HVL Solar Energy Laboratory

Fredrik von Schlanbusch
Erik Amlie Eagan

Bachelor's thesis in ETK16
Bergen, Norway 2019

HVL Solar Energy Laboratory

Fredrik von Schlanbusch
Erik Amlie Eagan

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

IMM 2019-M72

Fredrik Von Schlanbusch, Erik Amlie Eagan

Høgskulen på Vestlandet
Fakultet for Ingeniør- og Naturvitskap
Institutt for maskin- og marinfag
Inndalsveien 28
NO-5063 Bergen, Norge

Norsk tittel:	HVL Solenergilaboratorium
Author(s), student number:	Fredrik von Schlanbusch, 182408 Erik Amlie Eagan, 182399
Study program:	Energy technology engineering
Date:	May 2019
Report number:	IMM 2019-M72
Supervisor at HHVL:	Richard John Grant, Professor at HVL
Assigned by:	HVL
Contact person:	
Antall filer levert digitalt:	1

Preface

This bachelor thesis is written at the Department of Mechanical and Marine Engineering at Western University of Applied Sciences (WNUAS) in the study program Energy Technology Engineering under the supervision of Professor Richard J. Grant.

Firstly, we would like to extend our gratitude to Professor Richard J. Grant who has guided us and been available to our disposal through every step of this project. We would also like to thank Harald Moen for lending us his expertise with practical solutions within the project. Lastly, we are thankful to the Department of Mechanical- and Marine Engineering for letting us take part in the start of the construction of their solar energy laboratory.

Abstract

Department of Mechanical and Marine Engineering wants to start the construction of a solar laboratory at the school campus in Bergen. In this thesis, the initial construction process has been documented, which includes the moving of a passive house to the site of the laboratory and the production of foundation blocks for the house to be placed onto. The passive house will be the centre of the laboratory upon its completement. The various solar panels included in the laboratory will be heating the passive house.

The thesis also focuses on various layout designs that was considered for the laboratory, and how they were presented for Statsbygg, how owns the site the laboratory will be located on. Multiple shadow analyses have been done of the site in order to find the best arrangement of the components making up the solar laboratory.

Furthermore, a mounting system for the solar panels with adjustable inclination has been designed to fit on the roof and wall of the passive house. The maximum wind loads that will be present on the solar panels when in a 90° inclination has been the biggest factor when dimensioning the mounting system. Realising how the structure would be handled on top of a tall building was a deciding factor that came into play when choosing a building material for the structure. It was important that a light, yet strong material was chosen for the construction of the mounting system.

Lastly electrical components and wiring for the laboratory is discussed as well as what kind of electric energy output that can be expected from the laboratory.

Sammendrag

Instituttet for maskin- og marinfag ønsker å starte konstruksjonen av et solcellelaboratorium ved Campus Bergen. I denne avhandlingen har den innledende konstruksjonsprosessen blitt dokumentert, hvilket inkluderer flyttingen av et passivhus til tomten til laboratoriet og produksjon av fundamentblokker som huset skal stå på. Passivhuset skal være sentrum for laboratoriet ved ferdigstilling av prosjektet. De forskjellige solcellepanelene inkludert i laboratoriet skal varme opp passivhuset.

Avhandlingen fokuserer også på forskjellige situasjonsplaner som var overveid for laboratoriet og hvordan de ble presentert for Statsbygg, som eier tomten laboratoriet skal stå på. Det har blitt gjort flere skyggeanalyser av tomten, for finne en optimal plassering av komponentene som laboratoriet skal bestå av.

Videre har et solcellestativ, med justerbar inklinasjonsvinkel, blitt designet for å passe på taket og på veggen til passivhuset. De største vindkrefter som påvirker panelene i en 90° vertikal stilling har vært den viktigste faktoren i dimensjoneringen av stativene. En avgjørende faktor ved valg a materialet for stativet var hvordan solcellestativet skal benyttes og justeres på toppen av et høyt hus. Det var viktig at et lett, og sterkt materiale ble valgt for konstruksjonen av solcellestativet.

Til slutt vil elektriske komponenter og kabling for laboratoriet bli diskutert, samt hva slags elektrisk effekt som kan forventes fra laboratoriet.

Table of Contents

Nomenclature

WNUAS – Western Norway University of Applied Sciences

IMM – Department of Mechanical and Marine Engineering

CSP – concentrated solar power

PV – photovoltaic

CAD – computer-aided design

F_W – wind forces

c_sc_d – is the construction factor

c_f – is force factor for the construction

A_{ref} – is the reference area for the construction

$q_p(z_e)$ – is the peak velocity pressure

ρ – is the air density

v_m – is mean wind velocity

cr – is the roughness factor

c_o – is the orography factor

v_b – is basic wind velocity

Iv – is turbulence intensity

k1 – is the turbulence factor

z – is height above the terrain

φ – solidity ratio

s – is snow loads on roofs

μ_i – is the shape coefficient

C_e – is the exposure coefficient

C_t – is the thermal coefficient

S_k – is the snow load on the ground

F_{snow} – snow force

HSS – hollow structural section

P_{cr} – critical force

I – moment of inertia

K – effective length factor

L – length

E – modules of elasticity

EV – electrical vehicles

1. Introduction

1.1 Background

The Department of Mechanical and Marine Engineering (IMM) at Western Norway University of Applied Sciences is planning to build a solar laboratory at its campus in Bergen. When completed, the laboratory will consist of two solar trackers, one with solar panels and one with mirrors concentrating light on a focal point, and one ground-based solar array with solar panels. There will also be a passive house on the site. The passive house will have solar panels mounted to its roof and will also contain a battery pack that will be able to store excess energy. The passive house is going to receive its energy from three different power generating components of the laboratory, the solar tracker and the solar panels on the two different solar arrays.

The goal is that when completed, the school campus will host a solar laboratory to conduct various experiments on solar energy. The laboratory will be an arena for experiments performed by future bachelor's and master's programmes, as well as research conducted by faculty staff. It will also be possible to use the facility for smaller-scale projects such as exercise-type experiments and educational purposes.

For the laboratory to be a beneficial research station one should be able to customize it to the needs of the experiments proposed. The laboratory must therefore be designed in such a way that it can easily be changed for the purpose of the experiment that is to take place. Since the passive house roof, the solar tracker and the ground-based solar array all contain different types of solar panels, one should be able to change the locations of all the solar panels between the different arrays. There should also exist a possibility to connect external power inputs to the laboratory, such as an electrical generator or even a small-scale wind turbine.

This project will focus on the construction of the solar laboratory, the design of its initial layout and getting the passive house and the solar panels mounted on the roof connected to the grid. There will also be designed and produced a solar array for the passive house roof and a design produced for the ground-based solar array.

1.2 Aim
To design and initially develop a solar energy laboratory which will include a passive house with a mounted solar cell system, and permit a ground-based solar array and a solar tracker to be installed.

1.3 Objectives
Find an appropriate location for the passive house.

Find a suitable location for the ground-based solar panel.

Propose a location for the solar tracker.

Logistics: Move the passive house.

Analyse wind pressure exerted on the passive house and the solar array mounted on the roof.

Design and produce a mounting system for the solar panels to produce an array. (May permit a change of inclination.)

Attach mounting system to the roof of the passive house. (Change of inclination.)

Planning out the electrical installation.

1.4 Outline of the Thesis

The thesis will first present a method chapter, Chapter 2, where the method of designing the layout of the solar laboratory, roof and ground-based mounting systems are considered. The layout includes locations of each component; the passive house, the ground-based array, the solar tracker, the concentrated solar power tracker (CSP), and the evacuated tube collectors. Following the method, the solutions for electrical wiring of the laboratory are designed, which is shown in Chapter 3, Electrical Wiring. Towards the end of the thesis, there will be a Discussion chapter (Chapter 5) and a Conclusions and Further Work chapter (Chapter 6). The Discussion chapter will discuss and compare different solutions vs those decided upon and offer explanations for why these were not chosen. In the concluding chapter the project's more important points and results will be reviewed, and further work ahead will be discussed.

2. Method

2.1 Specifications

2.1.1 Overall Design

The solar laboratory will consist of a passive house; a roof-based solar array, a ground-based solar array, a solar tracker, a CSP tracker and two vacuum tube solar collectors. The passive house will be the centre of the laboratory, with a battery package for energy storage, and inverters to send electricity to the power grid. In total, the laboratory will consist of 6 mono- and polycrystalline panels, as well as 14 thin film panels. These panels are meant to be interchangeable with each other as to not limit the research possibilities for future students.

2.1.2 Component List

Passive house
The passive house is going to be the central component of the solar laboratory that will connect most other components together. Electricity generated by the solar panels will mainly be used for heating of the

passive house, and excess energy generated will be stored in the battery pack located inside the passive house. The house will also be the most noticeable part of the laboratory when looking at it from a distance, as it is the biggest object at the site of the laboratory.

The passive house stands 4.2 meters tall and has a length of 6.23 meters and a width of 2.66 meters. It is estimated to weigh between 4 and 6 tonnes by the private company Royal Transport, based in Sotra outside of Bergen, which are responsible for moving it to the site.

Battery pack
An energy storage system will be installed in the passive house to store energy produced by the solar laboratory. Specifications for the battery system is described in further detail in Chapter 3.

Solar panels
The solar laboratory will consist of three different kinds of solar panels; mono-, polycrystalline, and thin film panels. Specifications for the different solar panels is described in further detail in Chapter 3.

Solar panel mounting system
The solar laboratory will also include two mounting systems. The original plans for the solar laboratory included a roof- and a ground-based solar array. However, due to last minutes changes the ground-based solar array was changed to a wall-based design. Both solar arrays will use the same mounting system design, as to include compatibility with all solar panels.

Solar Tracker
The solar laboratory will include a solar tracker. This tracker has been designed as part of a previous bachelor thesis. The tracker will carry six of the photovoltaic (PV) solar panels available at the solar laboratory.

Concentrated solar power tracker
A CSP tracker will be available to the laboratory. This component is however somewhat fragile and will not be stationed at the site permanently. The tracker is mainly part of a project that aims to heat up a nearby greenhouse, run by Professor Borris Balakin, and is primarily not part of this thesis. However, the CSP tracker will be taken into consideration when planning the layout of the laboratory.

Vacuum tube collectors
As of January 2019, there were already some vacuum tube collectors on the site of the laboratory. These are part of the same project as the CSP tracker.

2.2 Layout Design

2.2.1 Initial Planning

The designated site for the solar laboratory is in the far south-west side of the school campus, on the concrete ground behind the L-building. As of January 2019, the site mostly consisted of open space with a few benches and bicycle racks as seen in the picture below. Between the racks and the benches, there was a small passage wide enough for a car. It was used to move objects through the green door on the brown house in the middle of the picture. On the site, there was also some vacuum tube collectors prior to construction start. The vacuum tube collectors are part of a different project aiming to heat the nearby greenhouse. The heliostat that will be presented as part of the layout propositions later in this thesis is also part of that same project, run by Professor Boris Balakin in the Department of Mechanical and Marine Engineering at WNUAS.

Figure 1 Solar laboratory site, January 2019

Before the construction of the laboratory could start, there was a need for a layout of how the finished laboratory would look on the site. This was needed so as to have a clear picture of how the different components would be placed in order to get the best possible lighting conditions for the solar panels and the vacuum tube collectors. A layout was also important to have to be able to show Statsbygg, which owns the building and the site, what was required to be done at the location in order to get the project running.

2.2.2 Site Model

It was decided that the best way to get an overview of how the finished laboratory would look on the site was to build a scaled down 3D-model of it. This was done using the engineering drawings of the school, digitally constructed and available as CAD files, which were provided by the institute leader Nils Ottar Antonsen. [1] The height of surrounding buildings was not included in the drawings. Finding the heights was solved by going out to physically measure the buildings. From the CAD drawings and the height measurements, an accurate model of the site was made using SketchUp, currently developed by Trimble Incorporated, a software designed to let the user make 3D-models.

The advantage of using SketchUp for the 3D-model was that SketchUp has a wide range of third-party plugins. As the 3D-model of the site was finished a plugin called Shadow Analysis, designed by DeltaCodes, was then used to analyse the lighting conditions at the site. This made it possible to look at the shadowing from surrounding buildings and how it would affect the different components of the laboratory. The use of this plugin will be discussed further in Chapter 2.2.4.

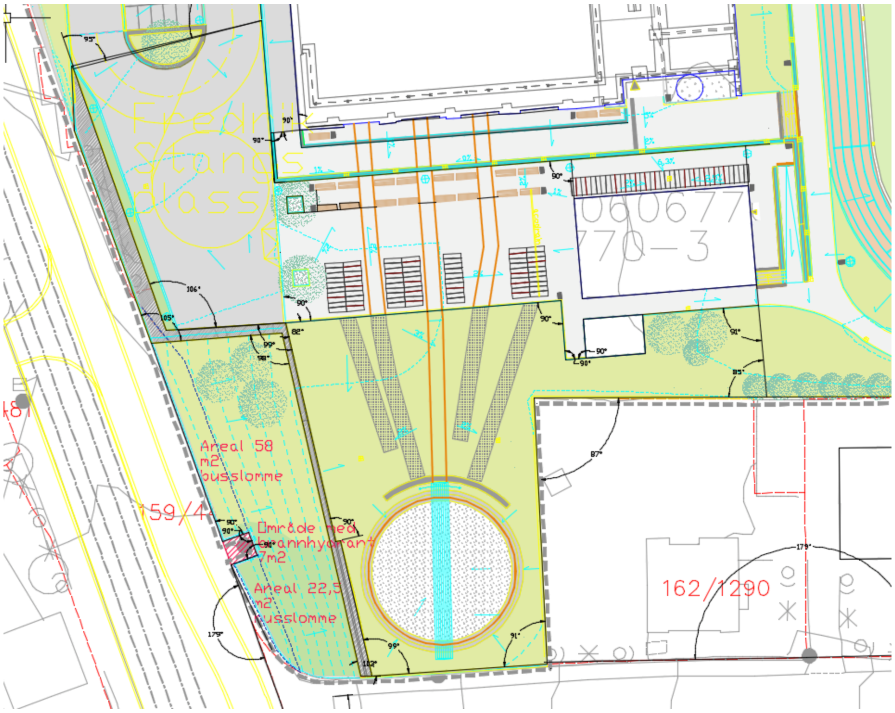


Figure 2 CAD drawings of the site [1]

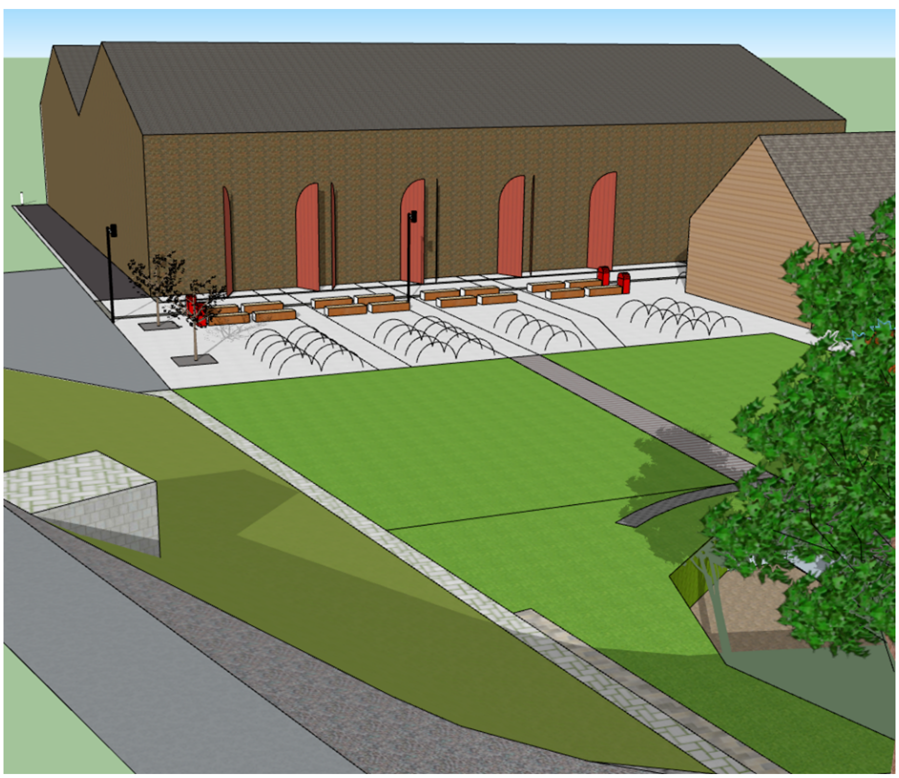


Figure 3 3D-model of site as seen from the south-western pedestrian walk

2.2.3 Placement of Laboratory Components

A meeting was set up with Statsbygg, as well as the other involved parties from the school during February. At the meeting, the concept of the solar laboratory was pitched for Statsbygg, and they were shown some proposed design layouts for the laboratory with the components making it up.

When the 3D-model of the site was finished, 3D-models of the four components that would be standing out in the open had to be made. These four components were the passive house with roof-mounted solar panels, the ground-based solar panels, the solar tracker and the CSP tracker.

When choosing placements for the different components, there were two main criteria that had to be emphasised: the site should look aesthetically pleasing and the components should get as much lighting as possible. Making it aesthetically pleasing was necessary to convince Statsbygg that they should give permission to build the laboratory on their site. Good lighting conditions was important to let the different components of the laboratory have an energy output as high as possible throughout each day of the year.

When the 3D-model of the site was finished and compatible with Shadow Analysis, it served as a tool to test different laboratory layouts and many different placements for the passive house and the other components. The model also made it possible to find out if there was a need to remove any of the bicycle racks or benches in order to have room for the laboratory.

It was concluded that the most reasonable way to make the laboratory look aesthetically pleasing was by placing the four components in a symmetrical manner, either in a square or on a line. This way the laboratory would look pleasing and orderly to everyone passing by. Optimal lighting conditions would be achieved by using DeltaCodes' Shadow Analysis. Using these guidelines, the design of layout proposals for Statsbygg could start.

2.2.4 Shadow Analysis

The most important part of proposing layouts for the solar laboratory, was finding placements for the components that would give them the maximum amount of direct sunlight each day of the year. To achieve this, Shadow Analysis, was found to be a very useful tool. Shadow Analysis is a plugin built for SketchUp which visualises how many hours of shadowing there will be on an object throughout the day as shown in the picture below.

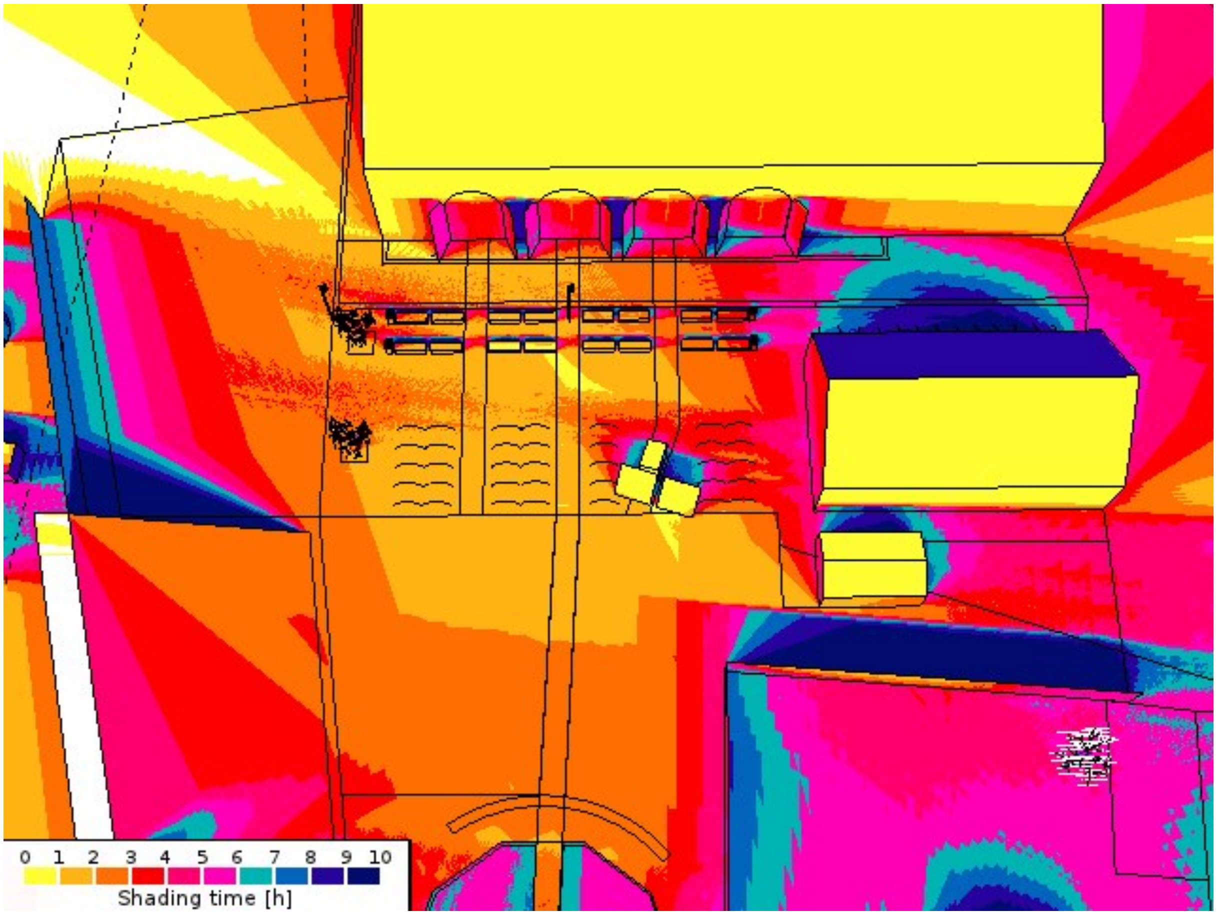


Figure 4 Shadow analysis of the solar laboratory site in March

Shadow Analysis works by connecting SketchUp with Google Maps. That way the 3D-model could be pinned to its exact geolocation. The sun's inclination in Bergen could then be simulated for any day of the year. Using this method, it was possible to get very detailed information regarding suitable placements for the different components of the solar laboratory.

When analysing the selected area, the software will provide a coloured picture of the area. Any date can then be selected for analysation, and the picture provided will show the shadowing situation throughout the day selected. It was, therefore, possible to analyse all four seasons of the year to see how the different components would be affected by shadows throughout the year. The different colours represent how many hours of shadowing an area would have between sunrise and sunset, where white is zero hours of shade, and dark blue is 10 hours or more. This explains why December, even though a very dark month, has no dark colours. There are approximately 5 hours and 45 minutes between sunrise and sunset on December 21st, thus there can only be a maximum of 5 hours of shadowing this day. [2] This is shown in the comparison between the analysis of June 21st versus December 21st below. As seen even though most areas are all white in June due to the sun's high position on the sky, there still exist areas of dark blue. While in December most areas are covered in pink, which means that the site is mostly shaded throughout the whole day.

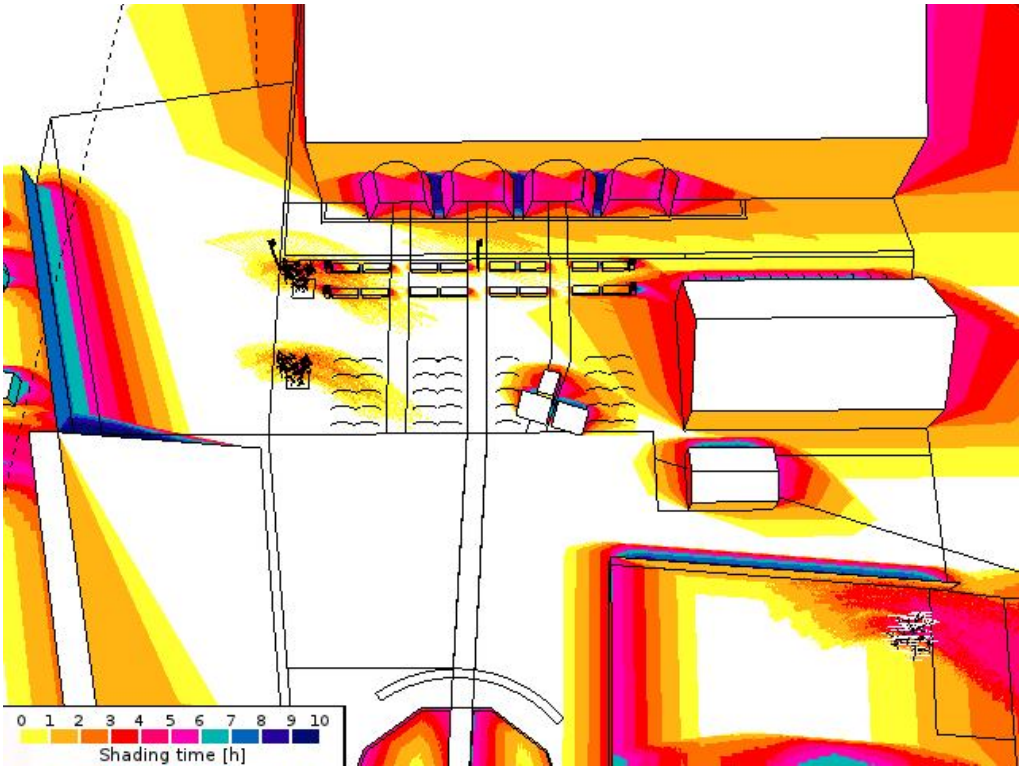


Figure 5 Shadow analysis of the solar laboratory site in June

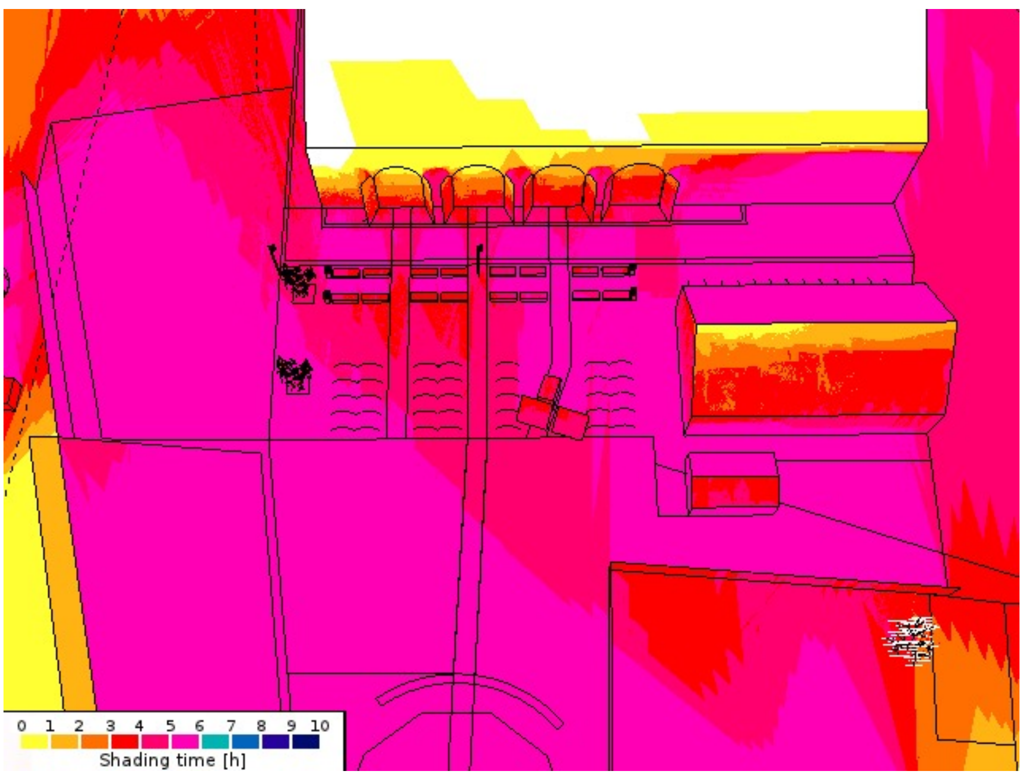


Figure 6 Shadow analysis of the solar laboratory site in December

The area which has been delegated for the solar laboratory is suitably located in one of the least shaded areas on the site, right next to the two trees, between the benches and the bicycle racks. This is seen in all three analyses shown above, as the colour represented is one or two shades lighter than the surrounding colour.

2.2.5 Initial Layout Propositions and Design

As the 3D-model was finished and Shadow Analysis was incorporated into it, a variety of different proposed design layouts for the laboratory had to be made to present for Statsbygg. This was done by testing out different placements for the four components making it up, ensuring that it would have an aesthetically pleasing appearance from the outside looking in. Then a shadow analysis would be run of the proposed layout; one for December, one for March and one for June. This way the optimal positioning for the components could be found based on the amount of direct sunlight they would get throughout the year. Analysing September was unnecessary as the sun has the same positioning in the sky during the two equinoxes in March and September.

Further, the four different layouts that were presented to Statsbygg will be discussed, as well as the pros and cons of each of them. For each proposition, there will be shown one aerial view of the site, as well as one shadow analysis for the same view done for the equinox, March 21st. So as to keep the presentation simple with a clear message for Statsbygg, it was decided to only show one analysis for each proposition. It was decided to present an equinox as it is the best way to give a representation of the shadow situation throughout the year in one picture, since it is by definition the date midway between the summer and winter solstices. All pictures are shown with south at the bottom and north at the top.

In figure 7, the grey box to the left with a rectangular, black object on top of it, is the passive house with roof-mounted solar panels. To the right of the passive house, the solar tracker is seen as a black rectangle, followed by the CSP tracker: and to the far right; the ground-based solar panels represented by the white box. It was decided to represent the ground-based solar panels by a white box as this served the purpose of showing how much space would be occupied by them, both in an upright position and while lying flat.

Proposition 1

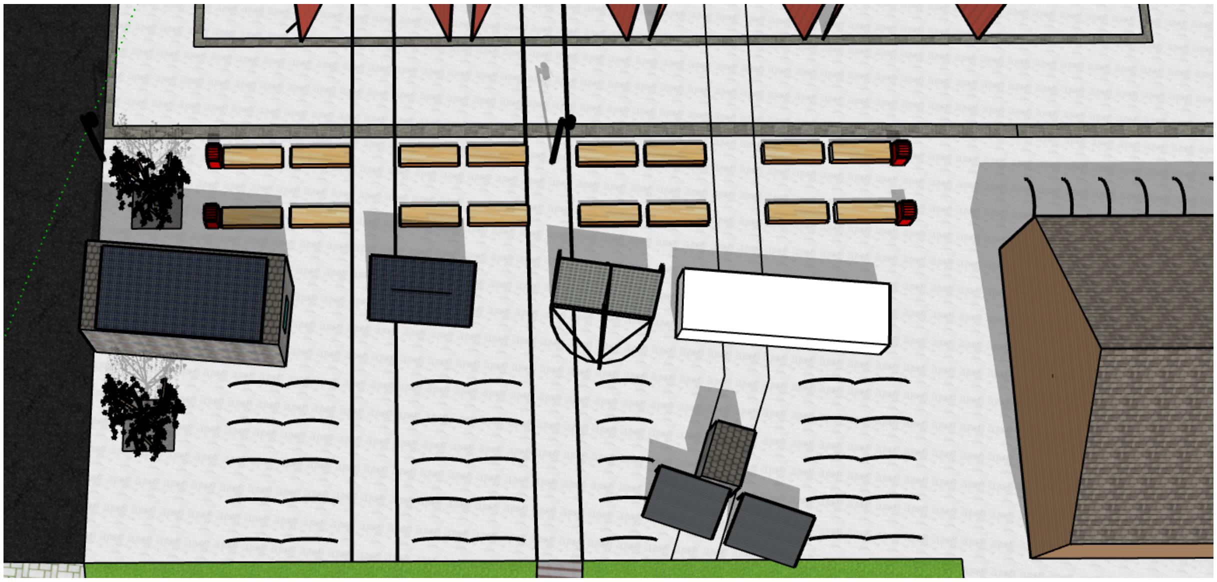


Figure 7 Arial view of layout Proposition 1

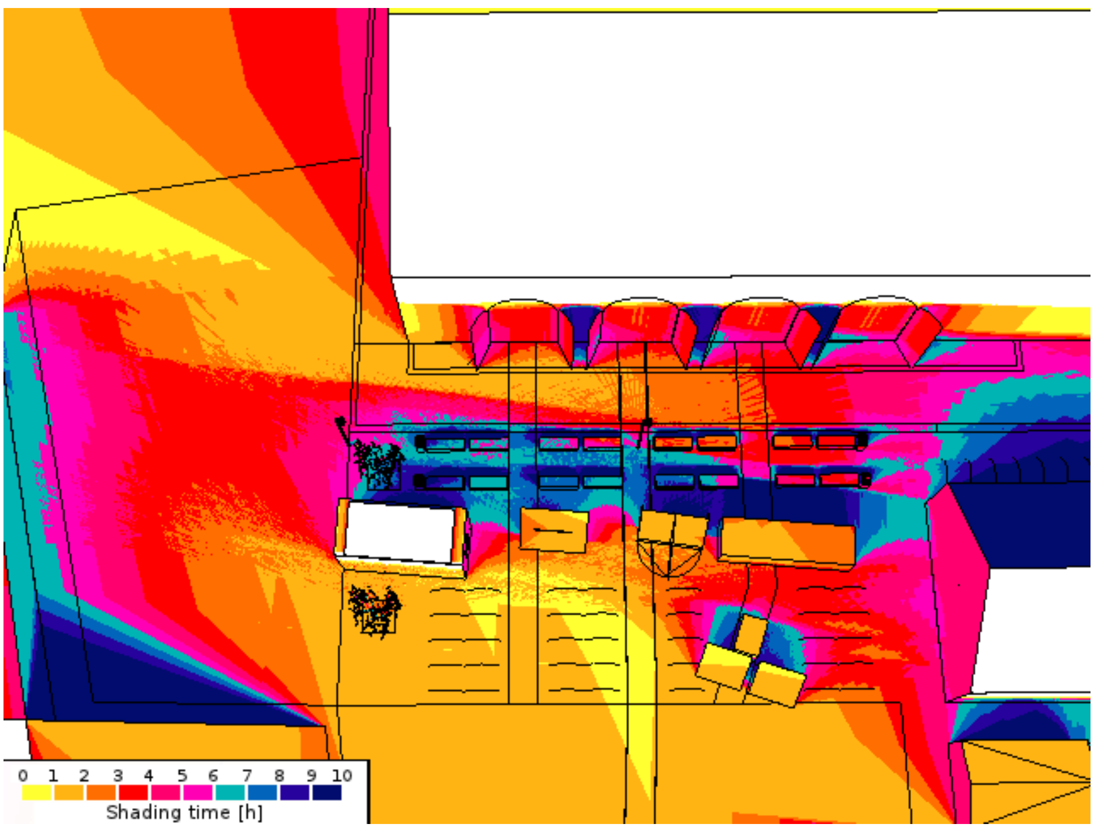


Figure 8 Shadow analysis of layout Proposition 1

Proposition 1 is a way to design the solar laboratory without having to remove any of the benches or bicycle racks at the site. This proposition looked aesthetically pleasing as all four components were lined up with one another between the racks and the benches. Whilst looking good, the proposition was not the most effective to fully utilize the sunniest area in the middle of the site. Due to the house to the east of the site, there will be between two and three hours of shading on the ground-based solar panels.

It was decided to show Statsbygg at least one layout where nothing already on site had to be removed. This was necessary in case they were unwilling to make any changes to the site. Even though looking aesthetically pleasing, it was concluded that this was the least favourable proposition since the shading conditions were bad for three out of four components.

Proposition 2

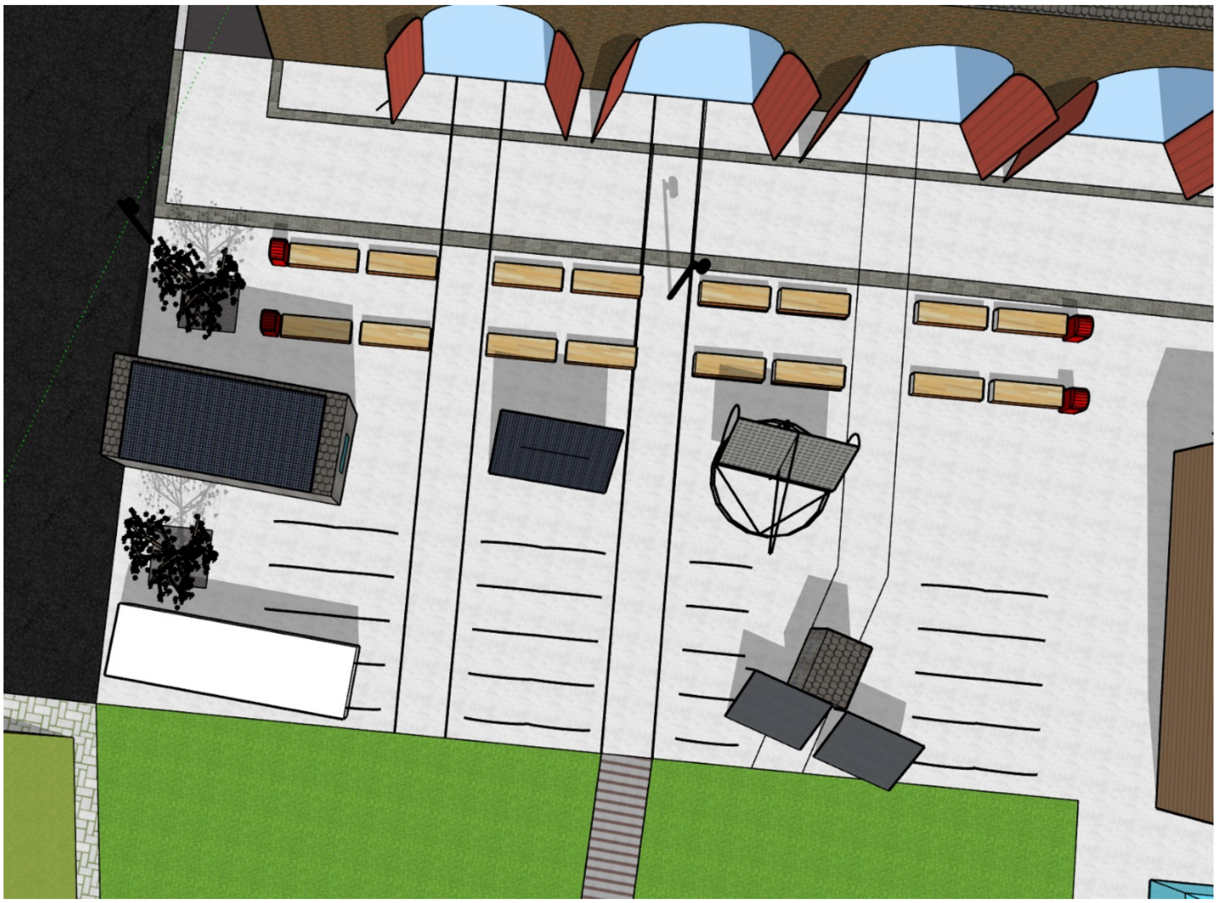


Figure 9 Aerial proposition of layout Proposition 2

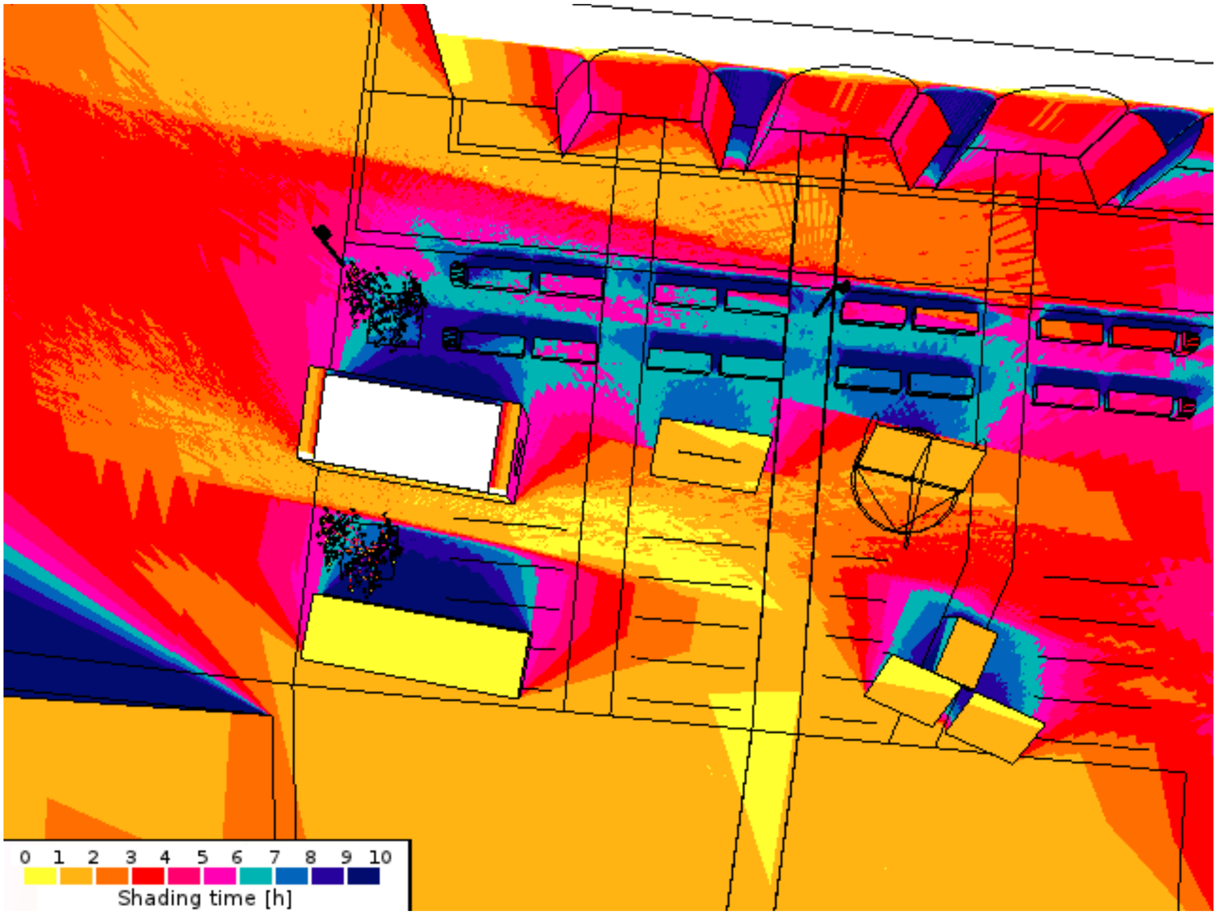


Figure 10 Shadow analysis of layout Proposition 2

In this layout it has been proposed to move the ground-based solar panels in front of the passive house. This is a more desirable placement as they would receive direct sunlight for nearly the entirety of the day. In this position it would be necessary to remove a few bicycle racks to make room for the ground-based panels. The solar tracker and CSP tracker are still shaded for up to two hours of the day.

This layout gives the ground-based solar panels a better position regarding shading time, while sacrificing the linear design of Proposition 1. It would also have been necessary to remove a few bicycle racks. While this proposal is better than the previous, and not too many adjustments to the site would have had to be made, it would be desirable to go for a more optimized solution regarding shading time.

Proposition 3

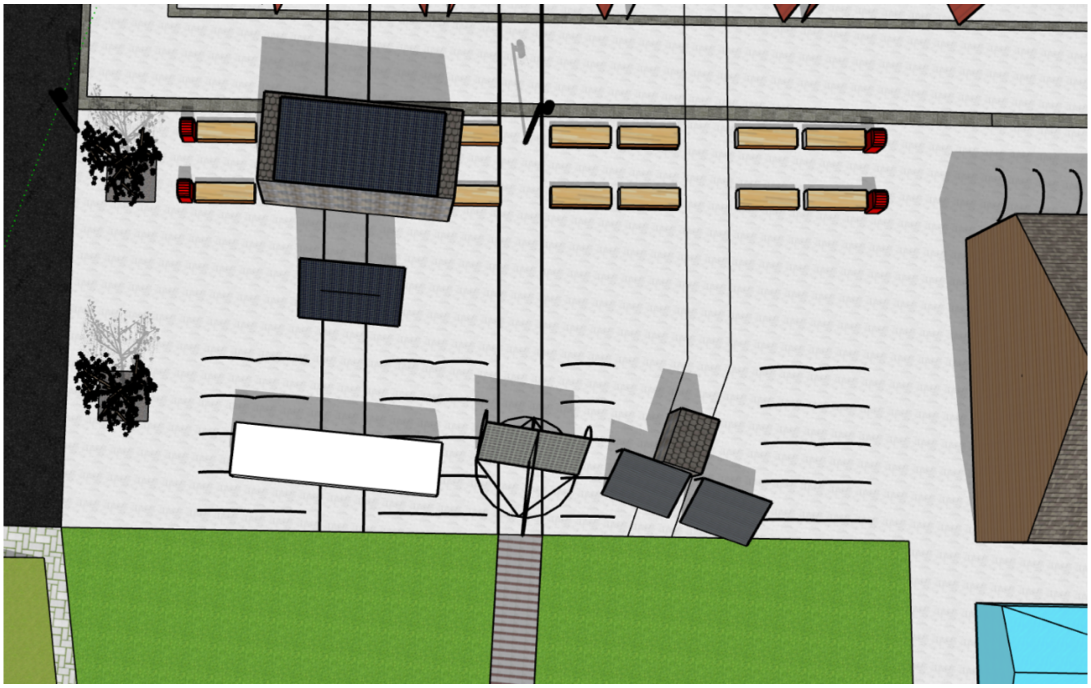


Figure 11 Aerial view of layout Proposition 3

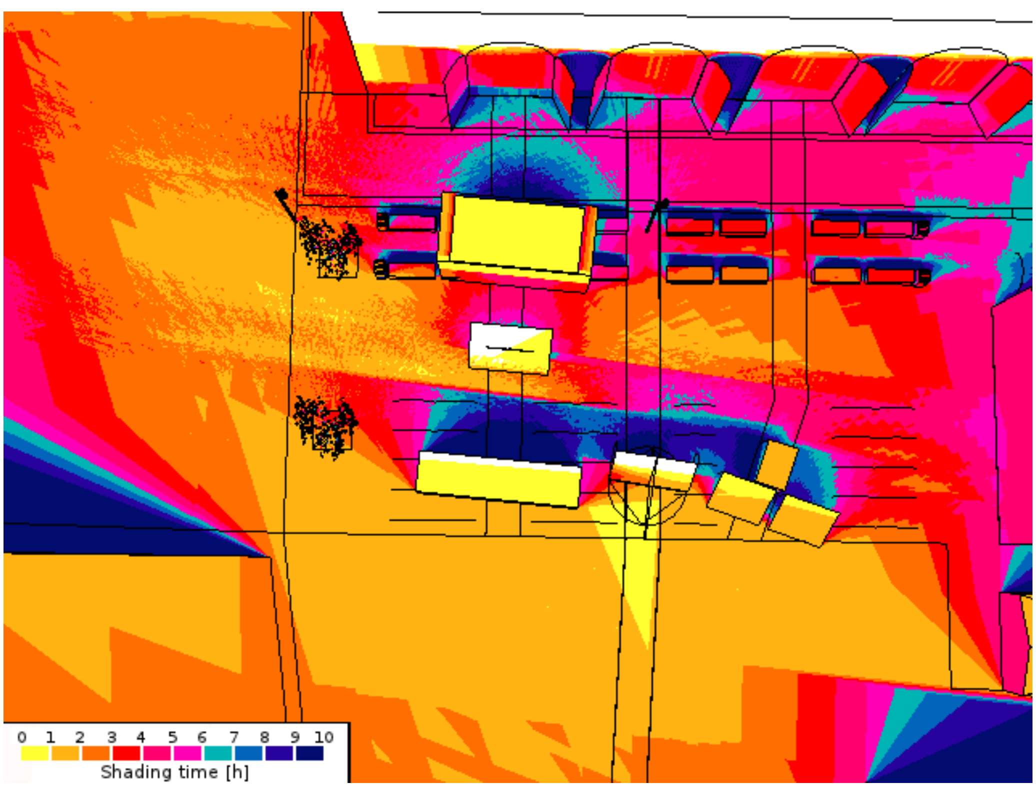


Figure 12 Shadow analysis of layout Proposition 3

When designing Proposition 3, trying to find the layout that would give each component the least amount of shading possible was a focus. This was found by arranging three of the components on a line from south to north in the middle of the site, while placing the CSP tracker in the front to the right. With this arrangement, shading time was brought down to a maximum of none to one hour for all components, except for a small part of the bottom left corner of the CSP tracker which was blocked from direct sunlight by the ground-based panels.

This layout proposition disregards aesthetics for the benefit of optimized solar conditions as it is by far the least proportionate layout so far proposed. Still, this is the best proposition presented so far, as the primary focus of the layout design should be to set up the components for as good lighting conditions as possible. One downside with this layout is that a few benches would have to be removed in addition to some bicycle racks.

Concluding the discussion about Proposition 3, one could argue that this is a good layout due to the large amount of direct sunlight that each of the components would be subject to. The downside is the lack of aesthetics and removal of benches from the site.

Proposition 4

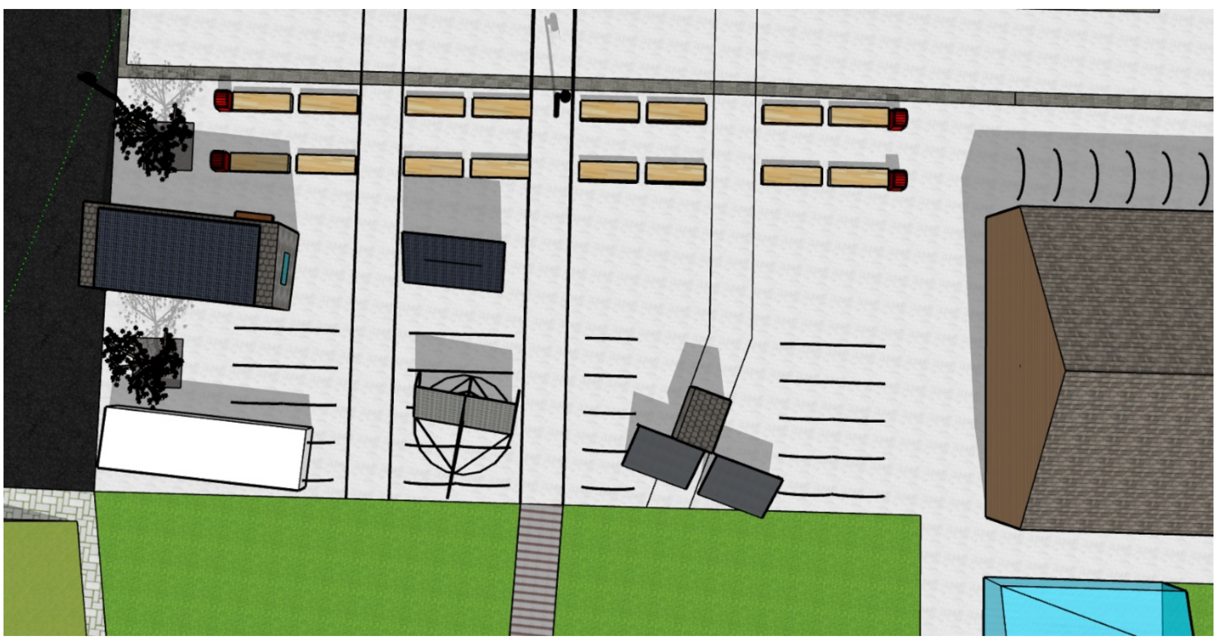


Figure 13 Aerial view of layout Proposition 4

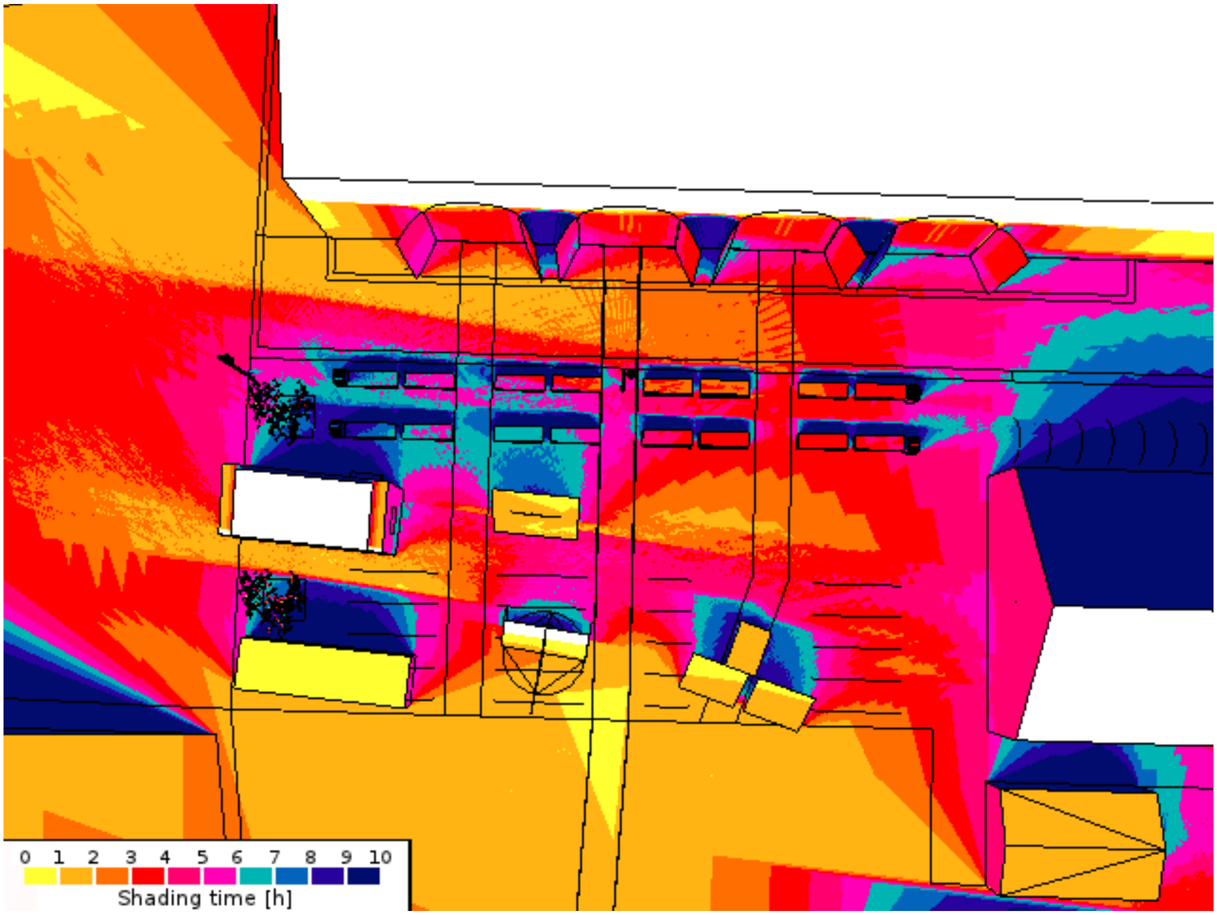


Figure 14 Shadow analysis of layout Proposition 4

In the final proposition, the four components have been put in a square formation with the ground-based solar panels in front of the passive house and the CSP tracker in front of the solar tracker. In this formation, both the passive house and the CSP tracker will be fully or partially without shade for the entire day. The ground-based solar panels will get one to two hours of shading with this layout.

This proposition will give the combined laboratory slightly less direct sunlight throughout the day compared with Proposition 3, but would provide much more than Proposition 1 and 2. In addition to the good lighting conditions, this proposition is arguably the most aesthetically pleasing of them all with its proportionate and tightly packed layout. Taking this into consideration, it could be concluded that this is the best proposed layout out of the four propositions.

In the meeting with Statsbygg they agreed that Proposition 4 was the best solution for the layout of the laboratory, and they gave the green light to start the building of the laboratory on the site. It was also agreed that they were to put pipes in the ground that could eventually carry the electrical wiring allowing the solar laboratory grid connection. They also agreed to remove the bicycle racks that took up the space needed to install the ground-based solar panels and the CSP tracker.

A few weeks after the meeting the bicycle racks were removed, and pipes were put in the ground as shown in the picture below.

Figure 15 Solar laboratory site, April 2019

Unfortunately, as will be discussed further in chapter 2.3.4, not all appropriate parties were present at the meeting, and the passive house, therefore, had to be relocated after it had already been put in the position agreed upon by Statsbygg and IMM.

2.2.6 Final Thoughts on Layout Design

The goal for this part of the project was to create a layout design of the solar laboratory that was to be presented and accepted by Statsbygg. The challenge was to find the right balance between good lighting conditions and a component setup that would be pleasing to Statsbygg. By using the 3D-model as a tool together with Shadow Analysis, it was possible to find this balance and Statsbygg gave the green light to move forward with the project.

2.3 Moving of the Passive House

2.3.1 Passive House Location

To get the best possible lighting condition for the passive house, it needed to face directly towards the south. From the CAD drawings of the site, it was known that the big brick house directly behind the laboratory site was angled 6˚ towards east. It was then possible to draw a line from the brick house and by using basic trigonometry, each corner of the house could be drawn up so the house would face south.

The site at which the passive house was to be moved to sits on a slightly sloped ground. The inclination was measured by using an accurate inclinometer able to measure to an accuracy of 0.1˚. This inclinometer was then placed on a long, straight metal plate to get the average inclination of the ground at the site. Various readings were done at different parts of the ground where the passive house was to be placed.

By using this method, the inclination at the site was found to vary from 1.1˚ to 1.5˚ by increasing amount from the east part to the west. Knowing the length of the passive house sitting in the inclined direction of the ground to be 2.66 m long, it could be calculated that the height difference between the two sides varies between 50 and 70 mm.

2.3.2 Foundation Blocks

At the previous location of the house, the foundation consisted of three wooden beams; two running along each of the short sides of the house and one going the same direction in the middle. The wooden beams were lying directly on the ground and were completely rotten. Due to the uneven surface at the previous site of the house, the middle beam was not carrying any of the weight of the house. This had resulted in the two remaining beams being compressed and deformed by the weight of the house.

By examining the house, the structure of the house was found to be resting on the beams that run along the long sides of the house. It was therefore found to be unnecessary for the foundation beams to go all the way under the house; instead the house could be supported by blocks on each side to save material. These would be placed directly under the structure supporting the weight of the house along the house' long sides. It was also decided to have five blocks on each side of the house instead of three. This would put less pressure on each block and thereby reduce the amount of deformation that would happen in the blocks over time.

To avoid, or at least postpone rotting in the foundation blocks it was decided to not have the wooden blocks directly on the ground. Instead, stone bricks would form the bottom of the blocks. These would lift the blocks off the ground and away from running water. Then a layer of thin asphalt sheets would cover the stone bricks. These would serve to keep moist from drawing up into the wooden blocks that would then be placed on the asphalt sheets.

The week before the moving of the house, the exact spots to put the foundation blocks were measured and drawn between the already drawn up corners of the house. The stone bricks were then put in place. To even out the difference, one extra wooden block with a thickness of 50 mm and one with 20 mm were put at the lower lying side. Using an inclinometer between the opposite foundation blocks, it was found that the two west-most blocks would need to be 50 mm taller, while the middle and two east-most blocks would be 70 mm taller than their opposite blocks. Since 20 mm thick blocks were the thinnest blocks accessible, this was the smallest increment possible to adjust the height of the blocks by.

The blocks were placed out as seen below.

Figure 16 Foundation blocks laid out before the house were placed onto them

2.3.3 First Move

The moving of the passive house was carried out by Royal Transport. Before the moving, a meeting was held with the CEO of Royal Transport to discuss the various routes available for the transportation. The previous location of the house was on the north side of the school. To get to the site of the solar laboratory by the main road, the house had to be transported across the tracks of the Bergen Light Rail. It was desirable to avoid this as it required a special truck with a low deck, in addition to the crane truck that would lift the house. The low-deck truck would about triple the cost of transportation and was necessary to ensure that the height of the house would not exceed 4.5 meter and hit the Bergen Light Rail cabling. Unfortunately, the only other possible route to take was on the back side of the school. Taking this route involved passing under a four-meter-tall bridge. That was not an option, and it was decided to take the main road crossing the Bergen Light Rail tracks.

The operation involving lifting the house onto the low-deck truck and driving it under the Bergen Light Rail cables went smoothly. The truck got the house to the site, and it was carefully lifted onto the foundation blocks that were accurately aligned with the edges of the house, making it face south for optimal lighting conditions.

Below is a series of pictures showing the moving.


Figure 17 To the left, the passive house in its initial location

Figure 18 To the right, the passive house being loaded onto the low-deck truck

Figure 19 To the left, the passive house crossing the Bergen Light Rail tracks

Figure 20 To the right, the passive house being loaded onto the foundation blocks

Figure 21 The passive house in its final position

Just after the passive house had been put in place, two of the five blocks on each side were not carrying any of the weight of the house. Considering it was only possible to adjust the block height by 20 mm increments, this was concluded to be acceptable. The remaining non-supporting blocks could be adjusted at a later point using the school's forklift to raise the house and fit another thinner block onto them. However, as wood suffer from creep, the base of the house is probably distorted and is likely to settle down onto the blocks over time.

2.3.4 Relocation of the Passive House

The day after the moving of the passive house, information was received that the passive house had to be moved to a new location. Unfortunately, the institute management had forgotten to inform all appropriate parties about the moving of the passive house. The school's operational management informed that the house was blocking a path used to move objects by car back and forth to the brown house located to the east of the solar laboratory. The operational management agreed to still let the laboratory be built on the site if all objects were moved forward to where the bicycle racks used to be. This resulted in a few changes to the laboratory.

Since the passive house had to be moved forward there was no longer room for the ground-based solar panels in front of the passive house, without putting them on the grass. Statsbygg had already made it clear that putting anything on the grass would be unacceptable. This was solved by mounting the ground-based solar panels to the wall of the passive house instead. At this point information was received that the CSP tracker would not be permanently stationed outside because it could not withstand heavy winds. It was, therefore, possible to move the solar tracker to the front of the site as shown in the illustrations below.

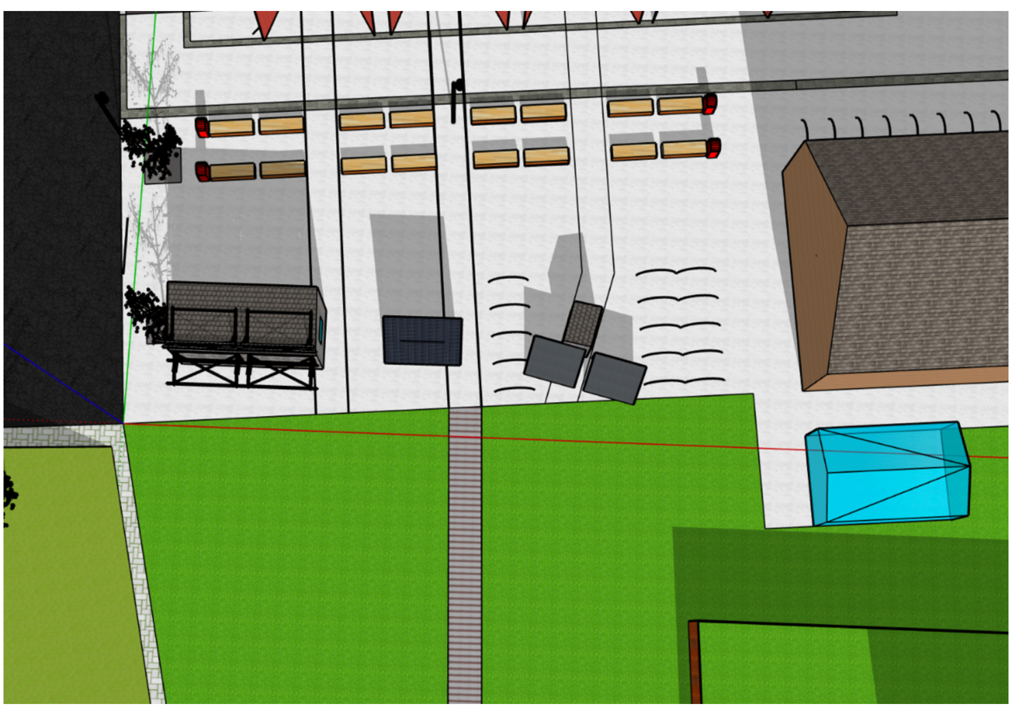


Figure 22 Aerial view of the final design layout

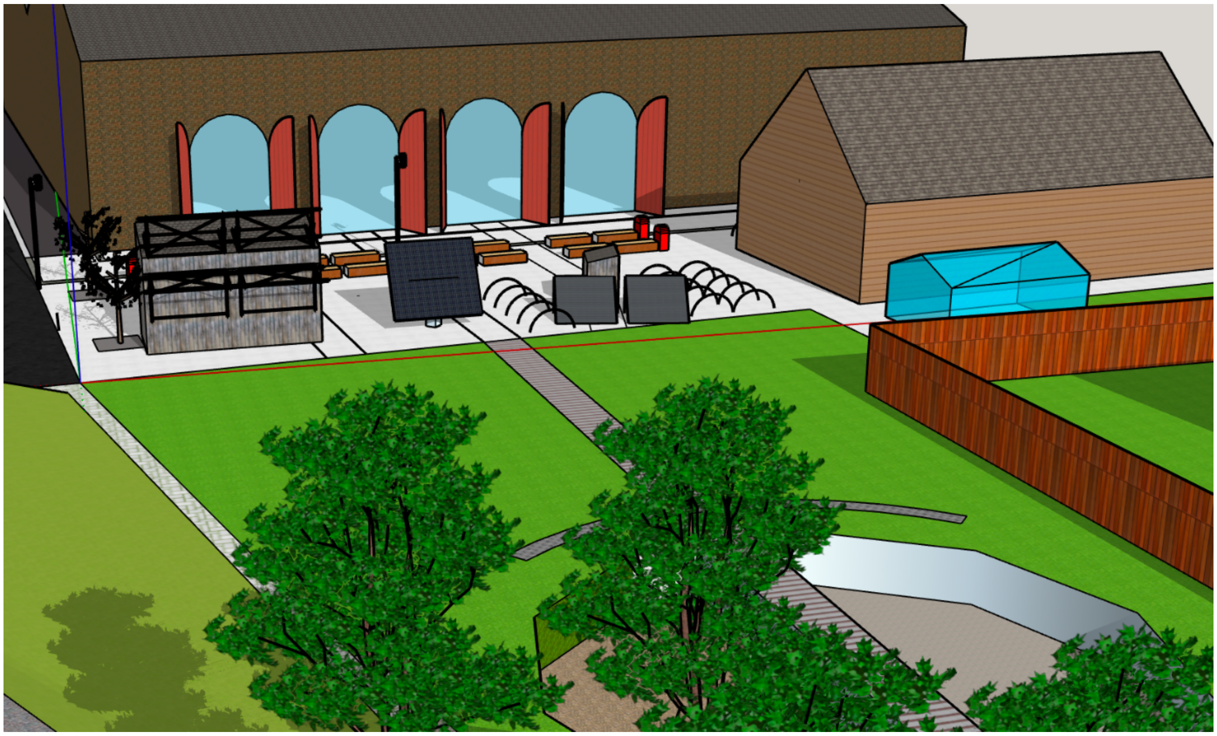


Figure 23 The final design layout as seen from the pavement

The sudden changes that had to take place happened quite fast, but this was possible to work around, and solutions were found to meet the new criteria from the operational management. Even though it seemed like a pretty huge set back at first, the new design was in many ways better than the previous. By getting the CSP tracker out of the way and mounting the ground-based solar panels to the wall of the passive house, the solar laboratory was compressed down to just two components, in addition to the already existing solar vacuum tubes. There are also a few advantages with putting the ground-based solar panels on the wall, which will be discussed further in chapter 5.

2.3.5 Final Thoughts on the Moving of the Passive House

The process of moving the house was one that involved many parties and people. Despite a few challenges, ranging from finding the best route and a way to move the house to installing it in an inappropriate location, the house was eventually put in place. It was levelled correctly with the ground and positioned facing south.

2.4 Solar Panels

2.4.1 Specifications

When deciding how to arrange the different panels, several considerations need to be taken into account. The PV panels are to be interchangeable between the solar tracker and both the roof and wall-based arrays. The thin film panels should be able to be mounted either on the roof-based or the wall-based mounting systems as required. The array on the roof should be able to pivot between a 90° angle and a 15° angle. The wall-based array should be able to pivot between a vertical and a horizontal angle with 15° increments.

The panels should also be easy to operate, in such a way that changing the inclination of the arrays is neither too time-consuming nor unmanageable for a small group of students or faculty staff.

2.4.2 Arrangement

When designing the layout, the location and space available for the wall-based array were decided upon. As it is desirable to design a similar solution for both the roof-based and wall-based mounting system, it makes sense to choose the same arrangement for the solar and thin film panels regardless of where they are mounted. This means that there are certain limitations on how the panels can be mounted, as the roof has limited space.

Since the PV panels are also intended to be interchangeable with the PV panels on the solar tracker, it is reasonable to mimic their arrangement. The solar tracker has been designed to mount the panels in a 3x2 panel arrangement. Arranging the panels in the same manner could be considered more aesthetically pleasing. However, as the roof area of the passive house has an area of 2.75 m x 6.23 m, it makes more sense to assemble the solar panels in a 1x6 panel arrangement to make full use of the length of the house.

Another possibility is to create two different arrays on both the roof and the wall. By creating two 1x3 arrays the mountings systems will be more manageable by users, if a manual solution is chosen to adjust the inclination of the panels. By splitting the 1x6 arrangement in two, one also gains certain possibilities in terms of research. The different arrays can now be set at different inclinations and results can be compared more accurately. Considering that the main use of the solar panels will be research purposes, the 1x3 arrangement has been chosen.

2.4.3 Rails and Clamping

The rails available for mounting the solar panels are already provided by WNUAS. In previous work done by the thesis for the solar tracker, the optimal distance between the rails for both the mono- and polycrystalline panels have been calculated to be 981 mm. [3] This distance allows for swapping between mono- and polycrystalline panels on the tracker and is then ideal for research possibilities. By adopting the same distance between the rails on the roof and wall-based mounting systems, easier swapping between all three systems has been ensured. However, their calculation does not account for the thin film panels, which are far longer than the solar panels. To ensure that the thin film panels are able to withstand the pressure from external forces, the plate and frame, which the thin films will be glued onto must be dimensioned properly.

2.5 Mounting System Designs

2.5.1 Specifications

As the solar laboratory is to contain as few limitations as possible, the mounting system has to be able to adjust its inclination as to be able to measure at different angles. To be able to compare results with other inclinations, the mounting systems will be divided into two parts with two different arrays. The mounting system must also be able to support all three panels; mono, poly, and thin film, as well as withstand 25-30 years of service at a low cost.

2.5.1.2 Overall Design

The mounting system will consist of two stands mounted on the roof and wall of the passive house. Each will support an array of either three solar panels or seven thin film panels. Each stand will be identical and have two rails which the panels will be mounted upon, a frame to support the rail, and struts which will support the system as well as dictate the inclination of the solar panels. The strut and supporting frame will be mounted on a foundation frame.

2.5.1.3 Method of Approach

The method of approach has consisted of several steps. Initially, there has been agreed upon certain attributes that the solar arrays must possess in accordance with their use and purpose. These attributes should consist of having inclinations that the arrays could be adjustable to, and also demonstrate how the arrays will change inclination.

Next, an assessment of external forces that the panels are subject, have been conducted. A worksheet in Microsoft Excel has been used to calculate wind forces acting on the system in accordance with NS-EN 1991-1-4:2005:+NA2009. [4] Thereafter, the material to be used was chosen with regards to climate and external forces that the system will be subjected to.

A first draft of the adjustment mechanism was created, defining certain lengths and dimensions of the structure with respect to what inclinations the panels should be able to display. Another worksheet has been used to analyse how the external forces propagate throughout the frame to decide the different component's necessary thickness and profile. Lastly, fixing locations have been defined, and necessary diameter of bolts and pins have been calculated.

2.5.2 External Loads

To determine what materials to use, as well as the thickness of the extruded profiles, external loads on the system will need to be assed. Initially, the mounting system will need to be able to support all three kinds of panels for 25-30 years without failure. Secondly, it has to withstand external forces such as snow and most importantly wind.

2.5.2.1 Wind Loads

To calculate the wind loads working on the panels, the Norwegian Standard (NS-EN 1991-1-4:2005+NA2009) has been used. [4] This standard offers instruction as to how to calculate wind loads on buildings, freestanding walls and roofs.

The standard does not offer an approach for the calculation of wind loads on the solar panels, as such, an approximation will have to be applied. Since the wind force will mostly act on the solar panels, as they have the largest surface area, the wind force on the stands will be neglected. The wind force will also be most extensive when the panels are in an upright position, normal to the ground with the wind striking the panels at 90 degrees to the direction of flow. In this position the panels will act, in an aerodynamic sense, as a wall and thus this approximation has been chosen as it is covered in the Norwegian standard.

When the panels are tilted, the panels will act more like a free-standing sloped roof then a wall. Consequently, when calculating wind loads on the panels at a tilted angle, it has been decided to calculate the loads as if the panels where a sloped roof.

The formulae for wind forces offered by the Norwegian Standard are as follows: [4]

$$F_w = c_s c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}, [kN]$$

Where

c_sc_d is the construction factor defined in Chapter 6 in the standard
c_f is force factor for the construction
A_{ref} is the reference area for the construction
$q_p(z_e)$ is the peak velocity pressure

$q_p(z_e)$ is calculated by the formula:

$$q_p(z) = \frac{1}{2} \cdot \rho \cdot v_m^2 \cdot \left(1 + 7\, I_v(z)\right), \left[\frac{N}{m^2}\right]$$

Where:

ρ is the air density (recommended value 1.25kg/m^3) [4]
v_m is mean wind velocity, calculated from $v_m = c_r(z) \cdot c_o(z) \cdot v_b$
c_r is the roughness factor, calculated from $c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$
c_o is the orography factor, taken as 1
v_b is basic wind velocity, calculated from $v_b = c_{dir} \cdot c_{season} \cdot v_{b,0}$
I_v is turbulence intensity

I_v is calculated by the formula:

$I_v = \frac{k_1}{c_o(z) \cdot \ln\left(\frac{z}{z_0}\right)}$ for $z_{min} \leq z \leq z_{max}$

$I_v = I_v(z_{min})$ for $z < z_{min}$

Where:

k_1 is the turbulence factor

z is height above the terrain

Before calculations can be done, terrain category must be chosen. The standard present five different categories; [4]

0) Open sea.

I) Coastal sea, mountain plateau and beach areas without trees or bushes.

II) Agricultural area, area with scattered small buildings or trees.

III) Suburban terrain, industrial areas and forests.

IV) Area in which 15% of the surface is covered with buildings and their average height exceeds 15m.

As the laboratory will be situated in a suburban area in the middle of Bergen with a fair amount of shelter, category III has been chosen. This gives the following values from table NA.4.1 of the Norwegian Standard: [4]

$k_r = 0.22$

$z_0 = 0.3$ m

$z_{min} = 8$

The reference height (z) of our calculation has been set to 5.5m which is the height from the top of the thin film panels to the ground when they are mounted at a 90 degrees angle from the ground. This is the maximum value z can have as the thin film panels are the tallest panels and will give the largest reference height. This gives $z_{min} \geq 5.5$m.

To calculate peak velocity pressure several values needs to be obtained. The values for c_{dir} and c_{season} and $v_{b,0}$ are all given in the standard. The recommended value for c_{dir} and c_{season} is taken as 1 for calculations for the whole year. $V_{b,0}$ is given in table NA.4(901.1) and is specified as 26 m/s for Bergen. This gives v_b to be 26 m/s.

Next, the roughness factor needs to be determined. The values k_r, z, and z_0 are all obtained from the terrain category. The value for $z = z_{min}$ as the reference height is smaller than the minimum value for z in the chosen category. The roughness factor is then determined to be 0.722.

$$c_r(z) = 0.22 \cdot \ln\left(\frac{8}{0.3}\right) = 0.72235$$

Now mean wind velocity can be decided.

$$v_m = c_r(z) \cdot c_o(z) \cdot v_b$$
$$v_m = 0.722 \cdot 1 \cdot 26\, m/s = 18.78\, m/s$$

The orography factor, $c_o(z)$, is recommended to be 1 by byggforsk.no when the wind velocity does not change because of hills and mountains. [5] Since this calculation is an approximation to actual wind pressure, an orography factor of 1 is deemed appropriate for these calculations.

The last value needed to calculate peak wind pressure is the turbulence intensity. Since $z_{min} \geq z$, z_{min} will be used for the reference height when calculating the turbulence intensity. Recommended value in the Norwegian Standard for k_1 is 1 and will be used for this calculation.

$$I_v = \frac{k_1}{c_o \cdot \ln\left(\frac{z_{min}}{z}\right)}$$

$$I_v = \frac{1}{1 \cdot \ln\left(\frac{8}{0.3}\right)} = 0.30456$$

Peak wind pressure is subsequently calculated as follows:

$$q_p(z) = \frac{1}{2} \cdot 1.25 kg/m^3 \cdot (18.78 m/s)^2 \cdot (1 + 7 \cdot 0.30456) = 0.69\ kN/m^2$$

Now the wind forces and wind loadings acting on the panels can be calculated. The most interesting scenario is the wind forces that will act on the system when the panels act as a wall. That will give the largest force and represents the maximum wind loads the panels might be subjected to. To calculate the wind force acting on a freestanding wall, net pressure coefficients need to be determined. First the solidity ratio φ of the panels will need to be determined, then the net pressure coefficient will be interpolated from table 7.9 in the standard. [4]

$$\varphi = \frac{A_{thin\ film\ panels}}{A_{total}} = \frac{2.598 \cdot 0.370 \cdot 7}{2.598 \cdot (0.370 \cdot 3 + 0.012 + 0.370 \cdot 4)} = 0.995$$

As $\frac{\ell}{h} = \frac{0.370 \cdot 7 + 0.012}{2.598} \leq 3$ the values for $c_{p,net}$ is 2.3 and 1.4 for zone A and B respectively.

Interpolation gives:
$C_{p,net} = 2.2725$ for zone A and $C_{p,net} = 1.395$ for zone B

The construction factor for the construction is set to 1 as is recommended for most buildings and structures in the standard.

The largest wind force acting on the panels when in an upright position is then calculated to be 10.55kN as follows:

$$F_w = 1 \cdot 2.2725 \cdot 0.69 \frac{kN}{m^2} \cdot (2.598\ m \cdot 2.59\ m) = 10.55\ kN$$

2.5.2.2 Snow loads

Seeing as the solar laboratory is in Bergen, it is highly likely that the solar panels will be subjected to snow loads. Snow loads will only occur if the panels are mounted in a position with less than 60° inclination between the ground and the panels. The snow loads that will occur, if the panels are mounted with a smaller angle than 60° increases as the angle decreases. The largest force will occur when the panels are mounted at a horizontal position. For this reason, a calculation of snow forces that will work on the panels at a horizontal position has been done according to the Norwegian Standard NS-EN 1991-1-3:2003+A1:2015+NA:2018. [6]

Since the standard does not include a chapter specific to solar panels an approximation will have to be applied, as done when calculating wind forces. In fact, the only scenarios that the standard does offer are calculations for snow loads on roofs, and snow loads on the ground. The snow loading on the roof has been chosen to approximate the snow forces that will act on the panels.

The equation for snow loadings on roofs offered by the standard is as follows: [6]

$s = \mu_i \cdot C_e \cdot C_t \cdot s_k$

Where;

s	is snow loads on roofs [kN/m^2]
μ_i	is the shape coefficient
C_e	is the exposure coefficient
C_t	is the thermal coefficient
S_k	is the snow load on the ground

The shape coefficient, μ_i, is given as 0.8 for a flat roof.

C_e is taken as 1 for normal topographies, defined as "areas where the wind does not substantially remove snow from buildings due to terrain, other structures or trees". [6]

C_t has been assumed as 1, since the standard recommends using $C_t = 1$ for most cases. The thermal coefficient is to account for heat loss through roofs which may reduce snow loads as the heat loss can cause the snow to melt. Considering that solar panels often generate some heat it is likely that some snow will melt and thus the thermal coefficient does not necessarily equal 1. However, since this calculation is done to find maximum snow loads that may occur on the panels and the fact that if any snow were to gather on the panels the solar panels would be ineffective, and no longer produce any heat, the thermal coefficient has been taken as 1 for this approximation.

The snow load on the ground, s_k, is given in table NA.4.1(901) in the Nation Annex of the standard as 2.0 kN/m^2 for Bergen. [6]

The resulting snow load then becomes:

$$s = 0.8 \cdot 1 \cdot 1 \cdot 2\frac{kN}{m^2} = \frac{1.6kN}{m^2}$$

The force acting on the thin film panels are;

$$F_{snow_{thin\ film}} = s \cdot A_{thin\ film} = \frac{1.6kN}{m^2} \cdot 7.92m^2 = 10.77kN$$
$$F_{snow_{PV}} = s \cdot A_{PV} = 1.6\frac{kN}{m^2} \cdot 4.95m^2 = 7.92kN$$

2.5.3 Choice of Materials

To decide what materials the mounting system should consist of, several factors need to be taken into account, the most important of which is corrosion. Since the structure will be situated outdoors, in a predominantly cold and wet climate, there is a high risk of corrosion. The material must, therefore, be able to resist such corrosion. Further factors to consider are mechanical properties, weight, cost, aesthetics and weldability.

Considering corrosion there are several options available. The most common corrosion resistant metals used are; stainless steel, galvanized steel, aluminium, and red metals like brass, copper and bronze.

Stainless steel is an excellent option when considering corrosion. The alloys available to the university for this purpose is mainly AISI 304 and AISI 316L, which are two of the most commonly used alloys. AISI 316L is slightly stronger and more corrosion resistant to climate with high concentrations of chlorides. Since the laboratory is situated in Bergen, in a coastal climate, this is worth reflection. The city is also known to use salts for de-icing in the winter which can increase the risk of chloride related corrosion. [7]

Brass, copper and bronze are materials most often used for decorative purposes as they are rarer metals, and often more expensive. Additionally, most copper and brass alloys have a much lower yield and tensile strength than most corrosion resistant steels and have thus been neglected from consideration. [8, 9]

In terms of mechanical properties of materials, both galvanized and stainless steel, could possibly endure the loads if the structure is dimensioned properly. However, galvanized steel is, in general, a lot cheaper than stainless steel and is thus favourable with regards to the cost of the mounting system. [10] The only problem posed by galvanized steel is the challenges with respect to welding. Welding galvanized steel cannot be done at WNUAS. The frames must, therefore, be galvanized after welding. Because of their size, dipping is not an option at the university. The remaining option of galvanization available is to use galvanizing spray.

Another option to consider is aluminium. Several alloys are available by the school supplier Astrup, including EN AW 6082 T-6 and EN AW 6062 T-6. Both are considered to have high resistance to corrosion. [11] Aluminium is also a favourable choice when considering the weight of the mounting system. Low weight is an advantage when installing the mounting system on the roof. If the frames can be lifted manually on the roof it saves money compared to heavier frames which might require a crane to install the system. A weight estimation is available in attachment 1, comparing the weight of a mount of stainless steel to a mount of aluminium.

Since the solar laboratory is situated next to the Bergen Light Rail it will be on display for any citizen in Bergen using public transport. For this reason, the aesthetics of the solar laboratory is important. Because the laboratory will not only represent the university, but solar and renewable energy in Bergen, galvanized steel may not be an ideal choice. Stainless steel is also consistent with the choice of material for the solar tracker, which will use AISI 316L. [3] Using the same material for all the components of the solar laboratory will likely be more aesthetically pleasing than a mixture of different materials.

Another option worth consideration is wood. A wooden mounting system offers several advantages, as wood is a more sustainable material and would be fitting for the image of the laboratory. A wooden mounting system would fit right into the exterior of the passive house and therefore be very aesthetically pleasing. However, wood would not likely survive a service-life of 25-30 years without rotting. Wood also poses several other problems; the weight of wooden beams could pose a problem for the roof-based mounting system in terms of installation and loadings on the roof. A wooden mounting system could also be potentially less flexible for future modifications than a metal system which will be easier to take apart and modify. For these reasons, a wooden mounting system has been disregarded.

The initial designs were based on stainless steel as this option was considered most likely to ensure a service-life of 25-30 years. However, further examination of stainless steel showed that the mounting system would be inconveniently heavy. The best choice of stainless steel with respect to corrosion is AISI 316L, which is also a very expensive material to use. While using stainless steel AISI 304 would cut cost, it offers no apparent advantages over aluminium alloy EN AW 6082, which is both lighter in weight, and has a higher yield strength than AISI 304. [11] A comparison of stainless-steel profiles and aluminium profiles is presented in subsection 2.5.6 Analysis of Mounting System.

In the end, aluminium is the preferred choice through the process of elimination. Aluminium's low weight offers fewer complications when mounting the system on the roof of the passive house and is cheaper than stainless steel. Alloy EN AW 6082 T6 offers a yield strength of 250 MPa, according to the supplier, which is found as suitable for this application. [11] Although aluminium may have a high energy cost, Norsk Hydro, the largest producer of aluminium in Norway, claims to produce aluminium in the cleanest way possible which is some consolidation for the high energy cost of the mounting system. [12]

2.5.4 Adjusting Mechanism Design

2.5.4.1 Method of Approach

Initially, a first draft was created, consisting of solutions for how to make the frame adjustable in inclination, and lengths of each member and strut were determined. Then several calculations were conducted in order to analyse the external forces working on the system. A spreadsheet in Microsoft Excel was used to calculate every force acting on each strut at all the different possible inclinations that the frame would be adjustable to.

Calculations were made without including wind forces, in order to determine how the weight of the panels propagated throughout the framework. Then wind forces were added to see what forces the frame would need to withstand in order to endure a Western Norwegian coastal climate.

Once the analysis of forces acting on the framework was complete, calculations were made to determine dimensions, profile and thickness necessary for each beam and strut. Estimates of maximum bending stress to occur in key struts were calculated in order to determine whether any strut was at risk of bending. For any strut that endures compression, there has been conducted calculations considering buckling, and critical force before buckling has been determined. Any necessary adjustments after these calculations were corrected.

2.5.4.2 Initial Design

The first design of the adjusting mechanism consisted of two U-profile steel members which are joint together and supported by a strut with a square hollow structural section (HSS). U-profile steel members were chosen to allow the mounts to fold into one another and allow the solar panels to be placed in a horizontal position.

The mount would be adjustable by fixing the strut at different points along the foundation beam, subsequently changing the inclination of the member designed to carry the solar panels.

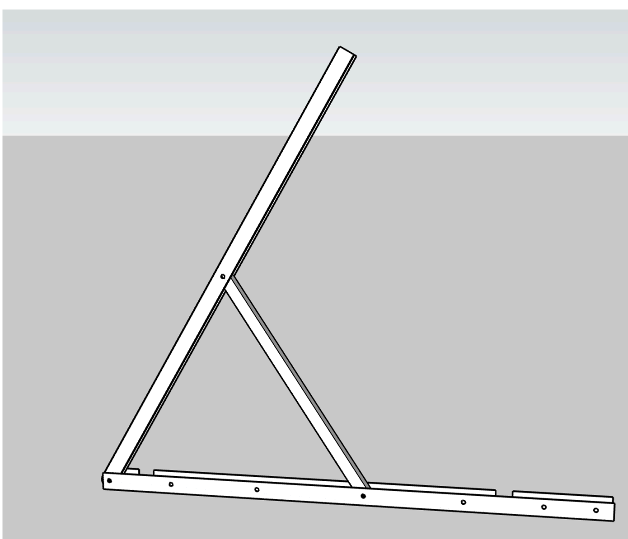


Figure 24 Initial design of Adjusting Mechanism

Each mount would consist of two adjustable supports joined together by crosspieces. Two parallel crosspieces welded at each end of the foundation beam were designed to create a foundation frame to support the rack. Two crosspieces would be welded diagonally between the members carrying the solar panels to support the rack in case of external forces working perpendicular to the panels.

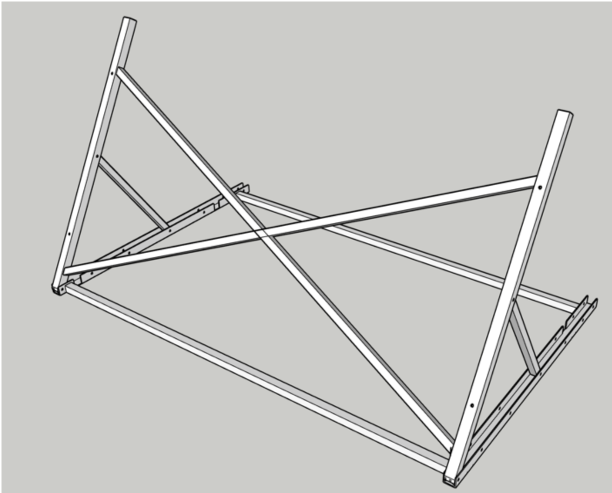


Figure 25 Initial design of mounting system

This design offers a simple way of adjusting the inclination. It enables every user, student or faculty, to use the solar panels for their own purpose. However, since the U-profiles have to fit perfectly into each other with specific tolerances, it proved difficult to find suitable profiles that fit perfectly, with specifications, like necessary section modulus, for this application.

2.5.4.3 Profile Selection

To solve this problem different kinds of profiles were considered. The two most promising options were L-profiles and rectangular hollow structural sections. Calculations were done to see if L-profile members would be able to support the solar panels and external forces as shown in the Chapter Analysis of Mount 2.5.6. By inspection, L-profile beams would have to be very thick, with long flanges to endure the stress that could occur when wind loads are applied. The dimension of bolts would increase from the original design since they would be subjected to a single shear force instead of double shear. Because of this disadvantage, rectangular tubes were explored.

To make the mounting rack adjustable with rectangular tubes, some adjustments to the original design would have to be made. To be able to join the different members, steel plates would have to be welded on each side of the strut carrying compression, and the foundation beam. These plates would be the new joints to connect the members together.

Hollow structural sections offer a higher section modulus in regard to thicknesses compared with that of L-shape profiles. This also makes them a cheaper alternative due to lower weight. [10] For this reason, HSS-profiles were selected to replace the U-profiles.

2.5.4.4 Geometrics of Adjusting Mechanism

In order to ensure that the different possible inclinations of the solar panels are placed at 90, 75, 60, 45, 30 and 15 degrees, certain geometric calculations have to be made. For the purpose of calculating these angles, the different members of the adjusting mechanisms and the angles they form have been given names. The purpose of these calculations is to find the location of the bolting holes which shapes the support structure into the desired angles.

The main triangle formed by the adjustable support has been named ABC, formed by three points; A, B, and C. Where AB is the distance between bolting holes at A and B, BC is the distance between bolting holes B and C, and so on. Before any geometric calculations can be done, some distances and angles have to be defined. Length AB is defined as half of the longest photovoltaic solar panel.

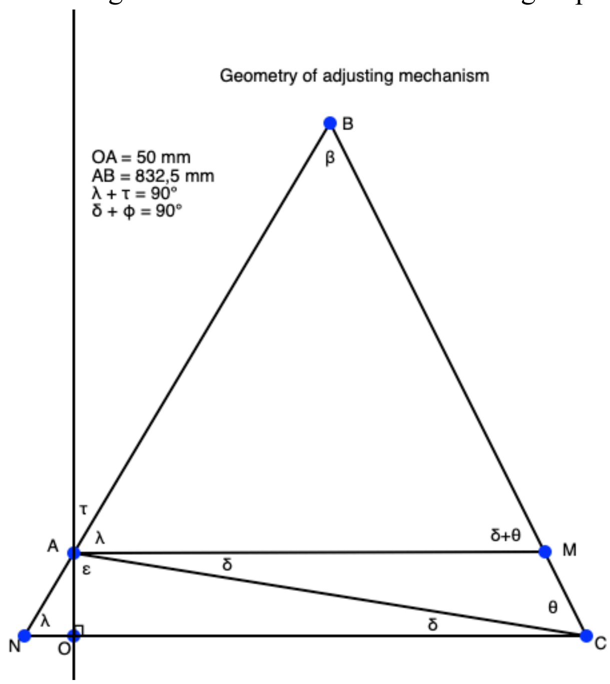


Figure 26 Geometry of adjusting mechanism

The reason for this is to ensure that all photovoltaic panels can be mounted at their optimal position and that their weight is evenly distributed along their beam. Since the thin film panels are very long compared to the PV panels, the structure would have to be of a considerable size to ensure evenly distributed forces along the member. Solutions to this problem were discussed in the Section 2.4.3 Rails and Clamping. Since the longest photovoltaic panels is 1.665 m, the distance AB is defined as $\frac{1.665\ m}{2} = 832.5mm$.

Another length necessary to define is the distance between point A and the horizontal line at which the bolting holes are located. This distance is called as OA. Since the hollow section profiles are unable to fit into each other like the U-profiles, the location of joint A has to be elevated above the joints between the strut and the foundation beam. This distance is defined as half the length of the sum of both members profile height. This distance is found to be 50 mm.

The last pre-defined value is the angle between AB and BC, when the panels are in an upright position. This angle was found through trial and error as 15°, larger angels resulted in a too long strut, and consequently a very long foundation beam that would have difficulty fitting on the roof of the passive house.

The length of strut BC is found by geometric calculations: $\frac{832{,}5\ mm+60\ mm}{\cos(15°)} = 923{,}984\ mm \approx 924\ mm$

Since the length of strut BC is constant, the angle between AB and BC can be calculated and the location of bolt holes can be found at all the possible inclinations of the solar panels.

	Triangle 1, formed by ABC						
Position (angle with respect to the ground)	90	75	60	45	30	15	degrees
Lengths							
AB	832,5	832,5	832,5	832,5	832,5	832,5	mm
BC	923,983991	923,983991	923,983991	923,983991	923,983991	923,98399	mm
AC	246,5566175	545,9134291	912,0256173	1248,120282	1513,946161	1687,1667	mm
Angles							
Alpha (Between AC and AB)	104,0844519	81,30998547	63,77207758	47,75540128	32,27131414	17,038015	degrees
Beta (Between AB and BC)	15	35,73541783	62,30490302	90,40973439	118,9737315	147,65471	degrees
Theta (Between BC and AC)	60,91554807	62,9545967	53,92301941	41,83486432	28,75495438	15,307274	degrees
sum = 180	180	180	180	180	180	180	

Table 1 Triangle1, formed by ABC

The location of the bolt holes is found along the horizontal member, and is represented in the spreadsheet as the distance OC.

	Triangle 4, formed by OAC						
Lengths							
OA	60	60	60	60	60	60	mm
AC	246,5566175	545,9134291	912,0256173	1248,120282	1513,946161	1687,1667	mm
OC	239,1446542	542,606185	910,0498484	1246,677279	1512,756748	1686,0995	mm
Angles							
90 degrees (formed by OA and OC)	90	90	90	90	90	90	degrees
Phi (formed by OA and AC)	75,91554807	83,69001453	86,22792242	87,24459872	87,72868586	87,961985	degrees
Delta (formed by AC, and OC)	14,08445193	6,309985469	3,772077577	2,755401281	2,271314144	2,0380155	degrees
Sum = 180	180	180	180	180	180	180	

Table 2, Triangle 4 formed by OAC

The full spreadsheet is available in attachment 2 and is used to calculate all variables in the geometrics of the adjusting mechanism.

2.5.5 Analysis of forces

Forces acting on each member must be calculated to dimension the system appropriately. To determine how the forces propagate throughout the system, software MD Solids made by Timothy A. Philpot, has been used to make shear and moment diagrams.

First, calculations have been done without external forces, to determine how the weight of the panels affects the system. The solar panels are mounted on the supports at two points 981 mm apart. The mounting points are located above and beneath the support strut with an equal distance of 490,5 mm. Since the weight of the solar panels acts on the mounting system at two points of each support, assuming the load distributes evenly on both supports, the load has been divided by four to determine the forces acting on each point.

The weight of the panels is given in the datasheets for each panel;

Monocrystalline Violin™ Crystalline PV Module ASM6610M Series: 18.2kg/panel [13]

$$18{,}2kg/panel \cdot 3panels = 54{,}6kg$$

Polycrystalline REC Peak Energy Series panels: 18kg/panel [14]

$$18kg/panel \cdot 3panels = 54kg$$

Thin film MiaSolé Flex Series -02N: 2,7kg/module (with adhesive) [15]

$$2{,}7\frac{kg}{module} \cdot 7modules = 18{,}9\ kg$$

Since the thin film modules will be glued on to a metal frame, the weight of these modules will be significantly higher. For the purpose of these calculations, a load of 54,6 kg have been applied to represent the maximum weight of the panels.

The forces acting on the mounting system have been tabulated in an Excel Spreadsheet:

Table 3 External forces acting on the framework

External forces acting on the framework							
	90	75	60	45	30	15	0
Forces							
Wind (kN)	10,56	10,20	9,14	6,50	6,50	6,50	6,04
Wind (kN/4)	2,64	2,55	2,29	1,63	1,63	1,63	1,51
Solar panels mass (kg)	54,60	54,60	54,60	54,60	54,60	54,60	54,60
Solar panels weight/4 (kN)	0,13	0,13	0,13	0,13	0,13	0,13	0,13

Resultant forces for the support structure have been calculated using principals of a rigid body at equilibrium;

$$+\uparrow \sum F_y = 0$$
$$+\rightarrow \sum F_x = 0$$
$$+\circlearrowright \sum M = 0$$

When the solar panels are at an upright position, neglecting external forces, the whole weight of the solar panels will be supported at point A, where the resultant force at point A will equal:

$$0.134kN + 0.134kN - A_y = 0, \quad \rightarrow \quad A_y = 0.268kN$$

When the system is tilted, forces will propagate through strut BC, and through the rest of the system. Calculations have therefore been done at every angle the solar panels can be positioned at.

The formula used to calculate the resultant force caused by strut BC is;

$$+\circlearrowright \sum M_A = 0$$
$$AD \cdot \cos(\lambda) \cdot F_{solarpanels} + AE \cdot \cos(\lambda) \cdot F_{solarpanels} - F_{BC} \cdot cos(90 - \beta) \cdot AB = 0$$

Where:

AD is the distance from A to first mounting point of the C-rails which the solar panels are mounted, termed D.
AE is the distance from A to second mounting point of the C-rails which the solar panels are mounted, termed E.
λ is the inclination of the panels with respect to the ground.

Table 4 Calculation of force acting on strut BC

Calculation of forces working on the framework, neglecting wind forces							
Inclination of panels: λ (°)	90	75	60	45	30	15	0
Resultant force in strut BC							
F_{BC} (kN)	0,00	0,12	0,15	0,19	0,27	0,48	-0,27

Note that the force in strut BC at $\lambda = 0$, is actually zero, since the design requires the strut to be removed to be positioned parallel to the ground. As expected, the resultant force increases, as the panels are positioned at a lower inclination and the strut carries more weight.

The resultant forces in each joint can now be calculated.

Table 5 Forces in joints A, B and C

Forces in joints A, B, and C	90°	75°	60°	45°	30°	15°	0°
A_x (kN)	0,000	-0,069	-0,134	-0,189	-0,232	-0,259	0,000
A_y (kN)	0,268	0,157	0,140	0,135	0,131	0,124	0,134
B_x (kN)	0,000	0,042	0,081	0,135	0,227	0,462	0,000
B_y (kN)	0,000	0,111	0,128	0,133	0,137	0,144	0,000
C_x (kN)	0,000	0,042	0,081	0,135	0,227	0,462	0,134
C_y (kN)	0,000	0,111	0,128	0,133	0,137	0,144	0,000

Calculations have also been done with wind forces to find the maximum force that can occur in the system.

$$+\circlearrowright \sum M_A = 0$$

$$AD \cdot \sin(\lambda) \cdot F_{wind} + AD \cdot \cos(\lambda) \cdot F_{solarpanels} + AE \cdot \sin(\lambda) \cdot F_{wind} + AE \cdot \cos(\lambda) \cdot F_{solarpanels} - F_{BC} \cdot cos(90 - \beta) \cdot AB = 0$$

Table 6 Calculation of forces including wind forces

Calculation of forces working on the framework, wind forces included							
Inclination of panels °	90	75	60	45	30	15	0
Resultant force in strut BC							
F_BC (kN)	20,396	8,540	4,617	2,829	2,131	2,083	0,000
A_x (kN)	0,000	0,104	0,479	0,904	1,394	2,152	0,000
A_y (kN)	-19,434	-7,716	-3,628	-1,710	-0,820	-0,337	0,268
B_x (kN)	5,279	3,032	2,477	2,023	1,833	1,993	0,000
B_y (kN)	19,701	7,984	3,896	1,978	1,087	0,605	0,000
C_x (kN)	5,279	3,032	2,477	2,023	1,833	1,993	0,000
C_y (kN)	19,701	7,984	3,896	1,978	1,087	0,605	0,000

As the wind acts on the panels, strut BC counteracts the external force and is put in compression. It is observed that the force caused by strut BC causes a pull downwards at point A to counteract the y component of F_{BC}. Because of the considerable high force that can occur at strut BC during high windstorms the strut BC and all bolts must be dimensioned accordingly.

The full worksheet with all values used in these calculations is available in attachment 3.

2.5.6 Analysis of Mounting System

Several simple analyses and calculations have been done when designing the mounting system. A spreadsheet has been used as a calculator to determine necessary dimensions and section modulus for different materials and profiles. When dimensioning the mounting system, a safety factor of 1.5 has been applied to ensure a long service-life of the mounting system.

The C-rails carrying the solar panels will be fixed on a member, from now on defined as member AF, at two points named AD and AE. Strut BC will be fixed at member AF at the midpoint between AD and AE as to distribute the force of from AD and AE evenly. This puts member AF at risk of bending and has been dimensioned accordingly.

Member AF

When calculating the maximum internal moment in member AF, a software called MD Solids 4.0 has been used.

The member has been applied the maximum wind forces that could occur when the panels are in a vertical position.

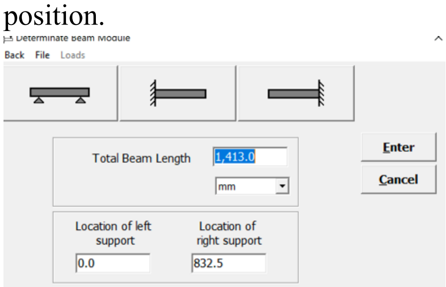


Figure 1 MD Solids 4.0 Determine Beam Module

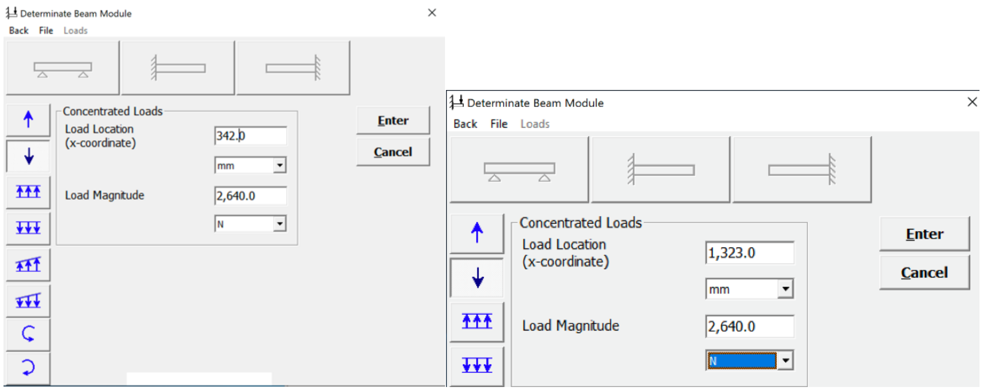


Figure 27 Adding forces to beam AF in MD Solids 4.0

After adding the forces to the beam, the internal moment can be found using MD Solids.

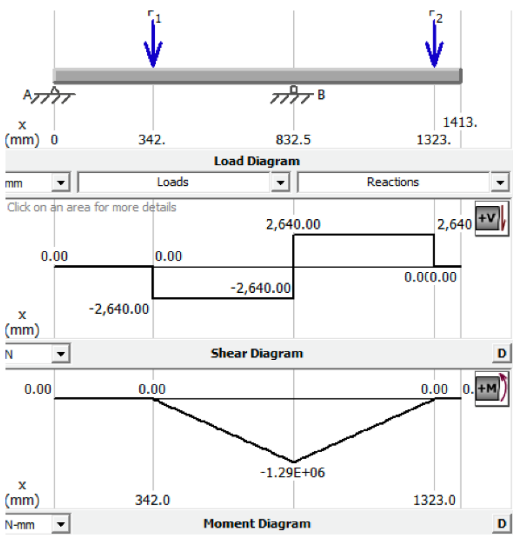


Figure 28 Shear and moment diagram for beam AF

Using MD Solids, maximum internal moment was found to be $1.29 \cdot 10^6$ MPa. This is consistent with our own calculations, available in attachment 3, were the internal moment is found to be 1294663,56 Nmm^2.

Comparisons have been done between different profiles and dimension for both stainless steel and aluminium to find the most suitable combination of mechanical properties for the design.

Stainless Steel: AISI 304

Comparison of profiles and dimensions, available at the WNUAS' main supplier Astrup, of stainless steel AISI 304 were conducted to see if stainless steel was a viable option. Yield strength for AISI 304 is 190 MPa, and a safety factor of 1.5 has been applied. [11]

L-profiles were explored, but necessary dimensions were found to be 80x80 flanges and 8 mm thickness. This resulted in a very high weight which would cause extra stress upon strut BC, and the roof of the passive house. This would also cause difficulties manually adjusting the inclination of panels on the roof. L-profiles with dimension 70x70x7 were found to have an insufficient section modulus.

HSS profiles were explored in more depth with two main options, with dimensions 60x60x3 and 50x50x5. The option with the lowest weight was found to be 5.49 kg in Option 2. Whereas HSS with dimensions of 50x50x5 is considerably heavier. Option 4 was found to have an insufficient section modulus and was disregarded.

Table 7 AISI 304 Stainless Steel profile and dimension comparison

304 Stainless steel

Requirements for AF
Section Modulus

$\sigma_{Allow} =$ 126,6666667 MPa

Mmax = 1294663,56 Nmm

$S_{req'd} = \frac{M_{max}}{\sigma_{allow}} =$ 10221,02811 mm^3

	Option 1			Option 2			Option 3			Option 4	
Profile	L		Profile	HSS		Profile	HSS		Profile	HSS	
Dim (LxBxT)	80x80x8		Dim (LxBxT)	60x60x3		Dim (LxBxT)	50x50x5		Dim (LxBxT)	50x50x3	
L	80	mm	L	60	mm	L	50	mm	L	50	mm
B	80	mm	B	60	mm	B	50	mm	B	50	mm
T	8	mm	T	3	mm	T	5	mm	T	3	mm
Weight (kg/r	9,85	kg/m	Weight (kg/r	5,49	kg/m	Weight (kg/r	7,45	kg/m	Weight (kg/r	4,66	kg/m
Section mod	12923,1193	mm^3	Section mod	12380,4	mm^3	Section mod	12300	mm^3	Section mod	8339,68	mm^3
I	737297	mm^4	I	371412	mm^4	I	307500	mm^4	I	208492	mm^4
σ	70,238374	MPa	σ	104,573645	MPa	σ	105,2572	MPa	σ	155,241395	MPa
Price/m			Price/m		kr	Price/m			Price/m		

Aluminium EN AW 6082 T6:

Yield strength for EN AW 6082 T6 is given as 250 MPa by Astrup. Safety factor used is 1.5.
After comparing L-profiles to HSS-profiles for stainless steel, HSS profiles were selected as the best alternative, when comparing the possibilities for aluminium, L-shapes were disregarded.

Four options were explored, all HSS-profiles with different dimensions. The two most important factors for selecting a profile were the amount of stress induced in the material, and the weight of the material. The first two options were found to have an insufficient section modulus, and therefore unable to support the solar array. Option 3 and 4, were both of satisfactory section modulus. Since Option 4 offers the lowest weight, this option was chosen for member AF.

Table 8 6082 T6 Aluminium profile and dimension comparison

6082 T6 Aluminium		
Requirements for AF		
Y.S	250	Mpa
S.F	1.5	
$\frac{\sigma_{Y.S}}{S.F} = \sigma_{A\,llow} =$	166,66667	MPa
Section Modulus		
Mmax =	1294663,56	Nmm
$S_{req'd} = \frac{M_{max}}{\sigma_{allow}} =$	7767,9814	mm^3

Option 1				Option 2				Option 3				Option 4		
Profile	HSS		Profile	HSS		Profile	HSS		Profile	HSS				
Dim (LxBxT)	40x40x3		Dim (LxBxT)	40x40x4		Dim (LxBxT)	50x50x5		Dim (LxBxT)	50x50x3				
L	40	mm	L	40	mm	L	50	mm	L	50	mm			
B	40	mm	B	40	mm	B	50	mm	B	50	mm			
T	3	mm	T	4	mm	T	4	mm	T	3	mm			
Weight (kg/n	1,24	kg/m	Weight (kg/n	1,61	kg/m	Weight (kg/n	2,06	kg/m	Weight (kg/n	1,58	kg/m			
Section modu	5098,6	mm^3	Section modu	6297,6	mm^3	Section modu	10461	mm^3	Section modu	8339,68	mm^3			
I	101972	mm^4	I	125952	mm^4	I	261525,33	mm^4	I	208492	mm^4			
σ	253,92531	MPa	σ	205,58047	MPa	σ	123,76082	MPa	σ	155,2414	MPa			
Price/m		kr	Price/m		kr	Price/m		kr	Price/m		kr			

Strut BC

Strut BC is subject to compression and has been designed accordingly. The initial design was based on U-profiles, allowing for an HSS-profile to fit into both frames. As the design was changed to HSS-profile, a different solution was necessary. Several options were proposed, such as welding plates on each side of an HSS profile and drill holes for bolting in each plate. This option was disregarded, as the HSS-profile would be very short to fit between the frames when solar array is positioned at lower angles.

Another option was to have several replaceable struts at different lengths to support the frame. However, this would require a place to store the unused struts, and a method of labelling the different struts which corresponds to different inclinations. This would also be a more costly option, as more material would have to be acquired.

The last option explored was to have two different struts, one on each side of member AF, to ensure double shear on the bolts.

Some simple calculations have been done with regards to buckling as the strut will be in compression. Minimum required moment of inertia was calculated using the buckling equation:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

Rewritten for moment of inertia:

$$I = \frac{P_{cr}(KL)^2}{\pi^2 \cdot E}$$

Since the strut will be pinned at each end, the effective-length factor (K) is taken as 1 which gives (KL) equal to the length of the strut. To calculate minimum required I, P_{cr} is taken as the maximum force found for F_{BC}.

This gives:
F_{BCmax}= 20.396kN
KL=913.6mm
E-modulus (6082 T6) = 70 GPa [16]

This gives minimum required I as 24643 mm^4

Table 9 Minimum required Moment of Inertia

Minimum required I		
$I = \frac{F \cdot (KL)^2}{\pi^2 \cdot E} =$	24643	mm^4

Since there will be two struts in place for each support, one on each side, no safety factor has been applied. Two give the strut maximum support in all directions, L-shapes were chosen as the best solution. Dimensions were chosen to be 40x40 flanges, with 5 mm thickness. These dimensions exceed the minimum required I, however smaller flanges were disregarded to ensure enough materials around the bolt holes to prevent failure.

2.5.7 Bolting

Dimensions of bolts in joint A, B and C must be calculated. For these calculations self-weight of the frame has been neglected due to its low weight compared to the external forces these bolts must be able to withstand. To ensure that the bolts are able to withstand these forces over a period of 25-30 years, a factor of safety of 2 has been applied. It is also important that these bolts are corrosion resistant to reduce risk of failure. For this reason, galvanized bolts of grade 4.6 have been chosen for this application.

Grade 4.6 indicates that the ultimate strength of the bolt is around 400 MPa with a 0.6 ratio of yield stress to ultimate strength.[17] Yield strength of a grade 4.6 bolt is then consequently;
$0.6 \cdot 400\ MPa = 240\ MPa.$

Since all bolts will be subjected to a shear stress the following formula has been applied;

$$\tau_{allow} = \frac{V}{A}$$

Where the shear force $V = \frac{F}{2}$ and allowable shear stress $\tau_{allow} = \frac{\tau_{Y.S}}{F.S}$
The necessary diameter of bolts in points A, B, an C have been calculated in table 10

Table 10 Diameter of bolts A, B, and C

Pins		A	B	C
$\tau_{allow} = \frac{V}{A} = \frac{V}{\frac{(\pi \cdot d^2)}{4}}$	Fail stress	240	240	240
	F.S	2	2	2
	Allowable str	120	120	120
F		19,43	20,40	20,40
V (double shear)		9,72	10,20	10,20
A		80,97	84,98	84,98
d		10,15	10,40	10,40

2.5.8 Final Design

The final design of the mounting systems consists of two adjustable supports, made of aluminium 6082 T6. Each support consists of two HSS-profile beams, and two L-profile beams which make up the supporting strut BC. L-shapes were chosen to give support in all directions and stabilize the strut. The HSS-profiles have the dimensions of 50x50 mm and a thickness of 3 mm, the L-shapes have the dimensions of 40 mm for each flange and a thickness of 3 mm.

The cross bars between the adjustable supports are HSS-profiles with dimensions of 25x25 mm a 2 mm thickness. They are made of the aluminium alloy 6062 T6 which is a slightly cheaper and weaker alloy. The university's supplier did not offer alloy 6082 T6 for dimensions that small, therefore alloy 6061 T6 was selected as it has good weldability an is more than suited to offer support to the mounting system.

A model of the mounting system is presented in figure 27.

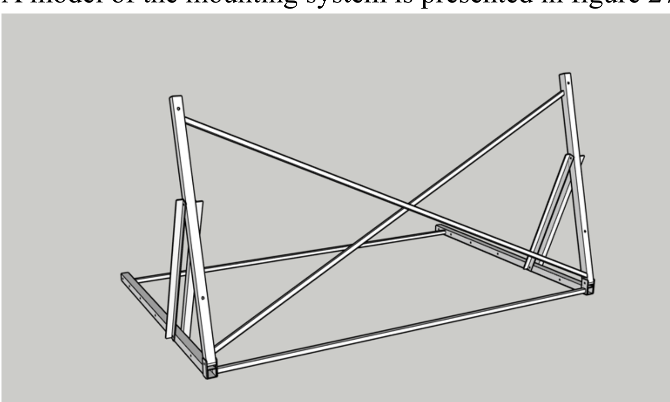


Figure 29 Final design of mounting system

The mounting system is designed to be supportive of all panel types, adjustable in inclination and flexible for future modifications. Detailed CAD files of each member of the mounting system are available in attachment 4.

2.5.8.1 Material List and Cost of Mounting Systems

The table included below shows the materials needed to build all four of the mounting systems. All beams are delivered in 6-meter sections and will be cut into the required lengths.

Table 11 Material list and cost of mounting system excluded cargo and tax

Material list and cost of mounting system			
Description	Count	Total length in m	Price excluded tax in NOK
50x50x3 mm HSS Aluminium 6082-T6	5	30	3422,28
40x40x5 mm L-Profile Aluminium 6082-T6	3	18	1364,58
50x5 mm Rail Aluminium 6082-T6	1	6	303,24
25x25x2 mm Aluminium 6060-T6	8	48	1802,11
Total Price excluded cargo and tax			6892,21

2.5.9 Roof- and Wall-Attachment

The mounting systems for both the roof and the wall will be attached in similar ways. The passive house roof is built with standard 48 mm barges with 600 mm. The mounting system is to be attached to the roof with bolts going through the mounting system’s horizontal member and into the barges. This same method will be used for the wall attachment.

As the barges on the wall of the passive house are directly exposed to rain, there is no need to waterproof the attachment to the wall. For the roof, however, waterproofing around the bolts attaching the mounting system to the barges is necessary. After consulting with lecturer at the Department of Civil Engineering, Anne Sofie Bjelland who constructed the passive house, instructions were given to bolt the mounting system to the roof, and to use silicone around the bolts to make it waterproof. This work has to be done by a certified roofer. It is crucial to get this operation right, so the passive house does not get any long-term water damages.

3. Electrical Wiring

Upon completion, the solar energy laboratory will consist of multiple electrical components. In this chapter these components will be presented along with their technical specifications. Further, wiring between the passive house and the solar panels and the tracker will be discussed together with sheilding of the wires. Installation of the different components should be done as specified in each component’s manual.

3.1 Component list

Panels

Astroenergy Violin ASM6610M - 280 Wp
The Astroenergy Violin ASM6610M are monocrystalline panels with a STC rated output of 280 Wp and a module efficiency of 17.12%. Six of these panels will be available for use at the solar laboratory. [13]

REC PEAK ENERGY REC275PE - 275 Wp
The REC Peak Energy REC275PE are polycrystalline panels with a STC rated output of 275 Wp and a module efficiency of 16.7%. Six REC275PE panels will be available for use at the solar laboratory. [14]

MiaSolé Flex -02N 120W
The MiaSolé Flex -02N 120W are copper indium gallium diselenide (CIGS), thin film panels with a STC rated output of 120 Wp and a module efficiency of 15.7%. Fourteen MiaSolé panels will be available at the solar laboratory. [15]

Power optimizer:

Tigo Flex MLPE TS4-O

The Tigo TS4-O is a module level power electronics DC Optimizer. The solar system will consist of 26 power optimizers to increase power yield and decrease typical losses such as mismatch and shading. Each module will be attached to one of the laboratories solar panels, to monitor and optimise the output of each panel. [18]

Internet connection:

Tigo Cloud Connect Advanced

The Tigo CCA is a solar data logger designed to collect data from the solar panels so analysis can be performed. The CCA requires an AC power sources and internet connection either as ethernet cable or wifi. [19]

Tigo Gateway

Tigo Gateway is a wireless antenna which permits communication between the TS4 modules. [20]

Inverter:

SUNNY BOY 1.5
Three Sunny Boy 1.5 Inverters will be used, one for each solar power system. [21]

Storage System:

ES5048 Series On/Off-Grid Hybrid Solar Energy Storage System
The ES5045 Series is an on/off grid hybrid solar energy storage system designed to store energy and allow for grid connection. The storage system has a built-in inverter, to store energy at night when electricity is cheap, and supply it during the day. It also has a built-in Batter Management System (BMS) to monitor the battery. [22]

Fuse box:

A fuse box has to be installed to ensure the safety of the electrical components. The fuse box has to be installed by a certified electrician to ensure compliance by all laws, norms and standards.

Wires:

HELUKABEL SOLARFLEX-X H1Z2Z2
The Solarflex-x cable is the main wire used for the solar laboratory; it is a double insulated wire with a cross-sectional area of 6 mm^2 and will be used to connect the different systems to the passive house. [23]

3.2 Wiring

Wires for the roof and wall-based solar arrays will use the c-rails as a cable channel. To ensure a tidy wiring system, cable ties will be used for all cables going in the same direction. The solar panels will be connected to the TS4-O using the attached cables, which all are compatible with standardised MC4 plugs. These will then be connected to the Sunny Boy inverter inside the passive house. Standardised MC4 plugs are used in almost all solar panels today and offers the possibility of swapping panels as required. [24] The panels can be connected in both series and parallel, according to the user's requirements and necessities. The Sunny Boy will then be connected to the energy storage system. A schematic system diagram offered by the Sunny Boy producer SMA is available and will be used to connect the system properly.

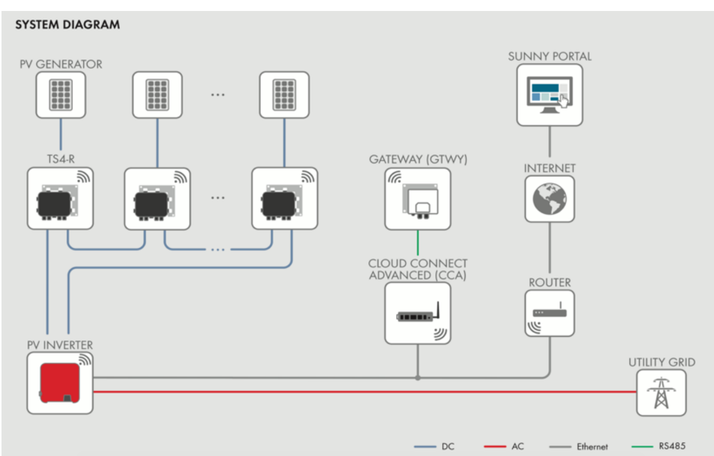


Figure 30 System diagram of the system used at the solar laboratory [25]

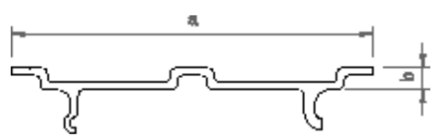
The passive house currently has an electrical input mounted at the south side of the house. As this input must be removed to allow space for the wall-based solar array, the remaining aperture can be used as a cable input for the solarflex-x cables. This aperture must be both water- and fireproof to ensure the safety of the system. A smaller electrical input must then be installed to cover up the opening.

To ensure the fire safety of the cables several standards must be upheld. There is however a high likelihood that these standards have already been applied to the existing cable gland. However, this must be investigated before any action is taken.

4.2.1 Shielding for the wires

To shield the wires from external conditions, and ensure neat wiring and an aesthetically pleasing environment, some precautions must be taken. As mentioned, the cables will use C-rails as a cable channel. It is recommended that the university acquire a top cover for the C-rails as to protect the cables from rainwater. Such top cover is available at the manufacturer BayWa r.e. which provided the C-rails in question. [26]

Top cover C-rail



Cover to clip on to the C-rail if using as cable channel.

Art.-Nr.	Bezeichnung	a in mm	b in mm	c in mm	Material
03-000134	Top cover C-rail 2.000 mm	50	3		Alu

Figure 31 Top cover for C-rails [26]

The cables running from the solar tracker to the passive house must be tied up and run along the ground or in the air through a tube, as to avoid the risk of tripping. The easiest and most aesthetically pleasing option is to run the wire along the ground in some protective cover.

Since the university has previously used Malmbergs' cable protector to supply the passive house, the simplest solution is to use the same cable protector between the solar tracker and the passive house.

With regards to the roof-based array, the cables must be tied down and protected in some way. The easiest solution would be to simply strap the cables along the frame of the mounting system and lead them down to the entry point. It is not an option to tape the wires since the solar panels will not be immobile, and thus some flexibility is necessary. A plastic tube could be installed to ensure further insulation and protection of the cables.

Figure 32 Malmbergs cable protector

4. Expected Energy Outputs

To have an idea of what kind of components one could be expected to be able to power with the solar laboratory, it could be interesting to see how much power generation one could expect from the solar laboratory during the various months of the year. The table below is taken from Byggforskserien. It shows the average total radiated energy in Bergen for each month of the year at 30˚ and 90˚.

Table 12 Total average radiation per month for a flat, unshielded surface in Bergen at 30˚ and 90˚, given in kWh/m2 [27]

Inclination	kWh/m^2/Month												Anual Total
	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Des	
30˚	20	35	85	110	155	145	136	119	76	46	18	13	958
90˚	28	40	81	79	96	83	74	81	62	47	22	19	712

Using this data, the total expected energy output of the solar laboratory can be found for each month. In the calculations done, it has been assumed that the thin film and REC solar panels have been put on the mounting systems with adjustable inclination. Since data is only available for 30 ˚ and 90 ˚, it has been assumed that the inclination with the best power output has been chosen for each month. Hence, power output has been calculated using 90° for January, February, October, November and December, while 30° has been used for the remaining months.

The Violin solar panels, which has the highest efficiency out of the three, has been assumed put on the solar tracker. There is no available data for average radiation per month with an optimal angle towards the sun at all time, as a solar tracker would have. Instead, according to Rizk and Chaiko, a solar tracker will receive 30% more energy input than that of a non-adjustable horizontal array. [28] Considering this, an approximation to the real power input of the solar tracker can be made by 30% more received energy per month than the panels would have had at a 30° inclination throughout the year.

Using these assumptions, we get the following table for the total energy output of the solar laboratory per month:

Table 13 Total Energy Output of the solar laboratory per month (kWh)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
149,1	227,1	505,8	654,6	922,3	862,8	809,3	708,1	452,2	277,5	122,2	100,0	5791,0

As seen above the laboratory, when finished, will be capable of producing quite a bit of power. Demonstrating solar panels ability to charge electric vehicles, (EV) like cars and bikes, is something that has been mentioned by the institute management at more than one occasion. Considering a Nissan Leafe, one of the most popular EVs in Bergen, with a battery package of 30 kWh, this would be very possible outside of the winter months of November, December and January. [29] Still, during these three months the laboratory should be capable of producing more electricity than needed to heat the passive house.

5. Discussion

Four different layout design propositions have been developed and presented for Statsbygg and IMM. Here, emphasis was put on finding ideal placement positions for the various laboratory components, and as such, creating as good lighting conditions as possible. This was done by creating a detailed 3D-model of the solar laboratory site, and the surrounding buildings and terrain. The 3D-model was then used together with a program for analysing shadow conditions to find optimal placements for the passive house, ground-based solar panels, solar tracker and CSP tracker.

In regard to moving the passive house, there should have been put more emphasis on communication between the different parties involved. This could have been done by defining one main contact person for the project that Statsbygg could address. Involving the school's operational management should also have been an obvious part of the process. This way, the moving of the passive house to an inappropriate location would probably have been avoided.

A large portion of this thesis was devoted to the development and use of the 3D-model to create the four proposed layout designs, as well as planning and preparing for the move of the passive house. In the end, most of this work had to be disregarded as the positioning of the passive house had not been approved by all appropriate parties. Still, the 3D-model was used to propose a new layout design that was approved by WNUAS's operational management. This new design included many adjustments to the former design. The CSP tracker is completely removed. Both the passive house and the solar tracker have been moved forward to open the passage that they blocked in the last design. Lastly, there will no longer be any ground-based arrays at the site. These have been put on the wall of the passive house to save space at the site.

The mounting systems were first designed so the same system could be used for both the panels meant for the roof of the passive house, as well as the panels meant to sit on the ground in front of the passive house. As the passive house later had to be moved forward from its original position at the laboratory site, there was no longer room for the ground-based solar panels. Fortunately, the solar mounting system was designed in such a way that it could be easily fixed to many types of surfaces, as long as one would be able to attach bolts to the surface. Due to this easy, universal attachment design, the solar panels could be put on the wall of the passive house without any alterations to the design of the mounting system.

Part of the aim of this thesis was to design a solar laboratory that would permit a ground-based solar array. Due to unforeseen events, this has not been completed. However, fixing the solar panels to the wall of the passive house may be discussed to be a just as good, or an even better solution. In regard to the use of the available space, this offers a more compact layout design. One could argue, though, that this new set up would be less aesthetically pleasing than the previous symmetrical setup.

When designing the mounting systems, they were first designed to carry six solar panels instead of three, as the length of the passive house enables six solar panels to lay side by side. It was later realized that a mounting system of this length would be both hard to install on the roof of the passive house, and adjustment of the inclination would become difficult to carry out. It was therefore decided to split each mounting system into two separate mounting systems, capable of carrying three PV panels each. This way, handling of the structures would become less strenuous for anyone involved in its installation, and for anyone wanting to adjust the structure's inclination. Splitting the mounting systems into two parts also gives anyone using the laboratory the possibility to simultaneously test the solar panels at different angles if desired.

Initially, the design of the mounting systems was based on stainless steel, due to its high corrosion resistance, strength and appealing exterior. At a later stage in the design of the mounting system, it was decided to build it in Aluminium instead. This was mostly due to the fact that during the design process there had not been put enough emphasis on how the mounting system would be handled after it had been produced and put on the roof of the passive house. It was discovered that the handling of an around 150 kg mounting system along with solar panels on top of a roof would be extremely difficult. By switching to aluminium, the weight would be drastically reduced along with the cost of producing the mounting system. It was calculated that this would have no effect on the strength of the structure.

Throughout the process of designing the mounting system, more effort could have been put into finding the best possible way to attach the mounting system to the roof and the wall of the passive house. Here future work must be done, deciding what types of bolts should be used to attach to the passive house. For now, the horizontal members of the mounting system have been dimensioned so that bolts with a diameter of 14 mm could be used, which is way more than needed to support the weight of the structure.

Part of the aim of this thesis was to “initially develop a solar energy laboratory which will include a passive house with a mounted solar cell system”. The mounting of the solar cell system has yet not been completed. This is due to the fact that action was taken too late to order the necessary materials for the mounting system. That the production of the mounting system would take quite a bit of time, is something that should have been taken into consideration at an early stage in the planning process. Then there might have been time to get this part finished. However, this is not the only factor to consider, as the solar cell system could not have been put in place on the passive house whilst in an inappropriate location.

6. Conclusion and Remaining work

6.1 Conclusion

Four different layout design propositions for the solar laboratory have been created and presented for Statsbygg. Finally, a fifth layout design has been agreed upon and presented in this thesis. These layouts were designed in SketchUp from CAD drawings of the school ground, provided by the institute management. Several shadow analyses have been done of the site in which the construction of the laboratory has started. These were made to find optimal placement for the components making up the solar laboratory.

A mounting system has been designed to be able to fit on the wall as well as on the roof of the passive house. The same mounting system has been made to fit both the thin film panels and the PV panels available at the solar laboratory. The mounting system is made so one can manually change its inclination with 15 degrees increments. The mounting system has also been dimensioned to be able to withstand a basic wind velocity of 26 m/s, while the solar panels are put in a 90°-degree inclination in relation to the ground.

Foundation blocks have been produced and put in place, and the passive house has been moved to the location of the solar laboratory. Although it has not been put in its final position yet, this is a much less complicated moving operation, not requiring the expensive low-deck truck.

Finally, materials for the solar panel mounting systems have been ordered. Though the mounting systems have not yet been produced, all necessary drawings have been made for the production to take place.

6.2 Remaining Work

There is still quite a bit of work left to be done before the solar laboratory, as depicted in this thesis, is completed.

- The passive house must be moved to its final location.
- Mounting systems for the solar panels must be produced and attached to the roof and wall of the passive house.

- All electrical components must be put in place. Required wiring must be put through the wall of the passive house.
- BKK must be contacted regarding connecting the laboratory to the grid.
- The solar tracker must be produced and put in its designated spot at the site.
- An aluminium frame must be designed to carry the thin film panels. This must be designed in such a way that it is compatible with the solar panel clamps.

6.3. Possible Future Work and Development

The solar laboratory offers many possibilities for potential future projects and development.

- A charging station for electrical cars and electrical bicycles could be designed and constructed. For example, the remaining bicycle racks could be transformed to a charging station for electrical bikes and scooters.
- The solar laboratory could be expanded to include other forms of renewable energy, such as wind power.
- A solar tracker could possibly be incorporated into the old train turntable at the site, using the turntable to track the suns position.

8. Sources and Citations

[1] Statsbygg, «Høgskulen i Bergen Landskapsplan,», 2010. Hentet: 24.01.19.

[2] Timeanddate.com, «2019 Sun Graph for Bergen,» 2019. [Online]. Tilgjengelig: https://www.timeanddate.com/sun/norway/bergen?month=12&year=2019&fbclid=IwAR1qFGO1i-pM0PV8p09J-ivxnLIhUsQFxVS-NtQhwJ355dmtTP_wUo1X91w

[3] N. Loftesnes, P. Nitsche og S. Rasmussen, «HVL Solar Laboratory with PV Tracking Array,» Bachelor, Department of Mechanical- and Marine Engineering, Western Norway University of Applied Sciences, Bergen, 2018.

[4] N. Standard, *Eurokode 1: Laster på konstruksjoner = Eurocode 1: Actions on structures. Part 1-4: General actions. Wind actions : Del 1-4 : Allmenne laster. Vindlaster* (Norsk standard). Lysaker: Standard Norge, 2009.

[5] Byggforsk, «Vindlaster på bygninger,» 2003. [Online]. Tilgjengelig: https://www-byggforsk-no.galanga.hvl.no/dokument/3118/vindlaster_paa_bygninger

[6] *Eurokode 1: : Laster på konstruksjoner. Del 1-3. Allmenne laster. Snølaster = Eurocode 1: Actions on structures : Part 1-3: General actions, Snow loads* (Norsk standard). Oslo: Standard Norge, 2008.

[7] A. Edvardsen, «Vegvesenet i full gang med salting. Snøen kommer til rushet i ettermiddag.,» i *Bergens Tidene*. bt.no: Bergens Tidene, 2017. Tilgjengelig: https://www.bt.no/nyheter/lokalt/i/2aoJl/Vegvesenet-i-full-gang-med-salting-Snoen-kommer-til-rushet-i-ettermiddag?spid_rel=2

[8] D. Kupferinstitut, «Copper,» 2019. [Online]. Tilgjengelig: https://www.kupferinstitut.de/en/materials/material-properties/copper.html

[9] E. F. Group, «Brass,» 2019. [Online]. Tilgjengelig: http://elginfasteners.com/resources/materials/material-specifications/brass-material/

[10] Norsk Stål, «Prisliste,» i *Prisliste*, N. Stål, Red. pub.webbook.no, 2018. Tilgjengelig: https://pub.webbook.no/norskstaal/prisliste//files/assets/common/downloads/publication.pdf?uni=23991e697f16800de03b267059857752, Hentet: 25.04.2019.

[11] Astrup, «Metall Katalogen 2016,» i *Metall Katalogen*, Astrup, Red. astrup.no: astrup.no, 2016
Tilgjengelig: https://astrup.no/pdf/hoy/mobile/index.html, Hentet: 20.04.2019.

[12] Hydro, «Renewable power and aluminium,» 2019. [Online]. Tilgjengelig: https://www.hydro.com/en/about-aluminium/renewable-power-and-aluminium/, Hentet: 07.05.

[13] Astroenergy, «Voilin™ Crystalline PV Module ASM6610M Series,», Astroenergy, Red., 2016. Tilgjengelig: http://www.astronergy.com/attch/download/ASM6610M_Violin_EN_2016_10.pdf, Hentet: 17.01.2019.

[14] REC, «REC PEAK ENERGY SERIES,», recgroup.com, Red. Tilgjengelig: https://www.recgroup.com/sites/default/files/documents/ds_rec_peak_energy_series_rev_y_eng.pdf, Hentet: 17.01.19.

[15] MiaSolé, «MiaSolé Flex Serie -02N,», MiaSolé, Red., 2015. Tilgjengelig: http://miasole.com/wp-content/uploads/2015/08/FLEX-02N_Datasheet_6.pdf, Hentet: 17.01.2017.

[16] aalco, «Aluminium Alloy - Commercial Alloy - 6082 - T6~T651 Plate,» 2018. [Online]. Tilgjengelig: http://www.aalco.co.uk/datasheets/Aluminium-Alloy_6082-T6~T651_148.ashx, Hentet: 08.05.

[17] A. S. Engineering, «What's the difference between 4.6 and 8.8 bolts,» 2019. [Online]. Tilgjengelig: http://www.aalco.co.uk/datasheets/Aluminium-Alloy_6082-T6~T651_148.ashx

[18] T. E. Inc., «TS4-O Optimization,», 2019. Tilgjengelig: https://www.tigoenergy.com/library/view/TS4-O+-+Optimization.pdf/

[19] T. E. Inc., «Cloud Connect Advanced (CCA) and Accessories,», 2018. Tilgjengelig: https://www.tigoenergy.com/library/view/Cloud+Connect+Advanced+%28CCA%29+and+Accessories+Kit.pdf/

[20] T. E. Inc., «Tigo Energy Gateway Datasheet,», 2012. Tilgjengelig: https://taspacenergy.co.nz/wp-content/uploads/2014/11/TIGO-gateway_datasheet_en_0_01.pdf

[21] SMA, «Sunny Boy 1.5/2.0/2.5 with SMA Smart Connect,», 2019. Tilgjengelig: https://files.sma.de/dl/26198/SB15-25-DEN1915-V32web.pdf

[22] L. Shenzhen PowerOak Newener Co., «On/Off grid ESS User's Manual,», 2019.

[23] Helukabel, «SOLARFLEX®-X H1Z2Z2-K,», 2019. Tilgjengelig: http://www.helukabel.com/opc/workarea/suppliers/SOL/documents/pdf/db/1DB_713529_en.pdf

[24] Wikipedia, «MC4 connector,» 2019. [Online]. Tilgjengelig: https://en.wikipedia.org/wiki/MC4_connector

[25] SMA, «TS4-R Module Technoloy,», 2019. Tilgjengelig: https://www.europe-solarstore.com/download/sma/SMA-TS4-R-datasheet.pdf

[26] B. R. Energy, «Mounting systems 2018,», 2018. Tilgjengelig: https://solar-distribution.baywa-re.lu/fileadmin/Solar_Distribution_Benelux/04_Products/03_Media/novotegra/Sonstiges/052018_novotegra_catalogue_mounting_systems_2018_en.pdf

[27] Byggforsk, «Solstrålingsdata for energi- og effektberegninger,» 1991. [Online]. Tilgjengelig: https://www.byggforsk.no/dokument/222/solstraalingsdata_for_energi_og_effektberegninger#i36

[28] J. Rizk og Y. Chaiko, «Solar Tracking System: More Efficient Use of Solar Panels,».

[29] Wikipedia, «Nissan Leaf,» [Online]. Tilgjengelig: https://en.wikipedia.org/wiki/Nissan_Leaf#Battery, Hentet: 15.05.2019.

List of Tables

List of Figures

Attachment 1 – Weight Comparison

304 Stainless steel

Requirements for AF

Allowable stress

Y.S	190	MPa
S.F	1,5	
$\frac{\sigma_{Y.S}}{S.F} = \sigma_{Allow} =$	126,66667	MPa

Section Modulus

Mmax =	1294663,6	Nmm
$S_{req'd} = \frac{M_{max}}{\sigma_{allow}} =$	6814,0187	mm^3

Option 1		
Profile	L	
Dim (LxBxT)	80x80x8	
L	80	mm
B	80	mm
T	8	mm
Weight (kg/	9,85	kg/m
Section moc	12923,119	mm^3
I	737297	mm^4
σ	70,238374	MPa
Price/m		

Option 2		
Profile	HSS	
Dim (LxBxT)	60x60x3	
L	60	mm
B	60	mm
T	3	mm
Weight (kg/m)	5,49	kg/m
Section modulus	12380,4	mm^3
I	371412	mm^4
σ	104,57365	MPa
Price/m		kr

Option 3		
Profile	HSS	
Dim (LxBxT)	50x50x5	
L	50	mm
B	50	mm
T	5	mm
Weight (kg/	7,45	kg/m
Section moc	12300	mm^3
I	307500	mm^4
σ	105,2572	MPa
Price/m		

Option 4		
Profile	HSS	
Dim (LxBxT)	50x50x3	
L	50	mm
B	50	mm
T	3	mm
Weight (kg/	4,66	kg/m
Section moc	8339,68	mm^3
I	208492	mm^4
σ	155,2414	MPa
Price/m		

6082 T6 Aluminium

Requirements for AF

Y.S	250	Mpa
S.F	1.5	
$\frac{\sigma_{Y.S}}{S.F} = \sigma_{Allow} =$	166,66667	MPa

Section Modulus

Mmax =	1294663,56	Nmm
$S_{req'd} = \frac{M_{max}}{\sigma_{allow}} =$	7767,9814	mm^3

Option 1		
Profile	HSS	
Dim (LxBxT)	40x40x3	
L	40	mm
B	40	mm
T	3	mm
Weight (kg/	1,24	kg/m
Section moc	5098,6	mm^3
I	101972	mm^4
σ	253,92531	MPa
Price/m		kr

Option 2		
Profile	HSS	
Dim (LxBxT)	40x40x4	
L	40	mm
B	40	mm
T	4	mm
Weight (kg/m)	1,61	kg/m
Section modulus	6297,6	mm^3
I	125952	mm^4
σ	205,58047	MPa
Price/m		kr

Option 3		
Profile	HSS	
Dim (LxBxT)	50x50x5	
L	50	mm
B	50	mm
T	4	mm
Weight (kg/	2,06	kg/m
Section moc	10461	mm^3
I	261525,33	mm^4
σ	123,76082	MPa
Price/m		kr

Option 4		
Profile	HSS	
Dim (LxBxT)	50x50x3	
L	50	mm
B	50	mm
T	3	mm
Weight (kg/	1,58	kg/m
Section moc	8339,68	mm^3
I	208492	mm^4
σ	155,2414	MPa
Price/m		kr

Attachment 2 – Final Design Geometry

Final design Geometri						
	Triangle 1, formed by ABC					
Position (angle with respect to the ground)	90	75	60	45	30	15
Lengths						
AB	832,5	832,5	832,5	832,5	832,5	832,5
BC	913,6312292	913,6312292	913,6312292	913,6312292	913,6312292	913,6312
AC	241,6935518	542,0898872	907,8658236	1242,992621	1507,500954	1679,091
Angles						
Alpha (Between AC and AB)	101,9391962	80,29223412	63,15711762	47,3053734	31,90070492	16,70641
Beta (Between AB and BC)	15	35,7916419	62,45125136	90,64982413	119,3144364	148,1084
Theta (Between BC and AC)	63,06080383	63,91612398	54,39163102	42,04480247	28,78485868	15,18522
sum = 180	180	180	180	180	180	180
	Triangle 2, formed by ABM					
Lengths						
AB	832,5	832,5	832,5	832,5	832,5	832,5
BM	861,8674202	860,1482844	854,3788722	842,1047456	815,6546899	741,5511
AM	223,0677027	520,7941988	874,694184	1190,839358	1422,413588	1513,691
Angles						
Lambda (formed by AB and AM)	90	75	60	45	30	15
Beta (formed by AB and BM)	15	35,7916419	62,45125136	90,64982413	119,3144364	148,1084
Delta + Theta (formed by BM and AM)	75	69,2083581	57,54874864	44,35017587	30,6855636	16,89163
sum = 180	180	180	180	180	180	180
	Triangle 3, formed by NBC					
Lengths						
NB	882,5	884,263809	890,2350269	903,2106781	932,5	1025,685
BC	913,6312292	913,6312292	913,6312292	913,6312292	913,6312292	913,6312
NC	236,4651623	553,1765309	935,3554359	1291,986576	1593,274079	1864,949
Angles	913,6312292					
Lambda (formed by NB and NC)	90	75	60	45	30	15
Beta (formed by NB and BC)	15	35,7916419	62,45125136	90,64982413	119,3144364	148,1084
Delta + Theta (formed by BC and NB)	75	69,2083581	57,54874864	44,35017587	30,6855636	16,89163
sum = 180	180	180	180	180	180	180
	Triangle 4, formed by OAC					
Lengths						
OA	50	50	50	50	50	50
AC	241,6935518	542,0898872	907,8658236	1242,992621	1507,500954	1679,091
OC	236,4651623	539,7790712	906,4879225	1241,986576	1506,671539	1678,347
Angles		303,3139089	366,7088512	335,4986535	264,684963	171,6753
90 degrees (formed by OA and OC)	90	90	90	90	90	90
Phi (formed by OA and AC)	78,06080383	84,70776588	86,84288238	87,6946266	88,09929508	88,29359
Delta (formed by AC, and OC)	11,93919617	5,292234116	3,15711762	2,305373397	1,900704924	1,706406
Sum = 180	180	180	180	180	180	180
	Triangle 5, AMC					
Lengths						
AC	242	542	908	1243	1508	1679
AM	223	521	875	1191	1422	1514
MC	52	53	59	72	98	172
Angles						
Delta (formed by AC and AM)	11,94	5,29	3,16	2,31	1,90	1,71
Theta (formed by AC, MC)	63,06	63,92	54,39	42,04	28,78	15,19
180-(Delta+Theta)	105,00	110,79	122,45	135,65	149,31	163,11
	180	180	180	180	180	180
	Triangle 6 NAO					
Lengths						
NO	0	13,40	28,87	50,00	86,60	186,60
NA	50	51,76	57,74	70,71	100,00	193,19
AO	50	50	50	50	50	50
Angles						
Lambda	90	75	60	45	30	15
Tau	0	15	30	45	60	75
90 degrees	90	90	90	90	90	90
	180	180	180	180	180	180

Attachment 3 – Analysis of Forces Acting on the Frame

Analysis of forces acting on the frame

Distances between points of interests							
Points	Lenght (m)	90	75	60	45	30	15
OC	236,4652	236,4652	539,7791	906,4879	1241,987	1506,672	1678,347
AF	1,665						
AB	0,8325						
BC	0,913631						
AG	1,7						
DE	0,981						
BD	0,4905						
BE	0,4905						
AE	1,323						
OA	0,05						
AD	0,342						

Key values used in calculations in degrees and radians							
Degrees	90	75	60	45	30	15	0
Radians	1,570796	1,308997	1,047198	0,785398	0,523599	0,261799	0

Angles between key struts and beams in the framework							
Lambda	90,00	75,00	60,00	45,00	30,00	15,00	0,00
Tetha+delta	75	69,21	57,55	44,35	30,69	16,89	180
Beta	15	35,79	62,45	90,65	119,31	148,11	0,00
sum=180	180,00	180,00	180,00	180,00	180,00	180,00	180,00

Analysis of strut AF		
Profile	Hollow Rectangle	
a (thickness)	3	mm
b (inner widt	54	mm
c (width) =	60	mm
A1	3600	mm
A2	2916	mm
A	684	mm
Moment of I	#DIV/0!	mm^4
c	30	m
Section Mod	#DIV/0!	mm^3
Sum I	#DIV/0!	mm^4
Maximum in	############	Nmm

Maximum bending stress in strut AF		
$\sigma_{MAX} = \frac{Mc}{I} =$	#DIV/0!	MPa
	Green highlight indicates acceptable value	

Yield Strength AISI304		
Y.S	190	Mpa
S.F	1,5	
σ_allowed	126,6667	Mpa

ield Strength Alum 6082 T6		
Y.S	250	
σ_allowed	166,6667	

Analysis of strut BC		
Profile	Square	
a (thickenss)	3	mm
b (inner widt	54	mm
c (width) =	60	mm
A1	3600	mm^2
A2	2916	mm^2
A	684	mm^2
Location of neutral axis		
x	0	
y	#DIV/0!	
	0,083333	(1/12)
Moment of Inertia		
Ix	#DIV/0!	mm^4
Iy	#DIV/0!	mm^4
L (length)	913,6312	mm
K	1	
E (6082 T6)	70	GPa
(Pcr)_y	20,396	kN
pi	3,141593	

Maximum bendin stress in strut BC		
$\sigma_{MAX} = \frac{Mc}{I} =$		

Minimum required I		
$I = \frac{F \cdot (KL)^2}{\pi^2 \cdot E}$ =	24643	mm^4

Critical force before buckling		
$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{(KL)^2} =$	#DIV/0!	kN

Elastic Displacement		
$\delta = \frac{PL}{AE}$	0,141159	mm
P_max	20396,313	N
L	913,6312	mm
A	684	mm^2
E	193000	N/mm^2

Formulas used to determine forces acting on the framework	
$\sum M_A = 0;$	$F_{\frac{vind}{2}} \cdot AD + F_{\frac{vind}{2}} \cdot AE - F_{BC} \sin(\theta) \cdot AB = 0$
$\sum F_x = 0$	$F_{vind} \cdot \cos(90-\alpha) + F_{BC} \cdot \cos(\theta) + A_x = 0$
$\sum F_y = 0$	$A_y + F_{BC} \cdot \sin(\theta) - F_{\frac{panel}{2}} - F_{\frac{panel}{2}} = 0$

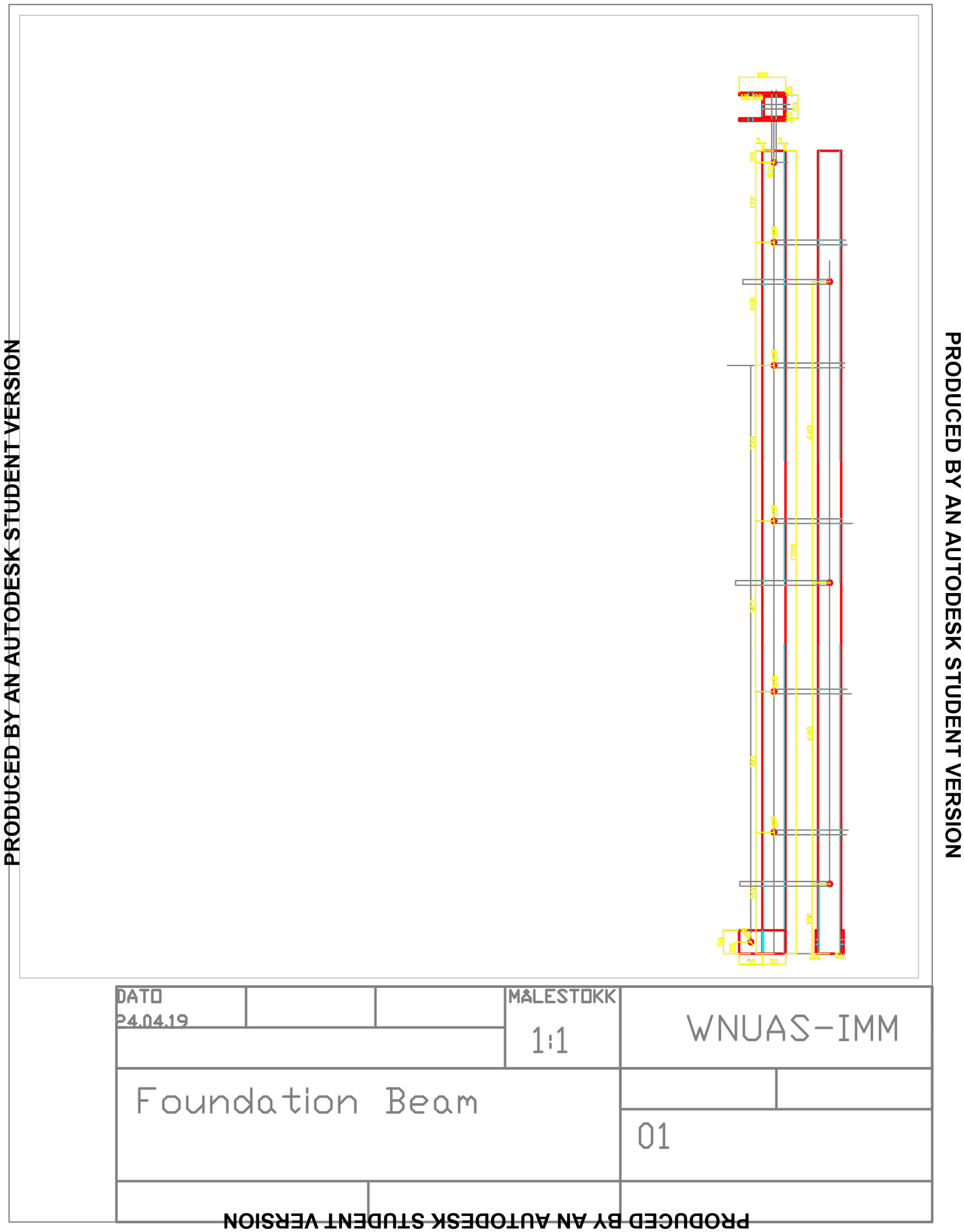
External forces acting on the framework							
	90 grader	75 grader	60 grader	45 grader	30 grader	15grader	0 grader
Forces							
Wind (kN)	10,56	10,20	9,14	7,465569	6,504322	6,50	6,04
Wind (kN/4)	2,64	2,55	2,29	1,87	1,63	1,63	1,51
Soar panels r	54,60	54,60	54,60	54,60	54,60	54,60	54,60
Solar panels	0,13	0,13	0,13	0,13	0,13	0,13	0,13
Thin film par	58,90	58,90	58,90	58,90	58,90	58,90	58,90
Thin film par	0,14	0,14	0,14	0,14	0,14	0,14	0,14

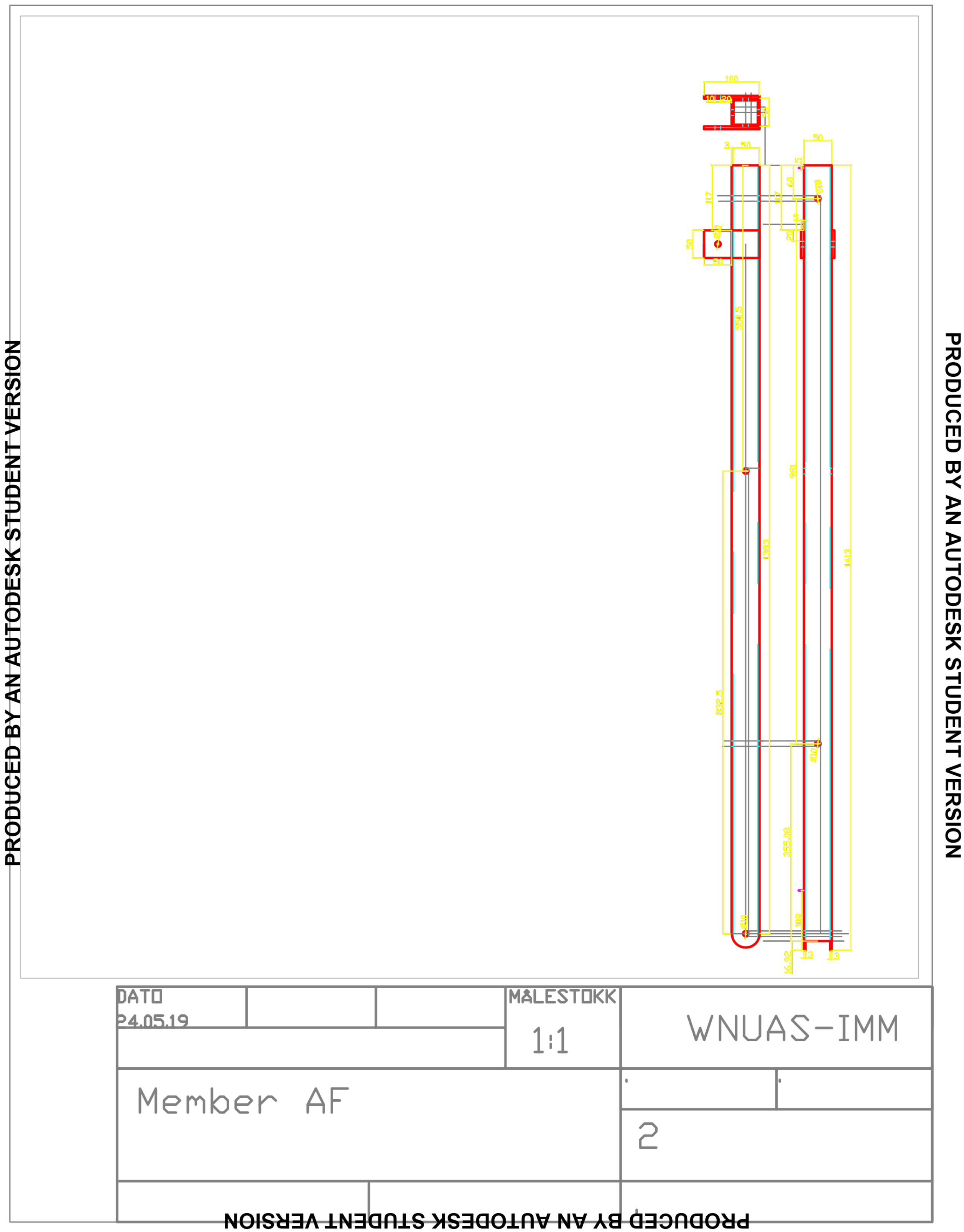
Calculation of statical forces working on the framework without windforces							
Degrees °	90	75	60	45	30	15	0
Resultant force in strut BC							
F_BC (kN)	0,00	0,12	0,15	0,19	0,27	0,49	0,00
Forces in joi	90°	75°	60°	45°	30°	15°	0°
A_x (kN)	0,000	0,042	0,081	0,135	0,229	0,469	0,000
A_y (kN)	0,268	0,157	0,140	0,135	0,132	0,126	0,268
B_x (kN)	0,000	0,042	0,081	0,135	0,229	0,469	0,000
B_y (kN)	0,000	0,111	0,127	0,132	0,136	0,142	0,000
C_x (kN)	0,000	0,042	0,081	0,135	0,229	0,469	0,134
C_y (kN)	0,000	0,111	0,127	0,132	0,136	0,142	0,000

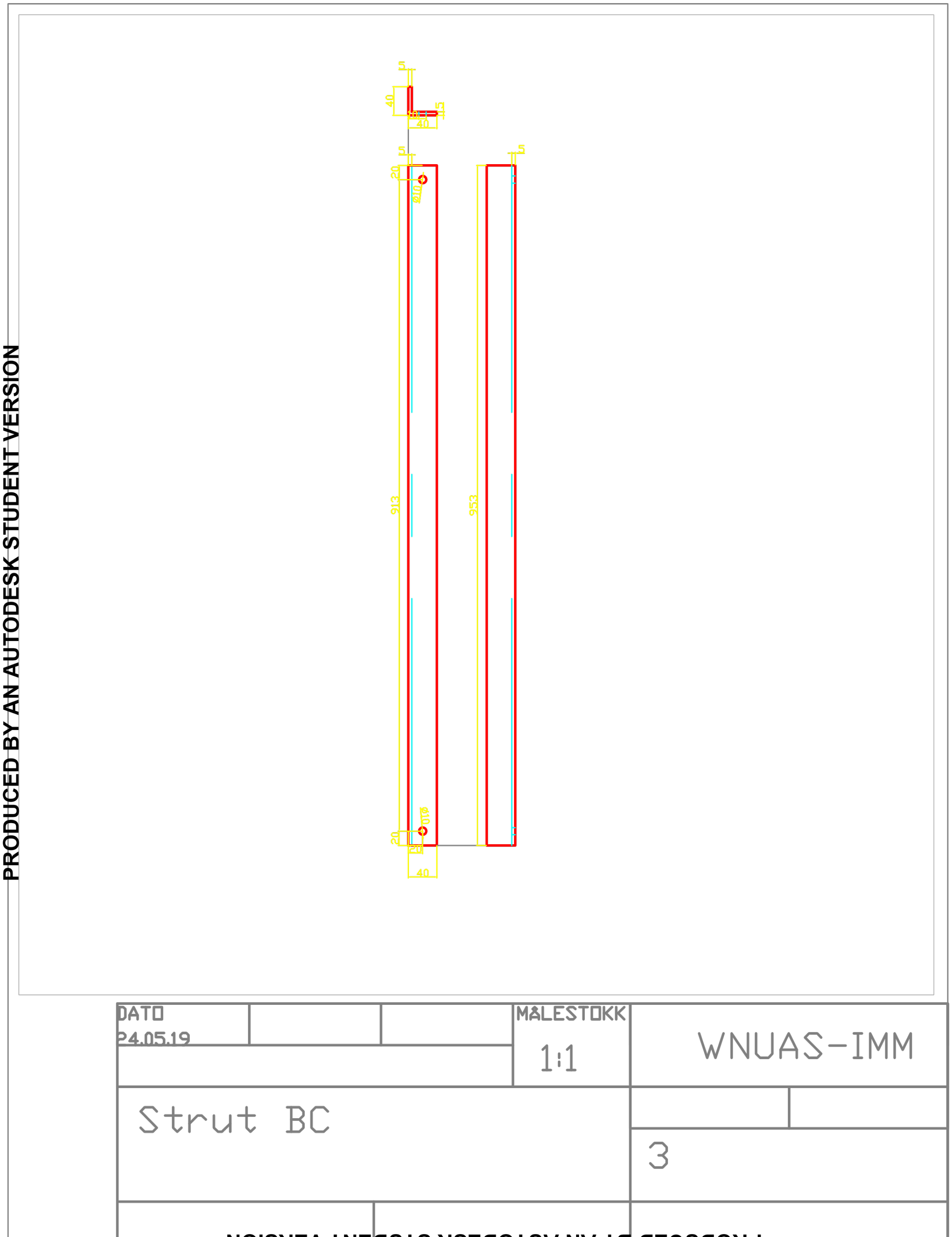
Calculation of forces working on the framework, wind forces included							
Inclination o	90	75	60	45	30	15	0
Resultant force in strut BC							
F_BC (kN)	20,396	8,540	4,617	2,829	2,131	2,083	0,000
A_x (kN)	0,000	0,104	0,479	0,904	1,394	2,152	0,000
A_y (kN)	-19,434	-7,716	-3,628	-1,710	-0,820	-0,337	0,268
B_x (kN)	5,279	3,032	2,477	2,023	1,833	1,993	0,000
B_y (kN)	19,701	7,984	3,896	1,978	1,087	0,605	0,000
C_x (kN)	5,279	3,032	2,477	2,023	1,833	1,993	0,000
C_y (kN)	19,701	7,984	3,896	1,978	1,087	0,605	0,000

Pins		A	B	C		
$\tau_{allow} = \frac{V}{A} = \frac{V}{\frac{\pi \cdot d^2}{4}}$	Fail stress	240	240	240		Grade 4.6
	F.S	2	2	2		
	Allowable str	120	120	120		
F		19,43	20,40	20,40		
V (double shear)		9,72	10,20	10,20		
A		80,97	84,98	84,98		
d		10,15	10,40	10,40		

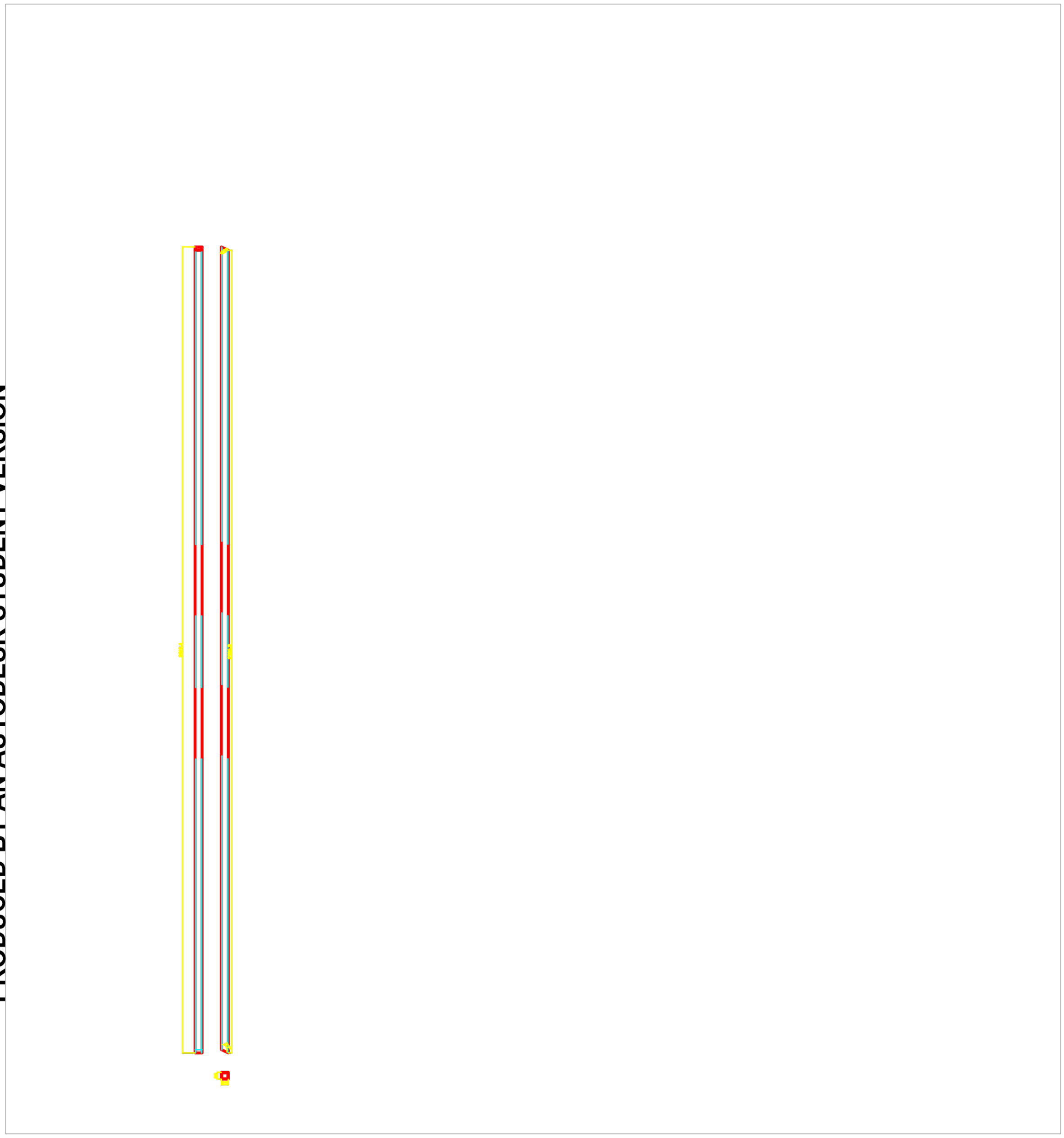
Attachment 4 CAD-files



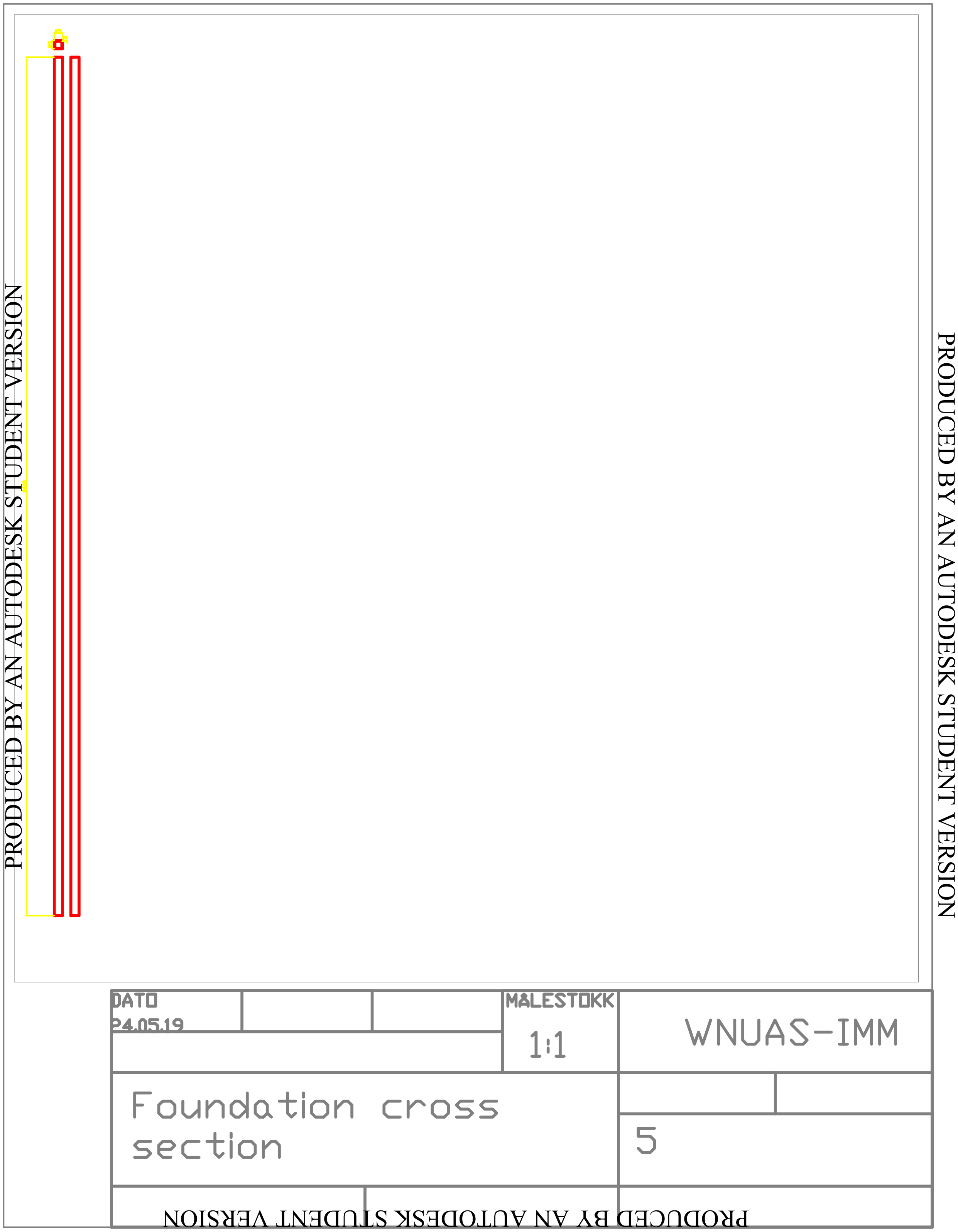

PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
DATO
24.05.19
MÅLESTOKK
1:1
WNUAS-IMM
Member AF
2


40
40
913
953
20
Ø10
DATO
24.05.19
MÅLESTOKK
1:1
WNUAS-IMM
Strut BC
3

Fredrik Von Schlanbusch, Erik Amlie Eagan



DATO 24.05.19			MÅLESTOKK 1:1	WNUAS-IMM
Cross section x				4


PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
DATO
24.05.19
MÅLESTOKK
1:1
WNUAS-IMM
Foundation cross section
5
PRODUCED BY AN AUTODESK STUDENT VERSION