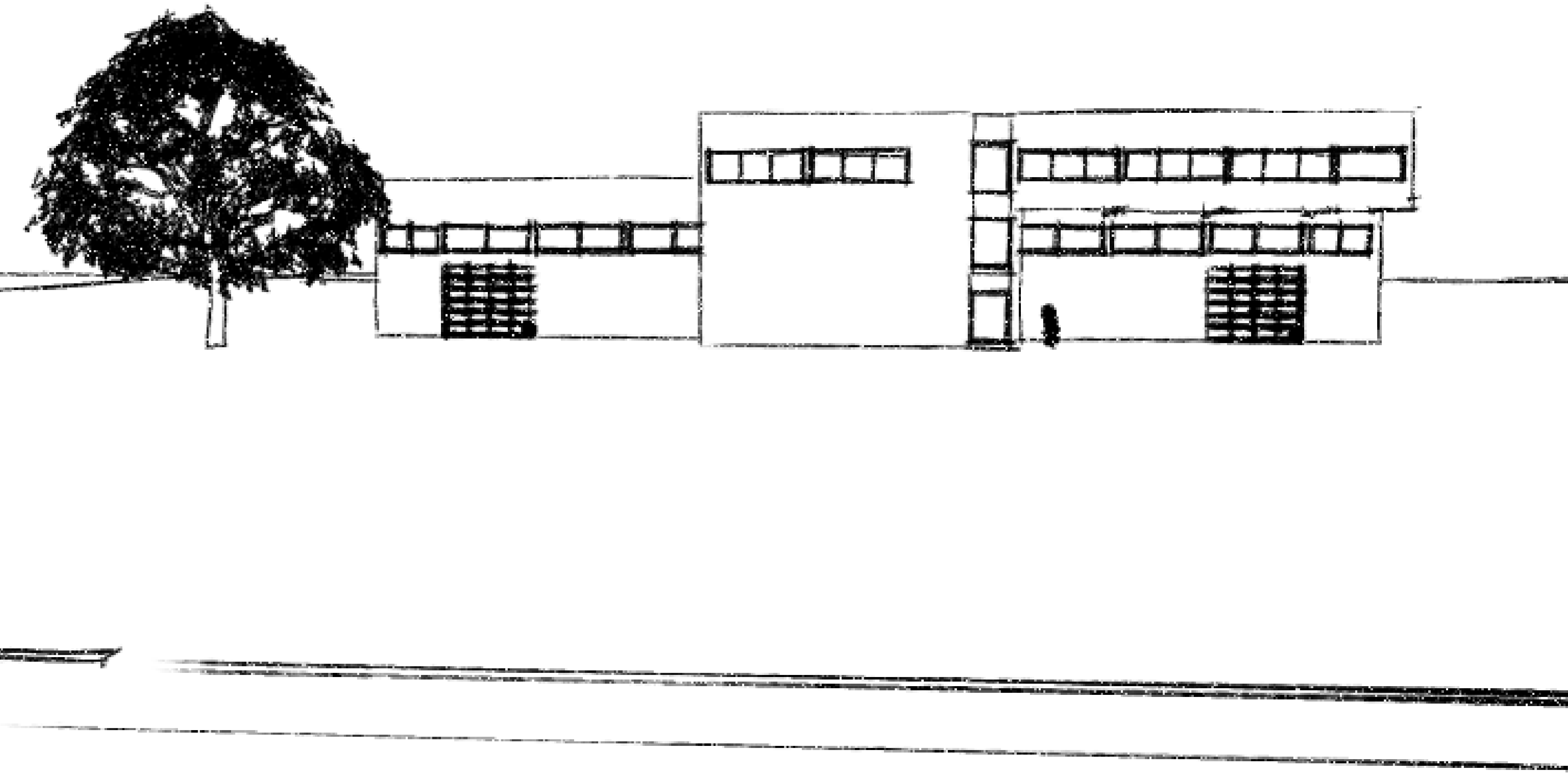


Figure 25: Details industrial area 1:50

CHAPTER VII:

MATERIALS



MATERIALS

FOUNDATION

Footing foundation is used in this project. The footings are placed under the columns. The material used is reinforced concrete.

A concrete slab is projected in the industry and office area with 15cm of thickness. The industry area request reinforcement due the trucks movements inside. This is done by a steel mat with bars 10mm spaced 10cm in both directions. The density of the steel net is 12.46kg/m^2.

The concrete slab is going to be exposed in the industry and in the office, leading to thermal mass effect. Concrete is a material with a high CO_2 factor. Even with new reasearches about a more sustainable concrete, the manipulation of the raw material (clinker) is responsible for high emissions.

The footings are in a rectangle shape, dimentions WxDxH 2000x2000x300mm with a pile of DxH 600mm 1000mm. At the external core, the foundation is not taken massive loads, so it is 1200mmx-1200mx200mm with a column of DxH 400mmx-1000mm high.

The floor is insulated with EPS below the concrete slab. The initial insulation considered for the shape is 200mm. The insulation is important to keep the heating in the building, specially in this case where the concrete is being used as thermal mass.

EXTERNAL WALL

CLT is being used in sustainable buildings due to its low impact on the environment. To compare CLT with other materials in the building industry, it is still a new solution that present a few uncertainties, such as reliability in the air tightness and moisture barrier after a long period of time (WAHLSTRØM, 2020). The modular system uses CLT. The structure is beneficial for horizontal forces from wind and crane.

The factories built in Norway lately use in general steel construction with insulation. According to Petersen (2002), a comparison between a construction of the Gardemon Oslo airport for steel and wood point to wood as a more sustainable material. Steel beams have an energy consumption two to three times higher than a glulam beams, considering for both the same structural capacity (0.14m^3 of wood and 60kg of steel). The results show that wood is a good alternative to be used in buildings and reduce the GHG emissions.

Some projects have uses external walls with 100 mm CLT. For this project, as the grid between two panels are maximum 5,5m, the thickness can be reduced to 60mm without harm for the structure.

CLT has a CO_2 emission factor of 140kgCO_{2eq} per m^3 while the insulation 200mm has 12.7 per m^2. Therefore, it is worth to replace part of the CLT for insulation and wood timber joints in terms of emissions and maintaining the same structural performance and U-value.

The insulation used in this project is glass wool, due to its low embodied emissions when compared to other types such as rock wool. Wood fibre is also a good alternative for insulation, but the emissions turn out to be higher. For the same resistance (R=1m^2k/W), wood fibre presents a CO_2 factor of 0.9 while glass fibre presents 0.7.

Brinks et al (2016) studies the cost optimization for industrial buildings in Germany, and concluded that for a warehouse of 2000m^2, the cost-effective insulation is 0.27W/m^2K for a pay back of 10 years, and 0.17W/m^2K for 20 years. In terms of cost, as much more the insulation, less energy demand for heating. A comparison in SIMIEN presents in table 13 values for energy demand for different U-values.

MATERIALS

It is possible that the payback time for the the low U-value used is longer for the industrial space than to the office space. The office has a higher energy demand so the influence of the insulation size is more critic.

The high insulation of the envelope is one of the most efficient ways to reduce the heating and cooling demand. As expected, the increase of a U-value increases the heating demand. The U value of 0.1 would be the most adequate to decrease the heating demand. The windows are a triple glazing type with high insulated wood frame and have an U-value of 0.59.

Table 13: Effect of wall U-value in the energy demand

External walls U value (W/m^2K)	Energy demand ($kWh/yr.m^2$)
0.1	95.18
0.12	95.78
0.15	96.66

MATERIALS

INTERNAL WALL

The internal walls are made with wood studs and 70mm of insulation in the middle. On both sides, a wooden cladding is considered. The internal walls will be assembled on site.

The meeting rooms and in the office space, the division walls are in glass, to offer more daylight quality into the corridor and make the space with an open concept.

INTERNAL FLOORS

The floor in the industrial area is in exposed concrete, to provide thermal mass. On the second floor, where it is only the stairs and technical room, and in all the office space, the floor is linoleum. Linoleum is a sustainable natural material, fairly water resistant, made from solidified linseed oil.

In wet areas, such as showers, ceramics are being installed on a membrane solution.

ROOF

The roof is going to receive 40cm of glass fibre insulation and wood studs for the frame. The roof is also done in elements, being placed in between the roof beams. All the roof is going to receive solar panels.

The covering of the roof is made with the PVs. In a large scale, the PV is replacing the bitumen in the roof, saving 4478.40kgCO_{2eq} in emissions A1-A3 (1555m^2 with a CO_2 factor of 2.9). Also, bitumen has a lifetime factor of 1 in this project, meaning that it should be replaced in 30 years, saving for B4 4478.4kgCO_{2eq}.

CHAPTER VIII:

ZEB BALANCE

EMBODIED EMISSIONS FROM MATERIALS

The ZEB balance was done with the ZEB Tool developed by SINTEF. The environmental product declaration (EPD) contains information about the emissions regarding the fabrication of producs. Most of the materials considered have a EPD in the Norwegian EPD database.

Some materials that are lacking in the database were estimated in the Finish CO_2 Data or in environmental reports.

Table 14 presents the values for the embodied emissions from materials A1-A3 and B4.

Emissions A1-A3 is related to raw material acquisition, transfortation of this material to the factory and the manufecturing process.

Emissions B4 consider the product lifetime during the building usage. It is related to the replacement of the material during the lifetime. The majority of the materials do not need to be replaced in ths project (lifetime factor equal to 0).

Nonetheless, the PV system available nowadays need to be replaced in 30 years (lifetime factor 1). The heat pump system also need to be replaced each 20 years.

In this project it is not considered emissions from the construction process stage (A4-A5), maintenance stage (B2), end of life stage (C1-C4) and benefits ands benefits from reuse or recycle (D).

ZEB BALANCE

Table 14: Embodied emissions

Material	Source	Amount	Emissions A1-A3 ($kgCO_{2eq}$)	Emissions B4 ($kgCO_{2eq}$)
Groundwork and Foundations				
Concrete slab and foundation	NEPD 283N (2014)	247.1 m^3	46511.63	
Steel bars reinforcement	S-P-00305 (2015)	369.40 kg	136.68	
EPS insulation	NEPD 322-185-NO (2015)	1681 m^2	4976.62	
Radom membrane	NEPD 209N (2013)	1425 m^2	1781.25	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**53406.2** **0.45**	**0** **0**

Material	Source	Amount	Emissions A1-A3 ($kgCO_{2eq}$)	Emissions B4 ($kgCO_{2eq}$)
Superstructure				
Columns Glue Laminated Timber	NEPD 336-22-NO (2015)	247.1 m^3	3243.92	
Beams Glue Laminated Timber	NEPD 336-22-NO (2015)	164.44 m^3	15128.48	
Slab CLT	NEPD 1269-410-EN(2017)	50.10 m^3	7014	
Insulation glass fibre	NEPD 221N (2013)	501.60 m^2	6347.25	
Spruse timber	NEPD 308-179-NO (2015)	100.32 m^3	5316.96	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**37050.61** **0.31**	**0** **0**

Material	Source	Amount	Emissions A1-A3 ($kgCO_{2eq}$)	Emissions B4 ($kgCO_{2eq}$)
Outer walls				
Entrance door	NEPD 393-278-NO (2016)	1 pc	132.97	
Entrance door factory	ecoinvent v3.1 (2014)	6.72 m^2	806.4	
Windows - fixed (included glazing for industrial door)	NEPD 392-278-NO (2016)	285.85 m^2	14146.56	
Windows - operable	NEPD 174N (2014)	162.95 m^2	10094.71	
Aluminum for industrial door	ecoinvent v3.1 (2014)	24 kg	295.20	
Windbarrier	NEPD 273N (2014)	1085.8m^2	460.38	
Vapour barrier	NEPD 341-230-NO (2015)	1085.8m^2	340.94	
Cross laminated timber 60mm	NEPD 1269-410-EN	65.15m^3	9120.72	
Insulation glass fibre	NEPD 221N (2013)	1628.7m^2	5182.52	
Spruce timber	NEPD 308-179-NO (2015	90.60m^3	3895.8	
External wood cladding	NEPD 1247-400-NO (2017)	1085.8m^2	647.14	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**46838.06** **0.40**	**0** **0**

ZEB BALANCE

Table 14: Embodied emissions

Material	Source	Amount	Emissions A1-A3 ($kgCO_{2eq}$)	Emissions B4 ($kgCO_{2eq}$)
Inner walls				
Interior doors	NEPD 157N (2012)	10 units	597.30	597.30
Glass walls	ecoinvent v3.1 (2014)	610.5kg	677.13	677.13
Insulation glass fibre	NEPD 221N (2013)	388.96m^2	431.75	
Spruce timber	NEPD 308-179-NO (2015)	31.5m^3	1669.5	
Internal wood cladding	NEPD 243N (2014)	15.42m^3	2743.22	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**6118.90** **0.05**	**1274.43** **0.01**
Floors				
Linoleum floor	12CA64879.101.1	457.70 m^2	75.93	151.87
Ceramics	IBU EPD-IKF-20	45.10 m^2	437.47	91.87
Binder	NEPD 1187-348-NO (2016)	315.7 kg	37.25	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**550.66** **~0**	**243.74** **~0**
Outer roof				
OSB plate	NEPD 1324-428-no (2017)	28,5 m^3	6355.5	
Spruce timber	NEPD 308-179-NO (2015)	124,4 m^3	5332.0	
Vapour barrier	NEPD 341-230-NO (2015)	1555 m^2	660.88	
Insulation glass fibre 400mm	NEPD 221N (2013)	1555 m^2	9896.02	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**22244.4** **0.19**	**0** **0**
Stairs				
Wood Spruse	NEPD 307-179-NO	2,8 m^3	120.40	
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**120.40** **~0.0**	**0** **0**
Renewable Energy system				
Photovoltaic panels	ecoinvent v3.1 (2014)	1808.4 m^2	379764	379764
Total of emissions ($kgCO_{2eq}$) **Total per area per year ($kgCO_{2eq}/m^2$/year)**			**379764** **3.2**	**379764** **3.2**

ZEB BALANCE

Table 14: Embodied emissions

Material	Source	Amount	Emissions A1-A3 (kgCO_{2eq})	Emissions B4 (kgCO_{2eq})
Technical system				
Heat pump 3kW	ecoinvent v3.1 (2014)	1 unit	550	1100
Air handling unit	ecoinvent v3.1 (2014)	2 units	77	
Ventilation duct	ecoinvent v3.1 (2014)	1000 m	1400	
Elevator	KONE RTS_66_20	2872 kg	8529.84	
Total of emissions (kgCO_{2eq}) **Total per area per year (kgCO_{2eq}/m^2/year)**			**10556.84** **0.09**	**1100** **0.01**

	A1 - A3	B4
Total of emissions (kgCO_{2eq})	**547341**	**382449**
Total of emissions per year (kgCO_{2eq}/year)	**9122**	**6374**
Total per area (kgCO_{2eq}/m^2)	**277.1**	**193.6**
Total per area per year (kgCO_{2eq}/m^2/year)	**4.62**	**3.23**

The total embodied emissions from the materials used in the project are 547341 kgCO_{2eq} in a 60 year of lifetime, and 9122 kgCO_{2eq}/year. The emissions per heated area are 4.62 kgCO_{2eq}/year/m^2.

The greatest contribution is from the PV system, accounting for 68.4% of the emissions. As the PVs has a high CO_2 factor, it is important to use the system with the maximum efficiency, optimizing the PV orientation for a maximum production as possible.

Emissions related to the lifetime factor of the materials (B4) also have a high contribution. The PV system contributed to almost 100% of the category of emissions.

Figure 26: Embodied emissions A1-A3 per building category

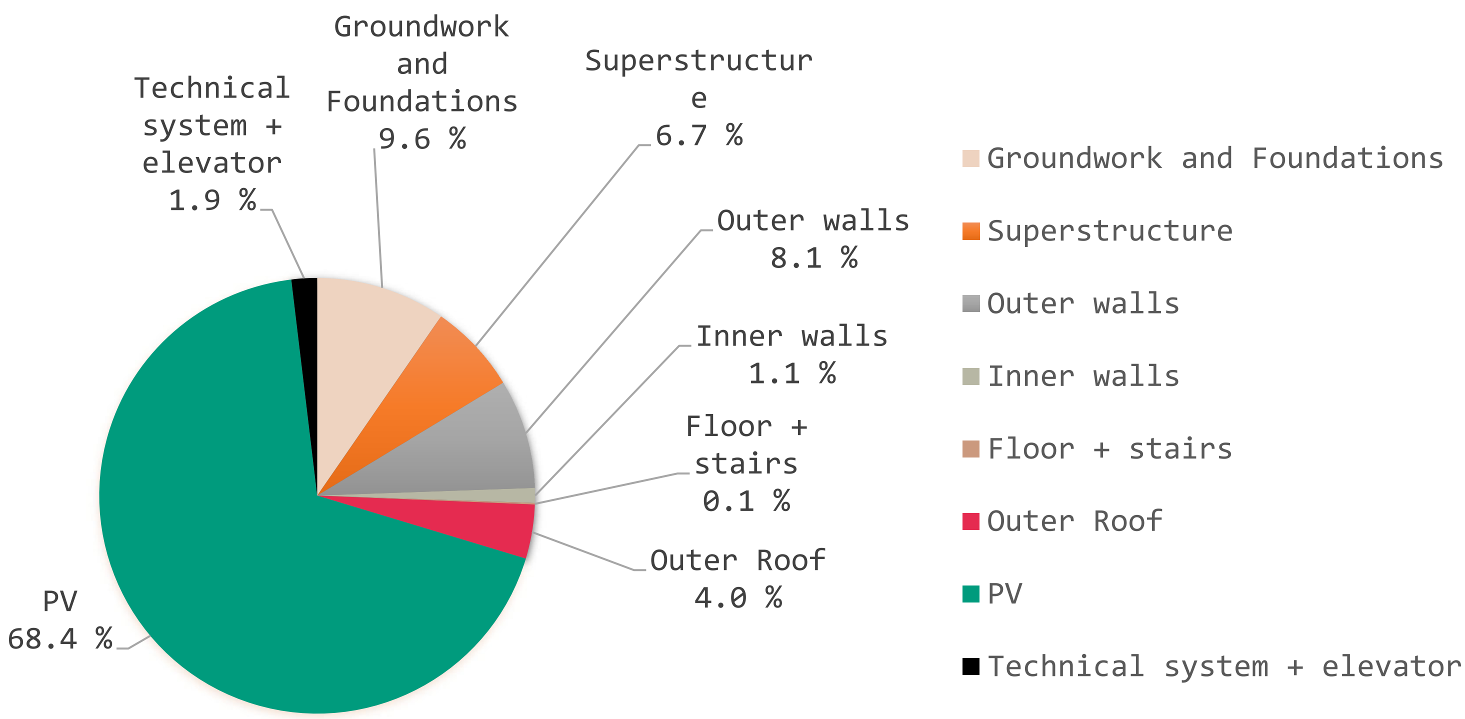
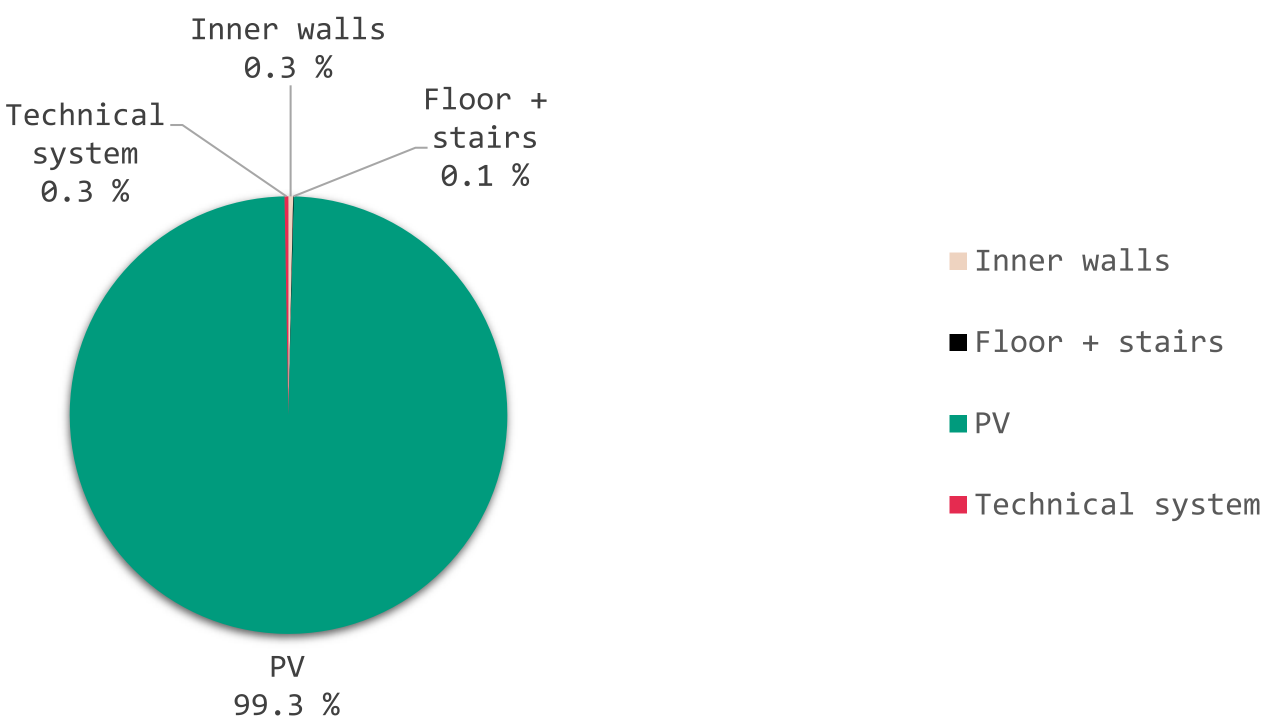


Figure 27: Embodied emissions B4 per building category



EMISSIONS FROM OPERATION EMISSIONS

The emissions from the operational phase of the building is accounted for a lifetime of 60 years. The energy demand imported from the grid is the emission driver. In this analysis it is considered that the electricity from the grid has emission factor of 0.132 $kgCO_{2eq}/m^2$ per kWh.

The energy demand for the building is 164 588 kWh/yr. Figure 10 presents the percentage of energy demand for each system. Most part of the energy demand comes from the technical equipment installed in the building, which will be used for the industrial area. Lighting also has a considerable contribution with 13%. Space heating contributes with 8%, mainly due the indutrial area, which has a low operative temperature and high heat gains.

Table 16 presents the emissions from the operation of the building. Each year, it is estimated that the operations emits 22619.85 $kgCO_{2eq}$.

Figure 28: Energy demand per category

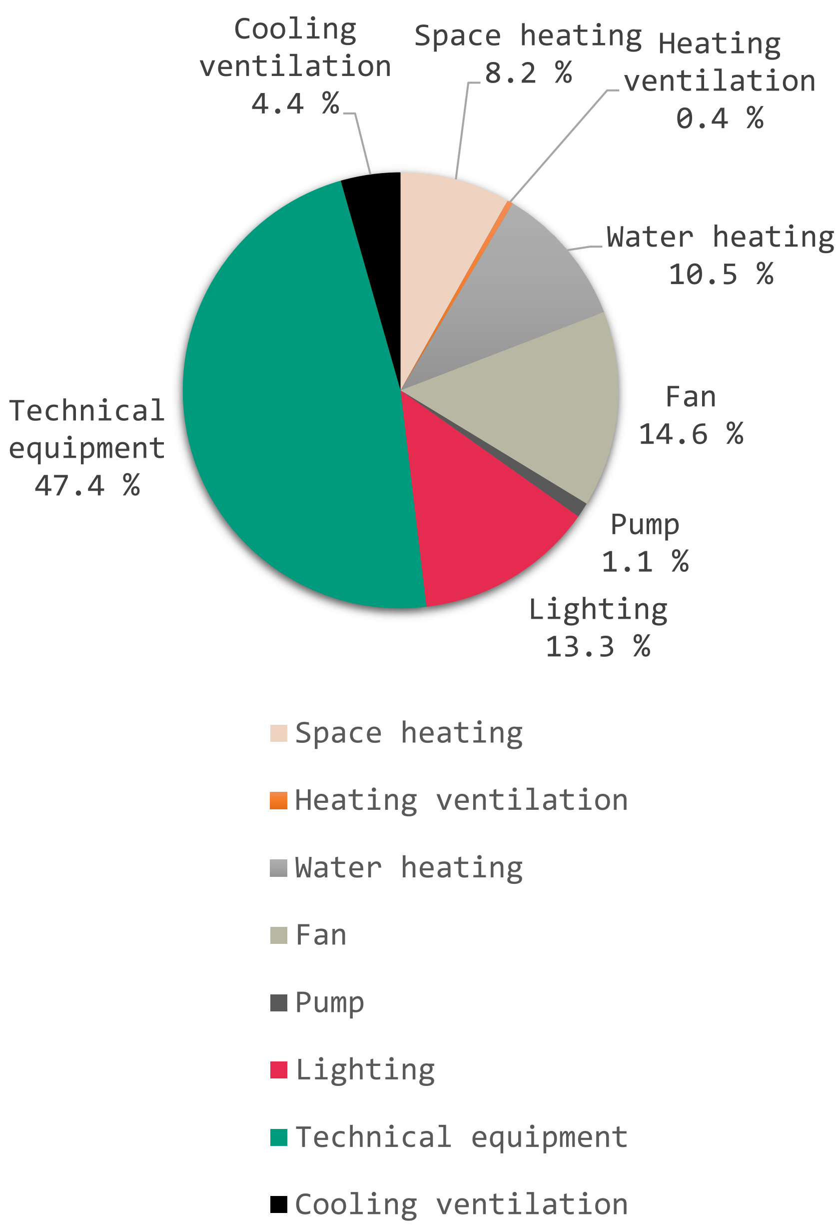


Table 15: Emissions from operation

	kWh/year	CO_2 factor	Emissions B6 ($kgCO_{2eq}$/year)
Electricity	151039	0.132	19937.1
District heating	13549	0.198	2682.7
total of emissions per year ($kgCO_{2eq}$/year)			**22619.85**
total of emissions per year per area ($kgCO_{2eq}/year/m^2$)			**11.45**

RENEWABLE ENERGY PRODUCTION AND EMISSIONS

The energy generated by the PVs is simulated using Rhinocerus - grasshopper. The PVs will generate 260227.7 kWh/year.

It is estimated 40% of the energy produced by PVs will be used in the building, and the other 60% will be exported to the grid. The percentage was simulated in SIMIEN. The PV production is higher in the summer months, generating more energy then the building need. In the winter, the PV is low and it is needed to supply the energy need with grid electricity.

The use of PVs in the building avoid 34350 $kgCO_{2eq}$/m2 per year, considering the total energy production.

The feasibility of the PV system in terms of emissions can be verified by analysing its embodied emissions and the avoided emissions through the energy production. The emissions payback time for this project is:

$$GPBT = \frac{CO_{2eq\ embodied}}{CO_{2eq\ avoided\ (year)}}$$

$$GPBT = \frac{379764}{34350}$$

$$GPBT = 10.8\ years$$

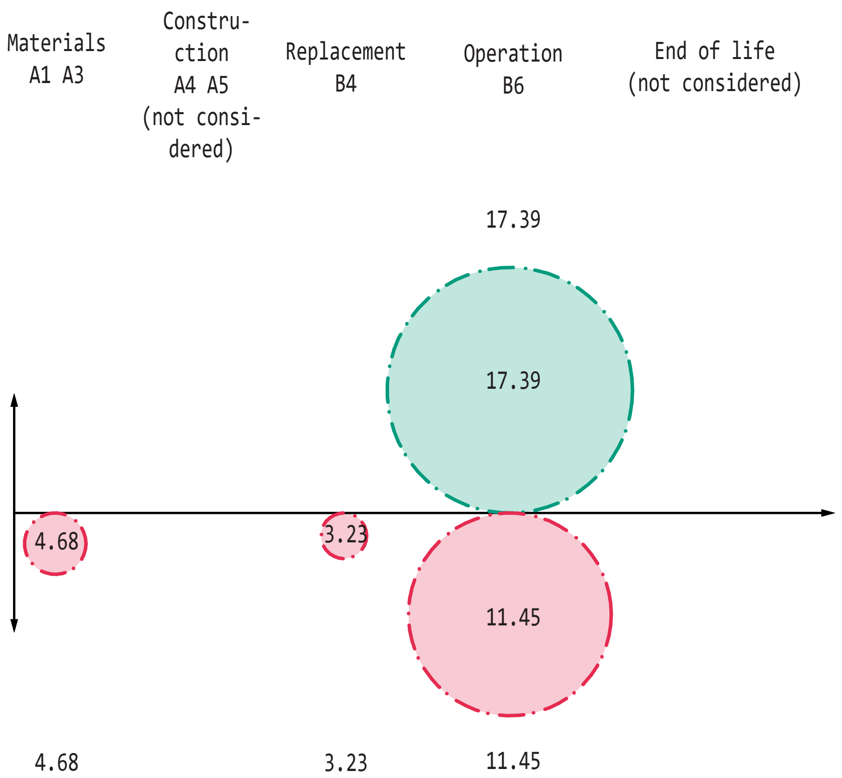
The BIPV system installed will take approximately 11 years to pay back for its embodied emissions.

Table 16: Avoided emissions from renewable energy production

	Energy (kWh/year)	CO_2 factor (CO_{2eq}/kWh)	Emissions B6 (CO_{2eq}/year)
Produced and used on site	104091	0.132	13740
Produced on site and exported	156137	0.132	20610
total of emissions per year (CO_{2eq}/year)			**34350**
total of emissions per year per area (CO_{2eq}/year/m^2)			**17.39**

ZEB BALANCE

Figure 29: ZEB - OM life cycle analysis

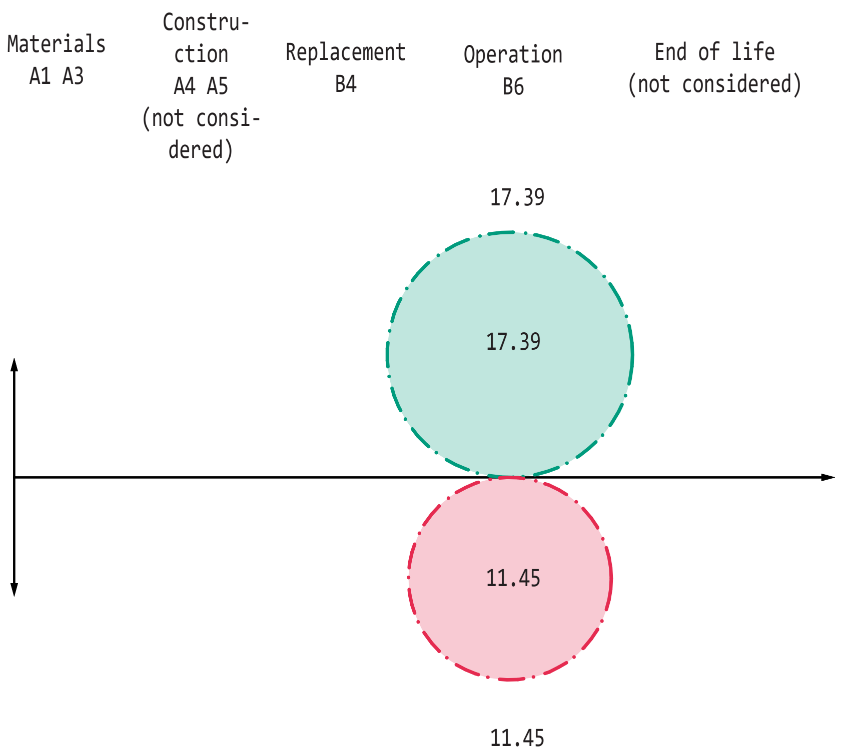


ZEB-OM balance

4.68 + 3.23 + 11.45 - 17.39

1.97

Figure 30: ZEB - O life cycle analysis



ZEB-O balance

11.45 - 17.39

-5.94

ZEB BALANCE

The balance of emissions result in a total +1.97 kg CO_{2eq}/year/m².

Similar results were found by Dokka et al (2015) that analysed a ZEB balance of a house in Norway. In the research the authors concluded that it is difficult to chieve ZEB-OM with mounted PV system. Chartrand (2020) also found similar values for residential low-rise housing. Both studies were done with residential buildings and did not consider the use of PVs in the fasades.

The total emissions in the building is 19.36 kg CO_{2eq}/year/m². The total renewable energy production needed to be 28966.7 kWh/year. This is 29475 kWh/year more than the present design.

Regarding the emissions related to ZEB-O, it is possible to achieve this level with the proposed PVs. The balance of emissions would be -5.94 kg CO_{2eq}/year/m².

Industrial buildings are more challenging to achieve a ZEB target due to its equipment's consumption, in this case responsible for most part of the energy demand. Even tough, it is possible to achieve a ZEB in the level O, compensating the emissions from operations.

CHAPTER IX:

CONCLUSION

CONCLUSION

Many different shapes were tested in this project to find the best compromise between the quality of indoor space, the client requirements, and the zero-emission balance.

Industrial buildings have higher energy demand due the technical equipment and appliances. It leads to more challenges to achieve a ZEB goal. The strategies used were important to reduce the energy demand, and by that avoid emissions related to operation.

The balance of emissions for ZEB-OM resulted in +1.97kgCO_{2eq}/m^2 in a 60-year lifetime. It means that the PVs designed in this building were not enough to compensate for the emissions related to materials and operation of the building.

However, the balance of emissions for a ZEB-O is possible, having a negative balance of -5.94kgCO_{2eq}/m^2.

Industrial buildings are challenging for placing PVs. As the benefits of a sloping roof predicts a higher energy performance from the PVs, the amount of volume without use produces emissions related to space heating and ventilation. For office buildings, for example, it is possible to use the space left out of the tilt of the roof. For this building typology, the extra space would not have use.

Solutions for PVs in large roof areas point to use of BIPV horizontal. When possible it is desirable to use minimum angles. It is possible to conclude that:

- The energy efficiency of PVs is better for systems facing east 15 degrees then facing east and west.
- Mounted systems facing south for the same angle presents better results.
- Horizontal BIPV installed on large roofs are more benefitable in terms of efficiency and emissions.

Most part of the total embodied emissions comes from PVs. Life Cycle Assessment and Environmental Product Declaration of photovoltaic systems are still to be developed and studied more. Furthermore, considering the amount of research being done in the subject, it is estimated that in the future, the embodied emissions related to PVs will be lower. Then, there is more chance to achieve a ZEB goal for the building with the same PV area.

Regarding the embodied emissions from materials and operation:

- it is benefitable to use high insulation in the walls to reduce the energy demand of the building.
- concrete has a high impact in the embodied emissions. Replace the structure by engineering wood products (EWP) is beneficial.
- EPS insulation in the floor is beneficial for the energy demand according to simulations. However, other studies claim that lack of insulation in the floor can be beneficial along the years due to heat storage in the ground. This effect is not considered in the simulation.
- the use of thermal mass save emissions from operation (B6) as reduces the energy demand.
- daylight is challenging to achieve in building with depth of 25m. To solve the problem, windows on the upper part of the building guarantee sunlight deeper in the area and high reflectance materials.
- industrial doors with glazing are beneficial for daylight. In general, insulated industrial doors have a high U-value and use steel. The replacement increased the daylight quality while the energy demand was not affected.

LIMITATIONS

The limitations for this project include:

- Some EPDs does not meet exatly the product designed. However, some assumptions were made in order to conclude the LCA.
- The software package used for the simulations does not consider all the factors that can influence the building's energy demand and production.

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APPENDICES

APPENDICES

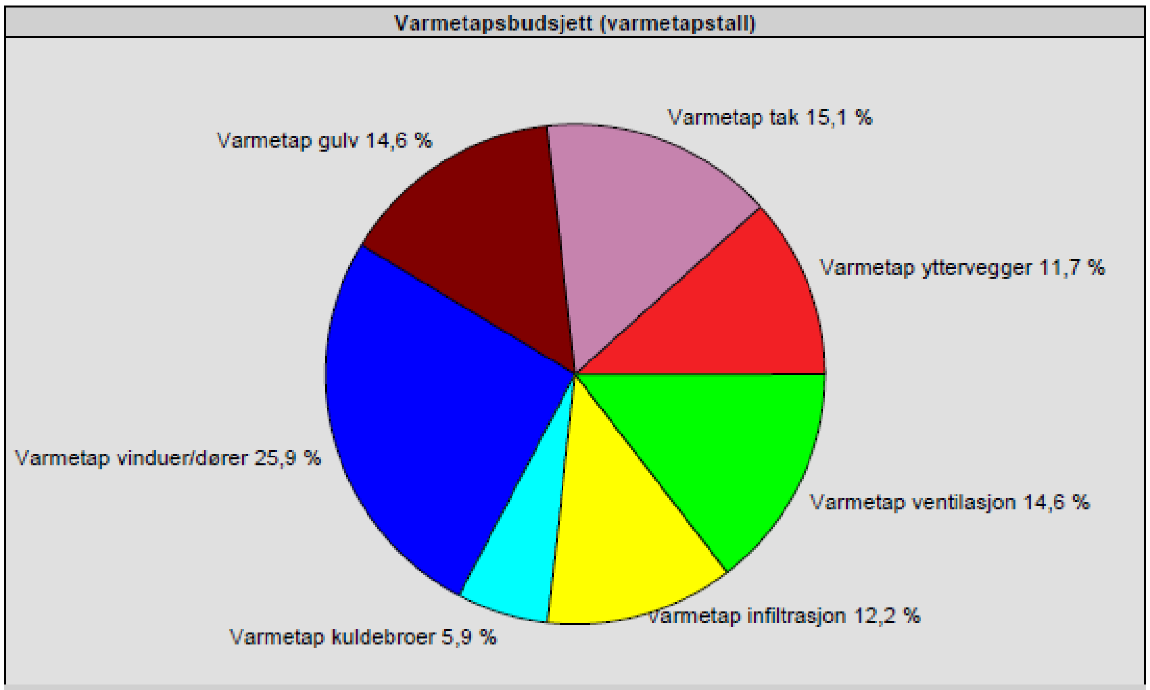
01 Energy demand per category

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	15354 kWh	7,8 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	836 kWh	0,4 kWh/m²
2 Varmtvann (tappevann)	19794 kWh	10,0 kWh/m²
3a Vifter	27355 kWh	13,9 kWh/m²
3b Pumper	2100 kWh	1,1 kWh/m²
4 Belysning	25014 kWh	12,7 kWh/m²
5 Teknisk utstyr	89195 kWh	45,2 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	8338 kWh	4,2 kWh/m²
Totalt netto energibehov, sum 1-6	187986 kWh	95,2 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	151039 kWh	76,5 kWh/m²
1b El. til varmepumpesystem	13549 kWh	6,9 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 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	-85492 kWh	-43,3 kWh/m²
Totalt levert energi, sum 1-7	79096 kWh	40,0 kWh/m²
Solstrøm til eksport	-156255 kWh	-79,1 kWh/m²
Netto levert energi	-77160 kWh	-39,1 kWh/m²

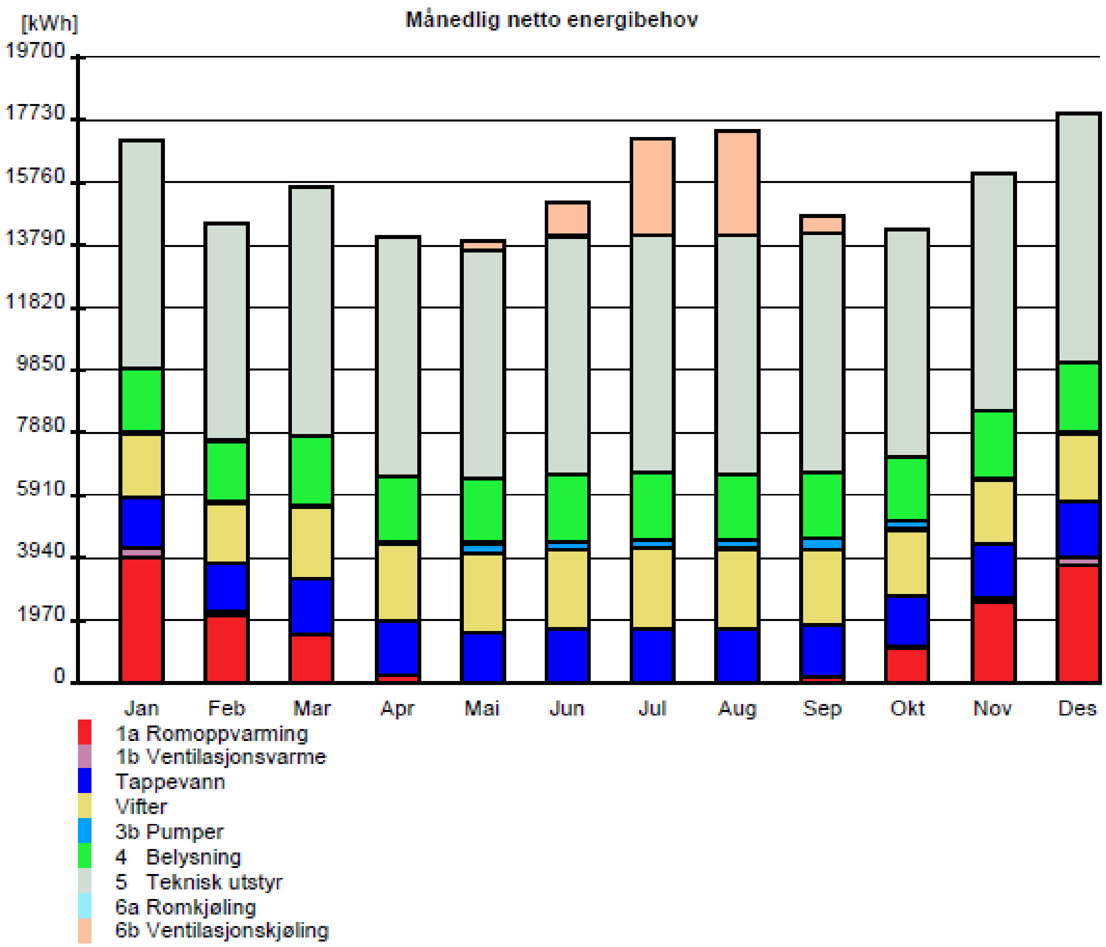
APPENDICES

02 Energy losses per category

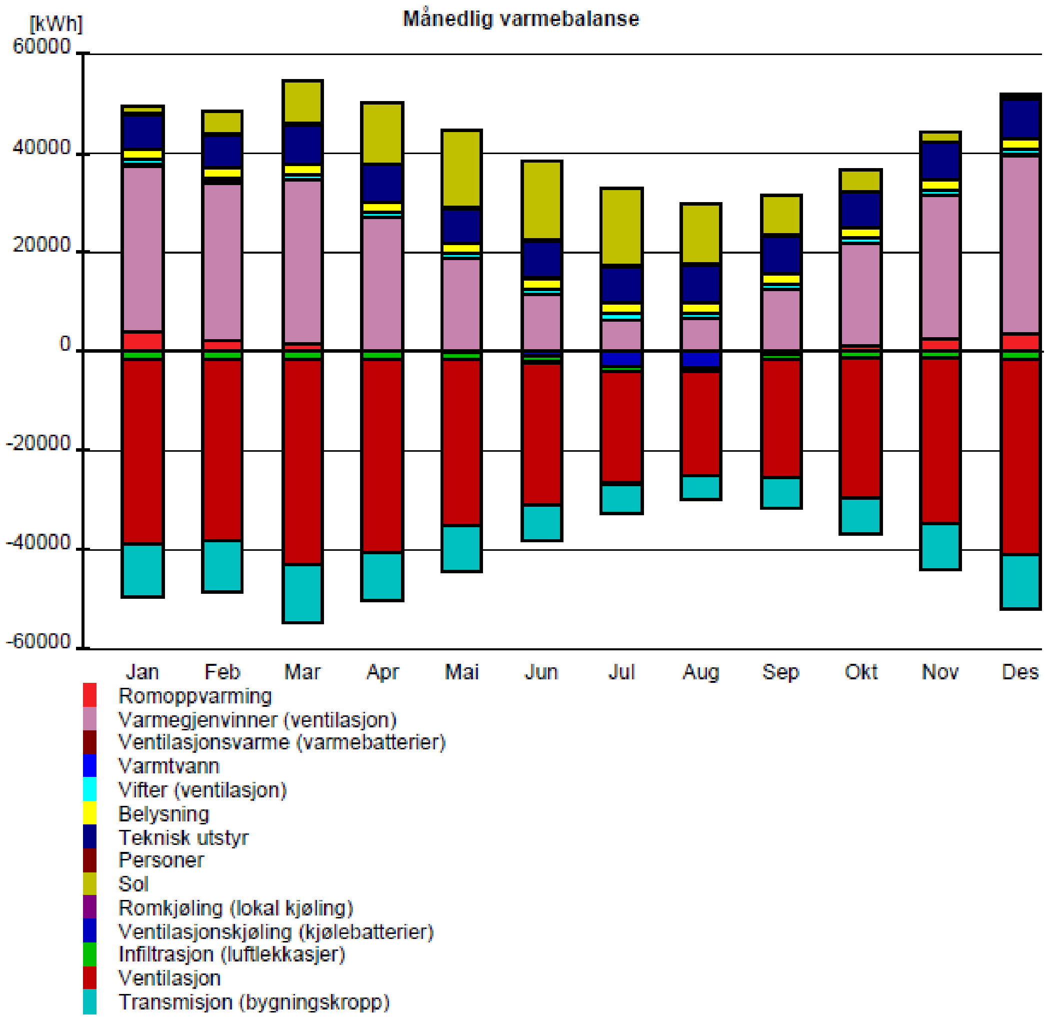


Varmetapstall yttervegger	0,06 W/m²K
Varmetapstall tak	0,08 W/m²K
Varmetapstall gulv på grunn/mot det fri	0,07 W/m²K
Varmetapstall glass/vinduer/dører	0,13 W/m²K
Varmetapstall kuldebroer	0,03 W/m²K
Varmetapstall infiltrasjon	0,06 W/m²K
Varmetapstall ventilasjon	0,07 W/m²K
Totalt varmetapstall	0,50 W/m²K

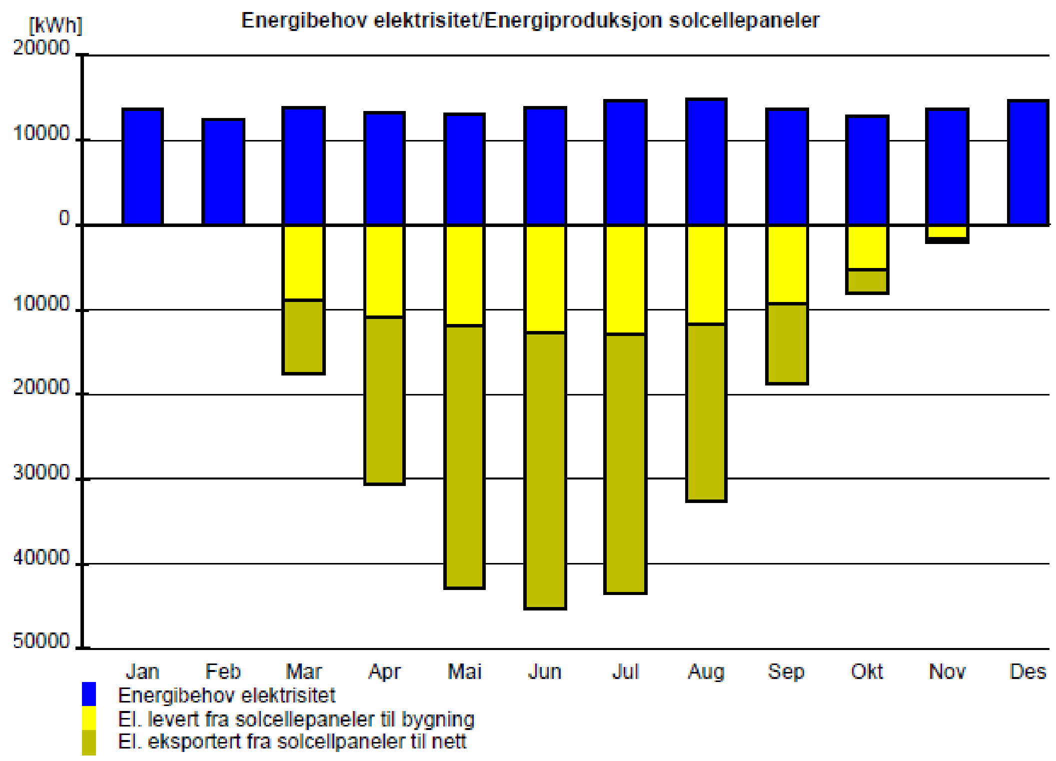
03 Monthly energy demand



04 Monthly energy balance



05 Monthly renewable energy production



06 Monthly temperature

Månedlige temperaturdata (lufttemperatur)					
Måned	Midlere ute	Maks. ute	Min. ute	Maks. sone	Min. sone
Jan	-1,2 °C	8,5 °C	-19,5 °C	21,0 °C (Office)	15,0 °C (Industri)
Feb	-1,7 °C	9,0 °C	-16,7 °C	21,2 °C (Office)	15,0 °C (Industri)
Mar	-0,2 °C	10,7 °C	-12,0 °C	23,7 °C (Industri)	16,0 °C (Industri)
Apr	3,8 °C	14,2 °C	-5,6 °C	24,9 °C (Industri)	18,1 °C (Industri)
Mai	7,4 °C	20,1 °C	-2,4 °C	26,6 °C (Industri)	18,9 °C (Industri)
Jun	11,1 °C	22,7 °C	1,2 °C	28,0 °C (Industri)	20,5 °C (Industri)
Jul	13,8 °C	23,6 °C	4,8 °C	27,6 °C (Industri)	21,4 °C (Industri)
Aug	13,7 °C	25,0 °C	3,5 °C	28,5 °C (Industri)	19,4 °C (Industri)
Sep	10,1 °C	20,8 °C	0,6 °C	24,3 °C (Industri)	18,0 °C (Industri)
Okt	5,2 °C	15,5 °C	-3,3 °C	23,3 °C (Industri)	15,0 °C (Industri)
Nov	1,0 °C	10,7 °C	-11,1 °C	21,0 °C (Office)	15,0 °C (Industri)
Des	-1,9 °C	9,6 °C	-17,6 °C	21,0 °C (Office)	15,0 °C (Industri)

Månedlige temperaturdata (operativ temperatur)					
Måned	Midlere ute	Maks. ute	Min. ute	Maks. sone	Min. sone
Jan	-1,2 °C	8,5 °C	-19,5 °C	21,0 °C (Office)	15,1 °C (Industri)
Feb	-1,7 °C	9,0 °C	-16,7 °C	21,1 °C (Office)	15,2 °C (Industri)
Mar	-0,2 °C	10,7 °C	-12,0 °C	23,7 °C (Industri)	17,6 °C (Industri)
Apr	3,8 °C	14,2 °C	-5,6 °C	24,8 °C (Industri)	19,2 °C (Office)
Mai	7,4 °C	20,1 °C	-2,4 °C	26,6 °C (Industri)	20,2 °C (Office)
Jun	11,1 °C	22,7 °C	1,2 °C	28,0 °C (Industri)	23,3 °C (Office)
Jul	13,8 °C	23,6 °C	4,8 °C	27,4 °C (Industri)	24,2 °C (Office)
Aug	13,7 °C	25,0 °C	3,5 °C	28,4 °C (Industri)	21,2 °C (Office)
Sep	10,1 °C	20,8 °C	0,6 °C	24,1 °C (Industri)	18,7 °C (Industri)
Okt	5,2 °C	15,5 °C	-3,3 °C	23,2 °C (Industri)	15,3 °C (Industri)
Nov	1,0 °C	10,7 °C	-11,1 °C	21,1 °C (Office)	15,2 °C (Industri)
Des	-1,9 °C	9,6 °C	-17,6 °C	21,0 °C (Office)	15,2 °C (Industri)

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