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Symbiotic Rooftop Green Structures and its application at Saupstad center

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Master of Science in Sustainable Architecture
Submission date: May 2022
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Abstract

With changing climate and progressive environmental degradation, urban agriculture (UA) is gaining importance as a nature-based solution for sustainable cities. It promotes new business model for farmers, citizen engagement, environmental and social benefits, new urban aesthetic, and acts as an educational tool. Given this, the Saupstad center at Trondheim is identified as a potential site for exploring a rooftop greenhouse (RTG) as a part of Trondheim Kommune's area development programme. The existing building is reprogrammed as a community center with food hall, community kitchen, bakery, and retail facilities to work symbiotically with the greenhouse.

As a part of this thesis, analysis has been done on RTG's envelope, crops grown and their impact on energy loads is performed. On overall analysis of the building integrated with RTG, it is observed that the net heating load and cooling load decreases. The RTG acts as a thermal buffer from above, thereby reducing heat losses from the building below. The structural shafts enable the residual heat flow from kitchen and bakery to the greenhouse for its heating requirements. It also uses the CO2 from the users in the building to aid the growing of crops. This symbiotic cycle is explored in this thesis to understand the energy savings and architectural implications at building and neighbourhood level. Consequently, this thesis showcases the potential of integrating rooftop greenhouses in the design of a community food space.

Acknowledgement

This thesis is the culmination of efforts, hard work and interests of many. I would like to express gratitude to my team of mentors for helping me realise this project.

I thank Neil Alperstein for consistently helping from the start of the thesis in finding the right site to conveying critical guidance and insights throughout the journey. It helped view my project at various perspectives from urban to technical scales. Thank you being an inspiration and constant source of energy. Dr. Ferne Edwards for timely suggestions and insightfulness related to communal food practices and habits. I am grateful for the food for thought you have shared with me. Dr.Inger Anderson for her critical insights on the energy studies and sharing useful resources.

I would like to thank Knut Hovland for the initial understanding of Nordic greenhouses and state of art technology at BBBLS. I thank Rett Hjem arkitektur and Saupstad Frivillig for meeting with me and sharing project inputs.

And to complete it, my deepest gratitude for family and friends for their constant support and compassion without which I can’t be where I am now.

ABBREVIATIONS

CO2 - Carbon Dioxide

CO2eq - Carbon dioxide equivalents

DF - Daylight factor

DLI - Daylight Integral

ETFE - Ethylene tetrafluoroethylene

GHG - Greenhouse gas

GWP - Global warming potential

LCA - Life cycle assessment

NIR - Near Infrared radiation

PAR - Photosynthetically active radiation

PPFD - Photosynthetic photon flux denisty

RH - Relative humidity

RTG - Rooftop greenhouse

SDG - Sustainable development goals

SHGC - Specific heat gain coefficient

UV - Ultra violet

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INTRODUCTION

This section introduces the thesis topic starting with background for the need and potential of the study. The scope of the thesis is further discussed and methodology is framed out.

Background

Urban agriculture(UA) is being encouraged as a strategy to reduce food imports while offering varied benefits. Environmental emissions from transportation are highly reduced by growing locally. It also provides the opportunity for local citizens to gain knowledge and first-hand experience on food production, thus increasing transparency and provides local job opportunities. UA can act as an educational and social tool along numerous health benefits.

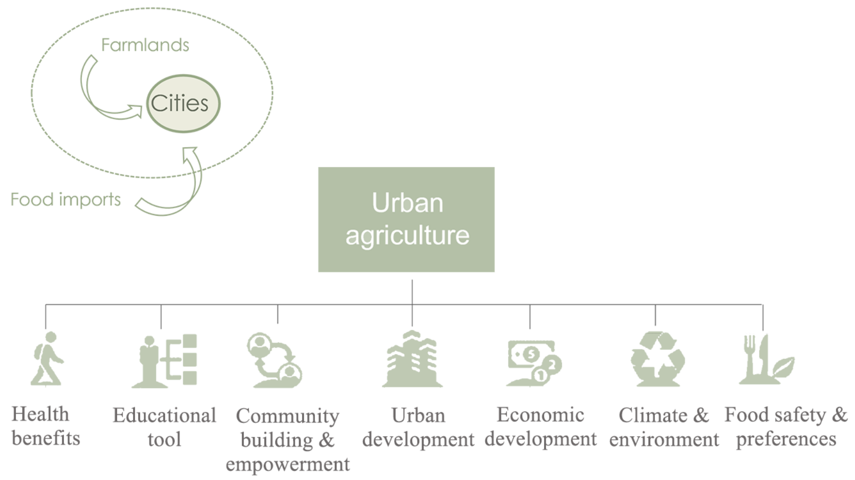


Figure 1: Illustration showing food flow into cities and factors influenced by urban agriculture

It is predominantly of two types: On ground farming and building integrated farming. Building integrated farming is explored in multiple ways among which rooftop greenhouses or RTGs is studied in this thesis.

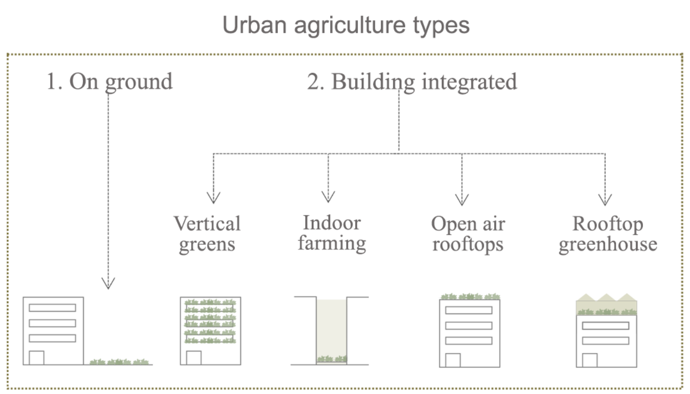


Figure 2: Urban agriculture types

RTGs offer various opportunities. They use the otherwise vacant rooftops in urban areas. It can benefit from access to sunlight at roof level. They reduce exploitation of land as well as save up on land costs. From building perspective, rooftop greenhouses can use the building heat for energy saving measures while acting as a thermal buffer from above. It can be designed to add to the circular food systems in the cities.

Along with these benefits, they also have some challenges to address. Construction on existing structures could be a limitation with respect to structural loads, aesthetic considerations, and allowance in building regulations, thus requiring them to be designed with a new building or to search for only capable existing structures. This could result in higher initial investment costs, but they can be compensated with time through food productions and energy saving costs. Their social and environmental benefits could be used gain investment support from authorities and other investors.

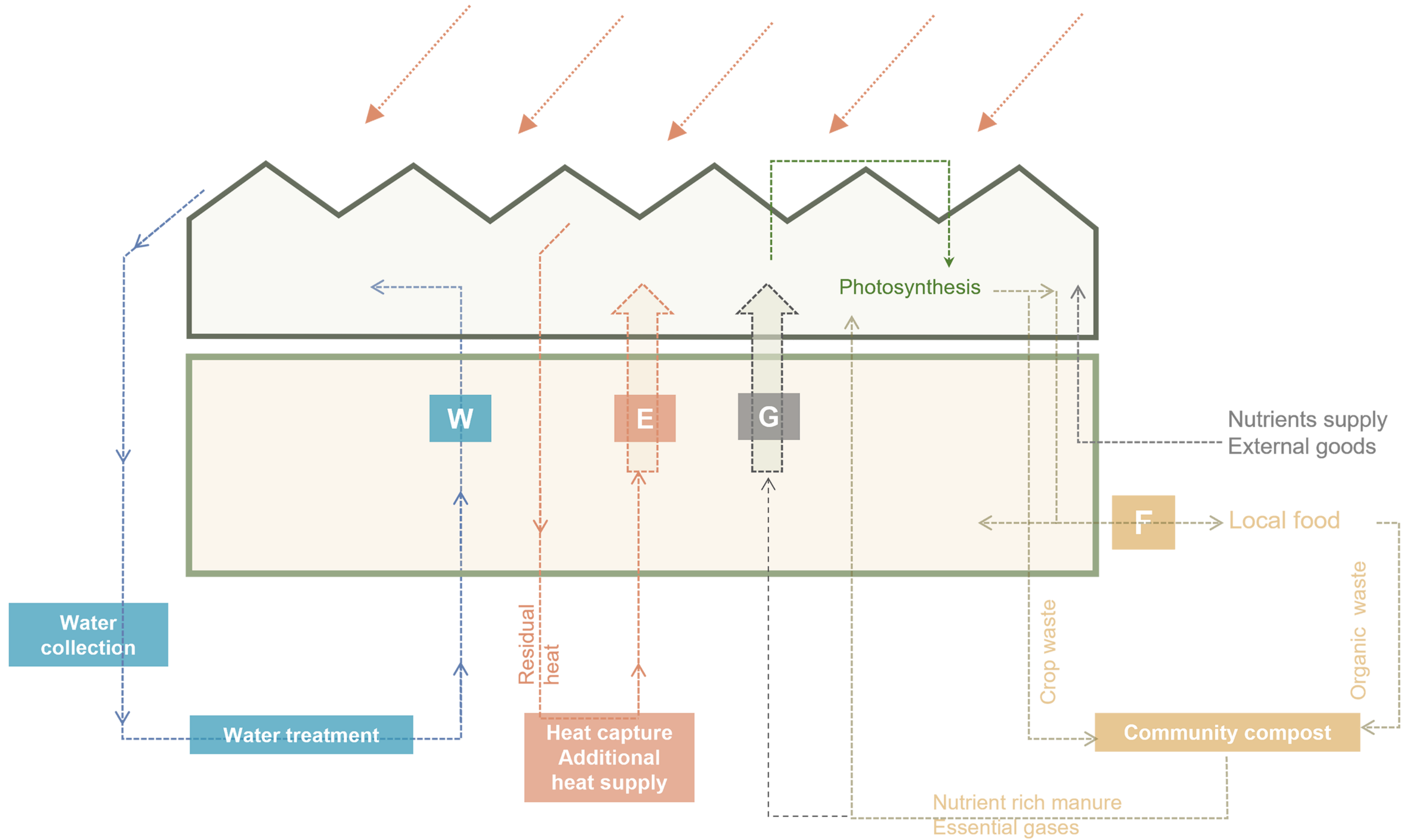


Figure 3: Symbiotic cycle of RTG and building

Aim

To design a sustainable RTG on an existing building and to study the possible symbiotic relationships of a RTG at neighbourhood and building level

Scope

The scope of the thesis involves the following:

(i) Finding a suitable site to explore the thesis topic and site analysis to understand existing urban and building features that impact design,

(ii) Design proposal for the existing building and greenhouse through architectural drawings and visualizations,

(iii) Symbiosis at neighbourhood level:

- Exploration of multiple programmes to work with a greenhouse (e.g. supermarket, restaurant, gym) for mutual energy exchange, social potential and economic benefits.
- Transportation and services integration
- Waste management and possibility of circular food systems through composting.

(iv) Symbiosis at building level:

- Thermal buffer impact of the greenhouse on the existing building,
- Heat & CO_2 capture from various occupational activities that can be used to grow plants,
-Rain water harvesting for water based cultivations

(v) Greenhouse design

- Envelope study
- Analysis on type of crops grown, and business model adopted for the current context.

Methodology:

Table 1 : Methodological framework

Primary method	Secondary method	Process & Outcomes
Theoretical framing	- Literature review - Talks with stakeholders,	- Understanding the concept and research done on RTGs - Assessment of potential sites under study in terms of thesis relevance and Saupstad Center at Trondheim was chosen. Drawings obtained had details regarding layouts only. Assumptions were made for structural system based on visual study with the help of the structural engineer.
Urban and Building assessment	- Site visit - Site analysis on available drawings using climate consultant and grasshopper plugins - Stakeholder interviews	- Climate analysis to have a framework on temperature, illumination and humdity levels and its implications - Neighbourhood analysis: various building programmes in the neighborhood, transportation routes, building services in the context - Rooftop analysis: light & shadow study to understand the rooftop potential for a greenhouse - Existing building study: to understand the structural system and need for reinforcements, to study the current building programmes to understand the feasibility of integrating RTG
Design exploration	- Design tools (sketching, autocad, rhino and sketchup) - Supervisor - Grasshopper with Honeybee for energy	- The process started with exploration of various programmes to work with a greenhouse and zoning proposal. The initial layout was done considering passive strategies accounting daylighting, natural ventilation and rain water harvesting and to understand circulation, connection between various functions and service routes. - Structural system for the RTG was proposed on consultation with structural expert based on assumptions made. Once the basic design was set, the materials for the envelope were studied for its thermal perfomance, embodied emissions, light transmittance and other factors. This gave the intial parameters for energy studies. - Energy modelling on Honeybee was conducted to understand energy balance and further steps were taken to reduce the energy loads. Crops grown indoors were analysed to see which needed the least heating loads. Other technical systems for room conditioning were studied and chosen. - Secondary research was done throughout the process to inform the design and the progress was discussed every other week with the supervisors for critical perspective.

The report is divided into four main chapters: i). Site and Climate, ii) Design proposal, iii) Greenhouse, iv) Symbiosis. Finally the main findings, limitations and further work are discussed.

2

SITE AND CLIMATE

From the various sites studied, the Saupstad center is chosen as the main case for this thesis. This section introduces the site and analyses it at neighbourhood and building level for inferences. It briefly discusses the current proposal for the site. This thesis proposes an alternate concept based on the analyses. The climate of Trondheim is studied to understand its implications for the greenhouse.

Site introduction and analysis

The site chosen for this thesis is located at Saupstad, Trondheim. It is part of the Saupstad center housing other common urban infrastructure such as Helsehus, Sobstad helsestasjon, Kultursenter and Bibiliotek. This center is the common hub catering to both Saupstad and Kolstad and is under Trondheim Kommune's area development programme for upgrade. The objectives are listed below:

1. Promote quality of life and health
2. Development of competence in youth
3. Sustainable district with high quality infrastructure and public spaces
4. An inclusive district with good meeting places and opportunities for participation

Context:

Towards the north runs Saupstad ringen running around the whole neighborhood and connecting to the main highway. Towards the east is the school axis with Tiller VGS, Heimdal VGS, Huseby skole and Kolstad skole. There is a need to connect the school axis with the center. Further east and towards north and west are residential developments.

The existing building in the site is double storeyed, owned by Coop and currently houses Coop Xtra, Gjenbruk, 3T gym and a cafeteria.

Figure 4 : Neighbourhood plan showing site and building sin context, circulation and school axis

Figure 5: Google aerial image showing site and immediate context

Proposal at site by *Rett Hjem arkitektur* company

For the current site, Rett Hjem currently proposed residential developments with lower floor commercial. The proposal looks at three residential blocks on the current site as well as the area towards the south where there is parking right now. The Saupstad neighbourhood has only one space where multiple public infrastructure are located, which is the current site. This design proposal doesn't allow for an open public space. It disperses the public nature of this site. Hence this thesis looks at an alternate proposal which brings the public infrastructure together and allocates the residential blocks at a distance as show in the figure 7.

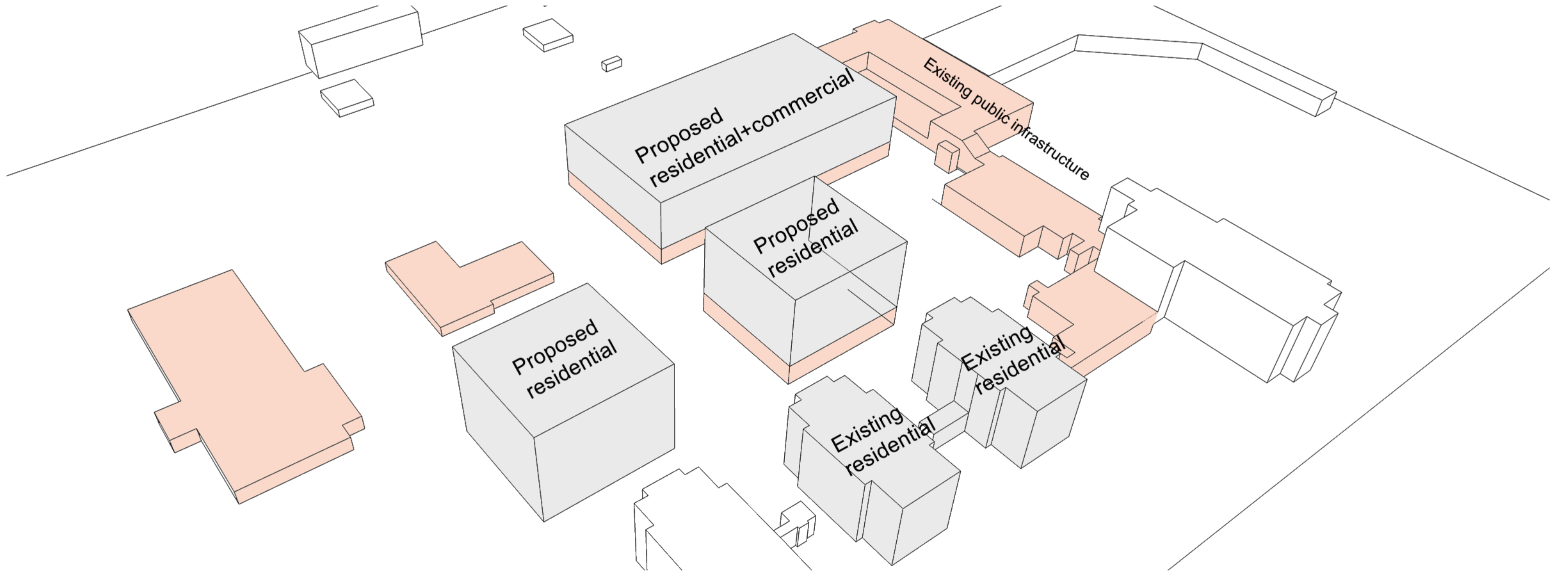


Figure 6: Current proposal by Rett Hjem with residential blocks and lower floor commercial

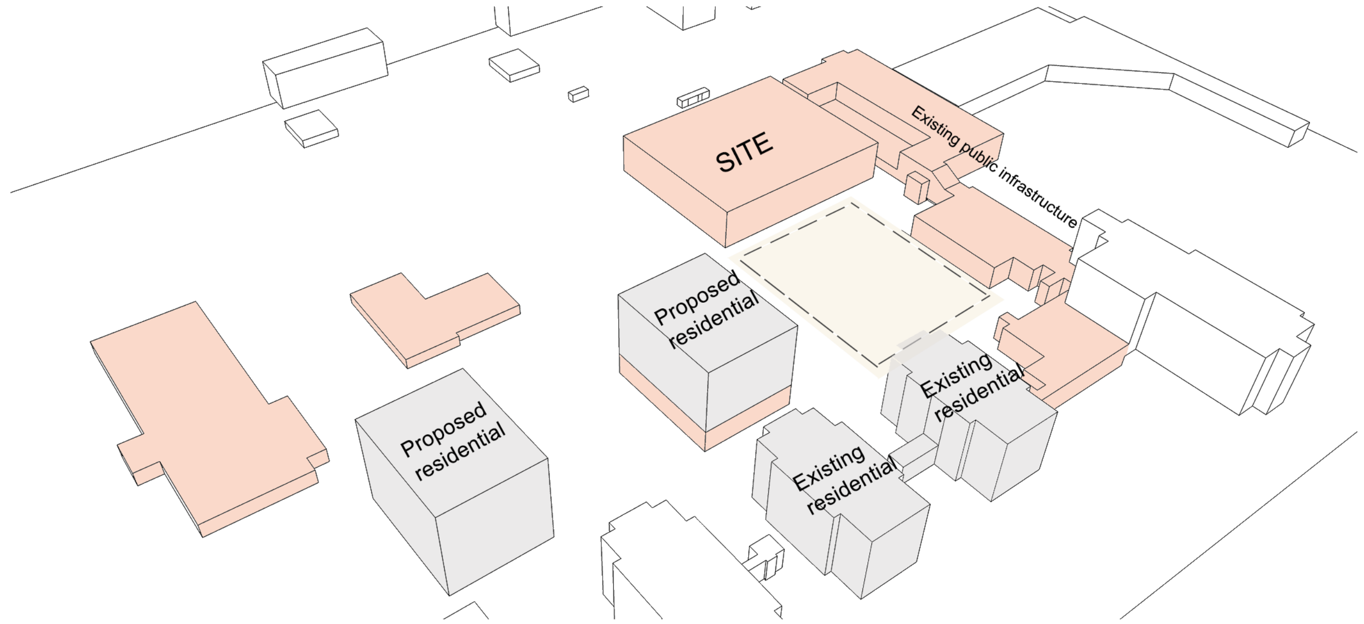
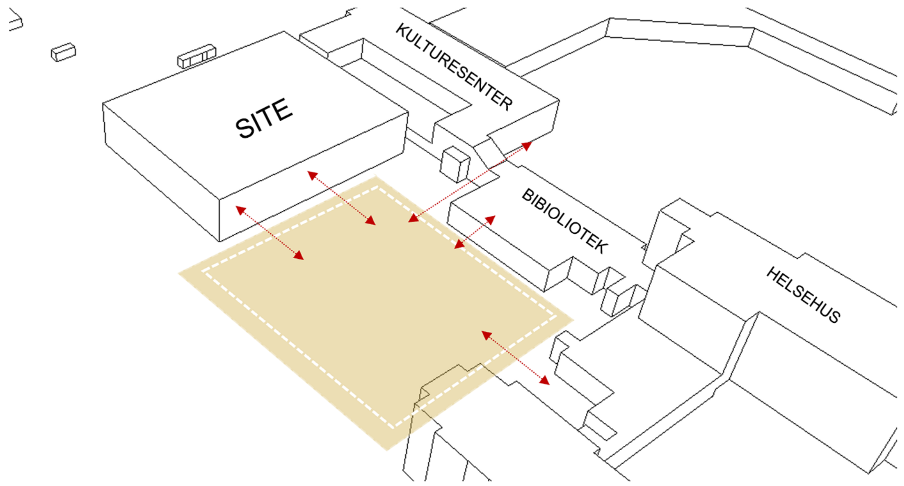
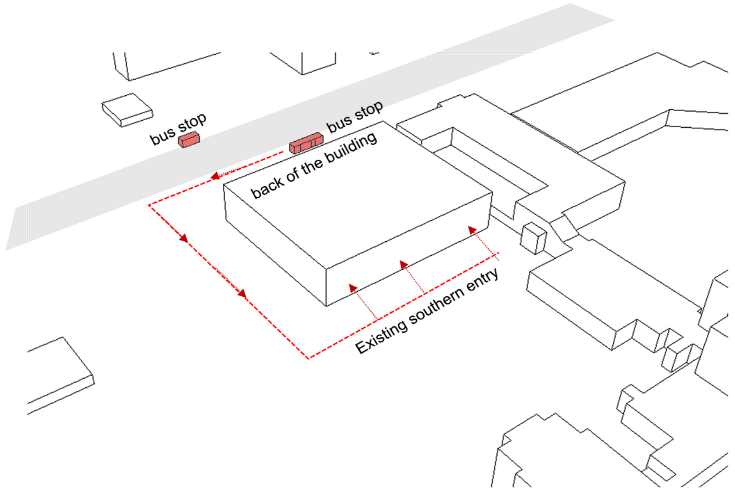


Figure 7: Alternate proposal with congregational space for all public infrastructure and relocated residential blocks with lower level commerical

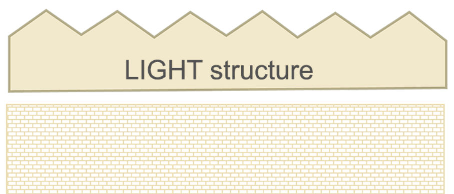
Site inferences



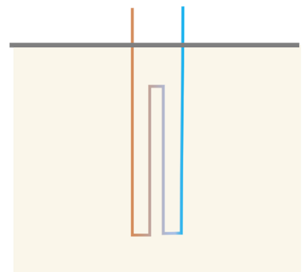
1. Need for congregational space connecting all public buildings



2. The building currently has southern entry with bus stop and main driveway in the north. The north facade of the building gives the impression of it being the backside. The north front can be activated for it to be inviting.



3. Existing building can't take in addional load of an entire greenhouse. Greenhouse structure needs to be designed accordingly.



4. Use of bedrock for ground source heating.

Figure 8: Site inferences

Climate analysis

Plant requirements

Suitable climate conditions are highly important for plant growth. Photosynthesis works well between 20ºC and 25ºC and comes to a saturation when sunlight level is 350W/sqm. The climate study for the site was done to get basic data on temperature, humidity and illumination ranges. Based on the plant requirements tabulated below, the following climate graphs were analysed.

Temperature	20 to 25 C
Photoperiod per day	16-18hours/day
Relative humidity	50 to 70 %
Illumination	700-2500 lux
CO2 level	1000 to 1500ppm
Air movement	0.3 to 0.7m/s
Outdoor air supply without CO2 enrichment	61 to 90 m3/m2h

Table 2: Indoor growing requirements for plants

Daylight

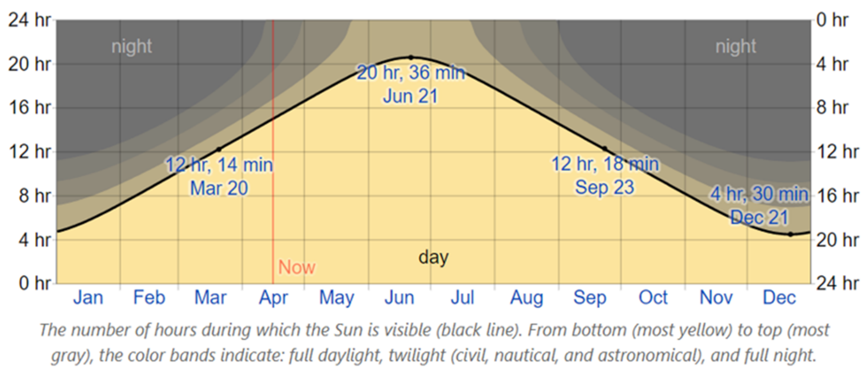


Figure 9: Daylight levels of Trondheim (© WeatherSpark.com, Obtained on May, 2022)

The daylight hours in Trondheim vary from 4hr30min in December to 20hr36min in June as seen in figure 9. Given that the required photoperiod ranges from 12- 20 hrs, there is need for artificial lighting in winters and light screens in summers.

Temperature

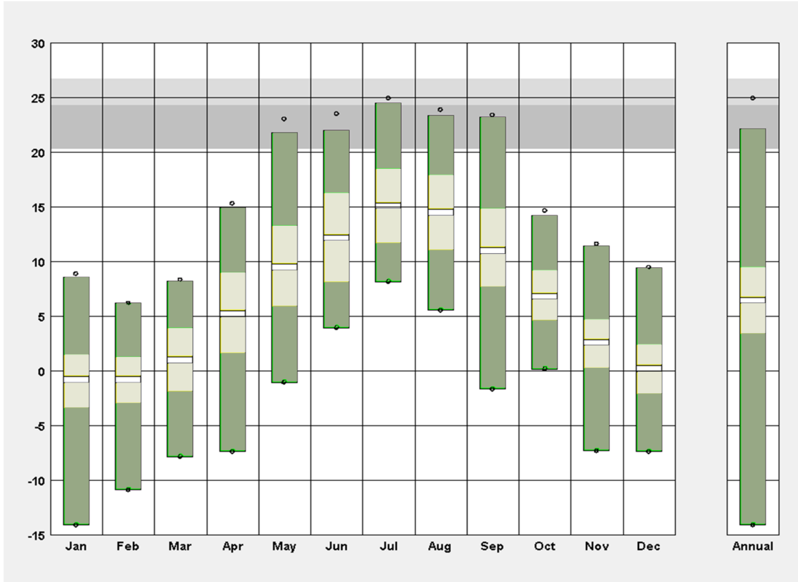


Figure 10 : Temperature graph (© Climate consultant 6.0, Obtained on May, 2022)

The average temperature ranges from -15 to 10ºC in winter to 7 to 25ºCin summer with only 3% comfort conditions specifying need to retain heat and supply additional heating.

Rainfall

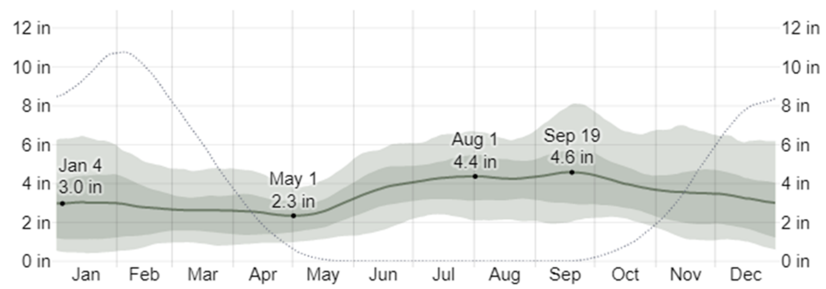
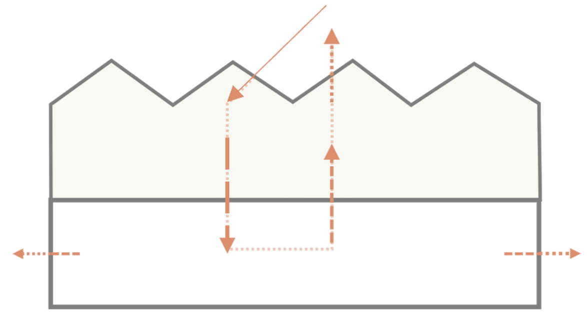


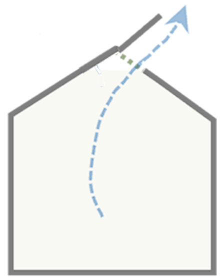
Figure 11 : Rainfall graph (© WeatherSpark.com, Obtained on May, 2022)

Trondheim receives rainfall almost every month and has a good potential to harvest it. Though Norway has no water scarcity currently, this can be adopted as a circular strategy.

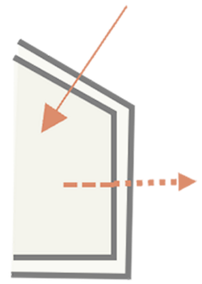
Inferences and strategies



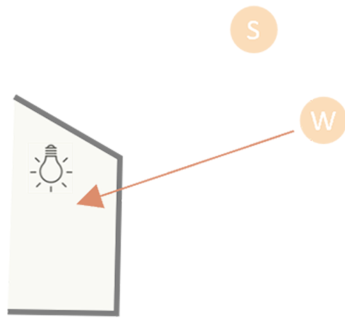
THERMAL BUFFER: Greenhouse can act as a thermal buffer in storing internal heat of the existing building.



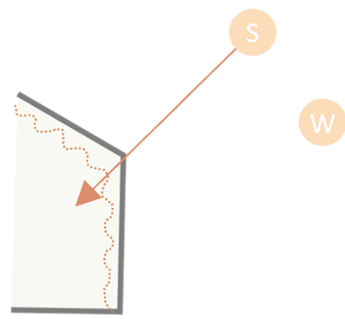
NATURAL VENTILATION during over heating



ENVELOPE DESIGN to maintain optimal indoor temperature for crops and users



ARTIFICIAL LIGHTING needed in winter



DAYLIGHTING in summer along with LIGHT SCREENS for darkness

Figure 12 : Inferences and strategies

3

DESIGN PROPOSAL

This section starts with the concept and design strategies followed in the development of the architecture. All the drawings are presented to visualise the space and support in further analysis.

Concept & zoning

Based on the analysis on site data and looking at various programmes that can work with a greenhouse, the design proposal for a community center was made with the following programmes: foodhall with stalls , multipurpose space for screenings, meetings, community kitchen , community bakery, zero waste store and rentable spaces. The existing gym at the basement is retained. Greenhouse is proposed at the second floor.

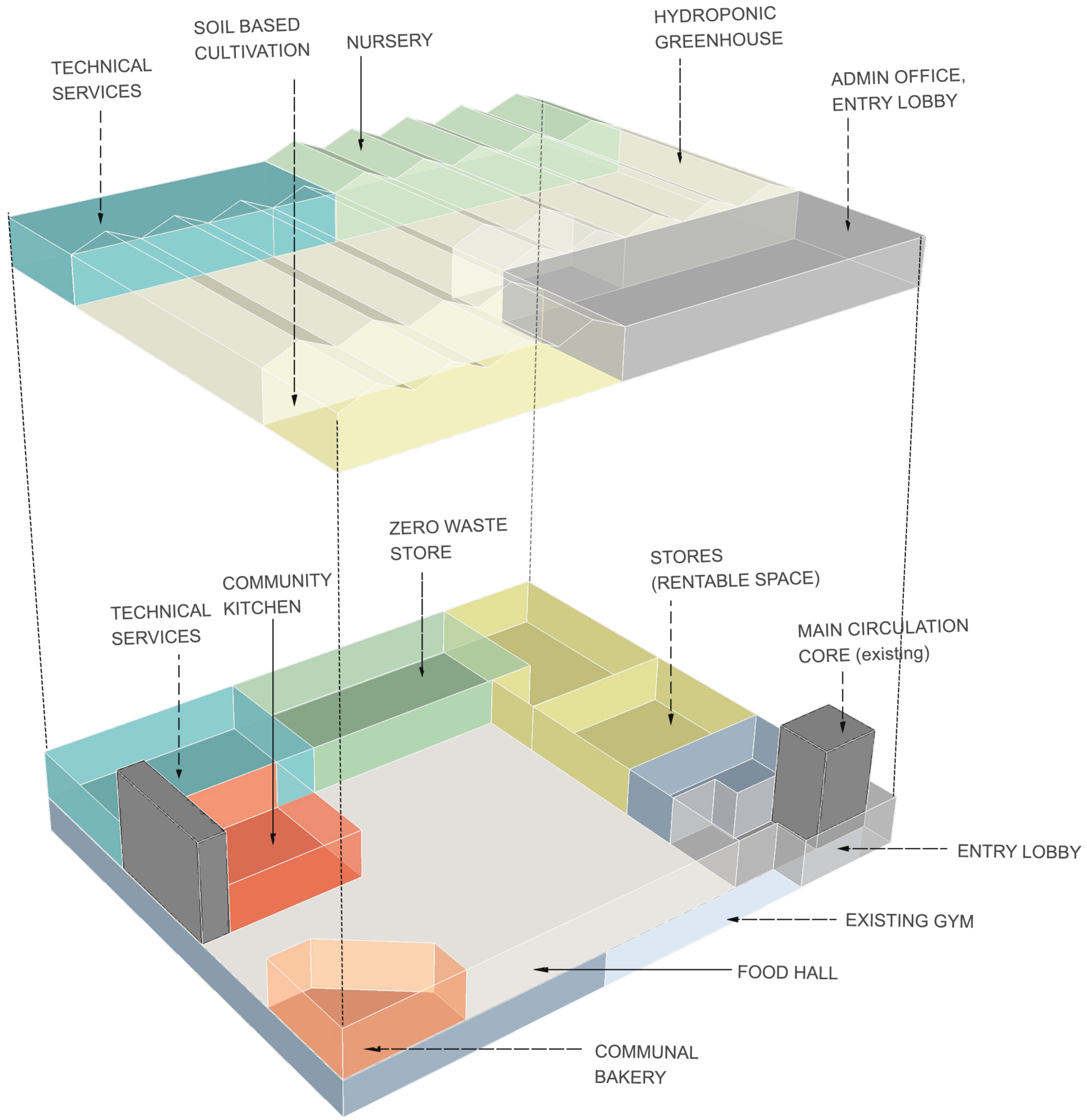
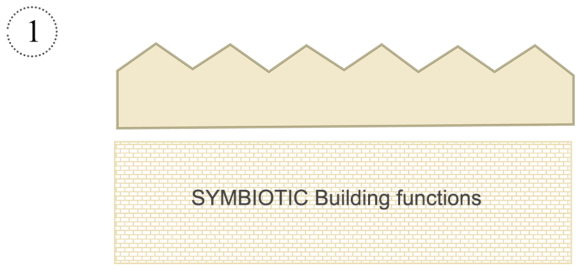
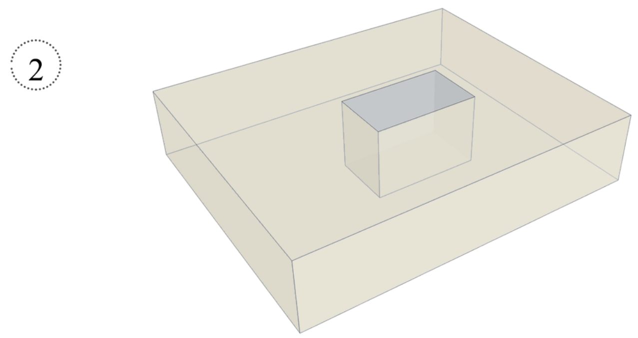


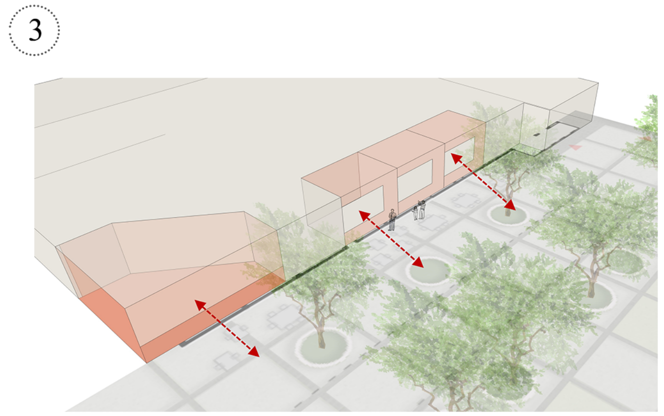
Figure 13 : Exploded 3D showing zoning of RTG and building



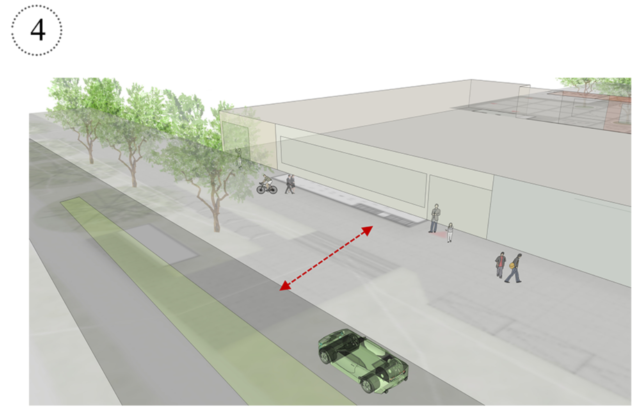
Existing building houses symbiotic programmes that work with the greenhouse such food spaces, stores, community kitchen and bakery



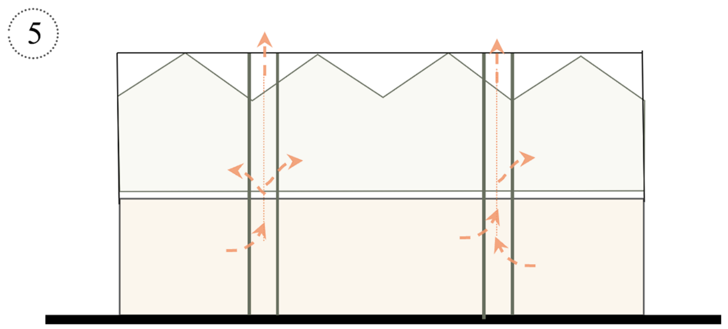
Central atrium : daylight and visual connection between interior spaces



Foodstalls and bakery as sensory devices to activate the urban space.



Northern facade to have stores for frontage from the main driveway.



Using proposed structural system to work as shafts for heating, ventilation and CO2 supply

Figure 14 : Concept and design strategies

Site plan

1. The site plan shows the design proposal at first floor level along with the context buildings and school axis. The building has multiple entries in the north, south and east. The main entrance to the community center is in the south-east that uses the existing circulation core. Towards the north, a store working the greenhouse is proposed to activate this facade.

2. Since Saupstad lacks a strong public space , an urban congregation space in the form of a plaza is proposed. It connects the existing Saupstad Helsesenter, Bibiliotek, Kultursenter and Helsehus providing a spillout space in the form of an amphitheater with a central feature element. The amphitheater is a natural outcome of the existing level difference from north to south.

3. The current entry to this urban plaza is through the buildings between Helsesenter and Bibiliotek from the bus-stop and Kolstad. This connection is extended to connect the plaza and the school axis as well.

4. Food stalls are proposed in the south front of the building to activate the urban space. Towards the west, the building functions extends into a kitchen garden connecting with the community kitchen and greenhouse above.

5. The services are congregated towards the northwest corner, providing for the greenhouse and stores at first floor. The store has a collection point for waste. The household waste is used for the compost in the kitchen garden.

Site Plan and Section 1:1000

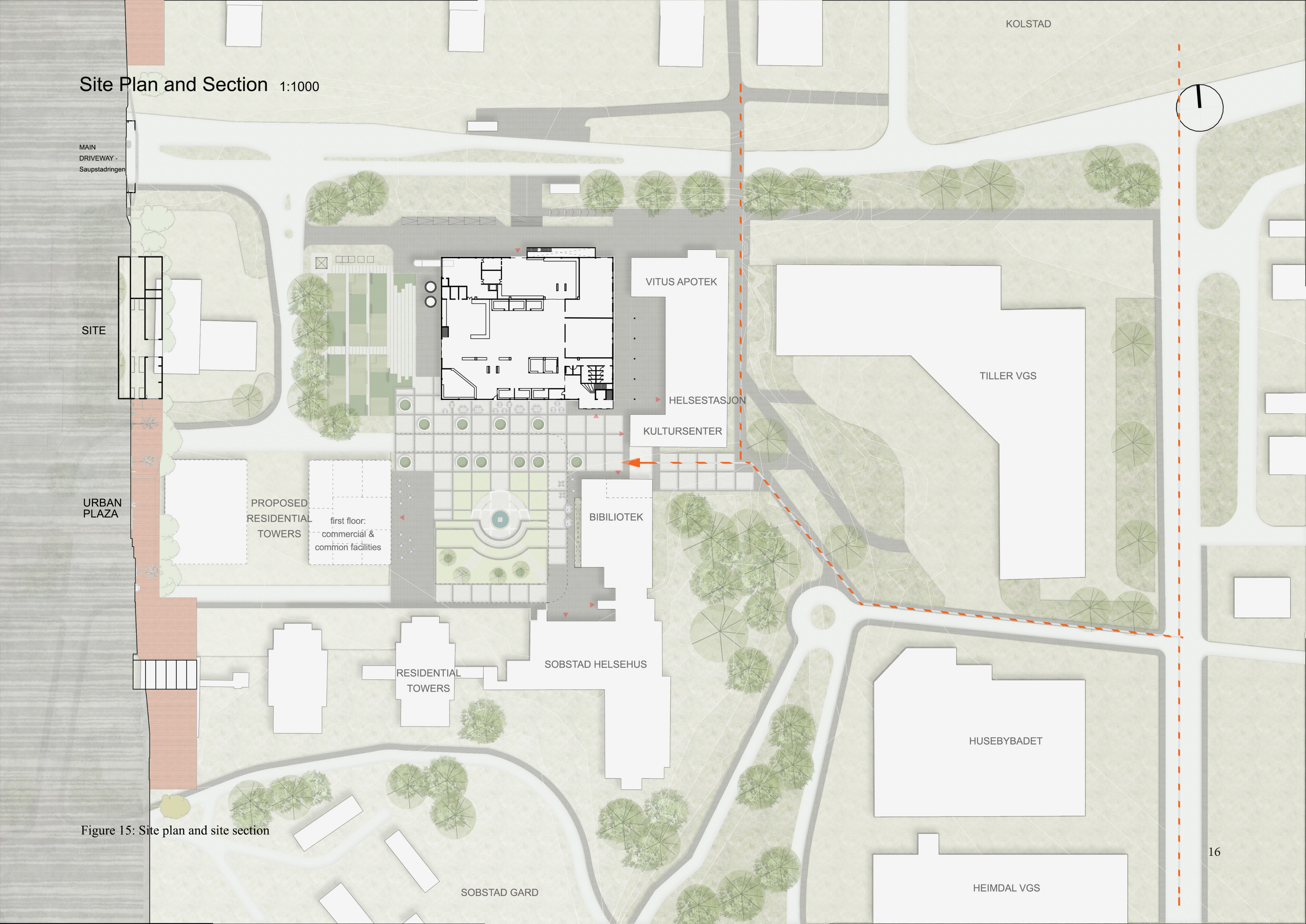


Figure 15: Site plan and site section

First floor plan

1. The overall zoning looks at public food spaces and main entrance to the south and west connecting with the urban plaza and kitchen garden. Towards the north are services, stores for frontage and proximity to the main driveway, Saupstadringen. Towards the east are rentable store spaces that open up to the alleyway which is currently used for pedestrian movement.

2. The main entrance to the community center is in the south east that uses the existing circulation core to go to the greenhouse above and existing gym below.

3. Moving towards south and west, the food stalls and bakery are located facing the plaza. They are connected internally with a multipurpose space for dining, informal meetings and screenings. This large space is lit by an atrium in the center.

4. The store in the north is proposed as a zero-waste store. A zero-waste store is a concept that sells fresh produce, grains and other utilities with no or reusable packaging. they house refill stations for regularly used products. This store also has a collection point connected with the service room.

5. The alleyway on the east used by pedestrians is brightened up introducing wall murals and more openings into the building.

First floor Plan 1:250

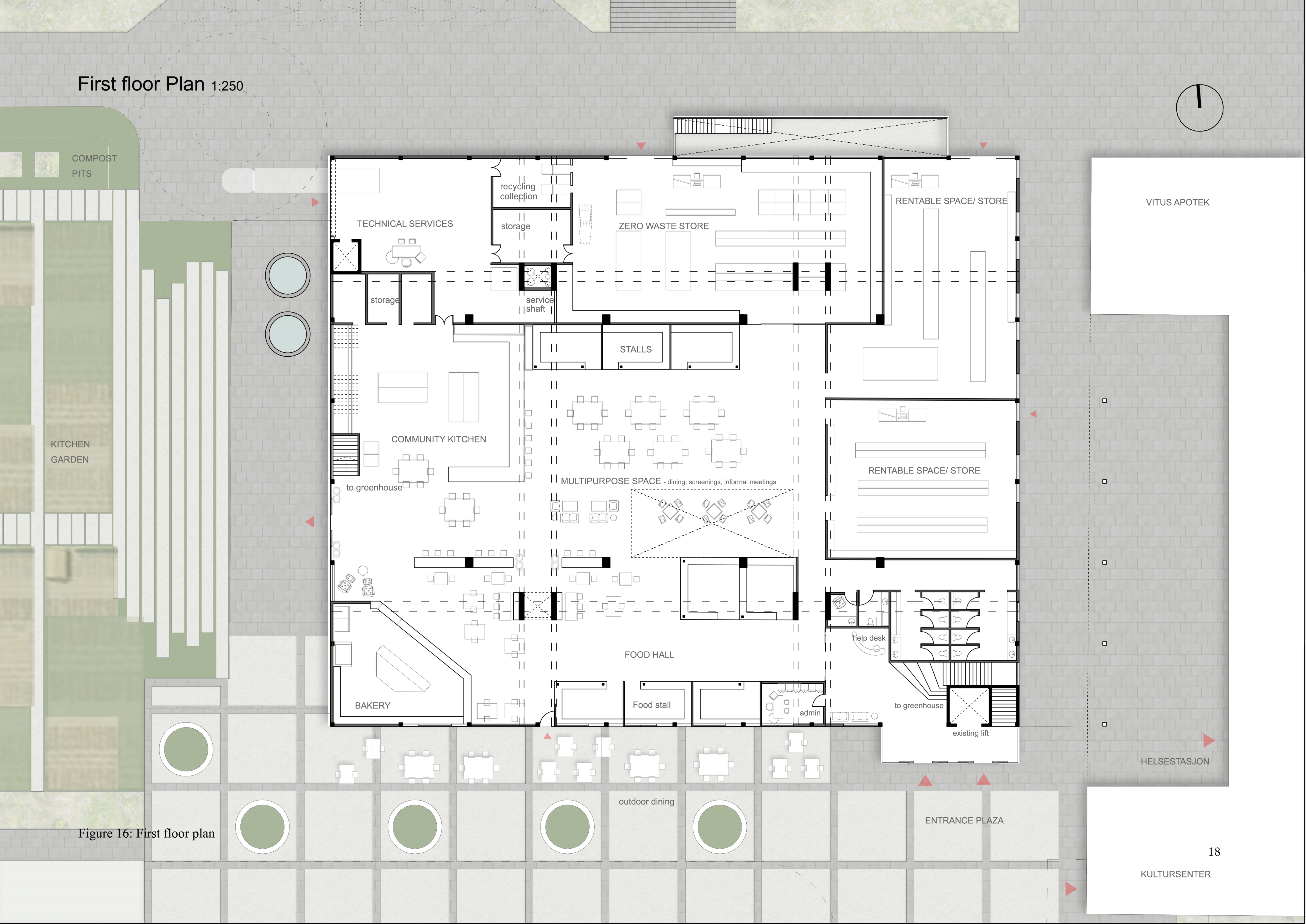


Figure 16: First floor plan

Second floor Plan 1:250

1. The greenhouse is zoned with entry, waiting lounge and social spaces to the sun benefiting from south sun, hyrdoponic greenhouses facing east -west to get direct sunlight almost throughout the day and in the north are services, offices and nursery as buffer spaces to avoid heat loss from the greenhouse to the cold side.

2. The main entry to this floor is from the south east which uses the existing lift and proposed stairs.

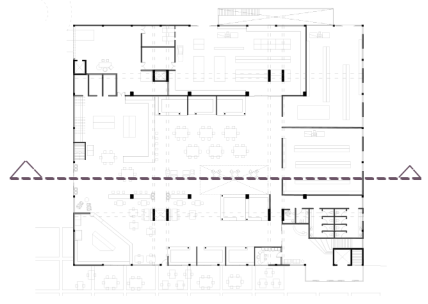
3. Soil-based cultivation is proposed in the south facing the urban plaza to provide a visual connect that is inviting and friendly.

4. The greenhouse is made of ETFE, which is translucent and has high light transmittance, providing daylight to all the spaces. The material is discussed in the later part of the report.

Figure 17: Second floor plan

Section 1:250

- The section is cut west to east across the atrium showing the various spaces and the indoor-outdoor connect.
- An atrium is designed to connect the greenhouse and lower floor. The lower level given its huge span(45x55m) could benefit from daylighting and also used for stack exhaust aided by extract fans. The size of the atrium is a balance struck between area of greenhouse lost to daylighting spread in the lower floor.
- The greenhouse follows Venlo standard with openings in the roof for efficient ventilation along with extractor fans to aid stack ventilation.
- The plants are suspended from the greenhouse roof structure to reduce the weight load on existing building.
- The greenhouse is made of ETFE with light transmittance of 94% providing diffused light through the whole space.


Keyplan

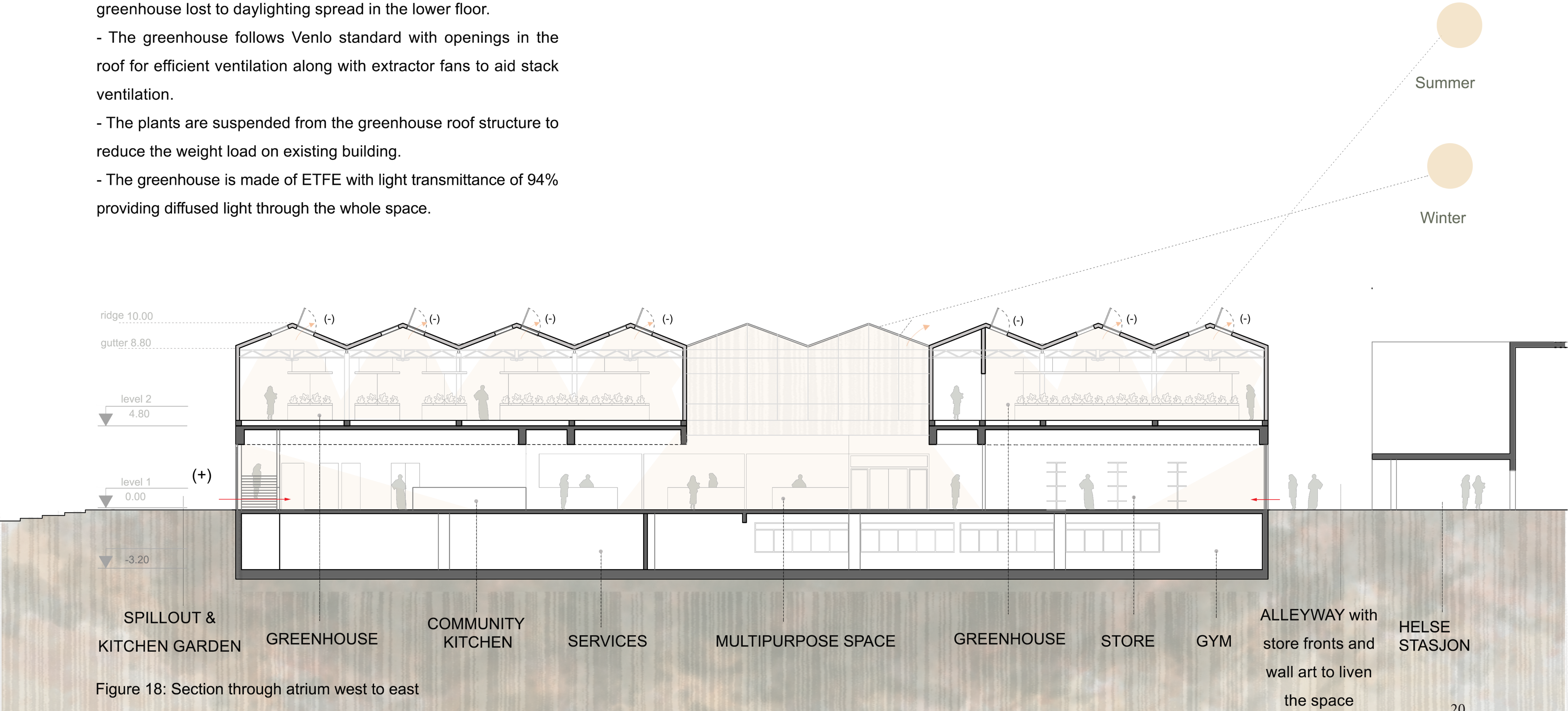


Figure 18: Section through atrium west to east

Elevations 1:250

Figure 19: South elevation - viewed from the plaza

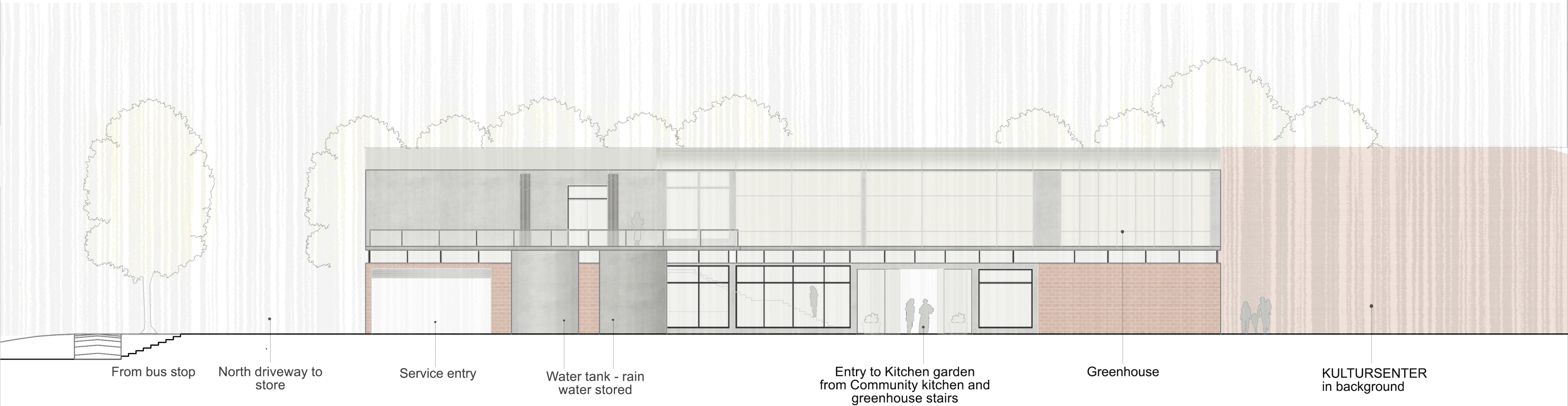


Figure 20: West elevation - viewed from the kitchen garden

Structural system

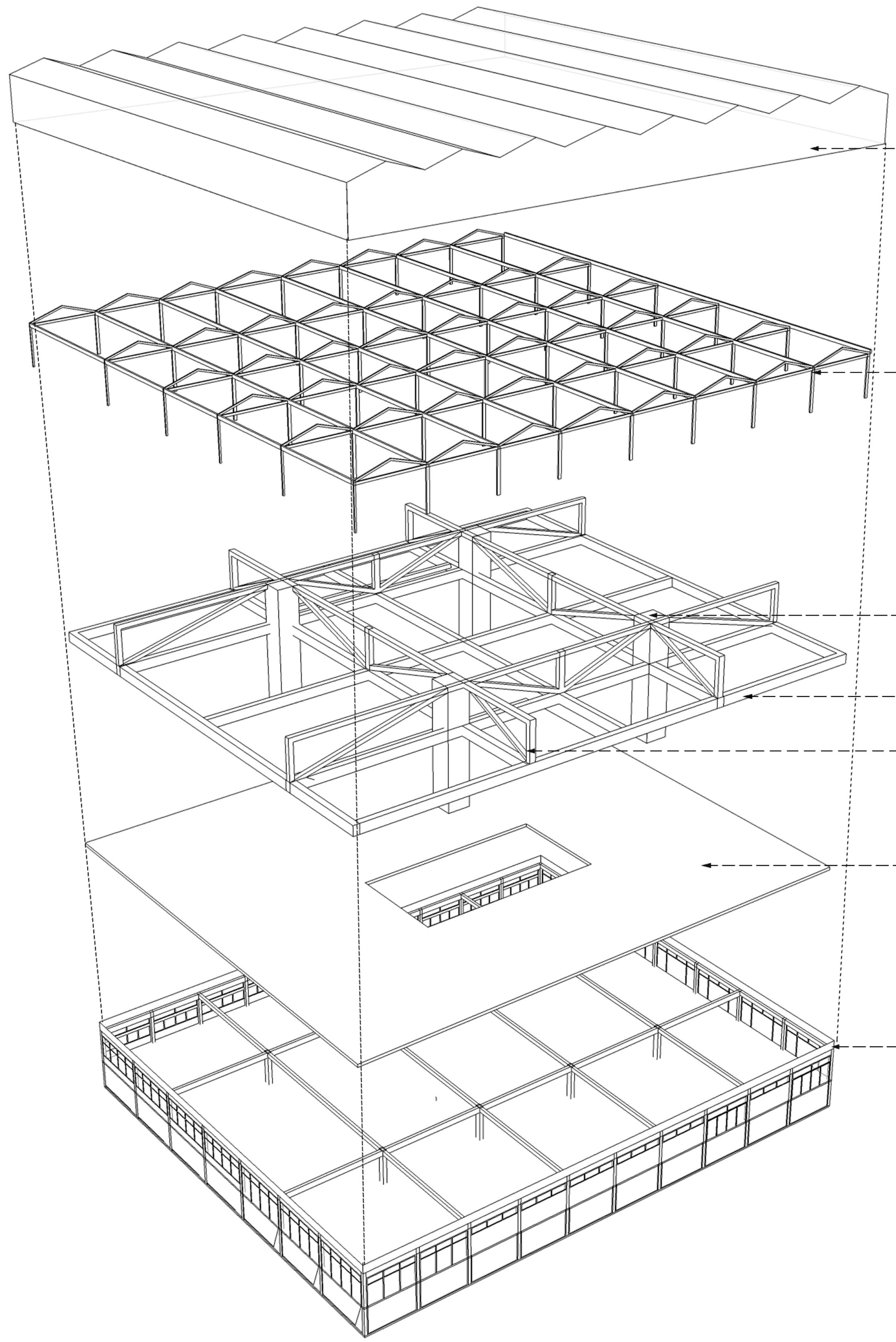


Figure 21: Exploded 3D view of proposed structural system with the existing structure

1. Drawings for the existing structure were unavailable and hence basic assumptions(column sizes, materials) were made based on site visit and photographs to design a conceptual structure on consultation with the structural engineer.

2. On consultation with the structural engineer, it was suggested that the existing structure must have been optimised for the current load of two floors only given its building function. Hence an additional load from a greenhouse wouldn't be possible.

3. The following conceptual options were considered.

Option 1: Greenhouse load on the existing structure
- Option negated due to lack of information on its bearing capacity

Option 2: Box in a box (greenhouse reinforced outside the existing building) - Option negated because of larger span and lack of space on all sides of the site.

Option 3: Greenhouse structure independent but through the existing building in the space between the existing column-beam framework.

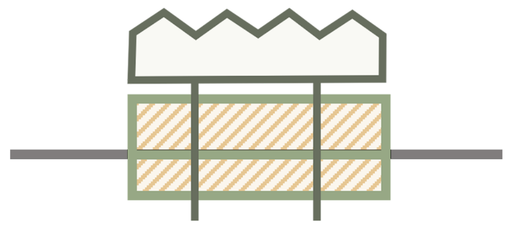


Figure 22: Conceptual options for structural system

While there might be other options that cost less and lower impact with regards to LCA, Option 3 was chosen as the best of the ones discussed. The structure wasn't detailed further due to short time frame, as I wanted to focus on other aspects in this thesis (social, energy and building envelope). This would be taken up in the next phase of design development.

4

GREENHOUSE

This section introduces to greenhouse design overview, study of envelope materials based on multiple factors. Finally it looks at type of crops, growing mediums, business models and selection of suitable ones for this case.

Overview

Venlo standard:

The rooftop greenhouse proposed adopts the Venlo standard, which is the mostly used standard among professional growers. It is designed to allow natural sunlight in while managing ventilation and rain water collection. The structure is designed to be economical and lightweight. The roof vents are fitted with insect screens.

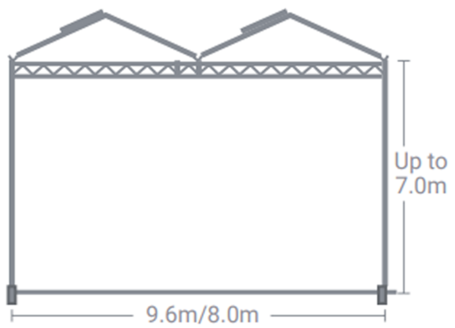


Figure 23: Venlo greenhouse (Netfim ™, accessed on May, 2022)

Structure: The structural framework is made of aluminium or steel frames which are lightweight. This reduces the structural load on the system. Looking at LCA perspective, though they have high life span. They also have high embodied emissions in A stage but have better returns in D stage, hence having high circularity value. This is adopted in the design of the framework.

Hydroponics equipment:
The hydroponic growing systems are lightweight and one of the most water efficient form of agriculture. The pipelines and other equipment used are majorly made of PVC and HDPE, which high embodied emissions. This is a trade-off in this scenario and provides an opportunity for improvement in the next phase of design detailing.

System	Functionality	Other uses
1. Growth lights	- Light that imitates photosynthetic quality of sunlight to extend photoperiods during darker days of the year.	Excess heat can be used to reduce heating demand.
2. Thermal screens	- To provide shading in summer months - To prevent heat loss through when heating is needed.	
3. CO_2 enrichment	- First supplied from indoor air from the kitchen, bakery and dining (CO_2 rich air) - Additional pure CO_2 supplied to reach 1000-1500 ppm for crop production	Excess heat
4. Ventilation -exhaust fans	- Exhaust fans fit near the roof vents help in driving the air out aiding stack ventilation - Necessary to maintain regular air movement to avoid fungal infestation	Excess heat
5. Heating	- First compensated by supplying air from the building below - from kitchen, bakery, dining - CHP or Ground source heat pump	Free cooling
6. Humidification	- Air conditioning to maintain 50-70% relative humidity	

Table 3 : Different technical systems necessary for greenhouse

Energy parameters:

Plant production in a greenhouse is usually considered energy intensive as they require high indoor temperatures and light levels. In summer, there is need for ventilation to deal with overheating. CO_2 enrichment becomes essential, which results in additional energy. Maintaining adequate humidity levels are also energy intensive. The Norwegian Horticultural association (Norsk Gartnerforbund) states an average energy consumption per sqm greenhouse is 414 kWh/sqm as on 2018 (NGF, 2020).

	1979	1985	1989	1999	2007	2010	2018
Greenhouse area, heated, acres	1,819 th most common	1,767	1,832	1,891	1,788 th most common	1,886	1709
Total energy consumption, GWh	1,269.7	945.2	981.5	971.7	905.5	884.3	708.3
Energy consumption per sqm greenhouse, kWh	698	535	536	514	506	469	414
CO_2 total emissions, 1000 tonnes CO_2*	325.1	173.8	186.6	125.2	82.3	75.2	52.2
CO_2 emissions per sqm greenhouse, kg CO_2*	184.0	95.5	101.9	66.2	46.0	39.9	30.5

Source: Statistics Norway; agricultural / agricultural / horticultural counts. Calculation for CO_2 emissions relate to fossil fuels in greenhouse production and are based on Statistics Norway's figures for energy consumption.

Figure 24: Greenhouse energy consumption over the years (NGF, 2020)

Envelope innovation:

To reduce this high energy consumption, BBBLS has worked on an envelope system that involves ETFE layers filled with soap bubbles. The soap bubbles are a dynamic system that are filled in during colder times for insulation and removed to let light. They reduce the number of air exchanges in ventilation thereby reducing CO_2 losses. (BBBLS, accessed on Feb, 2022)

Envelope study

Envelope:

MATERIAL	COST	R-value	SHGC	Light transmittance	PROS	CONS
Double Polycarbonate	$	1.4 to 1.8	0.77	83%	Very cheap, Rigid, lightweight, translucent, UV resistant , 10-12 years lifespan	Highly toxic (contains bisphenol)
Double polyethylene	$	1.5 to 1.7		60-80%	Low cost	3-4 years life span, careful installation
ETFE double layered	$$	2.0	0.75 to 0.93	94-97%	Inert, long life span, cheaper than glass counterpart, flexible	It is translucent material cutting off visual connect to the outside.
ETFE double layered (with soap bubbles 20cm)	$$$	24		82%	Very high insulation reducing heating loads	Dynamic system – requires regular change of soap bubbles
Double pane Glass	$$$, cheaper if salvaged	1.5 to 2.5	0.57	70-75%	Aesthetically pleasing, less signs of wear, high transmission of PAR and low NIR	Night light pollution , high heat losses

Table 3: Framework of various factors considered to choose envelope material

The different envelopes were simulated on Grasshopper enegry modelling to get the impact on energy loads. On simulating greenhouse with the traditional glass envelope, the heating load was 404 kWh/sqm.

On introducing buffer spaces in the north, and changing the envelope to double pane with air gap, the heating load reduced by half. This was simulated for different materials - polycarbonate, glass, ETFE.

On analysis, ETFE with soap bubbles was chosen in this case for its high insulation capacity for the hydroponic greenhouse and double glass with ETFE film for the southern zone with soil cultivation (facing the urban plaza).

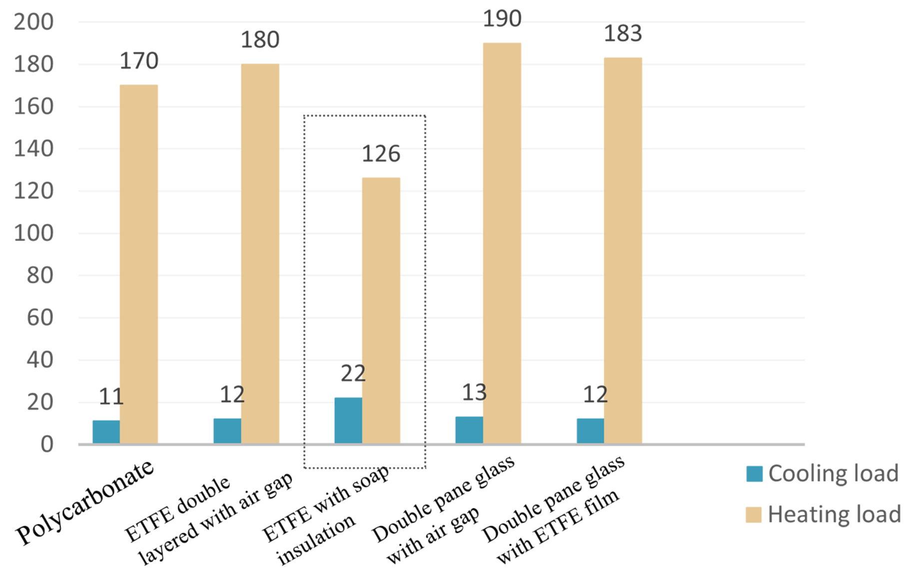


Figure 26: Heating and cooling load with different envelopes

Crops, medium and business model

Which crops to grow?

Imported crops ✓

E.g. leafy greens, tomatoes, cucumbers, eggplants, squash, melon, peppers etc

- The emissions involved in transportation are reduced immensely by growing locally.

Microgreens ✓

- Microgreens are usually grown for restaurants and are widely being adapted for their high nutritional value and unique taste.
- There is a growing trend in growing them at homes as they don't need require a lot of space.

Types of crops

Monoculture

- This type of culture is highly resource efficient because of its high yield to input ratio. It reduces the need for different type of resources hence reducing the investment and operational cost.
- It can be adopted for commercial ventures where profits are valued more than variety.

Polyculture ✓

- Polyculture has diverse design parameters for different crops such as growing temperature, medium, daylight requirements and nutrients. Crops of similar requirements need to be chosen for high yield if they are grown in the same greenhouse.
- It can be adopted for community greenhouses as it offers variety as per user's needs.

Business model

Pure yield dependent

- This model employs monoculture usually for crops high in demand like tomatoes, cucumbers etc in Norwegian context.
- The revenue is only dependent from the yield of the greenhouse.

Multifunctional ✓

- Along with greenhouse yield, this model aims to be profitable from varied activities such as education, social events, and renting out spaces for other businesses.
- It reduces the risk involved in terms of profits but needs attention to design to avoid pest infestation from varied activities.

Growing mediums

Soil culture

- Soil is used as the growing medium
- This is less tech-intensive and can be easily adopted for community spaces.
- It develops the needed human- soil connection.
- Although pests are a problem in this case, biological insects are used for control.
- The main drawback is it has high structural load in case of RTGs.

Soil –less ✓

- This is a widely used alternative to soil where similar substrates are used to grow crops. E.g. perlite, coconut fibres
- It has lower structural load than soil while having other similar characteristics and hence is a better option than soil.

Floatation technique ✓

- This is the simplest hydroponic system which uses water to grow.
- It is movable and hence flexible in terms of space usage.
- It is single layered and less tech intensive than multi-layered systems.

Hydroponics

- Water is chosen as the growing medium.
  e.g. Nutrient film technique (NFT)
- It has Lighter structural load
- This system is both water & energy intensive. For reducing water intake, rain-water harvesting is a good strategy. Greenhouses are usually designed for efficient water flow from the roof surfaces.
- It needs expertise guidance & continuous surveillance.

Aeroponics

- In this system, plants are suspended in an enclosed environment and misted with nutrient rich water solution.
- It has light structural load and less water requirement but is highly technology intensive and needs specific expertise.
- It is more expensive.

Aquaponics

- This system involves fish culture to reduce nutrient intake of plants.
- Water is recycled and hence adds to circularity coefficient.
- This requires large indoor space and the structural loads from water need to be taken care of in the initial design. Hence cannot be adopted for existing buildings always.

Growing requirements of different species

Species specific requirements used as simulation parameters:

Species	Optimum DLI (mol/m2d)	Optimum illumination levels (lux)	Photo period	Minimum temperature (Celsius)	Optimum indoor temperature
Pepper	22 to 45	1500 to 3500	<20h	12	21 to 30
Tomato	22 to 45	1500 to 3500	<18h	10	20 to 24
Cucumber	20 to 30	1400 to 2000	<12-20h	5	19 to 25
Herbs*	15 to 24	1000 to 1750	<12h	10	15 to 24
Leafy greens*	18 to 30	1300 to 2000	<12-20h	5	15 to 20
Microgreens*	10 to 18	700 to 1300	<14-16h	5	19 to 21

*depending on the chosen variety, the growing condition can vary

Table 5: Indoor growing requirements for plants

Heating setpoint	Based on species optimum indoor temperature
Cooling setpoint	Based on species optimum indoor temperature
Relative humidity	50 to 70 %
Air movement	0.3 to 0.7 m/s

Table 5 : Simulation parameters

From the table above, it is observed that peppers and tomatoes need a high illumination levels as well as higher indoor growing temperature than the other species.

Spinach, lettuce microgreens and different varieties of herbs can cope with colder climates and lower light levels, which could mean that they need much less energy for their cultivation. Also, these are crops have lesser time span of freshness and hence growing locally is an added advantage.

These crops were tested out on Grasshopper with Honeybee energy balance to find their heating and cooling loads throughout the year to choose the ones that needs the least energy loads. The simulation parameters adopted are tabulated in Table 5. The simulation model is a 2200 sq.m. standalone greenhouse (same area as the proposed).

The envelope studied in this case is ETFE double layered based on studies related to thermal performance, light transmittance, emissions and other factors. This is discussed in detail in the section ().

Energy loads of different species

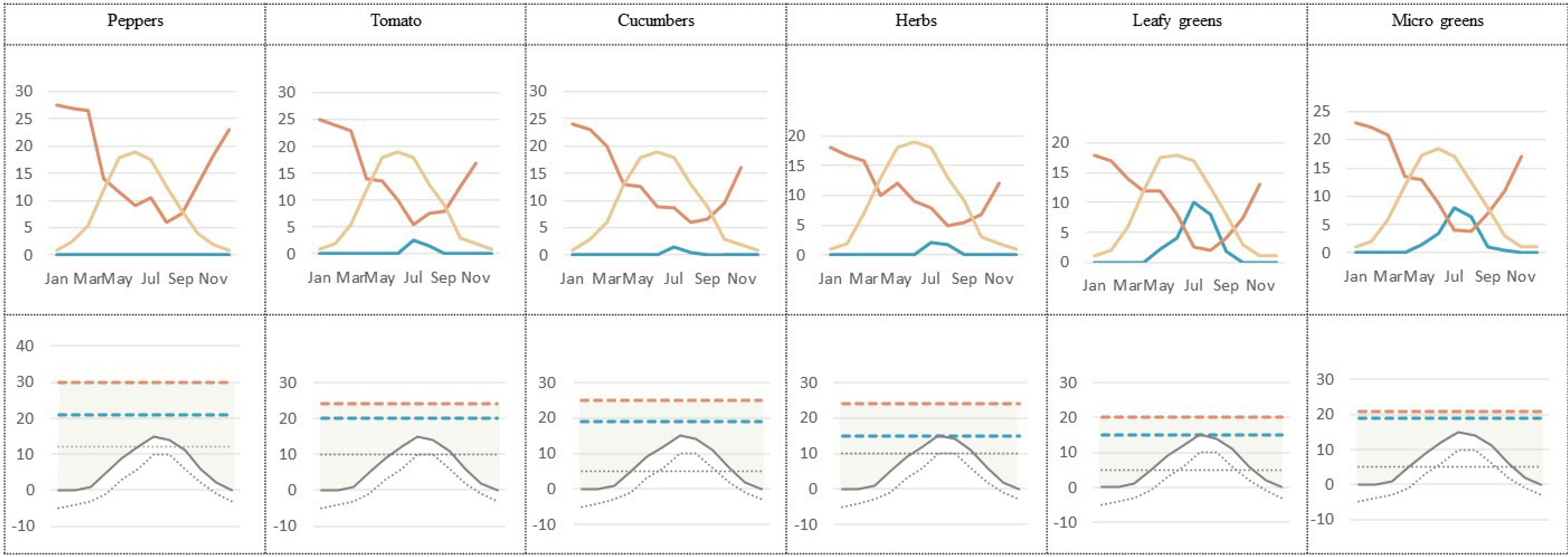


Table 6: Energy loads and indoor-outdoor temperature range for various species

Heating load (kWh/sqm)
Cooling load (kWh/sqm)
Solar gain (kWh/sqm)
Heating setpoint
Cooling setpoint
Minimum temperature
Dry bulb temperature
Dew point temperature

We observe that the heating load is the least for leafy greens and herbs and highest for peppers and tomatoes. At the same time, leafy greens have high cooling load than the rest whereas herbs have lesser in comparison.

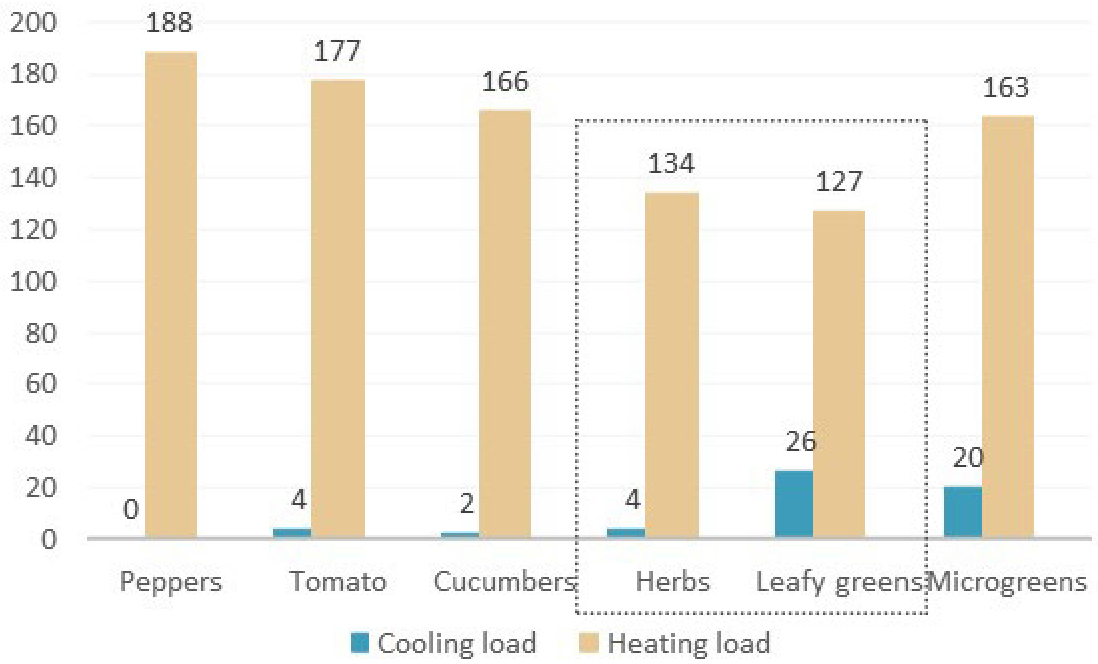


Figure 27 : Overall comparison of heating, cooling loads for different species

5

SYMBIOSIS

This section talks about the exchanges between the greenhouse and the building in the form of energy, water and CO_2 cycles. Each cycle gives a description of its functioning, potential benefits, calculations in this case if available and future work.

Energy cycle

Thermal buffer:

A rooftop integrated greenhouse eliminates heating losses through the building roof and greenhouse floor and can capture the exhaust heat resulting in energy savings.

Insulating envelope design:

The greenhouse envelope made of ETFE is design to retain heat while allowing enough light transmittance. The envelope can be further insulated with soap bubbles which provides 10 times more insulation for 10cm thickness of it. Thermal screens are another option instead of soap bubble filling which provide flexibility and are user controlled.

Ventilation during overheating:

During summer and times of overheating when the greenhouse temperature cross 26^{o}C, cool air of the building can be introduced first. This strategy helps retain the indoor CO2 levels while cooling the greenhouse. The greenhouse vents can regulate indoor air temperature for further cooling. The third option is to use free cooling from a ground source heat pump.

Heating at night and winter:

When the greenhouse temperature falls below 15^{o}C at night and in winters, the warmer building air can be introduced to regulate the temperature. The second option is to use a ground source heat pump for heating.

The energy demands were obtained from Grasshopper Honeybee Energy Modelling and Rhino for used for modellng. The obtained results were analysed with the help of case study reference.

	Heating demand (kWh/sqm)	Cooling demand (kWh/sqm)
Current building (standalone)	114	0
Building redesigned with food spaces (standalone)	59	0
Greenhouse (standalone)	126	22
Overall (Building & greenhouse integrated)	87	6

Using residual heat:

Excess heat from the building (bakery, kitchen and other spaces: equipments) - 97kWh/sqm

It is evident that integrating an RTG with a building for symbiosis in terms of energy, results in a positive net loss of heating load. The greenhouse recovers the heat loss from the building roof and uses it to heat its space. The residual heat from the building can be used especially in winter to reduce the heating demand.

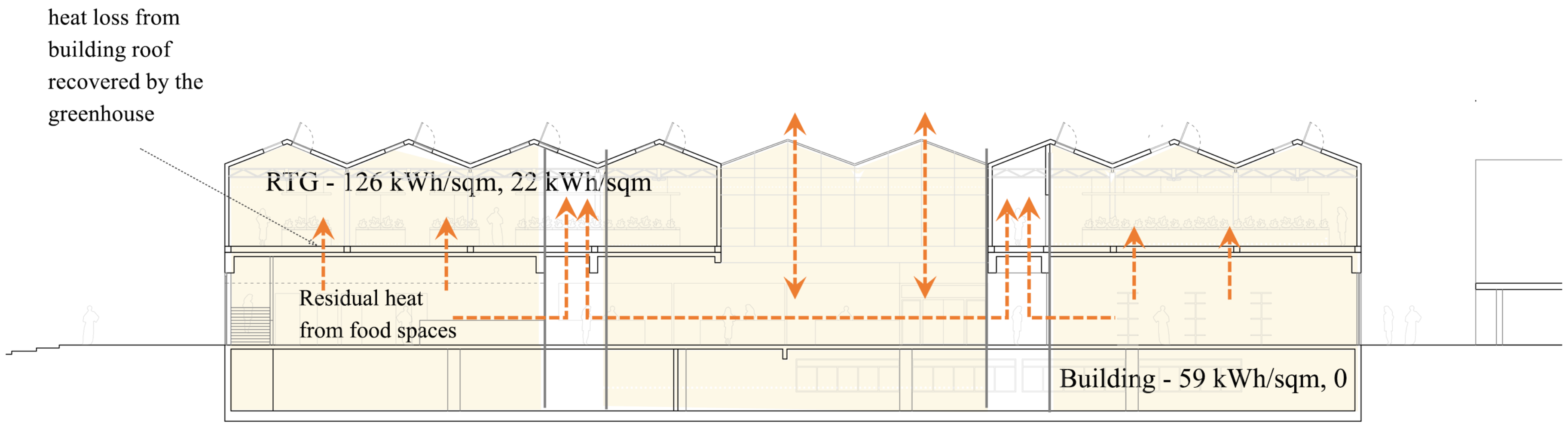


Figure 28: Energy cycle in the building

Water cycle

Water management is a key feature hence when it comes to any form mid - large scale agriculture as it is one of the largest consumers of fresh water (70% worldwide) (World Economic Forum, 2009).

Among the various types, hydroponics are the most water efficient form claiming to consume ten times less water than traditional agriculture, which is used majorly in the greenhouse for commercial production. Norway has abundant fresh water resource (European environment Agency, 2015) and hence there isn't absolute need to conserve water but for academic purpose to explore circular cycles, the topic of rain water harvesting is explored in this thesis.

Rain water harvested is stored in the water tanks, treated and used for hydroponic system, kitchen garden, building needs and ground source heating.

Calculation:

Roof area = 2106 sq.m.

Average annual rainfall in Trondheim = 1049 mm

Rain water that can be harvested = 2106 x 1.049 = 2209 cu.m.

The hydroponics water demand for leafy greens is 5-7 liters per sq.m. per day. This results in an annual demand of 2.19 m^3/m^2year.

Overall water demand for hydroponics = 1248 cu.m (for leafy greens calculated based on reference from case studies)

Water tank volume = 70 cu.m. (calculated based on case study reference(Menguel, 2014))

This shows that the crop can be grown self sufficient in terms of water needs.

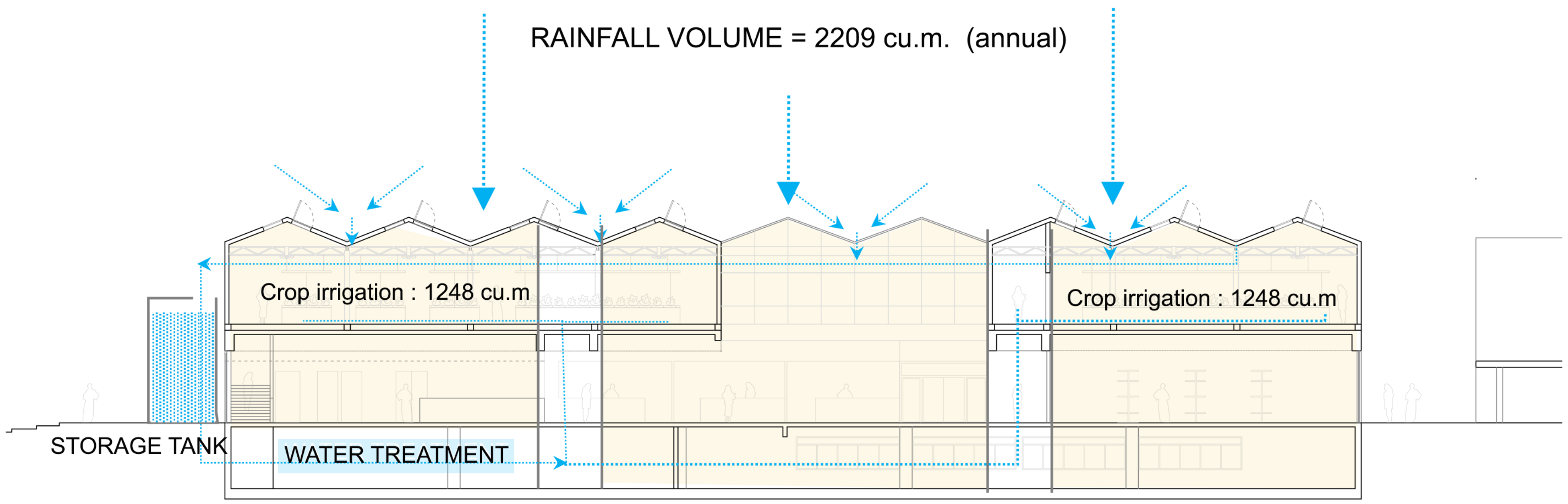


Figure 29 : Water cycle in the building

CO_2 cycle

The greenhouse benefits from the CO_2 concentration in the residual air from the building below. This acts as a source of CO_2 enrichment reducing the need for additional CO_2 to grow plants. Photosynthesis works best at higher concentrations of CO_2 at around 800 ppm and saturates at1000ppm (Menguel,2014). In contrast to energy cycle, CO_2 could be quite standard throughout the whole year.

This flow is currently proposed monodirectional from building to greenhouse. Leafy plants absorb CO_2 in the air during the day and provide fresh air. There is limited research on using greenhouse to provide fresh air to the building. This could be studied further in future.

The building programmes introduced in this project are chosen based on the heat and CO_2 they produce. . For example, bakery, kitchen and food stalls produce air with 500 to 900ppm of CO_2 (different cuisines have different levels) This value is for 10 workers and 100 person seating area. (Lee, 2001) This can benefit the crop yield. However exhaust air from cooking chimney also contains other gases depending on the cooking fuel. Exact number of CO_2 levels were unavailable to calculate in this case. This can be researched further in the next phase to establish the cycle.

Overall, CO2 enrichment from residual air of building reduces the additional need and thereby reducing economic and environmental costs.

Conclusion

There is growing emphasis on urban agriculture in Norway. This thesis shows a Symbiotic Rooftop Greenhouse integrated with the Saupstad center provides various social, environmental and economical opportunities, which works towards Trondheim Kommune's area upgrade goals.

From social perspective, food spaces such as bakery, food halls, community kitchen and food stores work symbiotically with the greenhouse in relation to food-market-waste flows developing a circular cycle at source. Along with this, they are source of heat and CO_2 for the greenhouse, enhancing this symbiotic relationship. While a greenhouse may seem industrial or commercial, adding these food spaces in the building provides an opportunity to bring the food and community closer. It creates new job opportunities for the neighbourhood.

From environmental perspective, the potential of integrating greenhouse with the existing building is demonstrated in this thesis. This reduces resource consumption for energy, CO_2 and water needs. The design of the greenhouse envelope is crucial to maintaining optimal growing climate for the plants. The type of plants grown in a greenhouse impact the energy needs of it. This thesis chooses the options with the least heating loads to reduce operational costs. Along with plant waste, there is provision to collect other household waste to be composted at site. This circles food-waste system of the project. Reducing consumption is reflected in the building programmes chosen through a zero-waste store.

Overall, the design choices and assumptions led to a symbiotic building design, exchanging resources at building and neighbourhood level. This contributes positively to urban and building sustainability.

One of the main limitations was the lack of structural data of the existing building which impacted the design of the greenhouse. This required setting some assumptions based on a site study. The exercise of exploring various structural systems was none the less useful in understanding its impact and in further development of the concept. This study could be taken up in the next phase of development and the architecture can be tuned to this.

Further research

This thesis on symbiotic urban green structures opens up various possibilities of research. While this thesis focused on social aspects, and energy cycles, the other important fields of research are life cycle assessment and renewable energy production with biogas plant and photovoltaics.

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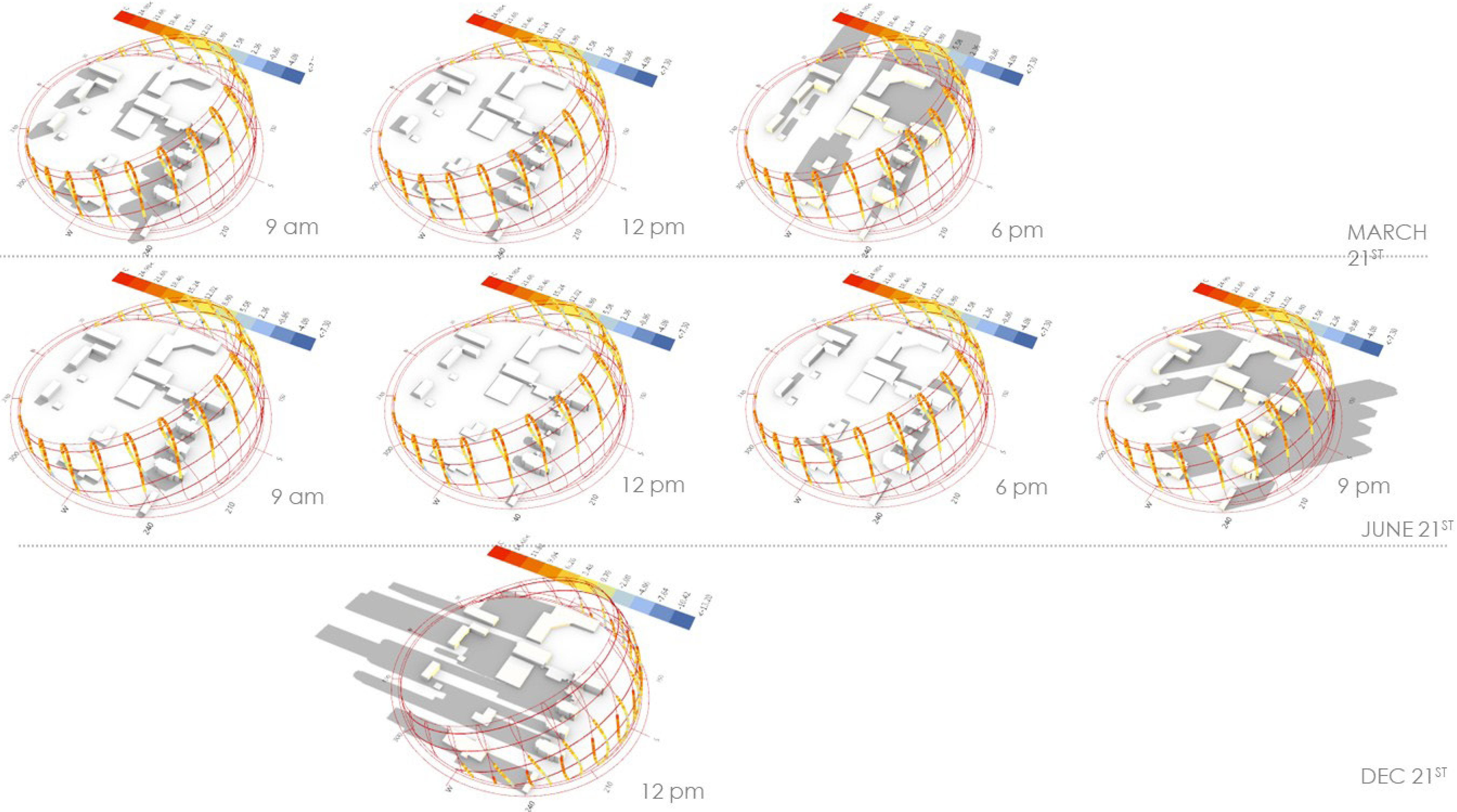
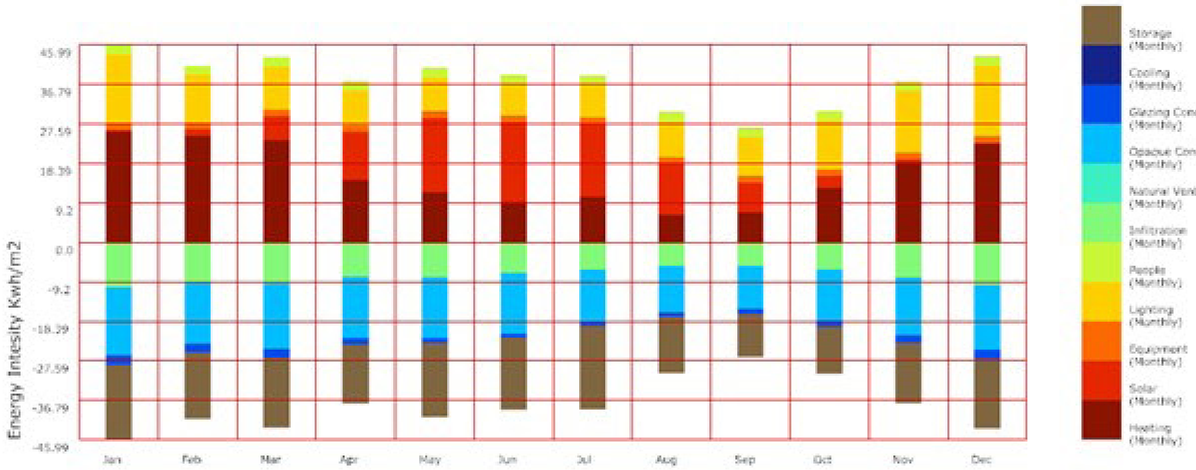
APPENDIX 1: Light and shadow study



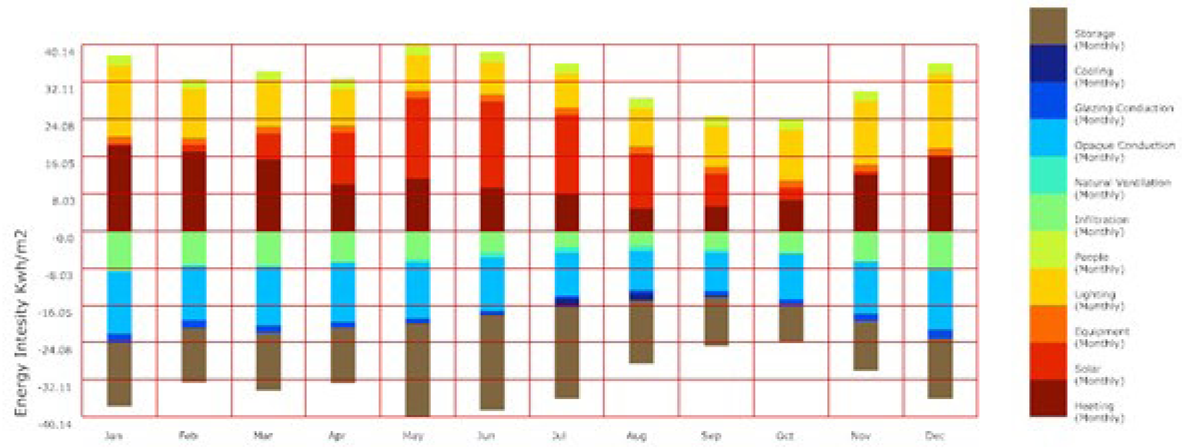
APPENDIX 2: Energy balance for various crops in ETFE envelope with soap insulation

Peppers



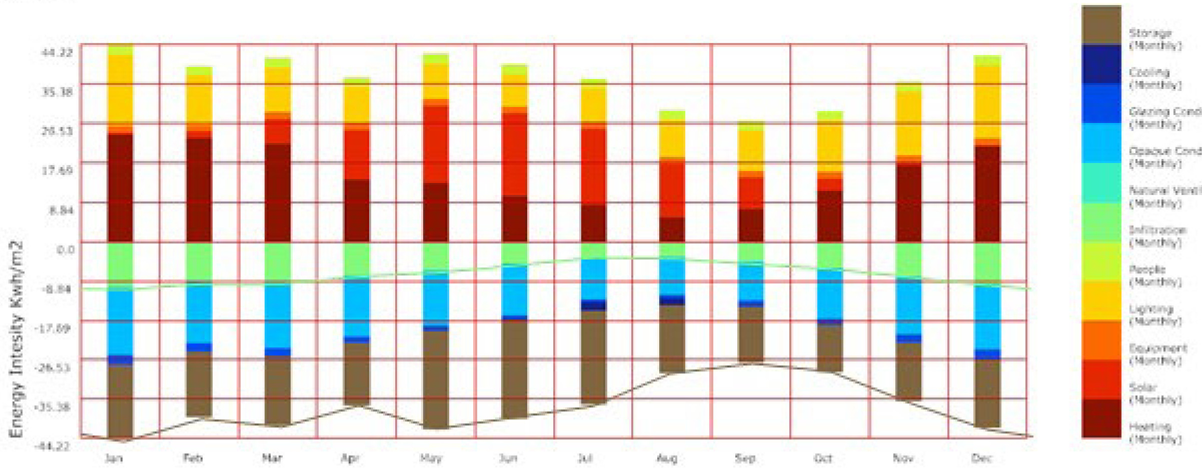
Cooling load 0 Heating Load (kWh/m2) 188

Herbs



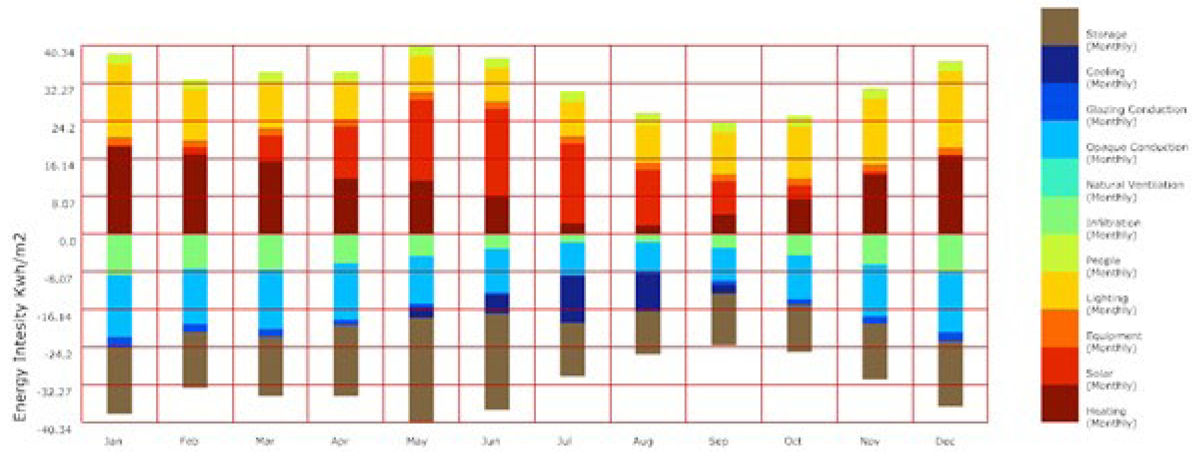
Cooling load 4 Heating Load (kWh/m2) 134

Tomato



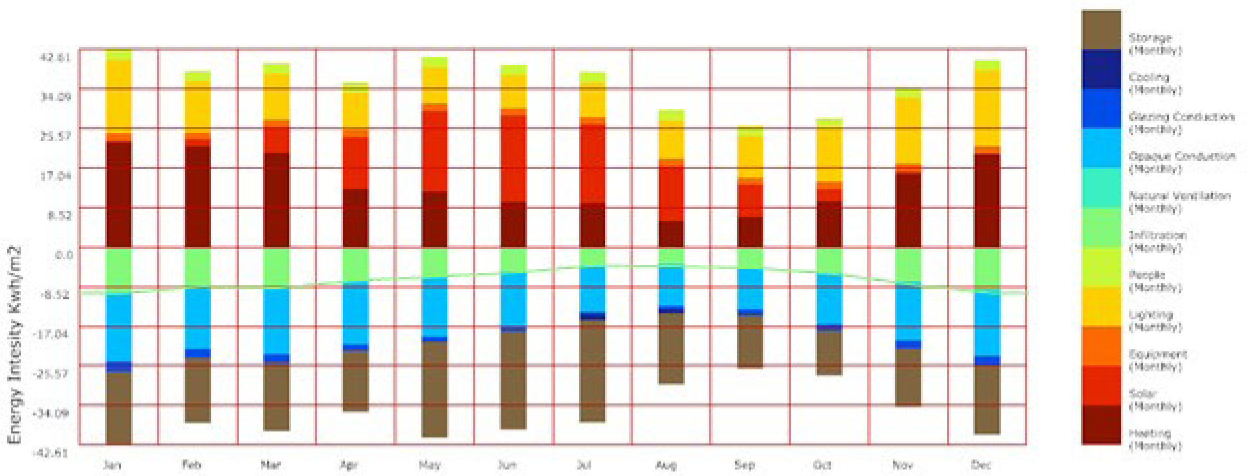
Cooling load 4 Heating Load (kWh/m2) 177

Leafy greens



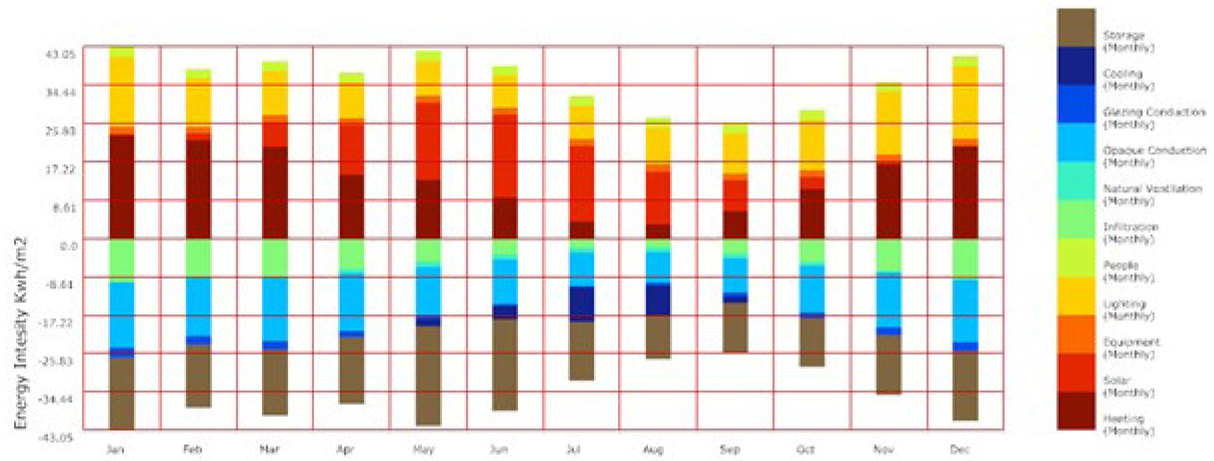
Cooling load 26 Heating Load (kWh/m2) 127

Cucumbers



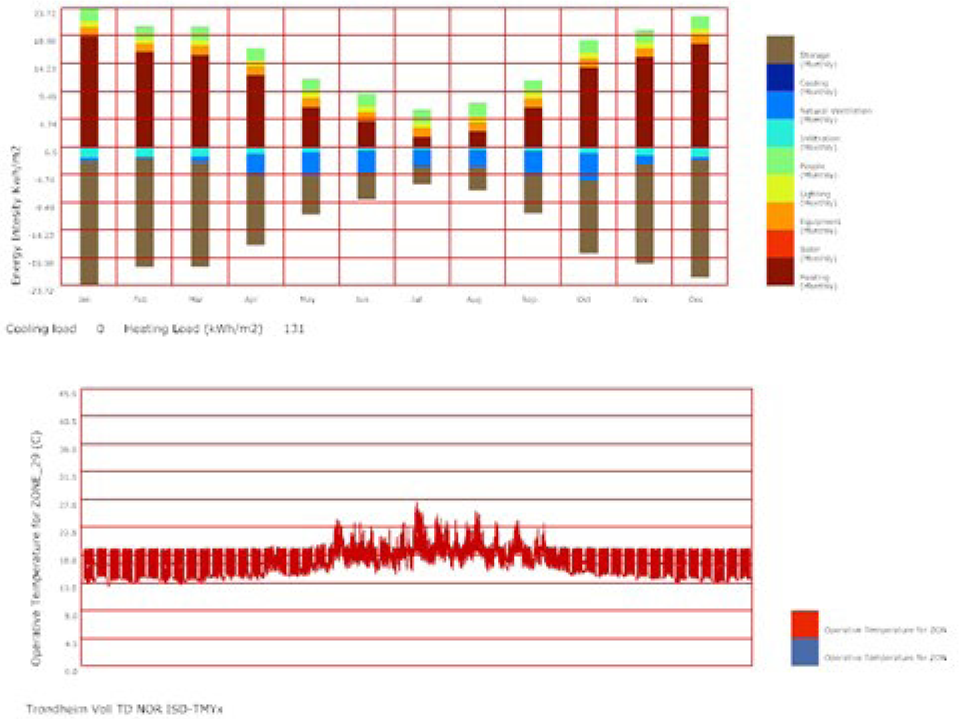
Cooling load 2 Heating Load (kWh/m2) 166

Micro greens

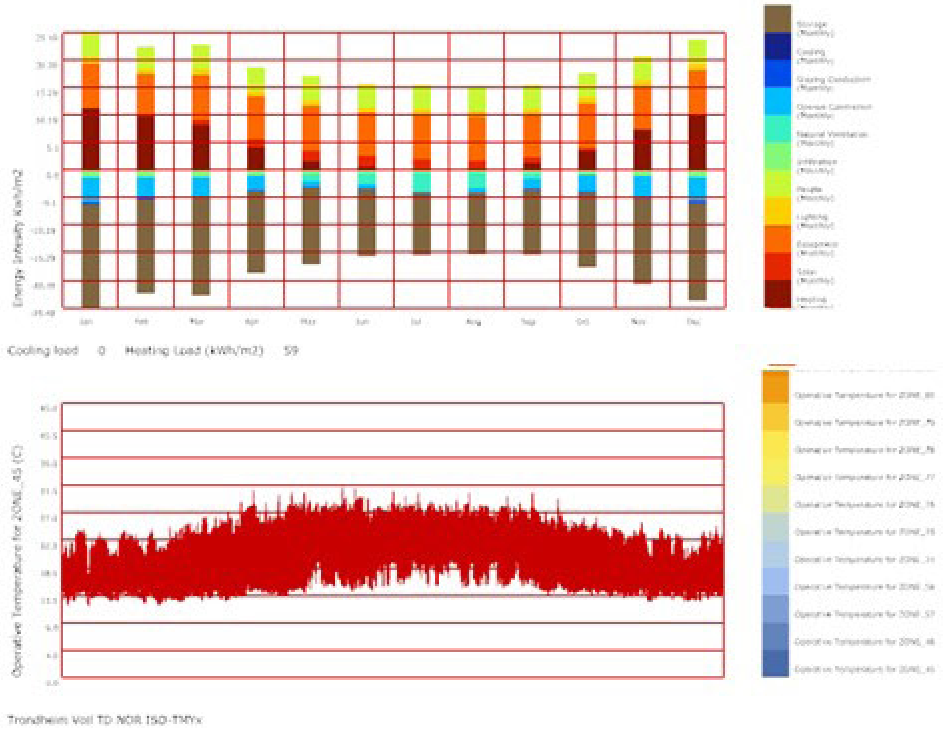


Cooling load 20 Heating Load (kWh/m2) 163

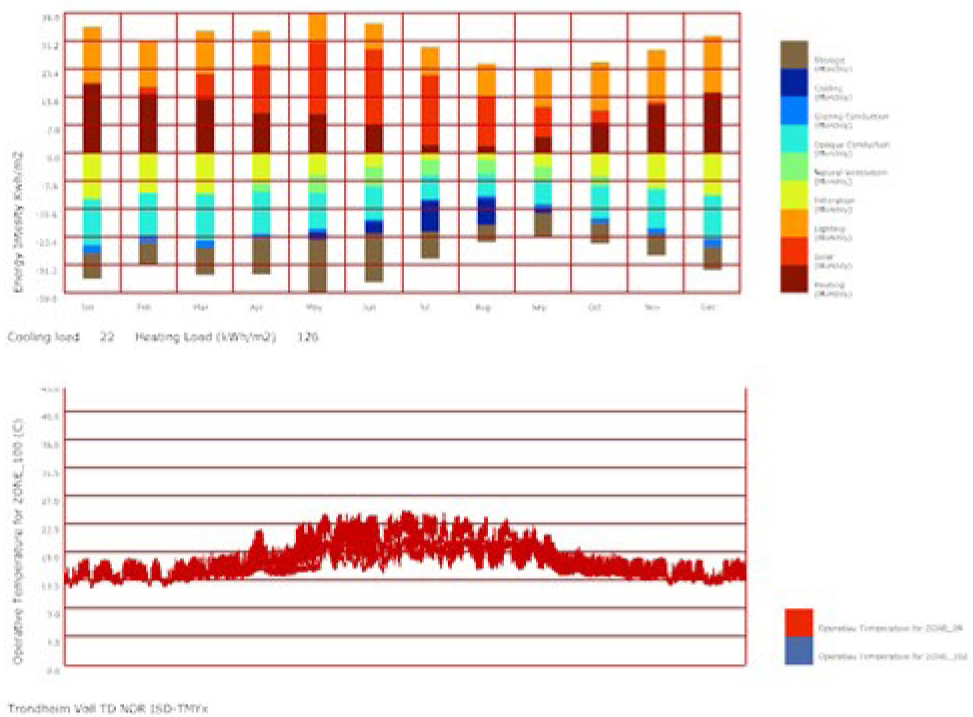
APPENDIX 3: Energy balance for various envelope options



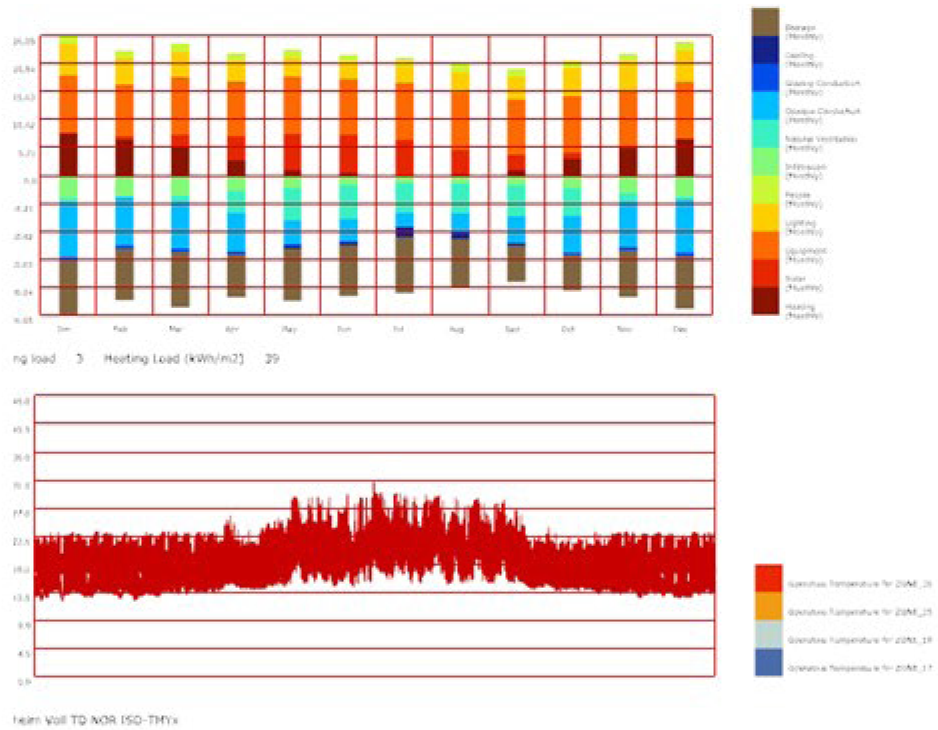
Current building: Supermarket



Building reprogrammed with food spaces



Greenhouse (standalone)



Overall integrated