URBAN SYMBIOTIC GREENHOUSE

An integrated approach to improve building performance

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Chapter 1 |

Introduction

1.1 Background

The population of the world in mid-2020 was 7.8 billion people, and it is expected to reach 9.7 billion by 2050. These statistics are according to the latest assessment by the United Nations (2019a). Out of this the urban population has increased by 72%, from 3.6 billion in 2011 to 6.3 billion by 2050. By 2050 the world's total population living in urban areas will be the same as the entire population in 2002. (United Nation, Population Division, 2012).

Since ancient times, cultivation of food was done inside cities in countries such as Egypt or Greece and eating came hand in hand wherever humans decided to settle. (Janick, 2002) However, after the industrial revolution and the subsequent invention of the steam engine, agriculture became a less tedious task for humans. Nowadays, cities do not rely on their own land anymore but are involved in global and continental supply chains of food and trading networks. This system does have economic benefits and is quite resilient. (Thomaier et al., 2014) However, there lies some major drawbacks in this system. The spatial distance between the consumers and the areas where food is produced, results in a longer transport distance, does not allow for organic recycling and overall increases the total price of production. (Thomaier et al., 2014) The sustainability aspect of the present food network system is questionable, mainly because of the scarcity of water, land and soil nutrients. (Germer et al., 2011) Conventional food production systems are limited by the intensity of production and the availability of land. Promoting expansion and intensifying the land to its limit can lead to irreversible effects such as depletion of resources, loss of biodiversity and degradation of the ecosystem. (Germer et al., 2011)

If the population growth trends continue, then the resource demands are expected to increase tremendously, and the resources of the cities will be under immense pressure. But at the same time, the production of these resources will reduce or rather won't be able to keep up with the demand since there won't be much land available for cultivation. (Balatsky et al., 2015)

A potential for a more sustainable agricultural system lies in local and high-density food production. This could be done within buildings, rooftop spaces, vacant ground spaces and larger peri-urban areas that are in the proximity of the consumer. Urban agriculture would not only solve the issue of environmental impact on the cultivable lands in rural areas but also increase the green spaces in cities. This could also add to the biodiversity of cities. Yet, the major challenge of this type of 'urban agriculture' is the availability of land and access to the spaces existing in urban settings. (Specht et al., 2013)

Another aspect of agriculture is energy-related carbon emissions which is an increasing concern nowadays. Aiming for a carbon neutral or low carbon future is the top priority of the international organisations. (European Commission, 2012)

40% of the total energy consumption and 36% of greenhouse gases are accounted for by the buildings in Europe. The number of buildings dating before 1970 are nearly 50% and do not adhere to current energy and thermal regulations. Thus, making them highly inefficient in terms of energy. (UNEP/Earth print, 200)

Fig 1.1 Global population growth and increased demand for food while declining ecological impact

Heated greenhouses and buildings are closely linked since they both require high thermal power and energy demands especially during their operational phases. (EEA, 2019). The energy waste flows from such buildings have a potential of being harvested by adapting a circular and integrated approach. (E. Sanye-Mengual et al., 2015) The waste energy from building could be used in greenhouses and vice versa to achieve a sustainable relationship between the two. This idea is an expansion of the concept that existing individual systems can be united to decarbonise multiple systems by including other factors as well. (J. Fiksel, 2017)

1.2 Problem Statement

The urban systems are the main causes of environment impacts. (IPCC,2014) As the population keeps growing, these impacts are expected to grow. Urban cities offer a potential for sustainable development even though they consume a vast number of resources. Urban agriculture is one such activity that adds value to urban waste resources which can be reused again in production of crops. (Grard et al., 2015). Thus, urban agriculture helps in decreasing resource needs in various sectors and helps in mitigating issues such as food security for an increasing population. Currently one of the biggest greenhouse providers in the world is Europe. (Tzilivakis et al., 2008). The efficiency of crop production is increase by using the controlled environments inside greenhouses. (Boulard et al., 2011). Yet, the primary inputs for these facilities can be furthers reduced by utilizing waste energy resources from urban infrastructure through Building Integrated Agriculture (BIA).

Studies show that meeting greenhouse energy demands using renewable resources are not economically beneficial. (IPCC 2014) To tackle this, one option could be using thermal energy paired with stored heat. Another option would be to utilize energy flows from industrial systems by forming synergies between greenhouses and industries. In such a manner urban agriculture could prove circular and help in lowering energy demands. (E. Mengual, et al., 2014) Also, these greenhouses could improve energy losses from building facades and help in energy conservation of buildings. Yet not many such examples of symbiotic energy relationships are currently available. (J. Fiksel, 2017)

Additionally, urban agriculture integration in building requires complex construction techniques and agricultural technologies. The construction industry is also trying to become carbon neutral and is gaining high importance. (Hossain et al., 2020). Building engineers are trying to aim for lightweight and flexible structures which have economical as well as circular benefits in terms of materials.

Similarly, a flexible approach in BIA could help in achieving cost effective and sustainable solutions yet currently such examples are rarely found. (Specht et al., 2014).

With growing global population there is an ever-increasing demand for resources, resource scarcity, and all of these are leading to adverse ecological impacts. To tackle these issues, new and innovative techniques for conventional activities need to be formulated. According to many studies, urban agriculture seems like a promising solution to meet the food demands while reducing the ecological impacts. Yet, this topic of urban agriculture is widely unexplored. It is not known how efficient urban agriculture would be in terms of resource utilization or how would it help in tackling the issues stated earlier. **There is a potential for capturing the waste resource flows from buildings and utilizing them as a feed for the urban agriculture processes.** To house these processes, greenhouses on a smaller scale that fit in the city or building's context could be designed. A novel idea would be to design these greenhouse units in a modular and flexible manner so that they can be made adaptable and reusable. This would ensure the circular nature of the greenhouse units in terms resource utilization as well as buildability. This forms the premise for this research project.

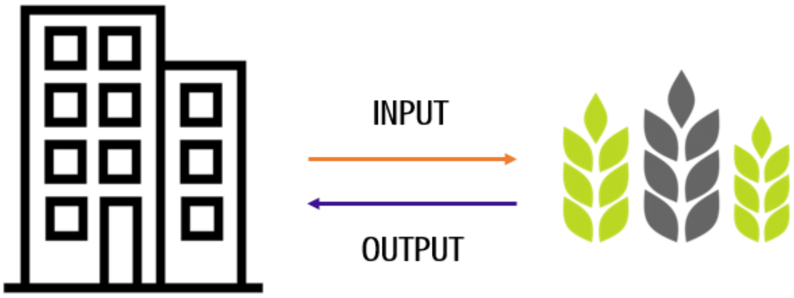


Figure 1.1 Synergetic relationship between building and agriculture

1.3 Objectives

The objectives of this research are threefold:

i. To study, analyse and select different technologies which hold potential in achieving sustainable urban agriculture. These technologies will be applied to 2 different case studies for experimentation.

ii. To understand how organic waste flows from buildings can be utilized by small scale greenhouse units and the produce (energy, food, etc.) generated in these units, given back to the buildings.

iii. To assess the general potential of greenhouse units in terms of building integration and compare the efficiency results of building with and without these units.

1.4 Research Question

The above objectives lead to formulating the following research question:

How can <u>modular symbiotic units</u> be designed and integrated in buildings in an urban context, to <u>utilize available waste resources</u> in exchange for <u>food production</u> while reducing primary resources of the building, where possible?

From this main research question, the following sub-questions arise:

(1) How can the symbiotic greenhouse utilize the existing energy waste flows from the building and in turn convert it to valuable crop produce? – ***Energy IN/OUT***

(2) What are the reductions in primary energy resources of the building, wherever possible, caused by the greenhouse unit? – ***Efficiency***

(3) How can the symbiotic greenhouse be made modular and circular in terms of its buildability to achieve flexibility in construction and adaptation? – ***Buildability***

The first sub-research question will be answered conceptually at the end of the literature review. It will discuss the opportunities where a co-symbiosis relationship is possible. The second sub-research question will be answered during the assessment stage, wherein the energy calculations will be made. Finally, the third sub-research question will be approached while designing the greenhouse unit.

1.5 Methodology and Approach

The problem statement points towards the fact that currently there are very few examples of urban agriculture that have a symbiotic relationship in terms of energy, food and resource produce, with buildings. Furthermore, modularity of these units is not readily available either. This forms the basis of the methodology chosen, wherein **research by design** is implemented.

The initial phase of the research starts by identifying the current scenarios and the problems arising out of it. This is a part of the literature review which will give an understanding of what needs to be solved. The next step is to formulate the objectives and propose a potential solution. A broad literature survey needs to be done before proposing this potential solution. The design guidelines formulated at the end of the literature study will help in designing the symbiotic greenhouse units in terms of its functions. These functions could be processes that occur inside the greenhouse unit to produce energy resources or food. The next step is to integrate the symbiotic greenhouse into existing case studies. The case studies would be 2 different buildings which vary in scale, type, energy efficiency, etc. Following are the types of buildings that will be studied:

(1) Typical Dutch house

(2) Multi storeyed residential apartment building in Netherlands

Standard values of heating, cooling, floor space area, occupants etc. for such building configurations will be used. To assess and validate the performance of the symbiotic greenhouse, a detailed excel data sheet and a SANKEY diagram will be formulated. A further comparative analysis would be drawn between the building with and without the design solution and their respective performances. The research will end with a final evaluation of the entire process and reflection on the solution formulated.

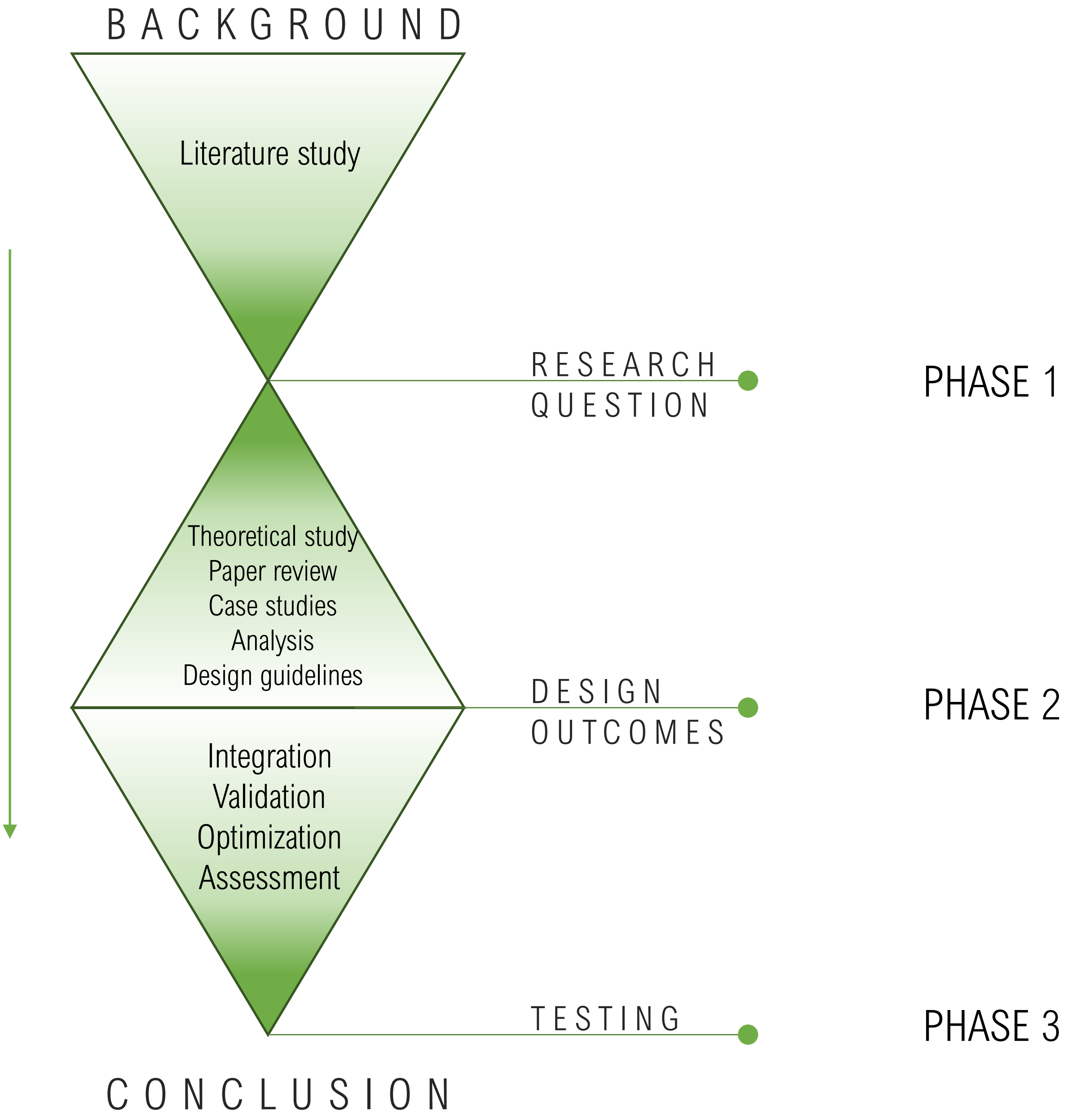


Figure 1.3 Methodology and Approach

1.6 Scope and Limitations

The scope of this research is limited to the application of urban agriculture production systems in 2 different types of residential buildings located in the Netherlands. The climate zone will be the same for both these cases. The most important factors that will help in assessing the design will be the amount of waste flows generated from the host building and production output by the symbiotic greenhouse units. These factors will vary as per the type of building. For instance, the amount of organic waste flow generated in an old, single family residential house will not be the same as a recently built, multi-storeyed residential apartment building. These factors will generate a wide range of outcomes. After the waste flows and production outcomes are calculated, a final assessment will be made to check how much is the reduction in the primary energy sources of the host building.

In this type of research, certain unpredictable variables may also change the output of the results. Although the design is modular in nature, the functioning of it will vary as per its locations, building type, culture, climate, etc. From this research, it will give us an idea of what could be the possible outcomes of the design, but a perfect figure is hard to predict.

As mentioned earlier, urban agriculture serves as a tool for increasing biodiversity and introducing green spaces in densely populated cities. In this research, this outcome will not be a main point of focus and might be a by-product arising out of the design.

Timeline

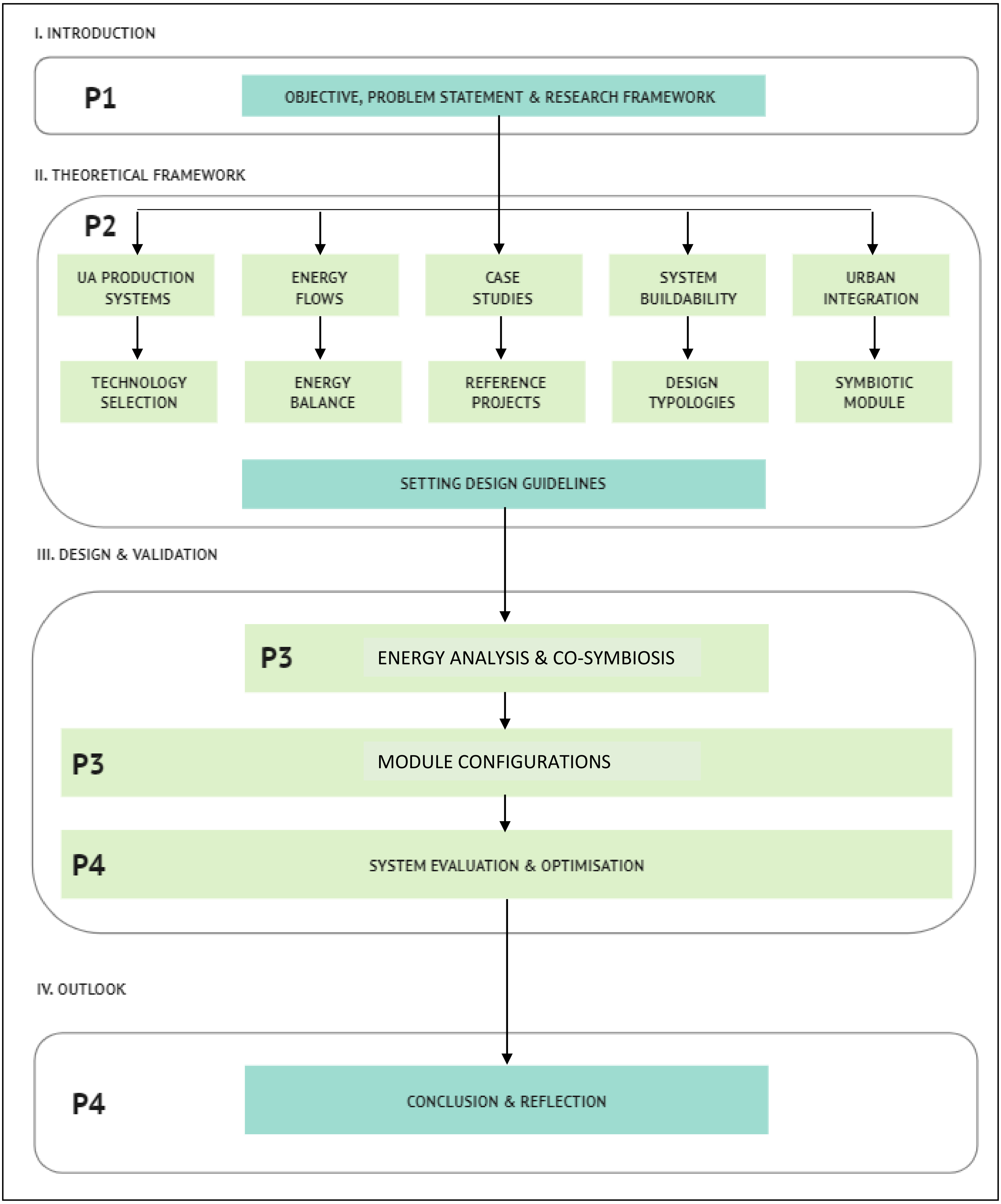


Figure 1.4 Timeline flowchart

1.7 Relevance – Social and Scientific

Social relevance

As the global population rapidly keeps increasing, the demand for food and energy resources steadily keeps growing. It is becoming a growing difficulty to meet these demands and might lead to a bigger problem of scarcity, in the coming years. Alongside these demands, another big concern is the issue of emissions and wastes generated after consumption. Currently, the resources that go into the urban environment simply end up as wastes after consumption. This linear system must change and replaced with a more circular approach, wherein the wastes are reutilized as much as possible.

Urban agriculture has social, economic and environmental benefits. Even though the function of any agricultural system is primarily to produce food, it could be also used as a tool to achieve multiple goals in the urban context. These goals include, sustainable agriculture practises, local scale energy generation, purifying the polluted air and water from urban areas, integrating green spaces in the cities and promoting social well-being. 'Culture, community and identity are created, enacted and reinforced' through food. (Stock, et. al., 2012) The physical, financial and psychological wellbeing of urban population may be enhanced by adapting such agriculture that is integrated in urban environments.

Scientific relevance

This topic finds itself under the realm of Urban agriculture and aims to explore the potential of co-symbiosis of agriculture integrated in the built environment. When such an integration occurs, the benefits obtained are multi fold. With this research, the scientific benefits of combining agriculture with urban environment will be explored. Currently, there are very few examples of such integrations. The technical challenges arising from a symbiotic greenhouse system that utilizes a building's waste resources are also widely unknown. These challenges will be investigated by providing a detailed study of design and construction of the building integrated greenhouse units and assessing the possibilities of energy and resource co-symbiosis. This will help in obtaining a clearer understanding of the working and benefits of such co-symbiotic modules in the built environment.

Chapter 2 |

Literature review

(A) Need for Urban agriculture

2.1 Global population & Infrastructural growth

By 2050, the total global population will be 9.7 billion. Consequently, the global food demand is also expected to increase that started in 1950s and will grow by 50% by 2050 as compared to 2013. Although the food demand is increasing, the space for its cultivation seems to be constrained. Same is the case with water and other natural resources. Meanwhile, global warming is also on the rise as a result of human activities that are unsustainable, and this negatively impacts the agriculture industry. (Energy roadmap 2050).

Food, water, energy and other supplies are already major challenges that are being faced by the cities. Larger cities currently are involved in global food networks. This network is ever increasing and has economic benefits, but questions have been raised about its resilience and sustainability. The links between food security, urban infrastructure and climate change are not widely explored. Since most of the total population of the world already lives in cities, this research should be a priority.

After a city is built, it rapidly grows and can often lead to an unsustainable sprawl. Population growth and expansion of urban land are not in proportion. Expansion is outpaced by 50% compared to growth of population. Within the next three decades, it is expected that an additional, 1.2 million km² of new built up in urban areas will be added. Such an expansion will put pressure on the resource availability and lead to undesirable outcomes. Two thirds of global energy consumption and more than 70% of greenhouse gases are accounted by the cities presently. (The World Bank, 2020)

The availability of agricultural land per capita has decreased significantly as an outcome of the global population increase. 0.38 hectares of global agricultural land was available per person in 1970 which reduced to 0.23 hectares by 2000. Only 0.15 hectares per capita will be available by 2050. (FAO, 2012). A single hectare of land will have to supply enough food for 6.7 people in 2050 due to this decrease in land. In 1970, a single hectare could supply enough for 2.6 people. (FAO, 2012) This gives an idea of how big of an impact caused by food scarcity, the future generations will be facing.

2.2 Global food demand, food security

The food supply chain or the global food system, is a term for the businesses, people and companies that are needed to the point of sowing to the point of consumption. The ways of growing food have fundamentally changed over the course of time due to geopolitical reorganisations, leading to imperial colonialism. (Friedmann, et al., 1989). The results of this reorganisation were increased food production, increased trade of food, and increased scale of operations. Extremely complex and multi-scaled governance of the global food system and, involving several private, public and civil stakeholders were the consequences. (Lang, et al., 2009).

The world's population doubled from 1961 to 2007, and agricultural production nearly tripled. Increase in production with new varieties of crops, improved pesticides, herbicides and fertilisers, and improved rural infrastructure and water management were all fuelled by the green revolution. (Mazoyer, et al., 2006). Yet, agricultural land area expanded by only 11 percent, and cultivable area grew by only 9 percent, during this period. (FAOSTAT, cited in Royal Society, 2009). As a result, global food consumption, also increased from 2280 kcal per capita per day to 2800 kcal per capita per day (Pretty, 2012).

It has been predicted that food production will need to increase between 70 and 100 percent by 2050 to meet global food demands without any major increase in price, despite the significant increase in food production in the last fifty years. (FAO, 2009a; Godfray, et al., 2010).

Food security

"Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". (World Food Summit, 1996)

Following are the four key dimensions of food security:

- ***Food availability:*** Availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid).
- ***Food access:*** Access by consumers to adequate resources and appropriate foods for a nutritious diet.
- ***Utilization:*** A state of nutritional well-being where all physiological needs are met by utilization of food through adequate diet, clean water, sanitation and health care to reach. This shows the importance of non-food inputs in food security.
- ***Stability:*** A household or individual or a population must always have access to adequate food to be food secure. A sudden shock should not result in losing access to food. (e.g., an economic or climatic crisis) or cyclical events (e.g. seasonal food insecurity). Therefore, the availability and access dimensions of food security together make up the concept of stability. (FAO, June 2006)

Land competition

Land competition occurs when some resources and ecosystem services are delivered simultaneously from the same area of land but are mutually exclusive. Especially when demand for resources exceeds the supply, competing claims can occur. As a result of limited land availability and limited natural resources, a major global challenge is to sustainably provide current and future generations with sufficient food and energy, without compromising ecosystem services and biodiversity. (Siemen et. al., 2012)

The main factors of competing claims:

- Increasing demand for resources and commodities to satisfy global, regional and local needs is influenced by changes in demography, economic development (GDP and wealth), scarcity

(relative prices of factor endowments and goods) and by policies at different levels (e.g., trade policies, policies on international development, conservation of biodiversity etc.).
- Requirements for natural resources in terms of availability, quality, sustainability, efficiency and timing of production, is the second factor. (Siemen et. al., 2012)
- Institutions that govern land use and land-use planning is the final factor. International and local power relations and customs play a significant role in competing claims and the result of competition for land. (Siemen et. al., 2012)

2.3 Ecological impact

Standard agricultural production techniques to feed a population of 7.6 billion people is proving destructive to the terrestrial and aquatic ecosystems, depleting water resources and causing climate change. (Yang et al, 2016)

- Food accounts for over a quarter (26%) of global greenhouse gas emissions (Poore, J., & Nemecek, T. 2018)
- Half of the world's habitable (ice and desert free) land is used for agriculture.
- 70% of global freshwater withdrawals are used for agriculture (FAO. 2011)
- 78% of global ocean and freshwater pollution is caused by agriculture(Poore, J., & Nemecek, T. 2018.
- 94% of mammal biomass (excluding humans) is livestock. Of the 28,000 species evaluated to be threatened with extinction on the IUCN Red List, agriculture and aquaculture is listed as a threat for 24,000 of them. (Bar-On, Y. M., Phillips, R., & Milo, R. 2018)

Therefore, **food is at the core of tackling climate change, pollution, resource depletion and restoring the natural habitats for protecting wildlife.**

Transportation of food

Nowadays it is popular amongst consumers to reduce travel distance of food through local food production and in turn reduce greenhouse gas emission. However, transport is a small contributor to the total emissions for most diets and individual products. (M. Ottele et al.,2011) But air transport emits 50 times more carbon dioxide per ton kilometre that water transport. Yet it just accounts for 0.16% of annual food miles. (M. Ottele et al.,2011) By shortening the supply chain, wastes on the path from cultivation to retail are eliminated. Improper storage conditions, breaking the cold chain and stock management inefficiencies are the causes for such losses. (M. Ottele et al.,2011) The most effective ways for reducing GHG emissions are shortening the supply chains for fresh products, such as fruit and vegetables. **Transportation of food holds a large share of total food losses and wastages.** (e.g., 42% in Portugal (N.H. Wong et al., 2010)

Production of crops

Land use and production phase of food production accounts for the largest shares in GHG: land use accounts for 24% and the production phase for 58% (livestock & fisheries 31%, crop production for human consumption generates 21% and animal feed generates 6%) (M. Ottele et al.,2011). Thus, sustainable cultivation of crops selecting the right crops could be more effective than limiting food miles. For example, in Sweden, producing tomatoes in greenhouses requires 10 times as compared to importing in season tomatoes from Southern Europe. (Swiss centre for lifecycle inventories, 2018)

Several factors influence the sustainability of crop production such as, local resource availability, climate, production systems (open field, greenhouses with various levels of technology or plant factories). Crop production and its resource use efficiency is directly influenced by the production climate. Use of water, energy and carbon dioxide and the crop yield can be used to compare the system performance. The effects of the production climate on system performance have been a focal point of agricultural research, in particular the effects of air temperature, root-zone temperature, ventilation, humidity, nutrient delivery, light intensity, light spectrum and light duration are the indicators of the effects of production on system performance. (C. Kubota, 2015)

2.4 Urban Agriculture – a solution

Research in the past few decades has proven that urban agriculture is a promising solution which can contribute towards lowering the effects of climate change and at the same time improve the quality of life in urban areas. It offers opportunities of living green and locally produced food, an idea most people are leaning towards these days. Therefore, the aim of urban agriculture is to adapt production of food within the cities by utilizing spaces efficiently. (S.L.G. Skar et al., 2020)

Within cities and suburban areas, urban agriculture helps to address local food security issues. Urban agriculture can be implemented in the form of roof top, backyard, vacant parking lots, community gardens, etc. Engaging the community, making food accessible and reconnecting communities are some of the features of urban agriculture. (USDA Climate Hubs)

A more sustainable agricultural system is high density food production in local areas and within existing building structures. The major challenges for deciding the feasibility are the availability of land and access to urban fabrics. (Specht et al., 2013) However, **to provide opportunities for food cultivation, incorporating agriculture in flexible modules attached to existing buildings could be a potential solution.**

(B) Need for Circularity in Urban agriculture

2.5 Energy and Urban metabolism

Fossil energy was the enabler of the industrialization of the late nineteenth century. Before, human societies used muscle power from animals and humans. Tremendous growth of cities and economic activity in the twentieth century was a result of this discovery. The twenty first century has continued to see this growth and currently is the century where most people live in urban cities than in villages. (S . Pincetl, 2012) The systems to support cities have become increasingly complex and interdependent, in the last 100-150 years. To supply urban populations complex systems such as pipelines carrying gasoline, natural gas, water, and information crisscross entire countries. Large scale warehouses, the size of districts, are used for storage and distribution of materials and goods to cities. Electrical lines run miles to supply power to urban areas. From far away lands, resources are drawn to the cities for use in relatively compact spaces. (EU Energy database, 2019) Between one-third and one-half of the earth's land surface has been transformed by human action. The most substantial human alteration of the earth system is the use of land to yield goods and services. It is an ever-increasing concern that the earth will not be able to sustain the pace and scale of such an extractive activity. (Vitousek et al., 1997).

"Urban metabolism (UM) is the accounting of energy and material flows into cities and the waste products generated. It is an initial means to quantify the amount of inputs extracted from the earth for urban use and, ultimately, the physical impact of cities on global biogeochemical cycling and ecological processes" (S. Pincetl, 2012)

Mass balance – UM measuring approach

The principle of matter can neither be created nor be destroyed forms the basis of mass balance. Thus, the inputs of resources that go into the ecosystem are balanced out by the output of products, waste flows and emissions. Tracking the applications of energy in material resources that enter, flow and transform into the urban systems is the widely used approach for energy mass balance. This includes buildings, crops, animals, livestock, etc. and the waste outcome for the same. (Haberl et al., 2001) Urban Mass balance provides a way of quantifying the raw material flows (such as food, nutrients, etc.) in different units of measurement (such as kgs, joules, tonnes) as they enter and leave the system.

2.6 Urban Waste flows (organic)

The potential environmental and socio-economic benefits of applying a circular approach to urban organic waste management by means of resource recovery is a growing trend. Currently, over 1.6 million tonnes of organic solid waste are generated by urban residents. (Kaza et al., 2018) and daily over 715 million m3 of municipal wastewater (Mateo-Sagasta et al., 2015) is generated. Large quantities of urban wastes are disposed into the environment. The effects of these are negative impacts on the ecosystem as well as human health.

However, there are opportunities to develop these systems and focus on resource recovery instead. Food waste and excreta contain nutrients, energy, water and other materials which can recovered post treatment.(Andersson et al., 2016) This is an example of implementing a circular economy (CE) approach to organic waste management. This can help to boost water, energy and food security in urban areas and reduce resource pressures. Only 4% of global urban nitrogen (N) and phosphorus (P) sources are presently recycled from urban organic matter. One example to recycle such waste is to use composts in horticulture. (A. Nadal et al., 2017) Urban farming and other community-based farming initiatives require fertilizers and nutrient rich soil which could be supplied by the recycling of organic waste matter from the urban areas itself. Therefore, urban wastes could be considered as a valuable resource, and the locally available waste could be used for producing materials required for other initiatives.

Figure 2.1 Urban metabolism linear approach – Unsustainable and inefficient

Figure 2.2 Urban metabolism circular approach – Sustainable and efficient

2.7 Circular approach of urban agriculture coupled with buildings – a solution

Circularity in agriculture

While analysing the agricultural system efficiency, the two stages of food production and consumption at the same time is relatively complete. Additionally, there is the problem of food waste. An important factor leading to food waste is people's consumption. Consumers tend to consume various types and high-quality foods. This includes consumption of imported foreign foods. However, Van Huylenbroek et al. (2009) realised that consumers' demand for food is driven by hedonistic thinking. Parfitt (2010) and Papargyropoulou et al.(2014) further proposed that the problem of food waste is brought by increase in food consumption. Katajajuuriet al. (2014) found that the amount of food waste in Finland during the production and consumption stages is equivalent to the carbon dioxide emitted by approximately 100,000 cars per year. According to United Nations Environment Programme, UNEP Food Waste Index Report 2021 reported that around 931 million tonnes of waste from food was generated in 2019, 61 percent came from households, 26 percent food service, and 13 percent from retail.

The global food waste in the food supply chain is causing environmental, social, and economic impacts. The increased burden on the environment, results in social costs and environmental risks. FAO believes that with the concept of circular economy, food waste recycling and ecological agriculture are the keys to achieving sustainable development goals.

Armington et al. (2020) discussed the treatment methods of recycling and power generation to solve the food waste situation in New York state. Asefi et al.(2019) found that through recycling and reducing food waste, bio-microbial mixtures can be successfully converted into electricity generation. Halloran et al. (2014) discussed the solutions, biomass energy and organic fertilizer to improve the efficiency of the food system. The studies of recycling food waste in the circular economy are currently of high priority.

Co-benefits of Agriculture coupled with buildings

To address the growing concerns of the environmental impacts of urban cities, an attractive solution are urban greenhouses that could yield higher efficiency and multiple benefits when designed in symbiosis with the surrounding urban environment. Goldstein et al. (2016) describe a 'renaissance of urban agriculture in the world's wealthy, northern cities as new technologies like hydroponics, with their higher yields and water recycling ratio per square metre, offer the potential of competing with traditional agriculture'. Research into urban agriculture has developed considerably over the past decade: from socio-economic analyses (Specht et al. 2013), and speculative futuristic ideas (Despommier 2011), to cost-benefit comparisons of alternatives for reusing roofs in cities (Benis et al. 2018). These studies highlight that the available resources need to be used synergistically with the surrounding built environment when designing BIA. This would reduce energy inputs for lighting, heating, water, and ventilation requirements. Nadal et al. (2017), for example, show that the potentially high energy cost of hydroponic rooftop greenhouses could be lowered by exploiting the symbiotic relationship between a greenhouse and the waste resources present in the host building. These waste resources could be in the form of heated carbon dioxide rich air and rainwater. Studies observing carbon sequestration and water vapour loss of houseplants have demonstrated the cooling effect plants can have on indoor environments. (Gubb et al. 2018)

Recently, (Sanyé-Mengual et al., 2015) stated the benefits of rooftop greenhouses (RTGs), which were categorized as per their scale of functioning. For instance, global benefits (climate change reduction), local benefits (greening of urban areas), benefits for the greenhouse and building (energy saving) and harvest benefits. More benefits can be gained by integrating the building and the greenhouse. Further benefits can be achieved if the greenhouse and building are integrated, so that they exchange and optimise energy flows, water flows and carbon dioxide flows. (Nadal et al., 2017)

(C) Conceptual and theoretical study

2.8 Building Integrated Agriculture

In most major urban cities, crop cultivation in the form of urban farming tends to be small and produce a low amount of output. The cause of this situation is the high cost of land which is scarcely available in populated cities. Yet, a potential space for cultivation lies on the vacant roof tops of buildings or vertical building skins, balconies, etc. These spaces are often underutilized and can be used for farming activities within the cities.

To utilize these spaces effectively, greenhouse, especially hydroponic farming techniques need to be adapted. If designed well, they also hold a potential for incorporating energy saving innovations. This idea of integrating agriculture with the built environment could significantly reduce resource consumption, improve urban biodiversity, promote food safety and conserve building energy. (K.Ackerman, 2012)

As an example, a survey and study of the rooftop spaces in New York indicated that sufficient rooftop space is available for generating 100% of the fresh vegetable demand for the entire city. (K.Ackerman, 2012)

Most urban buildings, let out significant amounts of heat through their facades throughout the year, either intentionally or otherwise. Although this heat is hard to capture but it is much simpler to utilize this heat for plants. Plants also consume the carbon dioxide let out from the exhaust systems of building ventilation system. This indicates the possibilities to achieve a symbiotic relation between the building and the plants in urban areas by adapting building integrated agriculture.(K.Ackerman, 2012)

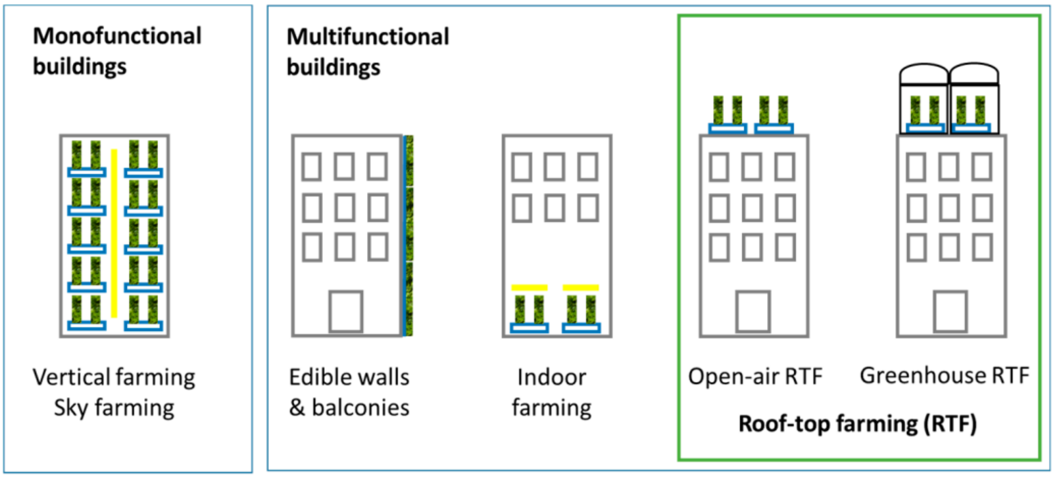


Figure 2.3 Types of Building Integrated Agriculture (Devi B., Ranka J., 2016)

Definition of BIA

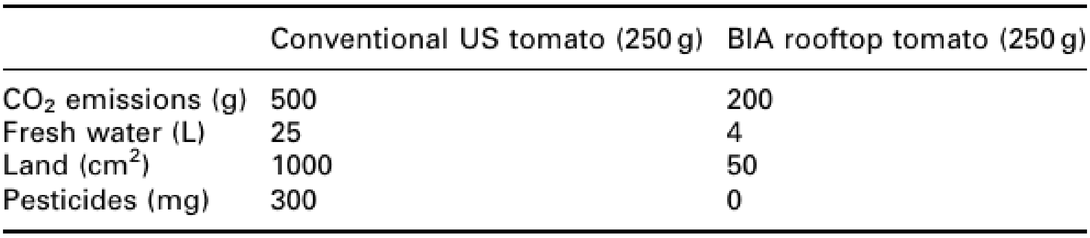
"Building-integrated agriculture (BIA) is a new approach to food production based on the idea of locating high-performance hydroponic farming systems on and in buildings, using renewable, local sources of energy and water." (D.Gould & T.Caplow, 2012) In greenhouses, hydroponics are usually the preferred methods for cultivation of plants. This technique utilizes water containing nutrients instead of conventional soil. The water is recirculated and used for further rounds until the nutrients are depleted, thus making it an environmentally sustainable approach. (D. Gould & T. Caplow, 2012)

System description

Mixed use buildings are the hosts for BIA systems wherein they are designed to exploit the synergies between the host building and the agriculture system attached to it, Technologies such as recirculating hydroponics, waste heat capture from HVAC units, rainwater harvesting, solar panels and evaporative cooling are features of BIA. The building size, local climate, structural load bearing capacity are some of the factors that influence the location of the BIA. This could either be located on the rooftop or on the vertical face or any other suitable vacant space on the building. (D.Gould & T.Caplow, 2012)

Ecological performance of BIA

BIA is a sustainable and environmentally friendly approach for food production in urban areas that helps in reducing transport costs, carbon footprint, enhances food security and combats global warming. In the USA, each hectare of rooftop vegetable farm could, on average, free up 20 ha of rural land, save 74 000 tons of fresh water each year and, if fully integrated with building heating systems and onsite solar power, eliminate 1000 tons of CO2 emissions per year compared with a conventional greenhouse. (D.Gould & T.Caplow, 2012) The following table shows a comparison between conventionally grown tomatoes and via rooftop in a BIA.



	Conventional US tomato (250 g)	BIA rooftop tomato (250 g)
CO_2 emissions (g)	500	200
Fresh water (L)	25	4
Land (cm^2)	1000	50
Pesticides (mg)	300	0

Figure 2.4. Comparison between the ecological impacts of tomatoes grown conventionally vs via BIA system (D.Gould & T.Caplow, 2012)

2.8.1 Energy feed for BIA

- *Water*

70% of the world's freshwater withdrawals is used by agriculture. (World Economic Forum, 2009). With the rapid growth of population, competition between agricultural demands and industrial and domestic demands will increase. This will result in increased costs of valuable resources such as water. For instance, a maximum of a ton of water could be required to produce just a single load of bread. Similarly, vegetables also require large amounts of water when produced using conventional methods. According to studies, 1800 million people will be facing water shortage by 2025. (FAO, 2010b).

Recirculating hydroponic technology which is used in BIA, uses water efficiently and water management is a key feature of this system. Harvesting rainwater, using gray water from buildings are similar features of BIA systems. Hydroponic agriculture consumes up to ten times lesser water as compared to conventional agriculture and eliminates pollution caused by chemical pesticides and fertilizer wastes, making it the most water efficient system. (Brown, 1995).
Plants are grown without soil, with their roots in direct contact with a
Nutrient-enriched water is directly supplied to the roots of the plants. Since this method has a closed loop system, the water is recirculated and reused. Graywater from its host building can either be used directly for crop production or can be filtered for uses such as evaporative cooling, In climates with high evaporation, water efficiency can be further increased by recovering the evaporated moist exhaust air and condensing it back to liquid water for the plants. (D.Gould & T.Caplow, 2012)

- *Power*

Controlled climate inside the greenhouses is the main factor influencing the quality of the crops and the harvest yield. To maintain a constant humidity and temperature inside, it requires energy. During winter seasons, in the northern regions, heating takes up most of the energy and leads to carbon emissions. In case of rooftop greenhouses in such climates, the heating losses from the roof of the building is prevented due to the position of the greenhouse on the roof and the waste heat from the building's exhaust is used by the greenhouse. Thus, saving energy. Design features such as thermal blanket and double glazing can also reduce the heat loss and heating demand. Urban heat island in dense city areas also help in reducing heating demands of the greenhouses. For the remaining heating demands, renewable sources can be used by the facility.

Cooling demands is the energy consuming challenge in warm climates. In this case, a rooftop greenhouse helps in evaporative cooling for the building and the greenhouse. Due to constraints of space, humidity or cost, evaporative cooling could be a challenge if not for the greenhouse. (Caplow and Nelkin, 2007). Solar gain and thermal losses can be eliminated by locating the greenhouse on the roof of the building, saving energy. The roof of the building is now the floor of the greenhouse with approximately the same temperature above and below, reducing thermal losses.

In areas with strong sunlight, the electrical demands of a BIA facility can be met by using solar photovoltaic panels. In a controlled environment where energy demands are high, and the hot climate is available, solar panels are a go to choice. Natural ventilation, evaporative cooling and high-efficiency pumps and fans can also help with reducing electricity consumption. (D.Gould & T.Caplow, 2012)

Example project:

The Science Barg is a hydroponic greenhouse located on a steel deck of a barge in New York. It was used a research facility for urban agriculture and spanned an area of 120sq.m. A 2.4 kW solar array, a 2kW wind turbine array and a 5kW generator running on biodiesel was used to meet the electrical demands of the facility. (Caplow and Nelkin, 2007). Cucumbers on 24sq.m. area were produced to study the yields using this system. 1.3 kg/m2 was the weekly yield of cucumbers which used 21.4 kWh/m of electricity. It was found that 3:1 ratio between greenhouse floor area and solar panel area would allow 100% solar operation (Caplow and Nelkin, 2007).

Figure 2.5 The Science Barge, New York by Rail

- ***Carbon***

  Solar photovoltaics, organic waste recovery onsite and from the urban areas, energy savings from shading and cooling of host buildings are the carbon efficient options of supply in BIA. Solar PV panels can be strategically placed on the roofs of the greenhouses or be integrated in the structure itself. In most locations and geometries of greenhouses, parts of the roof can also be shaded without reducing light availability to the crops. Solar panels and crops can also be placed on vertical surfaces of the greenhouses. Hence, by using maximum PV panels, carbon emissions can be entirely omitted. (D.Gould & T.Caplow, 2012)

- ***Materials***

  Greenhouses are required by most BIAs. Unlike commercial field greenhouses, BIA systems are more rigid, high-quality and long-lasting materials. Greenhouse structures are mostly made from aluminium or steel which can be recycled after its use. For the glazing systems, either single-pane glass, which lasts for a long time or multi-pane polycarbonate, which is replaced every 5 to 10 years due to photo-degradation is used. PVC and HDPE parts are used for the hydroponic systems inside the greenhouse. This includes buckets, hoses, tubes, gutters, etc. The sustainability of these materials is a question that needs to be investigated in BIA. In hydroponics, consumable materials are minimal. Media beds of rockwool, perlite, etc. are used for growing the plants. Some of these materials are not recyclable. New products in the market with eco-friendly alternatives include recycled glass and ‘unmined’ solutions. New and promising products in this market include expanded recycled glass and other ‘unmined’ solutions. Mineral salts made especially for the plants is used for its nutrition. These salts are entirely absorbed by the plants in case of fully recirculating nutrient flow systems. In comparison to the food produced, both initial application and any residual waste stream are very small. (D.Gould & T.Caplow, 2012)

2.9 Urban food production techniques

This section consists of a literature survey on the available technologies in urban agriculture systems to produce vegetables and fruit. Both soil-based and soilless methods of food production are listed. The focus is on the hydroponic method of production. The advantages and disadvantages of each system is investigated.

Due to the lack of wide-open spaces in densely populated urban areas, traditional agricultural techniques, such as ploughing the land to produce row crops, are unsuitable. Hence, when considering the integration of food systems within and upon existing buildings, novel methods of food production need to be implemented. approach.

2.9.1 Soil based systems

All farms and gardens require healthy soil. Sometimes soil can be contaminated and degraded by past uses and nearby activity. This includes industrial waste, unauthorized dumping, construction, heavy nearby traffic, and adjacent buildings using lead-based paint. For this reason, soil testing is critical. The contamination of soil poses a huge risk to farming.

- #### *Raised beds*

  Raised beds or containers over paved surfaces, such as parking lots, are often spots for urban agriculture in cities. The main challenge is to identify a source of high-quality soil to bring it to the site. Another challenge could be that the urban soil may have low fertility and may be extremely compacted. Continually improving soil through adding compost and other strategies fosters healthy, productive plant in both, growing in the ground or in raised beds. The most cost-effective way of separating soils deemed safe for food production from soils with high levels of contamination is using raised beds, in their many shapes and sizes. They help in creating a barrier to contaminated soils by using impervious membranes. Due to the height of the raised beds, it becomes more comfortable to work as compared to ground level agriculture. Raised beds are a simple and cost-effective solution but rapid evaporation leading to inefficient use of water and transportation of soils from far away areas to the raised beds, are its major challenges. Another major challenge is the availability of vacant space in cities. It is not a scalable method and can only be as big as the area left between buildings.

Figure 2.6. Raised beds in a densely populated urban area (agra.org)

- ***Roof gardens***

Rooftop of buildings are also a potential site for soil-based agriculture. Usually, spaces on roofs are vacant are underutilised while cost money to be maintained. These spaces are a perfect location from growing food since they are less prone to overshadowing and offer larger agricultural footprint as compared to soil based agriculture on the ground in cities. Having said that, the major challenge in this type of rooftop soil-based agriculture, is the heavy weight of the soil which is not a concern at ground level. Roofs are usually built to support small loads without considering the load of soil on it. The only consideration made is snow or wind loads. The depth required for root growth and drainage would require at least 300mm of soil which would exert heavy load on the roof.

Figure 2.7 The rooftop garden at Chicago's City Hall. DJANDYW.COM

2.9.2 Water based systems

Technical food systems or soil less agriculture is water-based agriculture that utilised various technologies and water to form a hybrid system for production of crops. The crops in this system are supplied with nutrient rich water and sometimes kept in a controlled environment, Cultivation in this manner, produces greater amounts of yields and reduces harvest time by using less amount of resources. (Bernstein, 2011).

Hydroponic means 'water culture for growing of plants without using any substrate' this term was coined by Gericke in 1937. In 1997 Jensen defined hydroponics in a broader sense as 'a technology for growing plants in nutrient solutions, with or without the use of an artificial medium (sand, gravel, vermiculite, rockwool, perlite, peat moss, coir, or sawdust) to provide mechanical support'. There are two distinctions within hydroponics, one with media and the other without media, named as liquid hydroponics and aggregate hydroponics respectively. Another distinction is based on the recirculation of the nutrient solution system. The nutrient solution is discarded after passing through the root mass or medium in an open system and in a closed system the nutrient solution is recovered for reuse.

Figure 2.8 Water based (soil less) agriculture Garden Design Plus

Hydroponic production techniques

a. *Liquid non-aggregate hydroponics*

Liquid systems are closed systems in which the roots of the crop are directly exposed to the nutrient solution and have no other growing medium. In this system the nutrient solution is reused. There are several systems in this category, such as the Deep Flow Technique (DFT) and the Nutrient Film Technique (NFT). All techniques listed below are primarily used in non-aggregate systems but can also be applied in aggregate systems.

- ### *Deep flow technique (DFT)*

In 1976, the deep flow technique was independently developed by Jensen (USA) and Massantini (Italy). In this technique, seedlings are planted in several floating plastic rafts, with the roots of the crop dipped in the nutrient solution.

Advantages

- The floating rafts helps in having a mobile production element. The basins filled with nutrient solution are almost frictionless conveyor belts that facilitate planting and harvesting.
- Root temperatures are controlled with this technique. The nutrient solution is either heated or cooled. (Jensen, 2002).
- A more constant temperature can be maintained in the nutrient solution by the DFT, due to the larger volume.

Disadvantages

- Aero roots are not introduced in standard DFT systems. In warmer climates, the ability to induce aero root formation is a key point in designing, due to lower uptake of dissolved oxygen. However, to induce aero root formation alterations to the raft can be made. (Kao, 1991)
- Only a limited amount of produce varieties can be made possible by this technique, due to the mobility and maximum buoyancy of the rafts.

Versatility and efficiency of space are the two main features of the deep flow technique. Minimal additional input is required when this system is applied on a larger scale.

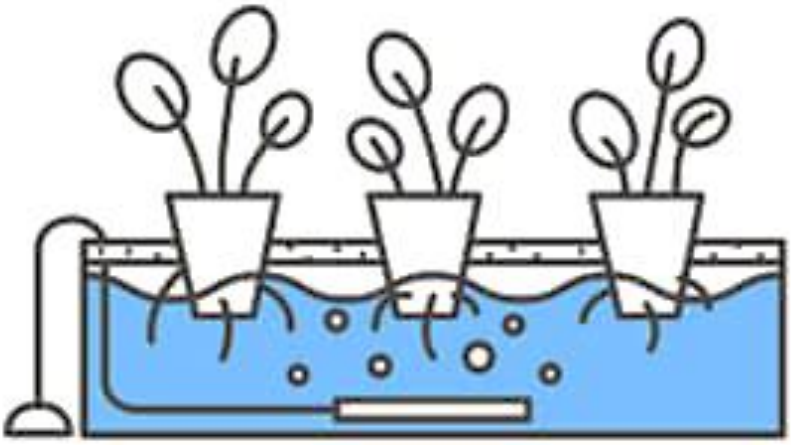


Figure 2.9 Deep Flow Technique (Hydroponics China)

- ***Nutrient Film technique (NFT)***

The nutrient film technique (NFT) was developed by Dr. Allan Cooper in the late 1960's at the Glasshouse Crops Research Institute (Cooper, 1968). Later, numerous refinements were made at the same institution (Graves, 1983). Many modified systems followed. These systems are most used to produce leafy vegetables. The higher end of each channel is pumped with nutrient rich solution that flows by gravity along the plant roots before being collected. Before it is recirculated, the solution is monitored for its nutrient content. (Jensen, 1997)

Advantages

- Significantly less total nutrient solution is required in NFT systems compared to other systems. Therefore, heating the solution in winter months is easier to obtain optimal temperatures for root growth and during hot summers in arid or tropical regions it can be easily cooled down. Another advantage of reduced volumes is the treatment of nutrient solution for disease control.
- Aero root formation is possible in this technique.

Disadvantages

- The NFT system has stationary production beds. Space utilization is less efficient since a significant amount of space is reserved for seeding and harvest.
- Energy use - Due to its relatively small volume, constant movement and relatively large surface area for heat exchange, it is difficult to maintain a constant temperature in the nutrient solution.
- A major drawback of NFT system is that it is less resistant to higher temperatures. Kao (1991) noted that when air temperature reaches 37°C, dissolved oxygen levels fall dramatically, which reduce the growth process of vegetable crops.

Nevertheless, the NFT system has proven to be highly responsive and versatile. A broad variety of crops can be produced on a larger scale using this system.

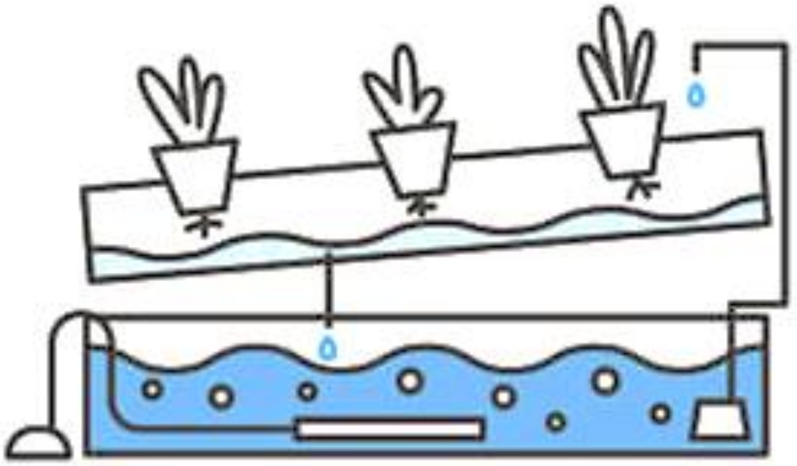


Figure 2.10 Nutrient Film Technique (Hydroponics China)

- ***Aeroponics***

A more unusual application of closed system hydroponics is constituted by Aeroponic system (Jensen, 1997b). Plants are seeded in panels of expanded polystyrene or any similar material. The plant roots are suspended in mid-air under the panel and are enclosed in a spraying box which is then sealed. The roots are kept in saturated humidity and darkness (to inhibit algal growth). Every 2-3 minutes, for a few seconds, a misting system sprays the nutrient solution over the roots periodically. This helps in keeping the roots moist and the nutrient solution aerated. Jensen developed Aeroponic systems in Arizona for lettuce, spinach and even tomatoes. The latter application was judged not to be economically viable (Jensen & Collins, 1985).

Advantages

- The required water volume can be smaller in aeroponics than in other hydroponic systems (Despommier, 2012). However, there is few scientific supports for this claim.
- Space efficiency is a benefit of aeroponics when using an A-frame structure and the production of lettuce or spinach production is doubled compared to standard systems. This system supports a better utilisation of the cubic volume of the growing facility (Jensen, 1997b).

Disadvantages

- Stationary production beds are used in aeroponics. This reduces space usage efficiency since a significant amount of space is reserved for crop harvest.
- To avoid nutritional deficiencies, the application of nutrient solution needs to be continuous. (Raviv et al., 2008)
- Uneven growth patterns are a result of the A-frame aeroponic constructions due to variations in light intensity on the inclined crops (Jensen,1997).

NFT and Aeroponic systems both are deemed to be equally versatile and responsive. A broad variety of crops can be produced on a larger scale. However, the system is more complex in terms of its technology and parts (notably, the misting system) that increase its energy usage and maintenance.

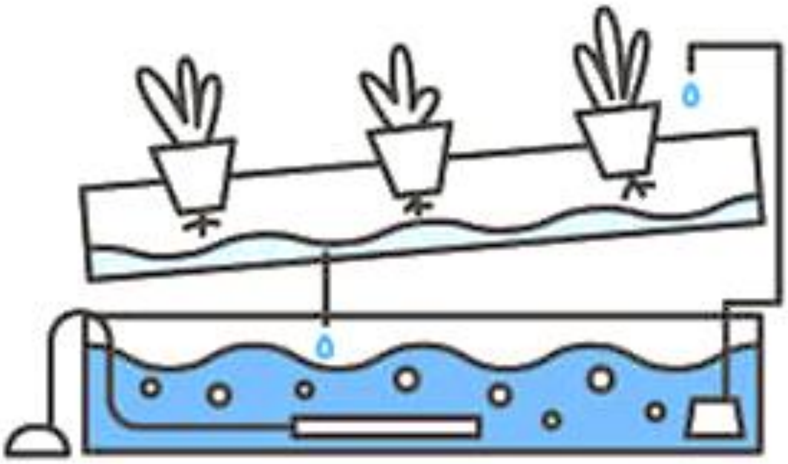


Figure 2.11 Aeroponics (Hydroponics China)

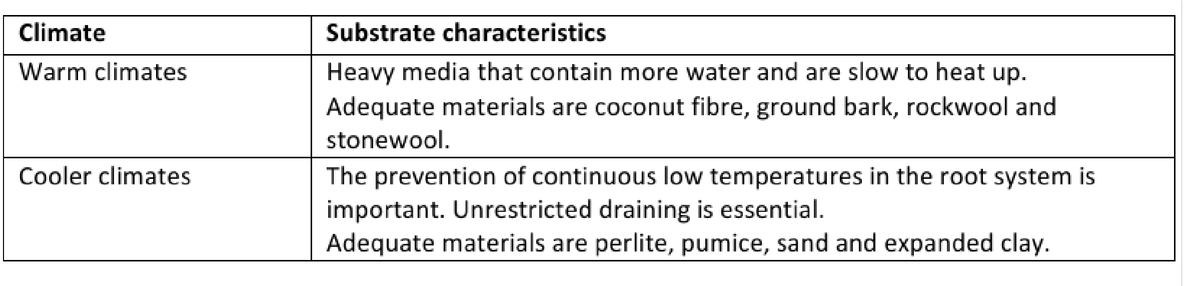
b. Aggregate hydroponics

In aggregate hydroponics, an inert-solid medium is used to provide support and nutrients to the roots of the plants. Rockwool, choir made from coconut, polystyrene, etc. are the types of materials used as ‘media’. (Jensen, 1997b) The nutrient solution is delivered to the roots directly similarly to the liquid systems.

Growing media

Specific solid media that act as aggregates are used in this system. Perlite and rockwool are quite famous as an artificial media to grow crops such as pepper, cucumber and tomato. The most efficient way is to use locally available materials for media beds. Examples of this are coconut coir in Malaysia, Mexico and China.

The aggregate substrates are closely linked to the local production climate. Substrates that can maintain a constant temperature are preferred in warmer climates. Uninhibited flow capacity is preferred in cooler climates.



Climate	**Substrate characteristics**
Warm climates	Heavy media that contain more water and are slow to heat up. Adequate materials are coconut fibre, ground bark, rockwool and stonewool.
Cooler climates	The prevention of continuous low temperatures in the root system is important. Unrestricted draining is essential. Adequate materials are perlite, pumice, sand and expanded clay.

Figure 2.12 Substrate characteristics in particular climate (Jones, 2005)

Figure 2.13 Fired clay pebbles (hydroponicgardening.com)

Figure 2.14 Hydro Stones using recycled glass (hydroponicgardening.com)

Ebb and Flow technique (EFT)

Originally used by the U.S. Army in World War II, the ebb and flow technique (EFT) was developed to supply troops operating in the Pacific with fresh tomatoes. Eventually, it was adapted for commercial use. However, this technique, is no longer commercially used on a large scale.

A watertight exterior rooting bed, a perforated interior rooting bed containing an inert rooting medium (such as gravel, coarse sand), a nutrient solution tank (equal in volume to the growing beds), an electrical pump to circulate the nutrient solution and a piping system make up the structure of the EFT. Gravity can be utilised to return the nutrient solution from the growing beds to the tank to reduce energy expenditure (Jones, 2005). Every 1-2 hours the circulation system pumps the nutrient solution into the rooting bed for approximately 30 minutes. Fischer et al. (1990) determined that the most important factor in EFT production is the duration of flooding. For each case, this should be determined.

Advantages

- The EFT system operates on smaller scales and is relatively easy to (Jones, 2005).
- A temperature element in a thermally conductive rooting bed can be placed to locally cool or heat the root zone (Resh, 2012).

Disadvantages

- This technique is relatively inefficient in terms of its expenditure of water and nutrients (Jones, 2005).
- Due to intermittent flooding of the root area, the EFT system is very susceptible to root diseases.
- A piping system that is closely linked to the root area of the crops is present in the EFT system that can lead to roots growing into the pipes and hindering the flow (Jones, 2005).

The system has had little application due to its inefficient use of water and essential elements. Commercially, the EFT system has proven difficult to manage.

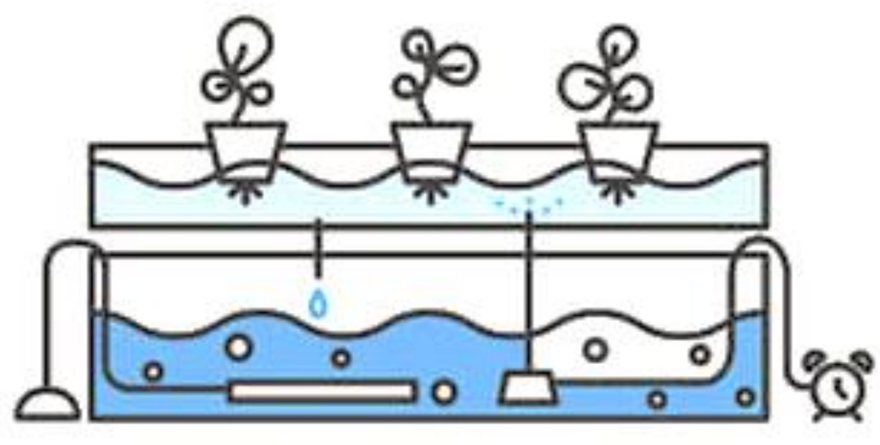


Figure 2.15. Ebb and Flow system (Hydroponics China)

- *Aquaponics*

The basis for aquaponics is the integration of fish and plant for production. The rearing fish provides the nutrients for crop production and vice versa. The nutrients needed by the plants are dissolved in the fishponds. An efficient relationship using nutrients and water is formed by integrating the two systems.(Licamele, 2009) A climatised fish tank is paired with a NFT system. Nutrient rich water is circulated through a piping system that connects the two systems. An electric pump is used for this circulation.

Advantages

- The energy cycle is closely connected by utilizing the crop wastes that act as a feed for the fish and vice versa.
- Large climatised tanks are required to hold the fish which can also be used for thermal storage.
- In aquaponics, less nutrient input is required compared to other techniques.

Disadvantages

- Extra cooling and heating processes are required due to the difference between the temperatures of the fish tank and the crop. The temperature of the solution for fish and crop are not the same: 28-35°C (Chervinski, 1982) and 21-25°C (Licamele, 2009), respectively.
- The exact quantity of nutrients supplied by the fish to the crops is hard to predict. It can be variable and depends on the fish. Nutrient supplementation, including iron, manganese and zinc is needed by the crops (Licamele, 2009. Therefore, it might be tough to achieve an ideal balance.
- The nutrient rich water also poses a risk of contamination due to diseases in fish. In any aquaculture systems, fish survival and growth parameters are very detailed. (Lennard & Leonard, 2006)

Advantages and disadvantages of hydroponic production

The major advantages of hydroponic production include High-density and maximum crop yield, crop production without ideal soil, more efficient use of water and fertilizers independence from seasons or outdoor temperature, lack of manual labour or mechanization and control of disease are the key advantages of hydroponic systems. Problems caused due to disease, salinity and poor structure are avoided since in hydroponics, the crops are separated from the underlying soil. A rapid turnaround of crops is easily achieved without any time consuming and expensive tasks. The result of a hydroponic production facility in a controlled environment is that the harvests are largely greater as compared to open field cultivation. The quantities are 5.5 to 20 times higher yields compared to open field agriculture system. (Jensen, 1997b).

However there lie some major disadvantages in hydroponics. These are its high costs and energy inputs, as well as the knowledge and skills required to operate such systems. Currently only crops with high economic values and in specific regions are cultivated using this technique. (Jensen, 2001).

The following are the advantages and disadvantages of hydroponic techniques listed by Jensen (1981):

Advantages of hydroponic production

- Location freedom – Soil is not a deciding factor for the crops to be produced. They can be grown anywhere with this technology.
- Low labour intensity – It does not require any manual labour like in conventional agriculture.
- Low infestation rate – Soil borne pathogens are absent in this system.
- Recycling – Since these are closed systems, recovered water, nutrients, etc. can be reused in subsequent production rounds. Additionally, this can reduce the pollution water and land.
- Full climate control – The production climate in these systems can be entirely controlled. Irrigation, nutrient supply times, root environment can be all controlled.
- Flexibility –They are organized, lightweight and clean. This promotes flexibility of its location.

Disadvantages of hydroponic production

- Costs – Construction costs of hydroponic systems per acre are relatively high.
- Technological expertise –To sufficiently manage the growing process, extensive skills are necessary. One needs to know about nutrition and growth patterns.
- Spread of infestation – Soil-borne diseases and nematodes can easily spread to production trays in the closed system.
- Produce variety –In order to adapt available plant varieties to controlled growing conditions additional research and development is required.
- Reaction speed – Constant observation is necessary since the crops react to poor or ideal growth conditions extremely fast.

(D)Conclusions of literature survey

- ***Urban agriculture***

The literature of Urban energy metabolism indicates that urban agriculture is a promising solution to impact a variety of issues faced by urban areas currently. These issues range from food security to energy use to linear waste flows. Vast research is needed to understand the full potential of urban agriculture. Integrating agriculture in buildings, gives the residents a chance to be involved in their food production. The nature of this system is circular in nature since the building and the agriculture survive on a co symbiotic relationship. The waste flows can be efficiently utilized by the production unit and the outputs from the production units can be delivered back to the buildings. This could be the ideal solution to form a sustainable flow of energy in urban built environment.

- ***Production techniques:***

In soil-based production techniques, the disadvantages of space constraints, weight and soil contamination, make water based or hydroponics a preferable method of production, especially in Building Integrated Agriculture (BIA).

For assessing the outcome of water based growing techniques following parameters can be taken into consideration –

- Space use efficiency – Amount of production per m2 of floor area
- Water use efficiency – Amount of production per m3 of water
- Energy use – Amount of energy required per m2 of production area
- Harvest manageability – Accessibility of crop for seeding and harvest

After studying the different types of production techniques mentioned above, following chart can be summarised:

	Space flexibility	Water efficiency	Energy efficiency	Harvest management
Deep Flow technique (DFT)	●●	●●●	●●●	●●●
Nutrient Film technique (NFT)	●●	●●●	●●	●●●
Aeroponics	●●	●●●	●	●●
Ebb & Flow technique (EFT)	●●●	●●	●	●●
Aquaponics	●●	●●	●●●	●●

● Poor ●● Average ●●● Good

Table 2.16 Comparison chart of different Hydroponic techniques

Closed hydroponic systems are preferred, due to their potential for the recovery of energy, water and nutrients. The deep flow technique seems most suitable for production in spacious areas. The nutrient film technique seems most suitable for production near the façade and other spatially inefficient areas

- *Modular and flexible nature of the production unit*

Presently, the urban cities are packed with infrastructure and the main challenge for urban farming is to find space availability for crop production. This leads to choosing hydroponic systems over traditional soil-based systems. To make the units more efficient in terms of output produce, in a small area, combination of technologies can be used.

The location of the food production units also adds up to the ecological impact. Further away the unit, more is the carbon emission. The consumer is no longer aware or involved of where their food is coming from.

In such a scenario, having a modular and flexible production unit could be beneficial. The locations of these units could be decided based on availability of vacant spaces in urban areas. These spaces could also be on balconies of buildings or facades. A similar approach is applied in building integrate agriculture.

In some examples of BIA, the production units lack flexibility in terms of its construction. This hampers the efficiency of harvest. For instance, in rooftop gardens, the temperature conditions are dependent on outdoor climate and hence might vary throughout the year. This would either require increased energy use to control the indoor climate or compromise on the harvest. A modular or flexible unit could change its location and arrangement depending on the season.

From materials perspective, most hydroponic systems use PVC and HDPE parts which are not easily recyclable. On the other hand, the structural parts of a greenhouse can be recycled but the scale of the greenhouses restricts it from dismantling and reusing easily.

Thus, a small-scale production unit that is modular and flexible in nature could address all the points above. It could be energy efficient, easily dismantlable and could be transferred or reconfigured to another location for further use.

Chapter 3 |

Project Cases

Introduction

In the previous chapters, various literature topics related to building integrated agriculture in the urban context were summarised. Various techniques of urban farming were discussed such as soilless hydroponics, aquaponics, and so on. These techniques are currently used in small and large-scale food production in greenhouses, but there are very few examples of building integrated agriculture (BIA), where these techniques are used. Another aspect is the symbiotic energy relationship between these agricultural units and the building which is not commonly seen. In the following chapter, two residential archetypes are chosen to understand their energy performance and future energy efficiency goals. The aim is to design modules with different functions that could be connected to the chosen buildings, to create resource synergies.

3.1 Building selections

The Netherlands is a leading example in the EU climate policy and has advocated the climate related targets laid by the EU Climate Law. The target is to achieve 55 percent emission reduction by 2030 and climate neutrality in 2050 (Government of the Netherlands, 2014).

The Dutch government aims to have all the buildings in the Netherlands switch to a low-carbon alternative to fossil fuels by the year 2050. (Cole, 2021a) With this as a background, two residential dwellings were chosen in the Hillegersberg district of Rotterdam. The buildings were chosen such that they have striking differences in their types, year of construction, living area, energy label, etc. This would help in assessing the overall impact of the modules in the built environment across different properties.

(a) Case 01

A **multistorey residential apartment building** which has been recently constructed was chosen as the first case. This building is situated in the Hillegersberg-Zuid area near the river Rotte. The data obtained from various housing rental websites such as Funda is summarized below.

Location: *Philips Willemstraat 91*
3051 PN Rotterdam
Year of Construction: *2005-2006*
Type of Building: *Residential apartment with multiple units*
Living area: *63 m^2 – 138 m^2*
Number of Apartments: *47*
Energy Label: *A*

Fig.3.1 Street view of the building (Funda, 2022)

(b) Case 02

A **'tussenwoning'** or a **typical Dutch house** that lies between two other similar houses has been selected as the second case. This house is located in the same block as the first case but has a striking difference in its appearance and year of construction. The data for this case is also obtained from various housing rental websites such as Huispedia and is summarized below.

Location:	*Willem van Hillegersbergstraat 60, 3051 RL Rotterdam*
Year of Construction:	*1914*
Type of Building:	*Dutch family home*
Living area:	*174 m^2*
Number of Bedrooms:	*5*
Energy Label:	*F*

Fig.3.2 Street view of the building (Huispedia, n.d.)

Neighbourhood character

Fig.3.3 Aerial view of the neighbourhood (earth.google.com)

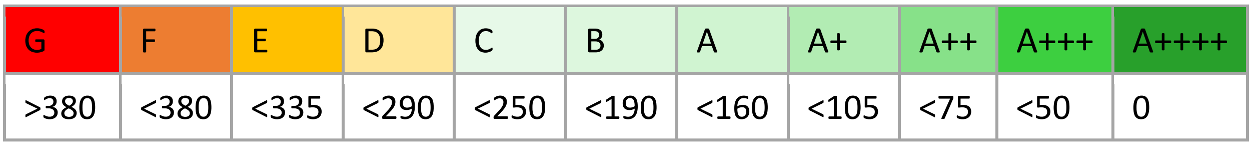
Both the project cases are located in the same block, in the neighbourhood of Hillegersberg-Zuid. The area has a wide range of buildings dating back to 1900s to recently constructed ones. The energy labels are also diverse for the buildings located in this area.

3.2 Present Energy efficiency situation

Buildings in the Netherlands are issued energy labels that indicate the energy efficiency of the building. These labels are determined using the fossil energy consumption per year which is expressed in kilowatt hours per square meter (kWh/m^2). While selling or renting a house, a valid energy label is mandatory. The energy label also helps in indicating options for improvement possibilities to achieve a more sustainable house. Another benefit of having a better energy rated house is lower energy costs and increased comfort of living. (Rijksdienst voor Ondernemend Nederland, 2017a)

3.2.1 Energy Label

Coal, oil, and natural gas are the fossil fuels that generate energy. Natural gas is widely used as an energy source for homes. The less the fossil fuel consumption, the better is the energy label issued. A+++ is the best and G is the worst energy label. (Rijksdienst voor Ondernemend Nederland, 2017a)



G	F	E	D	C	B	A	A+	A++	A+++	A++++
>380	<380	<335	<290	<250	<190	<160	<105	<75	<50	0

Fig. 3.4 Energy Label chart for houses in the Netherlands with Energy consumption values in kWh/m^2 (rvo.nl)

The above chart shows the energy label corresponding to the kWh/m^2 value of energy consumption per year. If a house has an energy consumption of less than 50 kWh/m^2 then it holds an energy label of A+++. **The amount of energy the house uses depends on the insulation, installations and compactness of the house.** A more compact house has relatively lesser surface area and hence, loses less energy. This gives a lower value for compactness resulting in a better energy label. If a house is well insulated, then it loses less energy and has a lower demand for heating or cooling. Installations such as renewable energy generators like solar panels, solar water heaters or heat pumps, also reduce the demand for fossil energy. (RVO, 2017)

Calculation for the energy label is based on the average number of residents, resident behaviour and the average Dutch climate. Consumption for appliances such as TV, washing machine, refrigerator, etc. are not counted since the energy label is only determined for how energy efficient the home is, by itself. (RVO,2017) Therefore, the electricity consumption on the resident’s energy bill would not match the estimated energy consumption on the label.

3.2.2 Energy Label improvement strategies

Once the energy label is established, the house can then be improved to achieve a better energy performance. For this, the Dutch government has advised certain improvement options. These include insulation modifications, energy efficient appliances and adapting renewable energy options. Below are some of the suggestions by *'milieu centraal'*.

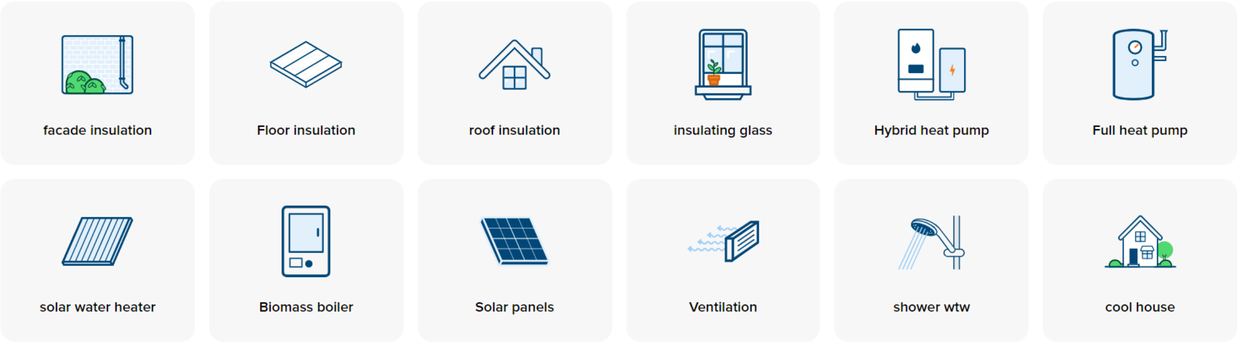


Fig. 3.5 Home improvement options (mileu central/https://www.verbeterjehuis.nl/)

- *Insulation* Houses built before 1920 might not have a cavity wall and can opt for insulation on the outside or the inside of the wall. Houses built after 1975 mostly have insulation on their façade but it can always be improved.
  The higher the insulation value (R_c), the better the insulation.
  Best value for insulation of Facades : R_c=6m^{2}K/W (approx. 26cm of insulation)
  Best value for insulation of Floor : R_c=3.5m^{2}K/W (approx. 14cm of insulation)
  Best value for insulation of Roof : R_c=8m^{2}K/W (approx. 35cm of insulation)

  However, the above target values are not always feasible to achieve. The achievable values as per standard building regulations for new buildings are as follows:
  Insulation for facades : R_c=4.5m^{2}K/W
  Insulation for floor : R_c=3.5m^{2}K/W
  Insulation for roof : R_c=6m^{2}K/Ws

- *Heat pump* **Hybrid heat pumps** work together with central heating boiler. Heat pumps run on electricity and together with a boiler, use 60% less natural gas for heating. Most heat pumps extract heat from outside air, whereas some use the mechanically extracted ventilation air from the house as a heat source.
  For a **fully electric heat pump**, the house needs to be very well insulated. It runs completely on electricity but is expensive compared to hybrid heat pump.
  Another alternative is connecting the house to a District heating system wherever possible. The Dutch government plans to have 1.5 million houses connected to district heating by 2030. District heating uses a network of pipes to distribute heated water from centralized or decentralized heat sources to houses. It uses heat sources that are already present in the

locality to avoid transportation over long distances and incur loses. It may also use new heat source generated sustainably.

- *Renewables* Prime example of renewable sources of energy are **solar panels**. A south facing roofs are the most suitable to harness maximum solar energy. They can be installed on flat as well as pitched roof.
  Another example of using renewable source of energy is a **solar boiler** that uses the heat from the sun to heat water for the shower and kitchen. This device is placed on the roof and can be used in combination with a heat pump or a gas-fired, high efficiency boiler.

- *Ventilation* Automatic control of the amount of fresh air that enters the house can limit the energy consumption for ventilation. Ventilation unit with a heat recovery feature can reduce the heat loss from the building, thereby reducing the heating energy demands. **Balanced ventilation with heat recovery** system is a good option for this goal.

- *Cool house* A cooler house in hot summer months can be achieved by simple installations and additions to the house. Sun protection in the form of canopy or awning can block the direct sun rays from hitting the house and provide shading. HR++ is a double glazing with a coating and gas infill between the glass panels which is insulated very well. **Sun protection** paired with **HR++ glass**, can block out 80% of the heat radiation. Another, more natural idea is to have greenery around the house. This could be in the form of green walls on the facades or green roofs with plants. Plants with their evaporative cooling and shading can drastically help to cool down the house. *(Government of the Netherlands, 2021)*

- *Biomass boiler* A biomass boiler burns 'biomass' which consists of wood chips, logs or wood pellets to produce energy for heating the home and hot water. The biomass is obtained from sawdust in wood industries or from pruned trees. A **biomass boiler** produces less CO2 emissions as compared to a gas fired high efficiency boiler. However, a biomass boiler needs large storage spaces for storing the biomass fuels, placing the buffer tank and a chimney to discharge flue gases.

- *Shower heat recovery* Recovering the heat from the shower water that flows out and preheating the cold water that flows in, helps in reducing the energy demand for heating hot water. A heat exchanger is used in combination with the shower pipes to recover the heat. By incorporating this system, 120m^3 gas can be saved per year.

3.2.3 (a) Energy performance of selected cases

After looking into the details of what energy label means and how a home can have a better energy performance, the energy performance of the chosen buildings is investigated.

Case 01 – Multi-storey residential apartment

This building was recently built, in 2005-2006. The buildings that have been built in recent years have already taken some degree of energy efficiency into consideration. The installations in these buildings deliver better energy performance however there is always room for improvement. Natural gas is still being used in many such buildings. In the future, natural gas-run boilers, will be replaced by all electric options or heat pumps or connected to district heating grid.
The following chart lists the installations and insulation that this building presently has.

Energy Label	A
Insulation	Good (wall, floor & roof), HR+++ glass
Heating	Central heating using gas boiler
Boiler type	High efficiency (HR)
Renewables	No solar panels
Ventilation	Natural supply & mechanical exhaust
Cooking	Electric

Fig. 3.6 Present building characteristics (Huispedia.nl, part data assumed from statistics and pictures)

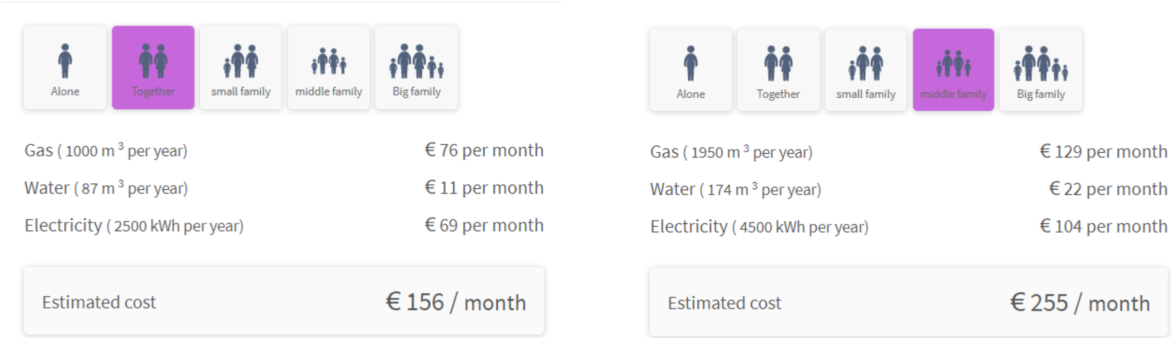
Case 02 – Dutch 'tussenwoning'

This house was built back in 1914. The buildings constructed during this time have poor insulation and energy performance was not a major consideration. Over the years some people have renovated and modified the houses to improve its performance. The old houses that have not been renovated yet, need considerable changes to achieve the current required energy performance. The following chart lists the installations and insulation that this house presently has.

Energy Label	F
Insulation	Poor insulation, largely double glazing
Heating	Central gas boiler
Boiler type	HR-combi (gas fired, privately owned)
Renewables	No solar panels
Ventilation	Natural supply & mechanical exhaust
Cooking	Electric

Fig. 3.7 Present building characteristics (Huispedia.nl, part data assumed from statistics and pictures)

Now that the present installations and insulation conditions of these cases are known, the next step would be to check the actual amounts of energy the individual units consume. To calculate the exact energy demands, an excel sheet is formulated. The statistical data is obtained from various governmental websites such as CBS statline. Furthermore, as per the number of occupants, an average estimate of energy consumption is obtained from housing websites such as Huispedia.



Gas (1000 m^3 per year)	€ 76 per month
Water (87 m^3 per year)	€ 11 per month
Electricity (2500 kWh per year)	€ 69 per month
Estimated cost	€ 156 / month

Gas (1950 m^3 per year)	€ 129 per month
Water (174 m^3 per year)	€ 22 per month
Electricity (4500 kWh per year)	€ 104 per month
Estimated cost	€ 255 / month

Fig. 3.8 for ***Case 01 & 02:*** *Estimated Energy consumption based on no. of occupants (huispedia.nl)*

The energy costs mentioned in the above images are subjected to change based on the present rates. The images have been used only to check the energy demands based on the number of occupants.

3.2.3 (b) Other resource demands for selected cases

Apart from the above discussed energy resources, the buildings and their occupants, also use water, food and fresh air.

The total water demand is divided into potable water use and water for flushing. Depending on the number of occupants, the amount of water required is calculated. Similarly, the quantity of food demand, and fresh air required for breathing is calculated depending on the number of people living in the house or apartment. Standard numbers, per person consumption are considered and multiplied by the total number of occupants. The standard numbers are obtained from different sources as mentioned in the references for the excel sheet in the appendix.

	Units	APARTMENT	DUTCH HOUSE
Energy Label		A	F
Living surface area	Sq.m.	77	174
Number of people		2	4
Year of construction		2006	1914
Average natural gas consumption	m^3 kWh	1000 11187	5600 62640
Natural gas for Heating	kWh	8950	58160
Natural gas for Cooking	kWh	-	-
Natural gas for DHW	kWh	2240 (for 2)	4480 (for 4)
Average consumption of electricity (incl. cooking)	kWh	2500	4500
Ventilation type		Natural supply & mechanical exhaust	Natural supply & mechanical exhaust
Total domestic water use	Litres/year	97674 (for 2)	195348 (for 4)
Potable water	Litres/year	71905 (for 2)	143810 (for 4)
Toilet flushing	Litres/year	25769 (for 2)	51538 (for 4)
Food – vegetables (incl. fruits & nuts)	Kg/year	182.5 (for 2)	365 (for 4)
Food – (excl. veg & fruits)	Kg/year	550 (for2)	1095 (for 4)

Fig. 3.9 Energy demands and consumption of the 2 selected cases (Appendix 1 for detailed excel sheets)

The quantified values of each parameter listed in the above chart, forms the INPUT for the energy co-symbiosis that will be formulated in the further chapters. For now, these values will be used to check where and how possible energy performance improvements can be made.

3.3 Future scenarios

As stated earlier, the Dutch government is aiming for a carbon neutral future, and this applies to the housing sector as well. The 2 cases have different quantities of energy demands and existing installations. The home improvement strategies given by the Dutch government can be utilised for these cases to achieve an energy efficient home. In the table below, the possibilities are listed for both the houses.

	Present condition	APARTMENT Future scenario	Present condition	DUTCH HOUSE Future scenario
Energy Label	A	A++	F	C or better
Living surface area	77	77	174	174
Number of people	2	2	4	4-5
Year of construction	2005-2006	NA	1914	NA
Glazing	HR+++ glass	No change needed	Double glazing	HR++ glass (triple unsuitable for old frames)
Heating	Gas boiler (high efficiency combi boiler)	Suitable for Full heat pump as HR+++ glass & good insulation	Gas boiler (high efficiency combi boiler)	Hybrid heat pump or electric heat pump or district heat
Façade insulation	Good	No change needed	Poor (no cavity wall since before 1920)	Insulation from inside/outside
Roof insulation	Good	No change needed	Poor	Insulate to Rc = 4 (13cm thick)
Ventilation	Mechanical exhaust	Ventilation unit with Heat recovery (if heat recovery not present already)	Mechanical exhaust	Ventilation unit with Heat recovery (if heat recovery not present already)
Additional energy	NA	Biomass boiler for heating	NA	Biomass boiler for heating
Renewable Energy	NA	Solar panels	NA	Solar panels

Fig.3.10 Future energy improvement possibilities

However, implementing these strategies might not be the most easy, minimum labour or cost-effective choice. Although the above solutions are the recommended methods to accelerate the energy transition, it is important to look into other ways that could either speed up, ease up or assist the present approaches, for reaching the same end goal.

3.4 Greenhouse selection

The final design of the greenhouse is going to be a type of building integrated agriculture (BIA). However, to begin with, first, a small sized greenhouse without any building integration is considered. Parameters such as size, shape, materials of façade, glazing, type of crop inside, etc. are decided. This will help in calculating the heating or cooling demand of the greenhouse. Once the basic calculations are obtained, later it can be integrated with the host buildings and checked for possible symbiosis.

Location:	*Rotterdam, Netherlands*
Type:	*Even span, A-frame structure*
Crops:	*Seasonal crops as listed below*

Fig. 3.11 Small sized greenhouse example (www.coolgardengadgets.com)

Crop selection

The greenhouse is subjected to varying temperatures throughout the year. For this project, no additional heating or cooling is going to be used. Therefore, the crops are selected based on the seasonal temperatures that favour their growth conditions. Depending on the harvest time, the crops can be planted in rotation throughout the year. Below is a list of crops and their required temperature ranges along with their harvest time period-

Crop	**Growing temperature range (°C)**	**1st Harvest time**
Tomato	21 - 26	2 months
Paprika	21 - 27	50 – 80 days
Cucumber	24 - 30	50 – 70 days
Lettuce	15 - 21	6 weeks
Beetroot	10 - 21	40 – 50 days
Spinach	5 - 18	1 – 1.5 months

Fig. 3.12 Crop growing temperature and 1st harvest time

Greenhouse specifications

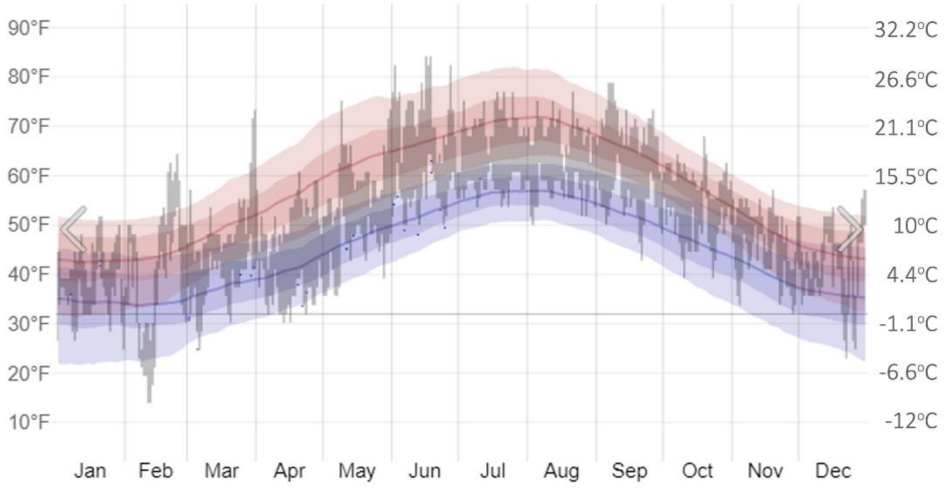
The greenhouse module has a size of 2.5m x 2.5m. This size allows multiple arrangements of crop trays along with the space required for placing supporting equipment such as water reservoir. In this space, one person can also move around to maintain the crops.

Structure		Description
Total area	6.25m^2 (2.5x2.5)	*Base cube module*
Height	2.5m	*Excluding rise of roof*
Angle of roof	23°	*Standard for Venlo type Greenhouse (also the best angle for NL)*
Main structural frame	Steel	
Roof & supporting frame material	Aluminium	
Roof panel	Single Glass 4mm	*Transparent, max. Natural light, Flame resistant, aesthetic*
Roof windows - openable	1 on each slope Size = 0.6m x 1.2m	
Wall cladding	Single Glass 4mm	*Transparent, max. Natural light, Flame resistant, aesthetic*

Fig. 3.13 Greenhouse specifications

Heating and Cooling

Now that the specifications of the greenhouse with temperature requirement for the crops to be grown inside are known, the next step is to calculate the amount of energy it would require to heat or cool the greenhouse to the set temperatures. This amount would vary as per the seasonal temperatures over the 12 months of the year. Since the greenhouse is located in Rotterdam, climate data of Rotterdam from the year 2021 has been used as a reference.



Grey bar - The daily range of reported temperatures
Red line and blue line - Daily average high and low temperatures with 25th to 75th and 10th to 90th percentile bands

Fig. 3.14 Rotterdam yearly temperature 2021 (WeatherSpark.com)

From the crop temperatures list in the previous table, the table below shows the comparison of the temperature outside during each season, and the temperature limit that the crops can withstand inside the greenhouse. This helps in planning out the crop cultivation schedule.

			January – March (winter)	April – June (spring)	July – September (summer)	October – December (autumn)
Crop	Temp In (°C)	Average temp (°C)	Temp Out (avg.) (°C)			
Tomato	20 - 26	23	5	15	25	10
Paprika	21 - 27	24				
Cucumber	24 - 30	27				
Lettuce	15 - 21	18				
Beetroot	10 - 21	15.5				
Spinach	5 - 18	12.5				

Fig. 3.15 Crop growth temperature vs outside temperature

As evident from the table above, in the autumn and winter season, the heating demands of the greenhouse are maximum. Spring with a small amount of heating and summer without any heating is the perfect temperature for the greenhouse. However, in summer the enclosure of the greenhouse might overheat and cross the ideal temperature. To maintain the temperature, cooling is needed.

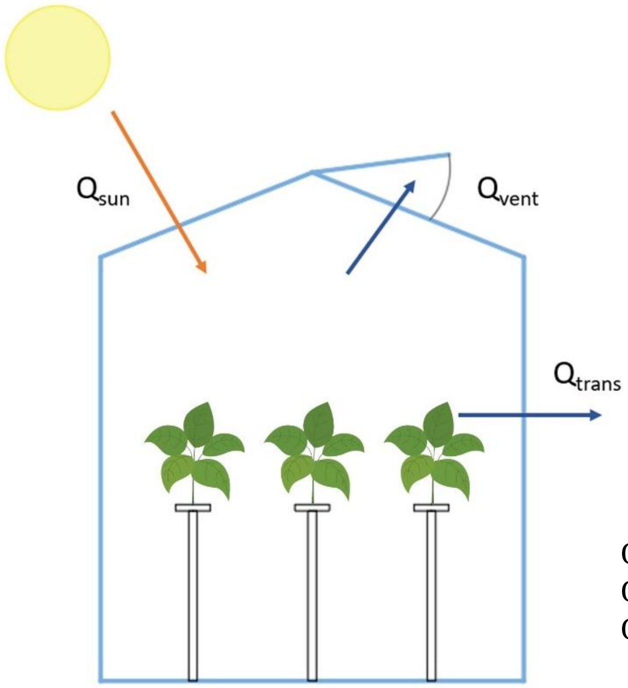
Since no artificial heating or cooling is being used in this project, the host building needs to supply the heating demand as much as possible and for cooling, the windows need to be opened or other strategies such as sunscreens need to be applied.

Using the temperature differences between inside the greenhouse and outside, and the properties of the greenhouse walls, roof and windows, the amount of energy required to heat or cool the greenhouse can be calculated. Once this amount is known, the next step would be to check if the host building can suffice the calculated amount of energy needed for heating using its own residual heat.

Greenhouse heating requirement calculation

The greenhouse undergoes energy transfer from inside to outside and vice versa in different ways. Conduction heat gain or loss occurs through the glazing of the greenhouse. Heat is lost from the greenhouse by convection through ventilation and infiltration. Heat gain occurs through radiation by the sun.

To further calculate the heating demand, an energy balance equation for this project case is formulated, as given below:



Q_{sun} : *Heat gain by sun*
Q_{vent} : *Heat loss through ventilation*
Q_{trans}: *Heat loss through transmission*

Fig. 3.16 Greenhouse energy flow diagram

Since the greenhouse in this project does not use artificial heating or cooling, only the natural heat incoming from the sun is considered. However, in this case, the heat from the building the greenhouse is attached to, is transferred to the greenhouse through the roof (if the greenhouse is on the roof) or through the wall (if the greenhouse is attached to the facade). Since, the greenhouse is relatively small, the infiltration heat loss is not considered. Therefore, with these conditions, the revised energy flow diagram is given below:

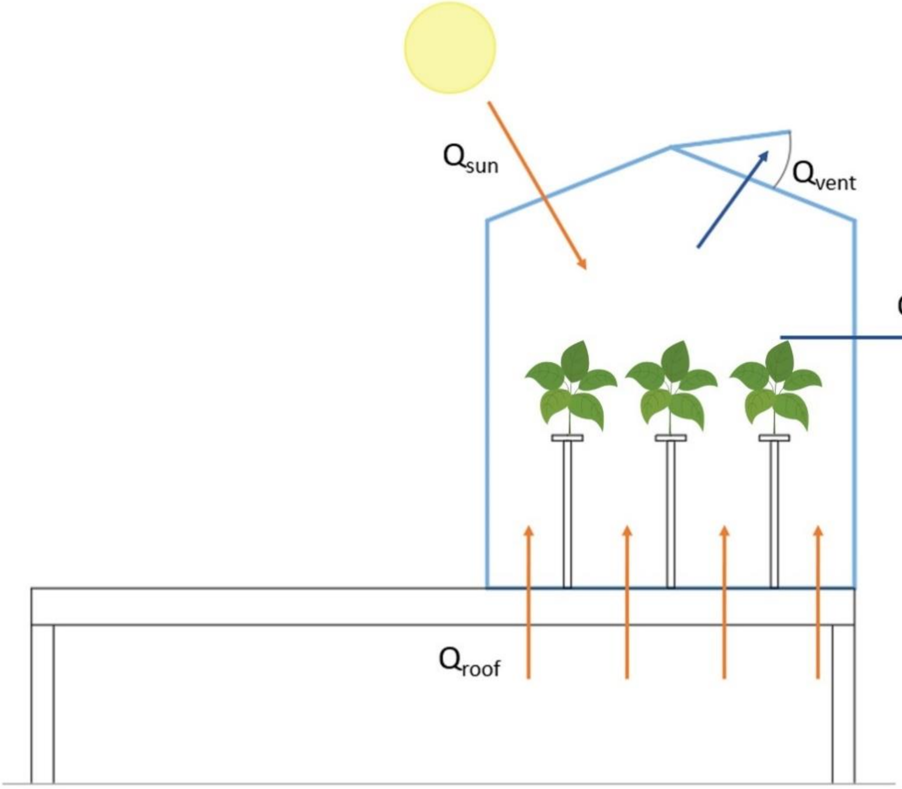


Fig. 3.16 Rooftop Greenhouse energy flow diagram

To maintain energy balance in the greenhouse, the total heat loss needs to be balanced by the total heat gain. The total heat gain consists of the radiation by the sun and the transfer of heat through the roof in the above case. The total heat gain is, therefore, the heating demand of the greenhouse.

Total heat loss = Total heat gain

$$Q_{vent} + Q_{trans} = Q_{sun} + Q_{roof}$$

Where,

$Q_{vent} = 0.33 \times n \times V \times \Delta T_1$
$Q_{trans} = U \times A \times \Delta T_1$
$Q_{sun} = G_i \times SHGC \times A$
$Q_{roof} = U_{roof} \times A_{roof} \times \Delta T_2$

n = number of air changes/hour

V = volume of greenhouse

ΔT_1 = Temperature difference between inside the greenhouse and outside

U = U value of greenhouse glazing

G_i = Incident irradiation of the sun

SHGC = Solar Heat Gain Coefficient

A = Surface area of greenhouse exposed to the sun

U_{roof} = U value of roof of house

A_{roof} = Area of roof acting as floor to the greenhouse

ΔT_2 = Temperature difference between inside the greenhouse and the room below

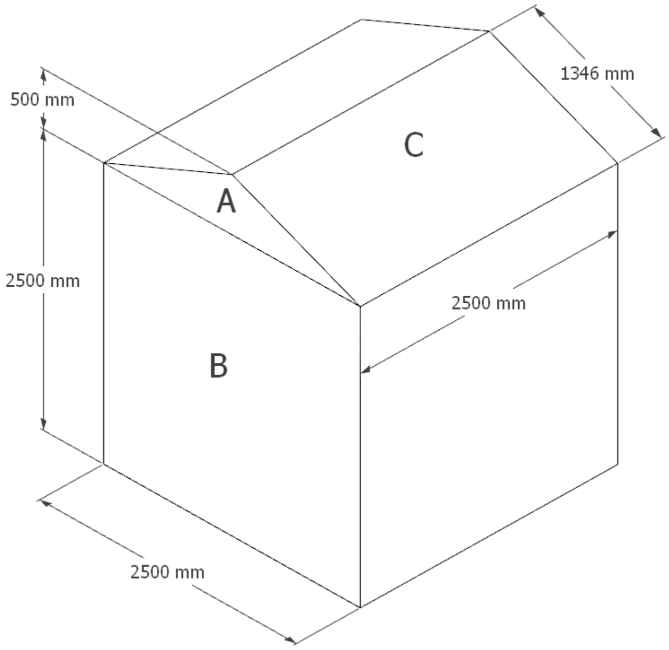


Fig. 3.17 Dimensions of the greenhouse module

The temperature inside the greenhouse is calculated for summer and winter conditions, in 3 different scenarios –

1) Summer – windows closed
2) Summer – windows open
3) Winter

Furthermore, the difference in temperature inside the greenhouse based on the insulation of the roof is also calculated.

Scenario 1 :

Placement of greenhouse: Roof of building
Orientation: South
Season: Summer, windows closed
T_{house} : Temperature inside house = 25°C
T_{out} : Temperature outside = 30°C
A_{roof} : Roof area with greenhouse = $6.25m^2$
A1 : Surface area of greenhouse = $33m^2$
A2 : Area facing sun rays = $9.6\ m^2$
U_{glass} = $5.8\ W/m^2K$
U_{roof} = $0.16\ W/m^2K$ (with insulation)
U_{roof} = $0.76\ W/m^2K$ (without insulation)
g (SHGC) = 0.8
Solar radiation intensity lower limit (q) = $300\ W/m^2$
Solar radiation intensity higher limit (q) = $400\ W/m^2$

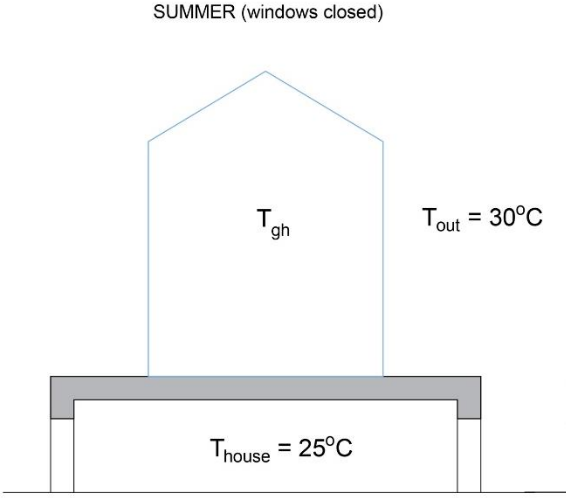


Fig. 3.18 Scenario - 1

Qin = Qsun + Qroof
Qout = Qvent + Qtrans

Windows closed, therefore Qvent = 0

Q_{sun} *(lower limit)* = **2310 W** ; Q_{sun} *(higher limit)* = **3080 W** (refer Appendix 5)
Q_{roof} *(with insulation)* = $U \times A \times (T_{house} - T_{gh}) = 0.16 \times 6.25 \times (25 - T_{gh}) = \mathbf{25 - T_{gh}}$
(without insulation) = $U \times A \times (T_{house} - T_{gh}) = 0.76 \times 6.25 \times (25 - T_{gh}) = \mathbf{118.75 - 4.75T_{gh}}$

$Q_{vent} = 0$
$Q_{trans} = U_{glass} \times A1 \times (T_{gh} - T_{out}) = 5.8 \times 33 \times (T_{gh} - 30) = \mathbf{191.4T_{gh} - 5742}$

Substituting these values in the energy balance equation,

$Q_{in} = Q_{out}$

Lower limit of solar radiation

(with insulation) 2310 + (25 - T_{gh}) = 0 + (191.4T_{gh} – 5742) = **41.98 °C = Tgh**

(without insulation) 2310 + (118.75 – 4.75T_{gh}) = 0 + (191.4T_{gh} – 5742) = **41.6°C = Tgh**

Higher limit of solar radiation

(with insulation) 3080 + (25 - T_{gh}) = 0 + (191.4T_{gh} – 5742) = **45.98°C = Tgh**

(without insulation) 3080 + (118.75 – 4.75T_{gh}) = 0 + (191.4T_{gh} – 5742) = **45.58°C = Tgh**

Scenario 2 :

Placement of greenhouse: Roof of building
Orientation: South
Season: Summer, windows open
Thouse : Temperature inside house = 25°C
Tout : Temperature outside = 30°C
Aroof : Roof area with greenhouse = 6.25m2
A1 : Surface area of greenhouse = 33m2
A2 : Area facing sun rays = 9.6 m2
Uglass = 5.8 W/m2K
Uroof = 0.16 W/m2K (with insulation)
Uroof = 0.76 W/m2K (without insulation)
g (SHGC) = 0.8
Solar radiation intensity on south (q) = 400 W/m2
Volume (V) = (l x b x h) + (1/2 x height of gable x b x l) = 17.18 cu.m.

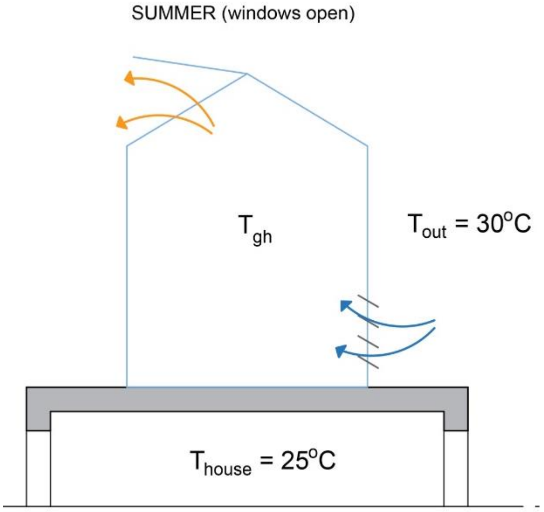


Fig. 3.19 Scenario - 2

Q_{sun} *(lower limit)* = **2310 W ;** Q_{sun} *(higher limit)* = **3080 W** (refer Appendix 5)

Q_{roof} *(with insulation)* = U x A x (T_{house} – T_{gh}) = 0.16 x 6.25 x (25 – T_{gh}) = **25 – T_{gh}**

(without insulation) = U x A x (T_{house} – T_{gh}) = 0.76 x 6.25 x (25 – T_{gh}) = **118.75 – 4.75T_{gh}**

Qvent = 0.33 x n x V x (Tgh - Tout) = 0.33 x 10 x 17.18 x (Tgh – 30) = **56.70T_{gh} – 1700**

Qtrans = Uglass x A1 x (Tgh - Tout) = 5.8 x 33 x (Tgh – 30) = **191.4T_{gh} - 5742**

Substituting these values in the energy balance equation,

$Q_{in} = Q_{out}$

Lower limit of solar radiation

(with insulation) 2310 + (25 - T_{gh}) = (56.70Tgh – 1700) + (191.4T_{gh} – 5742) = **39.2 °C = Tgh**

(without insulation) 2310 + (118.75 – 4.75T_{gh}) = (56.70Tgh – 1700) + (191.4T_{gh} – 5742) = **39°C = Tgh**

Higher limit of solar radiation

(with insulation) 3080 + (25 - Tgh) = (56.70Tgh – 1700) + (191.4Tgh – 5742) = $\underline{42.3^{o}C = Tgh}$

(without insulation) 3080 + (118.75 – 4.75Tgh) = (56.70Tgh – 1700) + (191.4Tgh – 5742) = $\underline{42^{o}C = Tgh}$

Scenario 3 :

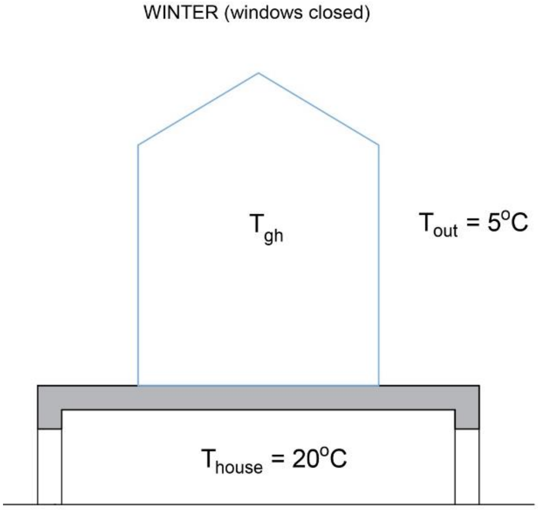


Fig. 3.20 Scenario - 3

Placement of greenhouse: Roof of building
Orientation: South
Season: Winter, windows closed
Thouse : Temperature inside house = 20oC
Tout : Temperature outside = 5oC
Aroof : Roof area with greenhouse = 6.25m2
A1 : Surface area of greenhouse = 33m2
A2 : Area facing sun rays = 9.6 m2
Uglass = 5.8 W/m2K
Uroof = 0.16 W/m2K (with insulation)
Uroof = 0.76 W/m2K (without insulation)
g (SHGC) = 0.8
Solar radiation intensity on south (q) = 330 W/m2 … peak
Volume (V) = (l x b x h) + (1/2 x height of gable x b x l) = 17.18 cu.m.

Q_{sun} *(lower limit)* = **770 W** ; Q_{sun} *(higher limit)* = **1925 W** (refer Appendix 5)
Q_{roof} *(with insulation)* = U x A x (T_{house} – T_{gh}) = 0.16 x 6.25 x (20 – T_{gh}) = **20 – T_{gh}**
(without insulation) = U x A x (T_{house} – T_{gh}) = 0.76 x 6.25 x (20 – T_{gh}) = **95 – 4.75T_{gh}**

Qtrans = Uglass x A1 x (T_{gh} - T_{out}) = 5.8 x 33 x (T_{gh} – 5) = **191.4Tgh - 957**

Substituting these values in the energy balance equation,

$Q_{in} = Q_{out}$

Lower limit of solar radiation

(with insulation) 770 + (20 - T_{gh}) = (191.4T_{gh} – 957) = $\underline{9^{o}C = Tgh}$

(without insulation) 770 + (95 – 4.75T_{gh}) = (191.4T_{gh} – 957) = $\underline{9.20^{o}C = Tgh}$

Higher limit of solar radiation

(with insulation) 1925 + (20 - T_{gh}) = (191.4T_{gh} – 957) = $\underline{15\,^{o}C = Tgh}$

(without insulation) 1925 + (95 – 4.75T_{gh}) = (191.4T_{gh} – 957) = $\underline{15.20^{o}C = Tgh}$

Greenhouse water requirements

Before calculating how much water the plants need, first the plants need to be planned out inside the greenhouse. To plan the arrangement and placement of the plants, the hydroponic technique also needs to be decided. This is decided based on the conclusion of the literature survey. After choosing the hydroponic technique, the space requirement for the hydroponic system will give an estimated number of plants that could fit in the greenhouse module. Then the water requirement can be calculated based on the number of plants of each type.

Hydroponic technique: The crops selected for this project grow best in Nutrient Film Technique (NFT). This technique uses less water and nutrients. The roots of the crops can be easily setup and maintained. In a closed loop system, the water for this system can be recirculated and reused by the crops. For a small sized greenhouse, NFT is ideal because it takes up less space and is modular and expandable.

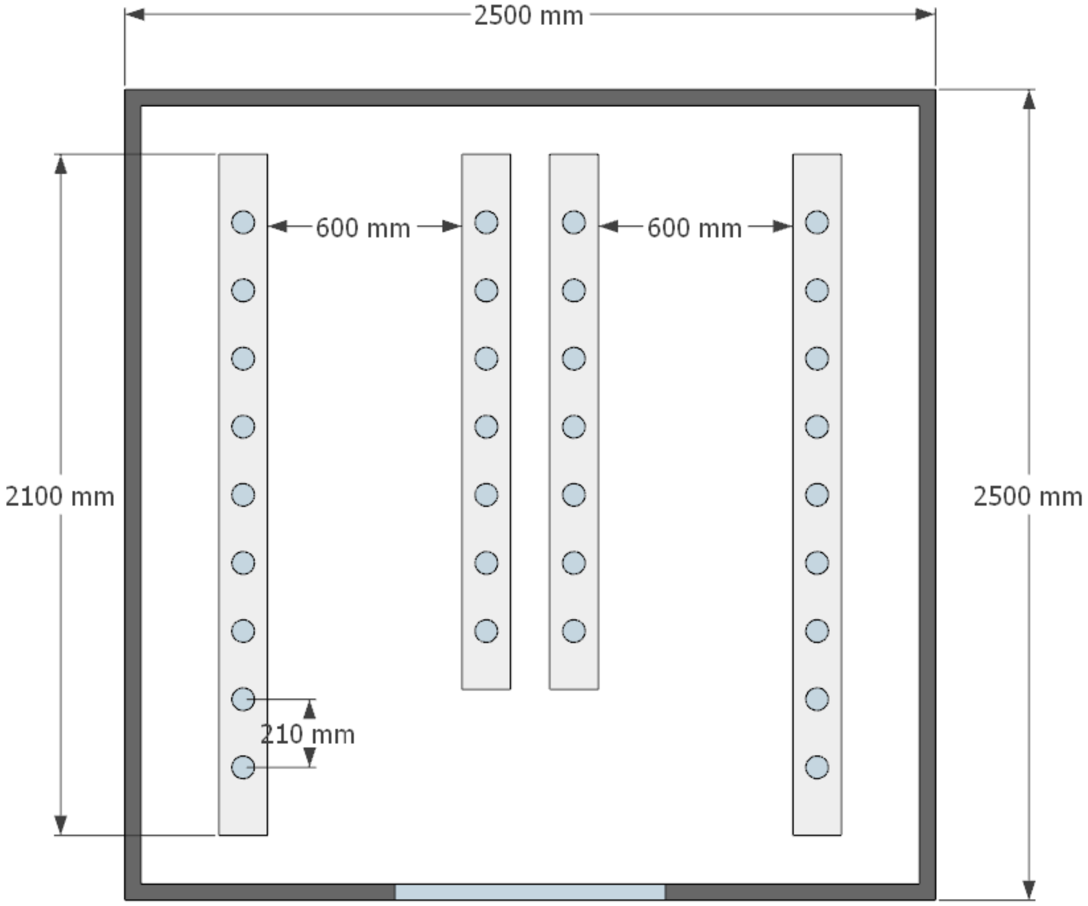


Fig. 3.21 Planning of the greenhouse

The diagram above shows a possible arrangement of the nutrient film technique set up. The same arrangement could be used for all the 3 selected crops, either in combination or 1 type of crop for the entire module, as per requirement.

The technique uses pipes which act as channels to supply the nutrients to the plants via a thin film of water. The channel width is decided based on the crop type and in this case, it is 150mm wide. The holes for the plants are 70mm in diameter and have a spacing of 210mm between their centres. (van Os et al., 2019a) 600mm space has been left between the pipes for accessibility. For tomatoes, only 1 layer of pipe is used, since tomatoes are climbing plants that grow vertically along a string. The other two crops, cucumber and paprika can also be grown in a similar manner without stacking the pipes up, since they grow vertically and require some space to grow freely.

Crop	Technique	No. of plants	Water needed (approx.)/2 weeks
Tomato	Nutrient Film Technique	9	**81L**
Cucumber		9	**81L**
Paprika		14	**126L**
Lettuce		9	**36**
Beetroot		14	**36**
Spinach		9	**56**

Fig. 3.22 Water demands of crops

The water tank or reservoir should have a capacity of the above-mentioned water amounts. The entire tank can be emptied and refilled from every 2 weeks to monthly, solely depending on the requirement. Some amount of water is lost due to evaporation and absorption by the plants. In this case, the water in the reservoir is topped with additional water to maintain the required water levels.

Greenhouse CO_2 requirements

800 to 1000 ppm of CO_2 is usually the ideal amount of carbon dioxide concentration in the air, for most crops grown in greenhouses.

Greenhouse electricity requirements

There are 4 main areas of electricity consumption in a greenhouse: LED lighting, water pumps, air pumps and heating or cooling. In this project, LED lighting for growing plants, and heating are not considered, and the system solely relies on the available sunlight, heat from the sun and from the host building.

However, a small light bulb is used inside the greenhouse for accessibility purposes during night-time. An LED bulb of 25watts is selected for the greenhouse. It is assumed that light is only turned on whenever the greenhouse is accessed at night. Hence, the power consumption is very little.

A small pump to circulate the water from the reservoir to the roots of the plants, is used 24/7 in NFT. A pump that can circulate maximum 350litres/hr is selected with a power consumption of 5W. Since it runs for 24 hours a day, it consumes 0.12kWh electricity per day or 43kWh electricity per year.

Therefore, approximately the greenhouse uses 50kWh electricity per year which includes light bulb and pump.

Chapter 4 |

Energy co-symbiosis & SANKEY

4.1 Design vision – a recap
4.2 Material flows in buildings and greenhouse
4.3 Possible greenhouse functions
4.4 Adjusted flow & co-symbiosis - SANKEY diagram

Introduction

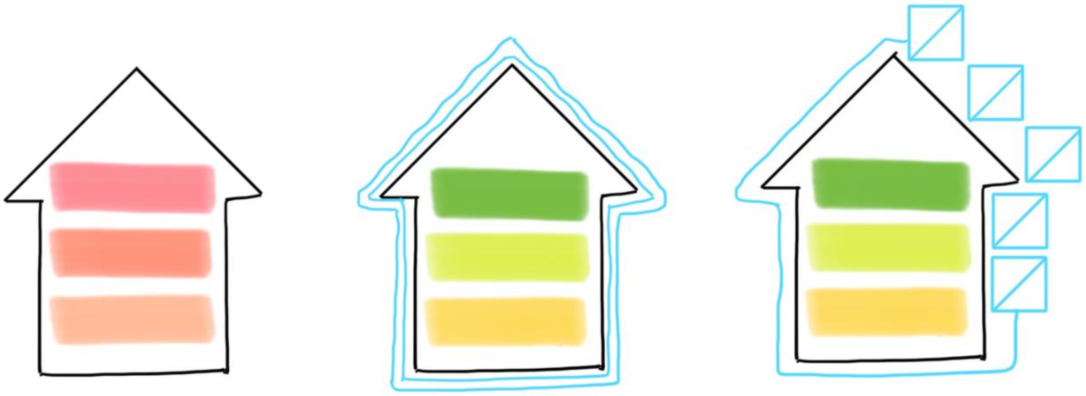
In the last chapter, two buildings were selected as the case studies for this project. The current energy efficiency of both the cases were compared and a future scenario was envisioned for a better energy performance of both. This chapter is the next step, wherein the energy and material flows of the buildings are investigated. Subsequently, the energy flow for a typical greenhouse unit is also studied.

4.1 Design vision – a recap

The main goal of this project is ***to speed up the Energy transition.***

- The Dutch government has suggested ways of modification or renovation for homes and apartments to become energy efficient and reducing the carbon footprint.

- The GH modules aim to serve as substitutes (where possible) or additional solutions for achieving this goal without major need for major renovations.



Without improvements
More energy demands

With improvements
Energy efficient

With GH modules
Less demands, energy efficient

Fig. 4.1 Schematic sketches of design vision

The design vision answers the question of ***why*** the building integrated greenhouses are being designed in this project. Following are the four main reasons for the same –

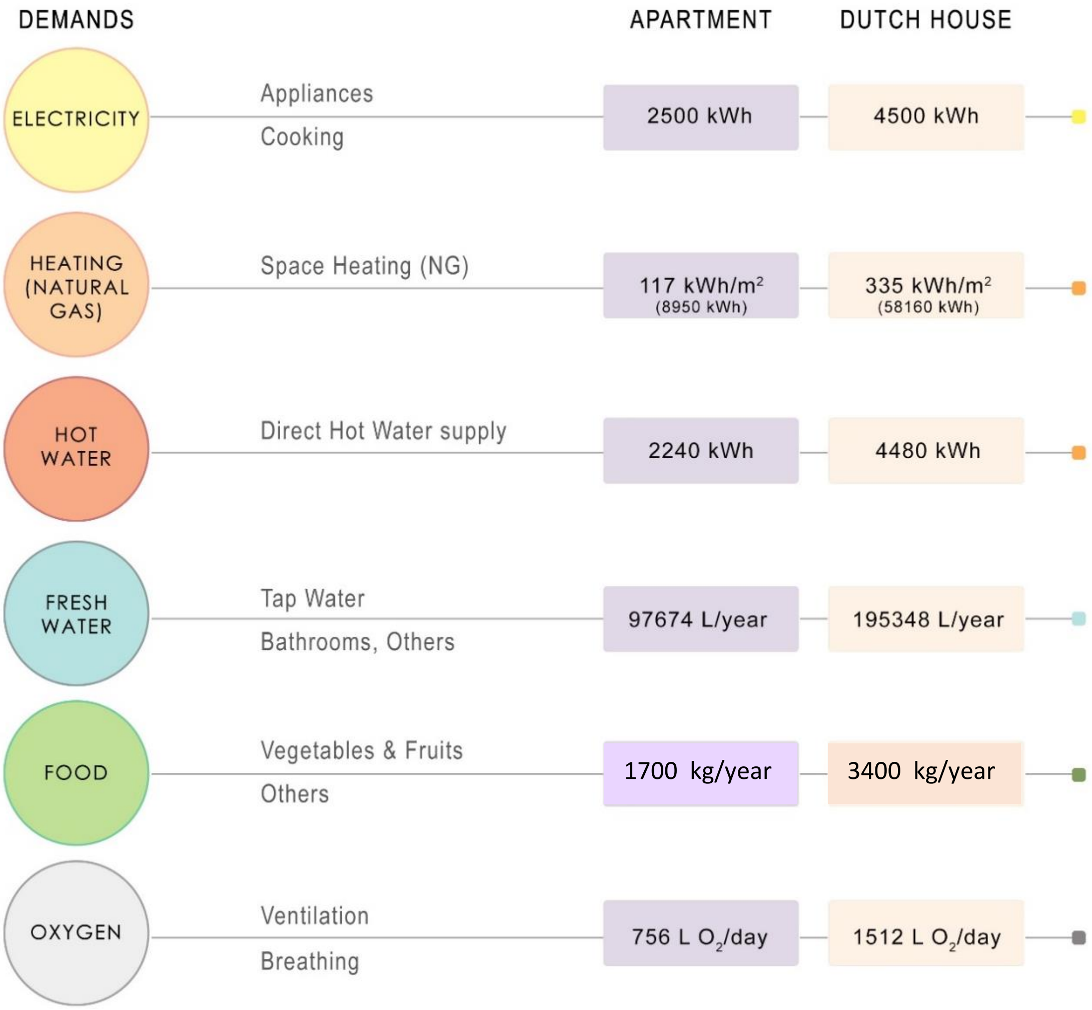
(1) Improve energy efficiency of the building
(2) Opportunity to grow food using waste flows from the host building
(3) Production of energy resources and food to partially meet the building's primary demands
(4) Utilization of vacant spaces on existing and future buildings

The basic concept of the GH module would be to coexist with its host building forming a partially closed loop system of energy symbiosis. The building will benefit from the greenhouse modules and the greenhouse modules will function with the building's outputs. This would result in achieving a symbiotic relationship between the two. Up until now, the energy demands of the case buildings have been studied. To design the Greenhouse modules, the energy waste flows will also need to be investigated. These waste flows would determine the amount of input resources available for the greenhouse module processes. The processes inside the greenhouse will be decided based on the requirement of the specific building.

4.1 Material Flows in Buildings and Greenhouse

4.1.1 Project cases - INPUTS

From the excel chart for the apartment unit and Dutch house (appendix 1 & 2), the values for energy and resource demand of both the buildings are obtained. These are calculated based on the data available for Dutch residences online and self-calculations made by referring to standards. Below is the amount of resources consumed by each of the buildings.



DEMANDS		APARTMENT	DUTCH HOUSE
ELECTRICITY	Appliances Cooking	2500 kWh	4500 kWh
HEATING (NATURAL GAS)	Space Heating (NG)	117 kWh/m^2 (8950 kWh)	335 kWh/m^2 (58160 kWh)
HOT WATER	Direct Hot Water supply	2240 kWh	4480 kWh
FRESH WATER	Tap Water Bathrooms, Others	97674 L/year	195348 L/year
FOOD	Vegetables & Fruits Others	1700 kg/year	3400 kg/year
OXYGEN	Ventilation Breathing	756 L O_2/day	1512 L O_2/day

Fig. 4.2 Demands for residential buildings

4.1.2 Project cases - OUTPUTS

The waste flows for both the residential buildings, consists of:

(i) Residual heat - Heat escaping through building surfaces and ventilation

Heat from inside the house, dissipates to the outside air through the roof, windows and façade walls. The amount of heat dissipated is given by:

Heat loss from roof *: Area of roof x U value of roof x* $(Temp_{in} – Temp_{out})$
Heat loss from window *: Area of window x U value of window x* $(Temp_{in} – Temp_{out})$
Heat loss from walls *: Area of façade wall x U value of wall x* $(Temp_{in} – Temp_{out})$

Applying these formulae for each building –

Case 01 : Residential apartment with 2 persons

For this calculation, temperature inside is assumed to be 22°C and temperature outside is 15°C.

	Area (m2)	U value (W/m2K)	$Temp_{in}$ – $Temp_{out}$	Heat lost (in Watts)	kWh/day
From roof	77	0.16	7	86.24	2.06
From window	18.9	0.7 (HR+++ window)	7	92.61	2.22
From walls	negligible	-	-	-	-

Case 02 : Dutch house with 4 persons

	Area (m2)	U value (W/m2K)	$Temp_{in}$ – $Temp_{out}$	Heat lost (in Watts)	kWh/day
From roof	53	0.16	7	59.36	1.42
From window	43.76	1.2 (HR++ window)	7	367.58	8.92
From walls	42.61	0.22	7	65.62	1.57

Similarly, the heat escaping through ventilation is given below. 2 conditions are assumed, with and without heat exchange unit.

Heat loss by ventilation without heat exchanger *: Specific heat of air (Cp) x density of air (ρ) x volume of air flow (m^3/s) x ($Temp_{in}$ – $Temp_{out}$)*

Heat loss by ventilation with heat exchanger : *(1 – efficiency of heat exchanger/100) x specific heat of air (Cp) x density of air (ρ) x volume of air flow (m^3/s) x ($Temp_{in}$ – $Temp_{out}$)*

Applying these formulae for each building –

Case 01 : Residential apartment with 2 persons

	Specific heat of air (Cp)	density of air (ρ)	volume of air flow (m^3/s) with ACH 0.35	(Tempin – Tempout)	Heat lost (in Watts)	kWh/day
Without heat exchanger	700	1.2	0.022	7	129.36	3.10
With heat exchanger with 80% efficiency	700	1.2	0.022	7	25.87	0.62

Case 02 : Dutch house with 4 persons

	Specific heat of air (Cp)	density of air (ρ)	volume of air flow (m^3/s) with ACH 0.35	(Tempin – Tempout)	Heat lost (in Watts)	kWh/day
Without heat exchanger	700	1.2	0.038	7	48.80	1.17
With heat exchanger with 80% efficiency	700	1.2	0.038	7	9.76	0.23

(ii) Gray water – Wastewater from bathroom, shower and washing machine

As listed in appendix 1 & 2, the amount of gray water generated per person is **88.4 litres per person per day.**
Therefore,
Case 01 : Residential apartment with 2 persons: **176.8 litres/day**
Case 02 : Dutch house with 4 persons: **353.6 litres/day.**

(iii) Black water – Wastewater from flushing toilets

As listed in appendix 1 & 2, the amount of blackwater per person is **35.3 litres per person per day.**
Therefore,
Case 01 : Residential apartment with 2 persons: **70.6 litres/day**
Case 02 : Dutch house with 4 persons: **141.2 litres/day.**

(iv) Kitchen waste – Organic waste from the kitchen

As listed in appendix 1 & 2, the amount of organic food waste per person is **34.3 kgs per year per person.**
Therefore,
Case 01 : Residential apartment with 2 persons: **68.6 kgs/year** or **approx. 200gms/day.**
Case 02 : Dutch house with 4 persons: **137.2 kgs/year** or **approx. 400gms/day.**

(v) Saturated air – Exhaled air saturated with CO2

A single person breathes 11000L of air per day of which 20% is Oxygen. The same amount of air is exhaled and consists of 15% Oxygen, 3.5% Carbon dioxide and remaining Nitrogen.
3.5% of 11000 = **385 Litres/day per person CO_2** or **38000ppm** (*What Is Carbon Dioxide?*, 2013a).

It is assumed that a person occupies the house for 14 hours in a day.
Therefore, the amount of carbon dioxide exhaled is 224 Litres/day.

Case 01 : Residential apartment with 2 persons: **448 Litres CO_2/day.**
Case 02 : Dutch house with 4 persons: **896 Litres CO_2/day.**

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Material flow diagrams

Now that the 'INPUTS' and 'OUTPUTS' for both the buildings are known, they can be represented in a diagram to visualize the flow of resources going in and going out

Case 01 – Apartment with 2 persons

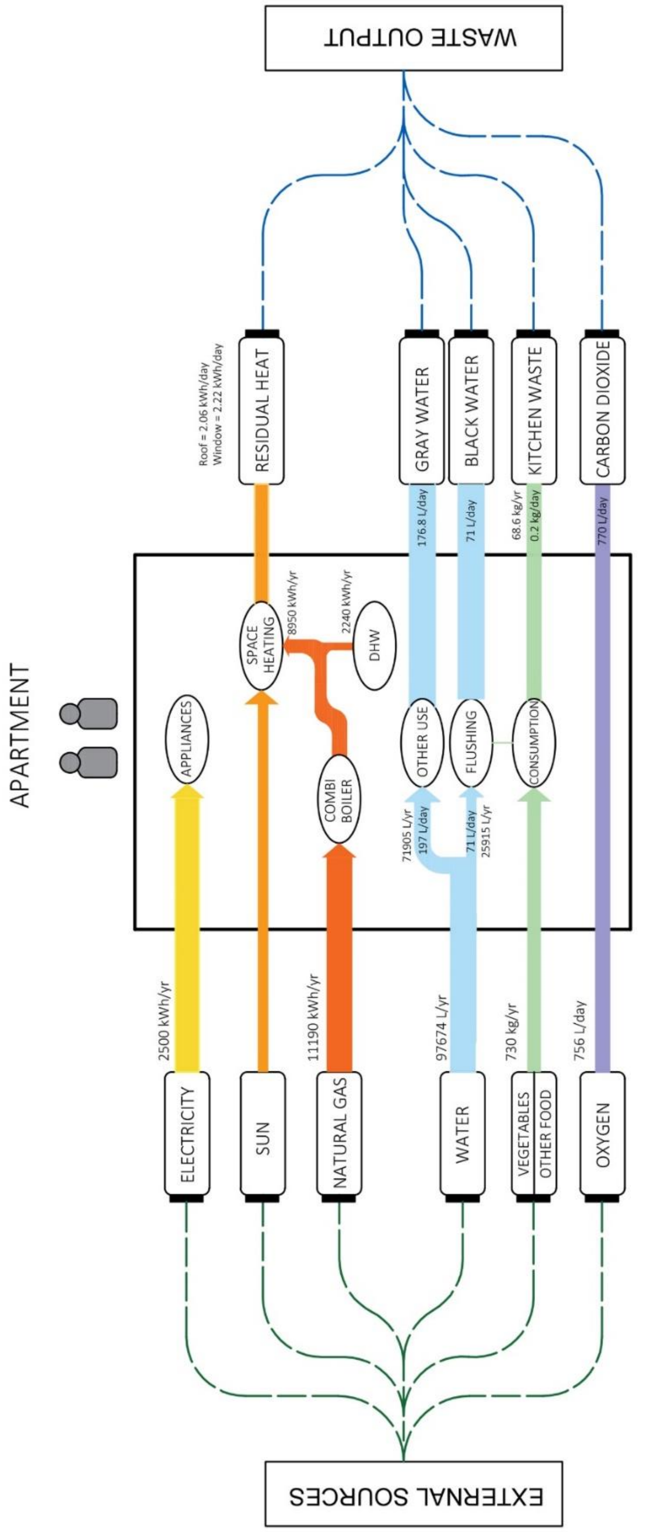


Fig. 4.3 Material flow diagram for case 01

Case 02 – Dutch house with 4 persons

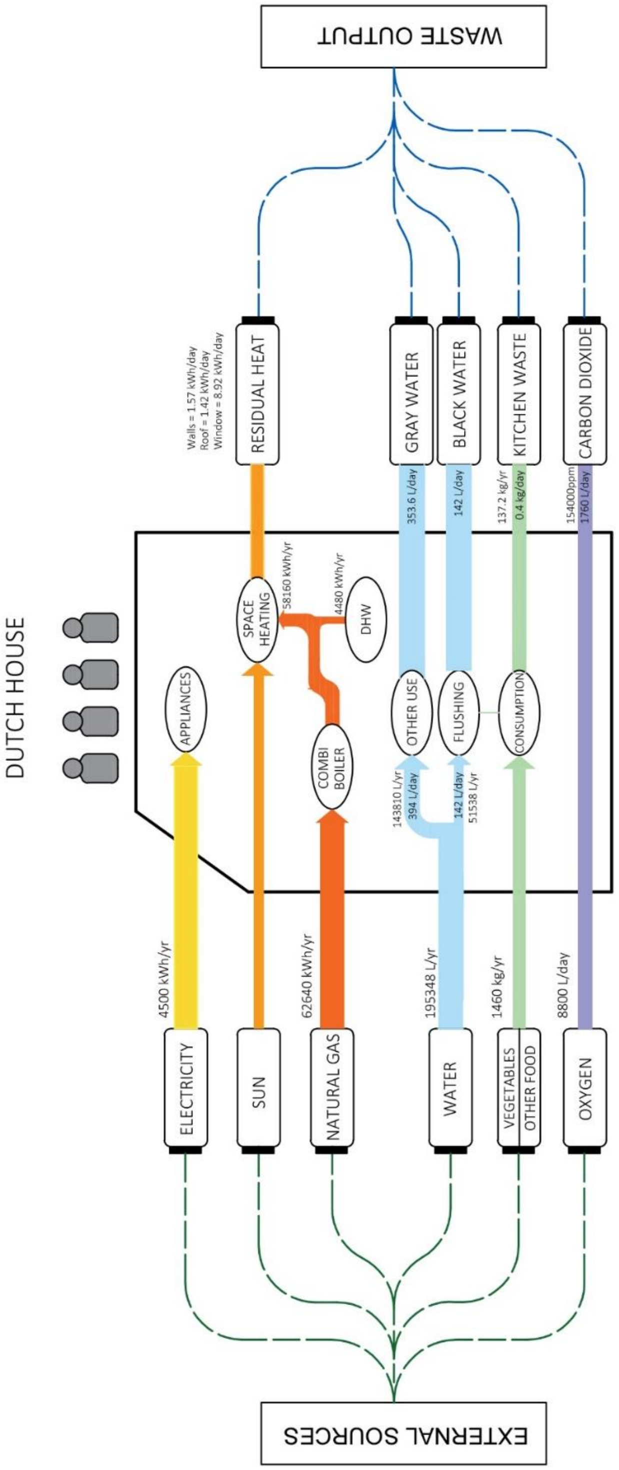


Fig. 4.4 Material flow diagram for case 02

Greenhouse with hydroponics

In a greenhouse with hydroponic system, the main 'occupant' are the plants inside. The resources are used directly or indirectly for the growth of the plants. Artificial heating or cooling is not considered. Similarly, LEDs for plant growth are not considered either. Water*, nutrition and carbon dioxide is directly consumed by the plants. The diagram below shows the interaction between these direct and indirect resources and the outputs obtained.

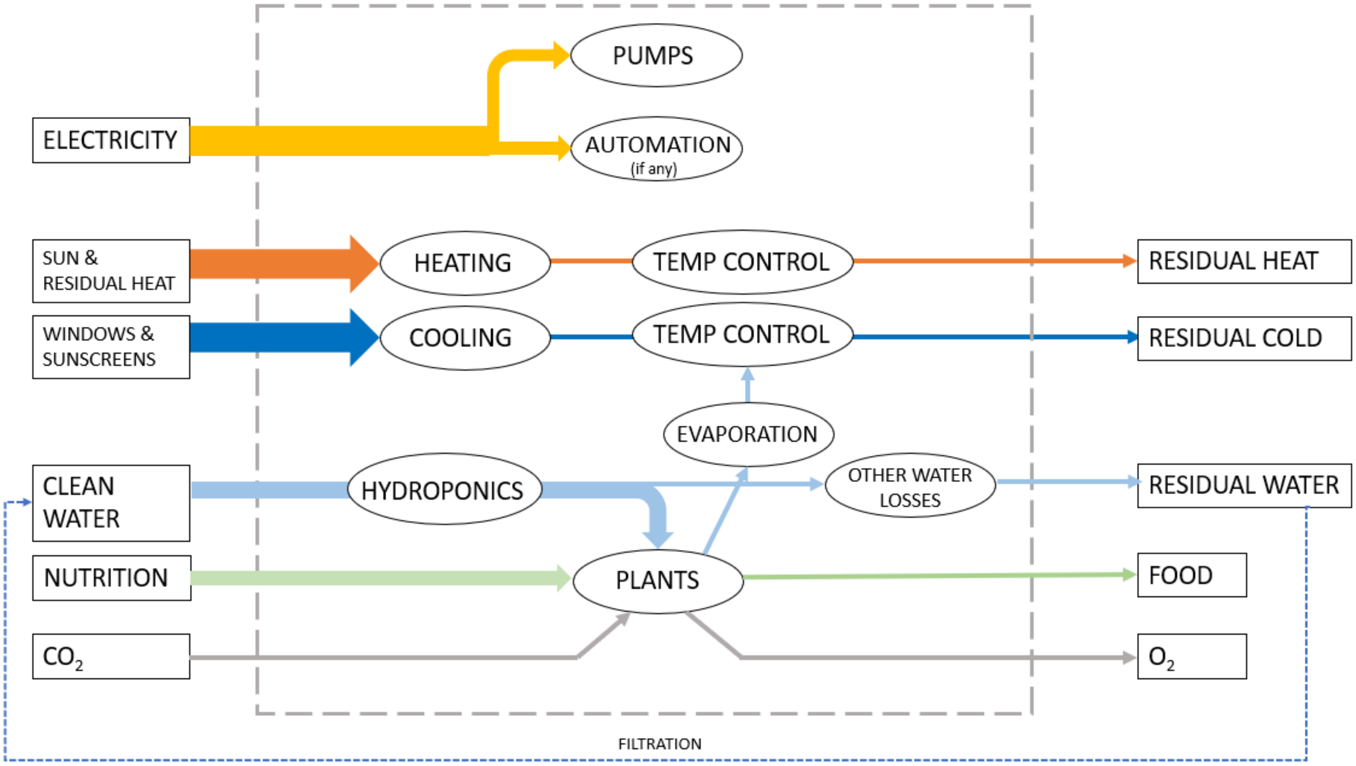


Fig. 4.5 Material flow diagram for greenhouses

Water scale

Both the residential buildings and the greenhouse use water as one of the main resources. However, the quality of water depends on the type of usage. The scale below gives an estimate of the purity of water based on its type. For example, how pure is gray water on a scale from 0 to 100, wherein 0 is the dirtiest water and 100 is the cleanest water.

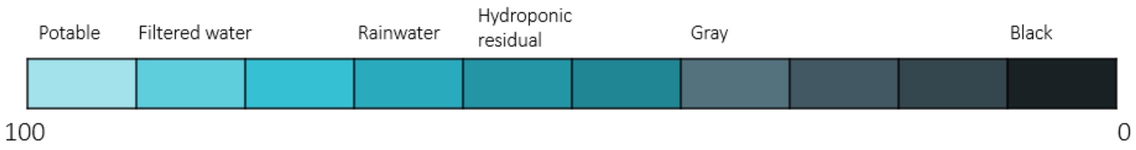


Fig. 4.6 Water scale for reference

4.2 Possible module functions

From the above material flow diagrams for residential building and greenhouse, it can be seen that both have a demand for some common resources. Obtaining these resources in a clean and efficient way could prove beneficial for the building as well as the environment. The greenhouse modules that are to be designed will be aiding the existing buildings to meet its demands and reducing the demand if possible. The process to decide the functions of these greenhouse modules is divided into two parts. First the functions that can meet the demands of the buildings are listed. Next, the functions which could utilize the outflows of the buildings are listed. This would finally give a comprehensive list of the possible functions.

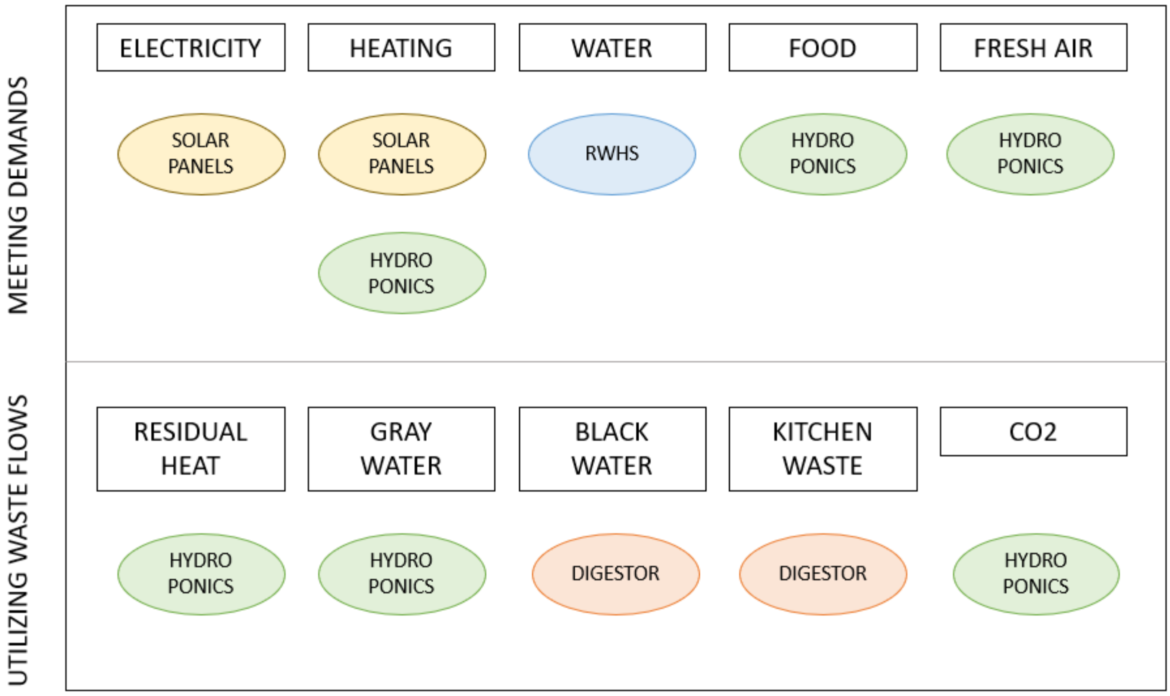


Fig. 4.7 List of possible functions of greenhouse units w.r.t. host building

A similar chart as above can be drawn to check if the demands of the greenhouse units can be met by the host building and how the outflows from the greenhouse can be utilized by the building.

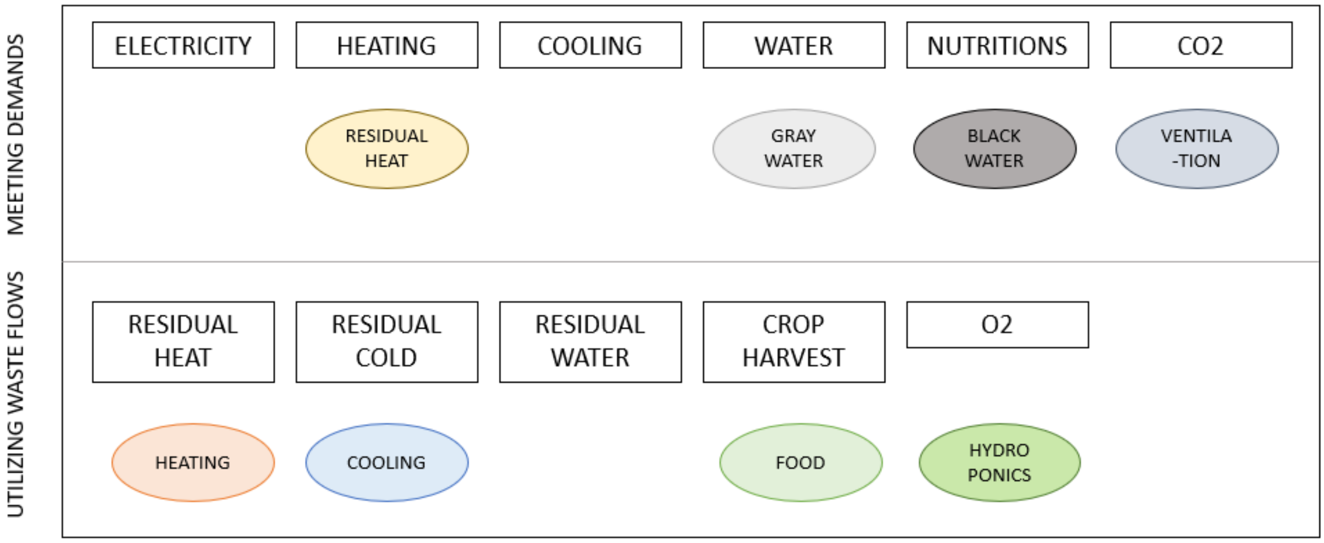
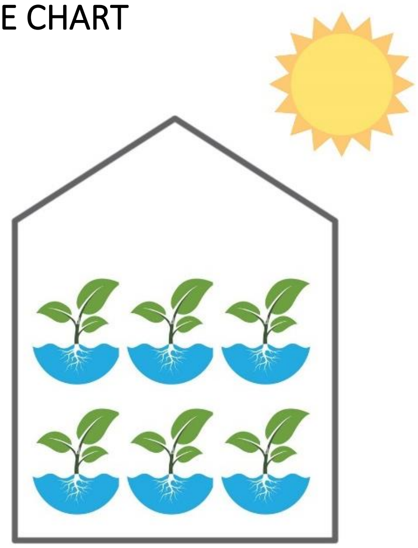


Fig. 4.8 List of possible functions of building w.r.t. greenhouse units

Summary

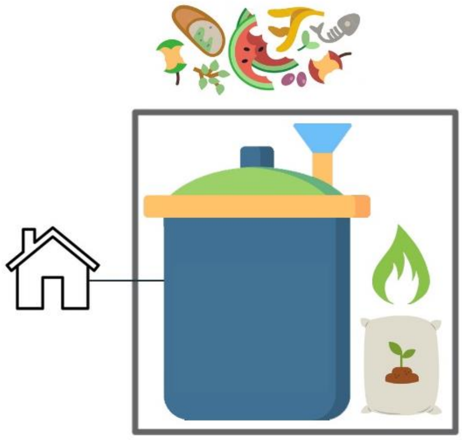
The functions of the modules listed in the above charts could either be stand-alone functions or additional accessories on the stand-alone modules. The chart below shows the summarized list of modules catering to the functions and a list of the accessories. In the next chapter, a detailed typology generation strategy is explained.

MODULE CHART



1 *HYDROPONIC FARMING (GREENHOUSE)*

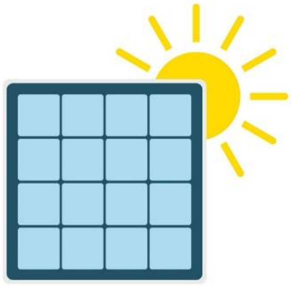
2 *RAINWATER HARVESTION + GRAY WATER FILTRATION*



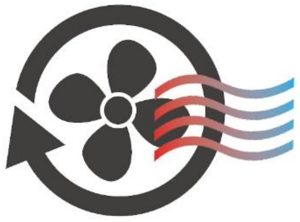
3 *ANAEROBIC DIGESTOR (FOOD WASTE)*

4 *PAVILION OR LEISURE SPACES*

APPLIANCES



SOLAR PANELS



WASTE HEAT RECOVERY UNIT

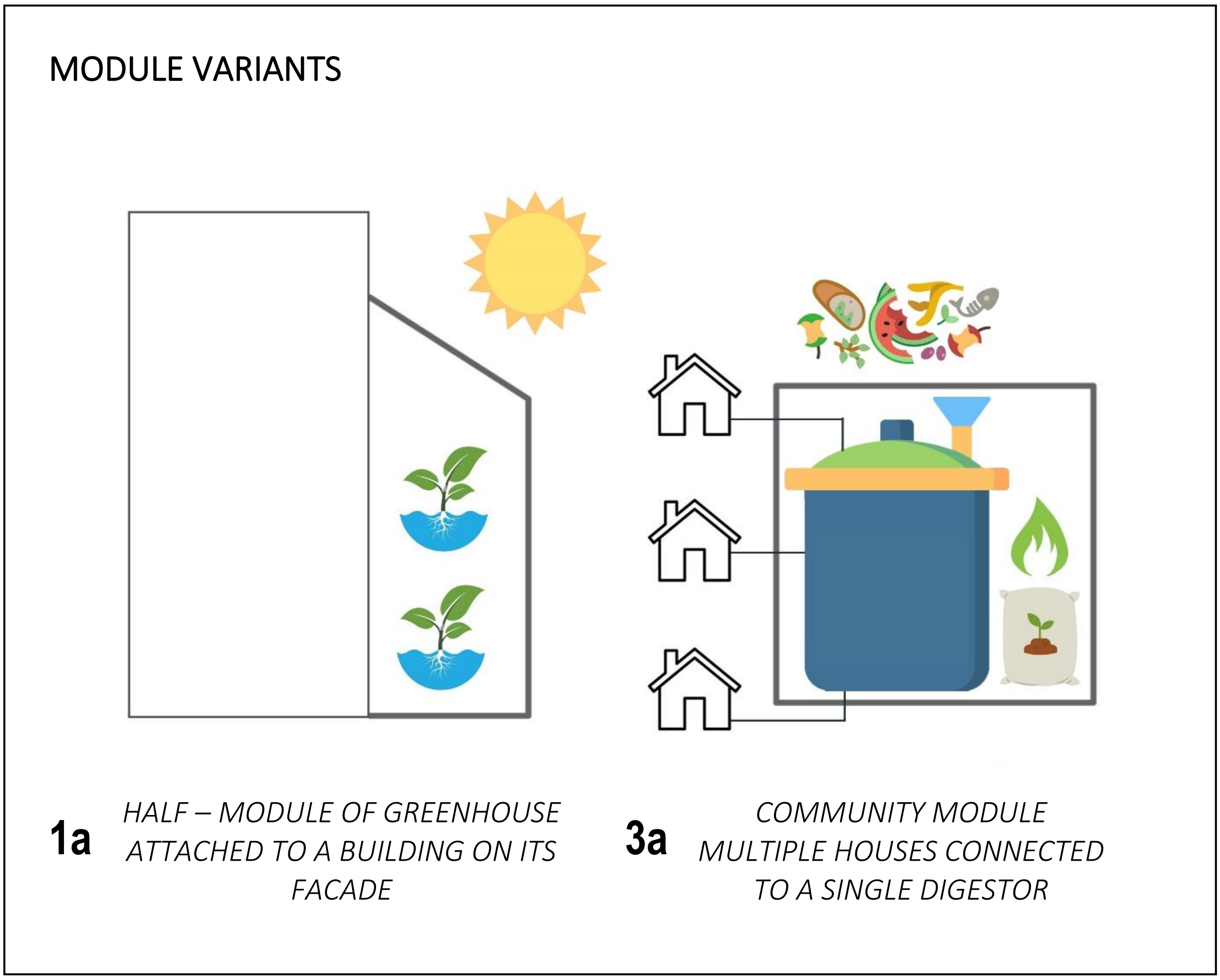


Fig. 4.9 Module chart - author

4.3 Calculations of modules and accessories

(a) Hydroponic greenhouse module

The chart below shows the total yield of each crop in a year. The crops are not grown throughout the year but for 6 months each.

Crop	Yield/plant	No. of plants	Period	Total yield (yearly)
Tomato	5-8kg	9	6 months	**72kgs**
Cucumber	1.5kg	9	Every week for 6 months	**324kgs**
Paprika	1.5 – 2kg	14	6 months	**28kgs**
Lettuce	300gms	9	Every 6 weeks for 6 months	**10.8kgs**
Beetroot	125gms	14	Every 2 months for 6 months	**5.25kgs**
Spinach	250gms	9	Every 6 weeks for 6 months	**9kgs**

(b) Rainwater Harvesting and Gray water filtration module

Rainwater harvesting calculation

The roof of the building is the catchment area for rainwater. The annual rainwater yield is calculated by using mainly the roof area and amount of yearly rainfall. Given below is the formula for calculating annual rainwater yield –

$$Y_R = A \times e \times h \times n$$

Y_R = Annual rainwater yield (Litres)

A = roof area (m^2)

e = coefficient of yield since not all the water is collected (80%)

h = depth of rainfall (mm)

n = filter efficiency (0.9 standard value)

Calculating the rainwater harvesting capacity for both the project cases:

Case 01 : Residential apartment with 2 persons

$$Y_R = A \times e \times h \times n$$

A = 77sq.m. for 1 apartment

e = 0.8

h = 835mm rainfall in Rotterdam

n = 0.9

Total rainwater capture in roof space of 1 apartment = 46292 Litres/year.

To calculate the volume of tank, 5% of the total yearly collection of water volume is considered.

Therefore, for 1 apartment the tank volume is 0.05 x 46292 = 2314 Litres

A tank with holding capacity of 2500 litres measures in diameter 1260mm and in height 2120mm

The module size in this project is 2500mm x 2500mm, thus having the space of accommodating a larger tank. Therefore, combining the roof space of 2 apartment and having a shared tank of 5000L is more space efficient. The size of a 5000L tank is 1900mm diameter and 2300mm height.

Total rainwater capture on roof space of entire building with roof area of 1765 sq.m.

= 1061118 Litres/year

5% of yearly collection to determine tank size = 53056 Litres

Total number of tanks = 53056 / 5000 = approximately **11 tanks.**

Case 02 : Dutch house with 2 persons

$$Y_R = A \times e \times h \times n$$

A = 57sq.m. for entire house

e = 0.8

h = 835mm rainfall in Rotterdam

n = 0.9

Total rainwater capture in roof space of 1 apartment = 34268 Litres/year.

To calculate the tank size, 5% of the total yearly collection of water volume is considered.

Therefore, the volume of tank is 0.05 x 34268 = 1713 Litres = 2000L appox.

A tank with holding capacity of 2000 litres measures in diameter 1300mm and in height 1500mm

Total number of tanks = 1 tank

Gray water filtration system calculation

As mentioned in the earlier chapters, the amount of gray water outflow from both the cases are known. A gray water filtration system includes an appliance that filters out this gray water to reuse it for non-potable activities such as flushing, garden irrigation and washing machine. A filtration unit readily available in the market is chosen as a reference to calculate the number of filtration units required for both the cases.

Filtration device specifications:

Brand name: Hydraloop H300

Volume: 300 litres

Cleaning capacity: 530 litres/day

Dimensions: 800mm x 34mm x 1870mm

Electricity consumption: 200kWh/year

Outlets: 1 valve for toilet and 1 valve for watering hydroponics

Case 01 : Residential apartment with 2 persons

Amount of gray water generated from bath, shower and washing machine = 176.8 Litres/day

Since the appliance has a larger cleaning capacity, the gray water from 2 apartments can be combined and filtered using 1 filtration unit.

Case 02 : Dutch house with 4 persons

Amount of gray water generated from bath, shower and washing machine = 353.6 Litres/day

No. of filtration units = 1

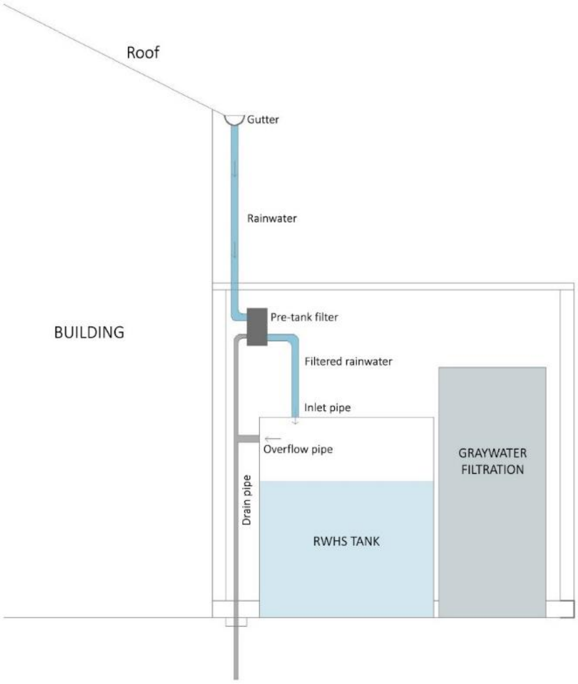


Fig. 4.10 Rainwater Harvesting system - author

(c) Anaerobic digestor module

A small scale digestor system can convert organic waste from the houses into biogas and liquid fertilizer. Usually, black water is also added to a digestor, but it poses potential toxic contamination risks if placed in the vicinity of the house. Therefore, only organic food waste and animal waste (if present), is considered as a feed for the digestor. Small scale biodigester units are available in the market and one such digestor has been chosen to calculate the organic waste needed and amount of biogas and fertilizer generated.

Brand name: HOMEBIOGAS HBG 2.0 household biogas system

Feed for the system: Kitchen waste up to 6 litres per day & Animal waste up to 15 litres per day

System volume: 2.1cu.m.

Dimensions: 2100 x 1150 x 1300 mm

Cooking time: up to 2 hours on single flame burner/day

Daily fertilizer output = equal to input volume

The digestor does not require a daily input of the maximum stated amount of kitchen waste to work. It can keep collecting the kitchen waste in small amounts over multiple days and remain activated. However, if needed, multiple houses can decide to connect to one digestor unit to achieve faster outputs.

Case 01 : Residential apartment with 2 persons

Daily kitchen waste = 200gms = 0.2 litres

Case 02 : Dutch house with 4 persons

Daily kitchen waste = 400gms.= 0.4 litres.

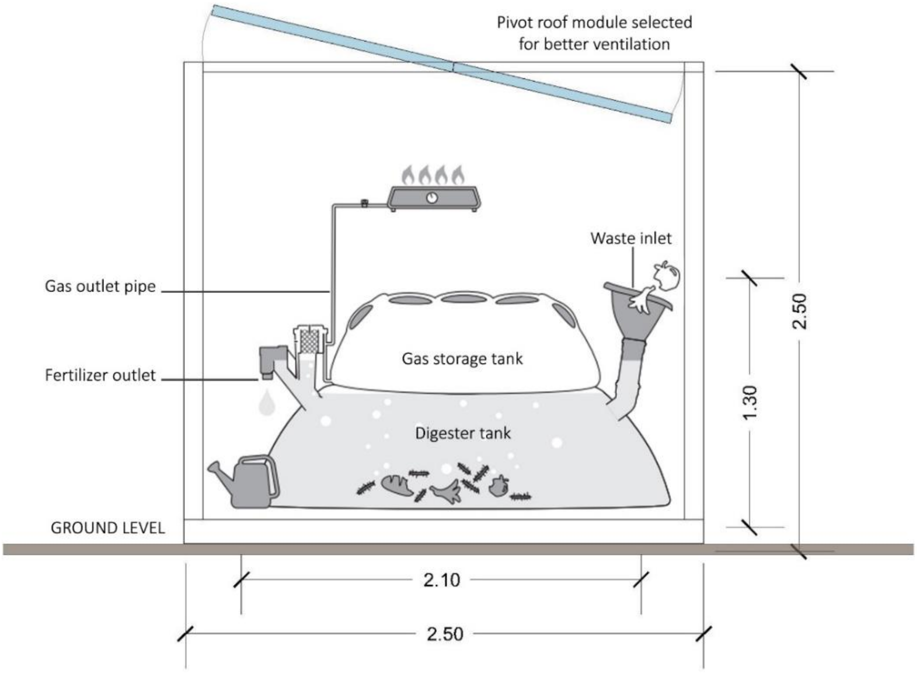


Fig. 4.11 Anaerobic digestor system - author & homebiogas.com

(d) Solar panels

The two cases in this project have different electricity demands. These demands could be potentially met using solar electricity generation. To calculate the number of solar panels required to power each project case, a reference solar panel from a reputed brand in the market is selected.

Panel type: Mono crystalline panel (best efficiency, sleek all black look)

Brand name: Sunpower – 400Wp

Size: 1690 x 1046 x 40 mm

Weight: 19kg/panel

Case 01 : Residential apartment with 2 persons

Electricity demand: 2500 kWh

Efficiency of solar panels in Netherlands: 0.9kWh/Wp (Watt peak)

For 2500 kWh, 2500/0.9 = 2778 Wp required

Number of solar panels = 2778/400 = 7 panels

Total electricity generated by 7 panels = 2520 kWh.

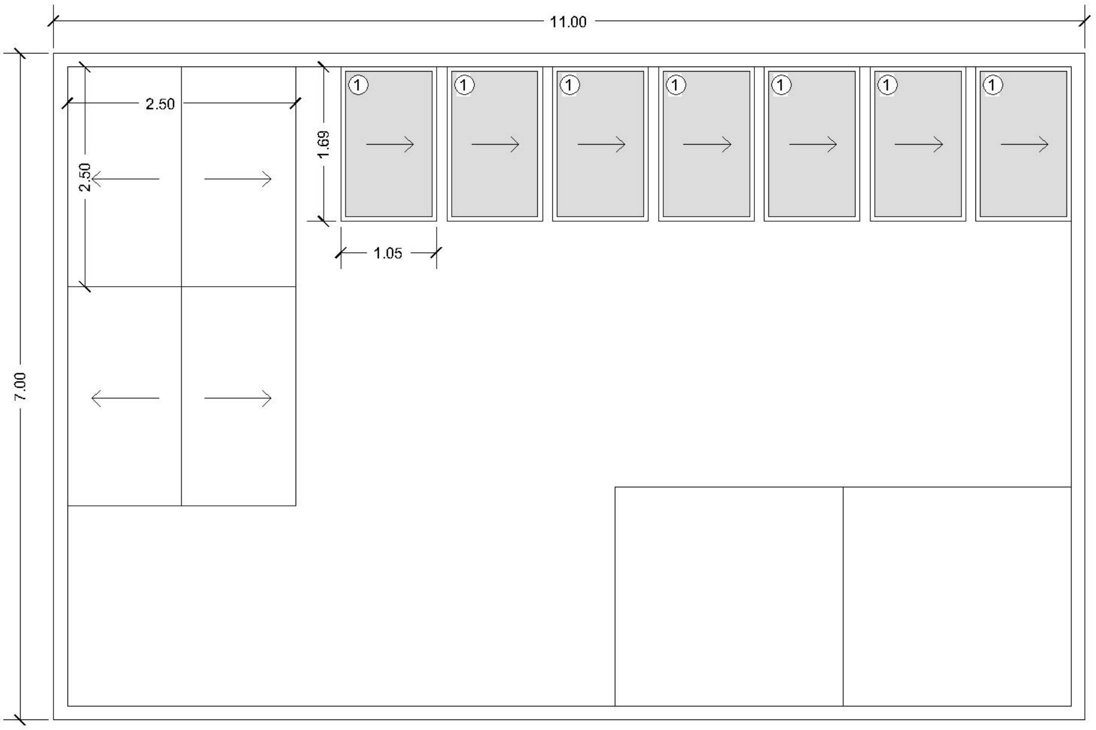


Fig. 4.12 Solar panel layout on roof of case 01

Case 02 : Dutch house with 4 persons

Electricity demand: 4500 kWh

Efficiency of solar panels in Netherlands: 0.9kWh/Wp (Watt peak)

For 4500 kWh, 4500/0.9 = 5000 Wp required

Number of solar panels = 5000/400 = <u>13 panels</u>

Total electricity generated by 13 panels = 4680 kWh.

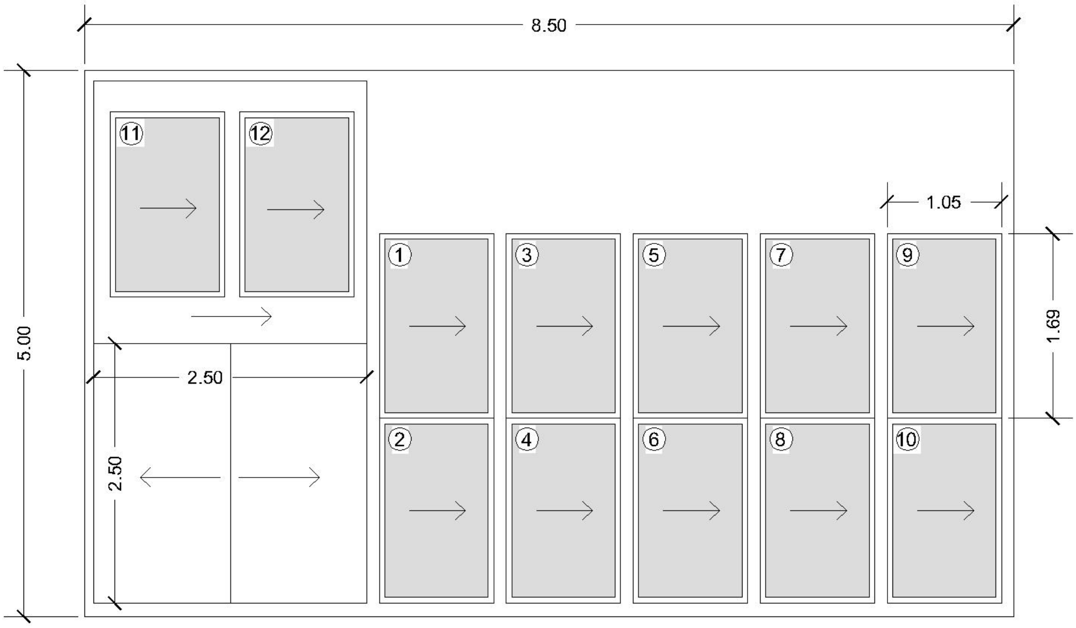


Fig. 4.13 Solar panel layout on roof of case 02

(e) Heat exchanger

The heat exchanger is an appliance that captures the heat from the outgoing ventilation exhaust air. A heat exchanger with efficiency of 80%, recaptures 80% of the heat from the exhaust air and heats up the incoming cold air and circulates it in the house. However, the 20% heat that gets lost with the exhaust air, could be used in the greenhouse. The exhaust air has both residual heat from the house and is also saturated with CO_2 that could be beneficial for the greenhouse.

As calculated earlier, the amount of residual heat in the ventilated air with heat exchanger and CO_2 in the exhaust air is as follows:

Case 01 : Residential apartment with 2 persons

Heat lost in exhaust air via heat exchanger = 0.62 kWh/day

CO_2 level = 880 Litres CO_2/day

Case 02 : Dutch house with 4 persons

Heat lost in exhaust air via heat exchanger = 0.23 kWh/day

CO_2 level = 1760 Litres CO_2/day

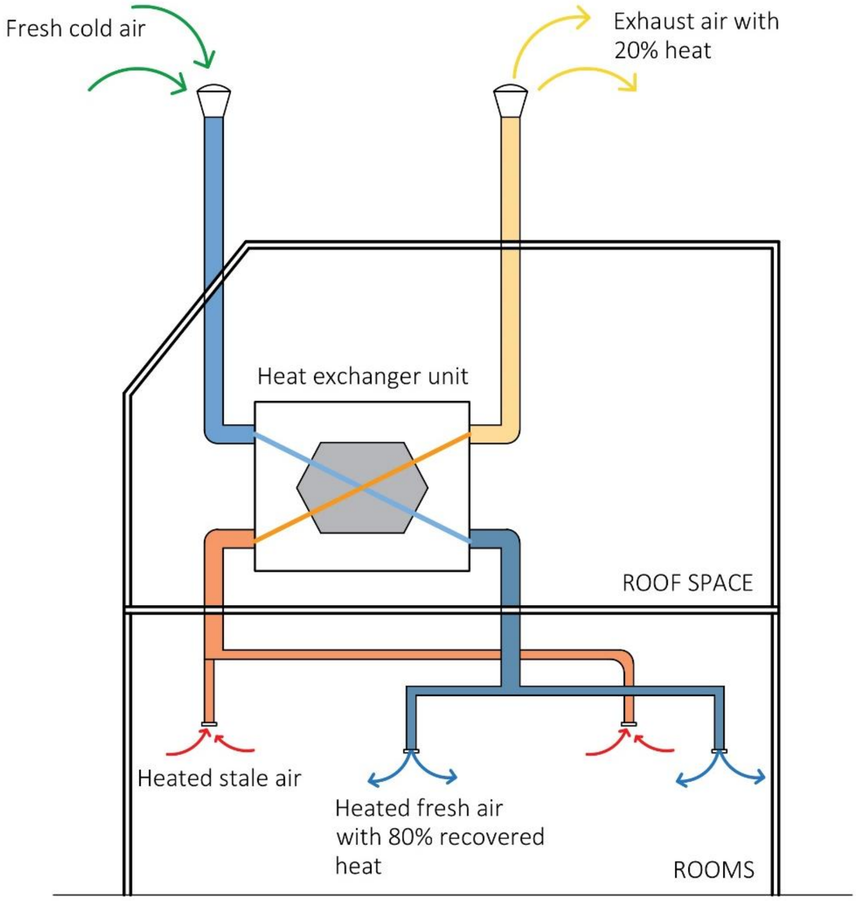
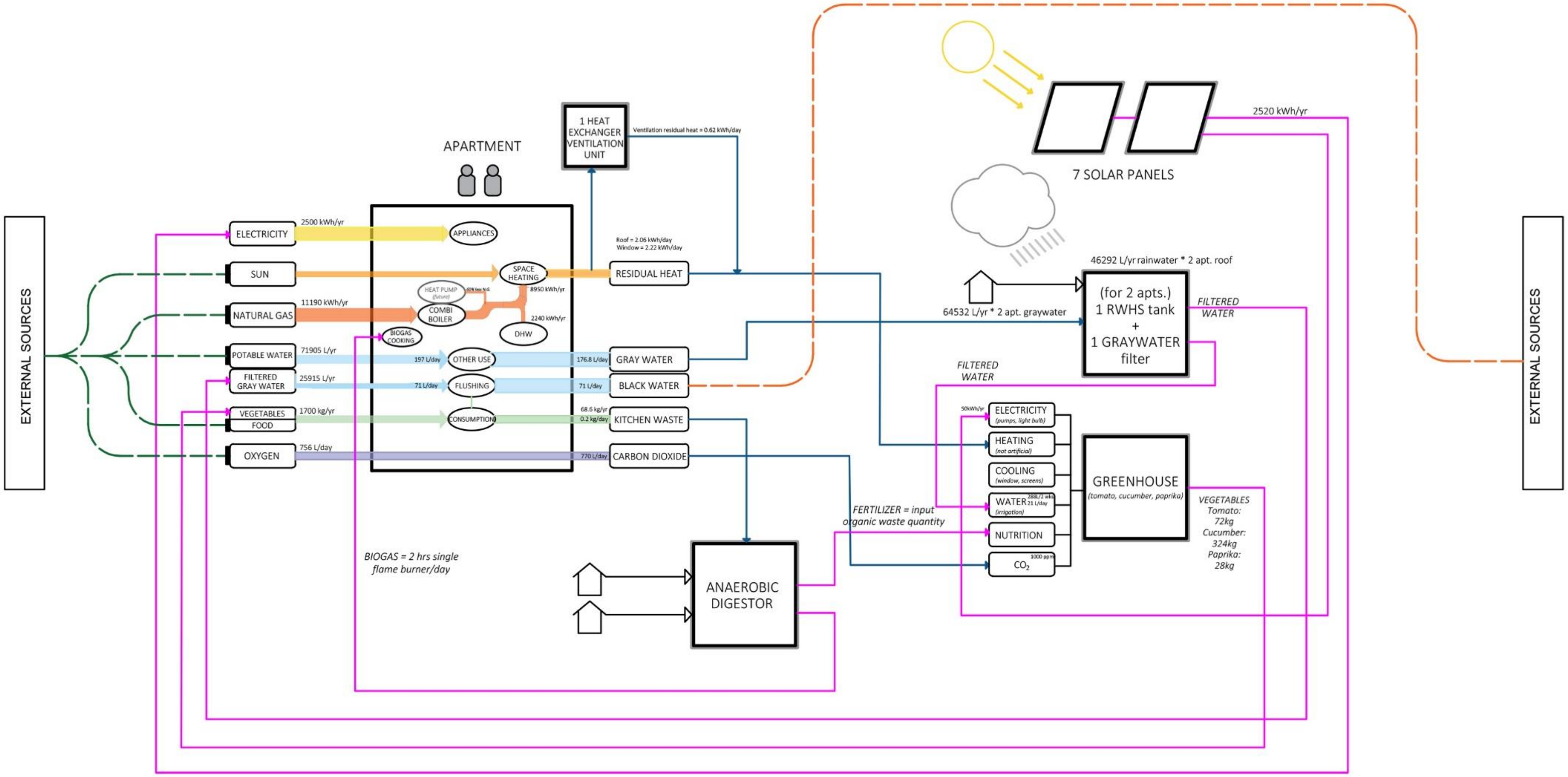


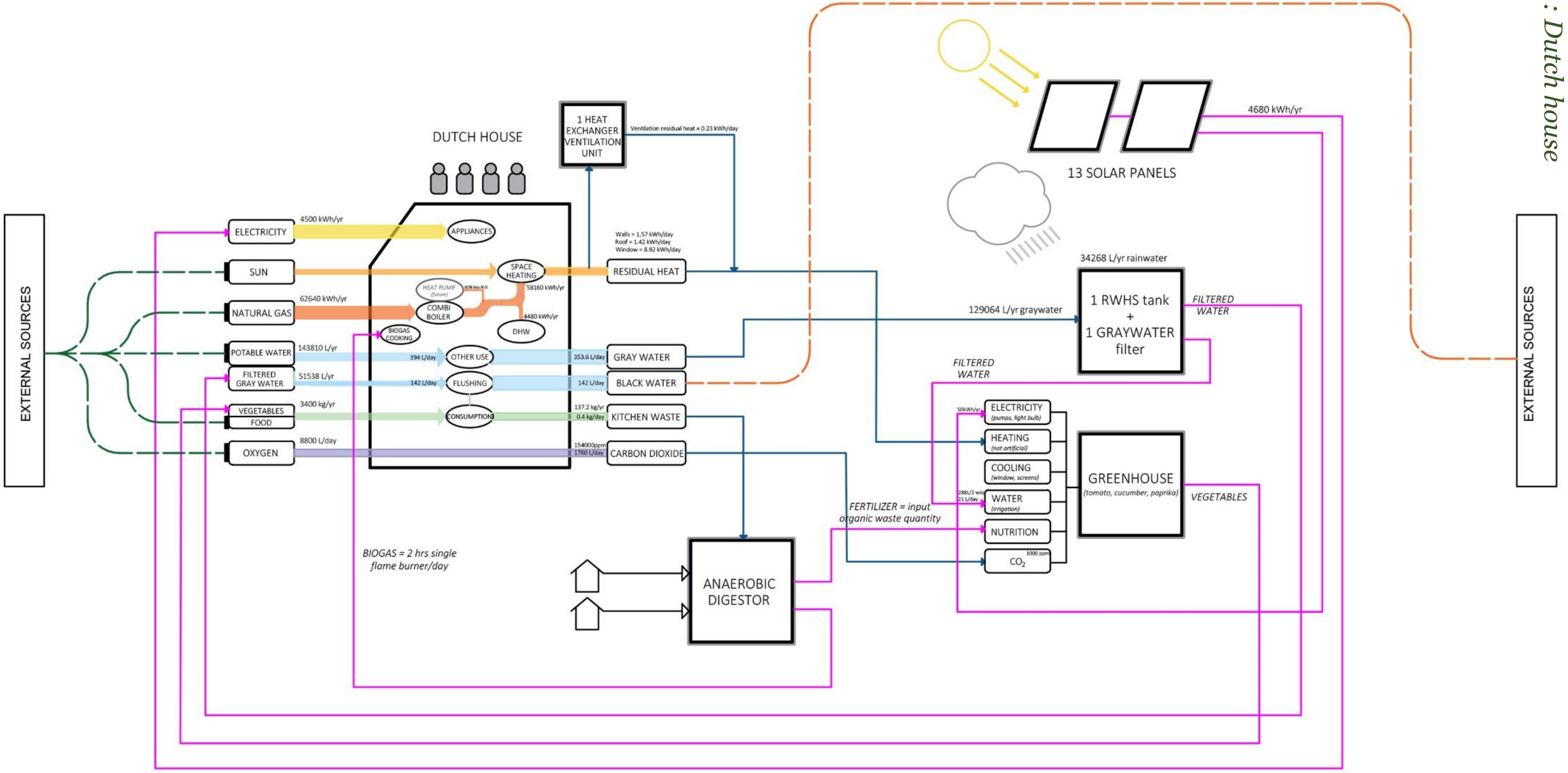
Fig. 4.14 Heat exchanger system for ventilation unit

4.3 Adjusted material flow and co-symbiosis SANKEY

Case 01 : Apartment unit



Case 02 : Dutch house



Chapter 5 |

Greenhouse module design

5.1 Typology generation strategy – module designs

5.1.1 Location

The location of the module is very important to avail the maximum output from the greenhouse module. To decide the location, a few factors need to be considered. These are –

- ***Weight*** The weight of the module depends on the kind of function that the module primarily performs. For instance, a Rainwater Harvesting module will have rainwater collection tanks which generate heavy loads. This could impact the roof and the house might not be able to sustain such heavy loads. In this case, providing extra reinforcement to improve the structural stability could be beneficial. If soil based growing techniques are used inside the module, the soil could also cause heavy loading. In such a case, switching to hydroponics could be a better alternative.

- ***Orientation*** If the module has solar panels, wind power generators or any such function that depends on the sun angle, wind direction, etc. then it is ideal to have the modules harness the maximum energy by aligning it to the right direction.

- ***Function*** Another location deciding factor for the modules could be its function. In case of a digestor unit, the smells, or simply the idea of having a waste digestor could make it an unwanted module in the building. However, it could be placed in a well-ventilated open area adjacent to the building. Similarly, a rainwater harvesting system could require catchment area for water collection and if the water weight is not a problem, then this unit could be placed on the roof itself to avoid extra piping network.

- ***Energy performance*** the location of the module along with the function inside, could provide energy benefits for the house it is attached to. For instance, having a hydroponic module on the roof could help in stopping heat loss from the roof of the house during winters and in summer the evaporative cooling inside the module could cool the house through the roof. To achieve the maximum benefit of this function, it is recommended to place the module above a heated room such as a living room or a bedroom. Placing it over a bathroom or a kitchen, where less time is spent, would not yield any benefit from this function. A similar technique could also be applied to cool the house through the facades by attaching the module on the façade.

5.1.2 Form

The next category of typology for the greenhouse units is its shape or form. There are some structures that are commonly used in small scale or commercial greenhouses. Each form has its own set of benefits and reasoning as to why it is shaped that way. Some of the widely used categories that are available in the market are –

- *Lean-to* This type is usually places against a building or attached to an existing structure. One wall of this greenhouse is attached to the wall of the building externally. Most of these are not too largely spanned and relatively shorter in height. It could utilise resources such as water and electricity from the building due to its proximity to the building.
- *Even Span* This is the most common type for a self-supporting commercial greenhouse. The roof has an A-shaped structure. All the surfaces are transparent to let natural light in when needed. This is a flexible design and can be sized as per requirements. The shape is also ideal for maintain uniform temperatures inside.
- *Ridge & Furrow* Multiple even span structures placed one after the another forms a ridge and furrow greenhouse. The roof again resembles an A-shaped frame structure and does not accumulate snow or rain. It is usually used in large scale commercial greenhouse structures. The space inside is sufficient to grow multiple crops since there are no walls in between.
- *Gothic Arch* This form doesn't need trusses in the roof structure since it has a pointed roof that emerges from the wall frame. It could be made as a big or a small structure. The design could be aesthetically pleasing to look at since it is not like conventional greenhouses. However, this form takes up more materials and doesn't have a uniform air circulation especially to its corners.
- *Uneven span* In this shape, as the name suggests, the roof is uneven, and one par of the roof is longer than the other. This is to allow more sunlight inside the greenhouse especially when it is in a hilly area. The longer side usually faces the south and is transparent. The shape also keeps winds at bay and is a strong, durable structure.

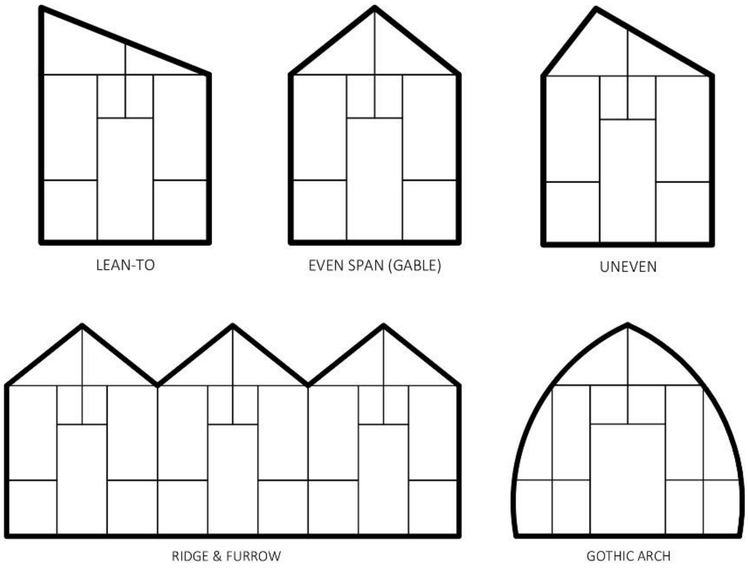


Fig. 5.1 Conventional forms of greenhouse structures

After looking at the various shapes and forms of most of the greenhouses, it can be concluded that the basic structure stays common which is a flat rectangular base and a shelter on top of it. The shelter shape is the best when the air and temperature conditions inside can be uniformly distributed. In this project, since not all the modules will be used for crop cultivation, an ideal greenhouse shape would not be required. Although having some flexibility in the roof of the module, could help in imitating the forms of a greenhouse to avail similar benefits. Such as having a pivoted roof which could be inclined to let fresh air in.

5.1.3 Function

The functions of the modules were decided theoretically in the previous chapter. Each module could either have only one function or a combination of few. The functions are based on the type of energy it is harvesting and generating or simply crop cultivation. Since the end goal is to assist the host buildings in energy efficiency using these modules, the functions could be associated with the needs of the building. These may vary as per the host building. For instance, for a cleaner electrical energy source, the surfaces of the module could be equipped with solar panels or glass with embedded solar cells while inside it produces crops using hydroponics. Possible functions could be-

- *Hydroponics farming* The occupants of the building could grow their own food and harvest the fresh in-house produce. Excess produce could be sold to neighbourhood citizens. This would reduce transportation cost for food while providing biologic home-grown food and promoting community bonding. The energy needed for this type of farming would be obtained from the waste energy flow of the host building as much as possible.
- *Rainwater Harvesting* Netherlands has abundant rainfall almost throughout the year. If the rain is falling on the roof of the buildings is harvested, it could be used for many activities in the building such as flushing toilets, gardening, car washing, laundry, etc. The harvested water could also be utilized in the hydroponic system.
- *Solar energy harvesting* Almost all appliances in the house run on electricity and electricity is the preferred option while opting out of natural gas. Generating clean electricity is therefore necessary and solar panels could be the solution for this.
- *Anaerobic digestor* Every house produces kilos or organic waste daily and all this waste is simply disposed of. With this technology, the organic waste generated can be converted into cooking gas and organic fertilizer for plants.
- *Building insulation* This is an additional function that the house could benefit from while having another function inside the module. For example, having a hydroponic cultivation system inside the modules and placing it on the building roof, could help in cooling the house due to evaporative cooling taking place inside the module. During winter months, the module on the roof would prevent heat loss from the building through the roof.
- *Space utilization for activities* Since the modules will be designed to be flexible in their construction and assembly, they could also be easily dismantled. This would give the possibility of using the modules for short periods of time for additional activities such as temporary vegetable selling kiosk or a pavilion for community activities. A single module could be used for multiple activities and disassembled when not in use.

5.2 Conceptual Design & System configuration –

As stated earlier, the Dutch government has advised various methods to increase the energy efficiency of existing buildings. These methods may or may not require major renovation work. The aim is to minimise the need for such major renovation work, using the greenhouse modules. To begin with, the low effort modifications are applied to the selected case buildings and then the functions of the greenhouse modules are decided depending on the requirement of the particular case.

5.2.1 Conceptual Design

Case 02 – Dutch 'tussenwoning'

Since the house was constructed in 1914, not all renovations are easily possible to be carried out. For example, HR+++ glazing cannot be installed since the window frames are quite old. Roof insulation of about 13cm could be added. For façade insulation, buildings built during that time did not have cavity walls. Thus, filling up the cavity for insulation is not possible, instead insulation is added from either side of the façade. The central heating boiler could be replaced by connecting the house to a district heating system in the near future. Till then a high efficiency combi boiler is sufficient.

On the roof of the house, there is ample space, and some greenhouse modules could be added there. One of them could be for rainwater harvesting. On the façade a 'half' module, oriented towards the south direction, could be attached with hydroponics inside to cool the space behind it. The modules could be equipped with solar panels wherever possible. A digestor module could be installed in the backyard of the house, which generates biogas and fertilizer. Additionally, the heat from the exhausts of the house could be utilized in the greenhouse module on the roof.

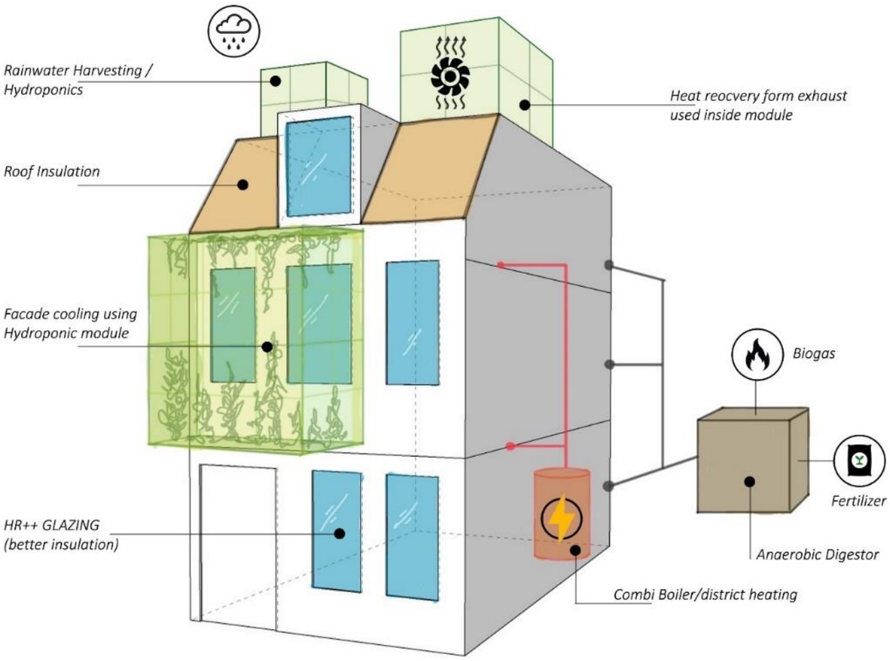


Fig. 5.2 Schematic diagram of Dutch house with the modules

5.2.2 Module matrix

To decide the functions of the modules, a matrix is formulated. This matrix lists down all the possible functions and then shows which functions can be paired up within a single module. This helps in choosing the appropriate module from the wide range of options.

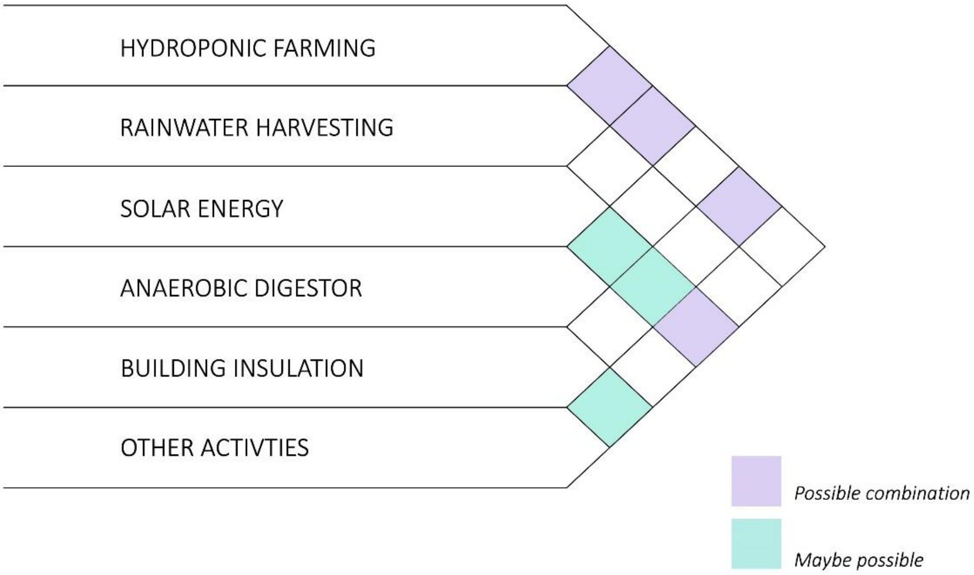


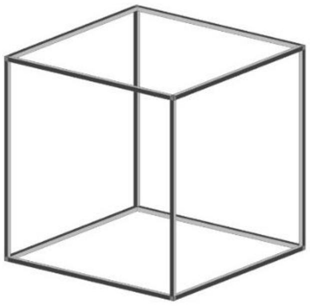
Fig. 5.3 Modules matrix of possible functions

5.3 Module design

Since this an architectural project that has a technical functional purpose, the module is designed keeping these two points in mind. The architecture of the module comprises of its planning, roof and wall design and material selections.

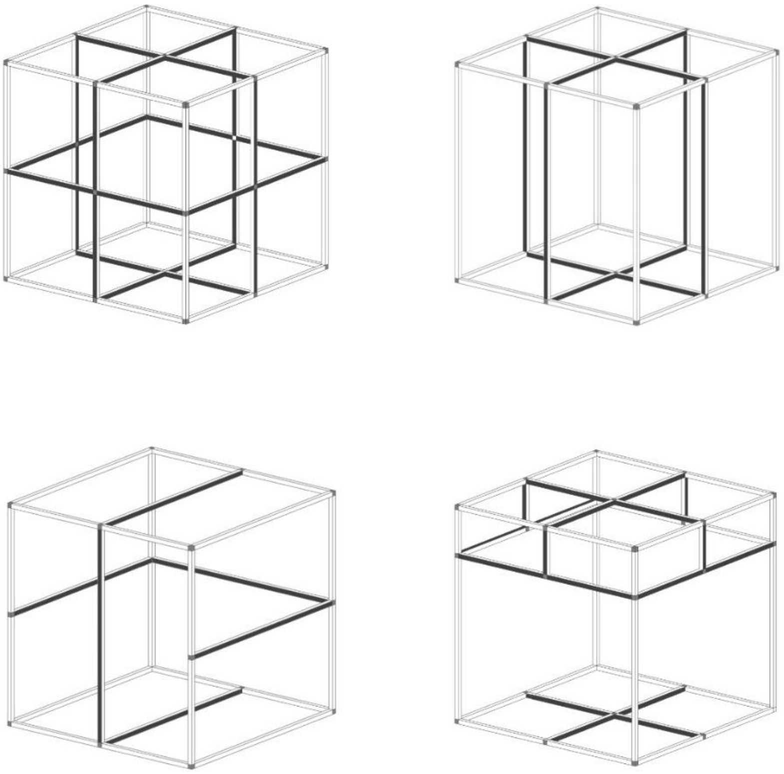
5.4.1 Architectural design

(1) Frame : First the outer frame is designed to make the structure stable. This is the main frame that would support all the loads acting on the structure. To begin with, a cube shape is considered and then options for its structural frame are made, as shown below.



BASE FRAME

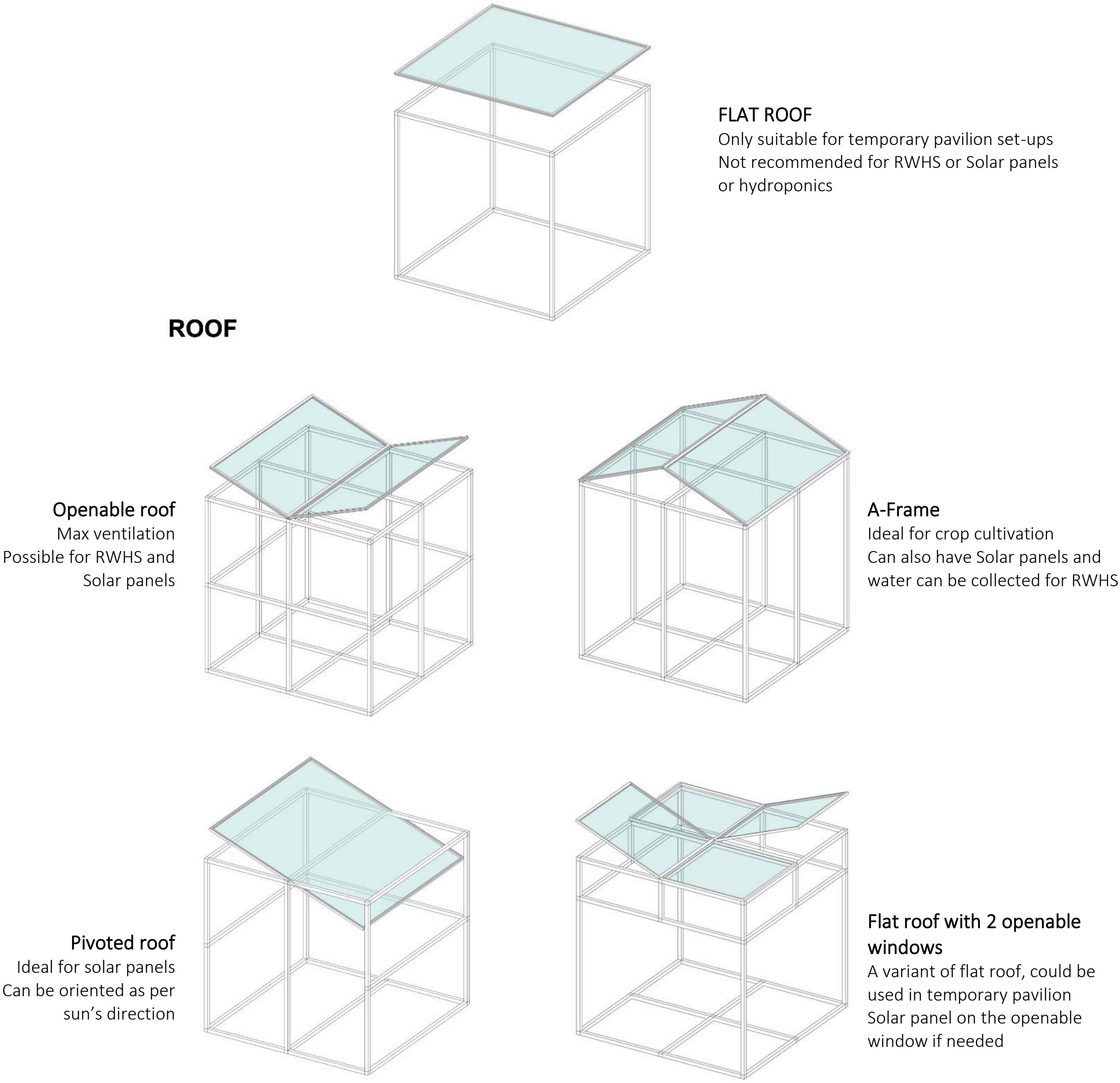
The base frame is a cube made of structural steel or aluminium



FRAME

Fig. 5.4 Structural frame options for the modules

(2) Roof : The next step is to design the roof of the module. The typical A frame roof of a common greenhouse is the reference for the roof design. A variety of options can be designed using hinges and pivots. The type of roof can be selected based on the function of the module. For instance, for a solar panelled roof, the centrally pivoted roof would be ideal which could orient itself depending on the sun direction.



ROOF

FLAT ROOF
Only suitable for temporary pavilion set-ups
Not recommended for RWHS or Solar panels
or hydroponics

Openable roof
Max ventilation
Possible for RWHS and
Solar panels

A-Frame
Ideal for crop cultivation
Can also have Solar panels and
water can be collected for RWHS

Pivoted roof
Ideal for solar panels
Can be oriented as per
sun's direction

Flat roof with 2 openable windows
A variant of flat roof, could be
used in temporary pavilion
Solar panel on the openable
window if needed

Fig. 5.5 Roof options for the modules

(3) Walls : The final step is to cover the module from all 4 sides. Usually in greenhouses, glass or polycarbonate sheets as panels are used. In this case, glass is chosen as the covering material since the materials for the modules are obtained from demolished commercial greenhouses. These types of greenhouses mainly use glass. Some of the wall panels are also possible to open if needed.

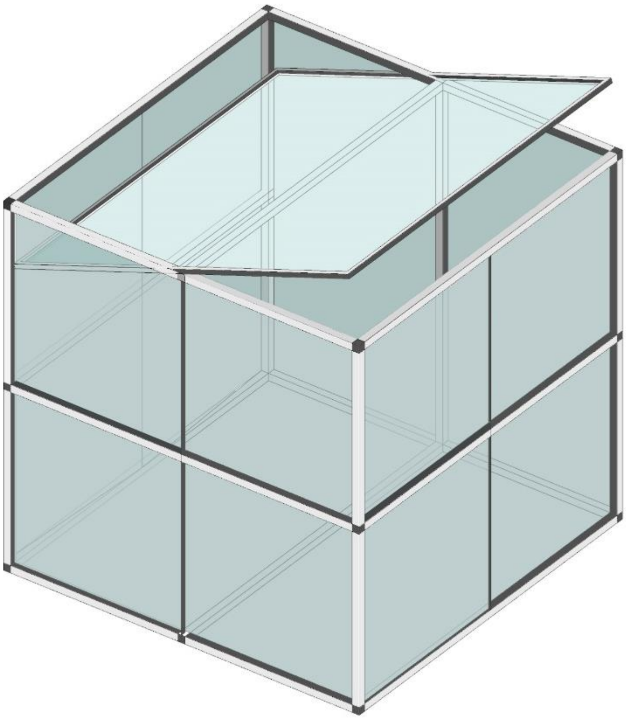


Fig. 5.6 Module with panels

5.4.2 Structural components

The components of the modules are reused parts of demolished greenhouses in the Netherlands. Netherlands has numerous small to large scale greenhouses, that are demolished

- *Structural design (frame, size, connection types, etc)*
- *Technical drawings (plan, sect, elevations, connections)*
- *3D visualizations*

Main structural components

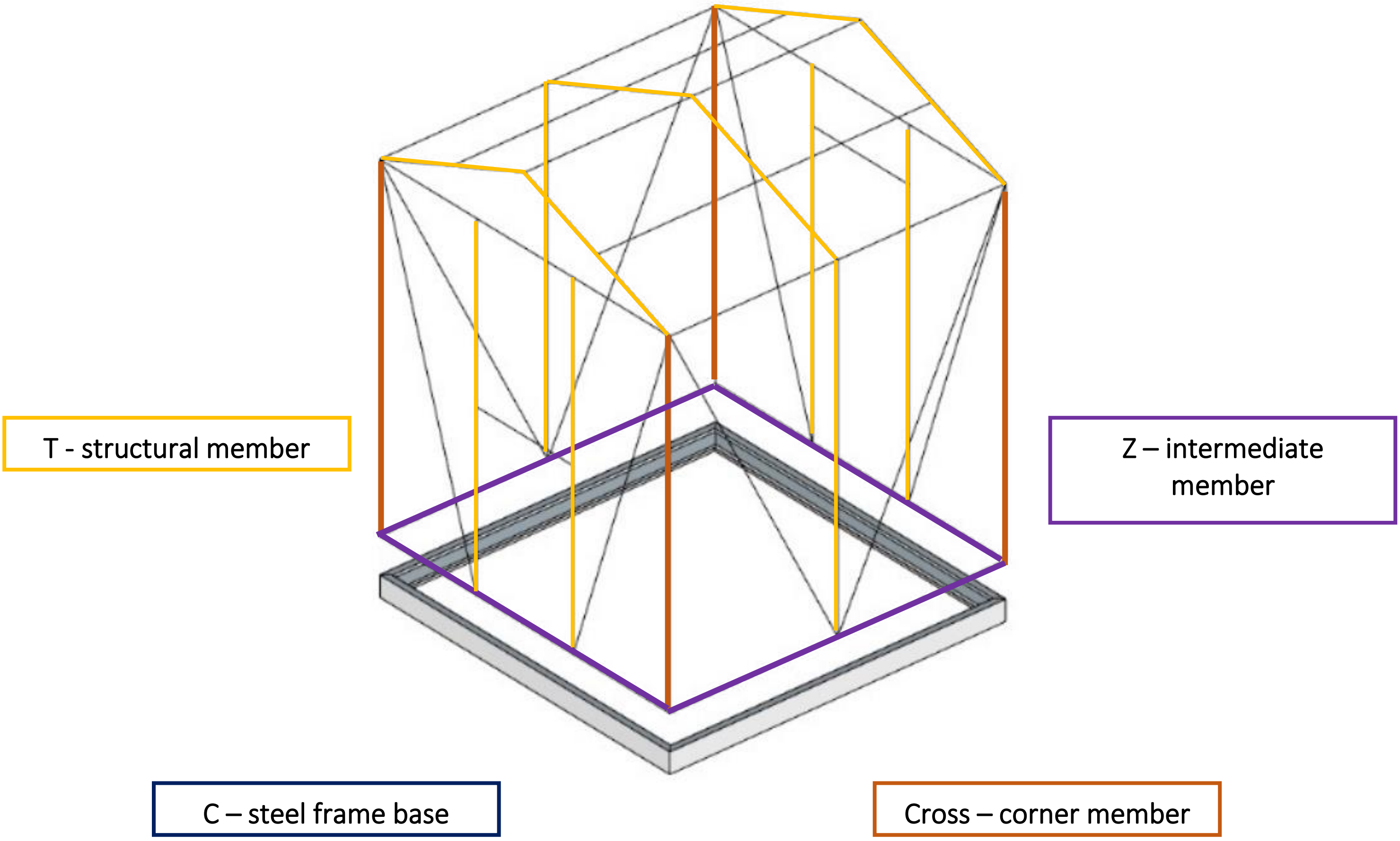
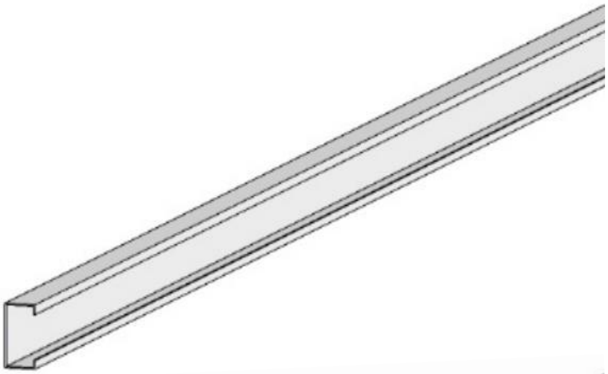
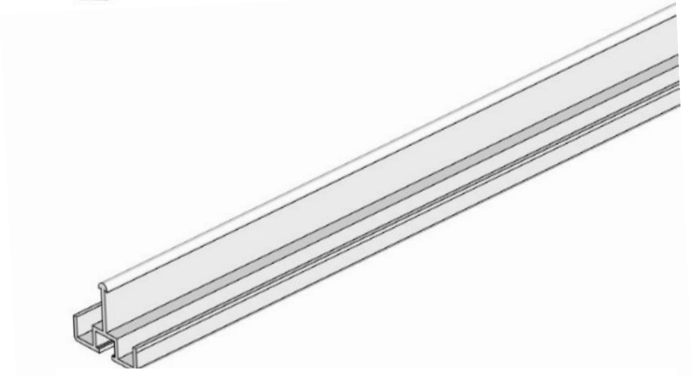


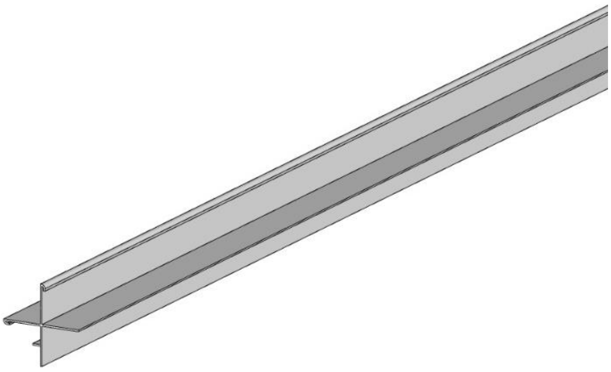
Fig. 5.7 Main structural components



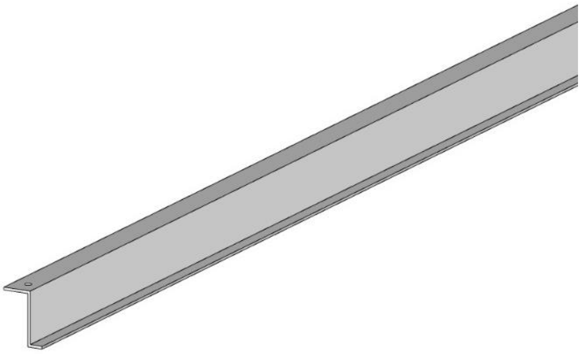
C – steel frame member for the base of the entire module, carries the entire load of the module



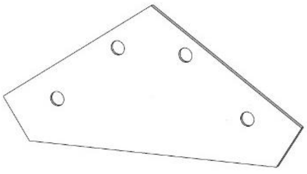
T – shaped structural member for vertical framing and space for glass panel connection on each flange



Cross shaped corner member for vertical posts, to connect glass panels on diagonally opposite sides, forming a corner



Z shaped intermediate member to form a connection between vertical and horizontal members.



Connection plate to join angular, horizontal, and vertical members

Fig. 5.8 Structural components

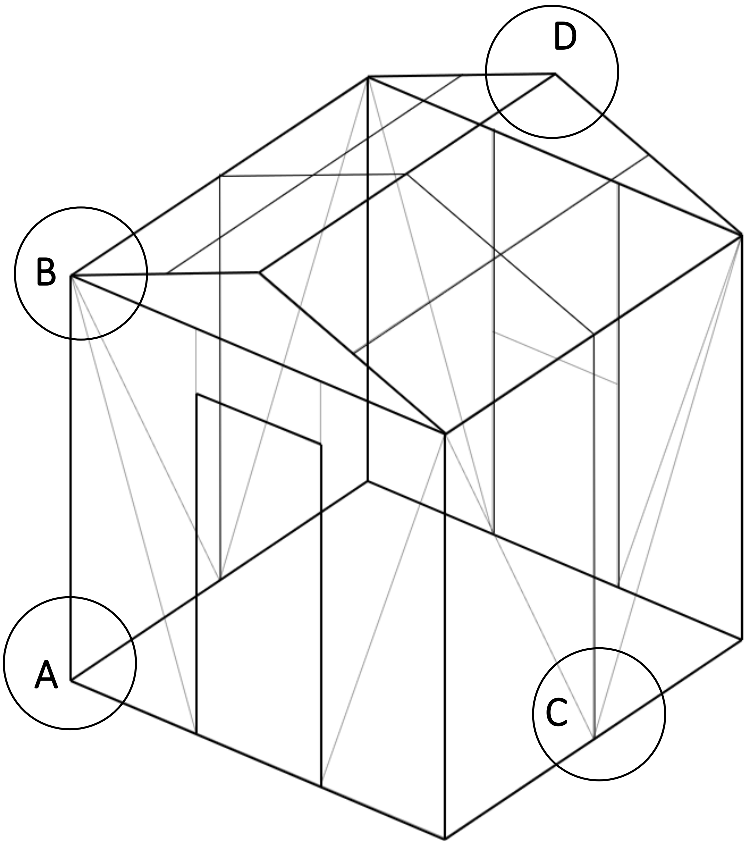


Fig. 5.9 Location of details

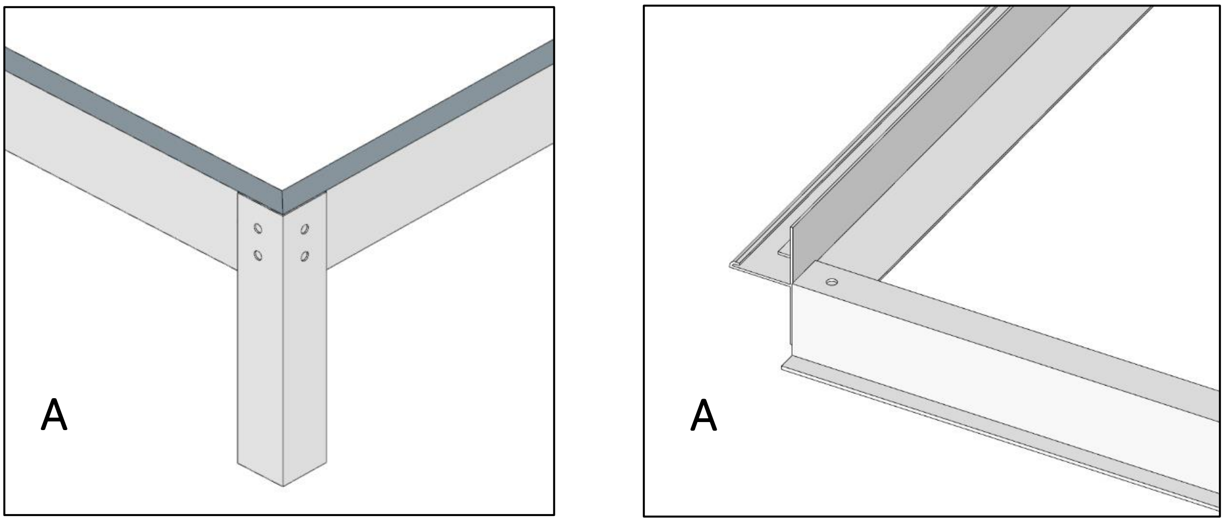


Fig. 5.10 Structural details

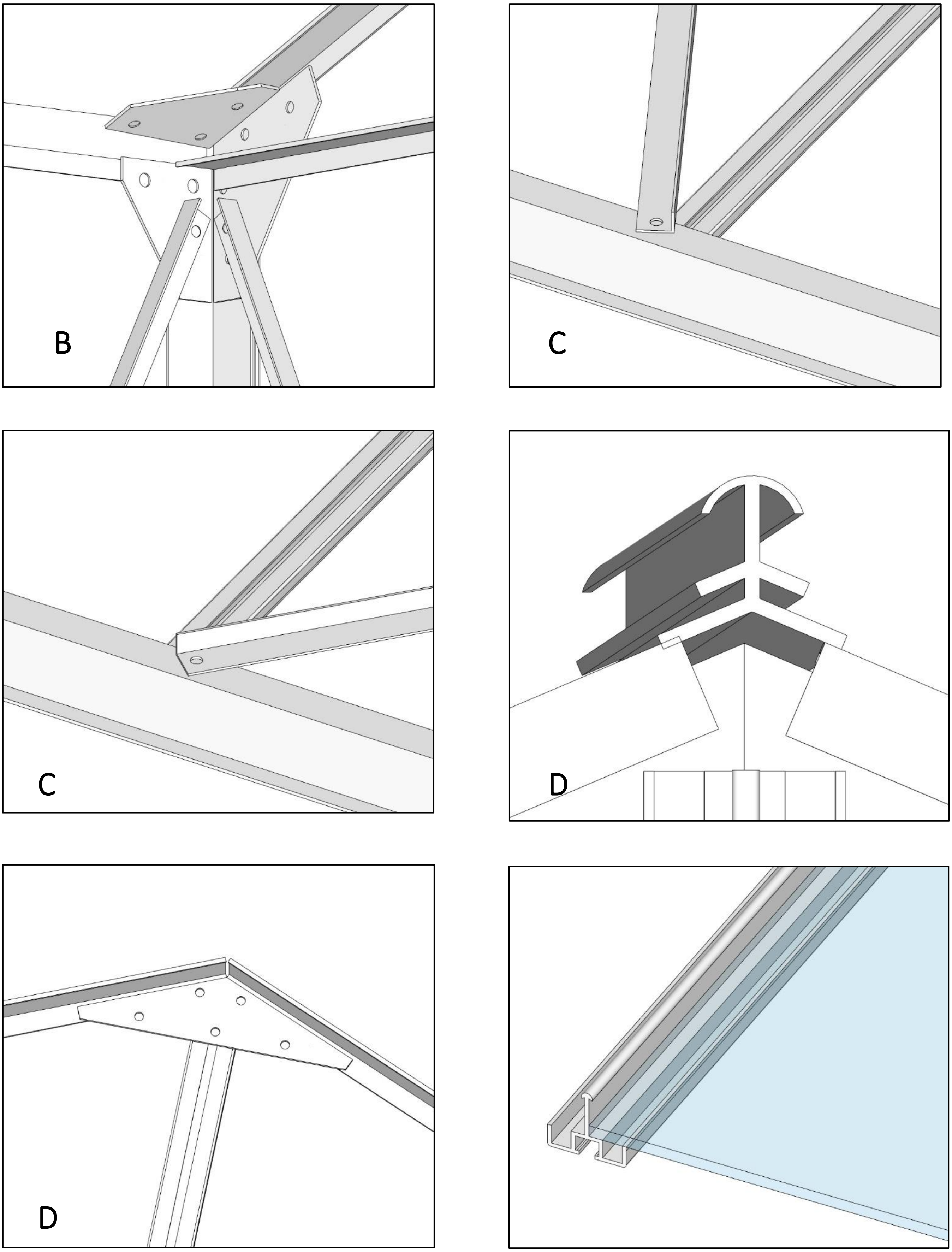


Fig. 5.10 Structural details

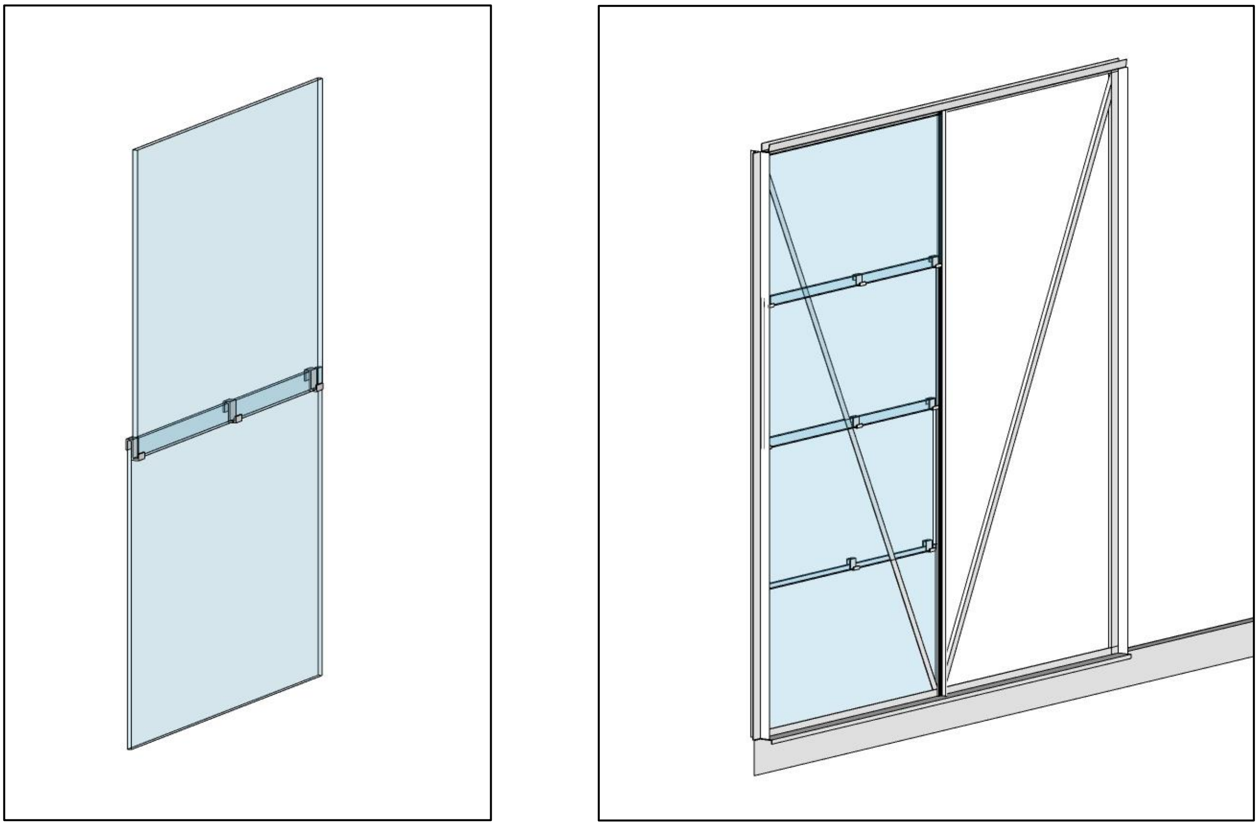


Fig. 5.11 Structural details - glass

Chapter 6 |

Evaluation & Validation

In this chapter, the different aspects of performance of the project cases are analysed and evaluated. The performance of the buildings in terms of energy, water, electricity, etc. before the addition of modules and after, are compared. The energy performance of the greenhouse module is also discussed in detail. Assessing the performance of the modified buildings with the module additions, will help in understanding the overall percentage improvement of the building.

6.1 Performance parameters

(1) Electricity

The electricity demands of both the buildings are different depending on the space and occupancy. Electricity demand is met by installing solar panels on the roof of the building that can harvest solar energy and convert it to electricity.

The apartment unit has a demand of 2500kWh electricity yearly and the Dutch house has a demand of 4500kWh yearly. From the calculations in chapter 4, it is found that 7 panels are needed for the apartment unit and 13 panels for the Dutch house. These number of panels would generate the entire yearly demand of electricity for the respective houses.

The main thing that needs to be checked is space for the solar panels. The apartment unit has a roof space of 77sq.m. and can easily accommodate 7 panels. However, in case of the Dutch house, the roof space is quite limited and only 10 panels can be installed directly on the roof surface. 2 panels have been installed on the roof of a module placed on the roof as showing the sketch below. This gives a total of 12 panels and has a deficit of 1 panel. All the roof panels are facing southwards.

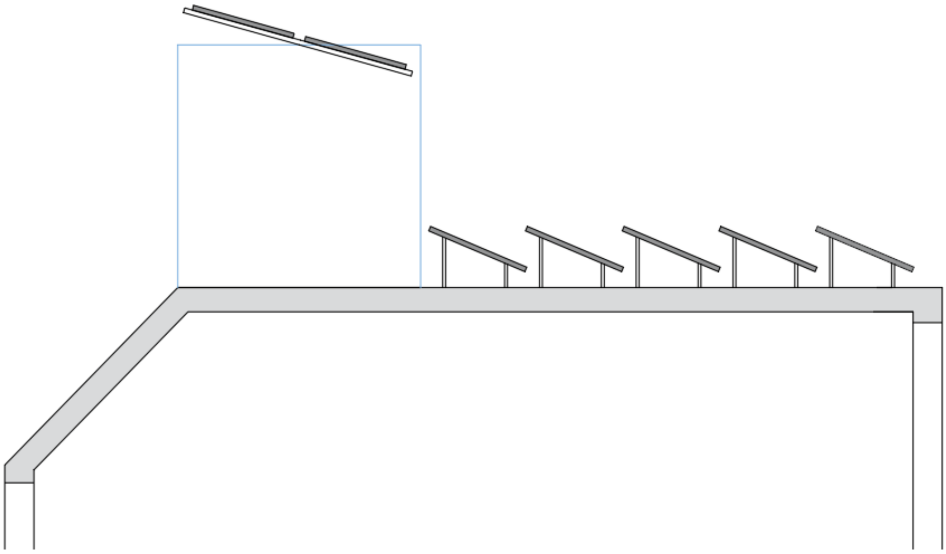


Fig. 6.1 Solar panels position on the roof of case 02

(2) Heating

Both the residential buildings use heating during winter months to keep the indoors warm. The heating is provided by using combi boilers running on natural gas and electricity. In the future this might be replaced by an all-electric option, or the house could be connected to district heating system.
To reduce the heating demands of the building, the heat loss needs to be reduced by improving the insulation of the building roof, walls and installing windows with better insulation values.

The heat from the heated indoor spaces, escapes as residual heat from the surfaces of the house such as roof, wall, and floor. Some of the heat also escapes through ventilation. The idea is to use this residual heat to heat the greenhouses without having any artificial heating for the greenhouse.

In case of a rooftop greenhouse, the heat that escapes from the roof of the building connected to the greenhouse is considered. If the greenhouse is attached to the façade, then the heat escaping from the wall is used. The heat from the ventilation unit could also be used as an additional heat source for the greenhouse.

Insulating the roof and wall of the house, could also affect the heat transfer between the house and the greenhouse. The calculations to find the temperature inside the greenhouse, have been made considering both the insulated and non-insulated conditions.

However, after calculating in chapter 4, the temperature inside the greenhouse during summer and winter, it is found that in summer the greenhouse is prone to overheating just by solar radiation and the heat from the roof of the building. This is tackled by opening the windows of the greenhouse. In winter the temperature inside the greenhouse is favourable for the crops grown inside. Therefore, an additional heat source from the ventilation unit is not required.

The chart below shows the temperature attained inside a rooftop greenhouse in summer (with windows open and closed) and winter in both the insulation conditions, and the required temperature for growing the planned crops.

Season	**Crop**	**Average Temp required for crops**	**Temp inside Greenhouse (insulated)**	**Temp inside Greenhouse (non-insulated)**
Summer (windows closed)	Tomato	20 - 26	41.98 – 45.98	41.6 – 45.58
	Paprika	21 - 27		
	Cucumber	24 - 30		
Summer (windows open)	Tomato	20 - 26	39.2 – 42.3	39 – 42
	Paprika	21 - 27		
	Cucumber	24 - 30		
Winter	Lettuce	13 - 18	9 - 15	9.2 – 15.2
	Beetroot	10 - 21		
	Spinach	12 - 15		

The chart above shows that the temperature inside the greenhouse during summer is extremely high and almost double than what is required for the crops. When the windows are opened, the temperature slightly reduces but still, it is very high for the summer crops.

High solar radiation during the summer is the main cause of overheating in the greenhouse. To combat this issue without using artificial cooling, additional shading or screens need to be provided to cover the greenhouse during summer. This will block the direct radiation of the sun and thereby reduce the heat gain.

In winter, the temperature inside the greenhouse is more favourable for the winter crops. A small amount of additional heat could still be used to heat the greenhouse by 3-4 degrees. This heat could be obtained by using the residual heat from the ventilation unit.

In terms of insulation, it is observed that during summer, the temperature of the greenhouse placed on an insulated roof is hotter than the one placed on a non-insulated roof. Logically, it should be the other way round. However, this could be happening because of heat being transferred from a hotter space to a relatively cooler space. In this case, the greenhouse is hotter due to the sun's direct radiation that the house below, and therefore the heat is transferred from the greenhouse to the house through the roof. When the roof is insulated, the greenhouse transfers lesser heat to the house and remains warmer as compared to the non-insulated roof, wherein the greenhouse transfers more heat to the house below and is slightly cooler.

(3) Water

The amount of water each building demands is based on the number of occupants. Presently, all the water that is supplied to the building is potable water. The potable water is supplied through external sources. However, the water used for flushing, gardening and other similar activities does not require potable water.

The water that flows out of the building is categorized into gray water and black water. A gray water filtration system can filter this gray water and provide it back to the building for non-potable usage. The water can also be used to irrigate the hydroponic greenhouse system.

Another source of water is rainwater that can be harvested from the roofs and used for non-potable activities. The chart below shows the water demand of the buildings and the greenhouse, and the amount of rainwater harvested, and gray water filtered.

Type	Water demand (non-potable) (L/year) *Toilet, washing machine & others GH irrigation*	Water demand (non-potable) (L/day) *Toilet, washing machine & others GH irrigation*	Amount of greywater filtered (L/day) *Shower, bathroom, & washing machine*	Amount of rainwater harvested (L/year)
Apartment unit	40369	110.6	176.8	46292
Greenhouse (tomato, paprika, cucumber)	3456 *(6months only)*	19	-	-
Greenhouse (lettuce, beetroot, spinach)	1536 *(6months only)*			
Total	**45361**	**129.6**	**176.8**	**46292**
Dutch house	80738	221.2	353.6	34268
Greenhouse (tomato, paprika, cucumber)	3456 *(6months only)*	19	-	-
Greenhouse (lettuce, beetroot, spinach)	1536 *(6months only)*			
Total	**85730**	**240.2**	**353.6**	**34268**

From the chart above, the daily non-potable water demands can be sufficiently met by filtering the graywater daily. The yearly rainwater collection is an excess and can be utilized when the greywater filtration is not used. The greywater filtration could not be in use, in a situation where the house is not fully occupied. Therefore, the rainwater and greywater filtration system could work together to balance out the supply depending on the situation.

Having enough reusable water for non-potable usage does not mean that it forms a closed loop system. Potable water is still supplied to the building from external sources, but it is no longer used for activities that do not require potable water. The loop thus formed is illustrated below.

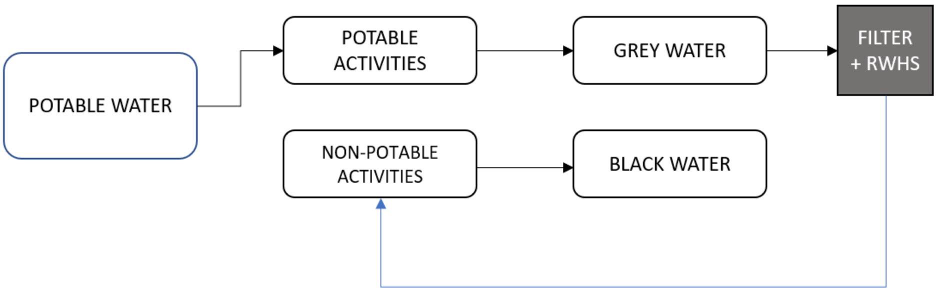


Fig. 6.2 Water filtration and supply loop

(4) Food

The total food demand of the house comprises of vegetables, fruits, meat, dairy, eggs, etc. Not all the food demands can be met by the greenhouse. The vegetables consumed could vary as per the preference of the occupants' diet. However, the vegetables that are grown inside the greenhouse can partly suffice the vegetable demands.

The chart below shows the yearly yield of the crops grown in the greenhouse and the average yearly consumption of the vegetables grown.

Crop	Consumption/year per person (kgs)	For 4 people	For 2 people	Yield (kg/year)
Tomato	10.8	43.2	21.6	72
Cucumber	3.62	14.48	7.24	324
Paprika	11.2	44.8	22.4	28
Lettuce	5.76	23.04	11.52	10.8
Beetroot	1.5	6	3	5.25
Spinach	1.3	5.2	2.6	9

The chart above shows that some of the crops have surplus yields than required. In such cases, the owner can choose to reduce the number of plants and add other plants that require similar temperature conditions for growth. Additionally, the surplus could also be distributed or sold in the local community.

(5) Organic waste

Organic waste comprising of kitchen waste and animal waste if available, can be fed to the anaerobic digestor module to generate biogas and fertilizer. The amount of organic kitchen waste generated, is very less for a single house (200 to 400gms) and to have a well-functioning digestor, multiple houses should be connected to it.

(6) Carbon dioxide

Exhaled air contains 38,000 ppm of Carbon dioxide. However, after exhalation, the exhaled air mixes with the ambient air and the ppm concentration of carbon dioxide reduces. In a well-ventilated

house, the concentration of carbon dioxide is 400 – 1000ppm. This amount can vary and increase up to 5000ppm depending on the occupancy.
The required amount by plants is between 800 to 1000ppm. The exhaust air from the house contains the carbon dioxide that could be directed to the greenhouse and benefit the growth of the crops.

6.2 Summary of evaluation

The above discussed individual performance parameters, can be summarized in the table below to calculate the percentage improvement of the selected project cases by addition of the modules.

For project case 01 (2 persons Apartment unit + 1 greenhouse):

Resource	Demand	Generation	Surplus	Deficit	% sufficed
Electricity	2500 kWh	2520 kWh	20 kWh	0	100%
Heating	11190 kWh/yr	-	-	-	-
Non-potable Water	45361 L/yr	110824 L/yr. (RWHS + Graywater)	65463 L	0	100%
Vegetables (tomato, paprika, cucumber, lettuce, beetroot, spinach)	69 kg/yr	449.05 kg/yr	380 kg/yr.		100%

For project case 02 (4 persons Dutch house + 1 greenhouse):

Resource	Demand	Generation	Surplus	Deficit	% sufficed
Electricity	4500 kWh	4320 kWh	-	180 kWh	96%
Heating	62640 kWh/yr.	-	-	-	--
Non-potable Water	85730 L/yr.	163113 L/yr. (RWHS + Graywater)	77383 L/yr.	-	100%
Vegetables (tomato, paprika, cucumber, lettuce, beetroot, spinach)	137 kg/yr	450 kg/yr	313 kg/yr.	-	100%

Additional generation for heating is not provided, however the building can be insulated properly, windows can be replaced with more efficient models and the heat from ventilation exhaust air can be recovered to reheat the air entering the house. By adopting these means, the heating demand can be reduced by considerable amount.

Chapter 7 |

Conclusion, Bibliography & Appendix

In this final chapter, the main research question posed at the beginning of this project, and the following sub-questions are answered. The limitations and further research possibilities of this project are discussed. Finally, the conclusion of the project is summarised.

7.1 Answer to research questions

First, the research sub-questions are answered and then the main research question is answered.

(i) *How can the symbiotic greenhouse module utilize the existing energy and material waste flow from the building and in turn convert it to valuable crop produce? –* ***Energy IN/OUT***

Buildings use various resources such as electricity, water, natural gas-powered heating, etc. Most of these resources, once utilized, a part of it is let out as waste flow to the environment. For instance, wastewater is flushed out as grey water and black water. Similarly, a greenhouse requires various energy resources and materials for its functioning. These include electricity, water, heating and cooling, nutrients for the plants, etc. In free-standing greenhouses, these requirements are met by external sources. However, there lies a potential of utilizing the waste flows from the building to power the greenhouse for crop production.

Small amounts of heat escape from the buildings through its walls, roofs, and floors. When the greenhouse is attached to the roof or to the external wall of the building, it can utilize this heat during winter to maintain a warm temperature inside. The heat that escapes through the ventilation unit of the house can also be used by the greenhouse for heating. Graywater from the building can be filtered and reused for watering the crops in the greenhouse. The organic wastes from the kitchen of the building can be composted in a digestor to produce fertilizer that can supply nutrients to the crops. Lastly, the carbon dioxide that escapes from the building's ventilation system as exhaust air can supply carbon dioxide to promote additional growth of the crops in the greenhouse.

In this way, the resources for the greenhouse are made available locally and additional resources are not required. Additionally, installing renewable energy sources like solar panels and capturing rainwater, benefits both the greenhouse and the building.

(ii) *What are the reductions in primary energy resources of the building, wherever possible, caused by the symbiotic modules? –* ***Efficiency***

The symbiotic modules are designed to assist the building in meeting its energy and resource demands. The primary energy resources of the building consist of electricity, water, heating using natural gas and electricity, food, and oxygen for the occupants. To meet these demands, the modules designed include rainwater harvesting system, greywater filtration system, anaerobic digestor, greenhouse with hydroponic crop cultivation, and accessories such as ventilation unit with heat recovery and solar panels.

Presently, the primary energy resources are supplied by external sources. By adding the modules, the quantities of these primary resources supplied by external sources can be reduced considerably. The rainwater harvesting system and greywater filtration system supply the water for non-potable usage in the building. Biogas is obtained from the anaerobic digestor that could be used for cooking. The greenhouse provides year-round vegetables for the building depending on the type of vegetables grown. Oxygen released by the crops could also benefit the building by supplying clean fresh air. The heat recovery unit recaptures 80% of the heat that would've been lost by exhaust and reheats the incoming fresh air before supplying it to the building. Lastly, solar panels generate electricity to power the building.

	Apartment unit	Dutch house
Electricity	100%	100%
Heating	Reduced demands	Reduced demands
Non-potable Water	100%	100%
Vegetables (Tomato, paprika, cucumber, lettuce, beetroot, spinach)	100%	100%

(iii) How can the symbiotic unit be made modular and circular in terms of its buildability to achieve flexibility in construction and adaptation? – ***Buildability***

Greenhouses in the Netherlands are built mainly using steel and aluminium structural members and different types of glazing. Sometimes these greenhouses are demolished and dismantled before their end of life, due to reasons such as replacing the old greenhouse with a new one that has new technologies. The parts of the greenhouse can still be utilized to build a new greenhouse by making small modifications wherever necessary. The structural members could be cut to the size requirement of the new greenhouse. This project uses such structural parts from demolished greenhouses and gives the parts a new life by building small-scale greenhouse modules. These modules do not use permanent joinery techniques and are simply bolted together so that they can be easily dismantled and reassembled whenever needed. In some modules, a pivoted roof is designed such that, it can align and adapt to the direction of the sun to harness the sun's energy by fitting solar panels on it. The module can also be constructed as a 'half module' to attach it to the wall of the building.

Main research question

How can modular symbiotic units be designed and integrated with buildings in an urban context, to utilize available waste resources in exchange for food production while reducing primary resources of the building, where possible?

As discussed earlier, buildings rely on a supply of energy and material resources to meet their demands. These demands could be met by generating and producing resources locally within the context of the building. There are two main ways of generating and producing the resources needed by the building. One way is by utilising the building's waste flows and making it available again for reuse. The second way is to harness renewable sources of energy that the building receives in the form of solar radiation and rainwater. The modular symbiotic units are designed to cater to these functions to generate and meet the demands of the buildings. By incorporating urban agriculture in the modules, the food demands of the occupants of the building can also be partially met.

From the assessment before, it can be observed that the generation capacity of the modules, helps in reducing the primary energy and resource supply to the building from external sources. The external sources mainly rely on fossil fuel consumption to generate energy. By reducing the primary energy and resource demands, a significant amount of fossil fuel consumption can be reduced, thereby promoting a sustainable and cleaner alternative for meeting building demands in the urban context.

7.2 Limitations

The project is limited to the data of two types of residential buildings in an urban context. It does not consider commercial or office buildings that could have a different set of demands and waste flow generation.

Details of hydroponic production technique, such as types and quantities of nutrients required for the plants are not discussed. The pH value or quality of water is not looked into either.

Due to time constraints, the effect of sun shading on reducing solar heat gain is not calculated. Detailed heat gains and heat losses are not calculated on an hourly/daily basis since this would require the greenhouse to be simulated on software such as Energy Plus on Design Builder. The calculations are based on standard and simplified data for each season.

Finally, for the apartment building, only one apartment unit is considered. The building comprises more such residential units which could be included in further research.

7.3 Further discussion

To further understand the effect of the symbiotic modular units on the buildings, a dataset of more types of buildings with varied energy demands needs to be considered. This project serves as the starting point for the concept of energy co-symbiosis between buildings and energy generating modules and greenhouses. As per the climate and location, the demands of the buildings could change, and one set of modules might not fit all. Formulating a universal system of co-symbiotic modules would require a lot of further research.

Parameters of indoor comfort could also be looked into for changing climate conditions. Presently, most of the energy is spent on heating the indoor spaces due to long and cold winters, however each year, the summers are getting harsher as well with rising temperatures. Cooling is becoming a need that could be met by evaporative cooling promoted by the plants. This is just an idea and needs to be investigated in detail.

The aesthetic architectural aspect of the module could be further explored by designing innovative modular solutions that integrate seamlessly with the buildings in urban areas. Instead of opting for a typical form of a module, parametric forms could be generated using the same dismantled materials available from deconstructed greenhouses.

7.4 Conclusion

With a rapidly growing population, the demand for resources is also increasing. Large amounts of waste flow in urban areas are leading to adverse ecological impacts. This project aims to tackle the issue of increasing resource and energy demands while reducing waste flows. The potential of capturing the urban waste flows and utilizing them to generate resources and energy is explored in this project.

The first step was to analyse the demands of the selected project cases and possible waste generations. The second step was to develop strategies and solutions for meeting the demands and utilizing the waste flows where possible. The third step was to design modular units to host these energy and resource-generating solutions. The fourth phase involved assessing and evaluating the performance of the modules that formed a co-symbiotic relationship with the host building. Lastly, the fifth phase was to answer the research questions that were framed at the start of the project and reflect on the solution designed.

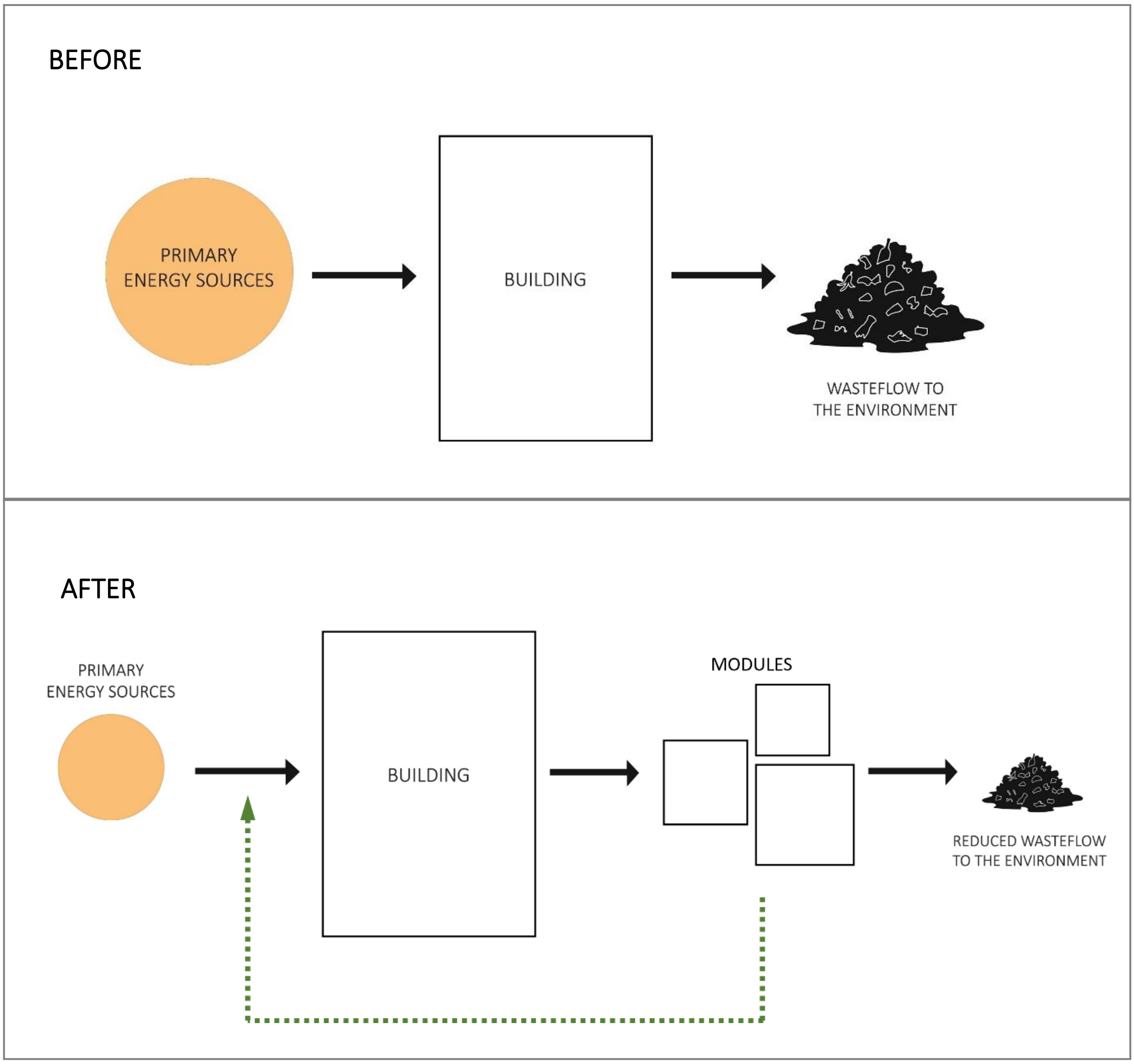
Following are the key conclusions derived from the research project:

- After the design intervention, there is a significant reduction in the demand of primary energy resources and materials of the case buildings. This is observed mainly in case of electricity, water and food.
- The waste flows as intended earlier can be successfully used to generate resources and grow food. Gray water is turned into usable water for non-potable usage, organic waste is

converted into biogas and fertilizer for plants, and residual heat from the buildings is used to heat the greenhouse during winter conditions.

- The modules are fairly small and easy to assemble, this ensures flexibility in its design and can be assembled as per requirement. In seasons with extreme weather, such as in summer, wherein the greenhouse transfers heat to the house below, it can be disassembled and kept aside.
- The modules can be attached to the building with temporary connections without changing the structure of the building permanently. Since, these modular units are being used to generate energy or in places acting as insulators for the building (on façade and roof), the need for deep renovations is temporarily avoided.
- Finally, the vacant spaces on and around the buildings, such as the terrace or roof space or blank facades, can be well utilized by the modules.

To summarize, the design intervention helps in improving the overall building energy performance by reducing the primary energy demands, preventing energy loss and reutilizing waste flows. This design concept would help in overall speeding up the energy transition as planned by the government.



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APPENDIX

(1) Energy demands of Apartment unit

Energy Label	**Type of unit**	**Sources**	**Function**	**Year**	**Unit**	**Energy demand**	**Energy demand**	**Unit**
77sq.m.	Apartment (Rotterdam/The Hague)	https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?ts=1656097580913	Avg. consumption of Natural Gas	2020	m3	**1000**	**11186.80**	kWh
			Avg. consumption of Electricity	2020	kWh	**2500**		
			District Heating	2020	NA	**NA**		
A	**Apartment (2 person, 77sq.m.)**	https://ce.nl/wp-content/uploads/2022/04/CE_Delft_210381_The_natural_gas_phase-out_in_the_Netherlands_DEF.pdf https://www.waternet.nl/en/service-and-contact/tap-water/average-water-use/	**Heating (Natural Gas)**		kWh/m2	**116.23**	**8949.44**	kWh
			Cooling		kWh	**0**		
			Cooking (NG)		kWh/m2	**0.00**	**0.00**	kWh
			Electricity (incl. cooking)		kWh	**2500**		
			Direct Hot Water supply (NG)		kWh/m2	**29.06**	**2237.36**	kWh
			Water consumption					
			Shower		L/day per person	63.7		
			Toilet			35.3		
			Washing machine			14.3		
			Bathroom			10.4		
			Dishwasher			1.4		
			Cooking			2.3		
			Drinking			0.7		
			Other things			5.7		
			Total domestic water usage		L/day per person	133.8		
			Total domestic water usage		**2 persons**	**267.6**	**97674**	L/Year

(2) Energy demands of Dutch house

Energy Label	**Type of unit**	**Sources**	**Function**	**Year**	**Unit**	**Energy demand**	**Energy demand**	**Unit**
	Tussenwoning (Rotterdam)	https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?ts=1656097580913	Avg. consumption of Natural Gas	2020	m3	**5600**	**62640.00**	kWh
			Avg. consumption of Electricity	2020	kWh	**2500**		
			District Heating	2020	NA	**NA**		
F	**Terraced house (4 person, 174 sq.m.)**	https://ce.nl/wp-content/uploads/2022/04/CE_Delft_210381_The_natural_gas_phase-out_in_the_Netherlands_DEF.pdf https://www.waternet.nl/en/service-and-contact/tap-water/average-water-use/	**Heating (Natural Gas)**		kWh/m2	**334.25**	**58160.00**	kWh
			Cooling		kWh	**0**		
			Cooking (NG)		kWh/m2	**0.00**	**0.00**	kWh
			Electricity (incl. cooking)		kWh	**2500**		
			Direct Hot Water supply (NG)		kWh/m2	**25.75**	**4480.00**	kWh
			Water consumption					
			Shower		L/day per person	63.7		
			Toilet			35.3		
			Washing machine			14.3		
			Bathroom			10.4		
			Dishwasher			1.4		
			Cooking			2.3		
			Drinking			0.7		
			Other things			5.7		
			Total domestic water usage		L/day per person	133.8		
			Total domestic water usage		**4 persons**	**535.2**	**195348**	L/Year

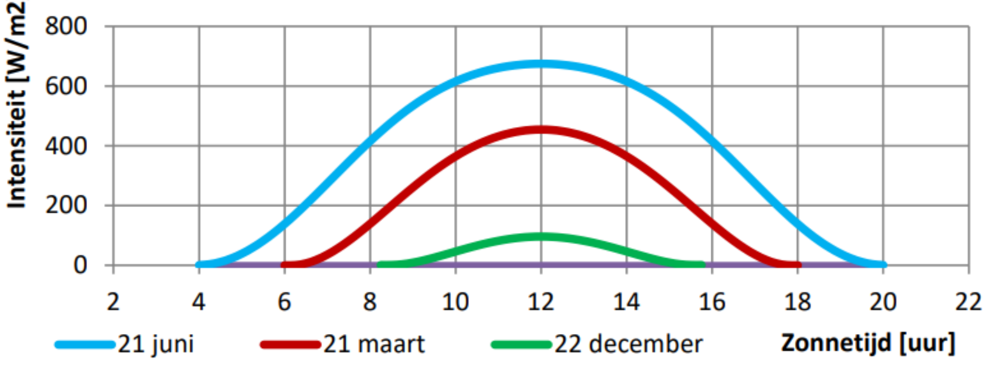
(3) Crop specifications

Crop	Growing temperature range (^{o}C)	1^{st} Harvest time	No. of plants	Water demand (L)	Yield/plant	Period	Total yield
Tomato	21 to 26	2 months	9	81	5-8kg	6 months	**72kgs**
Paprika	21 to 27	50 – 80 days	9	81	1.5kg	Every week for 6 months	**324kgs**
Cucumber	24 to 39	50 – 70 days	14	126	1.5 – 2kg	6 months	**28kgs**
Lettuce	12 to 20	6 weeks	9	36	300gms	Every 6 weeks for 6 months	**10.8kgs**
Beetroot	15 to 18	40 – 50 days	14	36	125gms	Every 2 months for 6 months	**5.25kgs**
Spinach	10 to 18	1 – 1.5 months	9	56	250gms	Every 6 weeks for 6 months	**9kgs**

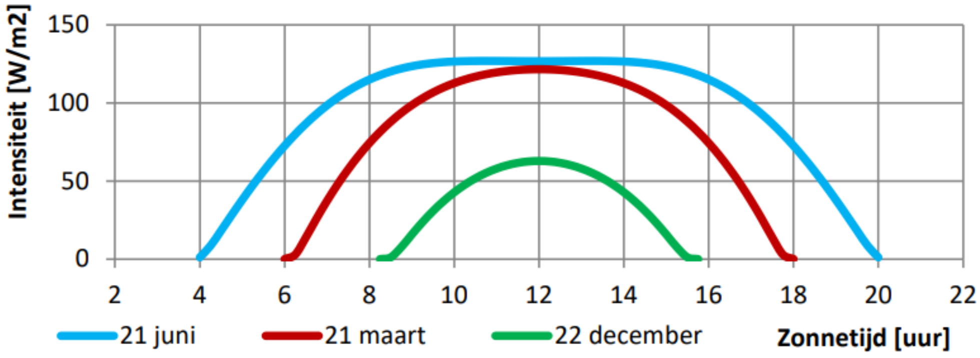
(4) Solar radiation graphs for calculating heat gain due to sun's radiation

Total global radiance = Direct radiation (depends on orientation) + diffuse radiation

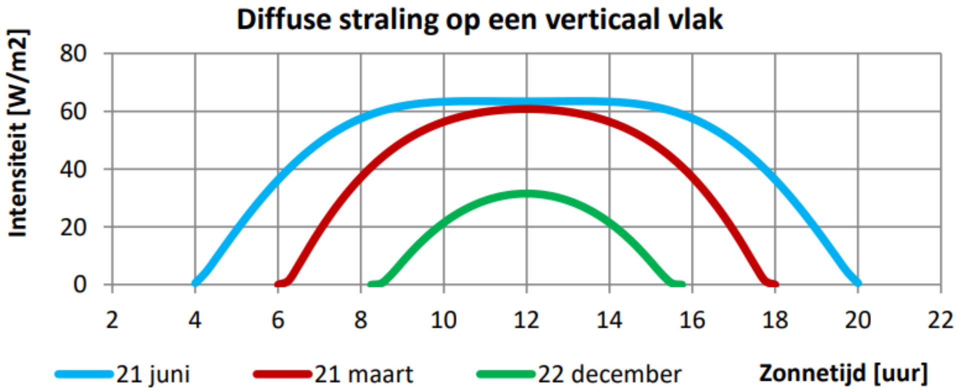
Direct radiation on a horizontal plane

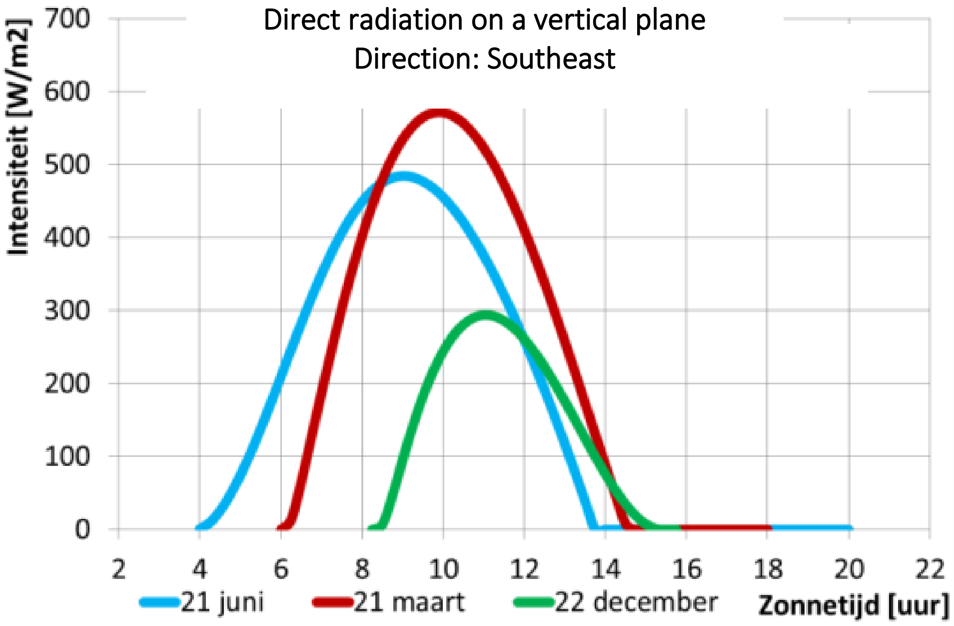


Diffuse radiation on a horizontal plane



Diffuse radiation on a vertical plane


Diffuse straling op een verticaal vlak
Intensiteit [W/m2]
80
60
40
20
0
2
4
6
8
10
12
14
16
18
20
22
21 juni
21 maart
22 december
Zonnetijd [uur]


Direct radiation on a vertical plane
Direction: Southeast
Intensiteit [W/m2]
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
18
20
22
21 juni
21 maart
22 december
Zonnetijd [uur]

URBAN SYMBIOTIC GREENHOUSE
REFLECTION

Date 24.10.2022

TRISHITA CHATTERJEE 5108543

1) Approach and preliminary results

The project started with an in-depth background research of the topic of Urban agriculture. This was followed by realising the need for urban agriculture within buildings. The research was carried in a 'research through design' manner – to study the outcomes and derive conclusions based on the performance of the modules designed.
The project was approached in 4 stages: (1) Literature study of methods for urban agriculture (2) Building selection for the project and energy performance study (3) Intervention by designing functional modules that are in co-symbiosis with the building (4) Material flow formulations based on the co-symbiosis. After these 4 steps, the design was evaluated and assessed for deriving conclusions.

2) Relationship between research and design

This graduation project was divided into 2 main sections – first a detailed research and findings on energy performance of buildings; and second, utilizing this research knowledge to design modules that could help in improving the buildings' energy performance. Without the preliminary research, it would not be possible to estimate the need for designing the modules. After the modules were designed, the initial energy research and analysis helped in validating the performance of the buildings with the added modules.

3) Relationship between graduation topic, studio topic, master track and master programme

The topic 'Urban symbiotic greenhouse' is a part of the Climate Design and Sustainability department in the Building Technology track of the master program 'Architecture, Urbanism and Building Sciences'.

In the track Building Technology, the main focus is on designing efficient and smart buildings that consume less energy and are sustainable in nature. This project is aimed at reducing primary energy resource needs of the existing buildings, while utilizing the waste flows from the buildings, thereby achieving a better energy performance.

Presently, there are very few examples of building integrated agriculture systems that are in energy co-symbiosis with their host buildings. It is important to carry out more research and study in this field since the idea of an energy symbiotic greenhouse in an urban context could be the future of food production in urban areas.

4) Scientific relevance and further research

This topic finds itself under the realm of Urban agriculture and aims to explore the potential of co-symbiosis of agriculture integrated in the built environment. When such an integration occurs, the benefits obtained are multi fold. With this research, the scientific benefits of combining agriculture with urban environment will be explored. Currently, there are very few examples of such integrations. The technical challenges arising from a symbiotic greenhouse system that utilizes a building's waste resources are also widely unknown. These challenges will be investigated by providing a detailed study of design and construction of the building integrated greenhouse units and assessing the possibilities of energy and resource co-symbiosis. This will help in obtaining a clearer understanding of the working and benefits of such co-symbiotic modules in the built environment.

As the global population rapidly keeps increasing, the demand for food and energy resources steadily keeps growing. It is becoming a growing difficulty to meet these demands and might lead to a bigger problem of scarcity, in the coming years. Alongside these demands, another big concern is the issue of emissions and wastes generated after consumption. Currently, the resources that go into the urban environment simply end up as wastes after consumption. This linear system must change and replaced with a more circular approach, wherein the wastes are reutilized as much as possible.

Urban agriculture has social, economic and environmental benefits. Even though the function of any agricultural system is primarily to produce food, it could be also used as a tool to achieve multiple goals in the urban context. These goals include, sustainable agriculture practises, local scale energy generation, purifying the polluted air and water from urban areas, integrating green spaces in the cities and promoting social well-being. 'Culture, community and identity are created, enacted and reinforced' through food. (Stock, et. al., 2012) The physical, financial and psychological wellbeing of urban population may be enhanced by adapting such agriculture that is integrated in urban environments.

5) Ethical issues

The Dutch built environment has a very strong and distinct architectural character. Especially the residential areas with buildings dating back to 1900s have a strong aesthetic charisma. The materials, colours, forms, all contribute towards the architectural character of a building.
While working on this project, the focus was mainly on the functional purpose of the modules designed, and the energy co-symbiosis they participated in. The architectural aspect of the modules in context with the location was unfortunately overlooked.