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Redesign of ZEB Lab building, NTNU - prioritising passive climate control & comparison with existing

Master's thesis in Sustainable Architecture
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Master's thesis

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ABSTRACT

Greenhouse gas emissions are by far the most critical concern of our era, and the building and construction sector plays a significant role in this regard. SINTEF and the Norwegian University of Science and Technology (NTNU) have been working on this matter for a long time, and they just obtained an entirely new arena for investigating and testing innovative solutions in real life which is well known as “ZEB Laboratory”. The ZEB Laboratory is possibly the only one of its kind to obtain the environmental goal of ZEB-COM with the support of active strategies and passive strategies in the design. It is important to noticed that the active solutions were the main focus points and even surpass the passive solutions in this building design’s strategies. According to that matter, therefore this thesis aims to re-develop an alternative design of ZEB Laboratory building with the goal of reaching the same environmental goal (ZEB-COM) as close as possible with passive control strategies being the foremost priority in design yet without excluding mechanical strategies based on the identical user brief, function, location, site boundary, regulation, construction material, energy efficiency strategies and energy supplies; but with a slight difference in building’s footprint.

The methodologies for this study include a literature review on the original ZEB Laboratory building and its strategies used as well as passive strategies to achieve ZEB-COM; architectural and environmental analysis of original building and the new alternative design; computerized simulations; LCA and ZEB Balance calculation with limitation for evaluation and verification of the setup goal.

By a foremost prioritized of passive strategies of maximizing solar heat gain with optimal orientation, optimal building form, optimal building envelope design and maximization of daylight condition, the total annual energy consumption of the building in the operational stage dramatically decreases compare to the existing building due to the lower energy demand for room heating and lighting in the building. With the supportive of the active strategies such as PV production and energy efficiency strategies and supplier, the new alternative ZEB building could possibly reach the ZEB-COM goal with the lower value of ZEB balance comparing to the original building.

These results of this alternative design with the main focus point of passive solar heat gain would suggest that in order to reach the ZEB-COM level, the building does need to focus both the passive and active strategies, for example, design with solar heat adpative form and maximize the PV production by having the optimal slanted roof. However, it is essential to prioritize and passively minimize the total energy consumption in the building in the initial phase. Then, the active strategies will play an important role in the remained energy consumption.

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1. INTRODUCTION

1.1. INTRODUCTION TO ZEB LABORATORY BUILDING

General background and goal

Emissions of greenhouse gases are still the most major challenge of our time, and the building and construction industry plays a key part in this. SINTEF and the Norwegian University of Science and Technology (NTNU) have been focusing on this for a long time, and they have recently acquired a brand-new arena for researching and developing revolutionary ideas in the real life, so called the “ZEB Laboratory.”

The ZEB Laboratory is a living office laboratory 4 stories high and has its gross total area (GTA, including external wall) 2000m² located in Trondheim at the NTNU Gløshaugen campus (Thorsell & Kommun, 2019). The ZEB Laboratory is a four-story living office laboratory with a gross total area of 2000m2 at the NTNU Gløshaugen campus in Trondheim. The ZEB laboratory is the only one of its kind in Trondheim. The building offers a source of ongoing experimental measurements for academic purposes. It hosts 80 researchers, PhD students, and those who work on zero-emission innovations (Time, et al., 2019)

ZEB-COM (Zero emissions from **C**onstruction, **O**peration, and **M**aterials during the building’s 60-year lifespan) is ZEB Lab’s environmental and energy performance ambition which is far more ambitious than Norway’s national building code (TEK17). In order to recoup emissions from construction and material production ZEB Lab will then need to generate more energy than it (Thorsell & Kommun, 2019).

Figure 1: ZEB Laboratory building. Illustration: LINK Arkitektur

Figure 2: ZEB Lab building’s glulam structure components and CLT staircase

Building Materials and Envelope Technologies

ZEB Lab are built with a loadbearing system of engineered wood. Column, beam and other structural parts are of Glulam (Glue Laminated Timber). The stairwells and floors, elevator shafts and some of interior walls are built with CLT (Cross Laminated Timber). Exterior walls are made of a typical timber structure insulated with mineral wool which has U-value (W/m2K) of 01.5 which help minimize embodied emissions of material used to achieve ZEB-COM level (Time, et al., 2019). The roof is built with an innovative wooden compact construction made of framework with a smart vapor barrier with the U-value of 0.09 and ground floor is floor foundation with insulation 250mm has the U-value of 0.10. The windows and doors have the U-value of 0.77 and the air leakage number measured by the contractor is 0.3 ACH (at 50 Pa) (Thorsell & Kommun, 2019).

The roof, the entire southern façade, and a portion of the other facades are covered in black PV-cells. Burned hardwood panels are utilized elsewhere to provide a uniform look while reducing embodied emissions. The first floor’s south façade, which includes the twin rooms, is designed in such a way that the entire façade or individual window components could be replaced and reconstructed. As a result, new products, components, and technologies could be used to examine and improve the building envelope and efficiency. This enables research on the effectiveness of devices and their impact on energy consumption and user comfort (Time, et al., 2019).

Energy Production

The building's entire renewable energy generation is based on solar power collected by building-integrated photovoltaic panels (BIPV). BIPV panels fill the entire roof with a 30o slope toward south as well as the majority of the south and east façades and the top section of the North façade. BIPV is only partially covered on the west and north facades. (Nocente, Time, Mathisen, Kvande, & Gustavsen, 2021)

A total of 701 panels have been mounted, covering a total area of 963.4m² (Time, et al., 2019). However, according to Zeb Flexible Laboratory's rapport created by Terje Jacobsen and Inger Andresen, the total area of PV installed on the roof and façade is 1147m2 with the efficiency of 21% and 16% respectively as can be seen in figure 3. Mono-Si cells features in all the panels, although different varieties from different manufacturers are used to optimize the size, allocation, and most essential to allow custom-made PV modules to fill the maximum possible area on the East and West facades.

There are 181 kWp of installed PV power (Time, et al., 2019). However, according to Zeb Flexible Laboratory's rapport the total PV power is 213 kWp. Solar panels are linked together in strings to maximize power conversion. At 400 V, AC output is delivered to the electrical grid. A 156MWh is an annual resulted in net electric work contribution of the solar power calculations on this design (Time, et al., 2019).

Flate	Virkningsgrad [%]	Helning	Azimut	Areal [m2]	kWp	Produksjon [kWh/y]	kWh/ kWp	kWh/m2
Tak	21	30	0	585	123	119 679	973	205
Fasade Sør	16	90	0	150	24	20 640	860	138
Fasade Øst	16	90	-90	188	30	17 310	577	92
Fasade Vest	16	90	66	224	36	24 408	678	109
Skråplan	16	60	0	55	9	9 342	1038	170
Sum				**1202**	**222**	**191 379**	**862**	**159**

Figure 3: Preliminary calculation of solar cell systems, done with PVsyst by Multiconsult as of December 2017

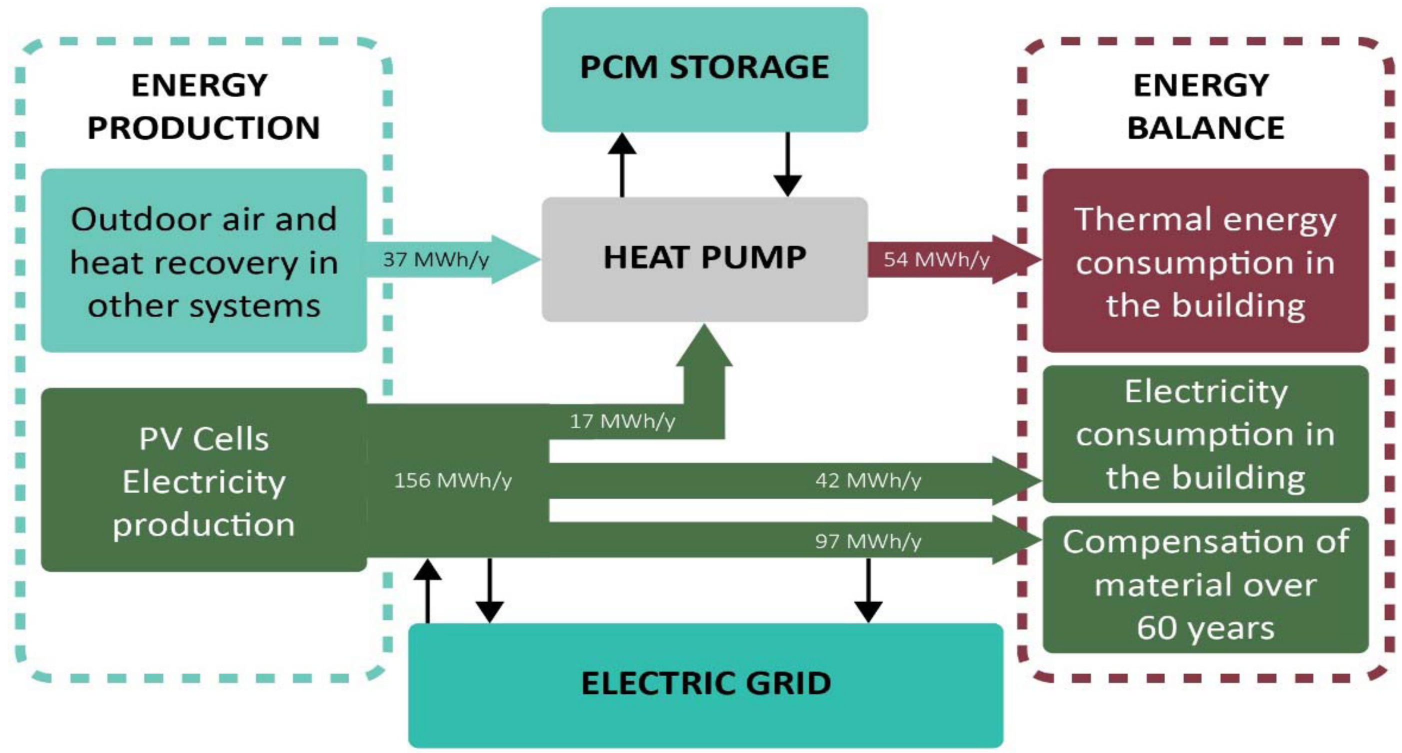


Figure 4: Sketch of the overall energy balance and energy system work.

Energy system

The building's heating and DHW systems are connected to two air-to-air heat pumps, and it includes a unique and huge prototype heat storage tank made of Phase Changing Material (PCM) that was made as special for this lab. PCM heat storage are intended to recapture thermal energy from the building-integrated photovoltaic (BIPV) roof, while serve as a thermal energy buffer to empower the heat pump function more effectively. The system has been made adaptable to enable for further investigation of such systems. This allows the machine to operate at the highest efficiency when heat pumps are only used for heating as this building. ZEB Lab does not have a cooling system. This is one of project's goal is to see how much the building can be cooled using only passive approaches and ventilation systems (Time, et al., 2019).

Natural Ventilation

The windows in ZEB Lab are set to offer cross ventilation on opening. Some of the building's windows can be manually operated by occupcant, while others have an automated opening mechanism. The main staircase is set up to draw both mechanical and natural ventilation air. With the chimney effect, the natural ventilation is drives through a fire hatch at the top of the stairs. In addition, the Natural ventilation and air extraction via ducts in different settings are provided for the twin rooms (Time, et al., 2019).

A total of 488m² is covered with windows, which cover around 28% of the heated floor area (BRA). The opening area the manual windows is limited to 20% and of the geometrical area and 60% for the automated window, respectively (Leinum, 2019). The openable windows are strategically placed to allow for natural ventilation. Figure 5 shows the two type of the window in the elevation of the building. Blue square represents manually controlled windows and red square are automoated window. Grey represents most of the window and unopenable. The yellow square indicates an automated fire hatch on each of the east and west facade.

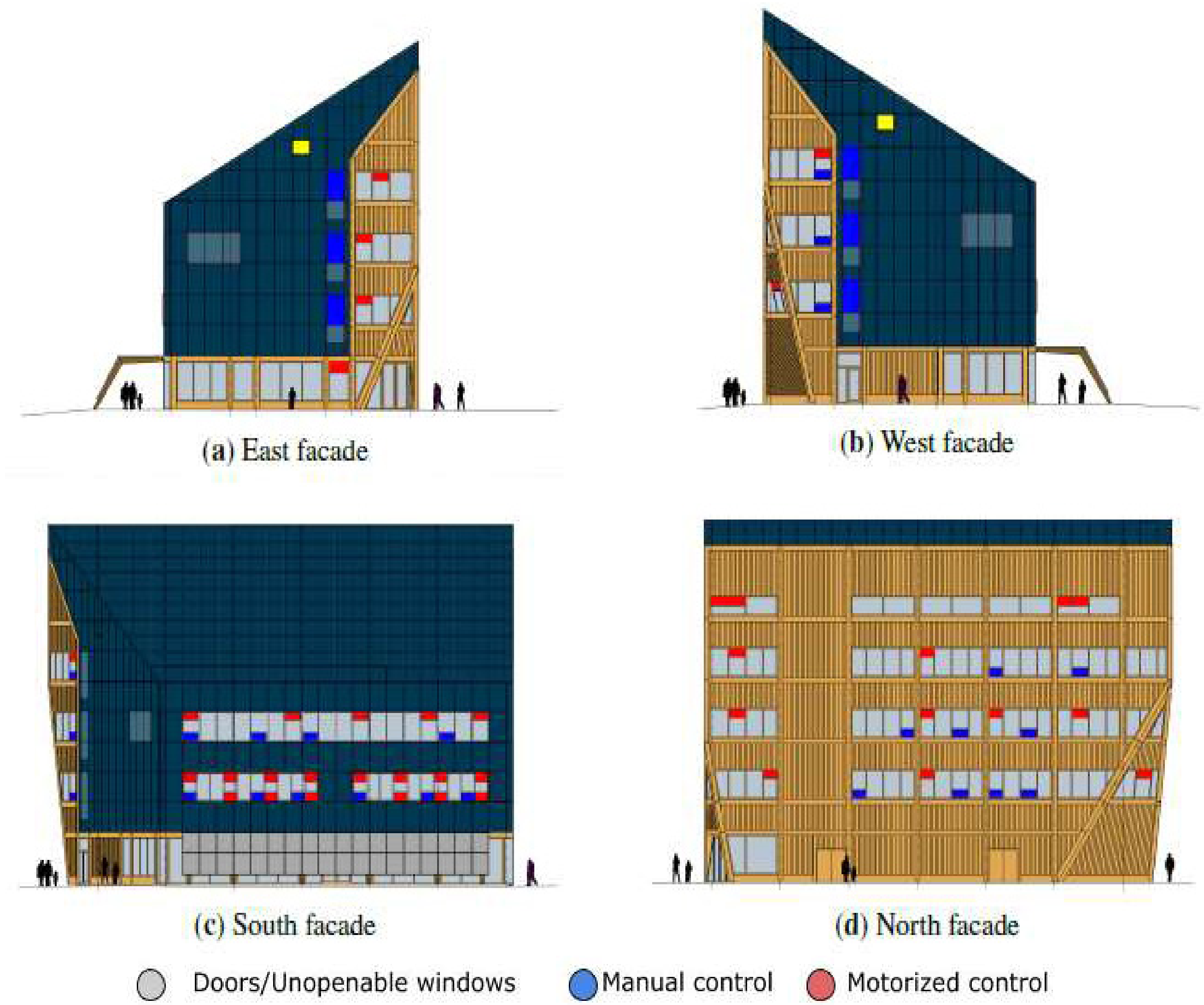


Figure 5: ZEB Lab's windows types and its position

Mechanical Ventilation

The building is also equipped with a central mechanical ventilation system. Different air distribution systems were designed for each of the four floors, but they all rely on the principle of displacement ventilation. At the ground floor the air is supplied through inlet devices in the floor, in the first floor through porous ceiling boards in the suspended ceiling, in the second floor through slots and in the third floor through wall air terminals places at floor level (Time, et al., 2019).

A central mechanical ventilation system is installed at ZEB Lab. The selected ventilation approach is displacement ventilation, although each floor uses a unique air distribution system (Time, et al., 2019). This is likely done to optimize research opportunities. Based on the SINTEF document “ZEB Laboratory-Research Possibilities”, inlet devices are installed at floor level on the first story. The second story has porous ceiling boards in the suspending ceiling board, the third has air supply slots, and the fourth has wall air terminal at floor level. Exhaust air is expelled via vents in wardrobes, toilets, and the main stairway duct (Leinum, 2019).

Ventilation Mode

The ZEB Lab was intended to examine different ventilation systems whilst tracking energy usage, user behavior and comfort. The design is intended for use and experiment with both natural and mechanical ventilation, as well as a hybrid mode.Therefore, Mechanical, natural, or hybrid mode could be run in ZEB Lab building. However, the hybrid mode changes depending on the season (Time, et al., 2019).

Supply air is limited to the HVAC system, and windows are manually regulated in the mechanical mode. Natural ventilation mode relies exclusively on windows (manual and motorized) and does not need mechanical air supply.

In hybrid ventilation summer mode, natural ventilation is prioritized with mechanical ventilation employed as a backup when necessary. The winter hybrid ventilation mode uses a converse technique. (Leinum, 2019).

1.2. THESIS'S GOALS, INTENTION AND SCOPE

THESIS'S GOAL AND INTENTION

The ZEB Laboratory is possibly the only one of its kind to obtain the environmental goal of ZEB-COM with the supportive of active strategies and passive strategies in the design. It is important to noticed that the active solutions were the main focus points and even surpass the passive solutions in this building design's strategies. According to that matter, therefore this thesis aims to re-develop an alternative design of ZEB Laboratory building with the goal of reaching the same environmental goal (ZEB-COM) as close as possible with passive control strategies being the foremost priority in design yet without excluding active strategies such as energy efficiency system (Heat pump, PCM, and mechanical ventilation system) and on-site renewable energy production collected from building integrated photovoltaic (BIPV). It is important to note that the redesign of the ZEB Lab building will also based on the identical original building's location, site boundary, region regulation, user brief, function, construction material, building envelope, energy efficiency strategies and energy supply system; however, with a slight difference in building's footprint.

The priority passive control strategies in this project are intended to minimize energy consumption in building's operation stage as much as possible and to reduce emboided emission from construction material and construction stage since the goal of the project is planned to reach the same environmental goal of original building, which is ZEB-COM.

The new alternative design of ZEB Lab will also enhance a value to architecture aspect of the building, user behavior and comfort. The design aim to be more climate adaptive design or bioclimatic design rather than PV production adaptive design.

Figure 6: Thesis's goal

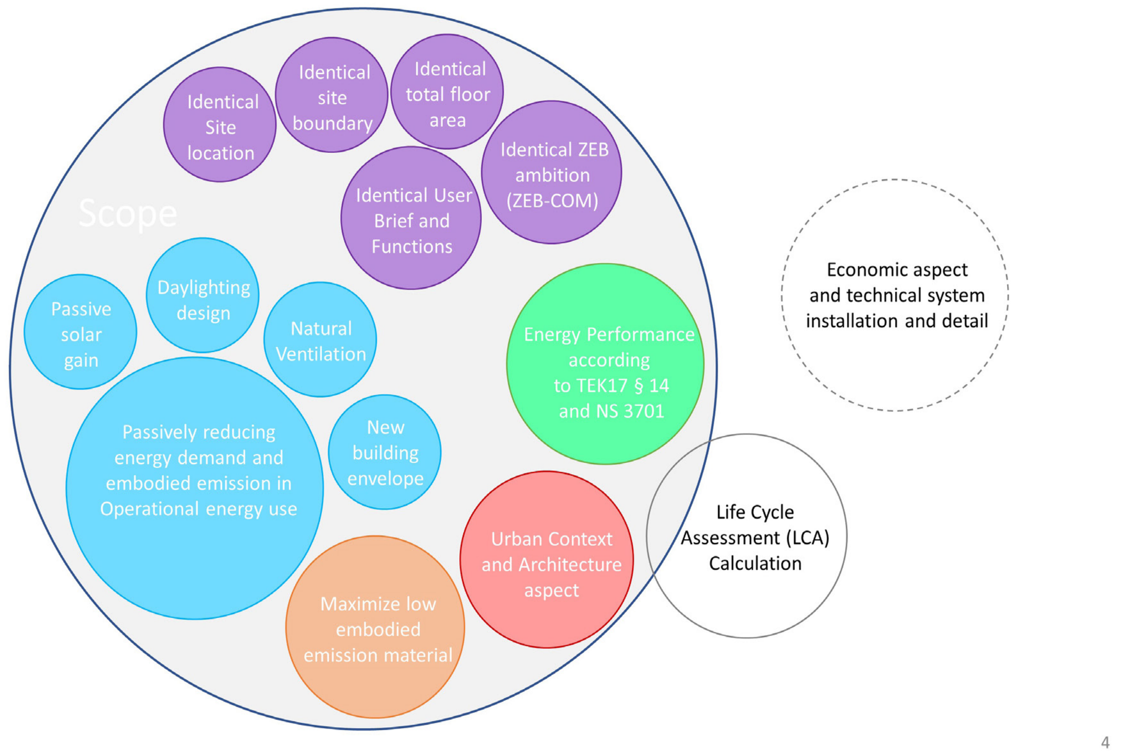


Figure 7: Thesis's scope

THESIS'S SCOPE

The first most priority passive design strategies is to maximize passive solar gain of the new building in order to minimize the annual heating demand in the operation stage. The seond passive design priority is to minimize the high emboided emission material in the building and the third priority strategies are maximization of daylighting condition and allow natural ventilation in summer period.

Despite from those passive strategies, building envelope design and active design strategies such as effective energy systems and on-site renewable energy production with BIPV are also considered; however the building envelope energy system are set identically to the original project (Air to air heat pump, displacement ventilation, Heating system equipped with PCM, hybrid ventilation system). Energy performance need to meet and surpass the energy requirement given in TEK17 § 14 and NS 3701 in order to achieve the ZEB-COM level.

There's a limitation framwork of the Life cycle assessment in this project. The CO2 emission related to the material production and construction stage of the new building are assumed to have similar amount to the original building.

Economic aspect, technical system installation and details such as heat pump, PCM, and mechanical ventilation system are out of the scope of the project.

1.3. THESIS'S LIMITATION AND METHODOLOGY

THESIS'S LIMITATION

ZEB Laboratory is a flexible living laboratory which has the main function for education purspose for researchers, related innovation firms, Phd student as welll as an experimental arena for all innovation idea related to zero emission. Therefore, there are many restrictions to redesign this building based on its functionality. Below are the limitation or restrictions that are considered carefully in this project.

The twin rooms which is located in the first floor's south façade is designed in such a way that the entire façade or individual window components could be replaced and reconstructed for the purpose of experimental of new products or technology. Therefore, in the new design, the twin rooms must be located in the same location (south facade), have the same total area, identical number and types of windows and the exterior wall and window must consider the possibility to replaced and rebuild.

In order to have an effective comparing with the original building, the new design must follow the same original building's site location, boundary, height, total area of the building (approx 2000m²), and functionality. In addition, the efficiency of PV panel should also be set to the same number of the original building for the efficient comparison in total net delivery energy and PV production.

Since the new project consider to have the same energy supply and system as original, thus, all technical rooms should have the similar total area. Also, the ventilation system is limited to displacement ventilation and each floor must have a different strategies approach as the original building for experimental purpose.

THESIS'S METHODOLOGY

In order to redesign the new ZEB Lab building in this project, the most essential part of the design is to do literature review of the original building to understand clearly about the building in every aspect such as its functionality, architectural design strategies, environmental design solution, low emission design strategies, energy performance, passive strategies and active strategies used in the building to achieve ZEB-COM level. Gathering as much data as possible of the ZEB building is also a crucial way that was done in order to have some data in hand and use it for new design when it is neccessary (especially, data of energy simulation) and compare with the original.

Despite from the literature review and essential data collection of ZEB Lab building, literview review on passive control strategies to minimize energy consumption in building's operation stage, high performance building envelope design, low emboided material, dayligthing design, and natural ventilation are also done to get inpsiring ideas to implement into the new design building, so that the goal of pushing the passive control strategies in design would be achieved.

After all the literature review and data collection, the project starts off with architectural analysis and evaluation of of the original building. Environmental analysis of original building and evaluation are also done simultaneously. These analysis and evaluations are critical ways to understand the strength and weakness of the design in both architectural and environmental aspect of the original building in advance before the new design is planned out. where there is strength, it is considered perseve and where there is weakness, it is improved.

The inital conceptual form and orientation of the new proposal are created right after the analysis and evaluation of the original building. The conceptual form are created based mainly on the project main goal (passive control strategies. passive solar gain), all of those literature reviews, analysis and evaluation of the original building. The conceptual form are eventually evaluation and follow up if it is in right track of the goal. The evaluation consists of environmental analysis, simulation related to passive solar gain, and a draft energy performance simulation and caclulation. The energy performance simulation and calcuation plays an important role in total CO2 emission calcuation in building's operational stage. That's why it is essential to have a draft simulation in early stage in order to achieve the project goal of ZEB-COM level.

Variety of forms are created, adjust, develop and evaluate in the same procedure after the environmental analysis, evaluation and draft energy simulation of the initial forms in order to seek for the best environmental adaptive form (form that maximize passive soalr heat grain and best daylighting considition and natural ventilation) as well as the hight energy performance building form with lowest CO2 emission in building''s operation stage.

The form that has the greatest passive solar heat gain and the highest energy performance with lowest CO2 emission is then used for further investigation and optimization to get the best outcome out of it. Different of optimization forms are then investigate with PV production in consideration. The evaluation of the energy performance and goal is followed the same procedure

The final programing, layout and precise modeling are done in revit software program for the architectural drawing and a better visualization of the new building form. The final analysis, evaluation, and energy performance simulation are also done in a very precise way by inputting the precise data for simulation and calculation in this phase, so that the result would be reliable and comparable with the original building. Evenually, the ZEB balance (ZEB-COM) of the building are calculation to verify if it reach the ZEB-COM level.

Main Programs used in the project and their purpose of usage:

1. Rhino: Conceptual forms modeling
2. Grasshopper & Ladybug tool: Environmental Analysis
3. Grasshopper & Honeybee tool: Energy simulation (inaccuracy)
4. Simen software: Energy simulation (accuracy and are made for Norway)
5. AutoCAD: Draft layout and programming of conceptual forms
6. Revit sofware: modeling and programming of the new building design

2. ANALYSIS OF THE ZEB LAB BUILDING

As mentioned in the methodology, the redesign of the ZEB building started off with the essential analysis and evaluation of ZEB Lab building in both architectural and environmental aspect in order to understand the pros and cons of the original building prior to the redesign new ZEB Lab. The result from this analysis would direct the redesign new ZEB Lab project to the right path toward the goal and a better building.

2.1. ARCHITECTURAL ANALYSIS OF THE ZEB LAB BUILDING

Initially, the ZEB Lab building is analysised and evaluated in architecture aspect. Strength and weakness of the building are the main evaluation. It is important to notice that the analysis and evaluation is based on my understanding and assumption after gathering all information, discussing with project leader as well as Phd students who work there.

Strength of the ZEB Lab

- The edge cut on the ground floor to the second floor of northwest facade and the northeast facade of the building has a good reason and purpose for urban context. The edge cut would provide an accessible path for the neighbor buildings and the people would not need to walk around the corner of the building when they walk pass by the building. This was mentioned by the PhD student who works there and toured us around the building during our site visit. Figure 8 shows the edge cut and how it offer an accessible path for the neighbor building and building itself.

- The building is orientated to south direction which is the best direction to maximize solar heat gain, especially in winter period and that's great for lower heating load in building.

- Technical room and technical shaft which do not require daylighting at all are placed in the middle part of the building which has the lowest daylighting condition.

- The main staircase's location is intended for natural ventilation and act as the stairwell to extract the air for both mechanical and natural ventilation (Time, et al., 2019).

Weakness of the ZEB Lab

- Kitchen placement is located in the middle part of the building without enclosed wall cause the smell of every cooking draw to all upper floors when there is a ventilation happen. This issue was mentioned by the PhD students that we have met there. Therfore, the new design building should take that in the consideration when planning out the layout of the building.

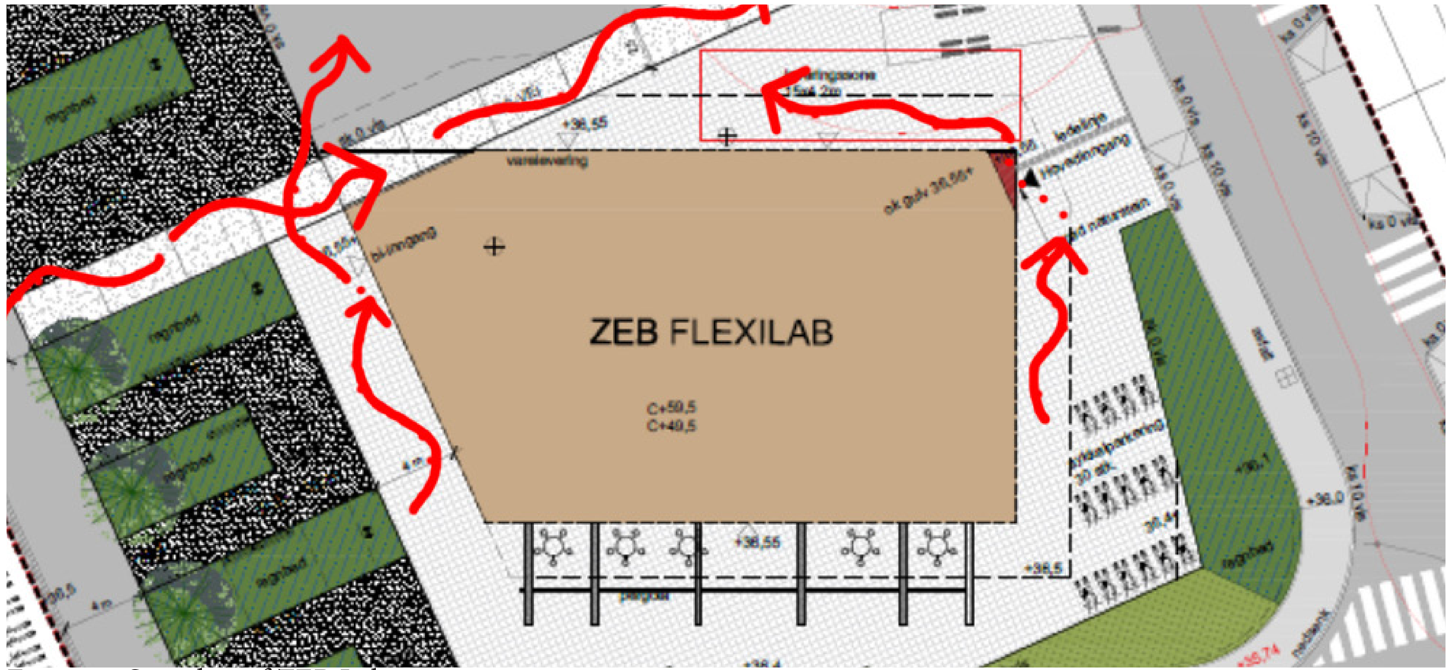


Figure 8: Site plan of ZEB Lab

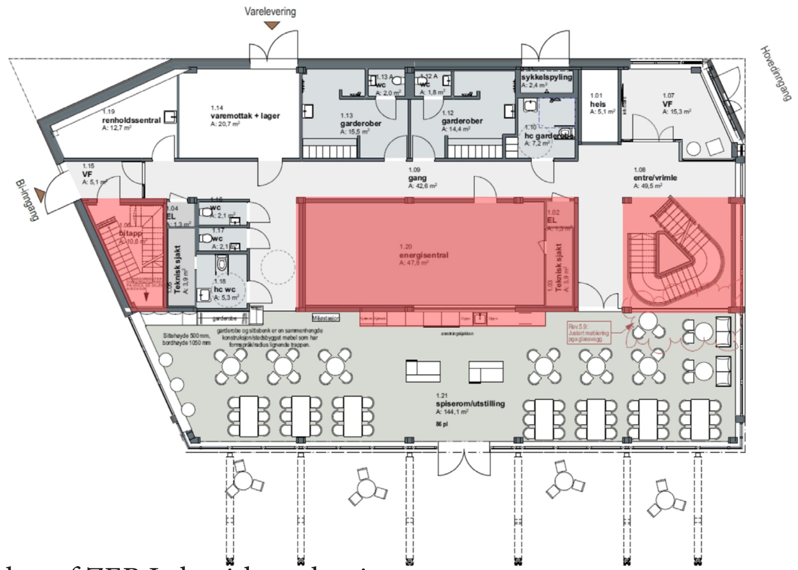


Figure 9: Ground floor plan of ZEB Lab with evaluation note

Figure 10: First floor plan of ZEB Lab with evaluation note

- The 30 degree slope roof facing south as shown in figure 2.4 made the entire southern part of building to have a very low ceiling height which lead to unuseable space for the rooms that require more daylighting and solar heat gain.

- Technical room is placed in the middle of the building is great, However, if we look that the workplaces in northern part of the building, the location of these place would have a low daylighting condition whilst the spaces need to have a good condition of daylighting because the users would spend most of time there working and researching.

- During the pandemic of Covid19, most of the meeting were shifted to digital meeting instead of physical meeting and most meeting is an individual meeting. However, the ZEB Lab building provide no proper digital individual meeting space. This make the occupants to use the common space or break area for individual digital meeting which is somehow difficult to communicate in that opening space. Therefore, even though it is a tiny issue, but if we could solve this properly, there is a huge change in user's satification or user's comfort.

- There is small break area in first floor, second floor, and third floor, however, there is no in the ground floor. The social space such as game zone/room or recreation sapce is not provided in the original layout which is a great space for refreshing both physical and mental for the occupants. Especially, most occupants are researchers and PhD students which is a great fit with this social space due to their load of works, so they could relieve their tension or pressure from work in that space for their productivity and creativity.

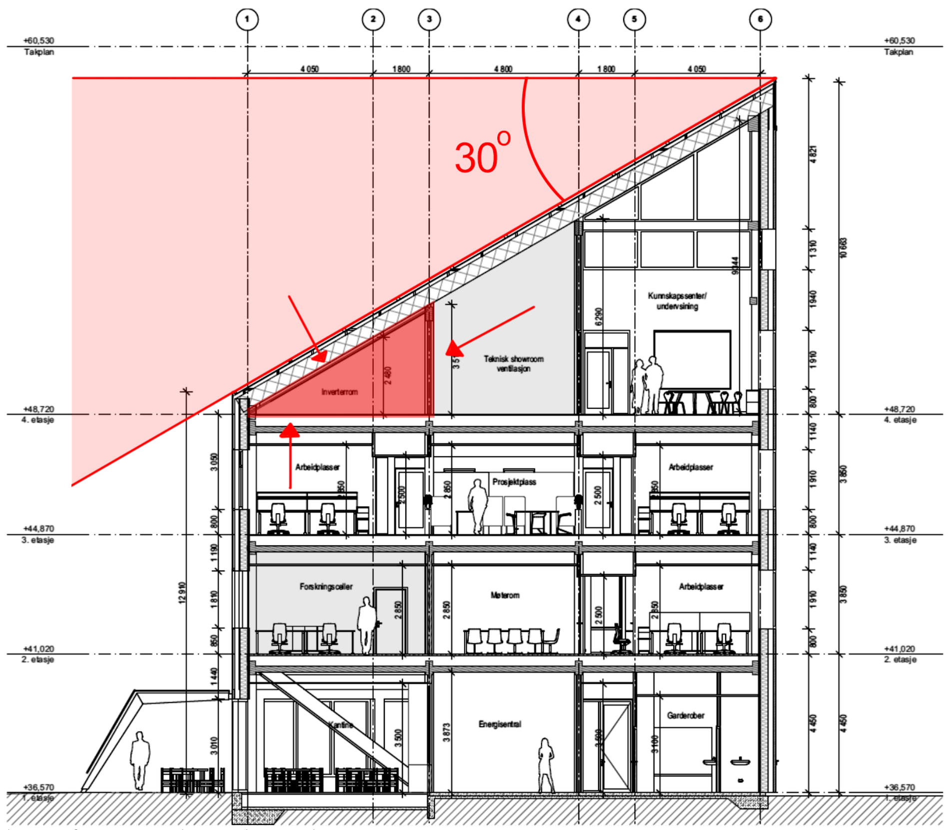


Figure 11: Section plan of ZEB Lab with evaluation note

Figure 12: Second floor plan of ZEB Lab with evaluation note

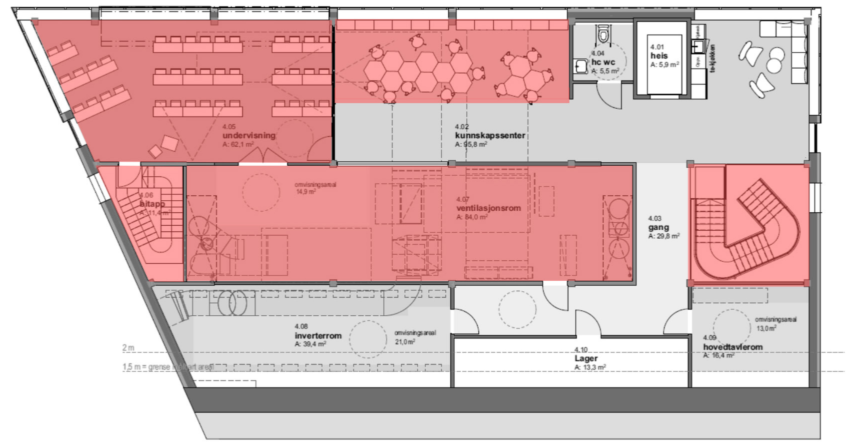


Figure 13: Third floor plan of ZEB Lab with evaluation note

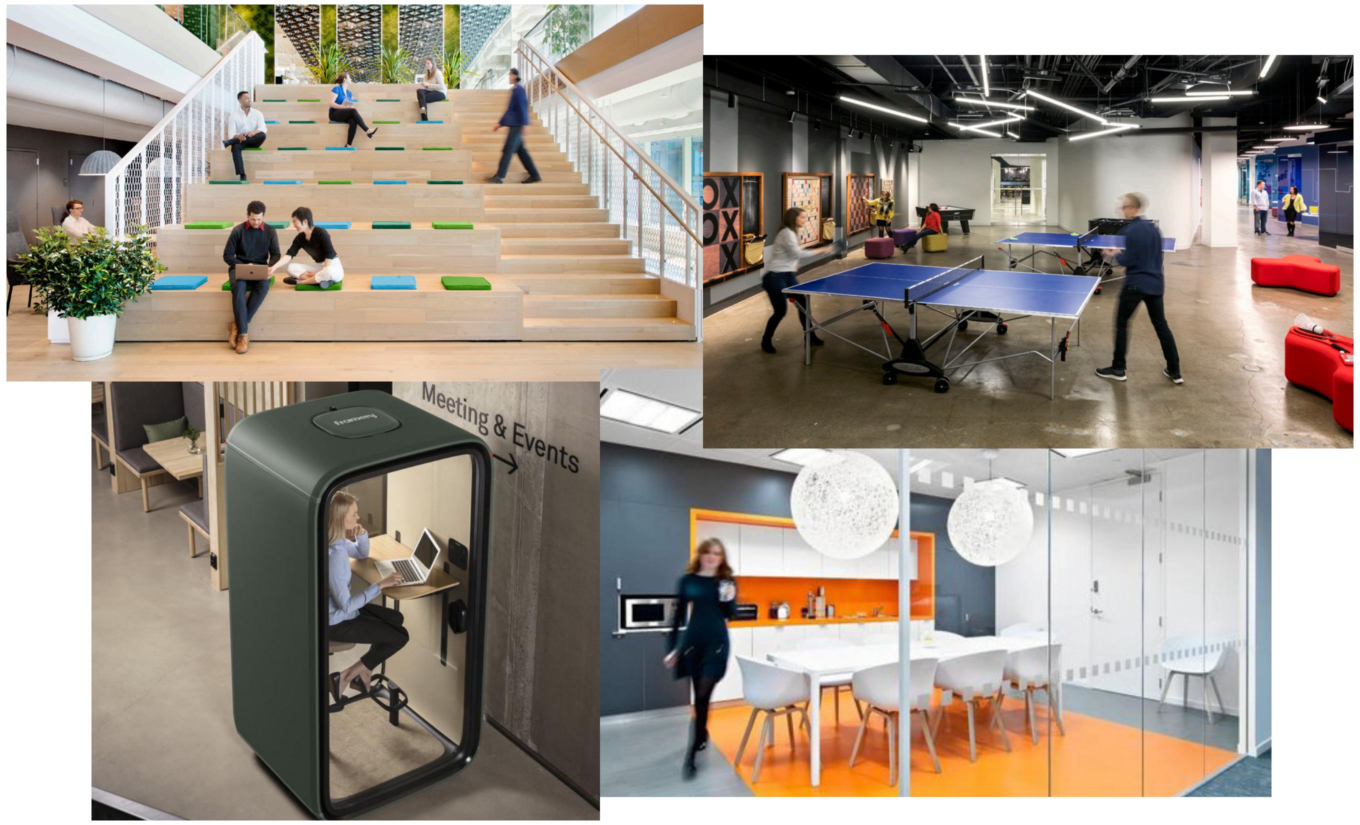


Figure 14: Image example of in social space, individual booth and enclosed

2.2. ENVIRONMENTAL ANALYSIS AND EVALUATION OF ZEB LAB BUILDING

In addition to the analysis and evaluation of the ZEB Lab building in architecture aspect, the enviromental analysis and evaluation are also conduct to better understand how the building design adapted to the local enviroment or climate and to investigate where to improve for the new . The result from this evaluation is one of the key factor for the futher development of the new ZEB Lab building.

Since the main goal of the project is to maximize passive solar heat gain, therefore in the environmental analysis of the original building , the solar radiation is the main focus point for the evaluation. Figure 15 indicates the annual radiation rose of trondheim and figure 16 shows the radiation rose of trondheim in winter period. It could be seen from annual radiation rose that the most radiation comes from from 190 degree south-southwest (SSW). The other two great radiation come from south direction and 200 degree SSW. Similarly, in winter period, the most radiation comes from south, following by 190 degree SSW and 170 degree SSE.

Figure 17 illustrates the annual solar radiation analysis of the ZEB Lab building form, view from southwest angle. According to that, it is noticed that the fire escape stairof the building which require no daylight was placed at the spot with medium level of solar radiation. This location should be functional for the workspace which require the most daylighting. The fire escape stair would be great fit in the northern part of the building where there is the least radiation. In first floor and second floor of ZEB Lab, there are workspaces that were arranged to the northern facade where recieves the least solar radiation. Similarly, the lecture room and knowledge space on the third floor are placed in the north facade. Those spaces should be fit wisely in the south, southeast or southwest where the most radiation occurs.

Figure 18 and figure 20 which show the radiation result of ZEB Lab in a whole year and winter period from southeast angle view definitely give the important clue that in order to achieve the goal of maximization passive solar heat gain for new ZEB building, east facade should be minimized due to very low radiation or the facade should be strengthen toward southeast or south where the hightest radiation occurs.

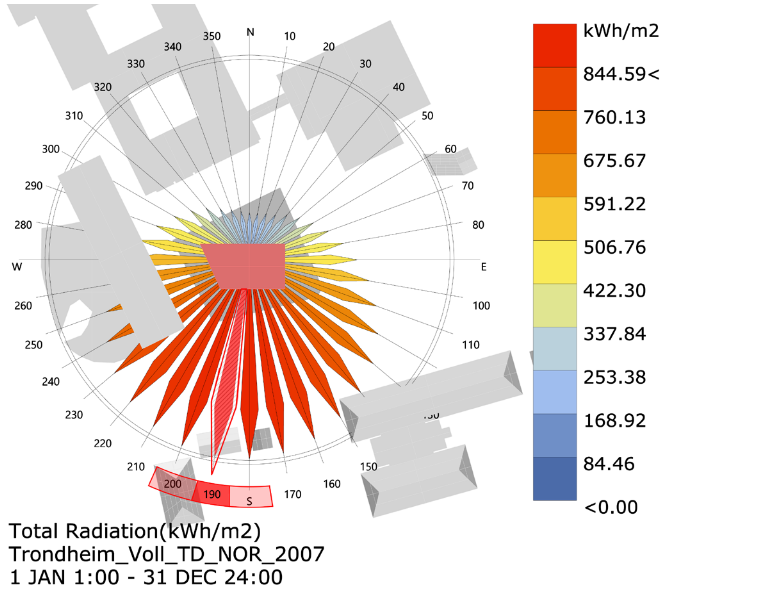


Figure 15: Annual radiation rose of trondheim

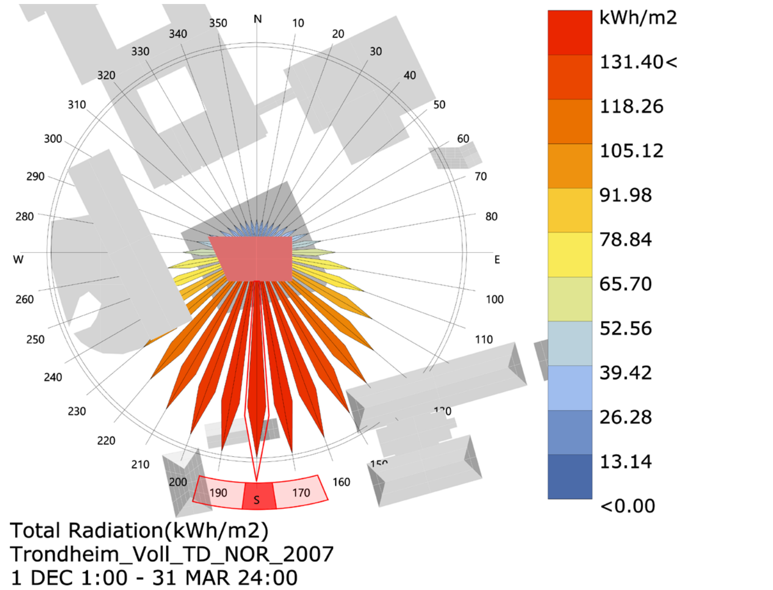


Figure 16: Winter radiation rose of trondheim

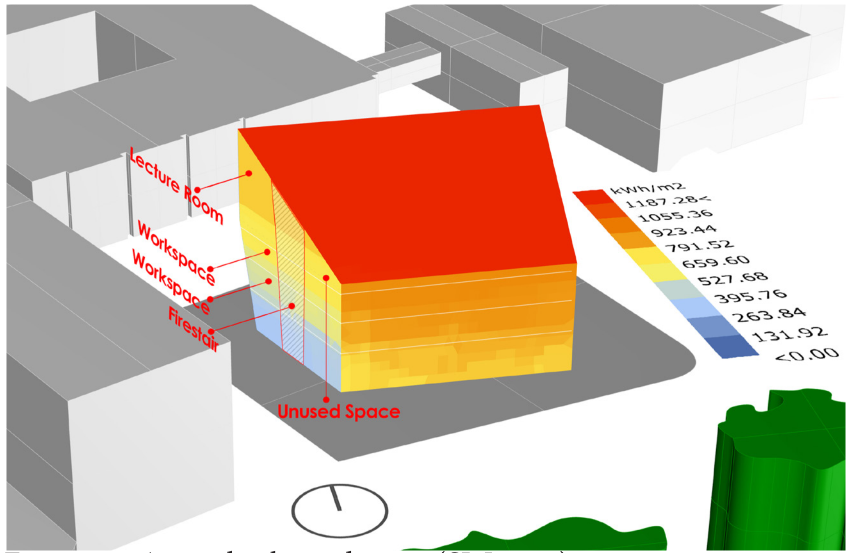


Figure 17: Annual solar radiation (SW view)

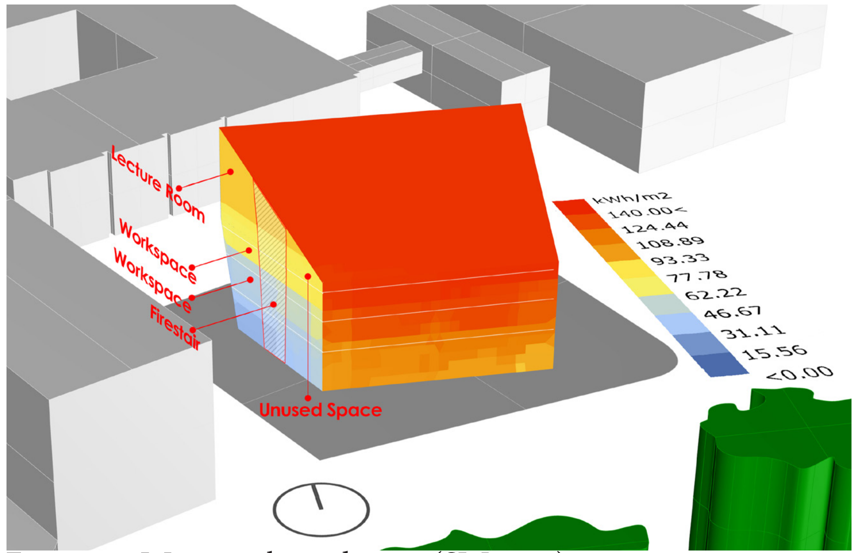


Figure 18: Winter solar radiation (SW view)

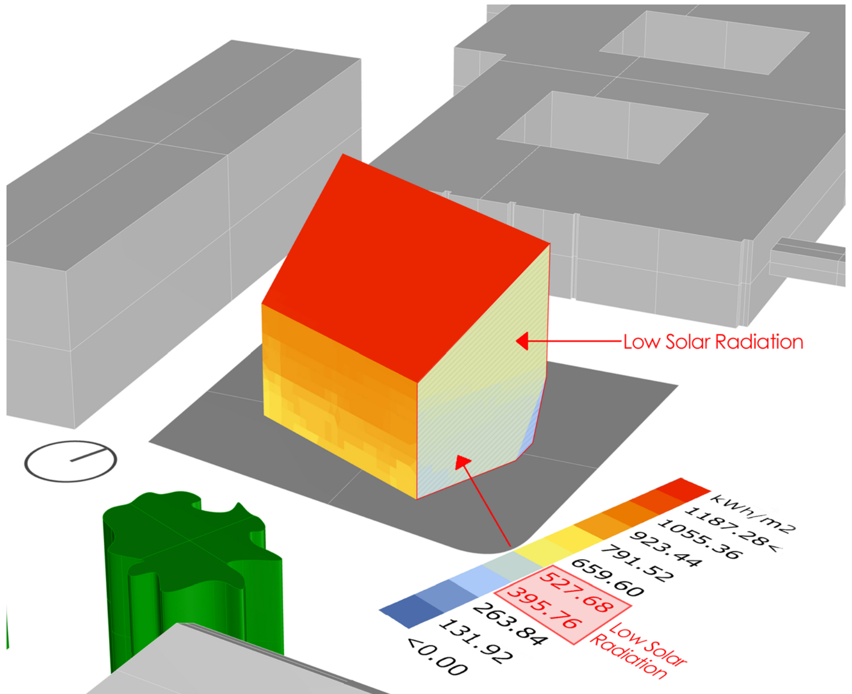


Figure 19: Annual solar radiation (SE view)

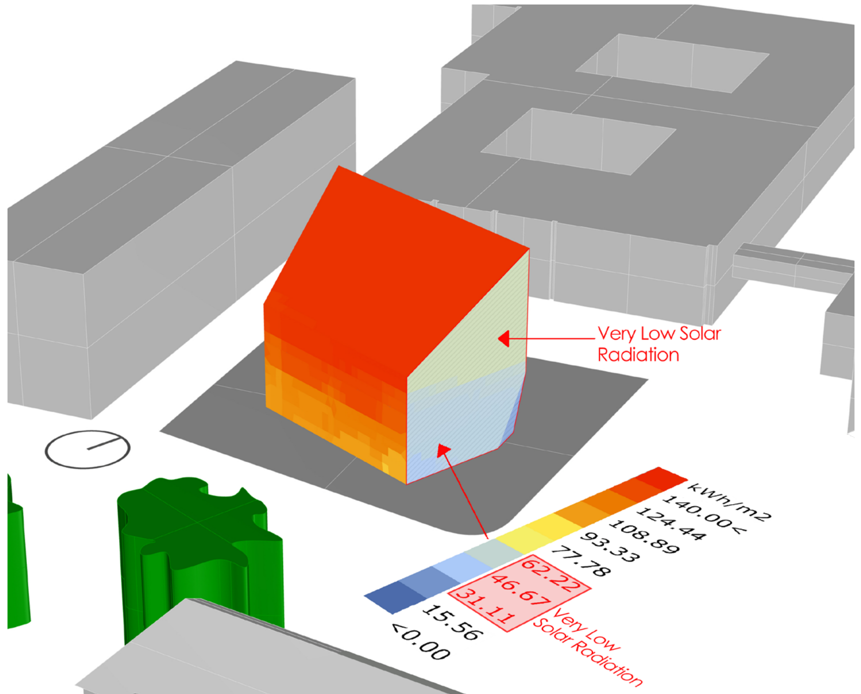


Figure 20: Winter solar radiation (SE view)

3. NEW DESIGN PROPOSAL

4. DESIGN DEVELOPMENT

4.1. FORM DEVELOPMENT WITH ANALYSIS, SIMULATIONS AND PV PRODUCTION

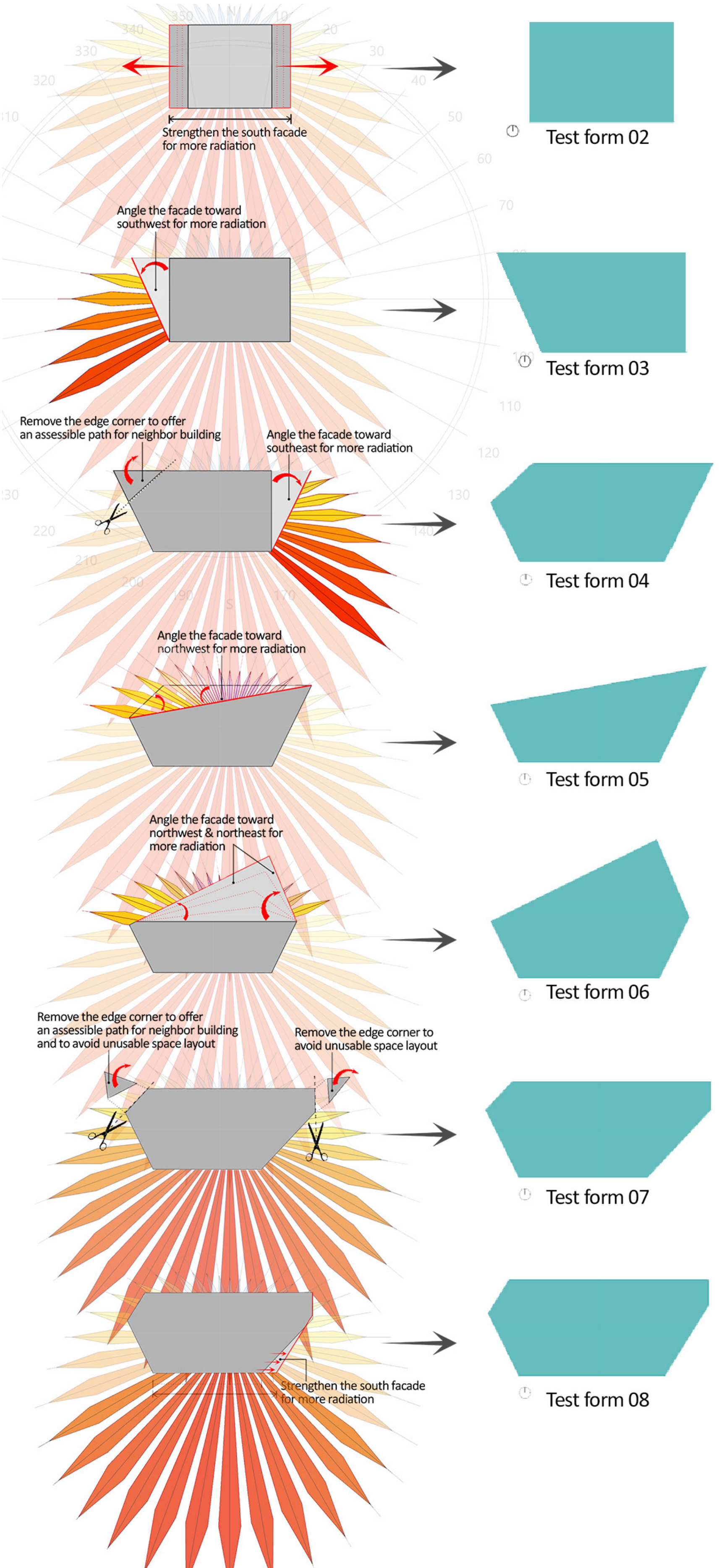


Figure 21: Test Forms development

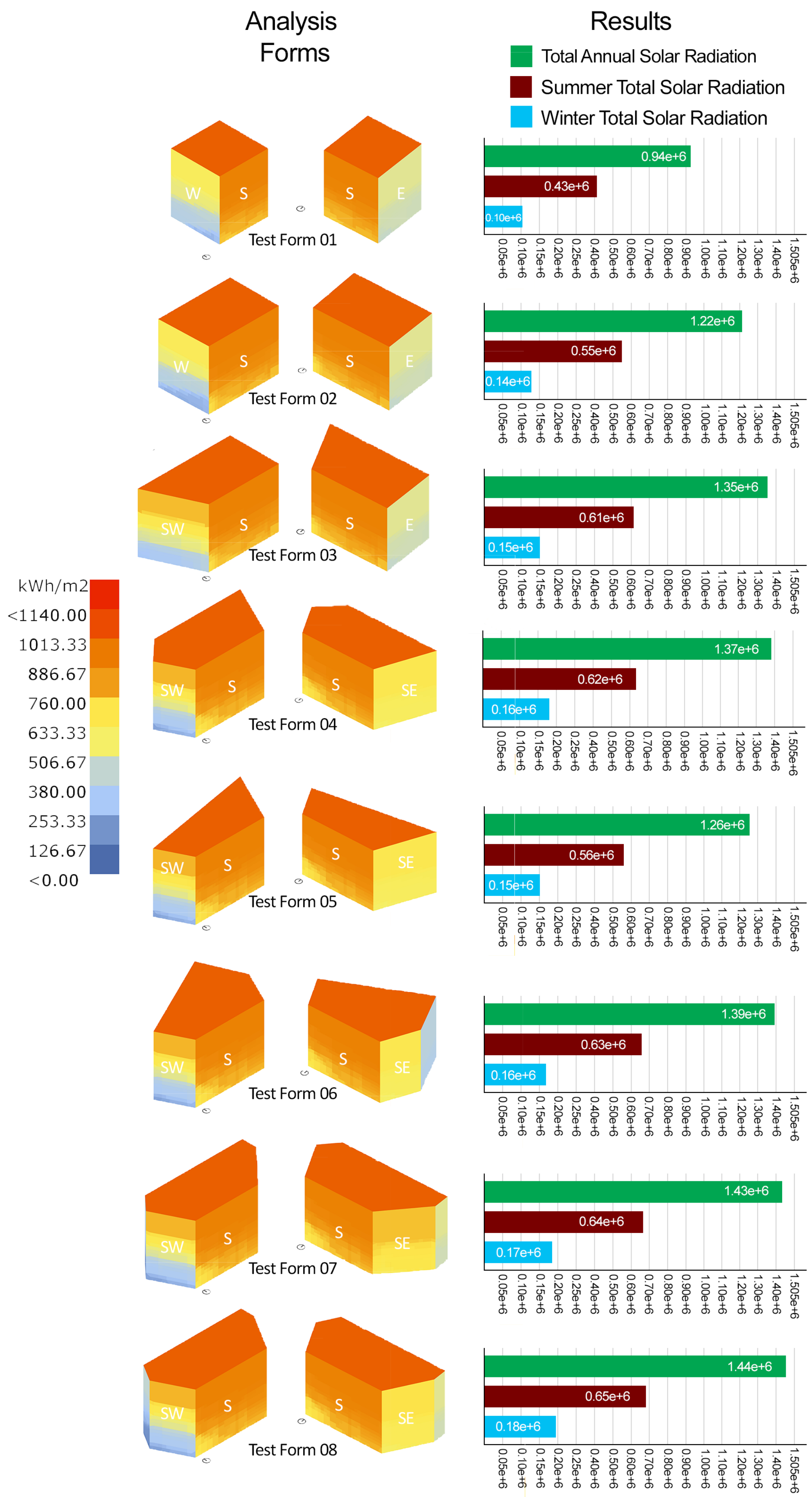


Figure 22: Radiation analysis of the Test forms

Orientation

The most criteria of designing new building are the building's orientation and based on the analysis and evaluation of the ZEB Lab building, the orientation of new ZEB building is considered toward south direction as well due to the most radiations occurs, especially in winter period. Also, based on Ar. Rutika Ajri Tendulkar, building oriented along an east-west axis is more efficient for both winter and summer. This orientation allows for maximum solar glazing to south for solar capture for heating.

Forms

Variety of forms are created according to the main goal of the project to maximize passive solar heat, thus the forms creation are mainly based on the result of the radiation rose, together with an architecture and urban context aspect. As can be seen in test form 3, the form are created so that not only the south recieve the radiation, but also allow the south -west facade because there is a better radiation from the southwest as well. Similarly, Test form 04, 07 and 08 are created mainly based on radiation, and additionally, the form's creation is also include architecture and urban context in consideration by removing the sharper edge of the form to provide an accessible path to neighbor building and a better layout arrangement of the floor plan (shaper edge creates unusable space).

Radiation Analysis of the forms

The forms are eventually investigated with radiation analysis and the result in figure 22 shows that the forms with east facade without southeast facade (test form 02,03) has a low radiation result. The forms which have facade to both southeast and southwest in addition to the south facade (test form 04,07,08) have the higher number in total solar radiation in winer, summer and annual. However, the form with the highest number in the total radiation which is the best form for passive solar gain strategy is "Test form 08".

Energy Simulation result of the original ZEB Lab building form and the investigation forms

The ZEB Lab building form without windows as shown in figure 23 are used in energy simulation done by SIMIEN software to calculate the draft energy budget, delivery energy and the CO2 emission related to operation use of the building. This energy simulation's result of the ZEB Lab building form is used as a reference number to compare the investigation forms that was done previously in radiation analysis. As can be seen in figure 23, the result marks a specific room heating of 21.2kWh/m² and 5.9kWh/m² of ventilation heating. The total specific net energy budget is 51.6kWh/m². It is essential to mention that the total specific net energy budget include room heating, ventiation heating, fan, pump, lighting, technical equipment and ventilation cooling. All the origin number from SIMIEN could be found in apprendix. The total specific delivery energy is 35.4kWh/m² and the annual CO2 mission for the operation stage is 4.6kg/m²/yr.

Test form 04, 05, 06, 07 and 08 which mark the high radiation from the previous analysis are used to simulate the energy performance to further investigate which forms could possibly minimize the heating demand by passive solar heat gain. The mininization would lead to a lower net delivery energy as well as operational stage's CO2 emission which is one of the key factor to achieve ZEB-COM level by pushing passive strategies. As could be seen from figure 24, Test form 05 has the highest number in both energy budget and delivery energy as well as the operational CO2 emission among other forms. The numbers even surpass the reference number of the original ZEB Lab. Whereas, there is a small difference in this simulation result between the test form 04, 06, 07 and 08. It is important to notice that all of the forms has lower number in room heating compare to the original ZEB Lab building's result, yet the total specific net energy demand is slightly higher than the original. Among all the forms, it could be seen that test form 08 has the lowest speicific energy demand in room heating which is 18.2kWh/m² compare to ZEB Lab's result; 21.2kWh/m². The total net energy budget, delivery energy and operational CO2 emission of test form 08 is the closest result to the ZEB Lab form. Therefore, it could be concluded that the "test form 08" is definitely the best form that could use for further development for this project.

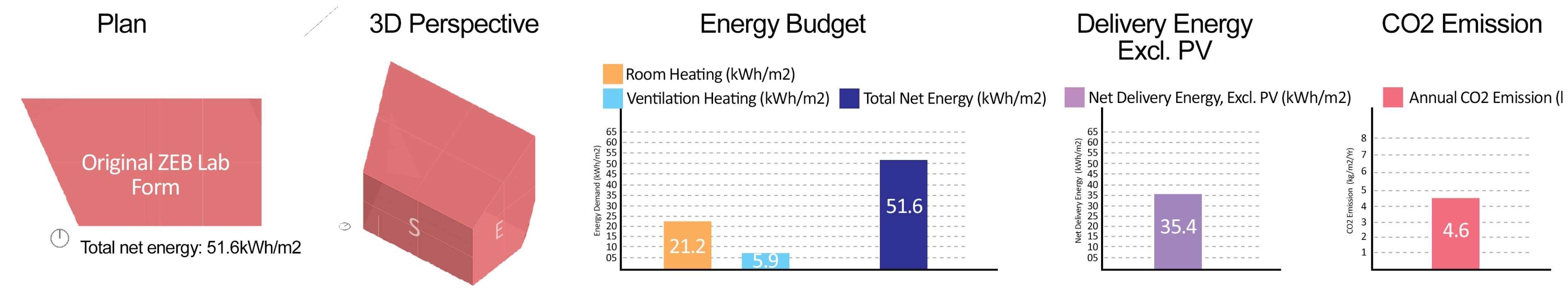


Figure 23: Energy simulation result of the ZEB Lab building without winodws

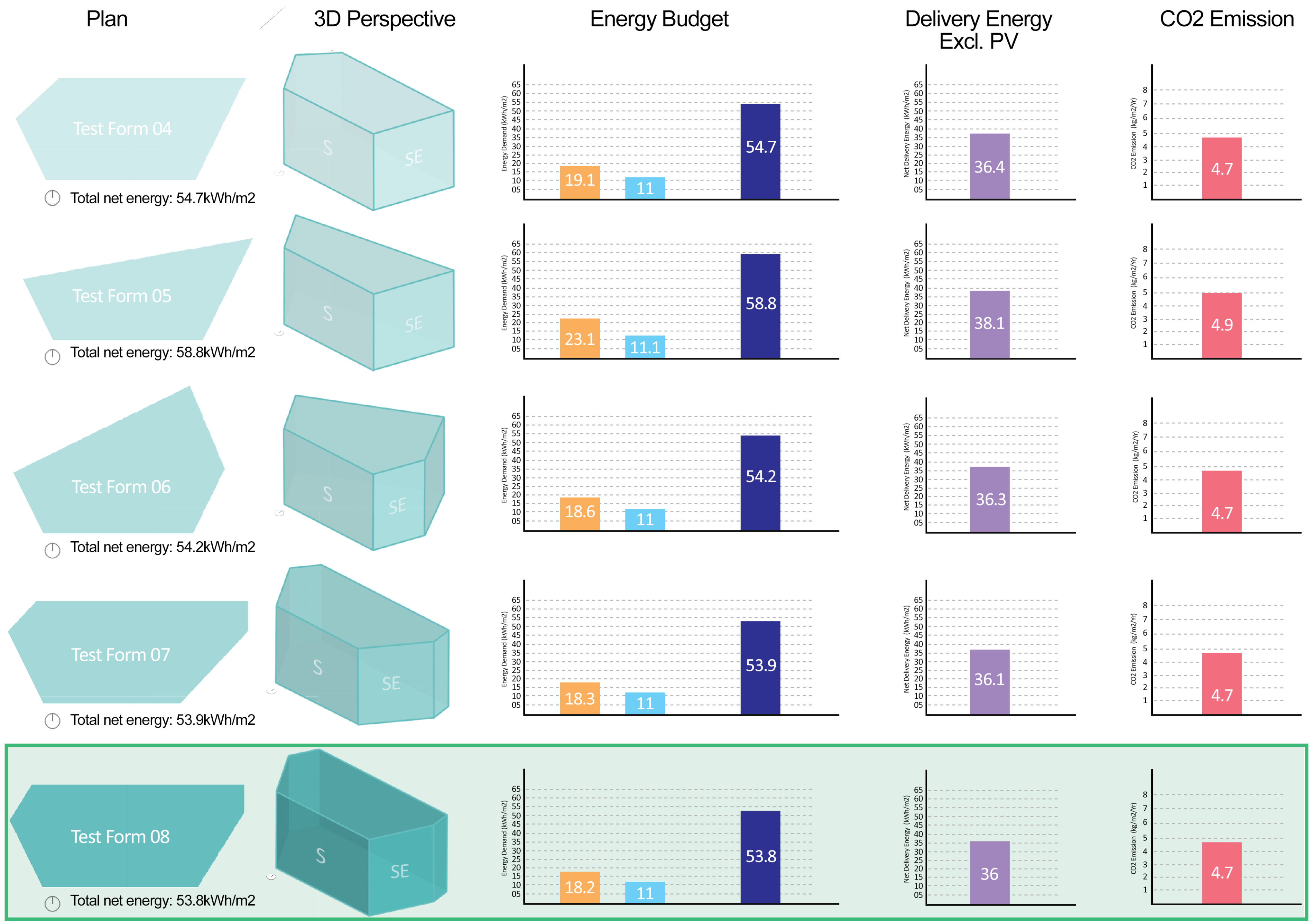


Figure 24: Energy simulation result of the Test forms

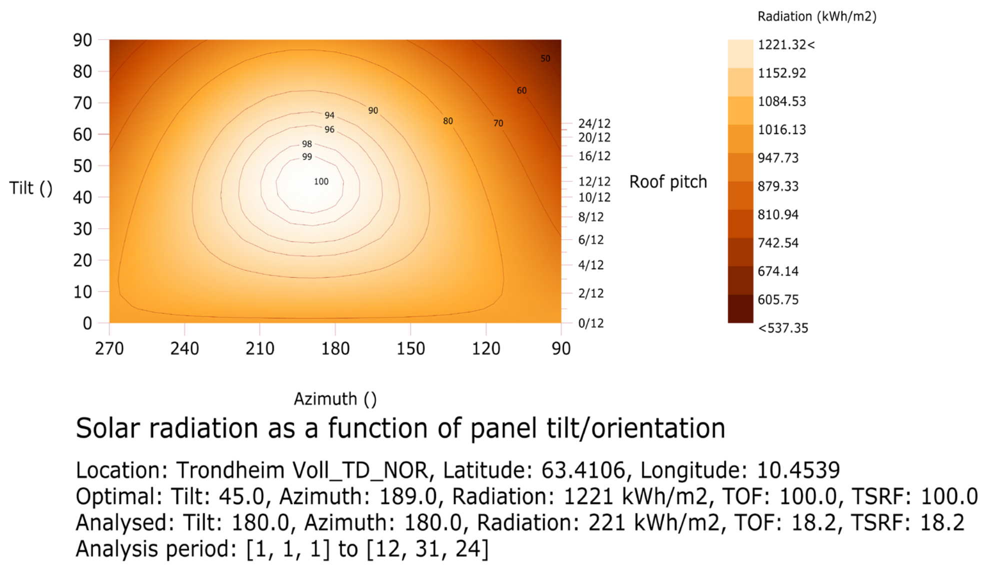


Figure 25: Optimal tilt and orientation for PV panel

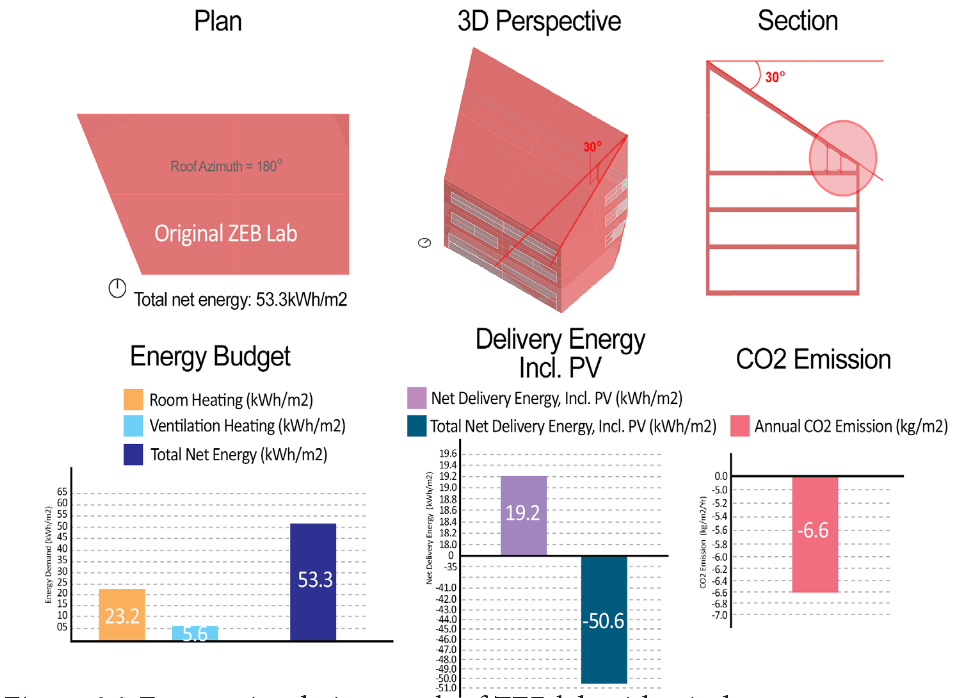


Figure 26: Energy simulation result of ZEB lab with windows

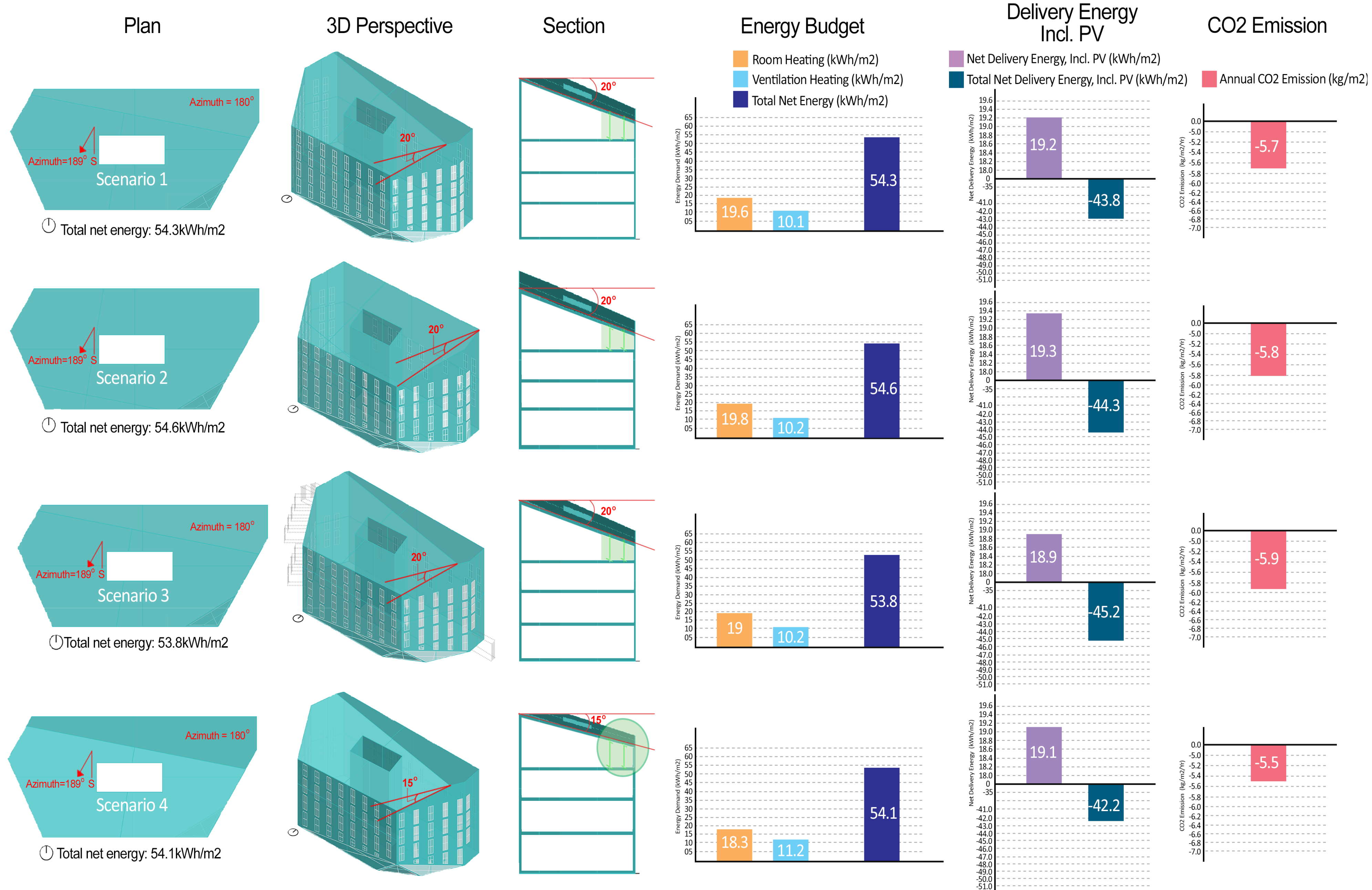


Figure 27: Energy simulation result of the optimization forms of Test form 8

Optimizations of "Test form 08" and their energy simulation results comparing with original ZEB Lab building.

Following the previous analysis and energy simulations to finalize the form for this project is the optimization of the selected form which is the "Test form 08". There are 8 scenarios testing for the optimization of the form as shown in figure 27. It is important to note that the tilted roof in each scenario is tilted to 189 degree SSW based on the analysis of optimal tilt and orientation for trondheim climate data and the tilt angle range from 15 degree to 30 degree as shown in figure 4.5. Window design for simulation is 3.2m height x 1m width in each scenario, except for scenario 6 and 7. Scenario 6 simulated with similar horizontal window design as original building and scenario 7 simulated with square 2m x 2m window design. Each scenarios are investigated with energy simulation in SIMIEN software same as the previous simulation, yet the input data is more precise; glazing designs and PV production are included in the simulation which could give out more precise result compare to the previous one. Similarly, the results are compared with the ZEB Lab building's result which is the reference result in this project. In this stage; however, the ZEB Lab building form is simulated with its design windows and PV production. This gives out accurate result to compare as shown in figure 26

From Figure 27, it could be noticed that scenario 3 which has a tilted roof of 20 degree and has 11 windows removed from the southeast and southwest facade has the closest result to the original ZEB Lab building's result among the other 3 scenarios. Surprisingly, the specific enery demand for room heating in scenrio 3 is even lower than the original building which is about 19kWh/m² compare to the original; 23.2kWh/m². However, the total specific energy budget is slight higher than the original about 0.5kWh/m². The annual operational CO_2 emission of scenario 3 is about -5.9kg/m²/yr which is slight lower than the original ZEB Lab which is about -6.6kg/m²/yr. It could be concluded that removing a certian amount of glazing from the building would help diminish amount of energy need for the room heating due to lesser heat loss through the glazing.

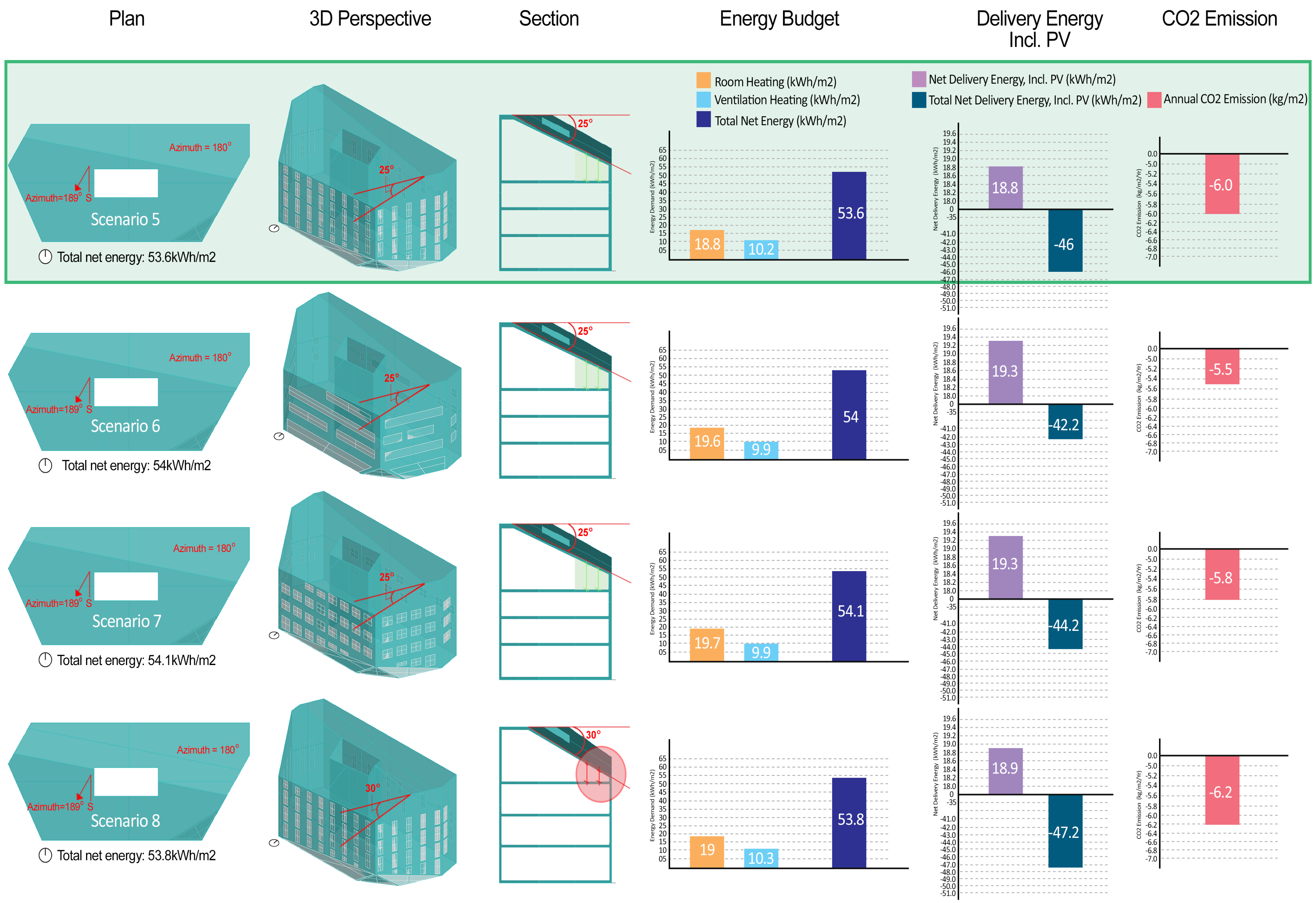


Figure 28: Energy simulation result of the optimization forms of Test form 8

Based on the previous analysis and the result, scenario 3 which is the scenrio that have the less glazing among other has the best result and closet to the reference result of ZEB Lab building. Therefore, more investigation should put into this scenario and that is where the scenario 5, 6 7, and 8 appeared. Scenario 5 is based from the scenario 3, yet with difference angle of the tilted roof; 25 degree. Similarly, scenario 8 comes from the adjustment of scenario 3's tilted roof to 30 degree (same as original). The windows design of scenario 6 is a horizontal window design which is similar to the ZEB Lab's window design. Whereas, scenario 7 has sqaure window design, 2m by 2m in dimension of the window. Investigating different designs of the window and different tilt angles of the roof in this energy simulation is the best way to understand and seek for the best optimization design in term of energy performance and total PV production. Each designs could possibly effect the result of both energy need and delivery energy which will effect the operation CO2 emission. The operation CO2 emission will eventually effect the calculate of total emission of ZEB-COM. This is why optimization of the efficient form in term of energy and PV production is very crucial in this project.

As could be seen in figure 28, the least effective optimazation is scenario 7 with the sqaure window design. Similarly, scenario 6 fo the horizontal window design give out approximate the same number of result. Scenario 5 and 8 is the contrast of scenrio 6 and 7 which give the best result among all the scenario. The two scenario has a very similar result. Scenario 5 give out a slight better total net specific energy need; about 53.6kWh/m2 and 53.8kWh/m2 from scenario 8. In term of operational CO2 emission, scenario 8 has the best result of -6.2kg/m2. However, scenario 5 is considered the best option of all since it give out a great result in energy need, delivery energy and CO2 emission as well as a great design of useable space compare to scenario 8. The 30 degree tilted angle of the scenario 8 lead to a very low ceiling height that could not be useable of the most uppe floor of the building. Whereas, scenario 5 provide a higher ceiling height that could be fully used in the upper southern part.

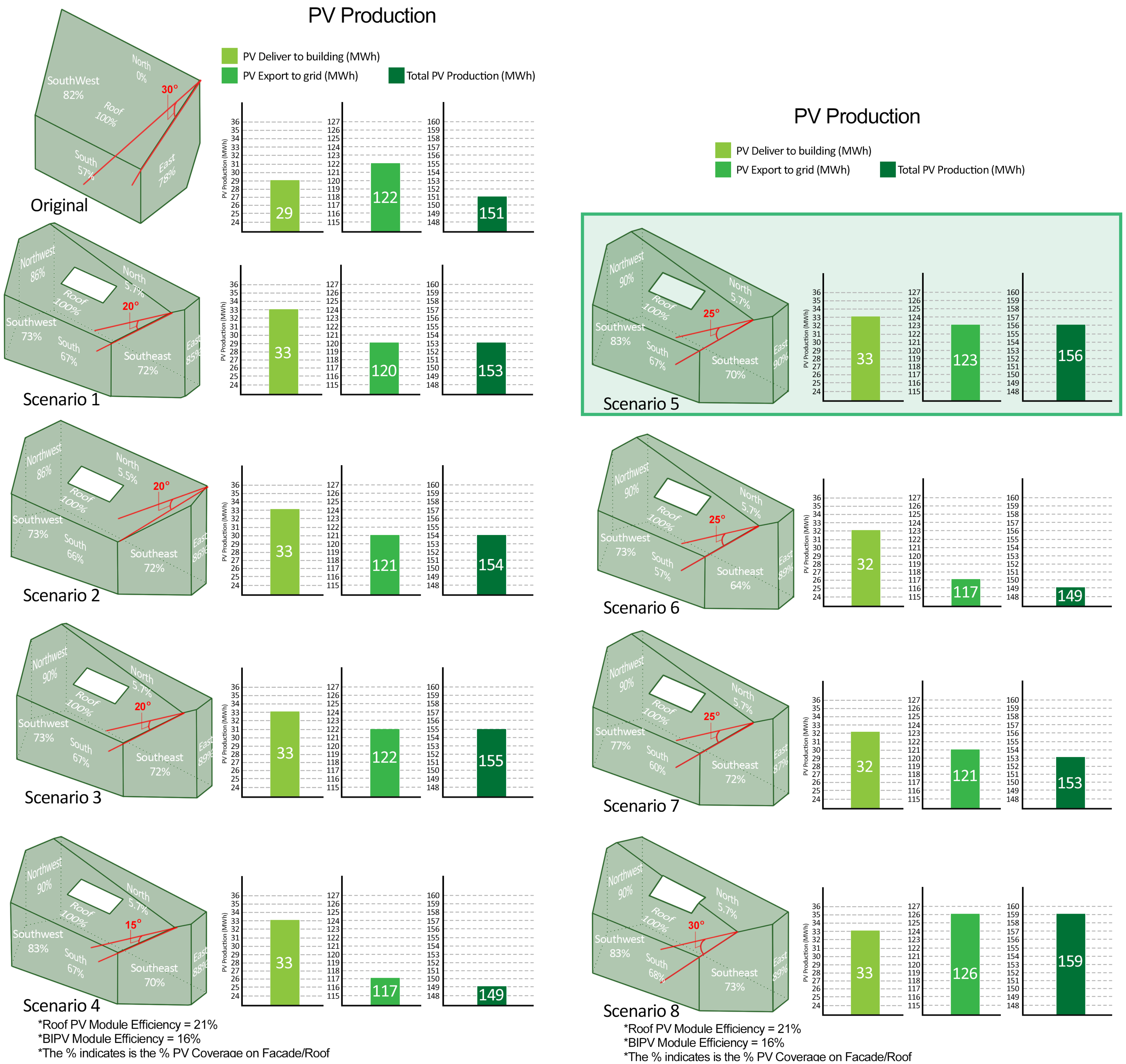


Figure 29: PV production result comparison the original ZEB Lab and the optimization forms of Test form 8

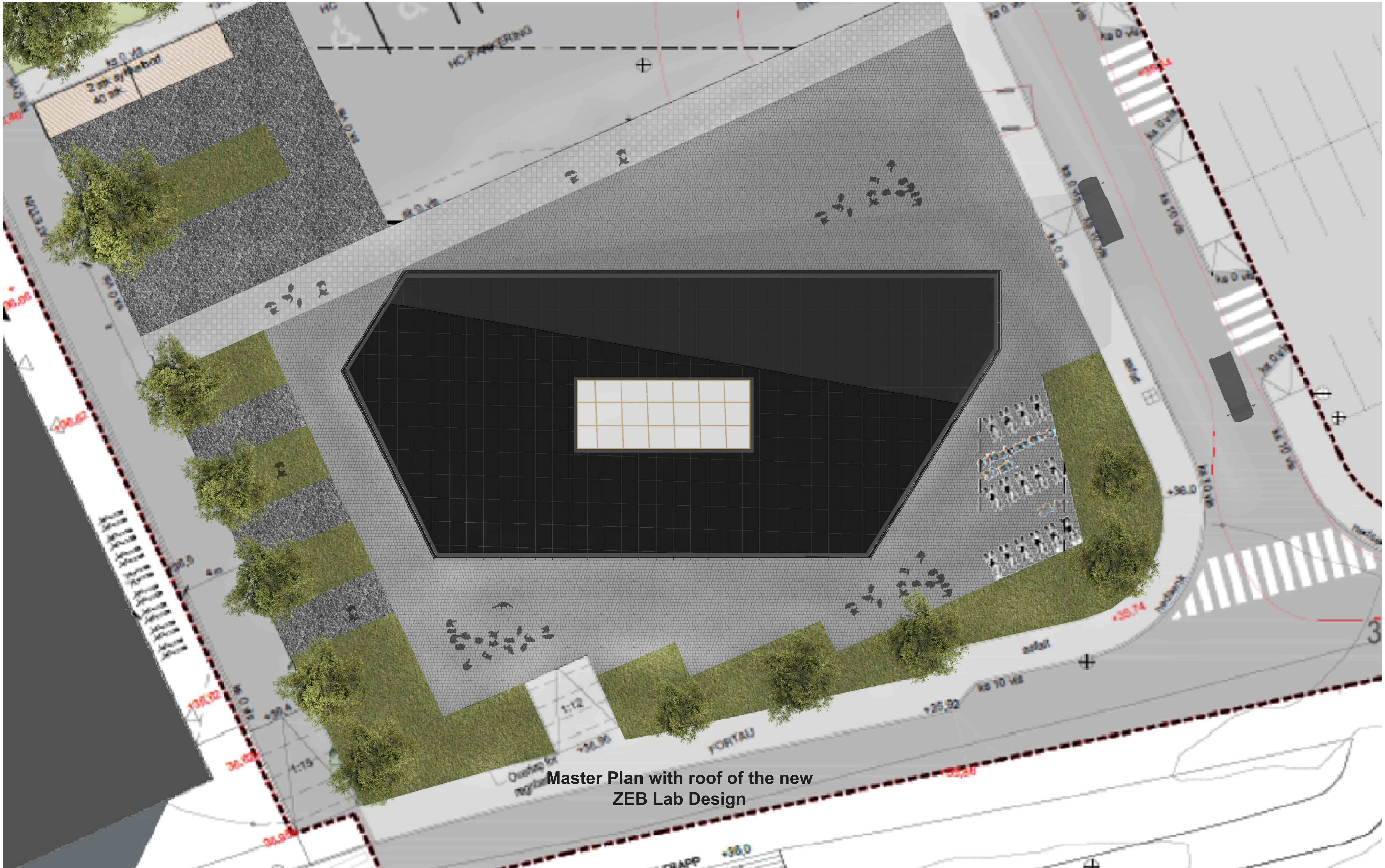
PV Production comparison between the scenarios and original ZEB Lab building

First of all. it is important to mentioned that the roof PV panel with efficiency of 21% and BIPV or facade PV panel with efficiency of 16% are used for the simulation and calculation of the PV production for this comparison. The efficiency of PV is based on "Zeb Flexible Laboratory's rapport"; a report created by Terje Jacobsen and Inger Andresen. The simulations are done by SIMIEN software as well and the input data for this simulation is mainly based on "ZEB flexible lab, Energy concept" by Thomos L.L. Baxter, and Arne Førkand-Larsen. This document was given by Tore Kvande, a project leader of the ZEB Lab building. The different input data in the each simulation are the total facade area, glazing area, tilted angle of roof, tilted PV panel, PV panel coverage area on each facade and roof and the orientation angle of facades based on each building form and design. It is important to note that PV coverage area in this simulation, it is considered the total area after the substraction of glaze or window area from facade area.

Based on the simulation, the original ZEB building has the total PV production of 151MWh which consist of 29MWh for own building's usage and 122MWh for the export to grid. These numbers are used as a reference numbers in this comparison. Scenairo 4 with the tilted roof of 15 degree and scenario 6 with tilted roof of 25 degree and horizontal window design have the lowest total PV production; about 149MWh per year. It is again the scenario 8 with 30 degree tilted roof that has the highest PV production which is about 159MWh per year even surpass of that of the original ZEB Lab building. In term of PV production, Scenario 8 is the most efficient form. However, as has been mentioned, the 30 degree slope roof causes the upper southern part of the building an unusable space where the most solar radiation occur. The second most PV production is scenario 5 which could generate of the total to around 156MWh per year and this number is also surpass the original building. With 25 degree tilted roof design, Scenario 5 creates a fully used space in the upper most soutern part of the buiding. Therefore, the scenario consider the most efficient design for this project.

5. ARCHITECTURAL DRAWING OF THE FINAL PROPOSAL

5.1. FLOOR PLANS



Master Plan with roof of the new
ZEB Lab Design

1 Ground Floor

1 : 100

LEGEND

- Hallway + Eating area + Informal meeting + Break area
- Cleaning Room
- Back Entrance
- Fire Escape Stair
- Technical Room
- Good/Stock Room
- Lift
- W.C
- Warerobes
- Recreation/Social Space
- Main Entrance
- Enclosed Kitchen

Ground floor plan of the new ZEB Lab Design

Ground floor plan of the original ZEB Lab

Level 1
2
1 : 100

LEGEND

- Twin Rooms
- Working Spaces
- Meeting Rooms
- Fire Escape Stair
- Technical Room
- Multi-Room
- Lift
- W.C
- Break Area
- Individual Booths
- Hallway

First floor plan of the new ZEB Lab Design

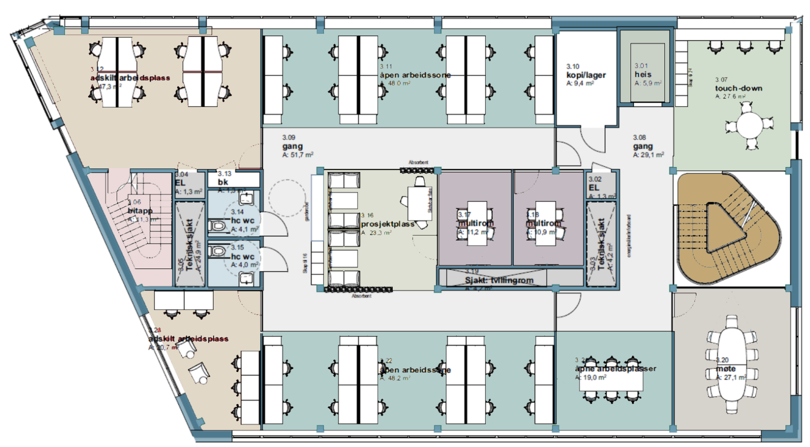
First floor plan of the original ZEB Lab Design

Level 2

1 : 100

LEGEND

- Separated Workspaces
- Open Working Spaces
- Meeting Rooms
- Fire Escape Stair
- Project Space
- Lift
- W.C
- Break Area
- Hallway
- Multi-Room



Second floor plan of the new ZEB Lab Design

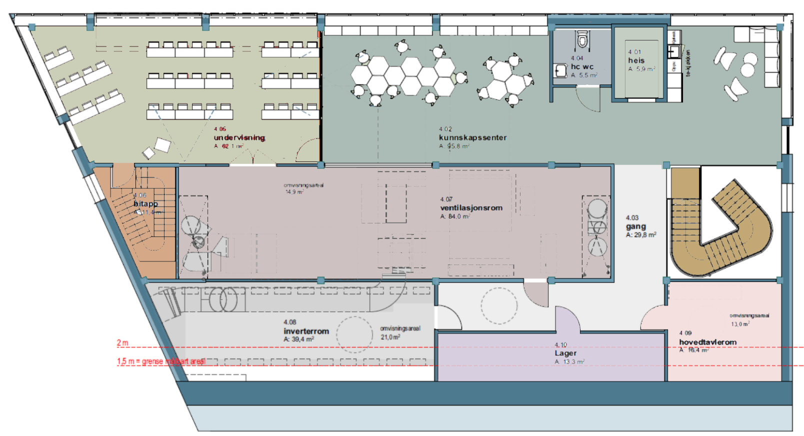
Second floor plan of the original ZEB Lab Design

4 Level 3

1 : 100

LEGEND

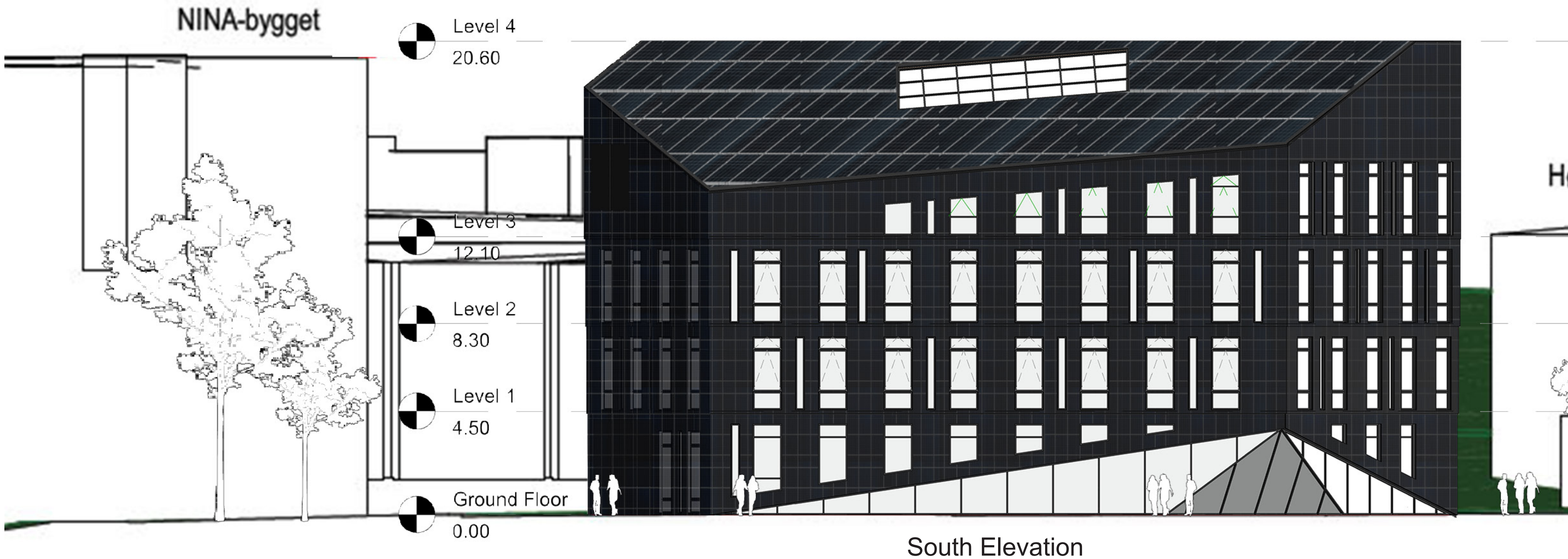
- Knowledge Room + Break Area + smanll pantry
- Lecture Room
- Resting Room
- Fire Escape Stair
- Technical Room
- Lift
- W.C
- Storage Room
- Hallway
- Main Board Room
- Invert room



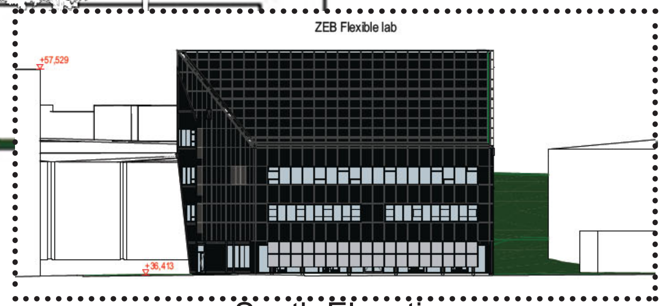
Third floor plan of the new ZEB Lab Design

Third floor plan of the original ZEB Lab Design

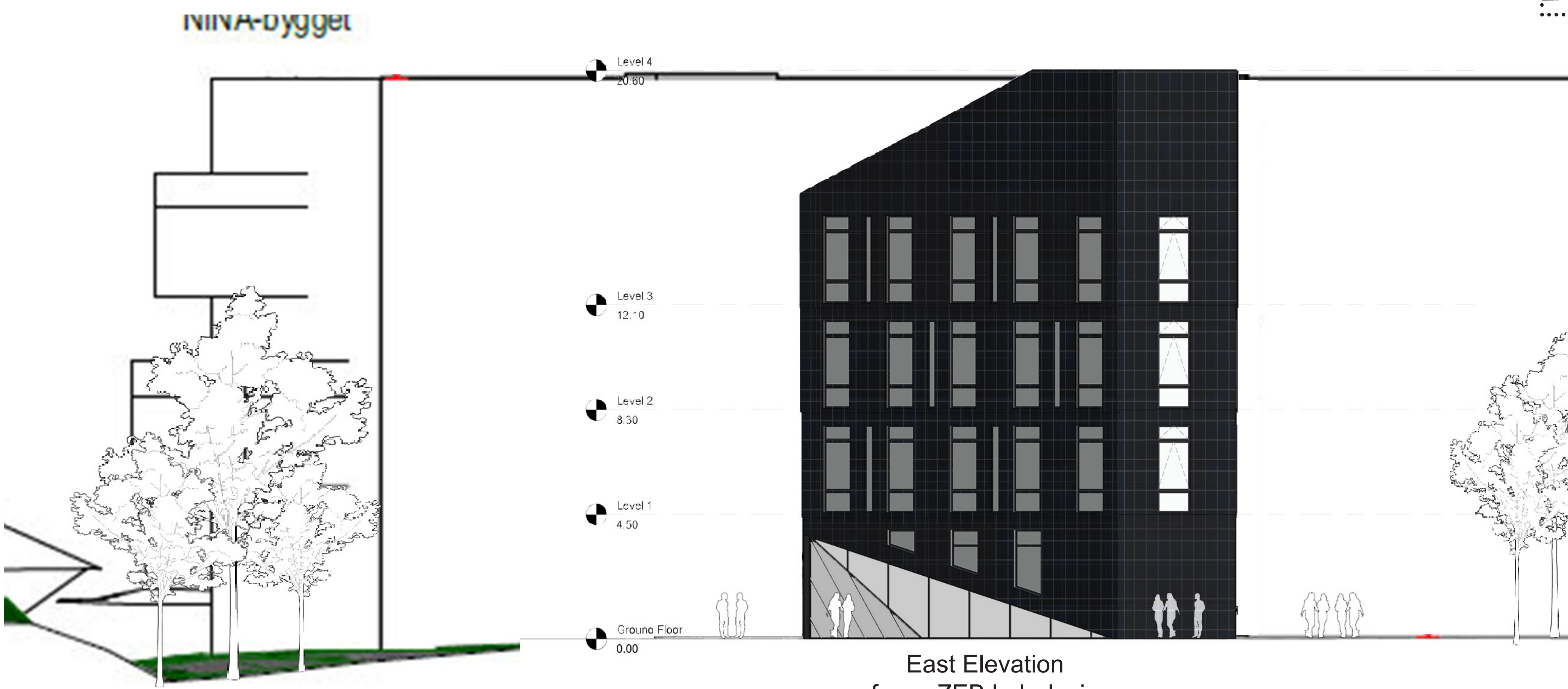
5.2. ELEVATIONS



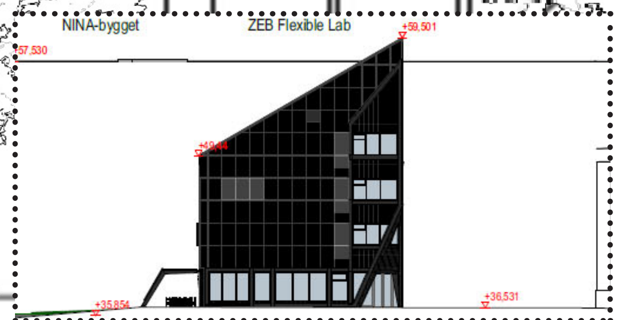
South Elevation
of new ZEB Lab design



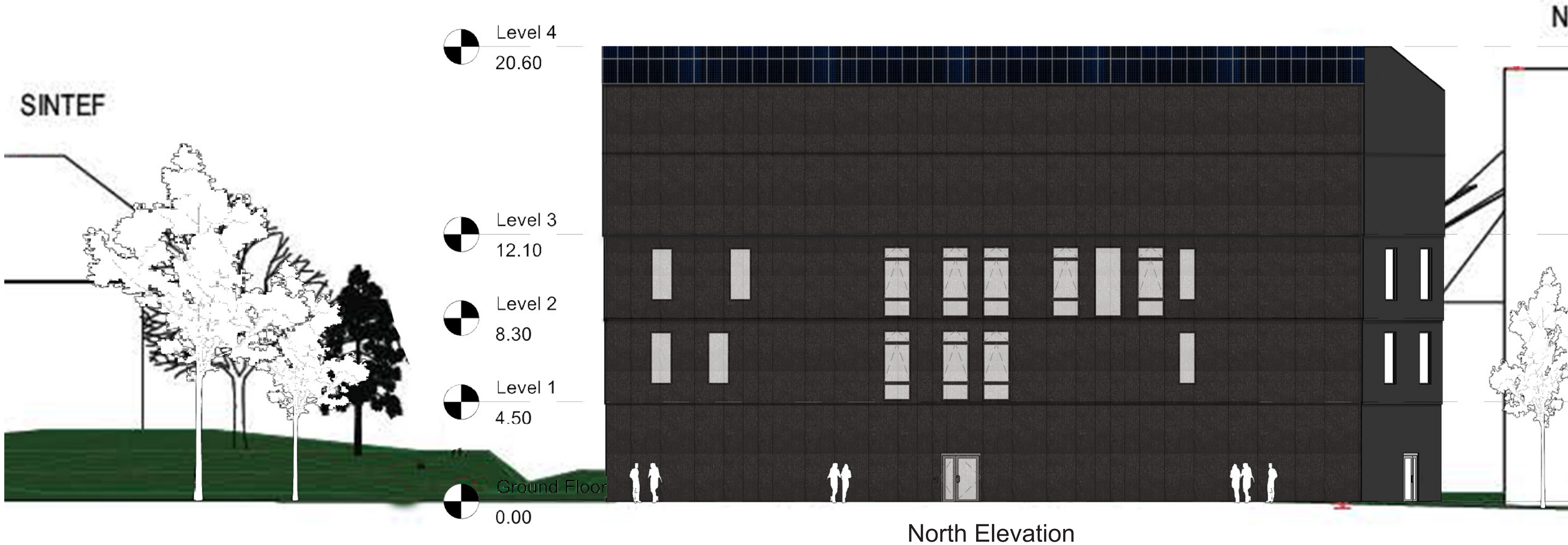
South Elevation
of original ZEB Lab design



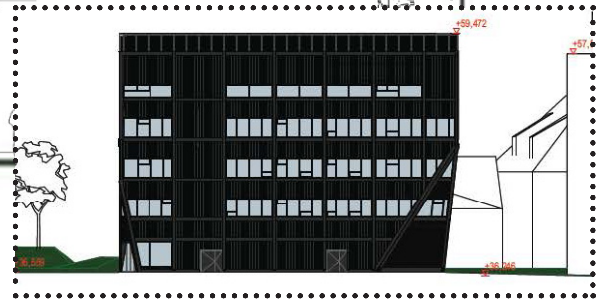
East Elevation
of new ZEB Lab design



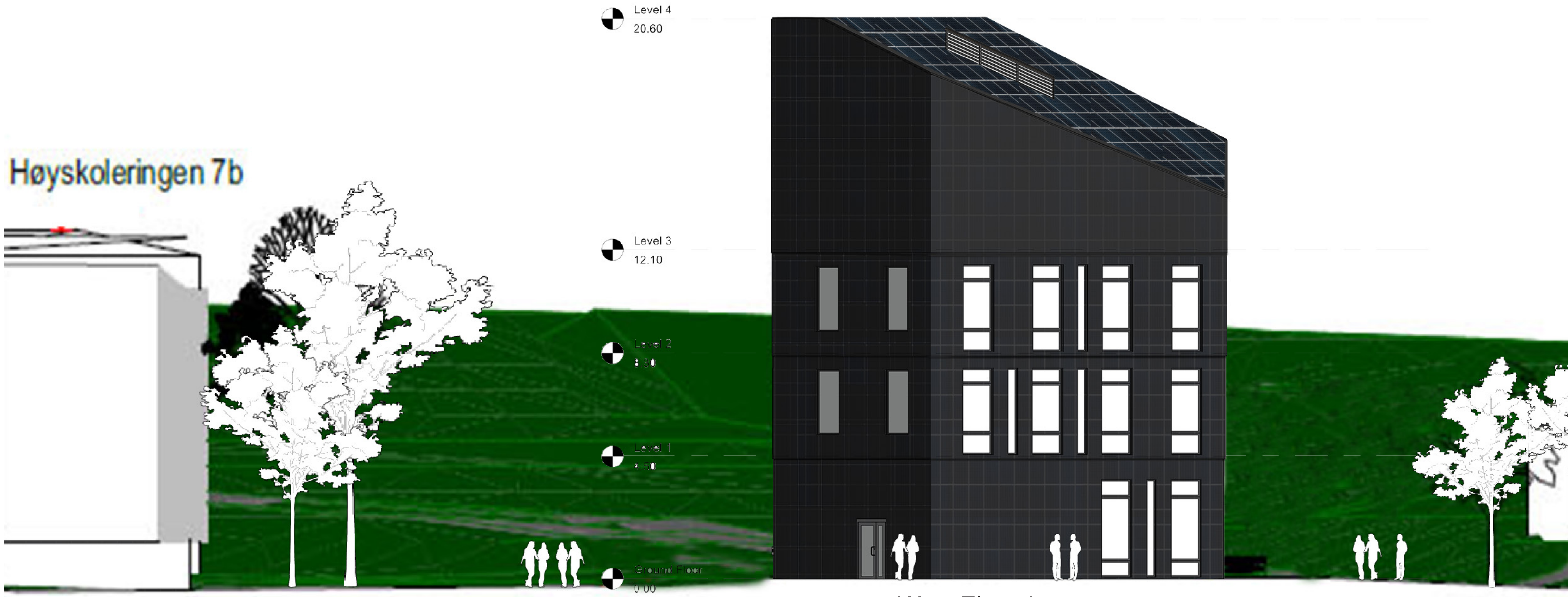
East Elevation
of original ZEB Lab design



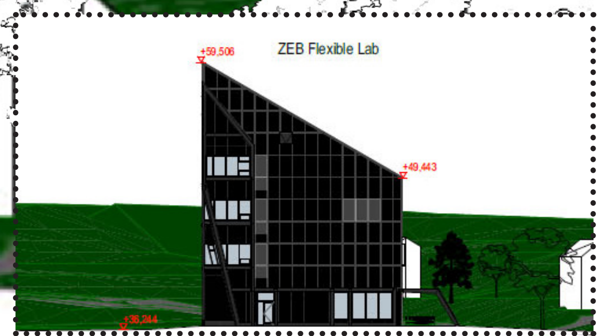
North Elevation
of new ZEB Lab design



North Elevation
of original ZEB Lab design

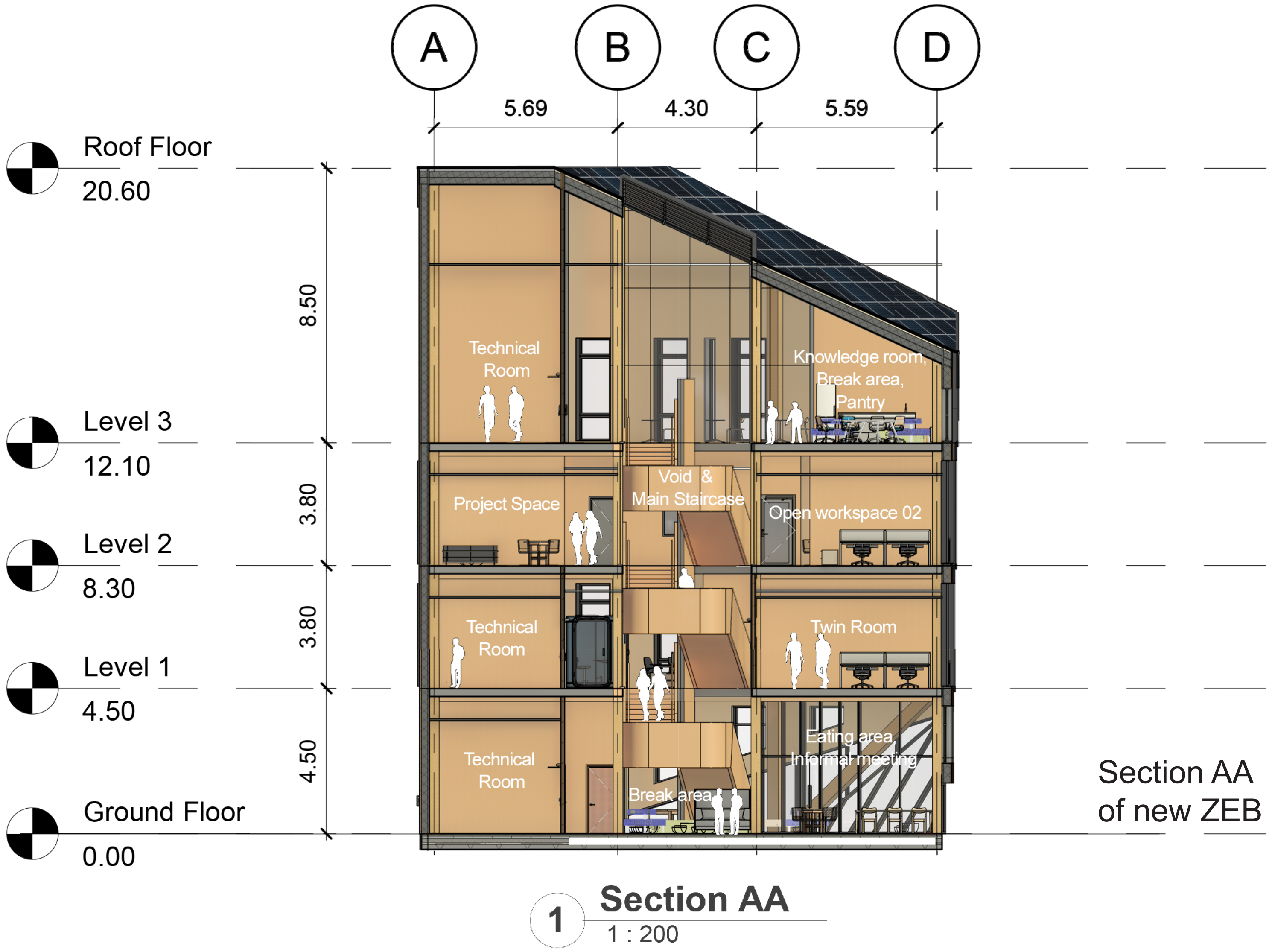


West Elevation
of new ZEB Lab design

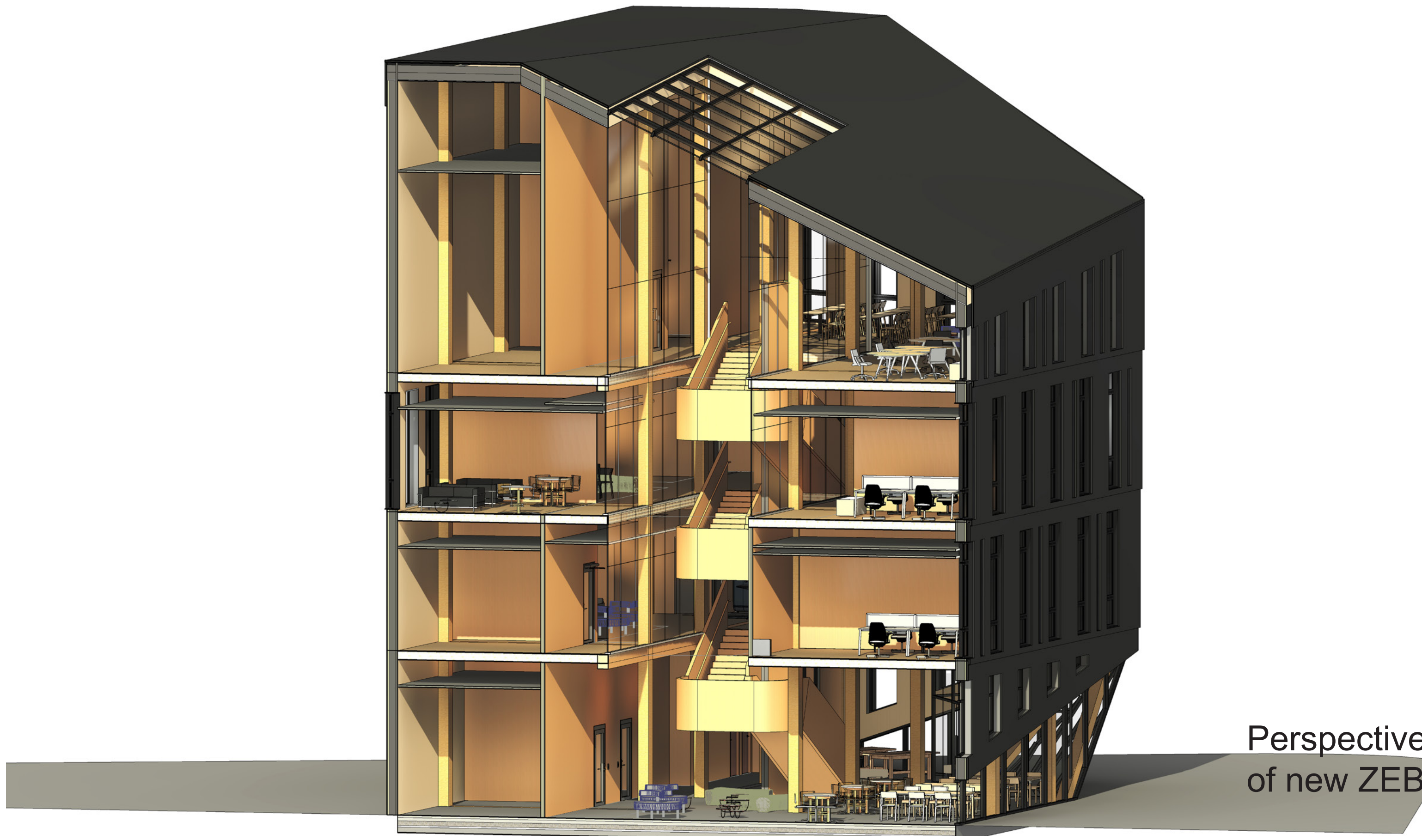


West Elevation
of original ZEB Lab design

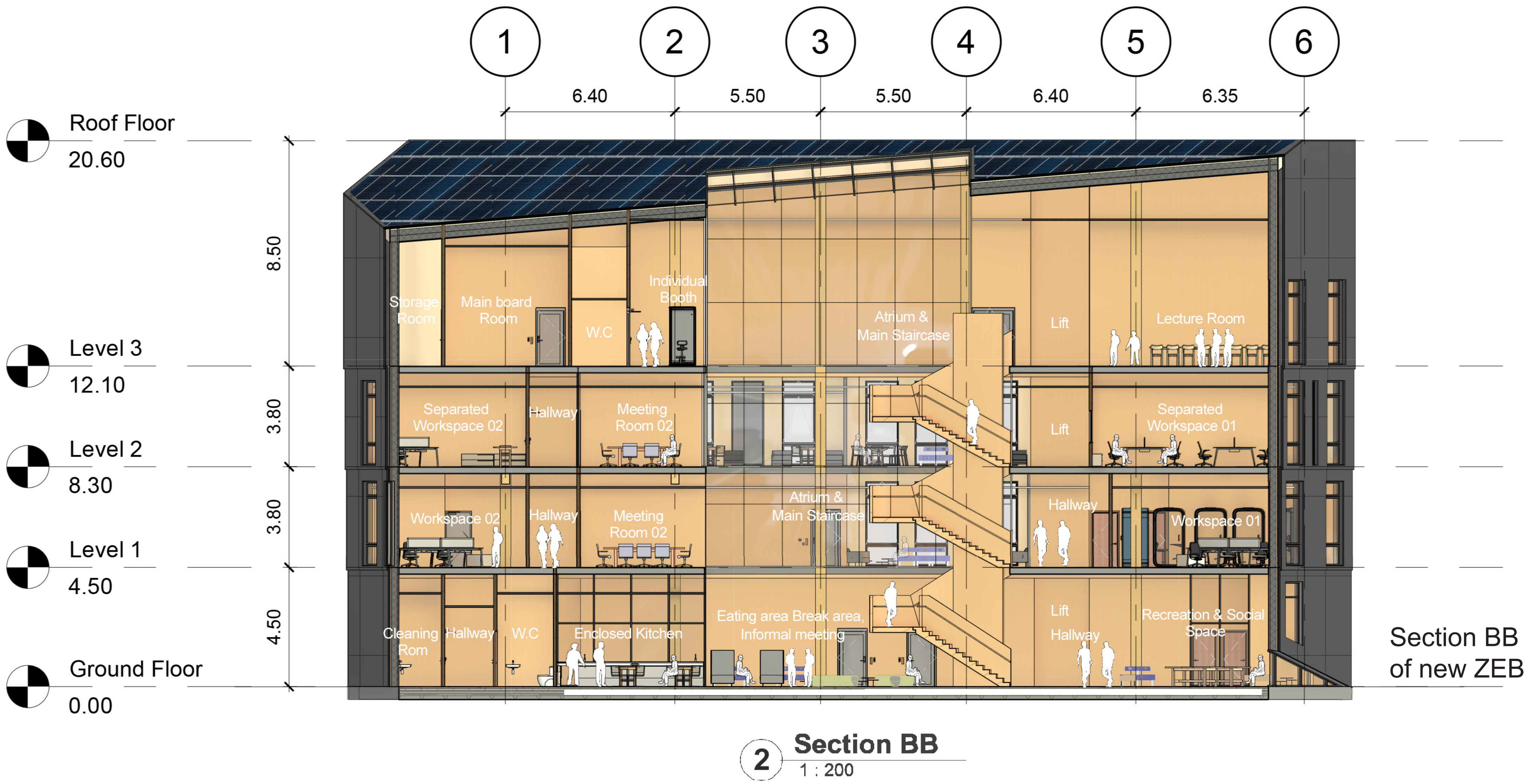
5.3. SECTIONS



Section AA
of new ZEB Lab design

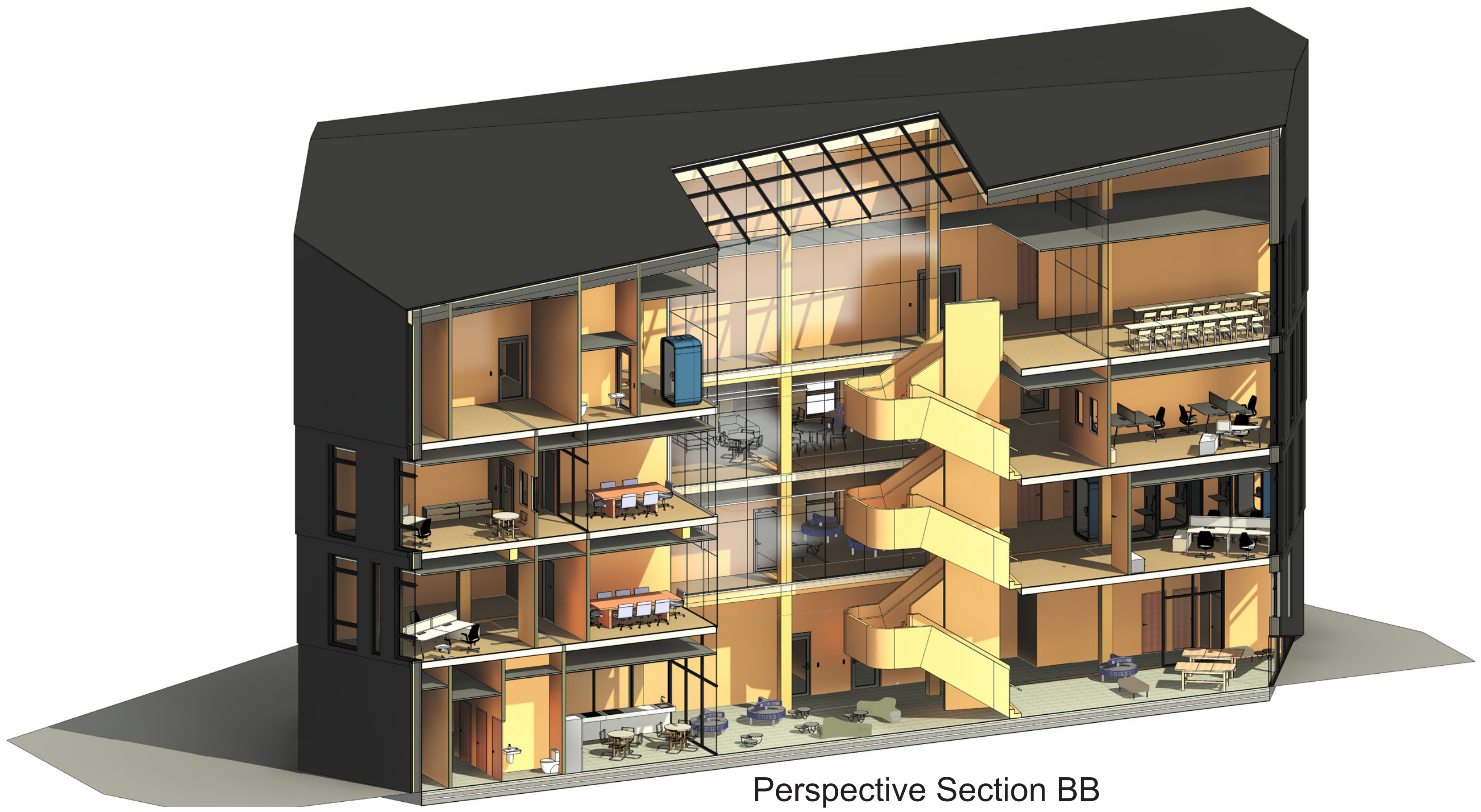


Perspective Section AA
of new ZEB Lab design



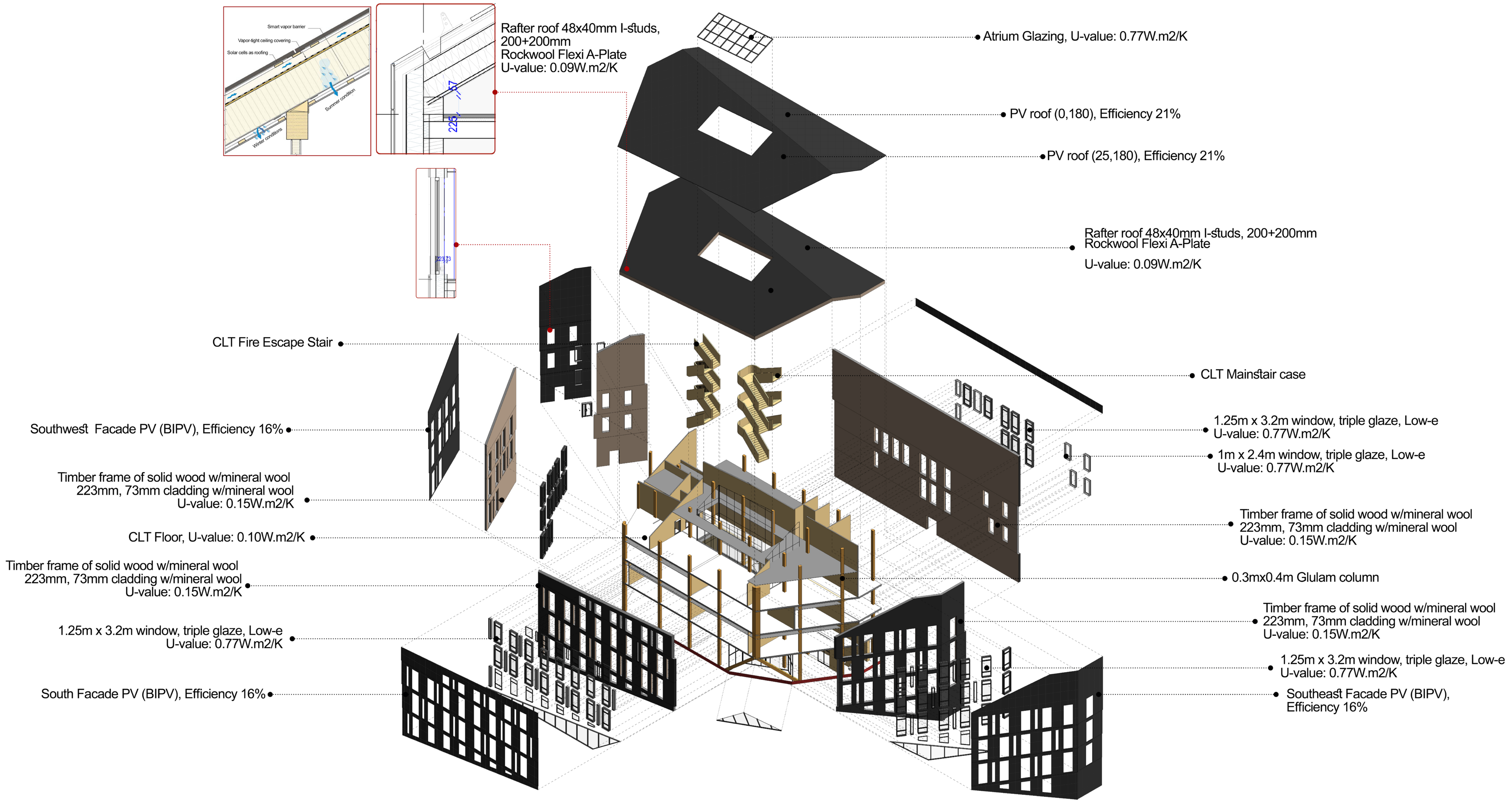
Section BB
of new ZEB Lab design

2 **Section BB**
1 : 200



Perspective Section BB
of new ZEB Lab design

5.4. Visualization of material used and critical details



3D Visualization of material used and critial details of exterior wall and Roof

5.5. Input data for SIMIEN energy simulation of new ZEB Lab design

	TEK17 Minimum requirement	TEK17 Energy Framework	Minimum Passive House	ZEB Lab	New Design ZEB Lab
U-value external walls/façade (W/m².K)	0.22	0.18	0.12	0.15	**0.15**
U-value roof (W/m².K)	0.18	0.13	0.09	0.09	**0.09**
U-value ground slab (W/m².K)	0.18	0.10	0.08	0.10	**0.10**
U-value floor slab (W/m².K)	0.18	0.10	0.08	0.10	**0.10**
U-value windows and doors (W/m².K)	1.20	0.80	0.80	0.77	**0.77**
Building leakage at 50Pa(ACH)*	1.50	0.80	0.60	0.30	**0.30**
Normalised thermal bridge (W/m².K)	–	0.07	0.07	0.04	**0.04**

***ACH = Air change per hour**

Table 1: Design values of building envelope comparison between TEK17, Passive House, ZEB Lab and new ZEB Lab

Net Energy need per purpose	TEK17 evaluation	ZEB Lab	New Design ZEB Lab
Lighting (kWh/m².year)	25	**7.5**	
Technical equipment (kWh/m².year)	34	**10**	
Domestic hot water (kWh/m².year)	5	**1**	
Total (kWh/m².year)	64	**18.5**	

Table 2: Standard net energy need for lighting, technical equipment and DHW from NS 3031:2014 used for TEK 17 evaluation, compared to design values for ZEB Lab and new ZEB Lab design

	Electricity	District Heating	Heat pump	Solar	Biofuel	Gas
Room Heating	0	2	98	0	0	0
Tap water***	35	0	65	0	0	0
Ventilation Heating	0	0	100	0	0	0
Ventilation Cooling	100*	0	0	100**	0	0
Room cooling	100*	0	0	100**	0	0
Electricity-specific enery needs	100	0	0	100**	0	0

*Cooling is not used in the calculation, this is only entered in the table since the calculation program requires that the coverage ratio is distributed, regardless of whether it is used or not.

**Total electricity use on the building is covered by solar power production on the building. Electricity use is balanced over the entire year. Energy production also compensates for greenhouse gas emissions for construction and materials (which is the minimum) a degree of coverage of 58% is obtained, with a condensation temperature of 47 (which is a maximum) a degree of coverage of 70% is obtained. In practical operation it will vary. An estimated average value of 65% has been entered here.

Table 3: Coverage of energy requirements in % of ZEB Lab and new ZEB Lab design based on the "ZEB Flexible energy concept report"

Input data for Simens Energy Simulation Software of New Design ZEB Lab		
		Input
Area (m²)	Exterior walls	1462
	Roof	564
	Floor	519
	Window, doors and glass panels	292
Heated floor area BRA [m²]		1907
Heated air volume [m3]		7144
U-value for building parts	Exterior walls	0.15
	Roof	0.09
	Floor	0.10
	Window, doors and glass panels	0.77
Normalized cold bridge value [W/m²k]		0.04
Normalized heat capacity [Wh/m²]		81
Building Leakage		0
Temperature efficiency for heat recovery [%]		84
Estimated year average temperature efficiency for heat recovery due to frost protection		84
Specific fan power (SFP) related to air volumes during operating time [kW/m3/s]		1
Specific fan power (SFP) related to air volumes outside operating time [kW/m3/s]		0.50
Average specific ventilation air volume during operating time(Von/Afl) [m3/m²h]		6
Specific amount of ventilation air outside operating hours (Vred/Afl) [m3/m²h]		1
Annual average (VP//EL/FJV) system efficiency / heating factor for the heating system [%]		3
Annual average (VP/EL/FJV) system efficiency / heat factor for heating hot tap water[%]		3.33
Installed power for room heating and ventilation heating (heating coil) [W/m²]		160
Setpoint temperatures for heating [ºC]		19
Annual average cooling factor for the cooling system [%]		2.50
Setpoint temperatures for cooling [ºC]		22
Installed power for room cooling and ventilation cooling[W/m²]		0
Specific pump power (SPP)[kW/ls]		0.50
Operating time for ventilation, heating, cooling, lighting, equipment, hot water and people		12/12/24 12/12/24 12/12/12
Specific power requirements for lighting during operating time[W/m²]		2.40
Specific heat supplement from lighting during operation(q"lys) [W/m²]		2.40
Specific power requirements for equipment during operating time [W/m²]		3.20
Specific heat supplement from equipment during operation (q"uts) [W/m2]		3.20
Specific energy consumption for hot water during operating time(q"w) [kWh/m²år]		1
Heat supplement from hot water during operation [W/m2]		0
Heat supplement from persons (q "pers) during operating time [W/m2]		4
Total sun factor (gt) or window and sun protection(E/S/W/N)		0.31
Average frame factor(FF)		0.20
Sun protection factor due to horizon, nearby buildings, vegetation and possible building origins (N/E/S/W)		0.74/0.95/ 0.97/0.95

Table 4: Documentation of key inputs for the energy calculation of new ZEB Lab design mainly based on the "ZEB Flexible energy concept report"

6. FINAL RESULT AND COMPARISON WITH ORIGINAL

6.1. FINAL SOLAR RADIATION OF THE PROPOSAL COMPARE WITH ORIGINAL

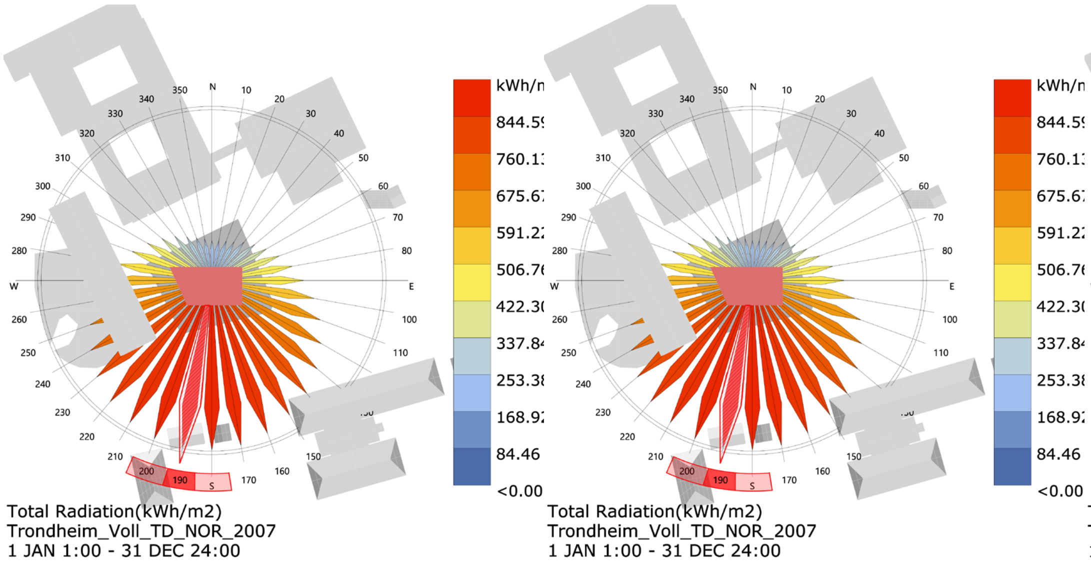


Figure 30: Annual and winter Radiation rose of trondheim with ZEB Lab form
Original ZEB Lab Building

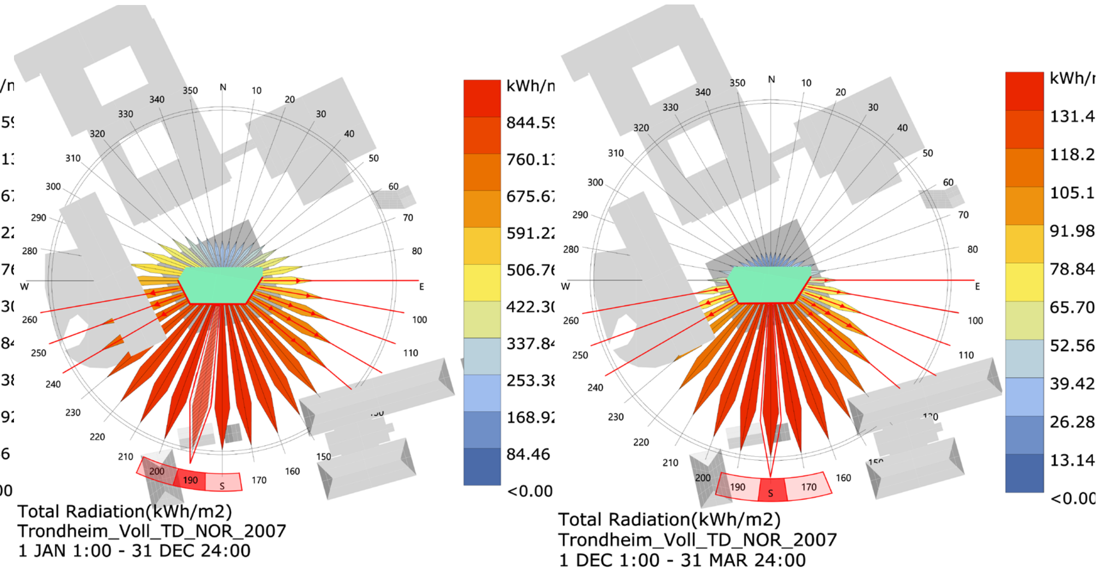


Figure 31: Annual and winter Radiation rose of trondheim with ZEB Lab
New ZEB Lab Design

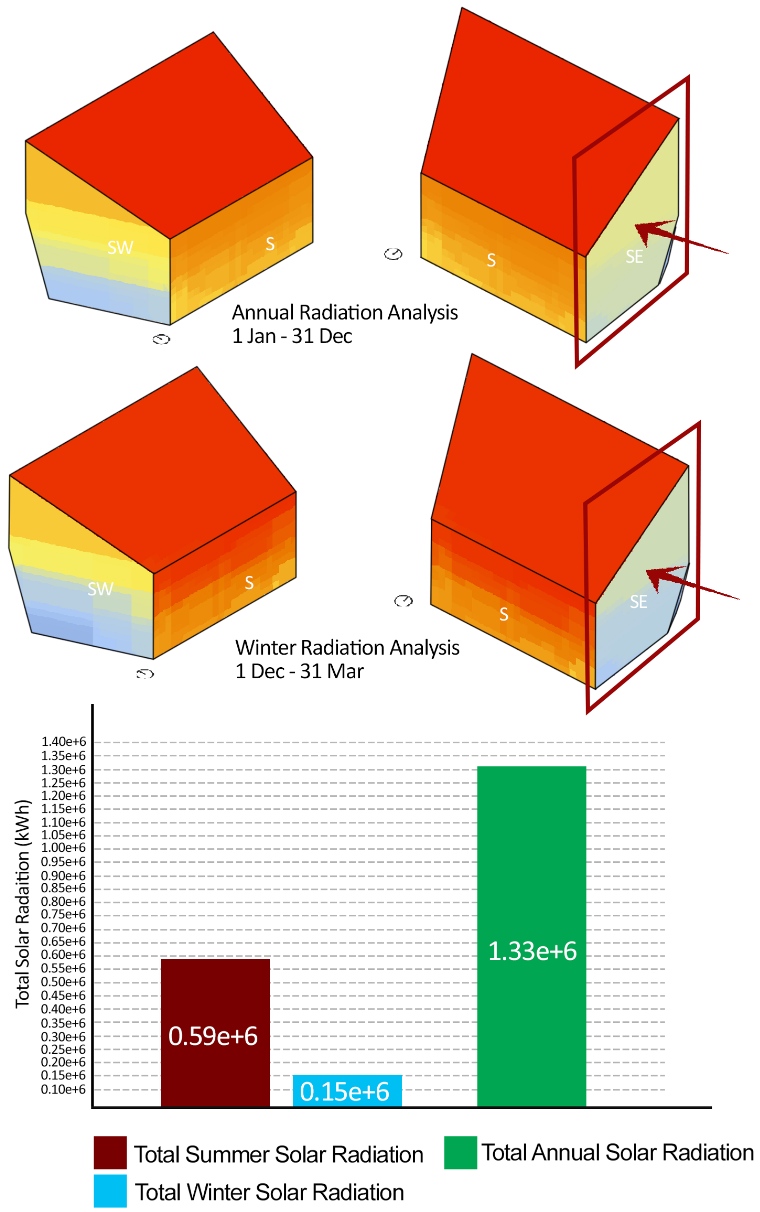


Figure 32: Solar radiation analysis and the result of the ZEB Lab

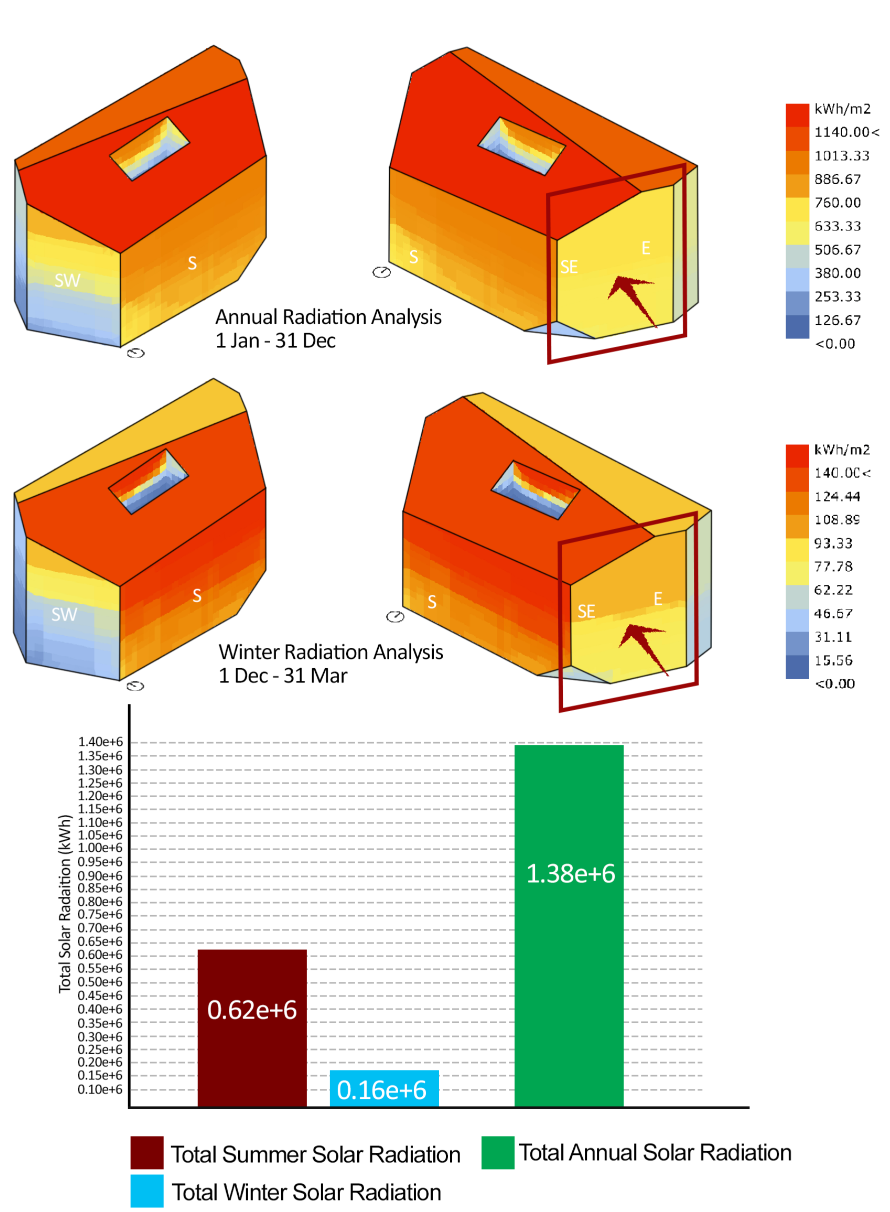


Figure 33: Solar radiation analysis and the result of the new ZEB Lab design

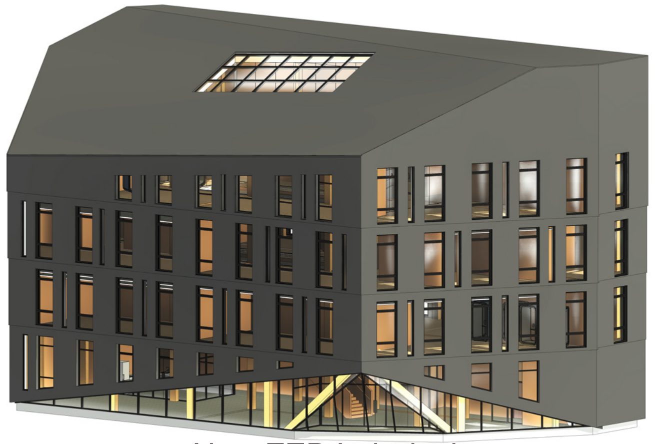
As could be seen from the figure 32, and 33, there is great improvement of the radiation for the new design form within the whole year and especially during the winter period.

This final form has the facade spread open toward southeast and southwest and the south facade are strengthen longer than the original to collect all the possible solar radiation for the passive solar heat gain. From figure 33, we could see that in the southeast facade of the new ZEB Lab building has a remarkable radiation occur there even during winter period while the east of the original ZEB Lab as shown in figure 32 could recieve a very less radiation especially in winter period.
This solar radiation adaptive form would maximize the passive solar heat gain leading to lower heating demand and the total energy's consumption of the building.

The total annaul radiation of the original building is around 1.33e+6kWh while the new design ZEB Lab has the total radiation up tp 1.38e+6kWh. This indicates a huge difference between the two design.

6.2. FINAL ENERGY SIMULATION OF THE PROPOSAL COMPARE WITH ORIGINAL

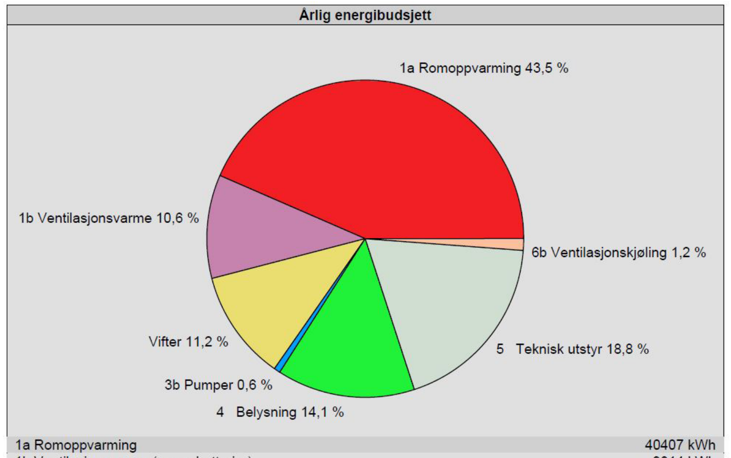
Original ZEB Lab building



New ZEB Lab design

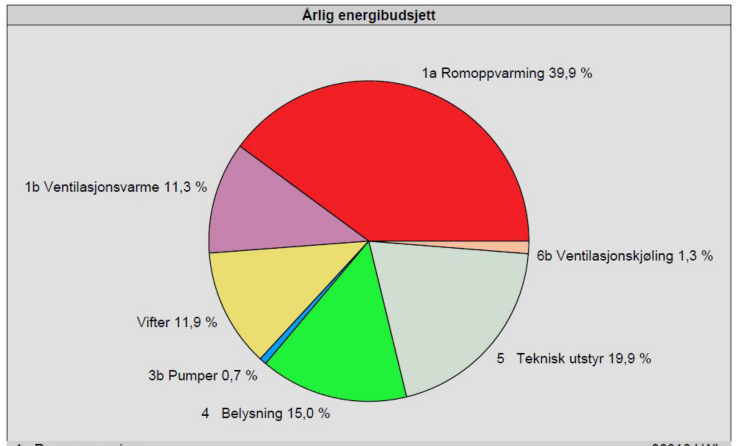
In this section, the energy simulation result of the original and the new ZEB Lab design are compared. The result of this energy simulation include the energy budget, the net delivery energy and the total emission in the operational stage of the two building design.

Energy Budget



1a Romoppvarming	40407 kWh
1b Ventilasjonsvarme (varmebatterier)	9814 kWh
2 Varmtvann (tappevann)	0 kWh
3a Vifter	10454 kWh
3b Pumper	595 kWh
4 Belysning	13093 kWh
5 Teknisk utstyr	17461 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	1102 kWh
Totalt netto energibehov, sum 1-6	92926 kWh

Figure 34: Pie chart of total energy budget of ZEB Lab building



1a Romoppvarming	36616 kWh
1b Ventilasjonsvarme (varmebatterier)	10362 kWh
2 Varmtvann (tappevann)	0 kWh
3a Vifter	10951 kWh
3b Pumper	655 kWh
4 Belysning	13718 kWh
5 Teknisk utstyr	18291 kWh
6a Romkjøling	0 kWh
6b Ventilasjonskjøling (kjølebatterier)	1154 kWh
Totalt netto energibehov, sum 1-6	91747 kWh

Figure 35: Pie chart of total energy budget of ZEB Lab building

From the pie chart show in figure 34 and 35, it is noticed that the percentage of energy demand needed for the room heating in the new ZEB Lab design is less than that of the original building. The original building need 43.5% of the energy demand for the room heating alone, yet the new ZEB Lab design only require 39.9%. Also, if we look that the bar chart of the specific energy budget in figure 36 and 37, the specific energy budget for room heating is only 20.1kWh/m² for new design building while the original ZEB Lab building required 23.2kWh/m².

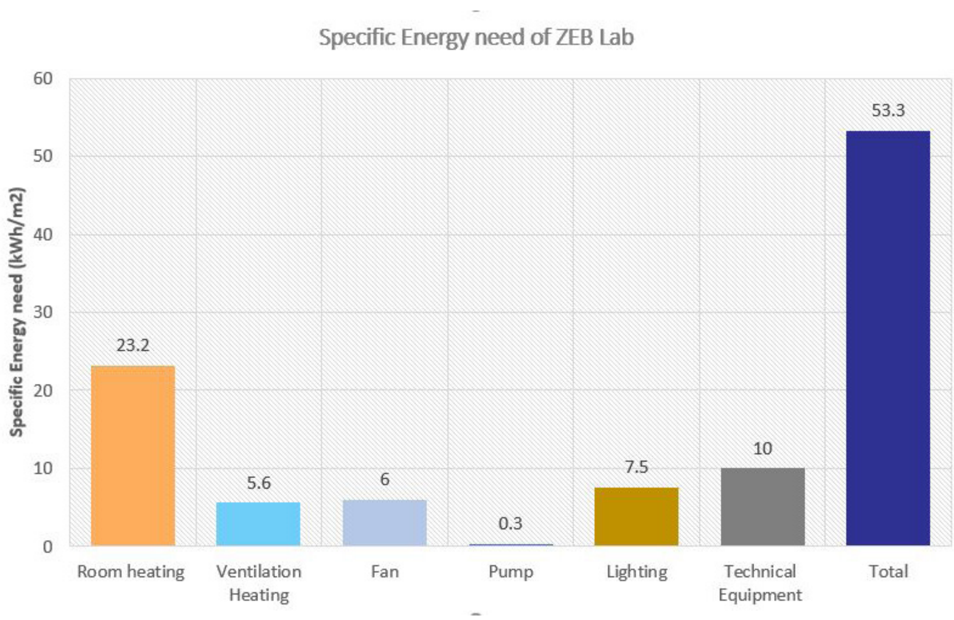


Figure 36: Bar chart of net specific energy budget of ZEB Lab building

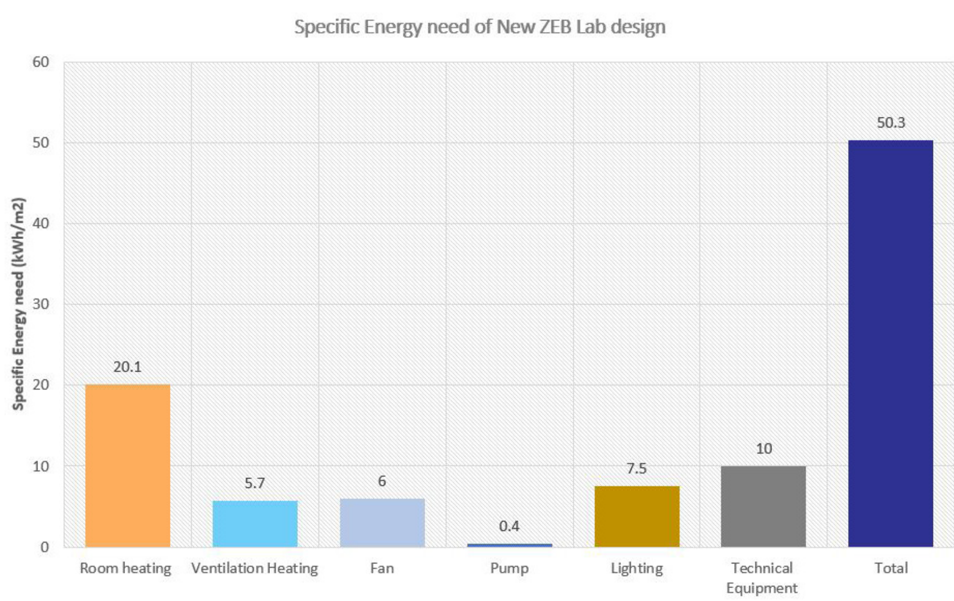


Figure 37: Bar chart of net specific energy budget of new ZEB Lab design

The result of energy budget indicates that passive solar heat gain adaptive form help diminish a certain amount of the heating demand of the building as has been predicted since the radiation analysis. This reduction of the heating demand would play an important role in the operation emission calculation and that is one of the stepping stone toward to goal of ZEB-COM level.

Delivery Energy

Original ZEB Lab building

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	42044 kWh	24,1 kWh/m²
1b El. til varmepumpesystem	19838 kWh	11,4 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	975 kWh	0,6 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-29368 kWh	-16,9 kWh/m²
Totalt levert energi, sum 1-7	33489 kWh	19,2 kWh/m²
Solstrøm til eksport	-121590 kWh	-69,8 kWh/m²
Netto levert energi	-88101 kWh	-50,6 kWh/m²

Figure 38: Table of net delivery energy of ZEB Lab building from SIMIEN software

New ZEB Lab design

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	44077 kWh	24,2 kWh/m²
1b El. til varmepumpesystem	18505 kWh	10,1 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	883 kWh	0,5 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-30962 kWh	-17,0 kWh/m²
Totalt levert energi, sum 1-7	32503 kWh	17,8 kWh/m²
Solstrøm til eksport	-124914 kWh	-68,4 kWh/m²
Netto levert energi	-92411 kWh	-50,6 kWh/m²

Figure 39: Table of net delivery energy of new ZEB Lab design from SIMIEN software

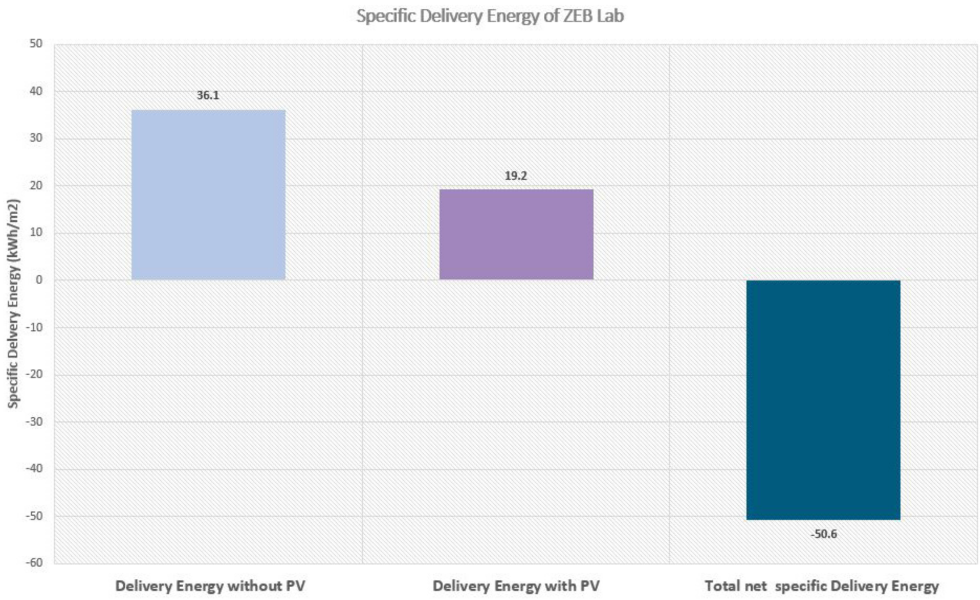


Figure 40: Bar chart of specific delivery energy of ZEB Lab building Retrieve from SIMIEN result

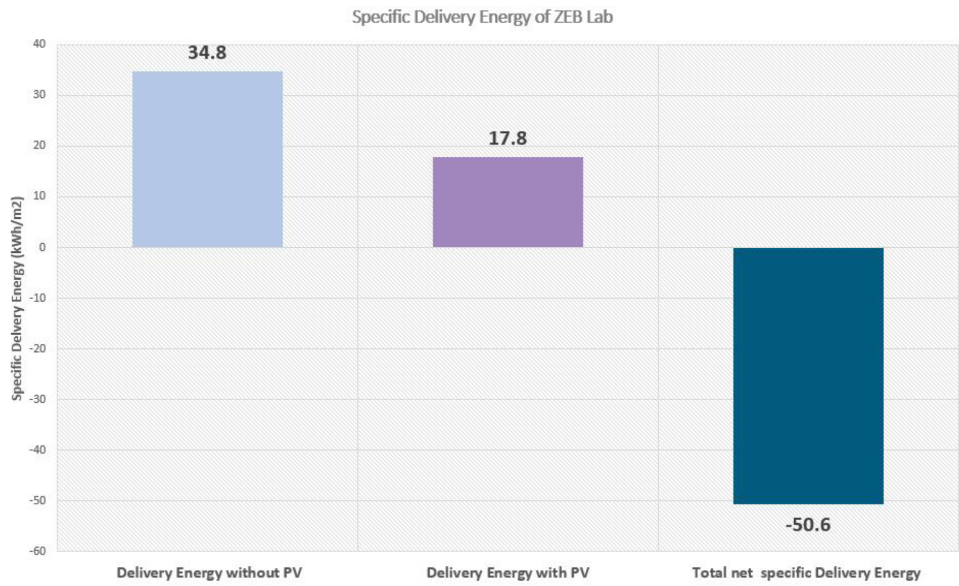


Figure 41: Bar chart of specific delivery energy of new ZEB Lab design Retrieve from SIMIEN result

Operational CO2 Emission

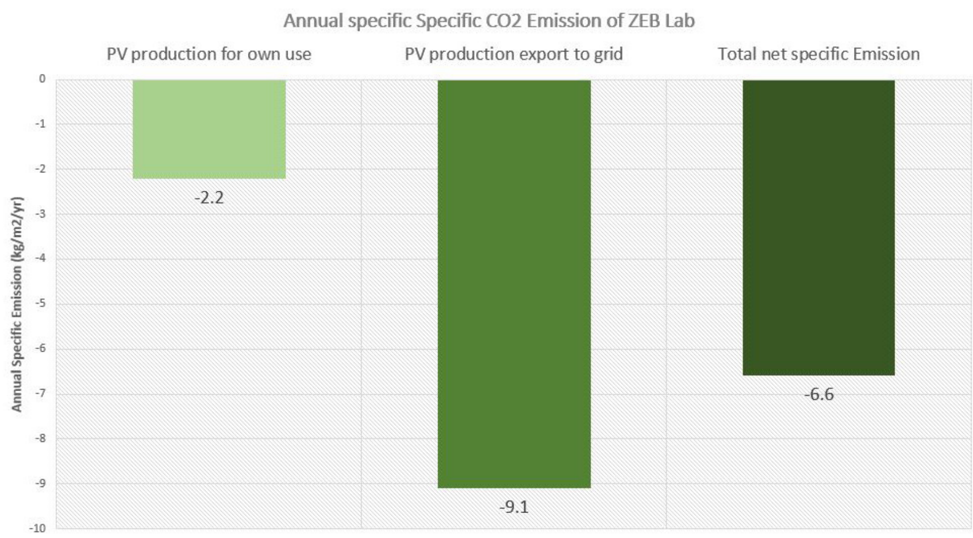


Figure 42: Bar chart of annual specific CO2 emission of ZEB Lab building Retrieve from SIMIEN result

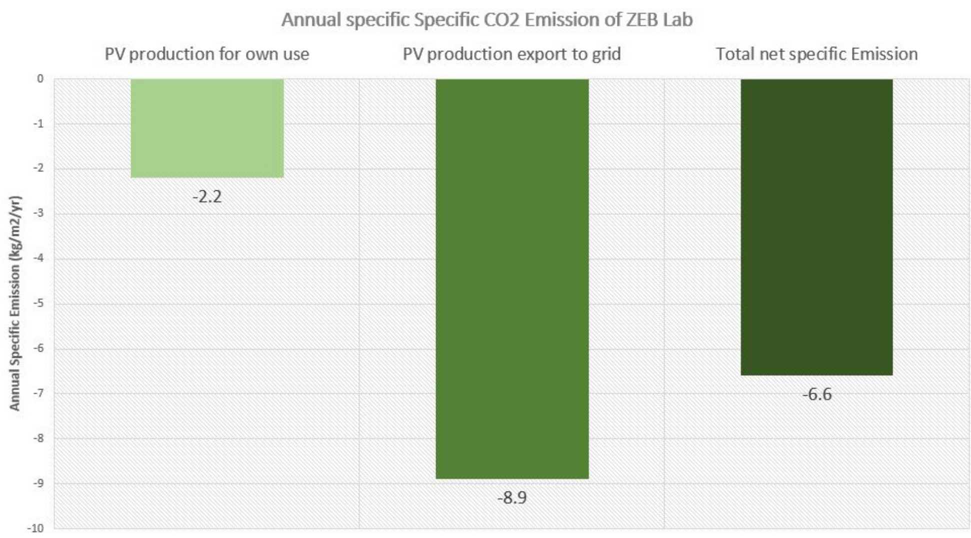


Figure 43: Bar chart of annual specific CO2 emission of new ZEB Lab design Retrieve from SIMIEN result

It is important to note once again that to create an effective and fair comparison between the new design form and original building, I and my teammate, Alisher who has a similar topic on this ZEB Lab building create our simulation of the original building mainly based on the report of "ZEB Flexible Lab, energy concept". Our simulation result of original building appeared to be better in number compare to those in the report and all the energy simulation results of both original ZEB Lab building and new ZEB Lab design in this whole section 4.2 are our own result from SIMIEN software.

We could see the result of the final form of the new ZEB lab design appear to be much better compare with the test form that has been done previously. The reason of that is because of the precise data input of the final form collected from the modeling software (Revit), for example heated floor area, and there is some adjustment of the other input based on the ZEB flexible report.

Surprisingly, the result of the net delivery energy of both building design include the pv proudction appear to be the same which is about -50.6kWh/m². This result of delivery energy lead to an identical result of operational carbon emission for both building which is about -6.6kg/m2/yr.

6.3. FINAL PV PRODUCTION OF THE PROPOSAL COMPARE WITH ORIGINAL

Original ZEB Lab building

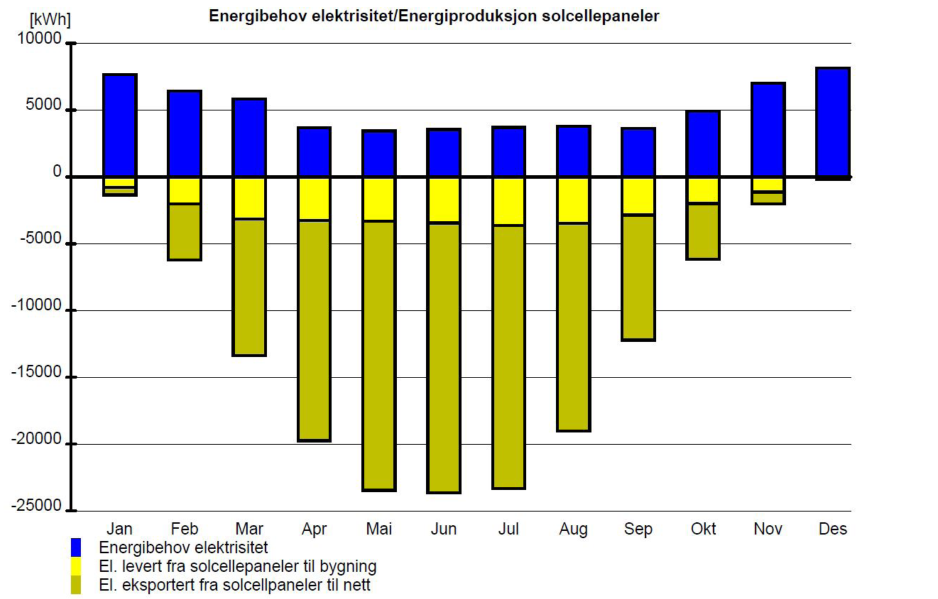


Figure 44: Bar chart of monthly energy need electricity and PV production of ZEB Lab building, result from SIMIEN software

New ZEB Lab design

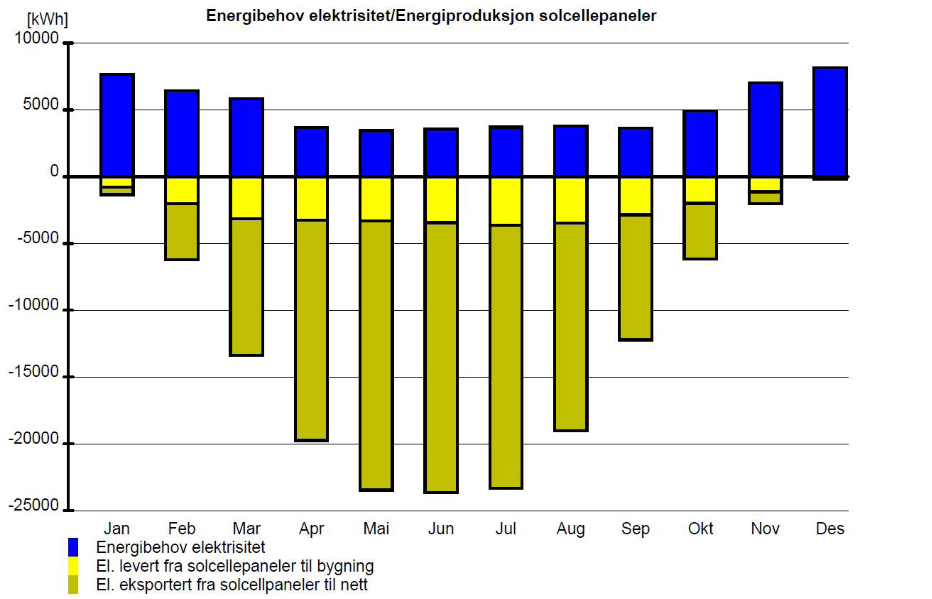


Figure 45: Bar chart of monthly energy need electricity and PV production of new ZEB Lab design, result from SIMIEN software

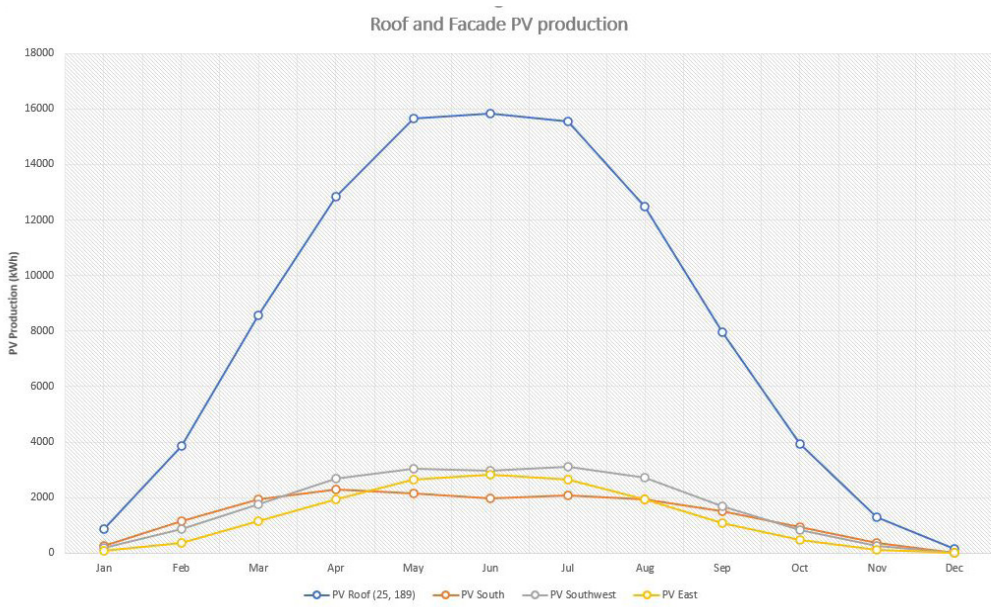


Figure 46: Roof and facade PV production of ZEB Lab building (monthly)

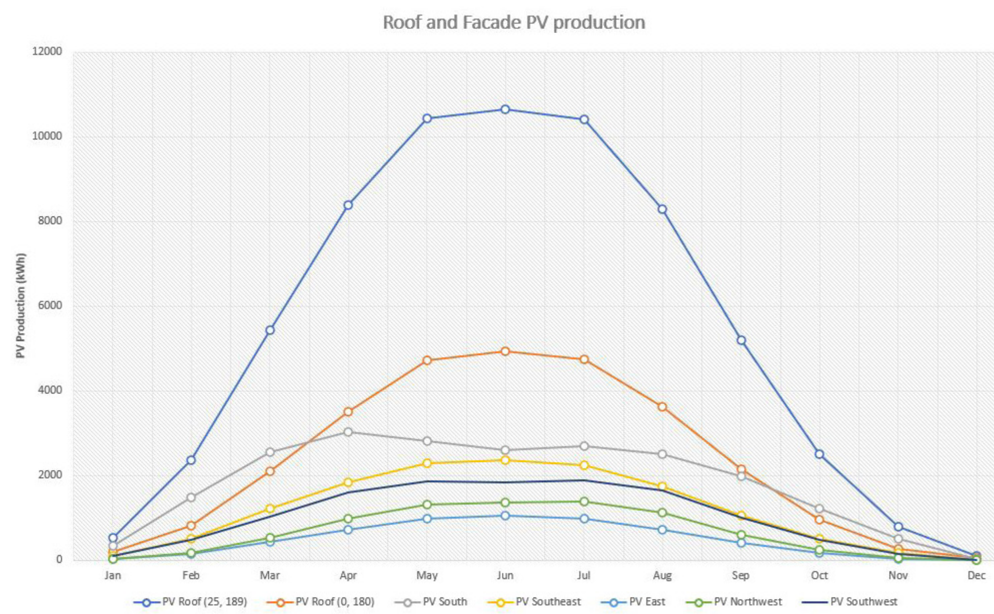


Figure 47: Roof and facade PV production of ZEB Lab building (monthly)

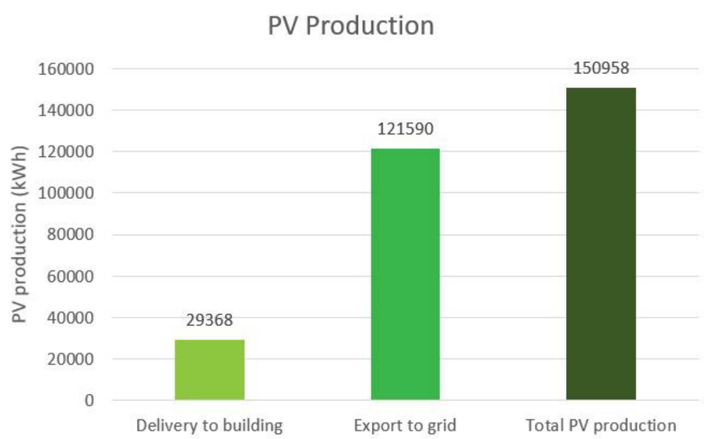


Figure 48: Total PV production of ZEB Lab building

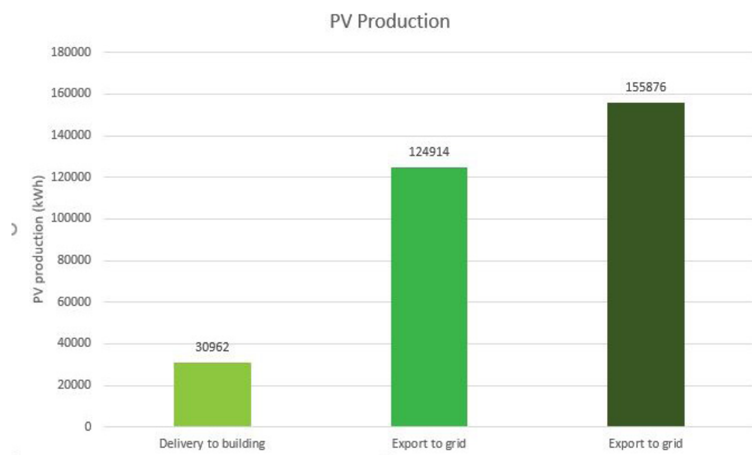


Figure 49: Total PV production of new ZEB Lab design

In this section, the PV production of the original ZEB Lab building and the new ZEB Lab design are compared. The result of this PV production was also taken from the simulation done by SIMIEN software. it is important to mentioned that the roof PV panel with efficiency of 21% and BIPV or facade PV panel with efficiency of 16% are used for the simulation and calculation of the PV production for this comparison. The efficiency of PV is based on "Zeb Flexible Laboratory's rapport"; a report created by Terje Jacobsen and Inger Andresen. It is aslo important to note that PV coverage area in this simulation is considered the total area after the substraction of glaze or window area from facade area.

It could be seen from figure 4.#, amd 4.# that the new ZEB Lab design has the highest number of the production which is equal to around 156MWh. Within that 125MWh are the export to the grid and around 31MWh are delivered for own used. Whereas original ZEB building has the total PV production of 151MWh which consist of 29MWh for own building's usage and 122MWh for the export to grid.

6.4. FINAL DAYLIGHTING OF THE PROPOSAL

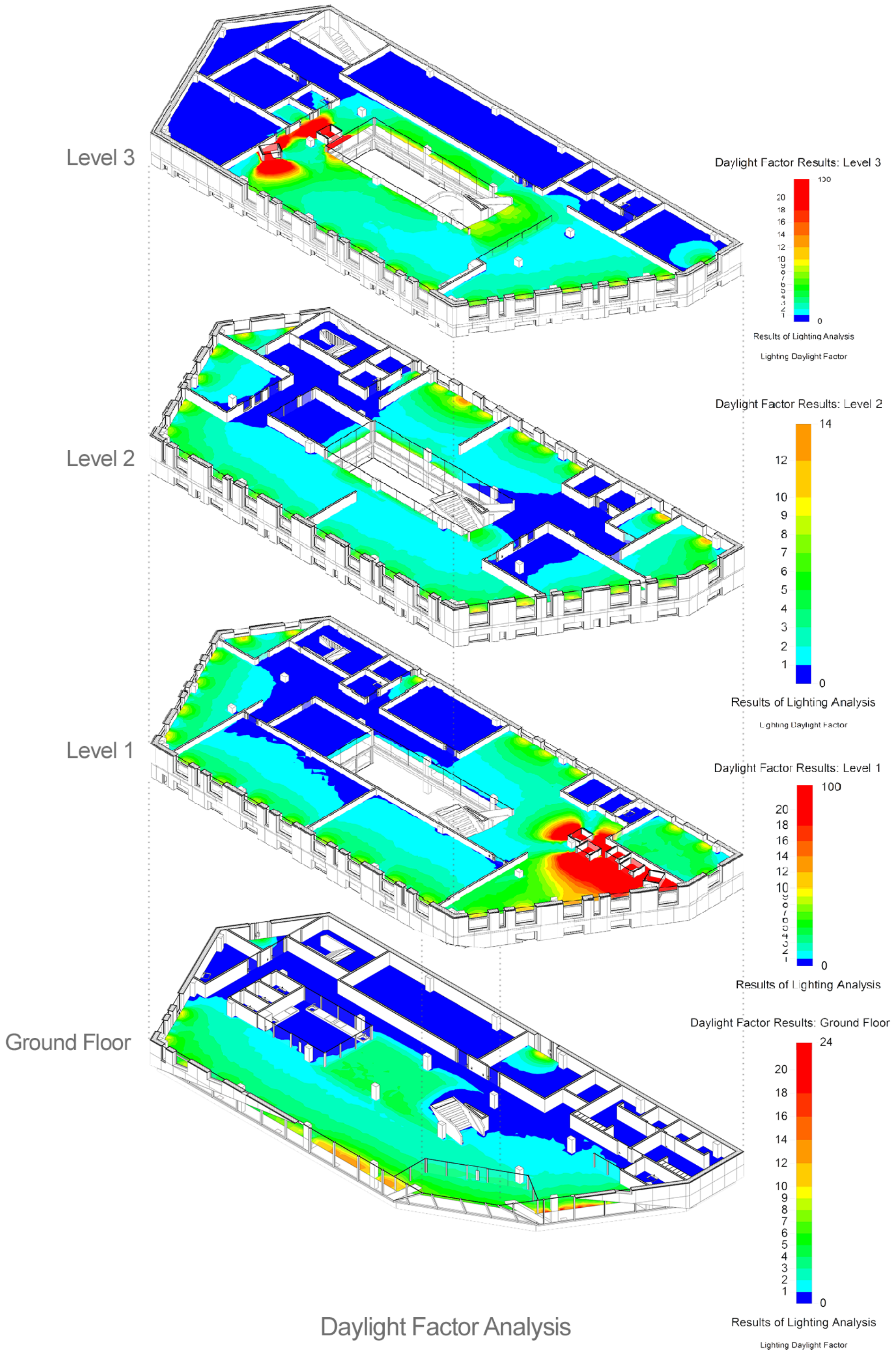


Figure 50: Daylight Factor analysis of the new ZEB Lab design

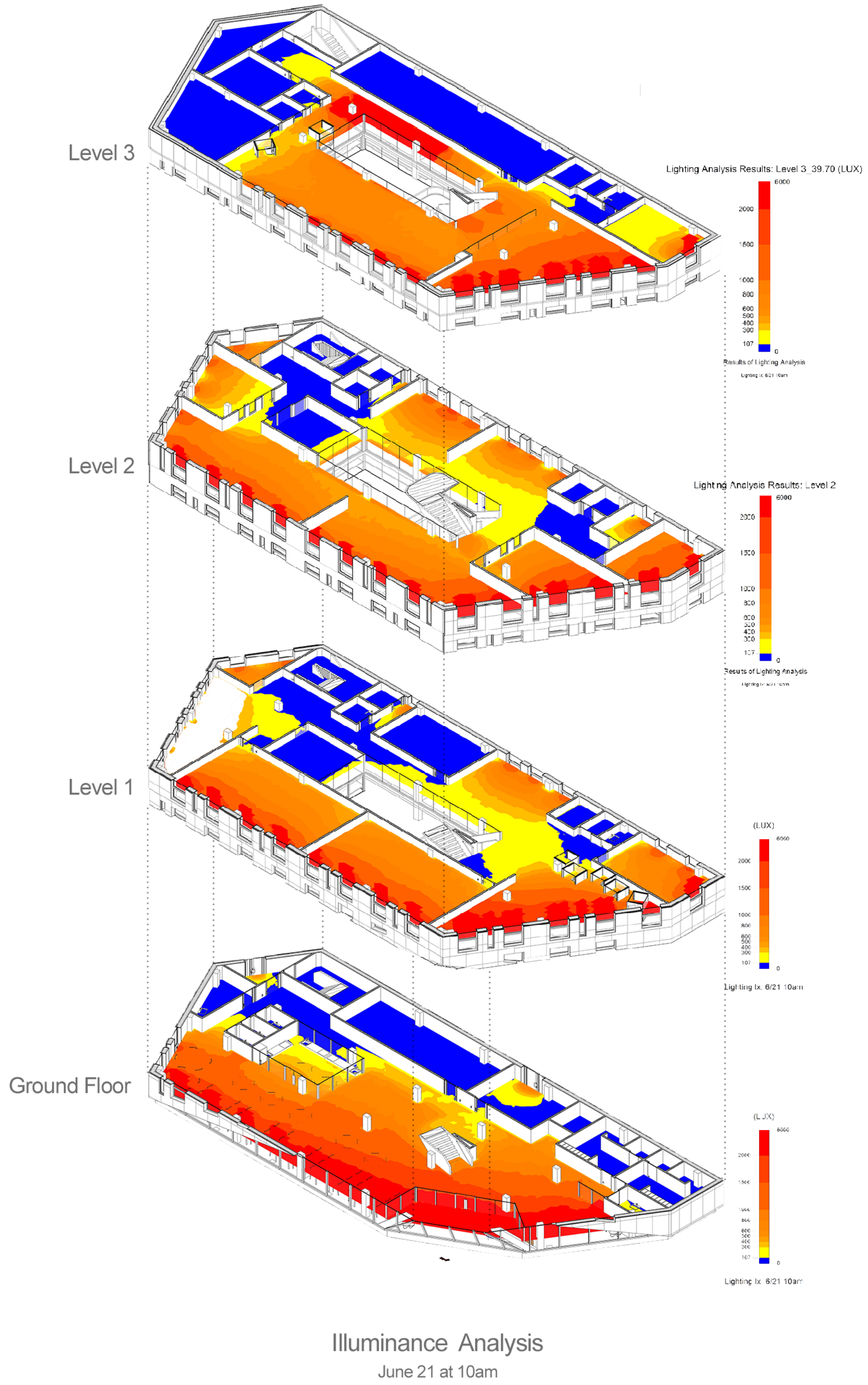


Figure 51: Illuminance analysis of the new ZEB Lab design

In order to validate our design and prove that the luminous environment has a sufficient quality for occupants, daylighting simulations using Daylight Factor as parameter have been performed. Daylighting also play an essential rule in reducing the energy demand for electricity use of lighting in the operational stage of building. The better efficiency of the daylighting, the lesser energy load consumption.

According to TEK17 and code for interior lighting, if electric lighting is not normally to be used during daytime hours, the average daylight factor should be not less than 5% and If electric lighting is to be used during daytime, the average daylight factor should be not less than 2%.

Therefore, for this project we aim for the average daylight factor to be Min 5% in order to reduce the energy load of artificial lighting during operational stage in the spaces. Figure 50 shows the final daylighting simulation results with the daylight factor as parameter in each floor of the building. The dark green color represents the daylight factor of between 5%-6% and the lighter green color represent between 3%-4% and the light blue color mark the 2% daylight factor. In level 1 and level 2, 4%-5% daylight factor occurs along the façade and getting lower respectively to the distance away from the façade, however, the daylight factor does not exceed below 2% over the space and more than 50% of the total area is set to be over 2%.

Figure 51 shows the illuminance analysis results in June 21 at 10:00 which is working hours for occupant. Overall, the results mark the adequate illuminance for occupant in all requirement space. In level 1, illuminance would reach up to about 2000 lux and over 50% of total area reach around 800 lux to 1300 lux. In level 2 and 3 which is office space floor, the illuminance would reach between 800 lux – 1200 lux over 50% of total space. Along the façade which is open office space, the illuminance would reach up to 1600 lux. This shows the best illuminance result which fall in the high recommendation level of daylighting condition according to TEK17 and EN17037.

6.5. ZEB BALANCE COMAPRISON BETWEEN THE PROPOSAL AND ORIGINAL

Furthermore, a ZEB balance calculation is evaluated to confirm whether or not this new ZEB design achieves the ZEB-COM standard. The primary calculation values in the ZEB balance of ZEB-COM are the emission from the construction stage (C), emboided emission of the construction material production (M), and operational emission of the building (O). Nonetheless, as stated in the thesis' scope, this project has a limitation framework of the Life cycle evaluation. The CO2 emissions associated with the material manufacturing and construction stage of the new building are assumed to be identical to those of the original building since this thesis's project uses the same construction materials as the original.

It's crucial to highlight that Erlend, a Ph.D. student who works at the ZEB Lab and has more access to the building, provided the original ZEB balance calculation. The ZEB balance of the original building from Erlend is "-0.57," as shown in figure 52 but since we simulated the original building manually, the calculation value of operational emission has been modified slightly (their vaule is -11.8, our is 11.3). As a result, the original building's ZEB balance is "-0.17." Since using their ZEB balance calculation would not be a fair comparison, we chose to compare our original building's ZEB balance to our new design (figure 53).

In comparison to the original ZEB Lab, the new ZEB Lab has a ZEB balance value of "-0.08" as shown in figure 54. The result indicates that it is reasonable to conduct that this thesis project of redesigning the ZEB Lab could accomplish ZEB-COM by pushing or prioritizing passive strategies control, but it could not achieve the same ZEB-COM level as the original building.

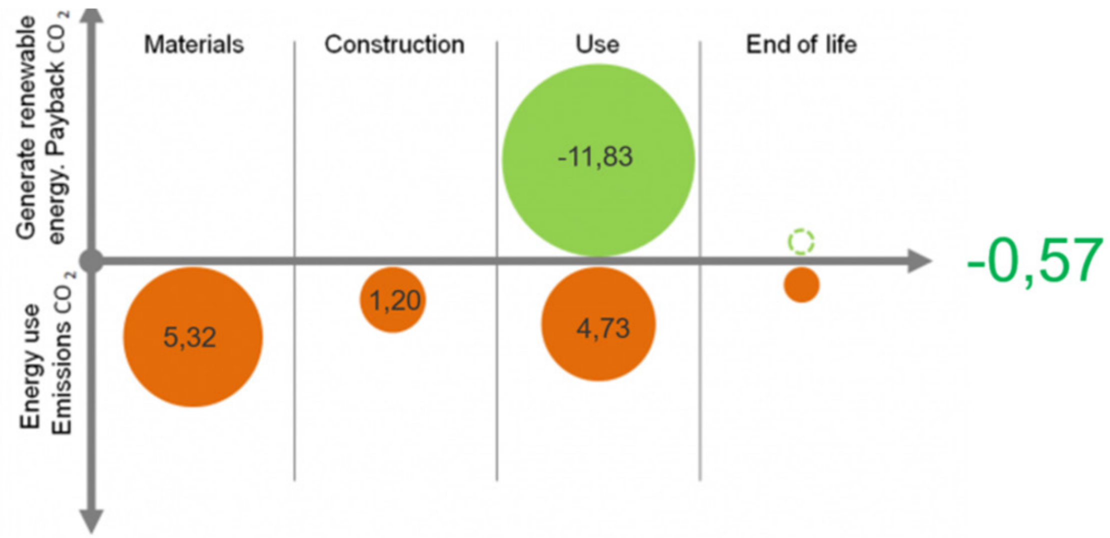


Figure 52: ZEB Balance calcualtion of original ZEB Lab building recieved from Erlend, a PhD student

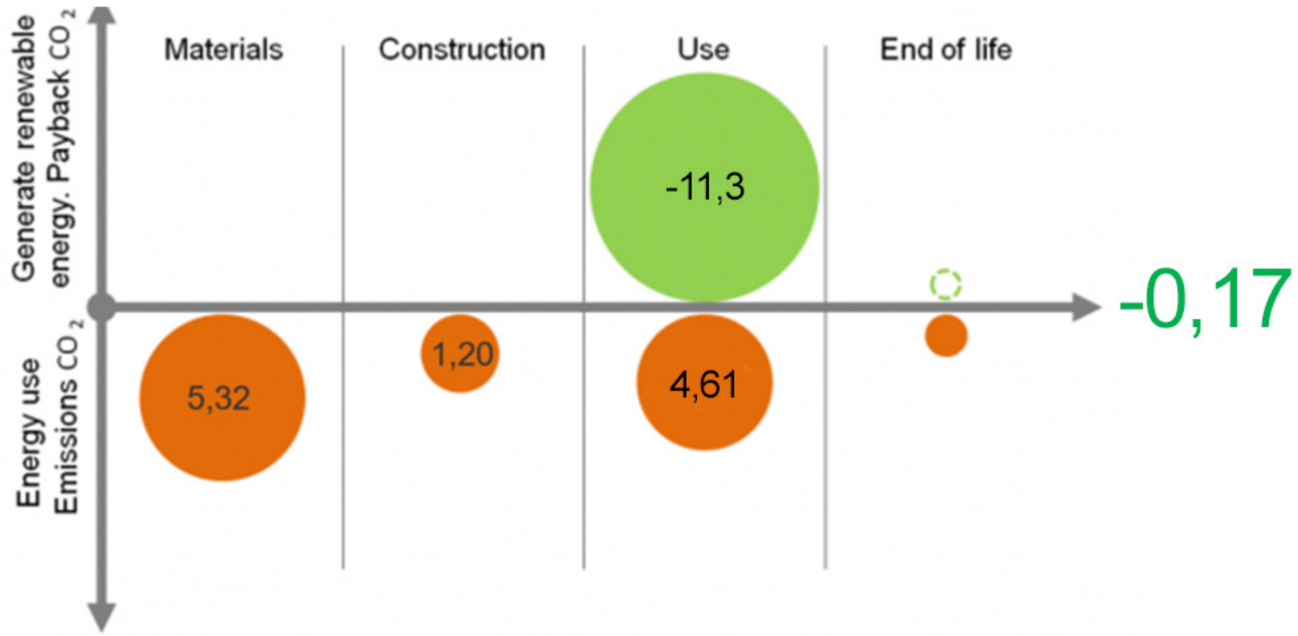


Figure 53: ZEB Balance calcualtion of original ZEB Lab building, done by Soumenh and Alisher

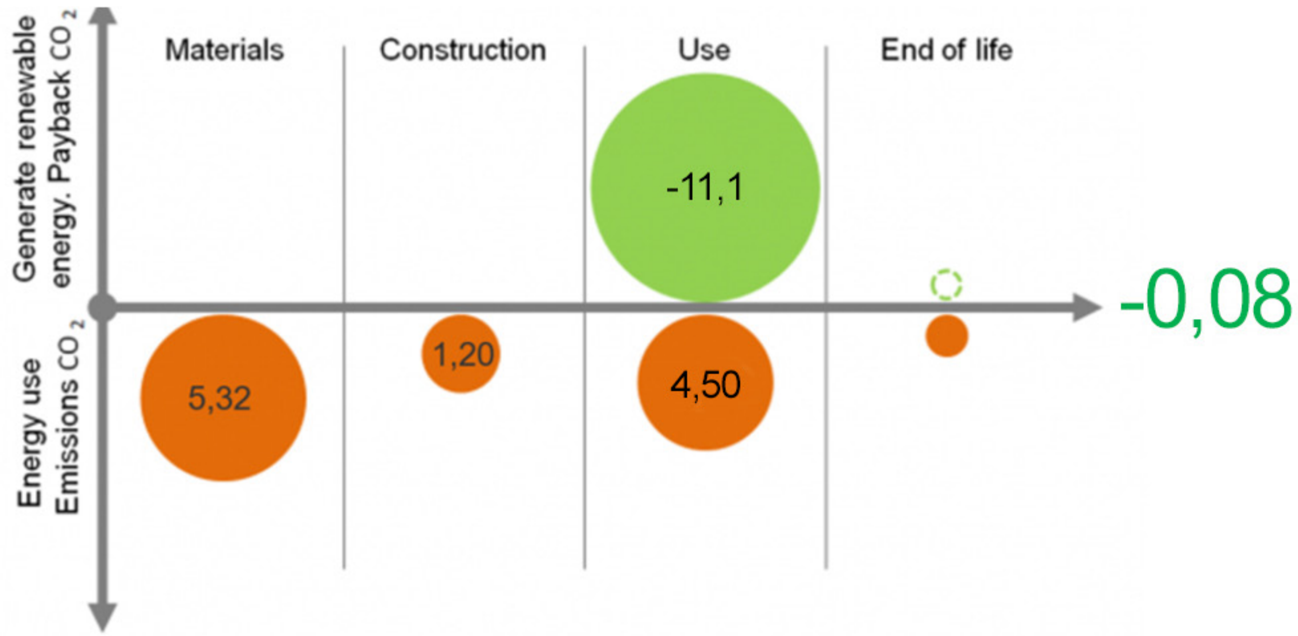


Figure 54: ZEB Balance calcualtion of the new ZEB Lab Design

7. DISCUSSION

First of all, it is important to remarked on the goal of this master's thesis which is the redesign the alternative new ZEB Lab building located in Trondheim at the NTNU Gløshaugen campus by foremost priotorizing the passive strategies control in design to and with the suportive of active control strategies such as energy supply system and on site renewable energy production. The main passive strategie used in this project is maximizing the passive solar heat gain, following by high performance building envelope, maximazation of daylighting condition, and natural ventilation (applied the similar strategies of the original building; stack effect ventilation strategies in the main staircase). The envivromental or energy performance goal of the ZEB Lab building achieved ZEB-COM level, therefore, the environmental goal of this thesis project is to achieve the ZEB-COM level as well which is one of the difficult task, but at the same time it is a task that gave out many incredible lesson learnts.

ZEB Lab is a flexible lab built for the educational and experimental purpose for all related reseachers, Phd students and other related firm. For this reason, there are a certain amount of limitations to redesign the building based on it own functionality and those limitations were an issue that I need to downgrade or limit some of the design idea such as the facade, especially the south facade that it was designed to make it easy for reconstruction and replacement for experimental purpose. The chosen ventilation strategies for ZEB Lab is displacement ventilation, and each floor has a different type of displacement ventilation for experiment purpose as well. Redesign the ZEB building would also need to include those different of ventilation strategies and would limit the design idea as well. ZEB Lab is ZEB COM level, thus to redesign the new ZEB Lab, the new building and design will need to produce more energy to compensate the emboided emission from Construction stage, material production and operational emission. This is also another challenging in this project.

During the literature review of the ZEB Lab building, it is hard to find out the precise information since there are different information in each report, article and website. However, I, my teammate which has a similar master thesis's about the ZEB building and supervisor arranged the meeting with Tore Kvande; a project leader in this ZEB building and Phd student; Erlend Andeæs who has knowledge about this ZEB building for gather a essential and precise data about the building. Eventually, we got a report "ZEB Flexible Lab, Energy Concept" from Tore which is the most essenital information we gathered.

After doing the literature review about the ZEB Lab, meeting with Tore and Erlend, gathering essential information in hand. I started off the thesis by doing analysis and evaluation of the building in both architectural and environmental aspect. Those literature view, discussion, analysis and evaluation of the building lead me to come up with an initial form design of the new building. The form are development into different new forms further depending on the solar radiation analysis that was done by using Ladybug tool, a plugin for grasshopper in rhino software. There were many attempt and investigation of this radiation analysis and it conclude that the most efficient form that could possible achieve the goal of maximizing the passive solar heat gain in order to minimize the heating load in operation use is the form that has the facade spread open to southeast and southwest in addition to south facade. The forms that has the facade to only east ,only west or both east and west in addition to south facade are all in lower number of solar heat gain and radiation. The form that showed the best result in radiation was also done the draft energy simulation to clarify about the heating load's consumption, total energy budget, delivery energy because those number of energy result would have a strong effect on the total CO2 emission's calculate. Similarly, the form that has the facade spread to south, southeast and southwest (Test form 08) has the lowest result in energy consumption. The form is chosen for further development and optimization. In this stage of developement, the goal remain the same; try to minimize the energy demand as much as possible with the passive heat gain while also take a consideration in pv production. That is why the form are optimized with proper window ratio with different design and the tilted roof angle range from 15 degree to 30 degree for more pv production.

It is important to note that to compare the new design form to original building, I and my teammate, Alisher who has a similar topic on this ZEB Lab building create our simulation of the original building mainly based on the report of "ZEB Flexible Lab, energy concept" so that we could have a fair comparison with our design. Our simulation result of original building appeared to be better in number compare to those in the report. However, we decide to use our simulation result as the reference to compare to our design due to create an effective comparison with our design since that our forms were also simulated in the same software with the same input data. The simulation result indicated that the form with tilted roof of 30 degree (scenario 8 in this project) has the lowest result in CO2 emission. It could be concluded that the roof tilted toward 42 or 45 degree, the better energy production roof, however, it would not fit well in an architectural aspect. A slight higher in CO2 emission is the form with tilted roof of 25 degree (scenario 5 in this project), yet it has a lowest total energy demand and a great design which creates useable space in the upper most southern part. As for the reason, the form is selected for further detail development and eventually, the energy simulation were done again with more accurate data from the modeling software and some adjustment of the input data for simulation based on the "ZEB Flexible Energy concept" report. The result came out better than the previous one and the total net specific energy demand is even lower than the original ZEB Lab building which is about 50.3kWh/m2 compare to original building; 53.3kWh/m2. Surprisingly, the total operational emission came out to be the same as the original building which is about -6.6kg/m2/yr. Furthermore, in order to verify whether or not this new ZEB design achieve the ZEB-COM level, ZEB balance calculate is needed. The main calculate values that need in the ZEB balance of ZEB-COM are the emission from construction stage (C), emboided emission of the construction material prodcution (M), and the operational emission of the building (O). Nevertheless, as mentioned in the scope of the thesis, there’s a limitation framework of the Life cycle assessment in this project. The CO_2 emission related to the material production and construction stage of the new building are assumed to have similar amount as the original building since that this thesis's project considered to have the same construction material used as the original building. The new ZEB Lab designed with the different footprint and different building form, thus there would be an argument stating that the total amount of material used would not be the same. However, one way to support my assumption of having the same amount of material used in this two building is that; there would be more exterior wall of the new design compare to the original building, yet the amount of windows in the new ZEB Lab building is much lesser than the original which could be proofed by the total area of the two buildings. ZEB Lab has 477m² and the new ZEB Lab design has about 311m² . The glazing or windows has the highest emboided emission if compare to the traditional exterior wall with mineral wool insulation. Therefore, the less windows design of new ZEB Lab could possible compensate with the exterior wall and assumed that it has approximately the same amount of material used as the original building.

It is essential to mentioned that the ZEB balance calculate of the original was given out by Erlend, Phd student who work in the ZEB Lab and have more access information to the building. The result of ZEB balance of the original building from Erlend is "-0.57", however, since we simulated the original building ourself, thus there is abit of adjustment to the calculation value of operational emission (their vaule is -11.8, our is 11.3). Therefore, our ZEB balance's result of original building is "-0.17". There is a huge different in the number, yet the result indicate the ZEB-COM level. After discussion with my teammate, we could assume that the huge difference in number would be due to the PV panel that they have on the ground floor in south facade outside the building that we did not include in our simulation. It is not fair comparison if we use their ZEB balance calculate, therefore, we decide to use our ZEB balance of original building as reference to compare to our new design.

The new ZEB Lab design has ZEB balance value of "-0.08" compare to the original ZEB Lab which is "-0.17". From the number, it could be concluded that this thesis project of redesign the ZEB Lab could possible achieve the ZEB-COM by pushing or prioritize the passive strategies control, however, it could not reach same ZEB-COM level as the original building with the ZEB balance's value of "-0.17". It is important to mention that, even the new ZEB Lab design did not reach the same value of the original one, yet it achieved ZEB-COM level with offering an incredible valuable of architecture aspect. I would say it achieve not only, the ZEB-COM but it is an valuable architecture building.

8. CONCLUSION

The goal of redesign the alternative ZEB Lab building by prioritizing the passive strategies control, yet with the supportive active strategies and on-site renewable energy to reach the same ambition of ZEB COM level with many remarkable limitations in the design is eventually achieved. The ZEB balance calculatuion of the new ZEB Lab design is "-0.08" which indicates that the design has reached the ZEB-COM, yet in term of the comparison with the original building's value, it still need more improvement. This result show that the ambition goal of reaching ZEB-COM is a difficult task and without the supportive of the active strategies and on-site renewable energy production, it would not be possible to achieve the ZEB-COM level for this project.

It could be seen that by maximizing the passive solar heat gain for the new building form help diminish a certain amount of energy's consumption for room heating and the number even lower than that of the original building. As a consequence, the total energy budget of the new ZEB building is lower than that of the original building.

This project represent the possibility of design to reach ZEB-COM level by prioritizing the passive strategies in design to minimize the energy's consumption in the operational stage of the building, however, the supportive from active strategies such as energy efficicent supply and on site renewable energy is a must to supply. ZEB-COM involves all the three main component in the building, emission from material used, emission in construction stage of the building and the operational emission, therefore, there are large amount of emboided emission that the passive strategies alone would not be able to avoid or compensate. For that reason, active strategies such as energy supply system and especially, the renewable energy on site need to play an important role for the compensate all of the emission. This project also represent the possiblity of an alternative design of the ZEB Lab building which could possible reached the ZEB-COM in a very different form. The project give more value to architecture aspect. In short, the project provide an valuable architecture point of view, and at the same time reaching the ambition of ZEB-COM as well.

9. FURTHER WORK

Since that this thesis project has a limitation framework of the life cycle assessment (LCA) of the new design and the number used for calculate the ZEB balance is just an assumption only. Therefore, the great further development of the project is to do the life cycle assessment of emboided emission of material used and the construction stage of the building so that the precise result would be redefined and reliable.

For the energy simulation, the input data is set in our SIMIEN simulation as have been listed in the energy concept report of the ZEB Lab. However, the result have a slight difference from report result. Therefore, it is still a great approach if this project design could run in the original SIMIEN file of the ZEB Lab so that the accuracy of the result could be seen.

Economic aspect is out of the scope of the project, thus, including the economic aspect to this redesign building would also a good improvement and strong.

10. REFERENCE

Ar. Rutika, T. A. (2017). Passive design strategies for cold and cloudy climate. University Road, Department of Interior Designing, Maharashtra.

Jacobsen, T., & Andresen, I. (2018). ZEB Flexible Laboratory. Trondheim: Sintef.

Leinum, M. E. (2019). Optimal combination of natural and mechanical ventialtion in ZEB Laboratory, NTNU.

Nocente, A., Time, B., Mathisen, H. M., Kvande, T., & Gustavsen, A. (2021). The ZEB Laboratory: the development of a research tool for future climate adapted zero emission building.

Tarun, N., & Sai Rahul, D. (2020). Zero Energy Building - A passive approach. Karnataka.

Thomos, B. L., & Arne , L. F. (2020). ZEB Flexible Lab, Energikonsept. Link Arkitektur AS.

Thorsell, J., & Kommun, V. (2019). Nero - Cost reduction of new Nearly-Zero Wooden buildings in Northern Climate Condition.

Time, B., Nocente, A., Mathisen, H. M., Larsen, A. F., Myhr, A. R., Jocobsen, T., & Gustavsen, A. (2019). ZEB Laboratory - Research Possibilities. Trondheim.

11. APPENDICES

APPENDIX A

A.1. All the inputs for simien simulation of the original ZEB Laboratory from PFD from LINK Arkitektur AS (received from Tore Kvande)

Bygningskategori		Kontorbygg	
Stшrrelse		**Inndata**	**Dokumentasjon**
Arealer [m²]	Yttervegger	1238	Tegninger, sist rev. 21.11.2018
	Tak	535	Tegninger, sist rev. 21.11.2018. Skretak gir stшrre takareal enn gulvareal.
	Gulv	440	Tegninger, sist rev. 21.11.2018
	Vinduer, dшrer og glassfelt	477	Tegninger, sist rev. 27.05.2019
Oppvarmet delav BRA (A_{fl}) [m²]		1742	Tegninger, sist rev. 21.11.2018
Oppvarmet luftvolum (V) [m³]		7691	Tegninger, sist rev. 21.11.2018
U-verdi for bygningsdeler [W/m²K]	Yttervegger	0,15	Isolert bindingsverk, t_{iso}=300mm, $t_{stender}$=48mm, λ_{iso}=0,033 W/mK Isolert bindingsverk, t_{iso}=225mm, $t_{stender}$=48mm, λ_{iso}=0,033 W/mK
	Tak	0,09	Isolert sperretak av I-profiler, t_{iso}=450mm, t_{bjelke}=48mm λ_{iso}=0,036 W/mK.
	Gulv	0,10 ekv.	Gulv pe grunn, t_{iso}= 250mm, λ_{iso}=0,038 W/mK.
	Vinduer, dшrer og glassfelt	0,77	Gjennomsnittlig for hele vindus- og dшrleveransen. Opplyst ved mail av 28.09.2020 fra Veidekke entreprenшr.
Arealandel for vinduer, dшrer og glassfelt (γ_{sol}) [%]		27,4	Tegninger, sist rev. 27.05.2019
Normalisert kuldebroverdi (Ψ`) [W/m²K]		0,04	Gitt i 418722-RIBfy-NOT-002.
Normalisert varmekapasitet (c") [Wh/m²K]		81	Massivtrekonstruksjoner. Stшpt kjerne og sele.
Lekkasjetall (n_{50}) [h⁻¹]		0,3	Konseptverdi gitt i 418722-RIBfy-NOT-002. Dokumentert med trykktest.
Temperaturvirkningsgrad (η_T) for varmegjenvinner [%]		85/88	Konseptverdi. God varmegjenvinner, for TEK beregninger. Aggregat kjшringer for NS 3701 luftmengder. Melinger pe eksisterende ventilasjonsaggregater har vist at denne verdien kan vжre pe den usikre side ved kjшring av aggregat pe dellast. I reel beregning er det lagt inn verdi svarende til konseptverdi.
Estimert ers gjennomsnittlig temperaturvirkningsgrad for varmegjenvinner pga. frostsikring [%]		85/88	Konseptverdi. God varmegjenvinner, for TEK beregninger. Aggregat kjшringer for NS 3701 luftmengder

Figure A.1.1: Documentation of key inputs for the energy calculation

Bygningskategori	Kontorbygg	
Stшrrelse	**Inndata**	**Dokumentasjon**
Spesifikk vifteeffekt (SFP) relatert til luftmengder i driftstiden [kW/m³/s]	1,0/ 0,9	Antatt verdi ut fra aggregat kjшring for TEK for balansert system. For passivhus er SFP dokumentert i NOT-RIV-01 ZEB FLEXIBLE LAB - DOKUMENTASJON AV BEREGNET SPESIFIKK VIFTEEFFEKT
Spesifikk vifteeffekt (SFP) relatert til luftmengder utenfor driftstiden [kW/m³/s]	0,5	For balansert system
Gjennomsnittlig spesifikk ventilasjonsluftmengde i driftstiden (V_{on}/A_{fl}) [m³/m²h]	6,0	For balansert system. Mot TEK17: 7,0
Spesifikk ventilasjonsluftmengde utenfor driftstiden (V_{red}/A_{fl}) [m³/m²h]	1,0	For balansert system Mot TEK17: 2,0
Ersgjennomsnittlig (VP//EL/FJV) systemvirkningsgrad/varmefaktor for oppvarmingssystemet [%]	3 / - / 0,89	Prosjektverdi med godt isolerte rшr. Turtemperatur < 45ºC
Ersgjennomsnittlig (VP/EL/FJV) systemvirkningsgrad/varmefaktor for oppvarmning varmt tappevann [%]	3,33 / 1 / -	Projektverdi og verdier for normert beregning
Ersgjennomsnittlig (VP/EL/FJV) systemvirkningsgrad/varmefaktor for oppvarmingssystemet [%]	3,07 /- / -	Projektverdi og verdier for normert beregning
Installert effekt for romoppvarming og ventilasjonsvarme (varmebatteri) [W/m²]	160	Inndata verdi, reelt uttak er vesentlig lavere
Settpunkttemperaturer for oppvarming [əC]	19/21	Standardverdier iht. Tabell A.3 NS 3031:2014. I og utenom driftstid.
Ersgjennomsnittlig kjшlefaktor for kjшlesystemet [%]	2,5	Ingen installert kjшling.
Settpunkttemperaturer for kjшling [əC]	22	Ingen installert kjшling.
Installert effekt for romkjшling og ventilasjonskjшling [W/m²]	0	Ingen installert kjшling.
Spesifikk pumpeeffekt (SPP) [kW/ls]	0,5	Standardverdi.
Driftstid for ventilasjon, oppvarming, kjшling, lys, utstyr, varmtvann og personer	12/12/24/ 12/12/12/ 12	Standardverdier iht. Tabell A.3 NS 3031:2014 for hhv: Belysning og utstyr/ Oppvarming, ventilasjon og personer
Spesifikt effektbehov for belysning i driftstiden [W/m²]	2,4	LENI-dokumentasjon. Beregning fra Glamox
Spesifikt varmetilskudd fra belysning i driftstiden (q''_{lys}) [W/m²]	2,4	LENI-dokumentasjon. Beregning fra Glamox
Spesifikt effektbehov for utstyr i driftstiden [W/m²]	3,2	Brukerbestemt-nive Mot TEK17: 11,0
Spesifikt varmetilskudd fra utstyr i driftstiden (q''_{uts}) [W/m²]	3,2	Brukerbestemt-nive Mot TEK17: 11,0
Spesifikt energibruk for varmtvann i driftstiden (q''_{w}) [kWh/m²er]	5 / 1	Standardverdier iht. Tabell A.2 NS 3031:2014, For NS 3701 beregning og ZEB COM benyttes 1 kWh/m2 er som avtalt prosjekt spesifikk verdi. Verdien er ikke dokumentert ved beregning, men me dokumenteres i drift.
Varmetilskudd fra varmtvann i driftstiden [W/m²]	0,00	Standardverdier iht. Tabell A.2 NS 3031:2014
Varmetilskudd fra personer (q''_{pers}) i driftstiden [W/m²]	4,0	Standardverdier iht. Tabell A.2 NS 3031:2014

Figure A.1.2: Documentation of key inputs for the energy calculation

Bygningskategori	**Kontorbygg**	
Stшrrelse	**Inndata**	**Dokumentasjon**
Total solfaktor (g_t) for vindu og solavskjerming (Ш/S/V/N)	0,31	Vinduer, hele bygget: - Tre-lags vindu med lavemisjonsbelegg (g_{tot} =0,45) Vinduer mot sшr som ligger bak transparente solceller: - Tre-lags vindu med lavemisjonsbelegg (g_{tot} =0,35) Solavskjerming mot sшr: - Tre-lags vindu med utvendig solavskjerming (g_{tot} =0,10) Solavskjerming mot шst og vest: - Tre-lags vindu med lavemisjonsbelegg og innvendig screen (g_{tot} =0,35).
Gjennomsnittlig karmfaktor (F_F)	0,2	Standardverdi
Solskjermingsfaktor pga. horisont, nжrliggende bygninger, vegetasjon og evt. bygningsutspring (N/Ш/S/V)	0,74/0,95/ 0,97/0,95	

Figure A.1.3: Documentation of key inputs for the energy calculation

	EL	**Fjernvarme**	**Varmepumpe**	**Sol**	**Biobrensel**	**Gass**
Romoppvarming	0	2	98	0	0	0
Tappevann*)**	35	0	65	0	0	0
Ventilasjonsvarme	0	0	100	0	0	0
Kjшlebatterier romkjшling	100*)	0	0	100**)	0	0
Lokal kjшling / romkjшling	100 *)	0	0	100**)	0	0
El.-spesifikt energibehov	100	0	0	100**)	0	0

Figure A.1.4: Coverage of energy requirements in %

A.2. Simien simulations results of existing building from PFD from LINK Arkitektur AS (received from Tore Kvande)

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	54355 kWh	31,2 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	7504 kWh	4,3 kWh/m²
2 Varmtvann (tappevann)	1745 kWh	1,0 kWh/m²
3a Vifter	10676 kWh	6,1 kWh/m²
3b Pumper	675 kWh	0,4 kWh/m²
4 Belysning	13093 kWh	7,5 kWh/m²
5 Teknisk utstyr	17461 kWh	10,0 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	105510 kWh	60,6 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	42516 kWh	24,4 kWh/m²
1b El. til varmepumpesystem	20541 kWh	11,8 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	1221 kWh	0,7 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	64278 kWh	36,9 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	64278 kWh	36,9 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	42516 kWh	24,4 kWh/m²
1b El. til varmepumpesystem	20541 kWh	11,8 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	1221 kWh	0,7 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-28317 kWh	-16,3 kWh/m²
Totalt levert energi, sum 1-7	35961 kWh	20,6 kWh/m²
Solstrøm til eksport	-118197 kWh	-67,9 kWh/m²
Netto levert energi	-82236 kWh	-47,2 kWh/m²

Figure A.2.1: Budsjett status netto og levert energi 05.10.2020. Budsjett levert energibruk vist uten og med solstrømsproduksjon

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	54355 kWh	31,2 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	7504 kWh	4,3 kWh/m²
2 Varmtvann (tappevann)	1745 kWh	1,0 kWh/m²
3a Vifter	10676 kWh	6,1 kWh/m²
3b Pumper	675 kWh	0,4 kWh/m²
4 Belysning	13093 kWh	7,5 kWh/m²
5 Teknisk utstyr	17461 kWh	10,0 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	105510 kWh	60,6 kWh/m²

Energy supplied to the building (calculated)		
Energy products	Delivered energy	Specific energy delivered
1a Direct el.	42516 kWh	24.4 kWh / m²
1b El. for heat pump system 1c	20541 kWh	11.8 kWh / m²
El. for solar collector system 2	0 kWh	0.0 kWh / m²
Oil	0 kWh	0.0 kWh / m²
3 Gas	0 kWh	0.0 kWh / m²
4 District heating	1221 kWh	0.7 kWh / m²
5 Biofuels	0 kWh	0.0 kWh / m²
6. Other energy source	0 kWh	0.0 kWh / m²
7. Solar power for own use Total	- 0 kWh	- 0.0 kWh / m²
delivered energy, total 1-7 Solar	64278 kWh	36.9 kWh / m²
power for export	- 0 kWh	- 0.0 kWh / m²
Net delivered energy	64278 kWh	36.9 kWh / m²

Energy supplied to the building (calculated)		
Energy products	Delivered energy	Specific energy delivered
1a Direct el.	42516 kWh	24.4 kWh / m²
1b El. for heat pump system 1c	20541 kWh	11.8 kWh / m²
El. for solar collector system 2	0 kWh	0.0 kWh / m²
Oil	0 kWh	0.0 kWh / m²
3 Gas	0 kWh	0.0 kWh / m²
4 District heating	1221 kWh	0.7 kWh / m²
5 Biofuels	0 kWh	0.0 kWh / m²
6. Other energy source	0 kWh	0.0 kWh / m²
7. Solar power for own use Total	- 28317 kWh	- 16.3 kWh / m²
delivered energy, total 1-7 Solar	35961 kWh	20.6 kWh / m²
power for export	- 118197 kWh	- 67.9 kWh / m²
Net delivered energy	- 82236 kWh	- 47.2 kWh / m²

Figure A.2.2: Net budget status and delivered energy 05.10.2020. Budget delivered energy consumption shown without and with solar power production

APPENDIX B

B.1. Simien simulation results of original building from our simulation

Energy budget		
Energy post	Energy needs	Specific energy needs
1st Room heating	40407 kWh	23.2 kWh / m²
1b Ventilation heating (heating	9814 kWh	5.6 kWh / m²
batteries) 2 Hot water (tap water)	0 kWh	0.0 kWh / m²
3a Fans	10454 kWh	6.0 kWh / m²
3b Pumps	595 kWh	0.3 kWh / m²
4 Lighting	13093 kWh	7.5 kWh / m²
5 Technical equipment	17461 kWh	10.0 kWh / m²
6a Room cooling	0 kWh	0.0 kWh / m²
6b Ventilation cooling (dress batteries)	1102 kWh	0.6 kWh / m²
Total net energy requirement, sum 1-6	92926 kWh	53.3 kWh / m²

Energy supplied to the building (calculated)		
Energy products	Delivered energy	Specific energy delivered
1a Direct el.	42044 kWh	24.1 kWh / m²
1b El. for heat pump system 1c El.	19838 kWh	11.4 kWh / m²
for solar collector system 2	0 kWh	0.0 kWh / m²
Oil	0 kWh	0.0 kWh / m²
3 Gas	0 kWh	0.0 kWh / m²
4 District heating	975 kWh	0.6 kWh / m²
5 Biofuels	0 kWh	0.0 kWh / m²
6. Other energy source	0 kWh	0.0 kWh / m²
7. Solar power for own use Total	- 0 kWh	- 0.0 kWh / m²
energy delivered, total 1-7 Solar	62857 kWh	36.1 kWh / m²
power for export	- 0 kWh	- 0.0 kWh / m²
Net delivered energy	62857 kWh	36.1 kWh / m²

Energy supplied to the building (calculated)		
Energy products	Delivered energy	Specific energy delivered
1a Direct el.	42044 kWh	24.1 kWh / m²
1b El. for heat pump system 1c El.	19838 kWh	11.4 kWh / m²
for solar collector system 2	0 kWh	0.0 kWh / m²
Oil	0 kWh	0.0 kWh / m²
3 Gas	0 kWh	0.0 kWh / m²
4 District heating	975 kWh	0.6 kWh / m²
5 Biofuels	0 kWh	0.0 kWh / m²
6. Other energy source	0 kWh	0.0 kWh / m²
7. Solar power for own use Total	- 29368 kWh	- 16.9 kWh / m²
energy delivered, total 1-7 Solar	33489 kWh	19.2 kWh / m²
power for export	- 121590 kWh	- 69.8 kWh / m²
Net delivered energy	- 88101 kWh	- 50.6 kWh / m²

Figure B.1.1: Net budget status and delivered energy. Budget delivered energy consumption shown without and with solar power production

Annual CO2 emissions		
Energy products	Emissions	Specific emissions
1a Direct el.	5466 kg	3.1 kg / m
1b El. for heat pump system 1c El.	2579 kg	1.5 kg / m²
for solar collector system 2	0 kg	0.0 kg / m²
Oil	0 kg	0.0 kg / m²
3 Gas	0 kg	0.0 kg / m²
4 District heating	73 kg	0.0 kg / m²
5 Biofuels	0 kg	0.0 kg / m²
6. Other energy source	0 kg	0.0 kg / m²
7. Solar power for own use	- 3818 kg	- 2.2 kg / m²
Total emissions, total 1-7	4300 kg	2.5 kg / m²
Solar power for export	- 15807 kg	- 9.1 kg / m²
Net CO2 emissions	- 11507 kg	- 6,6 kg / m²

Figure B.1.2: Annual CO2 emissions for calculation of ZEB Balance

Energiproduksjon solceller [kWh]													
Panel	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Des	Totalt
Produsert PV Roof	868	3845	8557	12840	15634	15844	15528	12470	7959	3943	1284	153	98924
Produsert PV South Wall	255	1139	1951	2307	2150	1988	2065	1921	1506	941	383	15	16622
Produsert PV West Wall	181	852	1757	2681	3042	2984	3104	2714	1688	843	268	22	20136
Produsert PV East Wall	68	384	1138	1932	2650	2836	2648	1940	1078	469	112	19	15276
Sum produsert	1372	6220	13403	19760	23476	23652	23345	19046	12231	6196	2047	209	150958
Levert til bygning	780	2022	3163	3276	3335	3458	3628	3496	2864	2004	1146	195	29368
Eksportert til nett	592	4198	10240	16484	20141	20194	19717	15551	9367	4191	902	14	121590

Figure B.1.3: Energy production from PV panels

B.2. Simien simulation results of the final form

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	36616 kWh	20,1 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	10362 kWh	5,7 kWh/m²
2 Varmtvann (tappevann)	0 kWh	0,0 kWh/m²
3a Vifter	10951 kWh	6,0 kWh/m²
3b Pumper	655 kWh	0,4 kWh/m²
4 Belysning	13718 kWh	7,5 kWh/m²
5 Teknisk utstyr	18291 kWh	10,0 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1154 kWh	0,6 kWh/m²
Totalt netto energibehov, sum 1-6	91747 kWh	50,3 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	44077 kWh	24,2 kWh/m²
1b El. til varmepumpesystem	18505 kWh	10,1 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	883 kWh	0,5 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	63465 kWh	34,8 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	63465 kWh	34,8 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	44077 kWh	24,2 kWh/m²
1b El. til varmepumpesystem	18505 kWh	10,1 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	883 kWh	0,5 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-30962 kWh	-17,0 kWh/m²
Totalt levert energi, sum 1-7	32503 kWh	17,8 kWh/m²
Solstrøm til eksport	-124914 kWh	-68,4 kWh/m²
Netto levert energi	-92411 kWh	-50,6 kWh/m²

Figure B.2.1: Net budget status and delivered energy. Budget delivered energy consumption shown without and with solar power production

Årlige utslipp av CO2		
Energivare	Utslipp	Spesifikt utslipp
1a Direkte el.	5730 kg	3,1 kg/m²
1b El. til varmepumpesystem	2406 kg	1,3 kg/m²
1c El. til solfangersystem	0 kg	0,0 kg/m²
2 Olje	0 kg	0,0 kg/m²
3 Gass	0 kg	0,0 kg/m²
4 Fjernvarme	66 kg	0,0 kg/m²
5 Biobrensel	0 kg	0,0 kg/m²
6. Annen energikilde	0 kg	0,0 kg/m²
7. Solstrøm til egenbruk	-4025 kg	-2,2 kg/m²
Totalt utslipp, sum 1-7	4177 kg	2,3 kg/m²
Solstrøm til eksport	-16239 kg	-8,9 kg/m²
Netto CO2-utslipp	-12062 kg	-6,6 kg/m²

Figure B.2.2: Annual CO2 emissions for calculation of ZEB Balance

Energiproduksjon solceller [kWh]													
Panel	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Des	Totalt
Produsert PV Roof#1 (25,189)	538	2371	5442	8381	10438	10642	10412	8292	5200	2513	793	106	65127
Produsert PV Roof#2 (0,180)	187	805	2102	3501	4721	4934	4742	3624	2157	964	272	52	28061
Produsert PV SouthWall	333	1490	2553	3018	2812	2601	2701	2514	1970	1231	501	20	21745
Produsert PV SouthEastWall	107	512	1219	1844	2288	2356	2252	1751	1053	516	165	15	14077
Produsert PV EastWall	25	143	424	720	988	1057	987	723	402	175	42	7	5693
Produsert PV NorthWall	8	26	71	129	240	285	259	163	89	39	11	3	1321
Produsert PV NorthWestWall	30	175	520	978	1317	1355	1376	1115	596	241	47	11	7759
Produsert PV SouthWestWall	100	481	1027	1603	1854	1829	1898	1645	1005	490	148	13	12092
Sum produsert	1328	6003	13357	20173	24657	25059	24627	19826	12471	6170	1978	228	155876
Levert til bygning	799	2093	3358	3510	3532	3639	3807	3683	3028	2131	1175	207	30962
Eksportert til nett	530	3910	9999	16662	21125	21421	20820	16143	9444	4039	803	20	124914

Figure B.2.3: Energy production from PV panels

The final form input data

Heated Floor Area (Based on Revit File)

GF: 500 Volume: 500 x 3.5 = 1750

1F: 463 Volume: 463x 3 = 1389

2F: 463 Volume: 463x 3 = 1389

3F: 463 Volume: 463x 5.5 = 2547

Total: 1825 Total: 7075

South Facade Area: 368

South glaze Area: 132

SE Facade area: 258 Angle of 110 degree

SE Glaze area: 78

East Facade area: 93

E glaze area: 10

N Facade area: 704

N glaze area: 28.8+9.6+3.84 = 42

NW Facade area: 135 Angle of 280 degree

NW glaze area: 9.6 =10

SW Facade area: 196 Angle of 250 degree

SW glaze area: 39

Roof (25,189): 363

Roof (0,180): 171

Figure B.2.4: Some essential input data of the final form for SIMIEN simulation

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