Energy Implications of Vertically Integrated Greenhouses on Office Buildings

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Abstract

The global greenhouse gas emissions from energy use in buildings and agriculture accounts for 17% and 18% respectively, which has a significant impact on climate change. Therefore, both the sectors are actively looking at energy-efficient methods to reduce their carbon emission by shifting to more sustainable solutions. One such solution is Vertically Integrated Greenhouses (VIG). This research investigates the impact of such systems on the building's energy consumption. The case study has been performed on the EEMCS building of TU Delft, in the Netherlands. The crop chosen for the study is strawberry, as it is one of the most consumed greenhouse fruits by the Dutch population. The energy needed for the building and the greenhouse to maintain the comfortable indoor temperature was calculated. An additional novel method of storing the surplus heat was incorporated in the design in the form of Aquifer Thermal Energy Storage (ATES). This system provides heating and cooling energy which reduces the dependency on fossil fuels and reduces the carbon emissions. A comparative study on the carbon footprint due to energy used in the building was done in order to analyse the impact of introducing an ATES system in mitigating climate change. Further, a rainwater harvesting system was incorporated aiming to fulfil the water requirement of the plants, this thereby reduces the dependence on an external water source. Such synergetic systems reduce the dependency on fossil fuels and thereby significantly reducing their carbon emission. The proposed design of integrating VIG on the facade of the existing building showed an additional 292 MWh of energy consumption when compared to the current scenario. However, the introduction of ATES resulted in a 40% total reduction in the carbon emission of the energy consumed by the building. In addition to the carbon emission reduction, an annual yield of 227 tonnes of strawberry is also achieved. Thus, the role of having such a synergetic system is highlighted.

Keywords: Vertically Integrated Greenhouses, synergetic system, carbon footprint, urban farming, Aquifer thermal energy storage, double-skin facade

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1. Introduction

1. Introduction

In the current context of climate change, it is important to investigate the different causes of global warming and to take the necessary steps to reduce the emissions associated with anthropogenic climate change. The current emissions have led to the global rise in temperature by 1^{o} Celsius since the preindustrial times (Ritchie & Roser, 2017). Additionally, the globally averaged concentration of CO_2 in the atmosphere has exceeded 400 ppm in 2018, for the first time in over 800,000 years (Loria, 2018) . The effects of this are already felt globally. Irrespective of the status of the country, it has been hit by natural calamities such as hurricanes, flooding, forest fire, draughts etc. more frequently and more erratically.

As the world responds to the reality of climate change, the construction sector is looking for methods to reduce carbon emissions and promote sustainable buildings. Around the world, the building and construction industry accounts for 39% of greenhouse gas (GHG) emissions and 36% of global final energy use (Global Status Report 2017). The two major ways to respond to climate change is by reducing the environmental impact of the building infrastructure and bracing for the impact of climate change that is already occurring.

Sustainable buildings minimise the impact on the environment by increasing efficiency and focus on self-sufficiency in terms of energy. Sustainable construction techniques employ an approach which is sensitive towards the site context of the built environment and this can eventually help in reducing the environmental impact.

In this study, the influence of growing crops on the facade and its impact on the building's energy performance is analysed. Research indicates, integrating agriculture into the built environment has the potential to significantly reduce fossil fuel consumption, improve urban ecology, enhance food safety and security, enrich the lives of city dwellers and conserve building energy (Gould & Caplow, 2012). This master thesis intends to explore the potential of Vertically Integrated Greenhouses (VIG) on the energy performance of the building. The greenhouse on the facade acts as a solar collector and this energy is stored in aquifers for later use. The potential of Aquifer Thermal Energy Storage (ATES) system is also investigated in this research.

1.1. Background

1.1.1. Climate Change

NASA describes climate change as the change in average conditions such as rainfall and temperature in a region, over a period. Earth's climate was constantly changing but in recent years, it has changed drastically due to human activities (NASA, 2018a). Human activities such as burning fossil fuels, cutting down trees and farming livestock are increasing the concentration of greenhouse gases. These changes cause the atmosphere to trap more heat than it used to, leading to a warmer Earth.

The built environment has the potential to reduce fossil fuel consumption and improve the environment. Aspects of built-environment include transportation systems and infrastructure, building construction and operation, and land-use planning (Gould & Caplow, 2012). Among these, construction practices are one of the major contributors to environmental problems. In the Netherlands, the building sector accounts for 14% of carbon emissions (Donat, 2013). Because of the long life of the buildings, it affects the environment and society for many years. The primary cause of the CO_2 emission in buildings is the energy used to provide heating, cooling, lighting, water and other building management facilities (Younger et al., 2008). Sustainable practices have been introduced in the building construction sector to address these environmental concerns.

1.1.2. Resource demands in agricultural sector.

Worldwide, agriculture occupies 40% of the land surface, uses 60 % of freshwater and causes up to 32 % of GHG emissions (Bellarby et al., 2008). With the rise in agriculture business, transportation and food preservation techniques, the distance between the farms and markets have increased significantly. These food miles, from ‘field to fork’, is highly unsustainable in the long run. Growing, packaging and distributing fruits and vegetables consume much energy. The energy for this comes from fossil fuels, and this leads to the emission of greenhouse gases. That, in turn, leads to climate change.

Food security and resilience

Food security is ensuring all people across the globe have access to sufficient food to meet their dietary requirements. Diminishing agrarian lands, loss of biodiversity, changes in climatic patterns and hydrological cycles due to the emission of greenhouse gases will have consequences for food security (Ericksen et al., 2009). With traditional farming practices and current consumption patterns, the cultivable land available will not be enough to produce sufficient food (FAO, 2017). In order to improve resilience and food security, building integrated agriculture (BIA) methods could be adopted.

Land use

Currently, 1.5 billion ha of the Earth’s land is allotted for agriculture, which is 11% of the total land area (Crop production and natural resource use, n.d.). Increase in the global demand for agricultural products is determined by 70% population growth and 30% by per capita income growth (Alexandratos, 2012). This increase in demand leads to an expansion in the arable land and this expansion is done sometimes at the expense of nature. The United Nations Food and Agricultural Organization (FAO) in its statistics show that the availability of arable land will decrease to one-third of what was available in 1970 (FAO, 2016). Also, intensive farming practices have depleted the soil of its nutrients and caused irreversible damage to the land (Astee & Kishnani, 2010; Hillel, 1991). Deforestation has increased in the recent past due to land-use development and agriculture. Deforestation increases atmospheric CO_2 and promotes climate change. Scarcity of the resources would demand us to preserve resources for future generations through environmentally responsible and sustainable use.

Energy

The transition from traditional farming to industrial was a result of the increased demand (FAO, 2017). It was supported through the rapid growth of farming technology. However, the usage of technology led to an exponential rise in the consumption of energy throughout the value chain. The increased production capacity is aided using fertilizers, pesticides, which are produced using fossil fuels (Woods et al., 2010). Transportation and food miles reduce the sustainability aspect when the product has to be brought from rural areas. On average, a food item travels 2400 km before it reaches the plate (Cho, 2015). This extensive transportation has great energy implications. Long transportation leads to altering the quality of food for longer shelf life. Food miles are reduced when production is brought closer to consumption which reduces the energy requirement hence lowering the carbon emission due to transportation (Astee & Kishnani, 2010).

Water

Agriculture uses 70% of the world's available freshwater, after which it becomes unsuitable for drinking as a result of contamination with fertilizers and pesticides (Despommier, 2009). New techniques such as hydroponics and aeroponics use 70-80% less water than conventional systems. Hydroponics is a farming strategy which does not use soil but grows food in nutrient-rich water. The hydroponic system uses four times less water compared to conventional farming for the same yield (Ziegler, 2005; Astee & Kishnani, 2010).. An additional benefit of the hydroponic system is a faster growth rate which increases the yield and the elimination of chemicals (Nelkin & Caplow, 2007). Adopting such modern techniques can reduce the water demand of the agricultural sector to a large extent.

1.2. Research Objective

The principal objective of this thesis is:

- To explore the impact of VIG on the energy consumption of an office building

1.3. Research Questions

Based on the problem statement, the following research questions are formulated. The main research question is:

What is the impact of VIG on a high-rise building?

The sub-questions are:

1. What is the impact of VIG on the energy consumption of EEMCS building?
2. What is the value of integrating ATES systems with VIG system?
3. What is the impact of VIG system on the carbon emissions?

1.4. Research Method

1.4.1. Background study

Initial study was conducted through academic documents and past research papers. Two of the main contributors of carbon emission, agricultural sector and built environment which leads to climate change was chosen and researched. The initial study was useful in narrowing down the topics.

1.4.2. Problem definition

Based on the initial study, the issues with conventional farming techniques and the energy consumption by the energy-inefficient buildings were investigated. Different techniques to address climate change in the agricultural sector and built environment were researched in the literature study to frame the research objective and the research questions.

1.4.3. Literature study

The significance and the relevance of urban farming techniques and different types of building integrated agricultural practices to address the energy inefficiency in buildings were looked up. Along with this, assessment methods to calculate the energy consumption of spaces was studied for the calculation purposes. Energy storage and producing techniques were looked into to reduce the system's dependency on fossil fuels.

1.4.4. Data collection and analysis

The current energy consumption data of the case study building, EEMCS was collected from the Real Estate Department of TU Delft (CRE). Also, the current design of the facade was assessed to understand the reasons for its inefficiency. This data was later used to compare the energy consumption of the building after the integration of VIG.

1.4.5. Excel model and calculations

Based on the literature study done in the initial stages, the VIG design parameters were chosen. Calculations were done to assess the energy requirements due to the integration of VIG using an excel model. Additionally, from a climate change mitigation point of view, the carbon footprint of such a system was compared to the current scenario. Along with this, methods and designs to reduce the carbon emissions such as rainwater harvesting, and aquifer thermal storage techniques were incorporated in the design and calculations.

1.4.6. Analysis of the result

Based on the calculations, the new energy demand of the building was calculated and later compared with the data collected to see the impact of the VIG system on the building's energy. A carbon footprint comparison was done to assess the carbon emission impact in both the cases.

1.5. Research Relevance

1.5.1. Scientific relevance

The aim of the research was to analyse impact Vertically Integrated Greenhouse systems on the energy consumption of the building. Understanding the energy balances in a greenhouse was an important step in calculating the energy demand of such systems. The research is, therefore, related to the energy balance and how the energy requirement can be estimated. The design principles suggest how it can be applied in other office renovations and the potential of thermal energy storage through ATES in combination with VIG. It is expected that the results of this research will help in implementing more VIG systems for energy storage and food production in office buildings.

1.5.2. Social relevance

The research investigates the impact of having facade greenhouses on the energy consumption of the building. Energy-efficient office renovation is a challenging task. Implementing green on the facade is expected to have an impact on sustainable office design and better work environment and thereby improving the productivity of the employees. This kind of strategy aims to increase productivity and reduce environmental footprint by producing local food in the urban environments, cutting costs and environmental damage by eliminating transportation and delivering products directly to consumers.

2. Literature Study

2. Literature Study

In this chapter, different topics that were explored during the initial study is briefly discussed. There are 6 section in this chapter starting with the definition of sustainable building in Section 2.1 followed by a method to make buildings more sustainable by integrating agriculture in the buildings in Section 2.2. Section 2.3 explains the VIG system used in the thesis along with the types of vertical greenhouse systems. Section 2.4 gives a brief introduction about thermal storage techniques followed by the explanation of ATES system which is a type of thermal energy storage. In the last section, the working of the heat pumps is explained.

2.1. Sustainable buildings

Sustainable buildings require a holistic, integrated, and multidisciplinary approach. Sustainable building design is also known as green design or high performance buildings. According to Miyatake (1996), the proposed principles for a sustainable building includes minimization of resource consumption, maximization of resources reuse, use of renewable and recyclable resources, protection of the natural environment, creating a healthy and non-toxic environment, and pursuing quality in creating the built environment. Most of the research in this field revolves around energy and water savings and environmentally friendly technologies to reduce the carbon emissions (Wang & Adeli, 2014).

A building uses energy throughout its lifespan. Different phases in which a building uses energy are production or retrofitting stage, operation stage and end-of life. Among these, the operational stage accounts for the biggest energy use in the life cycle of a typical building (Ramesh et al., 2010). The energy used for operation could be for space heating, domestic hot water, electricity for ventilation, fans, pumps and lighting, and cooling. Among these, space heating accounts for the largest share of the operational energy in today’s buildings. To achieve significant reduction in energy consumption, innovative technologies should be implemented, including renewable energy.

2.2. Building Integrated Agriculture

The elements of truly sustainable cities incorporate assessment of the energy, water and land consumed during food production, processing, storage, preparation, distribution and disposal (Five ways to make cities healthier and more sustainable, 2020). One method of implementing this is through Building Integrated Agriculture (BIA). Worldwide, agriculture occupies 40% of the land surface, uses 60 % of freshwater and causes up to 32 % greenhouse gas emission (Bellarby et al., 2008). The depletion in the available land has led to the utilisation of rooftop space and building facade for agricultural purposes in the urban areas. If planned and designed well, integrating agriculture into the built environment has the potential to significantly reduce fossil fuel consumption, improve urban ecology, enhance food safety and security, enrich the lives of city dwellers and conserve building energy (Gould & Caplow, 2012). The growth of urban farming is rather striking. Although not a new idea, it seems to have accelerated since the latter half of the 20th century primarily due to the population growth and the popularity of the cities (Miigle+, 2019).

The global population is expected to exceed 9 billion by 2050; 6.4 billion of those people are expected to be urban dwellers (ESA, 2007). To feed this growing population, an additional 1 billion hectares of land is required (Tilman et al., 2001). Vertical designs can maximize the use of land, an essential factor in the denser world we are approaching (Fischer et al., 2012). By the inclusion of such systems in the urban environment, urban spaces get used more efficiently; not only for social and infrastructural purposes but also to produce food.

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. They are designed to exploit synergies between the built environment and agriculture. Installations typically include features such as recirculating hydroponics, waste heat captured from a building's heating, ventilation, air condition (HVAC) system, solar photovoltaics or other forms of renewable energy, rainwater harvesting systems.

FAO estimates that an additional 70% (FAO, 2010) of agricultural production is needed to fulfil the dietary requirements of the population. In the future, clean, healthy and increased yield can be addressed with modern agricultural techniques such as soil less farming. Hydroponics is a farming strategy which does not use soil but grows food in nutrient-rich water. Such strategies have been found to provide increased yields while also eliminating harmful chemicals (Nelkin & Caplow, 2007). This increased yield can be attributed to the reduced resource demands (such as water) of the system as well as the smaller space required for this technique (Turner, 2009; Astee & Kishnani, 2010).

The important aspect about vertical farming is that the arable area of crops can be increased by construction on multiple stacked layers on the same footprint of the land (Benke & Tomkins, 2017; Despommier 2010). All year-round production and methods to maximize the growth due to the controlled environment can be achieved in this kind of system. Because this system is relatively lighter, it does not add too much burden to the existing structure and act as an ideal fit for retrofitting in buildings (Nelkin & Caplow, 2007).

The start-up costs for these kinds of systems are quite high (Benke & Tomkins, 2017). The food produced in such systems adds to the supply of fresh and local food which otherwise travels for longer distances (Puri & Caplow, 2009). Due to urbanization, the transportation and distribution of food require extensive infrastructure. An estimation by Lester Brown of the Earth Policy Institute states that two-thirds of the energy used for growing food is used for transporting it (Wilson, 2009).

Vertical farming is a new agriculture method of growing crops in high-rise buildings. The idea of vertical farming originated due to the limited access to agrarian land in urban areas. It has the potential to produce food sustainably in urban areas, and it could help in solving problems regarding food production and environmental degradation (Kalantari et al., 2017). It also has other benefits like reduction in the transportation cost and environmental footprint, improves food safety, enhances energy management of the building envelope and improves the physical and psychological comfort for building occupants. Another benefit of integrating or combining agriculture into the built environment is potential for an exchange of oxygen and carbon dioxide between crops and building occupants (Gould & Caplow, 2012).

2.3. Vertically Integrated Greenhouse

One of the innovations currently under study is the patented Vertically Integrated Greenhouse (VIG). It is a type of BIA where a highly productive, lightweight, modular, climatically responsive system for growing vegetables on a vertical curtain wall facade. The research on VIG was done by an interdisciplinary team led by New York-based BrightFarm Systems, with contributions from the fields of ecological engineering, plant science, architecture and HVAC engineering (Caplow et al., 2008).

Vertically Integrated Greenhouses is a technology of growing crops/plants in vertically suspended trays. The design is particularly well-suited for installation in a Double Skin Façade (DSF) of a building, or in an interior atrium or lobby. This system not only reduces the energy use but also increases indoor comfort in high rises by proving a second insulating layer of glazing. It provides solar heat gain, buoyancy-driven cooling flows, protection for external solar shades, and sound insulation (Kiss et al., 2010). In some cases, it also allows the opening of inner windows. This convenience enhances personal comfort and local climate control but is unavailable on traditional high-rise facades due to wind pressure and stack effect. But with advancement in technologies, these concerns can be addressed and studied in the initial design stage.

A Double-Skin Facade (DSF) consists of a vertically continuous void space enclosed by a second curtain of glazing over the entire facade. It provides solar heat in winter, and buoyancy-driven cooling flows in summer, and permits opening windows year-round. In the building sector, the double-skin facade is an innovation that can reduce the energy used for space conditioning in modern high-rise buildings by up to 30% (Gould & Caplow, 2012). Another study by Gratia & De Herde (2007) says that the cooling demand always increases with the addition of DSF. Despite these advantages, DSF applications remain limited due to economic concerns and the need to install an extensive shading system within the cavity to reap the full benefits (to avoid overheating to reduce the cooling demand). Growing greenhouse crops in the cavity add a financial return to the base case for a Double Skin Facade. This kind of strategy aims to increase productivity and reduces environmental footprint by producing local food in the urban environments, cutting costs and environmental damage by eliminating transportation and delivering products directly to consumers.

Figure 1: VIG render: strawberries in a high-rise cafe, Source: Kiss + Cathcart.

The VIG system combines DSF with hydroponic food production for installation on or in high-rise buildings, and as a potential retrofit on existing buildings. In a typical VIG design, a glazed curtain wall (a ‘double skin’) is located 1.5 m outside the southern facade.

Crops are cultivated in the cavity within the DSF, on an array of horizontally suspended trays (Figure 1), on two cables. Cables are looped around a pulley driven by a computerized motor. The seeds are germinated in 2 m long trays (Figure 2), at the bottom level and planted into bottom trays. These trays can then rise and pass over the pulley and can be brought back to the bottom for harvesting. The vertical alignment of the trays can be controlled by a slight turn of the pulleys, allowing the VIG to track solar elevation in real-time. The VIG functions alternatively as an adaptive solar energy capture device and a natural shading system in winter and summer, respectively. In addition to producing food, the installed plants in effect reduce building maintenance costs by providing shade, air treatment and evaporative cooling to building occupants (Adams & Caplow, 2012).

The building envelope is an essential element that impacts the thermal comfort and energy balance. Having a Vertically Integrated Greenhouse (VIG) on the facade could potentially be an innovative strategy in achieving high levels of energy-saving in the building. Integrating farming practices into the buildings have the potential to conserve energy (Gould & Caplow, 2012).

Despite these advantages, the double skin facade remains within economic constraints. The investment and energy cost are higher, but the production per cultivable unit area of a greenhouse is also higher than conventional farming due to the vertically stacked trays (yield per m^2 is higher). However, the yield and value are higher as it is grown in a highly controlled environment. And because of this highly controlled environment, the system is low maintenance and low workforce dependent.

The biggest challenge of VIG is the overheating in summer. Ventilation is the primary tool in dealing with this. Adopting a hybrid ventilation system allows this and helps in energy conservation with the HVAC system. Studies show that the interior temperature of a double skin is usually lower if plants are used instead of blinds (Feng & Hewage, 2014). Through the growing of crops indoors or under glass, a protective environment is created, which increases resilience to calamities.

A VIG system could potentially insulate the building from thermal losses and contribute to the improved performance of the double-skin facade due to the presence of plants. In addition to this, the heat storage and recovery system could prove beneficial to reducing energy loads. One of the main reasons to use DSF in a temperate climate is due to its effect on the heat load. The solar radiation entering the glass transforms the radiation into heat. This heat that is trapped in the cavity warms up the air creating convective airflow. This mechanism is beneficial as the heat losses through the inner skin are reduced, and this warm air can also be supplied to the interior, whereas cooling savings can be achieved either by supplying fresh air without (or with little) mechanical help or by extracting heat from the indoor space through stack effect.

2.3.1. Types of VIG configurations

The system comprises a set of trays, a tray suspension system to which the trays are attached, a water distribution system comprising a reservoir, a pump and a water supply tube. The suspension system comprises a drive train and a means to adjust the positions of the trays.

There are two types of suspension systems. Pulley Cable System (Figure 2) is the type in which trays can be raised and lowered individually or as a set. The trays may be collapsed one on top of the other when the greenhouse is not actively used. This would allow for daylight to enter the office space. Hence it is also called the collapsible system. Conveyor system (Figure 2) can move the trays in a circular loop while maintaining a constant distance between the trays.
Apart from the two configurations in the patented VIG system, double skin can be used to grow unconventional crops, tall plants and creepers as the vertical height is much higher and permits the growth of these plants in the cavity (Figure 3). This could be an advantage over plant factories and small vertical gardens and the verticality of the cavity could be taken advantage of. Figure 4 shows tall plants like peppers grown in the DSF.

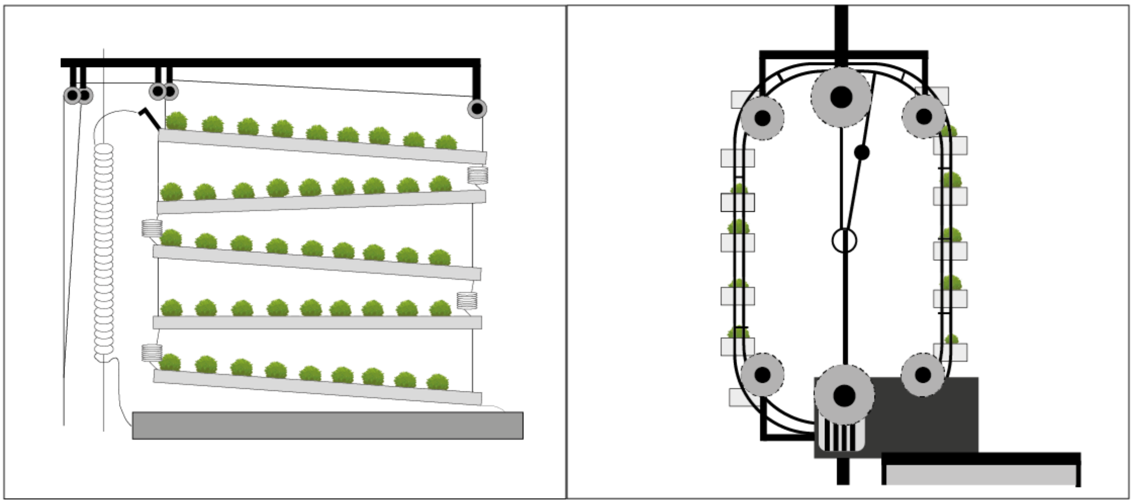

Figure 2: Pulley Cable System and Conveyor System

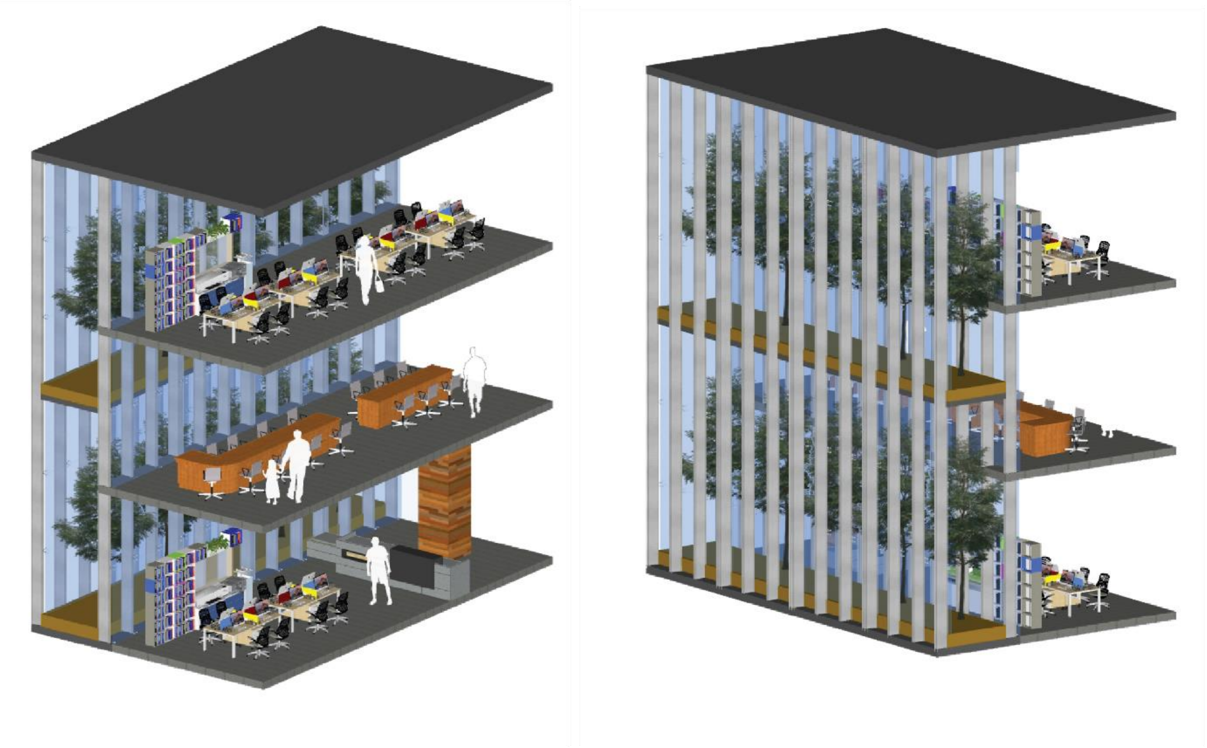

Figure 3: Tall plants and tress grown in the cavity of DSF.

Figure 4: Vertical facade farming with tall plants in the cavity
Source: (Ramachandran, 2019)

2.4. Thermal storage techniques

Thermal energy storage (TES) systems have shown economical and environmentally friendly solutions to energy problems. Carbon dioxide emission and fossil fuel usage can be reduced significantly with the development of TES systems (Paksoy et al., 2004). The different sources of heat are solar, geothermal, fossil fuel power plant, nuclear power plant, industrial waste heat and biomass.

The need for a thermal storage is because of the time difference between thermal energy generation and consumption, the distance between the source and place of consumption or the difference in cost in peak and off-peak hours.

Based on the frequency of the storage cycle, there are two types of systems, diurnal which includes Underground Thermal Energy Storage (UTES) and solar ponds. In the UTES, solar thermal power plants and seasonal/long duration thermal energy storage which includes water tanks, pits, aquifers and boreholes are the different types. The closed cycle is also called Borehole Thermal storage (BTES) and the open system is called Aquifer thermal energy storage (ATES).

2.5. Aquifer Thermal Energy Storage

There has been a growing interest in the past decades in energy-saving solutions as well as renewable energy sources such as solar or wind energy. The use of the subsurface to provide heating and cooling to buildings, greenhouses and industrial processes is a lesser-known sustainable energy technology. This is achieved by using the subsurface as a heat sink, or as a storage medium for thermal energy. During winter, the warm groundwater from the aquifer can be used to warm the building while extracted cold is stored in the aquifer to be used in summer. During summer, cool groundwater is used to cool the building while extracted heat is stored in the aquifer for use in winter (Sommer, 2015).

In ATES systems, storage and recovery of thermal energy in the underground is achieved by injection and extraction of groundwater into and from water-saturated subsurface formations (aquifers). ATES uses electricity only for pumping the water between the wells and for the heat pump needed to raise the temperatures to the required level if necessary. Even this electricity can be produced sustainably.

The ATES system consists of two groundwater wells, called doublets. This system commonly operates in seasonal mode. One well is used for the storage of cold and the other for the heat. In the summertime, cold groundwater is extracted from the aquifer using the cold storage well and directed through a heat exchanger to provide cooling to the building. This heats the groundwater, which is subsequently injected back into the aquifer through the warm storage well, typically at a depth of 100 or 200 meters (Sommer, 2015).

Hydrogeological and hydro chemical conditions of the area must be suitable for ATES. There should be a critical distance between the cold and heat well. This distance is necessary to avoid thermal breakthrough (mixing of both the wells). The critical distance depends on operational and thermohydraulic parameters involving the well production rates, the aquifer thickness, and the hydraulic and thermal properties that control the storage volume (Lee, 2010). One of the other challenges with the storages are the long duration and the amount of energy that needs to be stored. Long storage duration spanning several months leads to thermal losses (Alva et al., 2018).

The two types of system are closed source and open-source system. The open-source system is further divided into three types, high-temperature range (60^o C - ~90^o C), medium temperature range (30^o C - 60^o C), low-temperature range (< 30^o C). However, in this study a low-temperature open-source system is adopted, within the limits prescribed in Dutch regulation (Dutch Policy on ATES Systems 2, 2016).

2.6. Heat pumps

One of the challenges in these kinds of systems are the duration and the amount of energy stored. Long storage duration leads to thermal losses. Therefore, these systems work best in combination with heat pumps.

The main components of a heat pump are compressor, reversing valve, indoor heat exchanger, expansion valve, outdoor heat exchanger (Figure 5). In heating mode, the refrigerant leaves the compressor as a high pressure, high temperature vapour and passes through the reversing valve. Since the reversing valve is placed in heating mode, the refrigerant passes through the reversing valve to the indoor (heat exchanger) unit. Cool air is blown over the heat exchanger to remove some of the thermal energy and provide heating to the room. As heat is removed, the refrigerant will condense into a liquid. Having given out some of its energy, the refrigerant leaves as high pressure, slightly cooler liquid. The refrigerant then comes to the expansion valve, it expands in volume and turns into a low pressure, low temperature liquid-vapour mixture. The refrigerant then heads to the outdoor heat exchanger, the fan blows the outside ambient air over the heat exchanger (HE) coil adding heat to the cold refrigerant. The refrigerant boils at a very low temperature and as it boils, it carries away the thermal energy. It picks up the thermal energy and leaves the outdoor heat exchanger a low pressure, low temperature slightly superheated vapour and heads back to the reversing valve. From there to the compressor to repeat the cycle. The opposite happens in the cooling mode, where it acts like an air conditioner.

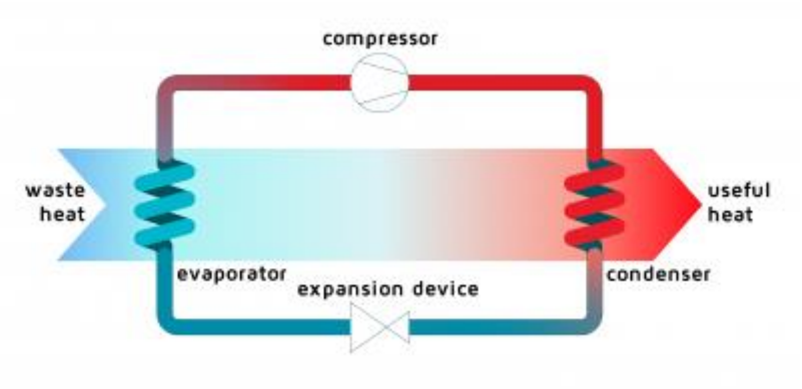

Figure 5: Components of a heat pump system
Source: (Industrial Heat Pumps, n.d.)

Electricity is used by the compressor to send refrigerant around the system and capture the heat from outside and bring it inside. The reason for the very low electricity demand for this is because the refrigerant has an extremely low boiling point (eg: R134a - Boiling point - -26ºC).

3. EEMCS Building

3. Case study Building

In this chapter, the case study building is discussed. Section 3.1 gives a brief introduction about the building followed by the current energy consumption of the building in section 3.2. The reason to choose this building for the thesis is discussed in the section 3.3.

3.1. Introduction

The Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) is located on the TU Delft campus (Figure 6). Delft is in temperate climate zone (Latitude: 51.9988° N and Longitude: 4.3735° E). The two dominant features are precipitation and wind. Rainfall is distributed evenly throughout the year. The construction of the EEMCS, synonymous with EWI in this report, dates back to the 1960s. It has three main buildings, a high-rise office building with the lower two storeys reserved for educational facilities, a low-rise educational building and a high voltage lab. However, only the first three storeys are used for educational purposes while the upper floors are used for office work.

Figure 6: EEMCS building

The high rise has a cellular office layout. A typical floor has 14 office rooms on the East side and 10 rooms on the west side (Figure 7). The west side has the lift well and lavatories. However, for the energy balance calculation, only the office space is considered.

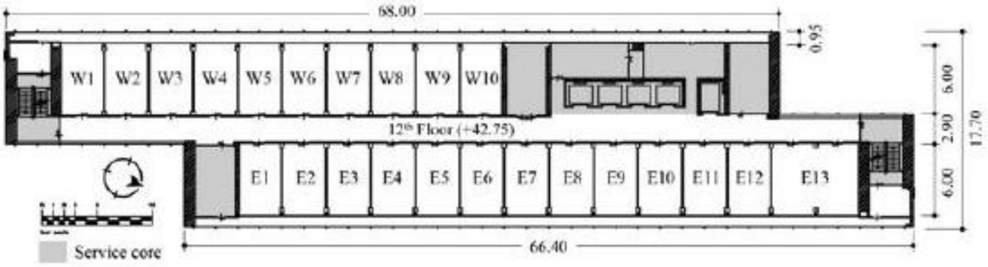

Figure 7: Floorplan of EEMCS
Source: Raji, 2018

The building's current envelope is a Double Skin Facade (DSF). The DSF consists of single-pane tinted glass with a steel frame for the outer leaf and single-pane clear glass in a fixed window with a wooden frame for the inner leaf and an air cavity between the two layers. The 95 cm width cavity of the facade is horizontally continuous along the length of the facade, but vertically segmented at each floor. Electric venetian sun blinds are installed in this cavity closer to the external glazing and that can be controlled manually by the occupants.

In summer, the cavity in the facade is ventilated with outside air, but for most of the year, the air inlets are kept closed to minimise heat loss in cold weather. The entire building is ventilated mechanically. The ventilation for the offices is separated from that of the cavity. The fresh air to ventilate the cavity is brought in from the centre of the facade and sucked out with the help of fans at the ends of the cavity (Figure 8). Ducts in the second leaf of the facade bring in fresh air for the office rooms. The stale air passes through openings in the dividing walls and is extracted from the corridor.

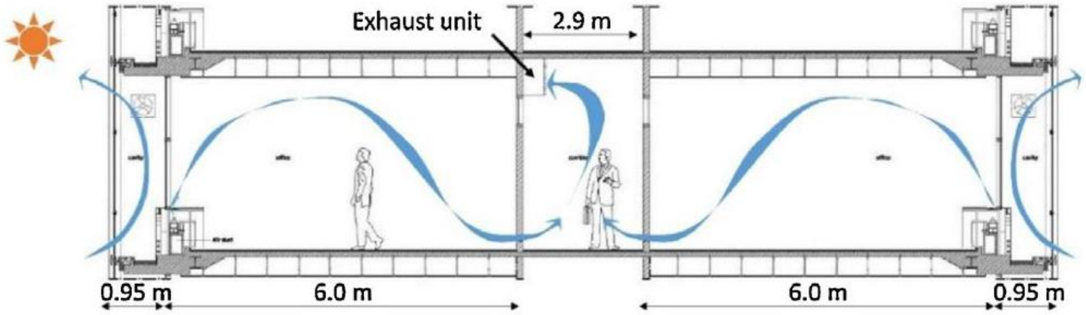

Figure 8: Cross-section of the case study EEMCS building with air flow patterns in the facade cavity and the internal spaces. Source: Raji, 2018

3.2. Current energy demand

From the data obtained from the Campus and Real Estate (CRE), the current energy consumption of EWI building is 2069 MWh of heating and 1775 MWh of electricity which includes the energy for cooling and the electricity required for running the mechanical equipment and lighting. Based on the data in Babak Raji's (2018) PhD dissertation, 17 kWh/m^2 of energy is used for cooling and 46.6 kWh/m^2 is used for running the heat pump, lights and fans. Based on this proportion, 1554 MWh is used for cooling.

3.3. Why EWI?

The building sector accounts for 14% of carbon emissions in the Netherlands (Donat, 2013). The emission of greenhouse gases has raised concerns about our energy systems and a shift towards energy-efficient strategies. The built environment has the potential to reduce fossil fuel consumption and improve the environment. The facade is the architectural element which separates the interior from exterior. It plays an important role in the thermal comfort and energy balance inside the building. The building facade performance influences the energy required for heating, cooling, lighting and ventilation (Planas et al., 2018).

Buildings have life cycles, and they need to be maintained and renovated periodically to keep it alive. The life cycle of the primary structure and the faced elements are different. There are buildings (facades) which have not met it is intended lifespan. Retrofitting these facades of the existing building stocks is a key to achieving lower energy consumption as better performing materials and systems could reduce the energy demand of the building. Furthermore, facade renovation can reduce energy consumption by up to 50% (Energy-efficient Buildings, 2011).

The iconic EEMCS building in the Delft University of Technology is one of the tallest buildings in Delft. This building is chosen as a representative of skyscrapers in densely populated areas. Skyscrapers have potential to incorporate VIG systems and they have the potential to maximize the usage of such systems. The replicability of the VIG system can help in identifying the outcome at scale. The facade design responsible for the high energy consumption is explained below.

The cavity and office space are ventilated separately using outside air in summer. Since the air supply ducts (for ventilating the office space) are placed on the facade, the chilled air is preheated before it enters the ducts. This lowers the efficiency of this cooling system. Therefore, there is a high electricity demand for cooling.

With respect to heating, it consumes more than 60% of its energy for heating (Raji, 2018). This proves that the facades are underperforming. The DSF should be acting as a thermal buffer. However, due to high infiltration, ventilation of the cavity with the outside air and poor performance of the single glazing, there is a high heating demand. There are also radiators installed below the single glazing along the hallway, which means a lot of heat is lost through the thin glass layer. The energy performance of the building is low, and measures to improve its energy performance is addressed in this research. Additionally, the given resources and constraints, only EWI building was accessible for its data and hence this building was chosen as the case study building.

4. System Design

4. System Design

This chapter provides an overview of the components involved in the system design. The assumptions made to do the calculations are discussed in Section 4.1. Section 4.2 explains the different energy fluxes used in the energy balance equation. Following this, a brief introduction about the type of hydroponic system used in this design is discussed. Section 4.4 consists of the formulae used to do the thermal energy storage calculations along with the COP of heat pumps. In Section 4.5, the system configuration is explained.

4.1. Assumptions

Few assumptions were made in the initial design stage to make the calculations simplified.

- Since the building is vacant in the night, no heating or cooling is provided from 8 p.m to 6 a.m.
- Only the elements with high thermal mass were considered in the indoor temperature calculation; the thermal mass of air, concrete and glazing is considered.
- For the thermal mass of air, ‘thick air’ is considered, which is 1.2 times the thermal mass of the air to account for furnitures and other objects in the room.
- The temperature of the node is assumed to be equal to the operative indoor temperature.
- The hot well size is determined based on the amount of surplus heat in the VIG in summer. To match the size of both the wells to avoid thermal breakthrough, the cold well size is made similar to the hot well.
- The hot well temperature is set to 25°C and to account for the dissipation losses in the aquifer, recovery efficiency of 75% is assumed. And the cold well temperature is set to 8°C.
- COP of the heat pump is based on the set temperatures of the wells.
- The air temperature in the room for the time step of one hour is assumed to be constant.

4.2. Energy fluxes

A systematic model-based approach could reveal the performance of buildings and various installation components. This can help in understanding the thermal problems and the impact of new applications in the early design stages (Spoel, 2017). Simplified physical principles are formulated to draw up the heat balance equations to calculate the energy demand.

The energy conservation law is the basics of solving heat transfer problems. In a non-stationary situation, the temperature and heat fluxes vary with time and the sum of all the flows from and to the surrounding areas must add up to zero. The term used for such an area is called ‘control volume’. To draw up the heat balance in a control volume, all the heat flows need to be considered (Figure 9). The ones having positive sign indicates incoming heat (towards the control volume) and negative sign indicates outgoing heat flux (equation 1); it is a flow of energy per unit of area per unit of time.

Application of energy conservation law helps in determining the energy required to maintain.
a comfortable temperature range in the control volume. The different fluxes considered in this control volume are discussed below:

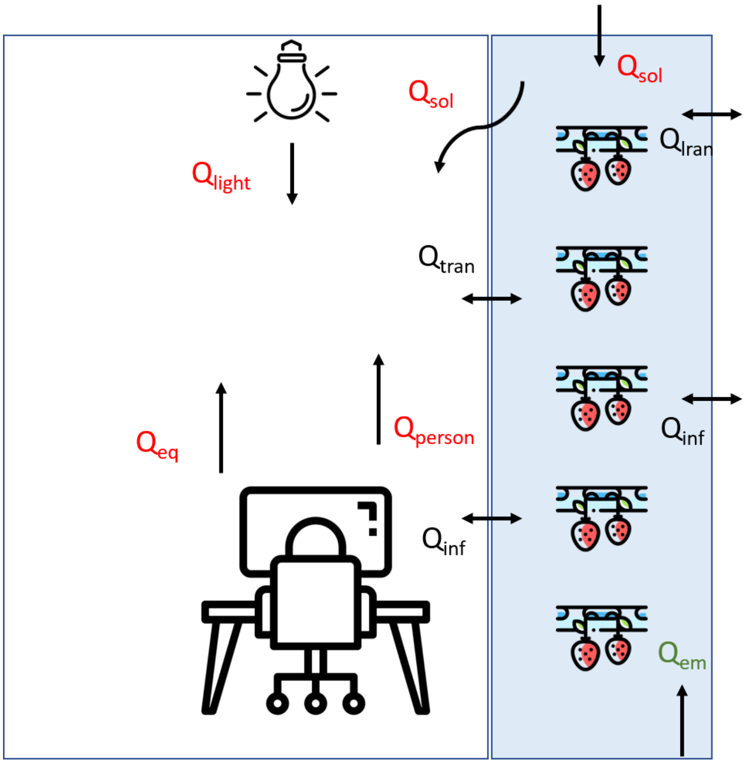

Figure 9: Energy fluxes involved in a two-space model with an office space and a vertical farm.

$$Q_{sol} + Q_{int} - Q_{em} - [(H_{inf} + H_{tran})*(T_{i(t-1)}-T_{o(t-1)})] - \frac{\Sigma M.dT}{dt} + Q_{(Heating/cooling)(t-1)} = 0 \quad ....(1)$$

Each of these terms will be explained in the subsection from 4.2.1 to 4.2.6.

The total height of the VIG is 72 m. It is on the East, South and West facade. Two sections of 36 m each with 1.5 m cavity width is considered in the design. However, for calculation purposes, only one floor height of 3.6 m is considered. The energy fluxes inside the greenhouse are explained in the following subsections from 4.2.1 to 4.2.6

In practice, the greenhouse starts heating when the sun starts shining, even in cloudy weather. It is a closed greenhouse system. If the outgoing energy fluxes are smaller than the sum of incoming and internal energy fluxes, the temperature in the greenhouse will increase. After the setpoint temperature (25 ° C), which is the ideal temperature range, cooling needs to be activated (the surplus heat is extracted for storage and later use). If the outgoing energy fluxes are larger than the sum of the incoming fluxes and internal heat flux, the temperature inside will decrease. Below the setpoint temperature of 15° C, heating is activated.

The indoor temperature of the EWI building is maintained between 18 °C and 24 °C between 6 a.m and 8 p.m (office working hours), beyond this, no external energy is provided to the building.

4.2.1. Solar gains

The solar radiation received is calculated by considering the position of the sun. This method is typically used to calculate the amount of solar irradiance received by the solar panels and in this case, the facade surfaces are considered as PV modules. The position of the facade (module) is given by the direction of the module normal, in the horizontal coordinates (A_m, a_s) (Figure 10).

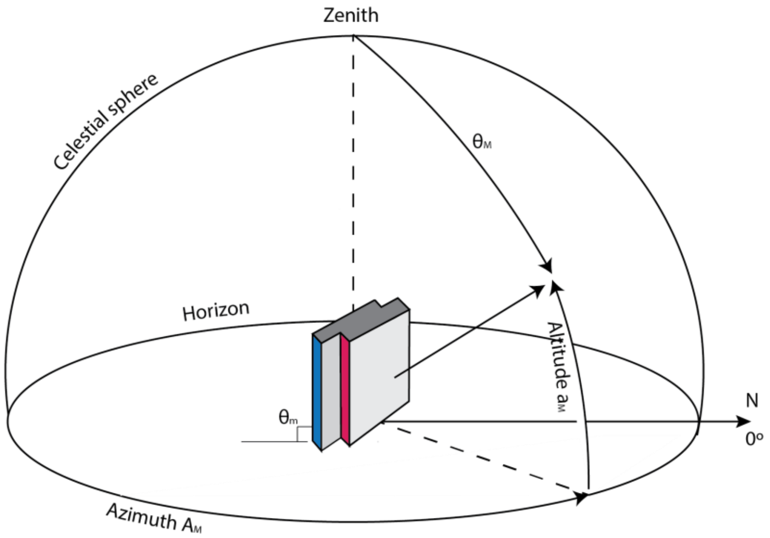

Figure 10: Case study building orientation and its angles to the sun and the horizontal, used to compute solar gains.

Solar gains are calculated as the sum of direct and diffused solar radiation received by each facade. The $G_m\mathbf{dir}$ value is calculated for East, South and West façades separately based on the azimuth (A_s/A_m) and altitude (a_s/a_m) of the facade and Sun. In the horizontal coordinate system, the position of the Sun is given by the solar altitude, a_s and solar azimuth, A_s. The climate data obtained for the calculations are from the NEN 5060.

$$G_m\mathbf{dir} = I_{dir}\,((\cos a_m * \cos a_s * \cos(A_m - A_s)) + (\sin a_m * \sin a_s)) \qquad ....(2)$$

$$SVF = \frac{(1 + \cos\theta m)}{2} \qquad ....(3)$$

Where, Azimuth A_m is the angle between the projection of the normal of the facade onto the horizontal plane and due North. The main facade of EEMCS has an East orientation (Figure 11). It is counted eastward, such that A_m= 67°, 157°, 247° corresponds to East, South and West, respectively. VIG is not installed in the North facade as the solar radiation received by the North is relatively low and is inefficient to add artificial lighting to meet the additional lighting requirements.

The $G_m\mathbf{dir}$ value is calculated for each hour based on the position of the Sun. I_{dir} is the direct normal irradiance (DNI), also received from the weather data. Θ_m is the angle of the facade makes with the horizontal plan and a_m is the altitude of the facade, given by $a_m = 90 - \Theta_m$; Since Θ_m is 90°, a_m for all the sides remain as 0°.

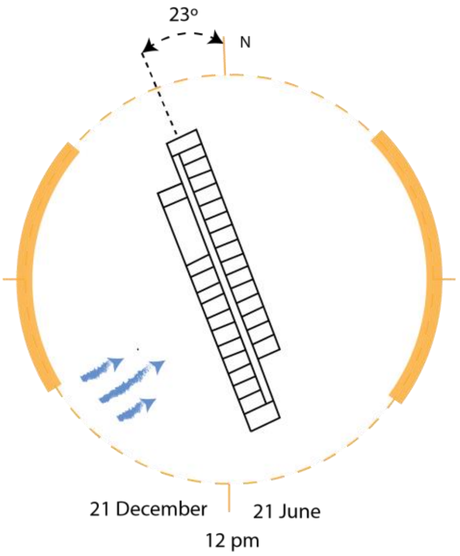

Figure 11: Orientation of the Case study building EEMCS.

$$Q_{sol} = [G_m; \mathbf{dir} + (G_m; \mathbf{diff} * (SVF))] * A * g \quad .... \quad (4)$$

Where,

Q_{sol}	Solar gains [W]
g	Solar heat transmittance coefficient; g = 0.5 (SG)
A	Total surface of glass facade in [m^2]
G_m;**dir**	Direct Solar radiation [W/m^2]
G_m;**diff**	Diffused Solar radiation [W/m^2]
SVF	Sky View factor

The solar gains for the office space is calculated the same as the VIG. However, a reduction factor of 0.5 is assumed for the office space to account for the obstruction due to the trays and plants in the 1.5 m cavity.

4.2.2. Internal gains

The internal heat gains are due to the heat released by the lighting system and functioning equipment.

Lighting

Greenhouses are designed to admit the maximum amount of solar light energy. This along with water and carbon dioxide is used in the process of photosynthesis to produce plant food. 37 % of the energy in sunlight is within the wavelength useful for photosynthesis. Of the rest, 62.4% is infrared (thermal energy) and 0.6% is ultraviolet (Mccullagh, 1978). One percent of the light received is used for photosynthesis and 10% of the light is reflected and another 10% passes through. The leaf retains 80% and this is mostly used for transpiration. Some of it is re-radiated and the fraction that remains is available for photosynthesis.

Since lighting is an important component for photosynthesis and there is an ideal photoperiod for each crop for maximum growth, artificial lights are used to provide light energy when the daylight is not enough to meet the requirement.

The DLI stands for Daily Light Integral. It is the number of photosynthetically active photons that are delivered to a specific area over a 24-hour period. It is expressed as moles of light (mol photons per square meter per day). The DLI for strawberry plants for optimum growth is 20 $mol/m^2 \cdot d^1$ (Essentials for Growing Hydroponic Strawberries, n.d.). Based on this, the light requirement for each hour is calculated after reducing the amount of natural light received. This gives varying values for each hour. The heat released by the light source is calculated with the help of input power based on the requirement and the efficiency (60%) of the light.

The heat load by the LED lights can be calculated as:

$$Q_{light} = q_{m2} * A_{floor} \qquad ....(5)$$

Where,
Q_{lights} Heat load by lights [W]
q_{m2} Heat load per square meter [W/m^2]
A_{floor} Total tray area [m^2]

Equipment

Heat gain from equipment is an important contributor to the overall heat gain of space. Climate control systems, water distribution systems, exhaust fans are all equipment necessary for the regular working of the greenhouse. Heat gain coming from active mechanical equipment and operational activities is noted by a standard value of 15 W/m^2 (Caat et al., 2021). For this greenhouse, we assume a 24/7 heat gain by the equipment. The heat gains due to operational equipment are given by:

$$Q_{equip} = q_{m2} * A_{floor} \qquad ....(6)$$

Where,
Q_{equip} Heat load by equipment [W]
q_{m2} Heat load per square meter [W/m^2]
A_{floor} Total floor surface area [m^2]

The office rooms are considered to just have 4 computers per room. The heat release due to this is calculated as:

$$Q_{equip} = q_{equip} * n \qquad ....(7)$$

Where,
Q_{equip} Heat load by equipment [W]
q_{m2} Heat load of one computer [W]
n Total no.of computers

People

The heat produced by human activities due to human metabolism provides additional heat in the space.

$$Q_{person} = q_{1person} * p \qquad ....(8)$$

Where,
Q_{person} Heat load by people [W]
$q_{1person}$ Heat load per person [W]
p Total no.of people

4.2.3. Emissivity

Transparent surfaces transmit and absorb the solar radiation falling on it. But non-transparent surfaces only absorb and reflect the solar radiation. These surfaces heat up due to the absorbed radiation and transmit heat and can have an impact on the greenhouse's energy balance. This released thermal energy depends on the difference between indoor temperature and sky temperature. The sky temperature is calculated as the fourth square root of the product of atmospheric irradiation and Stefan-Boltzmann constant. It is denoted by Q_{em} [W/m^2].

$$Q_{em}=F_{sky}*\varepsilon_{glass}*\alpha_R*(T_{in}-T_{sky}) \quad \text{..........(9)}$$

$$\alpha_R=4 * \sigma * T_{in}^3 \quad \text{.........(10)}$$

Where,

Q_{em}	Emissivity [W/m^2]
α_R	Heat transfer coefficient [W/(m^2.K)]
ε_{glass}	emissivity of the glass; ε_{glass} = 0.97(SG)
σ	Stefan-Boltzmann constant [W/m^{2}K^4]; $\sigma = 5.67 \cdot 10^{-8}$
F_{sky}	Sky view factor**;** F_{sky}=0.5
T_{sky}	Sky temperature [°C]
T_{in}	Indoor temperature [°C]

$$\text{v} \quad T_{sky}= \sqrt[4]{(q_{sky} * \sigma)} \quad \text{......(11)}$$

$$q_{sky}=\sigma*T_e^4*(a+b\sqrt{p}) \quad \text{......(12)}$$

$$p= RH*P\_max \quad \text{......(13)}$$

$$P_{max}(t) = 0.61121 * e^{(18.678-Te(t)234.5)*\left(Te(t)257.14-Te(t)\right)} * 1000 \quad \text{... (14)}$$

Where,

q_{sky}	Atmospheric irradiation [W/m^2]
T_e	Outside temperature [K]
RH	Relative humidity of air [Pa]
a	climate-specific constant; a=0.55
b	climate-specific constant; b=0.005

There is a heat loss to the surrounding by a combination of thermal conduction and air leaks through the facade. Whether it is a loss or gain depends on the difference in indoor and outdoor temperature.

4.2.4. Transmission Coefficient

Heat transfer through the facade and roof glazing based on the temperature difference between the interior and exterior, calculated as:

$$Q_{tran}= U * \Delta T * A \quad \text{...............(15)}$$

Where,

Q_{tran}	Energy transfer through the glazing [W]
U	Transmission coefficient [W/m^2 K]. Single glazing = 3; Double glazing = 1.2
A	Total surface of glass facade in [m^2]; (only 80% glazing)
ΔT	Difference in the indoor and outdoor temperature [K]

For the West and East facade, the transmission is not only to the outside but also to the inside of the building as it is attached to the office spaces. Double glazing separates the Office space and the VIG and the outer leaf is single glazing. In this case, the T_{out} in ΔT becomes the inside temperature of the office. Similarly, for the West and East facade of the office, the transmission to the outside is to the VIG.

4.2.5. Infiltration losses/gains

This is the uncontrolled airflow through gaps and cracks. It is caused by wind pressure or/and temperature difference. The heat loss/gain due to infiltration is given by:

$$Q_{inf} = (v_{wind}*i)*A_{fac}*\,ῤ_{air}*c_{air}*\Delta T \qquad ....(16)$$

Where,

Q_{inf}	Infiltration loss/gain [W]
v_{wind}	Wind velocity [m/s]
ΔT	difference between inside and outdoor temperature [K]
i	Infiltration coefficient; i = 0.00008
$ῤ_{air}$	Density of air; 1.21 [kg/m^3]
c_{air}	Specific Heat capacity of the air; 1000 [J/kg.K]

4.2.6. Thermal mass

For any system to be in balance, the total mass going into the system must be equal to the total mass coming out of the system plus the mass stored in the system. The total thermal mass, M [J/K] is the sum of the product of mass (m) and specific heat capacity (c) of all the ‘n’ components present.

$$M = \sum_n (m_n c_n) \qquad ......(17)$$

The components considered for thermal mass are the concrete floors, concrete side walls, hydroponic tray system, glazing and the air. Though the thickness of the side walls is 0.26 m, the thickness for calculating the volume is taken as 0.006 m as thermal storage in concrete happens only up to that depth. In the thermal mass of the office space, the partition walls and the floors are ceilings are considered. The floor is a composite floor consisting of gypsum board, concrete and vinyl sheets. In order to account for the other furniture in the room, the mass of air is multiplied with 1.2 (thick air).

Explicit Euler solution was used for calculating. The advantage of this scheme is that it is very simple, but the disadvantage is that it could cause numerical instabilities if the dT value is not small (Spoel, 2017). In order to check the numerical stability of the model, the following condition needs to be met:

$$\Delta t < \frac{2M}{S}$$

Where,

Δt Time step

M Thermal mass

S Sum of all the heat transfer coefficient

The temperature difference between each time step, dT, is calculated as:

$$dT = (dt * Q_{mass})/M \qquad \text{......... (18)}$$

Where dt is the time step and in this case one hour. And the indoor temperature is calculated as the sum of the temperature of the previous hour and the difference in temperature (dT) between the hours.

$$T_{i(t)} = dT + T_{i(t-1)} \qquad \text{...........(19)}$$

4.3. Nutrient Film Technique (NFT)

Usually, the VIG systems use Nutrient film technique (NFT), which is a well-established hydroponic system (Figure 12). This kind of farming technique uses 70% to 95% less water and 90% less land area while providing 80% more cultivable area (Cho, 2015). NFT is a type of hydroponic system where crops are grown without the use of soil. The nutrient solutions are supplied to the roots of the plants whenever the water level becomes lower than the set value. The nutrient solution that is not absorbed by plants returns to the nutrient tank and is recirculated.

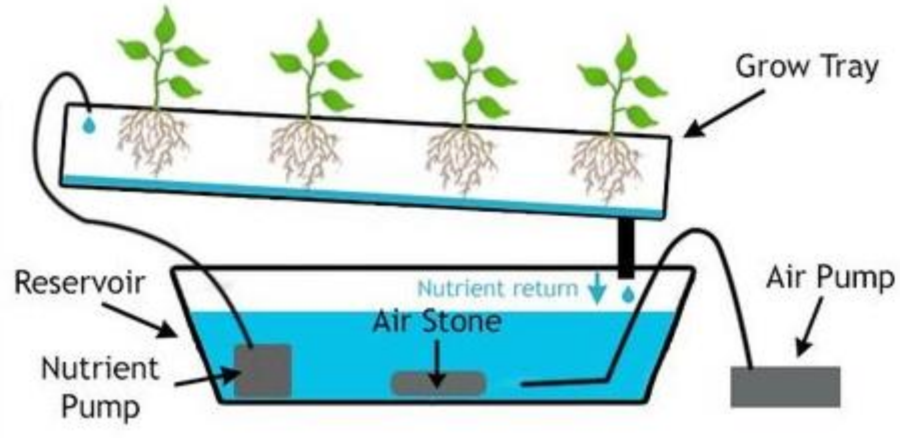

Figure 12: Nutrient Film Technique (NFT)

Strawberry plants require approximately 200 ml to 400 ml per plant per day to prevent it from wilting (Hydroponic Strawberry Irrigation, 2020). This is the water provided for a substrate-based system. Therefore only 70% water requirement is assumed for the NFT system and hence 90 ml/plant/day is provided.

The trays are provided with a slight gradation to permit water to drain. The solution which is not absorbed by the root is collected and drained back to the nutrient tank. It is monitored and adjusted for recirculation. This design is highly efficient as the solution is reused and transpiration is limited up to 10% of the flow rate by design (Kiss et al., 2010).

4.4. Aquifer thermal energy storage calculation

In summer, excess heat in buildings is used to heat water, which is pumped to underground aquifers and in winter, the stored heat is extracted from them; at the same time, cool water is stored in the cold well so that it can be pumped up to cool the building during the summer.

The ATES system is designed to provide a certain yearly energy demand. This amount of energy is distributed over the amount of time steps that is chosen for the model, which is per hour. Since we know the amount of energy that had to be provided, the following equation was used to calculate.

$$Q = m_w * C_{pW} * dT \qquad ....(20)$$

Where,

Q Amount of heat necessary to raise the temperature [W]
m_w mass of water [kg/s]
C_{pW} Specific heat capacity of water [J/(kg °C)]
dT Difference in temperature between the well [°C]

In order to keep the calculation simple, certain assumptions were made. We already know the amount of heat required to heat or cool the building, the specific heat capacity of water was taken to be 4200 J/(kg.°C) and the temperature in the wells were taken as constants. The cold well temperature was taken as 8^{o}C and the hot well temperature to be 25^{o}C. Based on this, the amount of water, m_w was calculated. This indicates the quantity of water that must be pumped to provide the required temperature.

The efficiency of the air-to-water heat exchanger is assumed to be 90%. The thermal recovery efficiency, which is the ratio of energy injected to that retrieved, was assumed to be 75% (Sommer, 2015). The energy recovered is generally lower due to dissipation losses to the surroundings.

Since the well sizes must be similar to have a balanced system, the entire cooling demand of the building cannot be met through the ATES system. Hence, heat pump in cooling mode is used to provide the additional cooling required. In the south facade, 50% of the energy is provided by ATES, in the west and east side 80% of the energy is provided by the ATES and the rest is provided with the help of heat pumps.

4.4.1. COP of Heat pumps

The efficiency of a heat pump is denoted by its Coefficient of Performance (COP). It is the amount of required energy (W, work) in order to produce a certain amount of energy (Q, heat of cold).

$$\text{COP}=\frac{Q}{W} \qquad ....(21)$$

The theoretical maximum efficiency of a heat pump is described by Carnot-efficiency. However, the system efficiency is usually 40% to 60% of Carnot-efficiency. Where, n = 0.5 to finalise the COP. Based on the well temperature, the COP of heat pumps were calculated and tabulated below:

Table 1: COP of the hat pumps used in VIG and EWI.

	COP
VIG	8.3
EWI	13

4.5. System Configuration

The heating and cooling to meet the indoor demand for the spaces are provided through duct systems (Figure 16). Based on non-stationary heat balance, mentioned in section 4.2, the energy demand of the spaces was determined. The amount of energy provided to raise the indoor temperature is the product of the difference between the required temperature and current inside temperature and thermal mass of the space. To lower the temperature to the optimum range, the excess heat is extracted and removed (and stored in the aquifer for later use).

Generally, in winter, heating is required by the building. But, due to high temperatures in the VIG, heat is imparted to the inside of the building. Due to this, the office spaces require cooling at certain hours in winter (Figure 13). During the scenario when there is excess heat that needs to be removed from EWI and the greenhouse requires heating, the EWI provides the excess heat to VIG (through heat exchanger, HE1) (Figure 14). If the greenhouse temperature is not within the setpoint temperatures, additional heating is provided from the hot well of the aquifer.

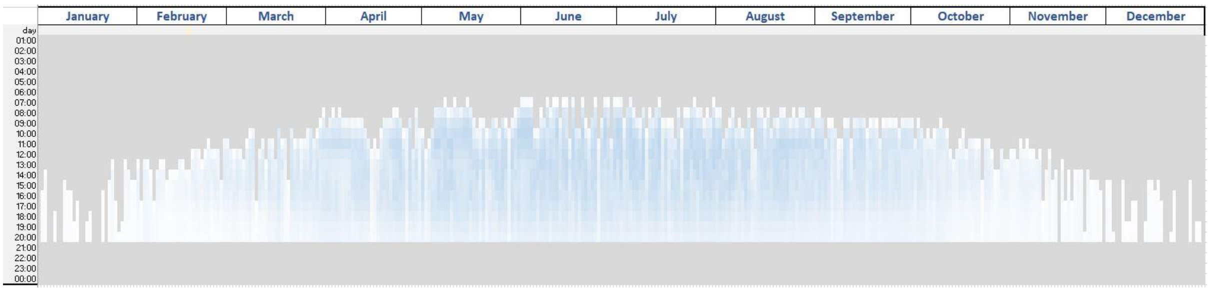

Figure 13: Energy demand of the EWI (west facade). The grey represents no energy needed and blue represents cooling energy.

The hot water from the hot well is pumped with the help of an auxiliary pump (AP1) and exchanges the heat to the air in the heat exchanger (HE2). This heated air is used to provide the additional heating required by the greenhouse. Similarly, whenever the EWI building needs heating, the energy is provided from the hot well to the building.

In summer months, April to September, the cooling is provided by the cold well. The surplus heat is extracted from EWI and VIG and exchanged with the water from the cold well. This heat is stored in the hot well after the exchange through the heat exchanger (HE2). ATES cannot meet the full demand, hence a heat pump (HP1 for VIG and HP2 for EWI) in cooling mode is used to provide additional energy required to maintain the optimum temperature (Figure 14). Figure 15 represents the flow of energy at a particular hour.

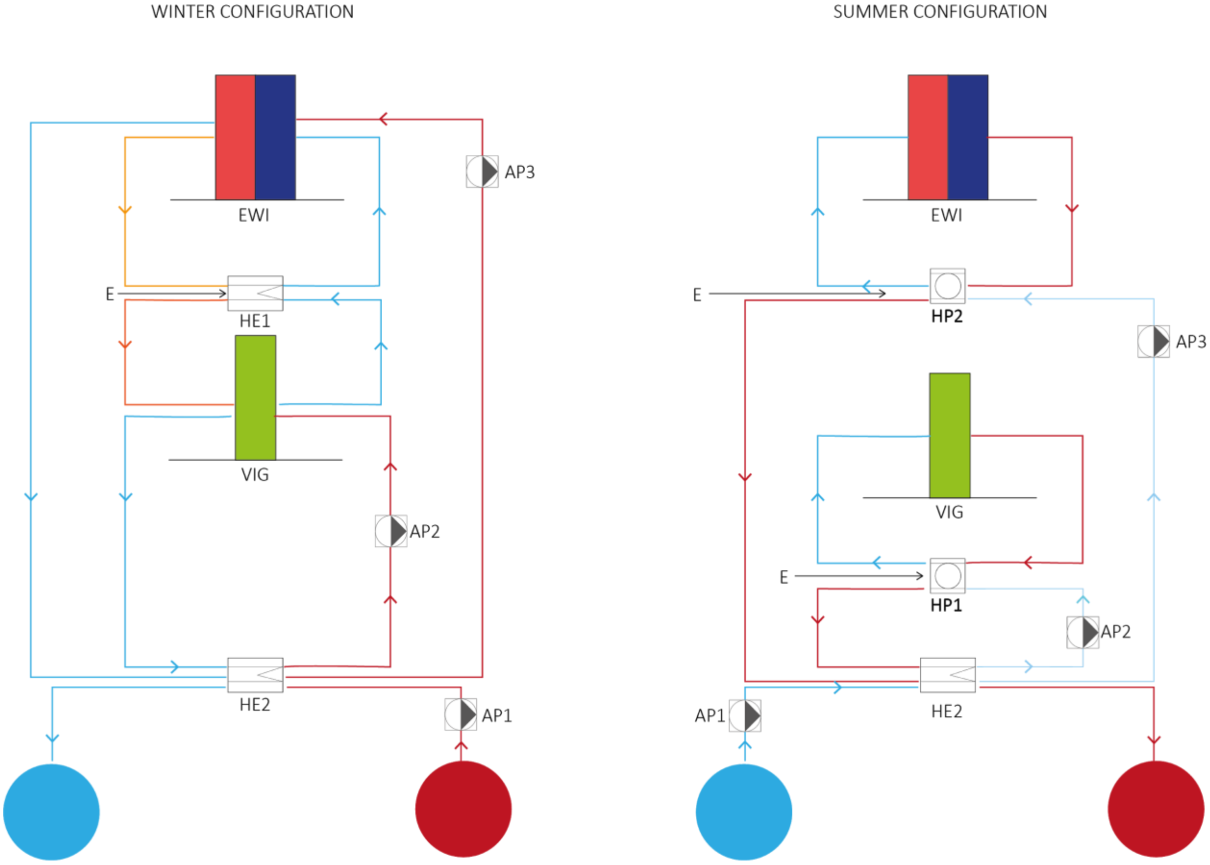

Figure 14: Winter and Summer System configuration - Indicating the energy flows between the EWI office space, the VIG and the ATES system.

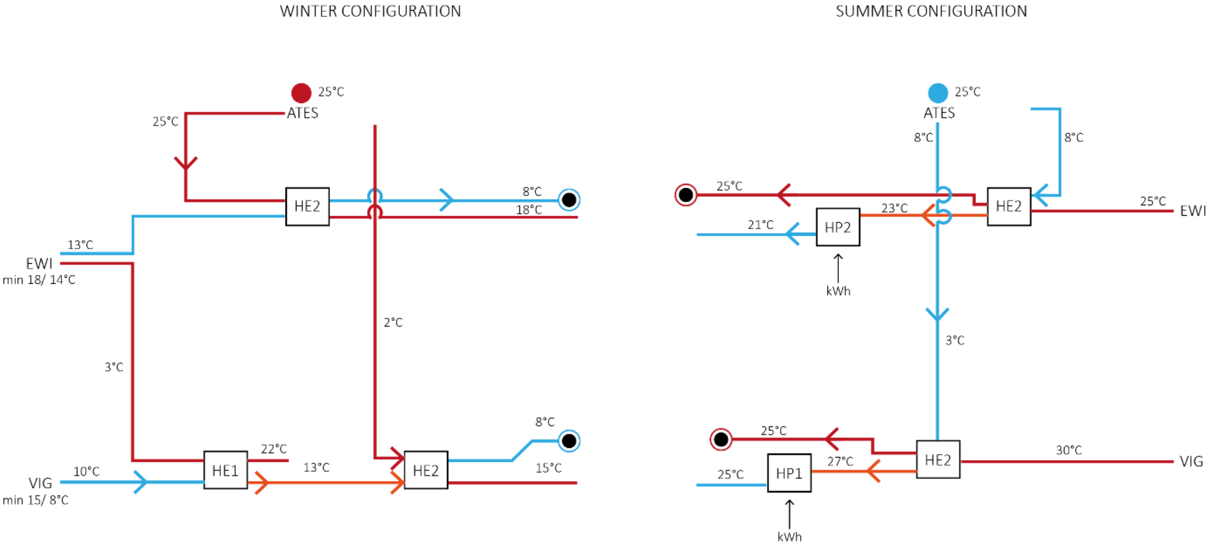

Figure 15: Representation of the thermal energy flows

Figure 16 shows the supply ducts providing warm air in the winter to maintain the optimum temperature for crop growth. The cool air is removes at the top. The office spaces are provided with cool air when the temperature exceeds the set point temperature. Similarly, in summer, cool air provided to the VIG and office space through the supply ducts.

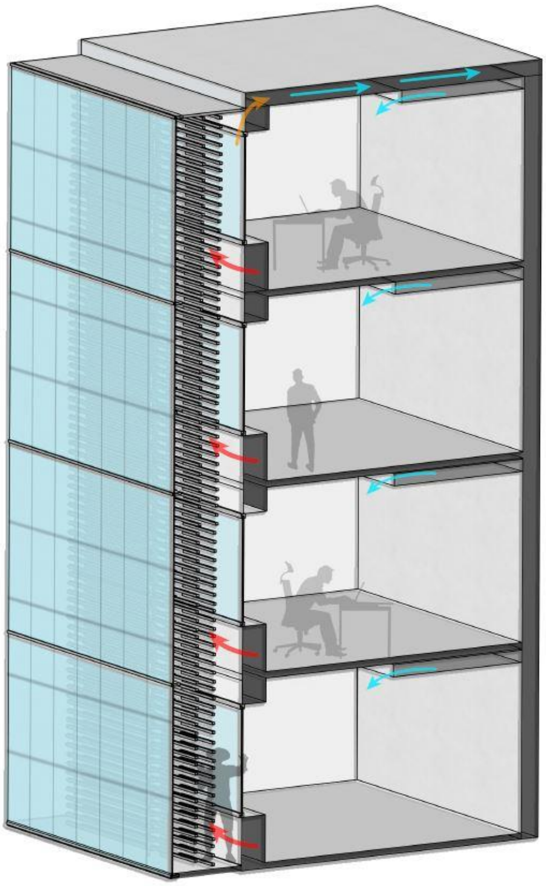

Figure 16: The energy supply to the VIG

4.6. Choice of crop

Strawberry is the 7th most consumed fruit by the Dutch, with an average consumption of 4.9 g/day (Figure 17). Even though it is a summer crop, year-round production is achieved by growing in greenhouses by heating in winter and cooling in summer, to meet the increasing demand.

For maximum yield and high crop quality, the indoor temperature needs to be maintained depending on the cultivated plant species. The ideal daytime temperature (Table 2) is between 15° C and 25° C and night temperature is 8° C and 12° C and relative humidity of 70-75% for strawberry’s growth and development.

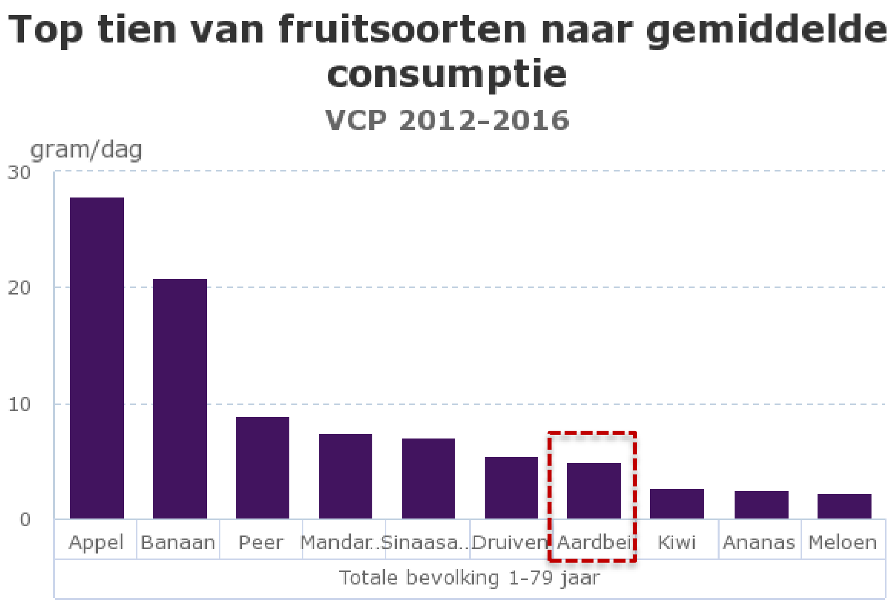

Figure 17: Average consumption of the top ten fruits in the Netherlands
Source: RIVM, 2020

The ideal temperature for Strawberry is tabulated in the table below.

Table 2: Temperature range for growing strawberry

Day Temperature		
T_{min}	15	°C
T_{max}	25	°C
Night Temperature		
T_{min}	8	°C
T_{max}	12	°C

4.7. Carbon Footprint

4.7.1. Introduction

According to WHO, a carbon footprint (CFP) is a measure of the impact your activities have on the amount of greenhouse gases produced through the burning of fossil fuels and it is expressed in CO_2 equivalents (CO_2 eq.). A carbon footprint is measured for the production, use and end-of-life of a product or service. This is based on the Global Warming Potential (GWP), which indicates to what extent a gas contributes to the greenhouse effect. It includes CO_2 and other gases such as methane, nitrous oxide and fluorinated gases (which are converted to CO_2 eq.) which trap heat in the atmosphere.

One of the most effective ways to begin thinking about how to reduce the carbon footprint is to reconsider the ways to make the building more sustainable/energy efficient. Small changes like having a food-producing facade, rainwater harvesting system and better insulation can improve the building's energy efficiency.

A building's carbon footprint is defined as the amount of CO_2 it produces during its operations and activities. There are many contributors to a building's carbon footprint, building's energy use, water use, the embodied energy of the materials used, transportation of these materials to the site are few of them. However, in this study, only the CFP for the energy consumption for the current and future scenario (with the addition of VIG for Strawberry production) is considered. To reduce the CFP of an existing structure, the options are limited. Factors such as orientation or shape cannot be changed anymore. However, renovations to improve the energy efficiency of the building in the use phase can reduce its carbon footprint in its life cycle.

In this study, the carbon footprint of energy use and water requirement by the building and by VIG has been considered. This has been compared to the current energy use and water demand scenario of the EWI building in combination with an offsite conventional greenhouse. Food systems can be described as comprising four sets of activities: (i) producing food; (ii) processing food; (iii) packaging and distributing food; and (iv) retailing and consuming food. In this study, the carbon emission from all these activities is considered.

4.7.2. CO_2 emission of EWI + Conventional GHs

The energy and water requirements of EWI is explained, followed by the global warming potential of strawberries.

Heating

In summer, the cavity in the facade is ventilated with outside air, but for most of the year, the air inlets are kept closed to minimise heat loss in cold weather. But the poor performing single glazing, high infiltration rate and the cavity ventilated with cold outside air increase the heating demand of the building.

Currently, the EEMCS building is heated by district heating and a ground-coupled heat pump. The double skin facade with 95 cm cavity should act as a thermal buffer and reduce the energy demand. However, the values show that it is underperforming.

Cooling

In summer, hot air in the cavity must run to the end of the cavity to be exhausted. Therefore, ventilation in the cavity is hardly working, even with the help of two exhaust fans inside the cavity. As a result, part of the heat is transferred from the cavity to the office spaces through a single pane window increasing the cooling load of the building during summer.

Cooling energy is provided by a ground-coupled heat pump. Air handling units (AHU) are used where a higher cooling demand is required, such as the lecture halls and labs. The cavity and office space are ventilated separately. The air from outside through the cavity is used by the supply ducts placed at the inner facade to provide cool air to the office space. Because of this setup, the intake air gets heated before reaching the ducts. The efficiency of the cooling system is therefore low, and this increases the electricity demand for cooling. A part of the energy is provided by a ground-coupled heat pump and the rest is by the city grid. And hence the total consumption for cooling is unknown. The total energy cooling requirement is included in the electricity consumption value.

Electricity

Electricity use does not cause direct emissions during use. But the factors taken into consideration are CO_2 emissions from the production of electricity and production of the energy carriers used by the power plant. However, only the CO_2 emissions from the production of electricity are considered in this study. The building's electricity consumption includes the energy needed for lighting, pumps and fans (for cooling).

Water

Steps involved in the water chain includes the production of drinking water and the transportation and purification of wastewater which releases greenhouse gases. In this study, the energy required for extraction, production and distribution of drinking water, collection, transportation and treatment of wastewater is considered. The GWP contribution of water for domestic use is 1.5 kg CO_2 eq./m^3 water and this value is used in the calculations (Frijns, 2008). The total water consumption of EEMCS is 3458 m^3 (based on the values provided by CRE).

Strawberry Production

Strawberries are available year-round, but the actual Dutch strawberry season is from June to September. Outside these months, strawberries are grown in heated greenhouses or it comes from abroad (mostly Spain), and could potentially be CO_2 intensive. Strawberries grown in greenhouses in the Netherlands have a higher carbon footprint than strawberries grown in tunnels or open fields in the Netherlands. The carbon footprint of these strawberries is higher than for the strawberries from Spain (More Sustainable Food: Fruit and Vegetables at the supermarket, 2018).

In this study, the global warming potential (GWP) of strawberries is taken as 2.65 kg CO_2/kg (de Valk, 2016). In this, 32 % of this emission is for packaging, distribution, processing/shipment, supermarket and consumers. The rest 68% is from the on-farm energy use (Figure x).

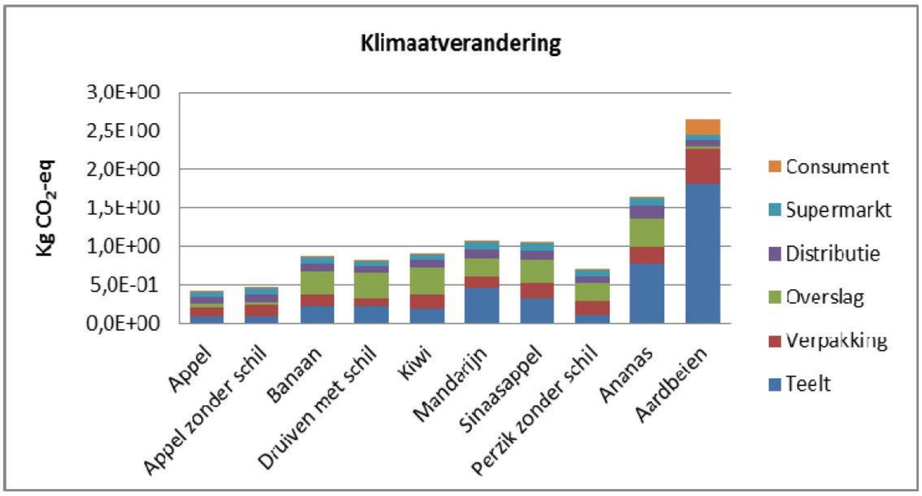

Figure 18: Carbon emissions associated with various stages in the supply chain of fruits, measured in kg CO_2eq. Source:(de Valk, 2016)

4.7.3. CO_2 emission of EWI + VIG

Heating

The heating demand of the building is calculated based on the hourly indoor temperatures. The total heating demand for EEMCS and VIG is 669 MWh, this is two times lesser than what the building currently consumes. This is because the VIG acts as a solar collector and it can maintain a warmer temperature.

Cooling

The cooling demand of the building is 2686 MWh (Table 3). This is 1.7 times more than the current consumption. This is mainly because the temperature goes up and in order to maintain the comfortable range, cooling must be provided. But to maintain the balance between the wells, only a certain percentage of energy can be provided from the ATES and the additional energy is supplied with the help of a heat pump.

Electricity

The electricity consumption is mainly by the grow lights in VIG and the lighting in the office space and the energy to run the heat pumps. This is much lower than a conventional source of energy as the heat pumps has a high COP.

Water

The total water requirement of EEMCS remains the same. Additionally, the water requirement of strawberries is added in this case. The annual water requirement of the VIG system is 5853 m^3. In this, 15% of the requirement can be met through the rainwater collected (Section 7.1.2.2). The CO_2 eq for rainwater is 0.56 kg CO_2 eq/ m^3 (Ward et al., 2011).

Table 3: Final energy consumed by the system.

	Heating Load (MWh)	**Cooling Load (MWh)**
VIG	669	1717
EWI	0	969
Total energy	669	2686
Net energy	**2017**	

4.8. Rainwater Harvesting

4.8.1. Introduction

Rainwater harvesting is the most traditional and sustainable method for conserving water both in residential and commercial buildings. This could reduce the demand for the supply of water and enhance green living. This system offers enough water and lowers energy consumption.

A Rainwater Harvesting System (RWH) consists of a catchment area, storage tank and some treatment options. The design of the system depends on factors such as precipitation rate, duration, frequency, catchment efficiency and the application of this collected water. RWH is a good way to cope up with the change in climatic conditions.

First Flush

Contaminants from the roof surface are usually concentrated at the first runoff. So, this water is used to wash off the roofs and the water collected after this first flush is considerably safer. The reason for this is the accumulation of dust, organic waste, heavy metals from atmospheric fallouts etc. The longer the dry period, the higher the pollutants present in the first flush. Diverting the first flush away from the storage tank can significantly improve the water quality. For areas with low pollution (open fields, no trees, no bird droppings or animal matter, clean environment) diversion of 0.5 litres of water per square metre of roof is done to account for first flush.

4.8.2. Design Calculation

The monthly rainwater yield or the quantity of rainwater that can be collected from a given catchment area is calculated by,

$$Q_m = \Sigma (A \times R_m \times C \times F) \qquad \text{........................(22)}$$

Where,

Q_m monthly rainwater yield [L]
A catchment area [m^2]
R_m average monthly precipitation [mm]
C run-off coefficient for a catchment material
F filter efficiency

The run-off coefficient is 0.9 (Roebuck et al., 2010) and filter efficiency is 0.8.

5. Results

5. Results

Based on the assumptions and methodology describes in Chapter 4, calculations were done, and results were obtained. This chapter is divided into five sections. Section 5.1 talks about the current energy consumption of the EWI building and the future energy demand of the building after the integration of the VIG system along with the influences of different fluxes responsible for the energy demand. In section 5.2, a comparison of the energy consumed in the current and future scenario is done. Section 5.3 discusses the production capacity of the VIG system followed by the results from the rainwater harvesting system in section 5.4. In the final section, 5.5, the carbon footprint calculation results are discussed. A comparison of the carbon emissions caused by the energy used in the current building and future building (EWI integrated with VIG) is tabulated.

5.1. Energy consumption

5.1.1. Current EWI consumption

Based on the data collected from CRE, the EEMCS building consumes 2069 MWh of energy for heating of which 183 MWh is provided through district heating and 2351 MWh is provided by means of a ground coupled heat pump. Similarly, the cooling demand is partially 478 MWh met through a ground coupled heat pump. Additionally, the total electricity supply from the grid is 1299 MWh, of which 221 MWh is assumed to be allotted to lighting, based on standard guidelines of 17% of electricity end use for lighting (Business Energy Advisor, n.d.). The remaining 1078 MWh of energy is provided to meet the remaining cooling demand. This is represented in Figure 19.

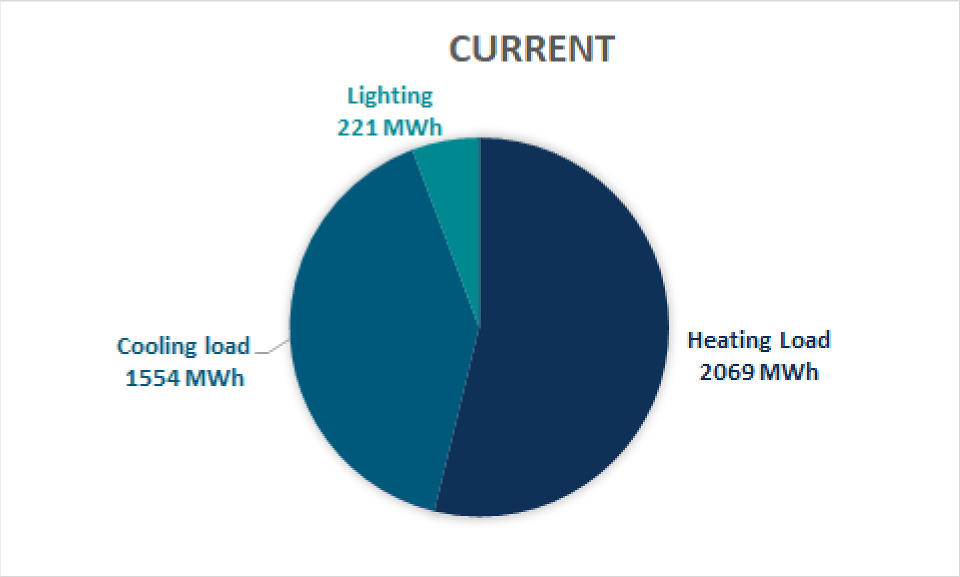

Figure 19: The current energy consumption distribution of EWI building.

5.1.2. Future energy consumption

With the VIG integration, the heating and cooling demand of the combined VIG-EWI system, calculated based on the energy fluxes are 669 MWh and 2686 MWh energy for heating and cooling, respectively (Table 3). The lighting for EWI independently was calculated as the same as mentioned in 5.1.1 (221 MWh) and VIG's lighting demand was obtained to be 1067 MWh.

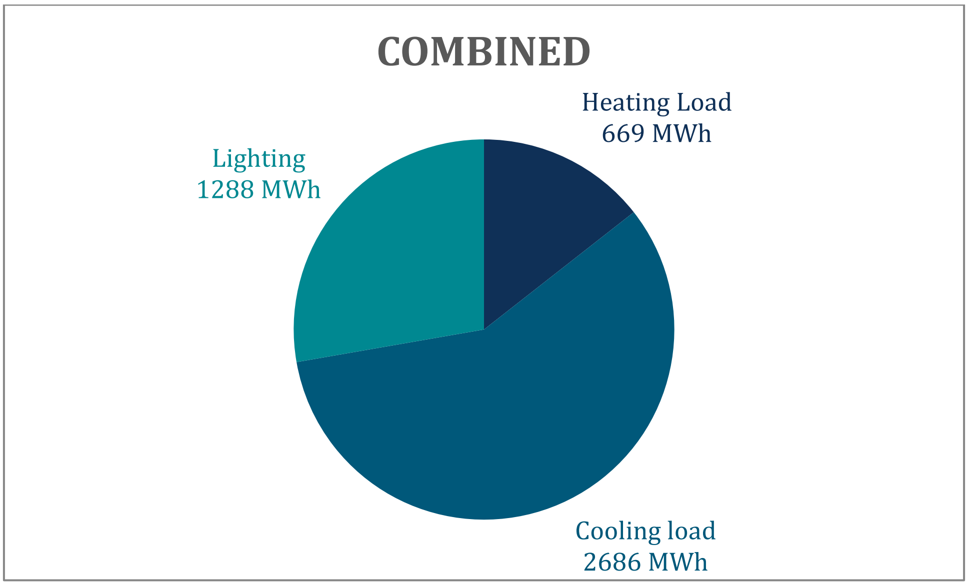

Figure 20: The combined energy consumed (VIG + EWI)

5.1.3. EWI

The corresponding energy fluxes on all three orientations (East, West and South) were summed in 365 * 24-hour matrices. This combined matrix was then used to build 24-hour annual average profiles for each of the energy fluxes. This is represented in figure 21.

Figure 22 shows the monthly averaged heat fluxes for the three orientations in the energy balance. This is done to understand the influence of each parameter on the indoor temperature.

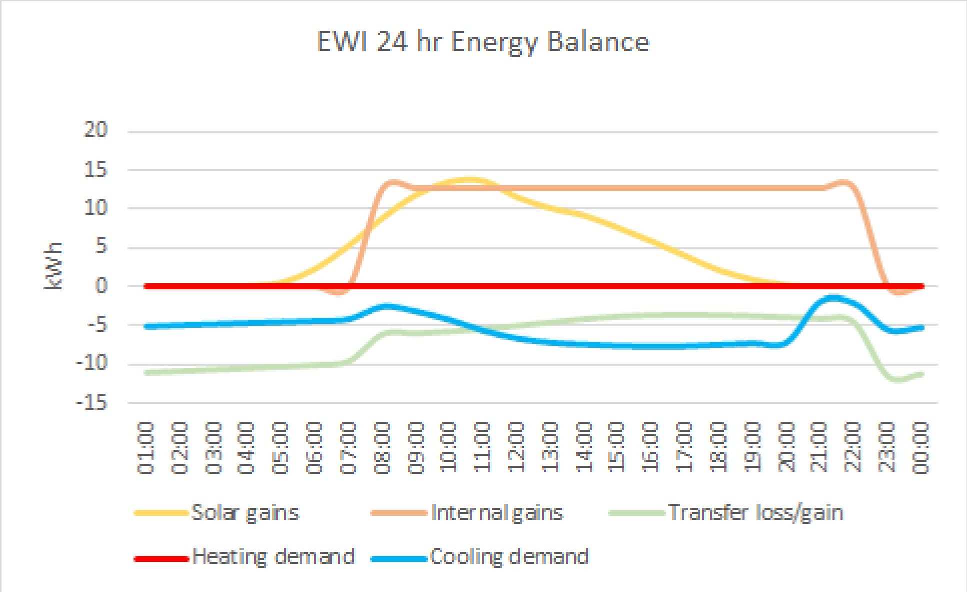

Figure 21: The annual averaged 24 hour energy profile based on the energy fluxes through the EWI office spaces.

The solar gain increases during the day and decreases as the sun disappears below the horizon. The internal gains from 6 a.m to 8 p.m remain as a constant as this is the office working hours. The transfer losses depend on the temperature difference between the inside and outside, the negative value indicates that the heat is lost from the inside to the outside. This indicates that the indoor temperature is higher and hence the cooling demand to maintain the optimum temperature levels.

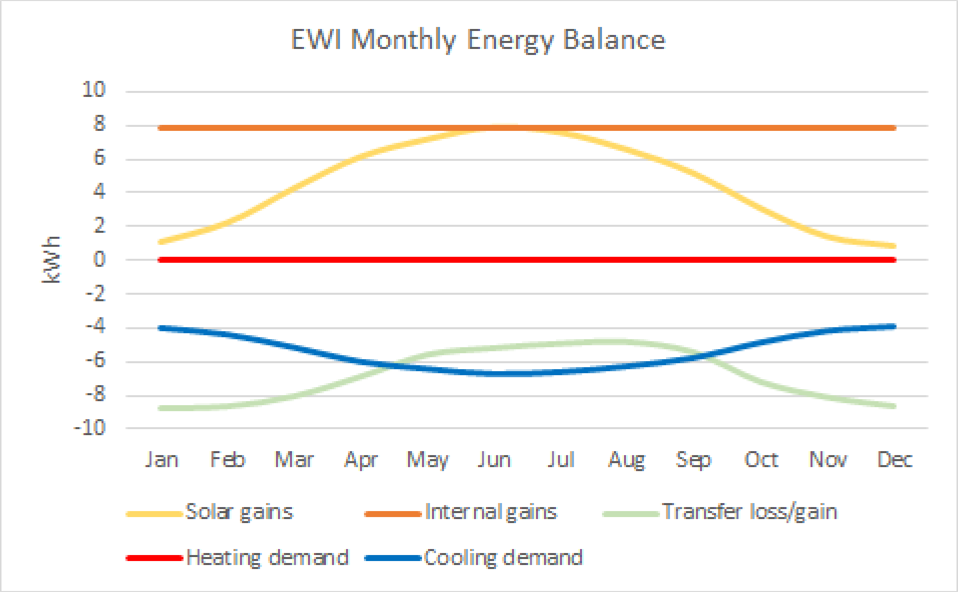

Figure 22: Monthly distribution of energy fluxes in the EWI building in kWh.

In the monthly average of the heat fluxes, the solar and internal gains seem to be dominating in summer, and to combat this, the cooling demand is higher in the summer months.

The heating demand is zero as the building is warm throughout the year due to the greenhouse surrounding the building, transmitting heat to the inside. Hence, the cooling demand is high, 969 MWh of energy.

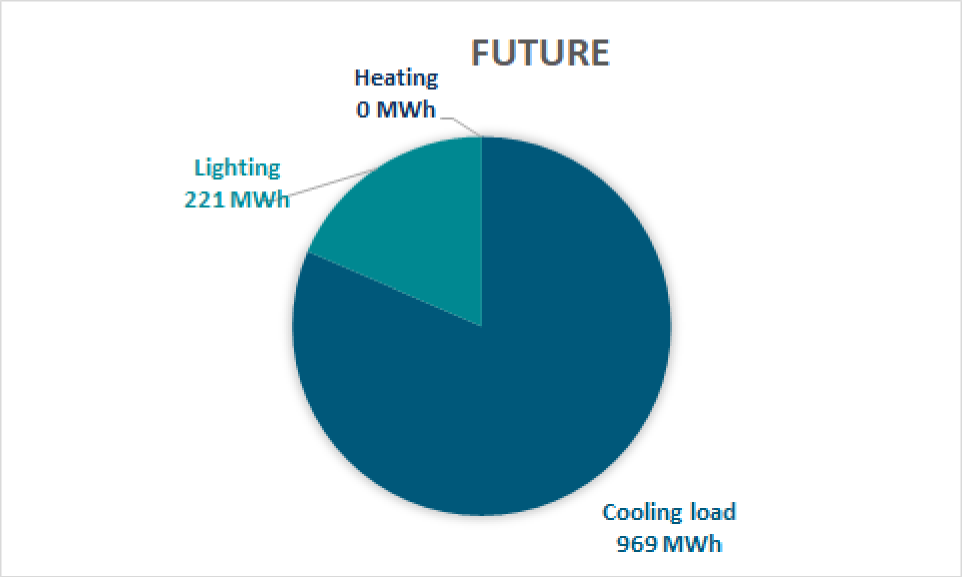

Figure 23: EWI’s energy consumption distribution after the integration of VIG

5.1.4. VIG

The different heat fluxes that have an influence on the energy balance of the greenhouse is represented below in the annual averaged 24-hour profile and in the monthly averaged figure 24. In figure 25, the sudden peak and drop in the heating between 5 a.m and 7 a.m and 8 p.m and 10 p.m is due to the set point temperature as mentioned in section 4.6, table 2. In figure 25, solar energy seems to be the dominant factor and cooling is done to maintain the comfortable temperature range for the plants.

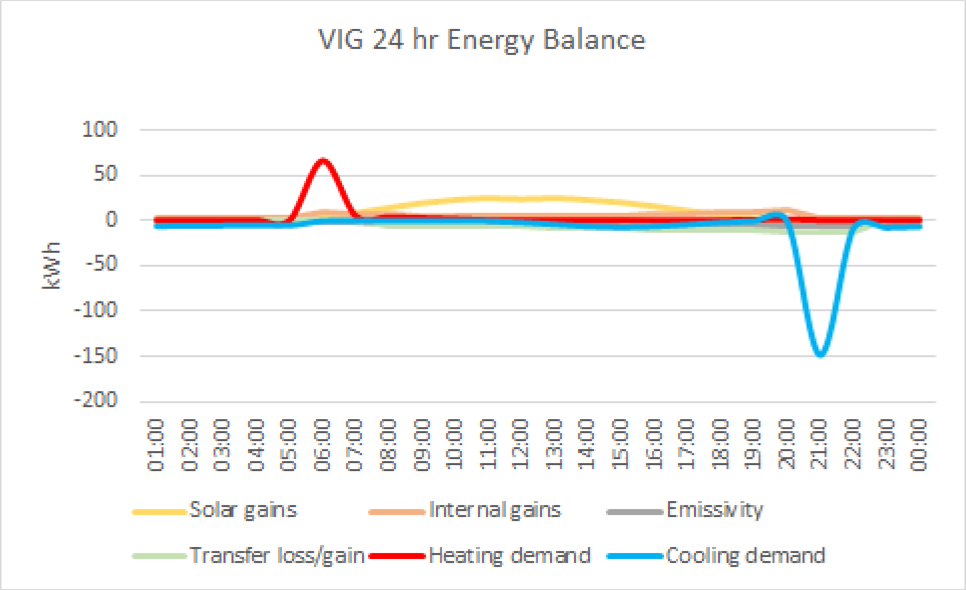

Figure 24: The annual averaged 24-hour energy profile based on the energy fluxes through the VIG.

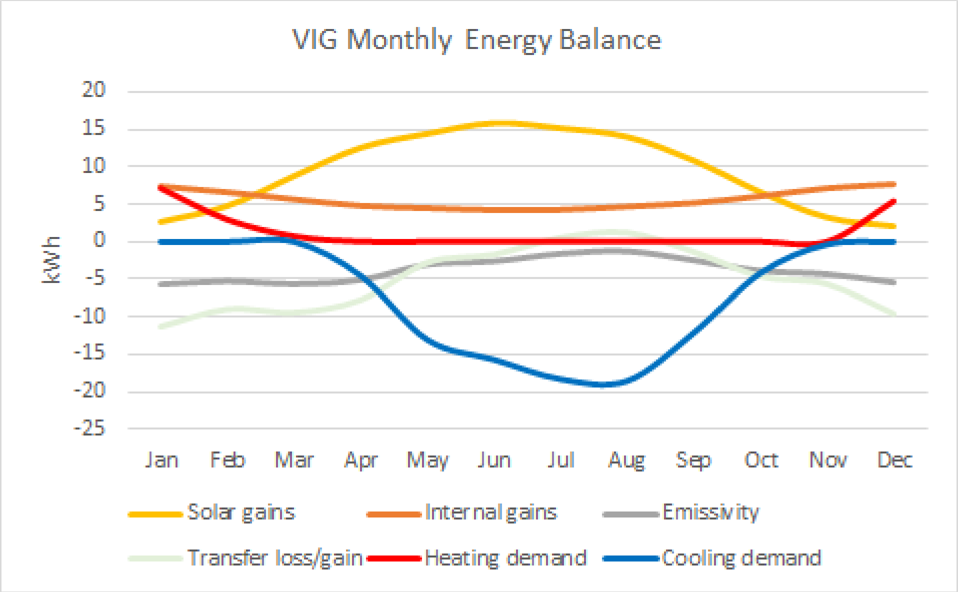

Figure 25: Monthly distribution of energy fluxes in the VIG in kWh.

The heating energy consumed by the greenhouse is 669 MWh of energy and 1717 MWh of energy for cooling. The strawberries require a minimum photoperiod of 12 hours, to provide this, artificial lighting is provided, and the electricity required to provide the lighting is 1067 MWh of energy (Figure 26).

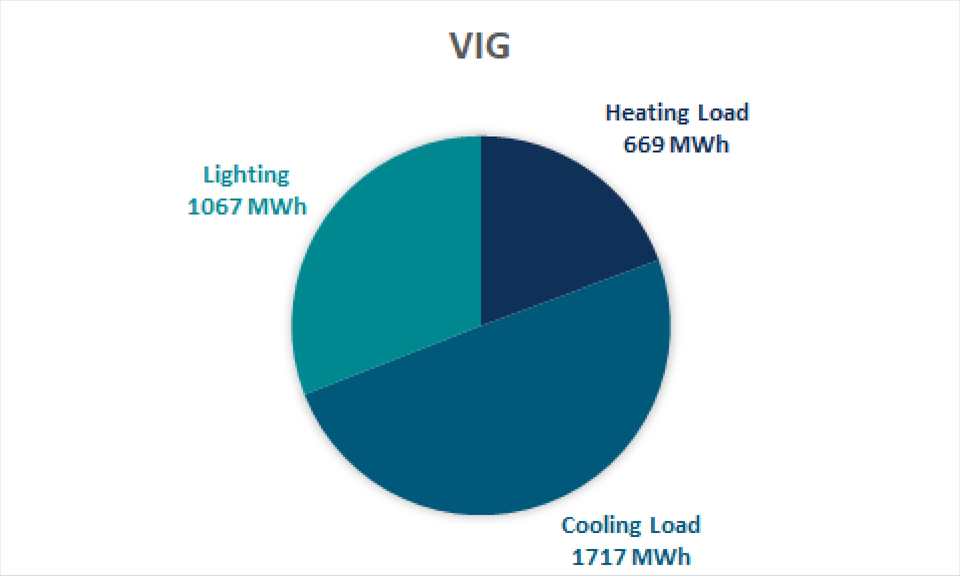

Figure 26: Energy consumption distribution of VIG

5.2. Comparative study of energy consumption

The total heating and cooling energy consumed by the new system is 669 MWh and 2686 MWh respectively. The greenhouse traps the heat whenever there is solar radiation, and the additional supply is reduced. Due to the same reason, overheating happens and this is the reason for the high cooling demand. An ATES is used to provide the heating and cooling to avoid the dependencies on non-renewable sources for energy. With the aquifer well size designed, it is not possible to provide all the cooling, and the additional energy is provided with the help of a heat pump. Electricity is used for the provision of the energy for the heat pumps in winter (as there is a cooling demand in winter) and summer, as well as the energy consumed by the lighting system. A comparison of heating, cooling and electricity demand of the current and future (EWI integrated with VIG) scenario is shown in figure 27.

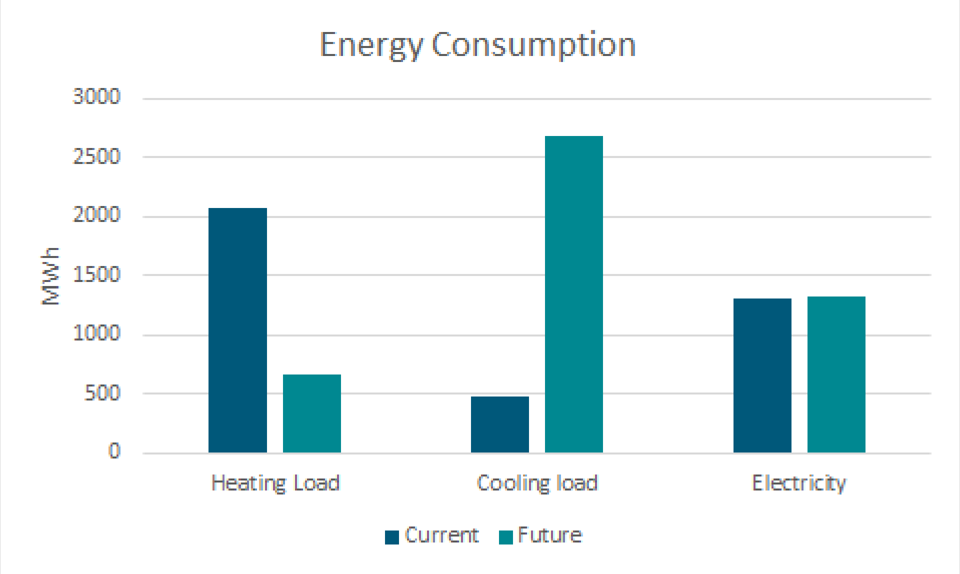

Figure 27: Comparison of present and future scenario’s energy consumptions.

5.3. Production capacity

To estimate the yield, the arrangement of the plants within the VIG is calculated, based on the facade areas. Using this arrangement and the estimated yield per area obtained from literature the total yield produced on the EWI building is estimated.

The spacing between the plants along the length is 0.3 m and the spacing between the trays is 0.4 m in the vertical direction. The width of the cavity holds two trays as seen in Figure 28 and the distance between them being 0.5 m. The number of plants is calculated based on this and the total number obtained for all three orientations combined is 180660.

The yield from the VIG is expected to be 6.99 kg/m^2. Since it is a closed greenhouse system where ideal conditions are provided all year round, 6 harvest cycles have been assumed. Based on the facade dimensions and the tray configuration, the total yield obtained was 227 tonnes of strawberries annually.

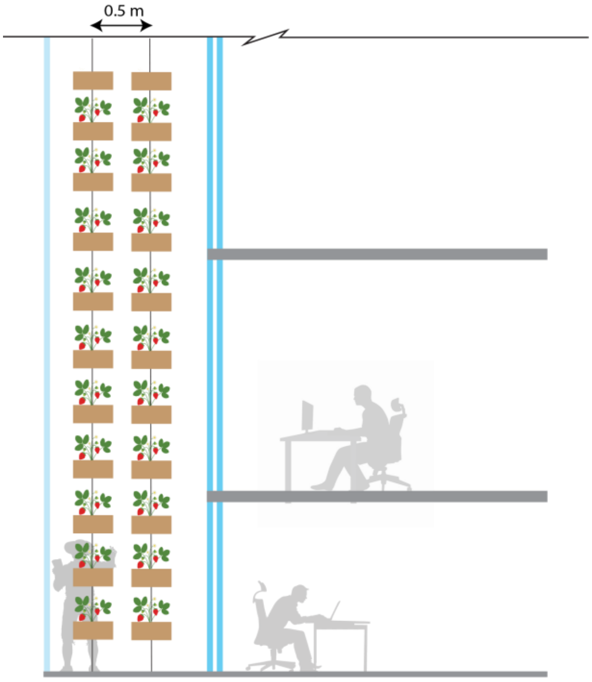

Figure 28: Sectional elevation of VIG integrated EWI building.

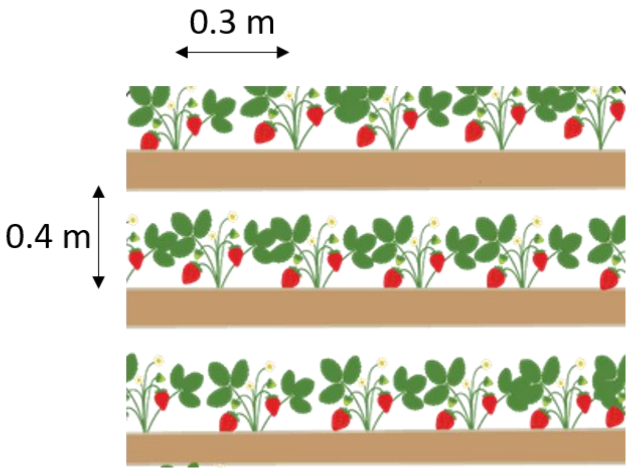

Figure 29: Elevation view of strawberry plants in the VIG (Images are only representative, not to scale)

5.4. Rainwater Harvesting

The water requirement of the EWI building is 3458 m^3 and water requirement per plant is 90 ml/day. The product of the total number of plants mentioned in section 5.3 and the daily water requirement of 90 ml gives the daily water requirement by the VIG system for irrigating the strawberry plants. It is 5853 m^3 of water annually.

The graph below (Figure 30) shows the amount of rainfall received each month. The water demand of EEMCS and VIG are also shown. From the calculations, it is understood that only a small percent of the water requirement can be met through the collected rainwater. 15% of VIG's water requirement or 25% of EEMCS's water requirement can be met through the rainwater harvesting system (Table 4 & Table 5).

Table 4: EWI monthly rainwater usage

Month	**Rainfall (mm)**	**Monthly water yield (m^3)**	**Cum. Water yield (m^3)**	**Monthly water demand (m^3)**	**Cum. Water demand (m^3)**	**Vol. Stored (m^3)**	**Monthly deficit/surplus (m^3)**	**Monthly % met**
Jan	70.9	61.5	61.5	255.0	255.0	-193.5	-193.5	24.1
Feb	79.8	69.3	130.8	211.0	466.0	-335.2	-141.7	32.9
Mar	42.3	36.5	167.3	230.0	696.0	-528.7	-193.5	15.9
Apr	47.6	41.1	208.3	371.5	1067.5	-859.2	-330.4	11.1
May	86.1	74.8	283.1	434.0	1501.5	-1218.4	-359.2	17.2
Jun	114.8	99.9	383.0	396.5	1898.0	-1515.0	-296.6	25.2
Jul	127.3	110.9	493.9	251.0	2149.0	-1655.1	-140.1	44.2
Aug	116.6	101.5	595.4	218.5	2367.5	-1772.1	-117.0	46.5
Sep	89.4	77.7	673.1	217.5	2585.0	-1911.9	-139.8	35.7
Oct	88.6	77.0	750.1	304.5	2889.5	-2139.4	-227.5	25.3
Nov	41.1	35.4	785.5	300.5	3190.0	-2404.5	-265.1	11.8
Dec	95.1	82.7	868.2	268.0	3458.0	-2589.8	-185.3	30.9
		868.2		**3458**				**25%**

Table 5: VIG monthly rainwater usage

Month	**Rainfall (mm)**	**Monthly water yield (m^3)**	**Cum. Water yield (m^3)**	**Monthly water demand (m^3)**	**Cum. Water demand (m^3)**	**Vol. Stored (m^3)**	**Monthly deficit/surplus (m^3)**	**Monthly % met**
Jan	70.9	61.5	61.5	487.8	487.8	-426.3	-426.3	12.6
Feb	79.8	69.3	130.8	487.8	975.6	-844.8	-418.5	14.2
Mar	42.3	36.5	167.3	487.8	1463.3	-1296.1	-451.3	7.5
Apr	47.6	41.1	208.3	487.8	1951.1	-1742.8	-446.7	8.4
May	86.1	74.8	283.1	487.8	2438.9	-2155.8	-413.0	15.3
Jun	114.8	99.9	383.0	487.8	2926.7	-2543.7	-387.9	20.5
Jul	127.3	110.9	493.9	487.8	3414.5	-2920.6	-376.9	22.7
Aug	116.6	101.5	595.4	487.8	3902.3	-3306.9	-386.3	20.8
Sep	89.4	77.7	673.1	487.8	4390.0	-3717.0	-410.1	15.9
Oct	88.6	77.0	750.1	487.8	4877.8	-4127.8	-410.8	15.8
Nov	41.1	35.4	785.5	487.8	5365.6	-4580.1	-452.4	7.3
Dec	95.1	82.7	868.2	487.8	5853.4	-4985.2	-405.1	17.0
	999.5	**868.2**		**5853.4**				**15%**

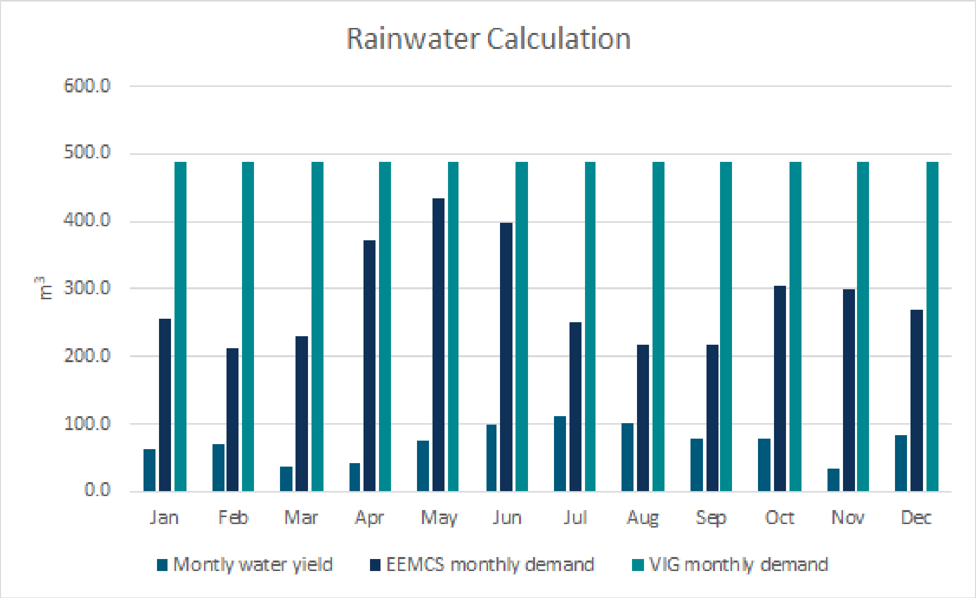

Figure 30: Monthly distribution of rainwater harvested, in comparison to monthly demands by EWI and VIG.

5.5. Carbon Footprint

The carbon emission of the current scenario is 1568 tonne CO_2, and the future scenario is 939 tonne CO_2. In Table 6 the carbon emissions due to the energy consumption of the building currently is calculated. The heat energy is provided through district heating (burning of natural gas) and with the help of a ground-coupled heat pump which receives the energy from the grid. The cooling energy is provided from the grid in combination with the ground-coupled heat pump. Similarly, the carbon emissions during the water treatment and carbon emission due to the energy used for 227 tonne strawberry production is included.

Table 6: CFP calculation of the current scenario

		Energy Sources	**Quantity**	**Units**	**CO_2 eq/unit**	**CO_2 emission (tonne CO_2)**
Heating		District Heating	6602	GJ	36	238
Cooling		Ground-coupled heat pump	846	GJ	0	0
Electricity	Lighting	Grid	220862	kWh	0.556	123
	Heat Pump		1078327			600
Water			3458	m^3	1.5	5.2
Strawberry	On farm (68%)		227306	kg	2.65	410
	Others (32%)		227306	kg	2.65	193
Total emission						**1568**

In Table 7, the carbon emissions due to the energy consumption of EWI along with the carbon emissions of the energy use in VIG system is estimated. All the heating energy for EWI and VIG is provided by the VIG, the excess heat from VIG which is stored in the aquifer. Most of the (80%) of the cooling demand can be met with the ATES system. The additional cooling is provided with the help of heat pumps which uses electricity from the grid.

Table 7: CFP calculation of the future scenario (with VIG)

VIG		**Energy Sources**	**Quantity**	**Units**	**CO_2 eq/unit**	**CO_2 emission (tonne CO_2)**
Heating	ATES	VIG	669662	kWh	0	0
Cooling	ATES	VIG	1373344	kWh	0	0
Electricity	Lighting	Grid mix	1067486	kWh	0.556	594
	Heat Pump		477	kWh	0.556	0.2
Water		RWH	868	m^3	0.56	0.5
		other	4985	m^3	1.5	7.5
Strawberry	On farm (68%)		227306	kg	2.65	0
	Others (32%)		227306	kg	2.65	193
EWI						
Heating	ATES	VIG	0		0	
Cooling 2	Heat Pump		27396	kWh	0.556	15
Cooling	ATES	VIG	775440	kWh	0	
Electricity	Lighting	Grid	220862		0.556	123
	Heat Pump		2598	kWh	0.556	1.5
Water		other	3458	m^3	1.5	5.2
Total emission						**939**

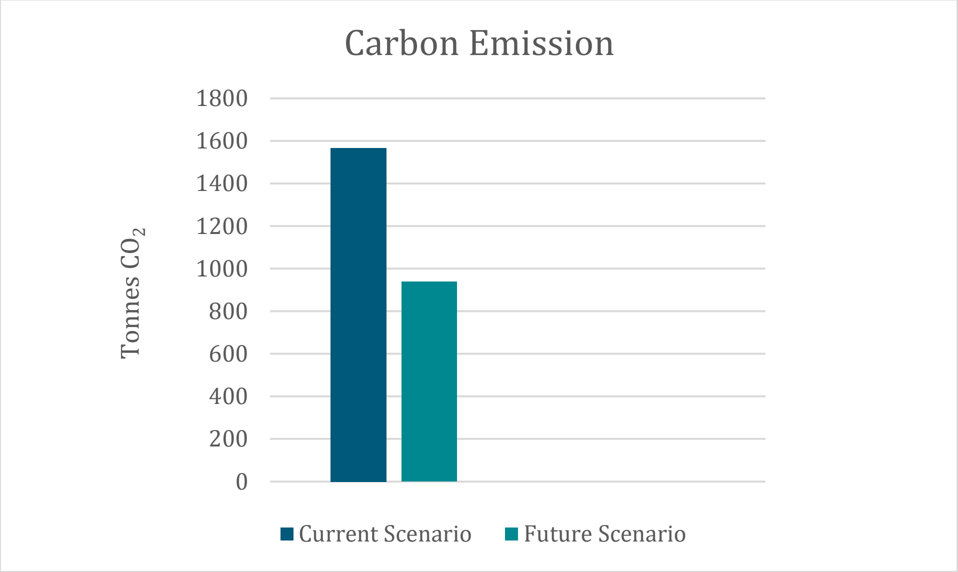

Figure 31: Carbon emissions associated with the current EWI building and a conventional greenhouse system, in comparison with the future scenario with a VIG integrated EWI building.

6. Conclusion

6. Conclusion

This chapter includes 3 sections. Section 6.1 starts with the general conclusion followed by the answers to the research question. Section 6.2 includes the limitations and challenges faced in the thesis followed by the future recommendation in Section 6.3.

6.1. Conclusion

The primary objective of the research was to investigate methods to mitigate climate change in the buildings and agriculture sector. Through this study, the potential of VIG in energy supply (with the help of ATES) and food production was explored. The aim of the study was to analyse the impact of VIG systems on the energy consumption of the building. This section will discuss the conclusions of the study by answering the main research questions. The results will be discussed in a hierarchy where first, the main research question followed by the sub questions will be answered.

What is the impact of VIG on a high-rise building?

Integration of VIG systems on the facade can potentially have a high energy demand as the greenhouse can act as solar collector and this could lead to over-heating. This will then require cooling energy which will increase the overall energy demand of the system. But with the integration of thermal storage system, the surplus heat in the greenhouse can be used as a source of energy. This will reduce the carbon emission due to the energy consumption as its a renewable source of energy.
The water demand of such a system will increase as the crops require certain amount of water for its growth and development. The yield per m^2 of VIG systems is higher than conventional greenhouses as the trays are vertically stacked. Since the system is integrated into the existing buildings in and around the cities, the transportation distance between the production and consumption can be reduced.

What is the impact of VIG on the energy consumption of EEMCS building of TU Delft?

From the study, it is understood that VIG integrated EEMCS consumes 3 times less heating energy but 1.7 times more cooling energy than the current EWI building. A net additional of 268 MWh energy (for cooling and heating) is required by the new system. Hence, the VIG integrated system consumes higher energy than now. However, the current scenario value does not account for the energy consumed by the conventional greenhouses that are the current food producing systems. Integration of greenhouses in the building facades and surfaces could still have a net reduction in the energy demand of the ecosystem as a whole.

What is the value of integrating ATES with VIG system?

In the absence of an ATES system, the total energy for heating and cooling required by the system is 2845 MWh. Because of the presence of ATES, the total energy goes down by 2818 MWh and the energy demand from the external source is only 27 MWh. This is 99% reduction in the primary energy demand. Implementation of renewable energy sources can reduce the GWP drastically as building’s consume a huge amount of energy for cooling and heating.

What is the impact of VIG system on the carbon emissions?

The carbon emission due to the energy consumed by the building currently can be reduced by 40% when VIG in combination with ATES is used. This amounts to a reduction of 628 tonnes of CO_2 annually.

In the absence of the ATES system, the energy source would be natural gas and grid and thsis would result in 25458 tonnes of CO_2. Apart from the CO_2 reduction, the system produces 227 tonne strawberries annually. This is possible through the vertically stacked trays which increases the yield per $m^{2.}$.

Since this is a highly controlled environment, the system is low maintenance and low workforce dependent and resilient to natural calamities. In addition to this, the strawberry production is brought closer to the consumption and hence the emissions due to transportation are reduced drastically.

6.2. Limitations and Challenges

The research is based on several assumptions and data from different literatures. There may be some gaps in the assessment method.

- Heat transfer is always a combination of conduction, convection and radiation. However, in heat exchangers, it is predominantly convection based, to be more specific, forced convection. Fluid dynamics calculations should be included to get exact results. However, a simplistic 1D heat transfer equation is used to make the calculations.
- VIG is relatively a new technique and it's still in the development/exploration phase. Owing to its nascent stage of development, the adoption of VIG needs further research before large scale implementation.
- The research focused only on the Global Warming Potential (GWP) indicator for the environmental impact of the systems, i.e., CO_2 equivalents of greenhouse gases. It does not consider other impact indicators such as acidification, eutrophication potential etc.

6.3. Future Recommendation

- Rainwater harvesting that utilises vertical envelopes instead of the roof surface to collect rainwater. This is particularly useful in high rises when the vertical surface area is much larger than the roof area. The system makes use of the transoms (horizontal members) to transfer the water to the mullions (vertical members) to the collection system. Research in facade rainwater harvesting is ongoing. Such interventions can be useful in increasing the rainwater potential of high-rise buildings such as the EWI building.
- The hot well size can be increased if other buildings are integrated into system design. This can reduce the dependency on heat pumps.
- Providing a green fuel source for the electricity of HP, can reduce the carbon emissions even further.
- Growing a variety of crops can help meet a larger proportion of the dietary requirements.
- Advanced analysis of heat transfer mechanisms, and simulation-based analysis can be developed to validate and improve the accuracy of the analysis.
- Designs must be developed factoring in the realistic sizing of equipment to provide more accurate solutions.
- Possibility of including evaporative cooling instead of heat pump-based design can reduce the cooling energy demand.

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