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Innovative Energy Saving and Climate Control System for Greenhouses

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ABSTRACT

Greenhouse development becomes more interesting to learn since various policies concerning low carbon emission emerge and researchers compete to apply various technologies, especially those that keep a greenhouse's indoor temperature and humidity stable. The problem faced by commercial greenhouses in northern climates is the high energy demand; especially for heating, which amounts to 80% of the greenhouse's total energy demand. Therefore, this research main aim is to provide a sustainable solution to the inherent problems of the greenhouses used in the protected cropping industry by proposing a low-cost energy saving and climate control system.

This work started by reviewing the state of the art of the technologies that have been applied in greenhouses recently in order to achieve the desired and stable humidity, lighting, and temperature in the greenhouse. Various technologies are discussed in this review, including PV Modules, Heat Storage, Heat Pump, Lighting, Wind-catcher, and Insulation system. Some preliminary research including in the theoretical and simulations have been done to give clear result before building the system.

The building has been built based on an energy-saving strategy review for the greenhouse system from the previous report. The building was built in East Leake, Loughborough and collection data has been done for one year. The data retrieved including Heat pump and energy storage system, and PV performance system.

The data analysis found that the seasonal COP heating and cooling of the heat pump varies between 1.48–2.97 and 1.20–3.45, respectively. While the COP_{sys} heating and cooling was found to be 1.51 and 1.55, respectively

the system success to maintain the indoor temperature at 18°C in summer and 16°C in other seasons but winter. In winter, the average indoor temperature dropped to 13.5°C due to the very low brine in less than -5°C (the heat pump automatically shut down for safety reasons).

The annual energy delivered for heating and cooling mode was 5175.92 kWh and 3997.82 kWh, respectively. Annual electricity generated by PVs panel found to be 16.56 kWh while the energy used was 62.09 kWh. This means that solar PV could contribute to the utility of 26.7%. Furthermore, the annual heat extracted from the SSBTESS was 13029.62 kWh. However, the proposed system has adapted the heat recovery in practice and successfully reduces the soil thermal imbalance by 2378.85 kWh, annually. The ratio of soil thermal imbalance achieved 32.76% which means the novel proposed system could gain soil heat recovery by 67.24% which is remarkable. Regarding the daylighting inside the greenhouse, the average illumination inside the greenhouse found to be around 1000lux which is three times lower than outside.

Besides the sophisticated technologies used in the greenhouse system, calculating the payback period is important in the industry. Therefore, some calculation has been done and it was found that the discounted and non-discounted payback period was 14th year and 11th year respectively, with an IRR greater than the loan discount rate. Moreover, the greenhouse gas emission could be cut up to 68% compared to the conventional greenhouse.

Keywords: greenhouse, soil thermal imbalance ratio, greenhouse gas emission, soil-based TES.

LIST OF PUBLICATIONS

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Jarimi H, Shihao Z, Xu Q, Santana JA, **Harjunowibowo D**, Riffat S. An affordable small calibrated hot box suitable for thermal performance measurement of a glazing unit. In: 17th International Conference on Sustainable Energy Technologies – SET 2018. 2018. p. 1–11.

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LIST OF NOMENCLATURE

T_{gh} : greenhouse temperature (°C)
T_{amb} : ambient temperature (°C)
E_t : thermal energy (kWh)
E_e : electricity energy (kWh)
E_{tex} : thermal exergy energy (kWh)
$\dot{Q}_r$: rate of discharged heat from air to the ground (kW)
Q : Heat loss (kW)
T_f : final temperature (°C)
T_i : initial temperature (°C)
T_{in} : initial soil temperature (°C)
T_{fs} : final soil temperature (°C)
$P^s_{p,t}$: rated PV power (kW)
η_p : solar panel efficiency ( )
$T^{s,a}_t$: outdoor temp at time t in ambient temperature a (°C)
Φ^s_t : solar irradiance (kW/m^2)
IRR : Internal Rate of Return (%)

a : ambient
PVT : photovoltaic thermal
BiPVT : building integrated photovoltaic thermal
BiPVW : BiPVT water based
PV : Photovoltaic
GSHP : Ground-Source Heat Pump
SAHLSC : Solar Air Heater with Latent Storage Collector
STTES : short term thermal energy storage
SSBTESS : seasonal soil-based thermal energy storage system
BTES : borehole thermal energy storage
HETS : Horizontal Earth Tube System
VGSHP : vertical ground-source heat pump
HGSHP : horizontal ground-source heat pump
EAHE : earth to air heat exchanger
GCHP : Ground Coupled Heat Pump
HGHX : Horizontal Ground Heat eXchanger
GHSSTESS : Greenhouse heating with soil-based seasonal thermal energy storage system
SVHXs : Single Vertical type heat exchangers
COP : coefficient of performance
$(COP)_A$: actual coefficient of performance
$(COP)_R$: Rankine coefficient of performance
SCOP : Seasonal coefficient of performance
HVAC : Heating Ventilation ang Air Conditioning

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CHAPTER 1 - Introduction

Outline of the Chapter:

> This chapter summarises the method by which the thesis is conducted. It contains the aim, objectives, scopes, and an explanation of the novelty of the research. There will also be a brief explanation of each chapter, which functions as a guidance for readers to understand the thesis easily and comprehensively.

1.1. INTRODUCTION

There are 130 countries that produce greenhouse vegetables commercially, with a cumulative area of over 1.1 million acres in 2016 (Cuesta Roble Greenhouse Vegetable Consulting, 2016). Most of the greenhouses face the challenge of high operational costs due to the great energy needs. The high rate of heat loss caused by greenhouse envelope materials (which have poor U-values) (Cossu *et al.*, 2014; Mongkon *et al.*, 2014) is responsible for the high energy demand in greenhouses (Santamouris *et al.*, 1994; Ghoshal and Neogi, 2014). In countries with warmer climate, however, the energy demand for cooling is more prevalent (Sonneveld, Swinkels, Bot, *et al.*, 2010; Mongkon *et al.*, 2014). In addition, regions with different climate for example in cold climate countries may have specific needs, which in turn affect its heating demand (Steenis, 2009; Van Beveren *et al.*, 2013; Bouadila *et al.*, 2014; Xu *et al.*, 2014). Those reasons cause the energy required for heating to become very dominant in a greenhouse's total energy demand (Santamouris *et al.*, 1994); up to 80% of the total greenhouse energy demand (Cuce, Harjunowibowo and Cuce, 2016).

Many references show the potency of heat pump technology for heating and cooling purposes (Sanaye and Niroomand, 2010; Tong *et al.*, 2012; Yildiz, Ozgener and Ozgener, 2012). Zhang et al. (Zhang et al. 2015) perform a simulation regarding the potency of solar seasonal soil heat storage system assisted heat pump. As a result, in the winter, the greenhouse space could be maintained at 12 °C. However there is energy loss reported by 13%. Additionally, Xu et al. (Xu *et al.*, 2014) proven that a system with seasonal soil-based thermal energy storage could enhance the heating performance. Without heat pump presence, they could maintain the greenhouse air space at 13 °C throughout the winter by using

10 m depth U-type heat exchanger, water storage and vacuum tube solar collector. In that respect, the integration of ground source heat pump, buffer tank, underground pipe heat exchanger, and solar collector might be powerful to provide the heat demand in greenhouse (Wang *et al.*, 2010; Xi, Lin and Hongxing, 2011; Zhai *et al.*, 2011). Even though, the heat loss in the soil should be minimised and the investment cost for piping.

Moreover, to preserve the environment, the UK (DECC, 2015) and European Union (Amanatidis, 2019) issues a policy to decline the greenhouse gas emission by 80% in 2050. Thereby, increasing the energy efficiency and using renewable energy become the best solution. Therefore, it is very important to provide a sustainable greenhouse with low energy demand. In minimising the total energy demand for greenhouse especially in heating season, innovations on thermal storage and grid independency are very crucial.

1.2. THE AIM OF THE PROJECT

Considering the previous problems in the introduction, the project's main aim is to provide a sustainable solution to the inherent problems of the greenhouses used in the protected cropping industry by proposing a low-cost energy saving and climate control system. The project presents an innovative integrated approach to enhance the energetic performance of greenhouses and improve the yield of various protected crops through employing a seasonal underground thermal energy store with an innovative insulation panels in addition to utilizing heat insulation solar PV glass as the greenhouse glazing, natural ventilation wind-catchers and innovative LED lights. The proposed solution enhances the greenhouse indoor conditions, improves productivity, and reduces reliance on conventional fuels in providing energy needs, thus reducing the carbon emissions and the high

running costs. Successful project implementation will benefit the whole community including the protected cropping growers and industry, the customers and the UK economy.

1.3. OBJECTIVE OF THE PROJECT

Providing a sustainable and innovative solution to the present high fossil fuel consumption and related high carbon emissions of the protected cropping (greenhouse) industry can be achieved by developing a low-cost, energy saving, and climate control system. Five thesis objectives have been recognised to achieve the thesis aim, and are summarised as follows:

(i) Highlighting the gap in literature regarding the technologies used in greenhouses on different climates, particularly in energy saving and climate control.

(ii) Carried out mathematical and experimental performance studies for soil-based seasonal thermal energy storage system in a greenhouse.

(iii) Evaluation based on experimental data of the energy saving and the climate control in the built greenhouse.

(iv) Evaluate the technologies, economic and environmental of the proposed greenhouse system.

(v) Recommendations for future work related to the innovative energy saving in the greenhouse improvement.

1.4. SCOPES OF THE PROJECT

Mitigating carbon emissions and the running costs of the greenhouse sector can be done by reducing the greenhouse's reliance on fossil fuel. Thus, a sustainable and energy efficient system is proposed by employing various

innovative technologies including heat insulation panels, wind-catchers, and LED lights in addition to an underground soil-based seasonal thermal energy storage system.

Production was intensified by establishing full control over key factors that affects plant productivity, including light levels, temperature, carbon dioxide, humidity, and exclusion of pests/diseases to optimise the nutrient content and the production rate of food in a specific facility. Dynamic control of the technologies allows the system to be tuned to suit the differing needs of various crops. Year-round production will allow crops to be produced within the UK avoiding the "food–mile" carbon emissions associated with importing crops from warmer climates, especially during winter. Despite the anticipated improvements in productivity, the energy consumption and the resulting carbon emissions were lower especially through the efficient and sustainable use of PV solar energy and seasonal heat/cool storage.

To provide heating and cooling, a heat pump powered by a semi-transparent and opaque photovoltaic panel was used. Since the weather of UK is cold most of the year, it was hard to get considerable heat from the sun. To address that, the greenhouse will be equipped with PVs on its rooftop and facades to gain maximum electric energy. The heat pump produced heat energy in summer and stores it in pipes exchanger buried on the ground under the greenhouse to be then used during winter. The cooling effect from the heat pump was used only if it is needed in summer because wind-catcher was opened when the inside temperature is too high to reduce the inside temperature.

To reduce the heat loss of soil-based seasonal thermal energy storage system due to conductive process, insulation panels is applied surrounding

the storage walls. The insulation panels were made from polyurethane (PU) which is light-weight, low-cost, and easy to be tailored.

In order to successfully achieve the above targets, the scopes of the research were divided into:

- Reviewing the background and literature review of past researches on greenhouses technologies system.
- Carrying out mathematical and experimental performances studies on Greenhouse heating with soil-based seasonal thermal energy storage system (GHSSTESS).
- Validating theoretical and simulation results findings with experimental results.
- Conducting a field trial on a full size occupied greenhouse in Loughborough city to validate the concept of charging the ground during summer months, and discharging the thermal energy in winter in this case using solar PVs powered Heat pump.
- Constructing and testing a small-scale field test to measure the U-value of the envelopes material.
- Constructing and testing small-scale field testing to measure the soil thermal properties to determine the undisturbed ground temperature, soil thermal conductivity, and borehole thermal resistant to design the system.
- Conducting simulations to overcome the problems found in the system and discussed the feasibility.
- Discussing the technical, economic, and environmental benefit of the innovate systems.

1.5. CONTRIBUTION TO KNOWLEDGE

This research has some contributions:

The insulation surrounding each sides of the soil used for heat storage is going to use polyurethane foam. The thickness of the insulation is 400 cm and height of 1500 cm. This insulation technique has never been studied in any of the past works reviewed during the process of this research; studies explained in all papers reviewed never use insulation to limit the heat loss in the underground heat storage.

This research used glycerol and coaxial vertical pipes and horizontal tubes as heat storage pipes which are buried on the ground with the polyurethane foam insulation. There has been no research or paper that uses this specific technique; the closest there is was one using vertical and horizontal U-tube. The heat produced by the heat pump uses the building's excess heat and saved into the underground soil in the cooling session. While in the heating session, the heat is taken from the soil, gained by the heat pump and delivered by fan coil unit to the air space.

1.6. METHODOLOGY APPROACH

The project works involve the following 6 (six) stages:

Stage 1: Background. A brief introduction of the research is described here. It includes the problems faced and the objectives which are going to reach. This chapter also explains the novelty and thesis structure also to make it more systematic and well-structured.

Stage 2: Literature Review. A brief literature review was carried out to collect relevant information on the use of technologies used in a greenhouse around the world, especially in countries with four seasons. In addition, this chapter also summarises previous published theory that is

crucial to understanding this project and on soil-based seasonal thermal energy storage system performances improvement.

Stage 3: Mathematical Modelling/Thermodynamic Analysis and Simulation will be used to evaluate the performance of the systems in various ways and under different operating conditions including different physical system, heating system, and orientation; the sensitivity analysis of the effects of the physical characteristic of materials used on the building also will be investigated.

Stage 4: Field Test The work was carried out on the solar PV combined with heat pump system to act as heat generation during summer period to charge the ground. A monitoring system was set up to measure during thermal charging, and discharging from the ground.

In addition, the field trial test was carried out on the solar PVs panels acting as a source to a soil-based seasonal thermal energy storage system and for LEDs. The field tests were conducted on May to September 2016 as preliminary testing, the comprehensive field test was taken from October 2016 to September 2017. The energy output from soil-based seasonal thermal energy storage system has been evaluated. The efficiency of the PV, LEDs, heat pump system, insulation, the energy delivered to the space and the total energy consumed by the greenhouse also have been investigated.

Some field experiments were done for the calculation in this chapter such as thermal response test experiment. This experiment was aimed to determine the undisturbed ground temperature, soil thermal conductivity, and borehole thermal resistant which were demonstrated in Section 5.1. Moreover, in-Situ facades thermal performance measurements have also

been carried out in order to determine the U-value of the facades after installation and compared with the data technical.

Stage 5: Testing Using Small-Scale Rig in the Laboratory A small-scale test rigs will be designed and constructed to test the performance of the envelope systems. The results were used to find out the effect to the greenhouse energy consumption. Various materials under the same condition will be tested in a rig to determine the optimum performances.

Stage 6: Assessing the Economic-Environment of the Innovate Greenhouse System An economic and environment assessment impacted by the innovated greenhouse has been done. The discounted and non-discounted payback period methods were used to determine the viability of the system accurately. The Internal Rate of Return (IRR) also been calculated to estimate of the upper level of interest rate for the loan. In addition, environmental impact caused by the project regarding the greenhouse gasses emission has been discussed as well.

1.7. STRUCTURE OF THE THESIS

This report consists of eight chapters and the explanation below elucidates the link between chapters and the plan of the thesis.

The eighth chapters involve the following:

The first chapter covers the introduction to the project driving forces. The project objectives, scopes are detailed. The methods of approach to meet various objectives are also given in this chapter.

The second chapter covers the background of the research and summarises previously published concept and theory that is crucial to

understanding the project. It also provides a brief review of the various studies and the state of art greenhouse technologies relevant to this work.

The third chapter describes the methodology mathematical models of the Greenhouse; the mathematical model of each component of the soil-based seasonal thermal energy storage system is presented. This chapter also describes the designs, technologies and systems properties which allow the unit to operate efficiently and minimise the effect of seasonal changes on heat pump performance.

The fourth chapter describes the theoretical and simulation performance analysis the set-up of PVs (semi-transparent and opaque), Heat pump, soil-based seasonal thermal energy storage system and its insulation. It also describes the mathematical model and experimental analysis of the greenhouse system; evaluates the performance of the system in various ways and under different operating conditions; the COP recommendation of the greenhouse is also given.

The fifth chapter describes the field test on the Greenhouse combined with PVs, Heat pump, and soil-based seasonal thermal energy storage system in Nottingham city climate. The method of soil-based seasonal thermal energy storage heat transfer has been presented, and the amount of heat injected and extracted to the ground. The result is compared with the previous theoretical and simulation investigation. It also summarises the benefits of the novel systems and findings.

The sixth chapter presents the small scale field trial and simulations of the u-value of various envelope materials to improve the greenhouse system. There are four methods discussed in order to fix the problems found which in turn could improve the greenhouse system.

The seventh chapter gives the general discussion on environmental, social, and economical benefits of the novels soil-based seasonal thermal energy storage system, it concludes, based on the previous theoretical and experimental investigation.

The eighth chapter gives the general discussion and summarise the whole chapters including problems of the research, solutions approaching and the findings. Also the future works that are recommended from the research findings is mentioned in particular section. It also suggests further works.

CHAPTER 2 – Literature Review

Outline of the Chapter:

In this chapter, a comprehensive review focusing on key strategies of energy saving and climate control technologies for greenhouses is presented. Following the brief and concise assessment of existing greenhouse systems in terms of their role in total energy consumption; cost-effective, energy-efficient and environmentally friendly technologies are analyzed in detail for potential utilization in greenhouses for notable reductions in energy consumption and emission levels. The technologies considered within the scope of this research are mainly renewable and sustainable based solutions such as photovoltaic (PV) modules, solar thermal (T) collectors, hybrid PV/T collectors and systems, phase change material (PCM) and underground based heat storage techniques, energy-efficient heat pumps, alternative facade materials for better thermal insulation and power generation (heat insulation solar glass, PV glazing, aerogel and vacuum insulation panel, polycarbonate sandwich panels), innovative ventilation technologies using pre-heating and cooling (high performance windcatchers), efficient lighting systems, closed concept, and control system. The findings from the research clearly reveal that up to 80% energy saving can be achieved through appropriate retrofit of conventional greenhouses with a payback period of 4–8 years depending on climatic conditions and crop type.

2.1. INTRODUCTION

Global energy demands rise by 2.2% in 2017 (BP, 2018) and 30% between today and 2040 in the New Policies Scenario (IEA, 2017), where the heating, cooling and transport sectors, together account for about 80% of global total final energy demand (REN21, 2018). The building involving greenhouses, contributing to greenhouse gas emissions in the world by 30% and energy consumption by up to 40% of total world energy (Lemmet, 2013). In which, the greatest contribution of energy loss are from windows and roof of the building by about 20-40% (Hee *et al.*, 2015). It can be worse when the commercial greenhouses which is growing up to 1.1 million acres of greenhouses (Cuesta Roble Greenhouse Vegetable Consulting, 2016), worldwide, still using conventional facades. Whereas, mostly, the greenhouses use glass (Benli, 2011; Joudi and Farhan, 2014), plastic/polyethylene (Cossu *et al.*, 2014; Mongkon *et al.*, 2014), semi-rigid plastic (Esen and Yuksel, 2013), and the plastic film (Sonneveld, Swinkels, Bot, *et al.*, 2010; Marucci *et al.*, 2012) as the cover material. While these materials have high transmission power that easily releases the heat to the environment (Ghoshal and Neogi, 2014). Therefore, almost of the total energy used in the greenhouse is only used for heating (Santamouris *et al.*, 1994). In this sense, definitive measures are required for minimization of worldwide energy consumption and earnest mitigation of carbon emissions.

Besides the physical structure, the types of cultivation and location have a significant role in terms of energy consumption. The reason for culturing in a greenhouse can be credited to prepare land which is helpful for the vegetables and organic products to develop and mature (Russo *et al.*, 2014), to protect them from the severe weather (Xu *et al.*, 2014), pests and disease (Yang *et al.*, 2014), and to increase the quality of the crop

(Pérez-Alonso *et al.*, 2012). Therefore, the expanding need for energy in a greenhouse becomes a key issue for securing sustainable cropping and harvesting (Aramyan, Lansink and Verstegen, 2007; Steenis, 2009). However for the sake of preserving the environment, some developed countries released a new standard to mitigate the carbon emission in building. For example, the UK government issued a policy to reduce greenhouse gas emissions (GHG) in 2008 by 80% from 1990 until 2050 (DECC, 2015). Moreover, European Union issued the same policy to decline the GHG by 40%, 60% and 80% below 1990 levels by 2030, 2040 and 2050 respectively, increase energy efficiency and intensively support renewable energy sources (Amanatidis, 2019). Therefore, it gives support researchers and scientists to seek extra sources of energy, environmentally friendly technologies, and energy-saving solutions.

2.1.1. Energy Saving

In terms of energy saving in a greenhouse, the need for temperature, lighting and humidity vary in each region (Yang *et al.*, 2014). Accordingly, the technology applied in greenhouses in various regions is also different (Qoaider and Steinbrecht, 2010).The countries of the four seasons are usually more in need of a technology that can provide heating for most of the year. For instance, British Columbia (Steenis, 2009), the Netherlands (Van Beveren *et al.*, 2013), China (Xu *et al.*, 2014), and some countries in the Mediterranean (Bouadila *et al.*, 2014) and Middle East (Joudi and Farhan, 2014) were mostly cold requires more energy for heating. Therefore in such climates, soil-based thermal energy storage systems are more suitable. The energy which is stored in water or soil can be used at night in accordance with the requirement of the greenhouse for heating (Panwar, Kaushik and Kothari, 2011). Passive solar heating technology on the existing greenhouse are differ from one to another by the thermal

storage medium, such as water (Zhang *et al.*, 2015), rock (Nisha, GN and MS, 2006; Sanaye and Niroomand, 2010), phase change material (Benli and Durmuş, 2009), isolation moves (thermal screen/curtains) (Barral *et al.*, 2000), soil water collector (Mongkon *et al.*, 2014), and north wall and mulching (Sethi and Sharma, 2008). With these systems, usually are able to maintain the air temperature in 2-4 °C higher than the outside temperature and promising.

Benli and Durmus (Benli and Durmuş, 2009) studies thermal performance of a latent heat storage system with phase change material for new solar collectors design in greenhouse heating. The system provides about 18–23% of total daily thermal energy requirements of the greenhouse for 3–4 h, in comparison with the air-type solar collector. In later work, Benli (Benli, 2011) investigates the performance of a ground-source heat pump (GSHP) greenhouse heating system integrated a horizontal closed-loop ground heat exchanger and use phase change materials (PCM) as energy saving and management in greenhouses. For that method, the overall system performance (COP) is obtained to be 2–3.5, which is noticeable. It is also noted that an additional heat source may be necessary in sudden heat drops and frozen. Hence, Esen and Yuksel (Esen and Yuksel, 2013) experimentally investigate greenhouse heating by biogas, solar and ground energy. As the result, 2231.83 l of gas production by biogas system could be provided to maintain the greenhouse temperature of 23 ^{o}C during the winter period. Solar air collector-PCM aided are reported as a very common technology in Mediterranean region by Bouadila et al. (Bouadila *et al.*, 2014). The night time heat recovering of the solar system attains 31% of the total requirements of heating at 12 ^{o}C. This kind of systems become much more cost-effective and efficient when integrated with PCM. The annual gain of energy is 1800kWh with payback period around 5 years. A

similar system was also used in Iraq for heating (Joudi and Farhan, 2014) and the results show that solar air heaters provide more than 60% of the heating load.

The Canada Government calculates the energy needs and cost as an approximation required by a 496 m^2 greenhouse with a conversion efficiency of 70% (Manitoba, 2016). By assuming typical double poly greenhouse energy consumption is 2.1 GJ/m^2 hence the heating need from September to May is calculated. As the results, The cost of the energy needed for propane, electricity, fuel oil, and natural gas to be $22,126.56/season, $17,355.04/season, $14,880.00/season, and $10,207.68/season, respectively. Therefore, fossil fuels play a large role in providing heating (Jaffrin *et al.*, 2003; Esen and Yuksel, 2013; Vourdoubas, 2015) particularly coal due to cheap and abundant (Nemś, Nemś and Świder, 2018).

Meanwhile, the tropical and subtropical countries cooling technology to diminish the excess heat in midday in the greenhouses is much more needed (Sonneveld, Swinkels, Bot, *et al.*, 2010; Mongkon *et al.*, 2014). Countries such as Indonesia (Campen, 2005), Malaysia (Al-Shamiry *et al.*, 2007), India (Bansal *et al.*, 2010), Turkey (Ozgener, Ozgener and Goswami, 2011), and Thailand (Mongkon *et al.*, 2013), almost always receive abundant sunlight intensity which results in overheating in their greenhouses. It encourages disease and insect pests. Therefore, passive cooling ground heat exchangers based on horizontal earth tube systems (HETS) are strongly recommended in tropical and subtropical climatic conditions.

Similar system are also utilised in South Asia (Ozgener, Ozgener and Goswami, 2011; Bisoniya, Kumar and Baredar, 2013), Mediterranean

countries (Benli, 2011), East Asia and South-West Asia (Sanaye and Niroomand, 2010). The results from the said works show that a daily cooling capacity can be achieved from HETS installed in those regions up to 75 kWh (Wu, Wang and Zhu, 2007). In Turkey, the U-bend ground heat exchanger for cooling summer have COP in the range of 0.98-10.88 (Ozgener, Ozgener and Goswami, 2011). EAHE system reduces the air temperature by 2.26 ^{o}C with a circulating power of 43.19W per kW of cooling. In India, HETS (Ghosal and Tiwari, 2006) maintains the greenhouse temperature of 7-8 °C higher during the winter and 5-6 °C lower during summer compared to the greenhouse without HETS. In Thailand, the same concept provides indoor temperature of 1-3.7 °C lower in summer with an average COP of 2 (Mongkon *et al.*, 2014). The system also enables thermally comfortable indoor conditions by supplying an ideal relative humidity range for the crops. It is underlined in the research that the plant growth with HETS is notably better than no-HETS plant.

To deal with these cooling and heating needs in all types of climates, thus the combination of technologies along with utilizing heat pump is keep going. In order to gain optimal results and to save energy, researchers implemented active and passive technologies (Khan, Su and Riffat, 2008; Max *et al.*, 2009; Mongkon *et al.*, 2013; Dehghani-sanij, Soltani and Raahemifar, 2015; Xu *et al.*, 2015). Sanaye and Niroomand (Sanaye and Niroomand, 2010) in Iran investigate the heating and cooling loads of the ground heat exchanger assisted a heat pump in a building in various climatic conditions. The suitable values of COP in heating and cooling increased from 3.9 to 5.4 with capacity from 8 to 32 kW. Further, it is found that the best heat transfer coefficient and a proper soil type for such system are damp clay. Tong et al. (Tong *et al.*, 2012) conducts an experiment for hourly heating energy consumption of a greenhouse in

Japan from January to March using a heat pump. The heating consumption is in the range of 0.22 to 0.56 MJm^{-2}, while heating with a kerosene heater is 0.42–0.76 MJm^{-2}. Concurrently, the hourly CO_2 emissions in the greenhouse with high COP electric heat pumps are in the range of 9.5–24 gm^{-2}, while that in the greenhouse with the kerosene heater is higher in the range of 31–55 gm^{-2}. It can be concluded from their experiments that heat pump technology for heating purposes in a greenhouse is found more cost-effective than the kerosene. Attar et al. (Attar *et al.*, 2014) use a storage tank and four capillary heat exchangers heating and cooling aided flat plat collector. However, in the winter, the heating mode is hard to reach the desired temperature thus an electrical grid is needed. Against this background, after storing the excess of energy to the ground, the temperature of greenhouse may increase by 6 °C at night which is suitable for the crops. Further in cooling mode, the system decreases the temperature by 12 °C for 9 h in daytime.

Most hot-season greenhouse vegetable plants grow rapidly at daily temperatures between 20–30 °C and 14–18 °C at night (Hassanien *et al.*, 2016). Meanwhile, some factors as outside local climate, structural materials, exposure, slope, soil, altitude, wind conditions, or cultivated plant species very influence the energy demand (Maurizio Carlini, Tommaso Honorati and Sonia Castellucci, 2012). In the area of Mediterranean climates which tend to be extreme, the greenhouse mostly utilising a ventilation system without any heating system (Attar *et al.*, 2014). Whereas, on hot and hot days, inadequate cooling during summer will cause poor crop conditions although for short periods of time. Particularly in Tunisia, annual sunshine can reach 3288 kWh/m^2, lead to crops languish.

In order to reduce the operational cost of greenhouses in extreme climate, solar power systems are needed. Moreover, the most efficient and promising sustainable energy delivered by heat pumps, solar collectors and energy storage seems suitable for heating and cooling (Yildiz, Ozgener and Ozgener, 2012). Since combining PV panels and crops on the same area unit of land could alleviate the dependency on electricity grid or fossil fuels, thereby, the conversion of cropland into PV plants is trending (Mekhilef *et al.*, 2013). However, solar energy utilisation having barriers that has to be overcome when applied in the agriculture sector.

2.1.2. Adapted Technologies

The eco-friendly PV modules are highly recommended to produce power for heating, cooling, and lighting energy (Al-Shamiry *et al.*, 2007; Kadowaki *et al.*, 2012; Nakoul *et al.*, 2014; Kumar, Baredar and Qureshi, 2015; Zimmermann *et al.*, 2015). The core of interest for a reliable performance evaluation of such technologies is thermodynamic analysis of PV systems. A good example is delivered by Nayak and Tiwari (Nayak and Tiwari, 2008). An exergy analyses of the PV/T integrated greenhouse system is calculated and show an efficiency level of approximately 4%. The yearly net electrical energy saving is 716 kWh and yearly exergy thermal energy is 12.8 kWh for the greenhouse temperature range about 25-45 ^{o}C. Similarly, Yildiz et al. report average exergy efficiency of PV found to be almost 5% for temperature reference about 15 ^{o}C (Yildiz, Ozgener and Ozgener, 2011). Nevertheless, most greenhouses still use the grid since the used of PV assisted earth-to-air heat exchanger (EAHEs) is only capable of providing electrical energy intake of approximately 31 up to 34% of the total demand for electricity in the greenhouse (Yildiz, Ozgener and Ozgener, 2011, 2012).

Since the efficiency of PVT is low, some improvements have been done utilising concentrator so called CPVT. Recently, the total efficiency of CPVT is greater than PVT collector (Kostic, Pavlovic and Pavlovic, 2010b). CPVT can produce thermal and electricity with efficiency 65% and 11.3%, respectively (Sonneveld, Swinkels, Campen, *et al.*, 2010). Under Dutch weather conditions the yearly produced electrical energy by the prototype is determined as 20 $kWhm^{-2}$ and the yearly thermal yield as 161 $kWhm^{-2}$ at temperature of 17.5 ^{o}C in winter and 19.5 ^{o}C in summer. However, some improvements were needed to increase the electricity supply for heat pump and well-insulated greenhouse with seasonal storage. After improvement, the electricity and thermal produced by the system achieved 31 $kWhm^{-2}$ and 270 $kWhm^{-2}$, thereby the system can be operated without fossil fuel.

Besides temperature management, a good greenhouse has to consider of other aspects such as sufficient ventilation, light transmission, construction cost, and low energy consumption (Max *et al.*, 2009). Therefore, on the facades of the greenhouse is necessary to use materials that have low thermal transmittance, lightweight and economical, and also high light transmissivity. For plants photosynthesis, visible light is a key factor (Gislerod, Eidsten and Mortensen, 1989; Ilieva *et al.*, 2010; Singh *et al.*, 2015) and known as Photosynthetically Active Radiation (PAR) (Benli and Durmuş, 2009; Benli, 2011; Yano, Onoe and Nakata, 2014). Thus the facade material, particularly for the roof, must not obstacle the sunlight since the shading to the plant will decrease the quality of the crop (Kadowaki *et al.*, 2012). Kadowaki et al. found that covering the greenhouse roof area by 12.9% causes the dry-matter weight (DW) and fresh weight (FW) of Welsh onion dropped significantly. In this context, the design of the greenhouse facade and roof are also very critical attaining better performance.

Correspondingly, retrofitting on the existing conventional greenhouse is the main focus of this chapter. Since the geographic location determines the plantation energy requirement to maintain temperature and humidity. Thus, technology retrofitting is very important to support the greenhouse operation. This effort has strongly related to operational cost, ease of operation, the overall performance and the payback which has to be considered from a business point of view. Therefore, to have a clear description of technology appropriately used in minimising the energy requirement and cost, the state-of-the-art of greenhouse technology is discussed.

2.2. TECHNOLOGIES FOR GREENHOUSE

Electric energy is one type of energy that can easily be used for many purposes in the greenhouse as heating, cooling and lighting. The use of renewable energy in the greenhouse will reduce carbon emissions and ultimately operational costs. Therefore, reliance on the grid should start to be reduced gradually. At the rest part of chapter will explore an effort that can be done to help conduct retrofitting on existing greenhouses using technology and materials which is more energy-efficient and environmentally friendly.

2.2.1. Photovoltaic Modules

The main energy source that is the easiest and the cheapest to be used and conversed to the form of electricity is the sunlight. However, photovoltaic module has low efficiency about 10-25% for Si type (Zimmermann *et al.*, 2015), 18-28% for GaAs type, 17-19% for Thin-film chalcogenide type, 10% for a-Si type, 9-12% for Photochemical type, and 8-11% for Organic (Barkhouse *et al.*, 2012; Green *et al.*, 2013), and it is also very sensitive to heat increase. The photovoltaic efficiency will

decrease continually upon receiving excessive heat energy (Chow, 2010; Wu *et al.*, 2012; Kumar, Baredar and Qureshi, 2015; Herrando and Markides, 2016). Therefore, various attempts are done to get plenty sun's visible light energy while keeping the temperature of the photovoltaic low.

2.2.1.1. Conventional Photovoltaic modules

Extensive use of photovoltaic technology recently stimulates many industries to compete in creating a durable and more efficient panel. Since the technology is superior in durability, high efficiency, and most importantly affordable as the production grows (Global Trends In Renewable Energy, 2014). Moreover, photovoltaic is able to convert the sunlight's visible light energy into electricity for DC or AC devices through inverters as well as saved in batteries (Kumar, Baredar and Qureshi, 2015).

In the market, mono and poly-Silicone type (Si) are widely used about 36% and 54.9%, respectively (Querini *et al.*, 2012; AG, 2015; Omar Z. Sharaf and Orhan, 2015). Even though, crystalline silicon is the most frequently used in greenhouses for clean energy generator as shown in Table 2-2. Furthermore, the usage of PV modules improves the ideal temperature inside the greenhouse and enabling remarkable energy saving also carbon emission reduction.

Table 2-1 shows PV development and its efficiency. The highest efficiency PV available in the market are made from multi-junction type (Green *et al.*, 2013; Omar Z. Sharaf and Orhan, 2015). However, that type is expensive and as such, in general, it is rarely used in greenhouses. The PV application in a greenhouse is mostly used to support the need of electricity as heater and alternative lighting in a greenhouse. However, the electricity produced depends on the PV area, the module efficiency, and location.

It is mentioned previously that photovoltaic often experiences drastic rise of temperature especially in areas with high intensity of sunlight radiation such as in Italy (Cossu *et al.*, 2014). It has been proven that the solar cell temperature will rise 50°C above the ambient temperature due to 50% of the sunlight is converted into heat (Chow, 2010). For four season countries, the average temperature differences between the temperature inside the photovoltaic module and that of its ambient is around 18°C. While, the highest temperature peak in the module is reached in summer that is 76°C, while the lowest temperature of 25°C is reached in winter. Therefore, it is suggested to use passive or active cooling systems to decrease the thermal excess in PV on each PV application in a greenhouse.

2.2.1.2. Concentrating Photovoltaic (CPV)

Due to the low efficiencies of conventional PV, in most cases, a large area of PV panels are needed to meet the greenhouse energy demand. Growers forced to install the PV module on the rooftop of the greenhouse because of limited area they have. However, this technique causes to daylighting to the crops is blocked and effected to the harvesting quality (Yano *et al.*, 2010; Kadowaki *et al.*, 2012; Cossu *et al.*, 2014; Yano, Onoe and Nakata, 2014). Hence, to avoid those losses, several researchers employed sunlight concentrator on the PV to achieve more power. Several concentrators are used in greenhouse such as Fresnel lenses (Sonneveld and Swinkels, 2010; Imtiaz Hussain, Ali and Lee, 2015), and Parabolic trough concentrator (Sonneveld, Swinkels, Campen, *et al.*, 2010) as shown in Fig. 2-1. Those concentrators have both many advantages and disadvantages.

The primarily advantage is the size reduction of the used PV module, which automatically decrease the capital cost (Omar Z Sharaf and Orhan, 2015; Omar Z. Sharaf and Orhan, 2015). Concentrating PV modules do not take a lot of space to increase the efficiency. Besides, a high concentrator can

boost the amount of sunlight up to 100 times more than the amount of light received by PV module of the same size (Chemisana, 2011). Furthermore, recently, CPV module has been reported reach efficiency up to 38.9% at Concentrator Standard Test Conditions (CSTC) (Philipps *et al.*, 2015).

Table 2-1. Several kinds of PV cell used in greenhouses and its efficiency measured at standardized condition (Barkhouse *et al.*, 2012; Green *et al.*, 2013)

Type	Efficiency (%)	Type	Efficiency (%)
Silicon		Multijunction devices	
Crystalline	25.0 ± 0.5	InGaP/GaAs/InGaAs	37.9 ± 1.2
Multicrystalline	20.8 ± 0.6	a-Si/nc-Si/nc-Si (thin-film)	13.4 ± 0.4
Thin-film cell	21.2 ± 0.4	a-Si/nc-Si (thin-film cell)	12.7 ± 0.4
Thin-film submodule	10.5 ± 0.3	a-Si/nc-Si (thin-film submodule)	11.7 ± 0.4
Organic		Amorphous/nanocrystalline Si	
Organic thin-film	11.0 ± 0.3	Si (amorphous)	10.2 ± 0.3
Organic (submodule)	9.5 ± 0.3	Si (nanocrystalline)	11.4 ± 0.3
Thin-film chalcogenide		III–V cells	
CIGS (cell)	20.5 ± 0.6	GaAs (thin-film)	28.8 ± 0.9
CIGS (submodule)	18.7 ± 0.6	GaAs (multicrystalline)	18.4 ± 0.5
CdTe (cell)	21.0 ± 0.4	InP (crystalline)	22.1 ± 0.7

Table 2-2. Type of PV used for heating, cooling and lighting on Greenhouse

Ref-erensi	Type of PV	Country	Result
(Shyam *et al.*, 2015)	Crystalline silicon (c-Si) semi-transparent	India	The highest electricity energy is 1.9 kWh/d
(Yano, Onoe and Nakata, 2014)	Crystalline silicon spherical solar microcells semi-transparent	Japan	The peak power output is 540mW when irradiates with 1213 Wm^{-2}. The conversion efficiency is 4.5%
(Ganguly, Misra and Ghosh, 2010)	Crystalline silicon solar cells (CEL-PM75)	India	The peak power is 3825 Wp. The module strengthens the viability of a greenhouse grid-independent (Simulation)
(Nayak and Tiwari, 2010)	Crystalline Silicon (c-Si)	India	The annual overall annual electrical energy savings is at 1185 kWh. Electricity production factor (EPF) is 2.04.
(Maurizio Carlini, Tommaso Honorati and Sonia Castellucci, 2012)	Mono-crystalline silicon	Italy	Saving energy approximately 30% for summer cooling and 11% for winter heating
(Sonneveld *et al.*, 2011)	Mono-crystalline Si-cells	Netherlands	An electrical output peak power of 38Wm^{-2}. The annual electrical energy to be 29 kWh m^{-2}. Electric efficiency yield of 11%.

(Yildiz, Ozgener and Ozgener, 2012)	Poly-crystalline silicon	Turkey	The total electricity energy consumption 8.10 kWh. 34.55% is provided from PV cells, others from grid. Temperature inside could be decrease by 19.9 ^{o}C, outside is 49.9 ^{o}C.
(Cossu *et al.*, 2014)	Multi-crystalline silicon	Italy	The annual electricity production is 107,885 kWh. The overall conversion efficiency of the PV system is 11.4%. Yearly average temperature inside the greenhouse 19.8^{o}C and the range is 12-30 ^{o}C
(Pérez-Alonso *et al.*, 2012; Urena-Sanchez *et al.*, 2012)	a-Si thin film	Spain	Electricity produces 8.25 kWh m^{-2}, with 9.79% of cover occupation
(Yano *et al.*, 2010; Kadowaki *et al.*, 2012)	a-silicon (FPV1024S)	Japan	The straight-line PVs and checkerboard PVc arrays generate electricity of 4.08 GJy^{-1} and 4.06 GJy^{-1}, respectively. But straight-line PVs decrease the fresh weight (FW) and dry matter weight (DW) of the onion.

However, overheating caused by the module concentrator PV could be a fatal disadvantage if they are not well-managed (Chow, 2010). It is reported on previous discussion that the PV's temperature reaches 120°C on the ambient temperature of 20°C and the intensity of the sunlight radiation of 1000 W/m^2. Moreover, for extreme weather conditions like Middle East in summer (50 °C), PV module temperature exceeds even 200 °C. Such high temperature will decrease the PV's efficiency down to 8% from the more or less 14% as shown in Fig. 2-2 and Table 2-3.

Table 2-4 shows the concentrators commonly used in greenhouse with the efficiency values. The maximum temperature of a solar panel considered safe is around 80°C. More than that can cause permanent damage and failure. Hence, a cooling system for the panel is required to maintain the temperature. There are several techniques can be used in the literature and utilise it as a heat source for the greenhouse or other purposes (Nayak and Tiwari, 2009; Sonneveld, Swinkels, Campen, *et al.*, 2010; Imtiaz Hussain, Ali and Lee, 2015). Such attempts not only increase the electrical efficiency of PV modules but also enable notable reductions in heating demand of greenhouses.

Table 2-3. A crystalline silicon PV electrical conversion efficiency at different temperature (Wu *et al.*, 2012)

Initial solar radiation intensities (W/m^2)	Electrical conversion efficiency (%)	
	Natural convective heat transfer only	
	Ambient temperature (20 °C)	Ambient temperature (50 °C)
200	14.12	11.89
400	13.01	10.85
600	11.96	9.86
800	10.97	8.79
1000	9.95	7.95

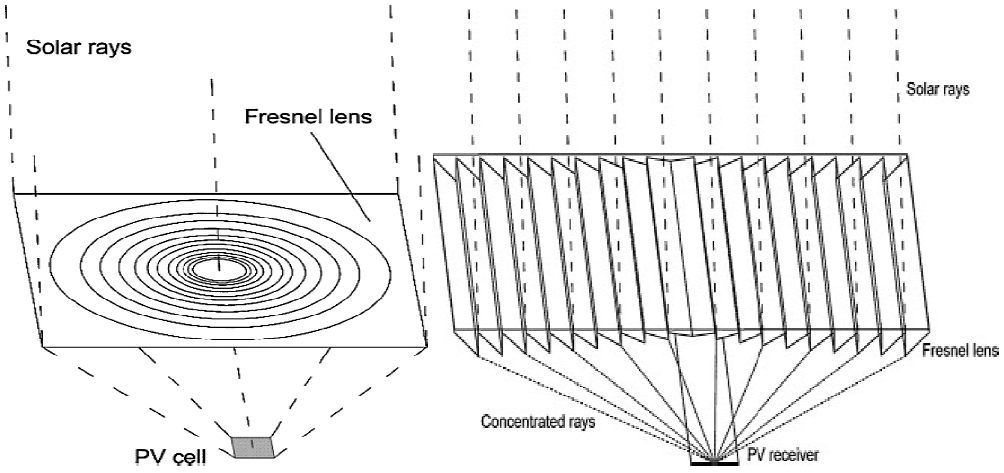


Fig. 2-1. Schematic of Aspheric/spot and Linear Fresnel lenses (Chemisana, 2011)

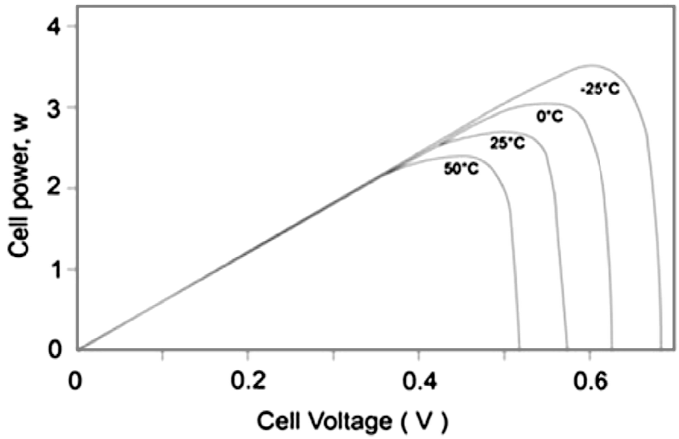


Fig. 2-2. The effect of silicon cell temperature against the power output (Muneer and Kotak, 2016)

Table 2-4. Concentrator type used in Greenhouse

Concentrator	Greenhouse Temperature (°C)	Electricity Efficiency (%)	Ref
Linear Fresnel lens	N/A	69.0	(Sonneveld and Swinkels, 2010)
Concave/curve glass	17.5 and 19.5	12.52	(Sonneveld, Swinkels, Campen, *et al.*, 2010)
cylindrical trough concentrator	20.8-31.2	15.7	(Sonneveld *et al.*, 2007)

2.2.1.3. Photovoltaic/Thermal (PVT)

Due to the negative impact caused by the extreme heat in the PV system, another innovation is also done to reduce the temperature of PV. The method used is conducted in various ways and even utilize the excessive heat as the heat source for greenhouse (Nayak and Tiwari, 2008, 2009, 2010; Ganguly, Misra and Ghosh, 2010; Sonneveld, Swinkels, Bot, *et al.*, 2010; Sonneveld, Swinkels, Campen, *et al.*, 2010; Yildiz, Ozgener and Ozgener, 2012; Aste, Leonforte and Del Pero, 2015). Besides harvesting electrical energy from sustainable energy, the heat which is simultaneously occurred utilising the PVT module (Buker and Riffat, 2015) enable to reduce the heating demand in greenhouse.

Fig. 2-3 shows the architecture of water based PVT module. Generally, the PVT arrangement consists of a solar cell, heat sink, ventilation and insulation sequentially. Several studies performed to improve the efficiency of solar PV panels by lowering the temperature of the solar cell utilise air conditioner, and water (Chow *et al.*, 2009; Agrawal and Tiwari, 2010; Chow, 2010; Sultan and Ervina Efzan, 2018). PVT modules for greenhouse applications are in the centre of interest in recent years (Kamthania, Nayak and Tiwari, 2011; Rekha, Vijayalakshmi and Natarajan, 2013). For example, Nayak and Tiwari (Nayak & Tiwari 2008) investigate a PVT system in a greenhouse under New Delhi climatic theoretically and experimentally. They mention that the system could recover the waste heat from the PV modules of 12.8 kWh, annually. Moreover, the remarkable electrical energy saving can obtain is 716 kWh, annually. Table 2-5 reveals PVT technologies usage and its result for greenhouses.

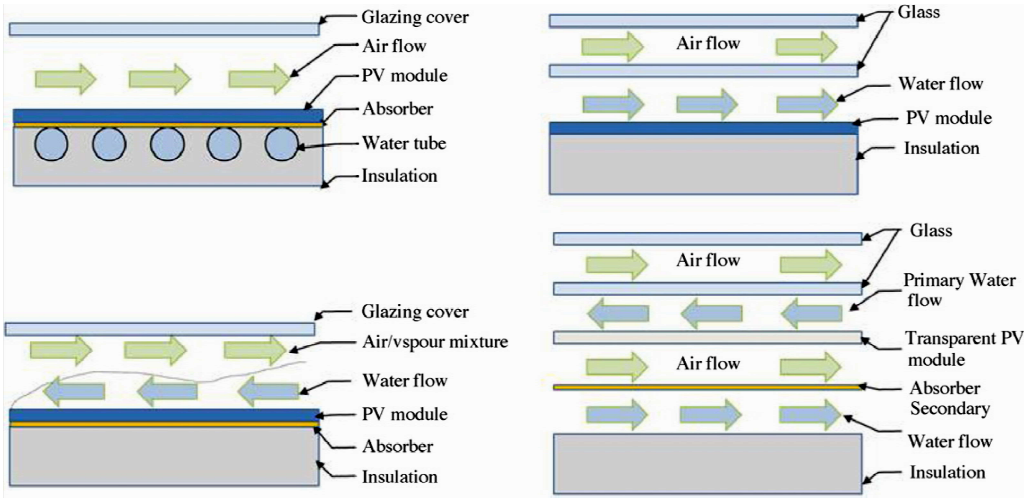


Fig. 2-3. Cross-sectional view of the PVT module (Zhang *et al.*, 2012).

Water as the heat exchanger seems to be the appropriate material to decrease the PV temperature for greenhouse in extreme weather (Chow 2010). Meanwhile, the air conditioner PVT based is more modest and suitable for moderate climate but the efficiency is still below the efficiency of water cooling PVT based (Zhang *et al.*, 2012; Al-waeli *et al.*, 2017). The efficiency of amorphous silicon BiPVT as shown in Fig. 2-4 to produce heat and electrical energy in India reaches 1,531 kWh and 16,209 kWh, consecutively in a year, for the solar panel cooling which use air (Agrawal & Tiwari 2010). While for BiPVT which uses water (BiPVW) for solar cell cooling medium reaches 2,257.6 kWh for thermal energy and 3,229.9 kWh for electrical energy (Chow *et al.*, 2009).

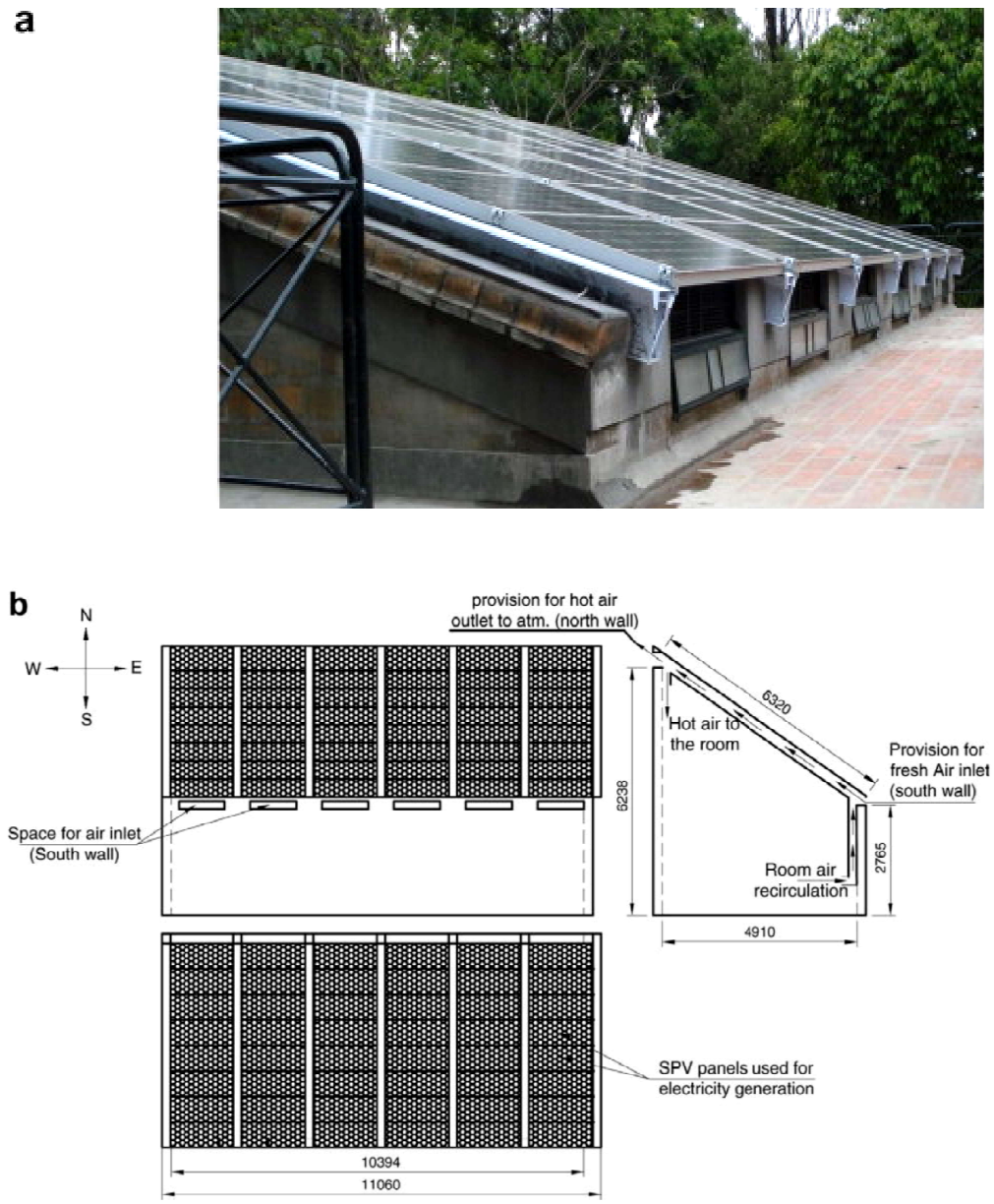


Fig. 2-4. (a) Perspective view of the PVT systems as rooftop, and (b) the waste heat recovery from PV modules (Agrawal & Tiwari 2010)

Table 2-5. PVT technologies used for greenhouses

Reference	PV	Country	Cooler	Result
(Nayak & Tiwari 2008)	0.605m^2 75W	India	Water	Annual electrical energy saving is 716 kWh. Annual waste heat recovery is 12.8 kWh. Exergetic efficiency of PV/T integrated greenhouse is 4%.
(Nayak & Tiwari 2009)	8 PV modules connected in series.	India	Air	7–8 °C enhancements in greenhouse temperature during day and night in sinter season owing to the waste heat recovery. Annual exergetic efficiency of greenhouse is 5.5%. Annual thermal energy is found to be around 24,729 kWh. Annual thermal exergy is found to be around 1006 kWh. Annual electrical energy saving is 805.9 kWh.
(Nayak & Tiwari 2010)	1200 Wp 1.62mx 6.5m	India	Water	Annual overall thermal energy is 29,157 kWh. Annual electrical energy saving is 1185 kWh. Annual thermal exergy is 1366 kWh
(Kamthania et al. 2011)	Semi-transparent PV double pass facade 0.6 m2	India	air	Annual thermal energy is 480.81 kWh. Annual electrical energy is 469.87 kWh. 5–6 °C enhancements in indoor temperature for a typical winter day in New Delhi. Thermal efficiency is 42% and electrical efficiency is 8.4%.
(Al-Helal et al. 2015)	Semi-transparent PV modules 280Wp electricity 1.2mx0.54 m	India	Water	Daily overall thermal energy is 20.5 kWh. Payback is 3.74 and 4.10 years for load and no load condition (CFD Simulation)

2.2.1.4. Concentrating Photovoltaic Thermal (CPVT)

In rural areas where the grid electricity is expensive to access for greenhouse application, concentrating PV/T (CPV/T) modules type is preferred. Therefore, the integration between a concentrator module and a PVT module is one of further innovations which can enhance the thermal and electric energy output (Lamnatou & Chemisana 2013b; Tyagi et al. 2012; Lamnatou & Chemisana 2013a; Chou et al. 2004; Sonneveld, Swinkels, Bot, et al. 2010; Sonneveld, Swinkels, Campen, et al. 2010). The typical CPVT module is shown in Fig. 2-5 (Kostic et al. 2010; Kostić et al. 2010).

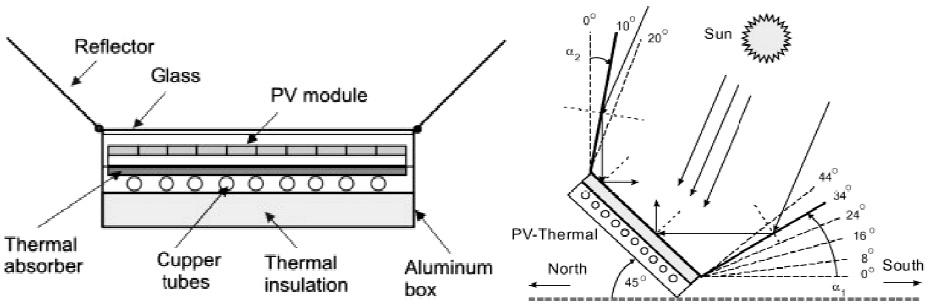
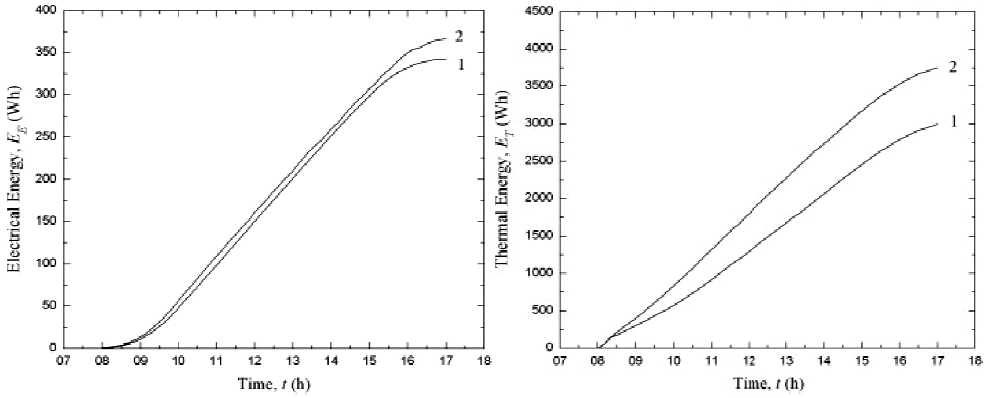


Fig. 2-5. A typical CPVT system for potential utilization in greenhouses (Kostic, Pavlovic and Pavlovic, 2010b, 2010a)

In order to focus the sunlight toward the PV module, on the system is installed reflectors on the edge thus the sunlight could be reflected and concentrated easily. The impact of these techniques on thermal and electrical output compared to the conventional one is revealed clearly in Fig. 2-6 and Table 2-6. Furthermore, innovation is performed continuously to make CPVT module to be more concise and compact by using Fresnel lens as shown in Fig. 2-7, thus it is easily mounted on the roof of greenhouse (Sonneveld et al. 2011). The supreme of Fresnel lens on CPVT make this module very often used in greenhouses. The efficiency of CPVT with various concentrator models is strongly influenced by the incidence

angle of sunlight on the reflector or collector (Kostic et al. 2010; Kostić et al. 2010; Sonneveld et al. 2011). CPVT applications on greenhouse is widely carried out and succeed in supporting the provision of electricity and thermal energy, especially at night or in cold weather (Imtiaz Hussain et al. 2015; Lamnatou & Chemisana 2013b; Sonneveld et al. 2011; Sonneveld, Swinkels, Campen, et al. 2010).



A. B.

Fig. 2-6. Changes of the total generated A. electrical energy, and B. thermal energy by PV/T collector: (1) without reflectors and (2) with reflectors (Kostić et al. 2010)

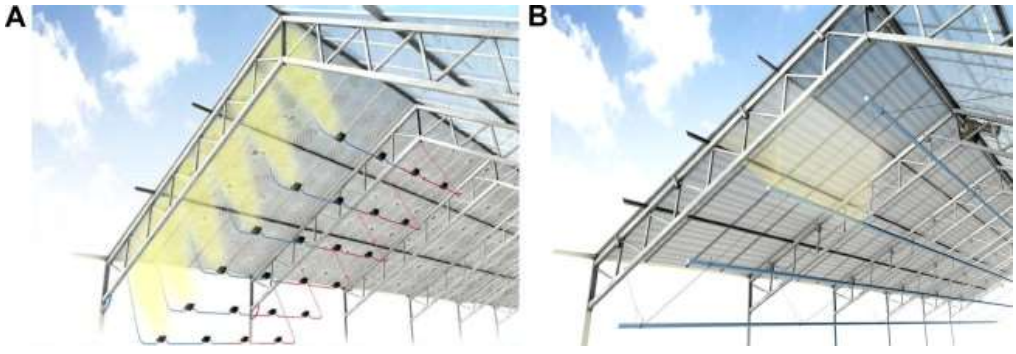


Fig. 2-7. Integration of a greenhouse hood with: (A) normal Fresnel lenses with PV/T modules, and (B) linear Fresnel lenses with PV/T modules (Sonneveld et al. 2011).

Table 2-6. CPVT frequently used in Greenhouses

Reference	PV/T module	Country	Cooler	Result
(Sonneveld, Swinkels, Campen, et al. 2010)	PV modules with Parabolic and tracker	Netherlands	Water	Annual electrical energy is 20 kWh m^{-2} Annual thermal energy is 160 kWh m^{-2} η_{ex} PV: 11.3%. η_{ex} T : 65%
(Del Col *et al.*, 2014)	PV modules with Parabolic and tracker	Italy	Water	Annual electrical energy is 29 20.7 MJ Annual thermal energy is 41 MJ. η_{ex} PV: 23.1%. η_{ex} T : 41.6%
(Sonneveld et al. 2011)	PV modules with Linier Fresnel lenses	Netherlands	Water	Annual electrical energy is 29 kWh/m². Annual thermal energy is 143.89 kWh/m².
(Swinkels *et al.*, 2011)	PV modules with Linier Fresnel lenses and tracker	Netherlands	Water	Annual electricity energy 20 kWh/m². Annual thermal energy 110 kWh/m² η_{ex} PV: 11%. η_{ex} T : 56%

2.2.1.5. Brief findings on PV modules for greenhouse applications

Generally, from previous literature reveals that PV module are very promising to partially cover the energy demand of greenhouses (heating, cooling, lighting and ventilation) (Sethi et al. 2013; Awani et al. 2015; Mehrpooya et al. 2015; Zhang et al. 2015; Xu et al. 2014; Hassanien et al. 2016; Benli & Durmuş 2009; Imtiaz Hussain et al. 2015; Ganguly et al. 2010; Yildiz et al. 2012; Carlini et al. 2012; Joudi & Farhan 2014) due to its sustainability energy resources. Thus, the use of PV modules becomes very dominant since it is flexibility in use and enables shorter payback period (Eltawil & Omara 2014; Michael et al. 2015; Singh & Agrawal 2015; Yildiz et al. 2011; Peng et al. 2013; Rosenbloom & Meadowcroft 2014; Kandilli 2013; Qoaider & Steinbrecht 2010; Yano et al. 2010; Nayak & Tiwari 2010; Querini et al. 2012; Nakoul et al. 2014; Cossu et al. 2014; Aste et al. 2015; Carlini et al. 2012; Yildiz et al. 2012; Pérez-Alonso et al. 2012). However, the biggest problems which commonly happen in PV modules like overheating decrease the efficiency and life time especially for hot and extreme climate (Muneer & Kotak 2016; Cossu et al. 2014) if an appropriate cooling system is not utilized. In addition, PV modules which are installed on the rooftop of greenhouses could reduce the PAR needed by the plantation for photosynthesis.

Insufficient lighting and shading on the crops affect the quality, size, colour and taste of the vegetation (Yano *et al.*, 2010; Kadowaki *et al.*, 2012; Fan *et al.*, 2013; Cossu *et al.*, 2014; Yano, Onoe and Nakata, 2014). Concentrating PV modules provide significant energy production (Chemisana, 2011), area-savings and can resolve the lighting problem in greenhouses. Nevertheless, they have to be performed along with a proper cooling system. To resolve this problem, plant production and the energy production via solar panel and intensive farming systems should be

considered. Building of huge photovoltaic greenhouse farms that generate energy savings on a great scale with some openings would be promising. This technique could maintain the temperature inside steady by decreasing the heat loss from the walls and rooftop.

Therefore, the semi-transparent PV Module might be appropriate choice as the rooftop. The PV modules usually covered with transparent glass in order to protect the modules against bad weather such as dirt and overheating. PV is positioned above the double glazing air filling. Recent works show that the semi-transparent PV module has more electrical efficiency than opaque PV module (Kamthania et al. 2011). This is because a semi-transparent PV module will transmit the incoming sunlight, as the result, the shadow on the leaves will not happen under the PV module. In addition, this type of PV module will not experience excessive heat so that the efficiency will be relatively stable similar to the efficiency at its temperatures work. Additionally, semi-transparent amorphous silicon PV could save energy up to 30% and energy cost about $12,000 per year when applied on a building (Chae *et al.*, 2014).

Chow et al. reported that natural-ventilated PV double-glazing could decline the power consumption of air-conditioning by 28% as compared to conventional single absorptive glazing system in Hong Kong (Tin Tai Chow et al. 2009). Moreover, the PV glazing can transmit the incoming light which is almost identical with the incident light spectrum (Fath et al. 2002), and also reduce the radiation thus very good to insulate the greenhouse (Han et al. 2010).

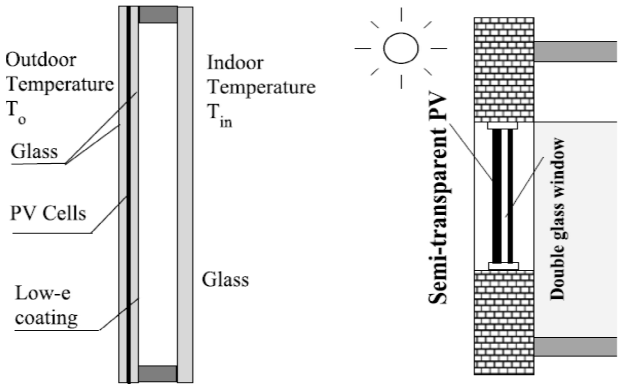


Fig. 2-8. Schematic diagram of PV double-glazing with low-e coating (Han et al. 2010)

Fig. 2-8 shows that PV cell is attempted at outside face on the sunlight. It purposes to reduce the excess heat inside the room, thus the cooling demand can be reduced. Low-e coating determines the U-value of the glazing since huge amount of the long-wave radiation can be reflected. Using this technique, the excess heat on the STPV could be reduced and increase the electricity conversion efficiency. Since the double glazing has low U-value, thus the heat energy inside the greenhouse could be maintained much better and reduce the heat loss significantly. Therefore the heating demand in night or winter will decrease as well.

2.2.2. Solar Thermal Collector

Principally, a solar thermal collector works by collecting heat from the absorbed solar radiation. Solar thermal collectors are often known as solar hot water modules. However, solar thermal collectors can be designed with concentrator or without (Sonneveld, Swinkels, Campen, *et al.*, 2010; Kamthania, Nayak and Tiwari, 2011; Imtiaz Hussain, Ali and Lee, 2015). Concentrated solar thermal collectors could generate electricity by heating the working fluid to drive the turbine, while solar thermal collectors are commonly used in residential and commercial house for space heating

since its simplicity, therefore this system widely used in greenhouses (Benli and Durmuş, 2009; Patil and Gawande, 2016).

2.2.2.1. Flat Plate Solar Collector

Flat Plate Solar Collector (FPSC) is one of solar collector modules rarely used in greenhouses. One of the causes is its low thermal efficiency. In heating experiment using 10 pieces of flat plate water solar collectors in Turkey (Fig. 2-9), this system is able to provide 18-23% of thermal energy every day for 3-4 hours (Benli & Durmuş 2009). In addition, 10 m^2 of flat plate collectors are used to provide heat energy for greenhouse of 130 m^2 in Tehran in order to be stable at 18 °C. It is noted that thermal supply which could be met by flat plate collector is only 30% in greenhouse simulations (Mehrpooya et al. 2015).

The performance of flat plate solar collector on the greenhouse is improved with a combination of the various types of absorber plate, the type of fluid used, and the heat storage material to the heat storage system. For instance, Attar et al. (Attar *et al.*, 2014) used a type of flat plate solar collector as heat collector combined with ground as a coolant in a greenhouse in Tunisia. A flat plate solar collector with area of 2.18 m^2, 200 L of hot water storage tank, and 200 L of cold water storage tank can be used to control greenhouse (10 m^3) temperature at 20 °C (Fig. 2-10). Although in the winter this system still needs electricity from the grid but the system is promising enough to provide good condition for the pepper plants.



Fig. 2-9. Air circulation lines and solar collectors (Benli & Durmuş 2009)

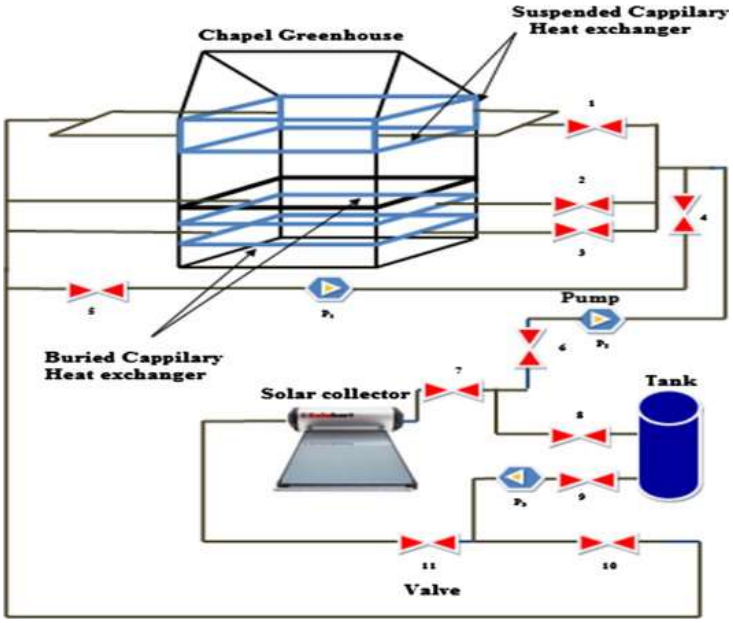


Fig. 2-10. A greenhouse control system equipped with flat plate solar collector (Attar *et al.*, 2014)

2.2.2.2. Solar Evacuated Tube

The effort to increase the solar collector performance such as lowering the heat loss has been done by vacuum system. Solar evacuated tube has two cylindrical tubes with vacuum in between to reduce the conduction and convection heat losses as seen in Fig. 2-11. The inner tube is coated with thermal absorber hence could produce temperatures of 80°C up to 120°C (Belessiotis, Kalogirou and Delyannis, 2016).

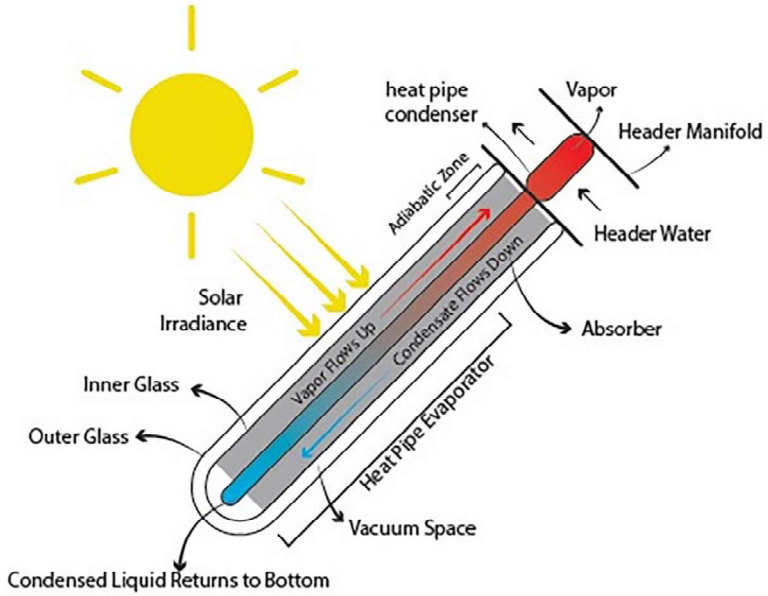


Fig. 2-11. An evacuated tubes schematic (Elsheniti, Kotb and Elsamni, 2019)

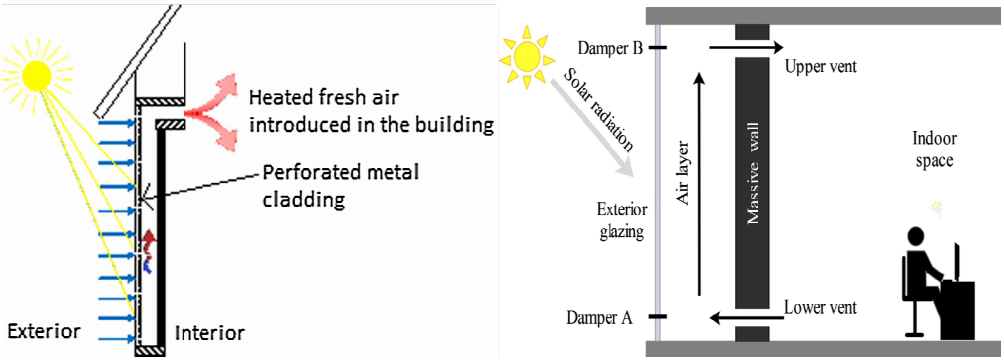
In full sunshine condition, flat plate collector has higher efficiency than evacuated tube collectors. However, in cloudy or extreme cold condition the energy produced by evacuated tube is slightly better than the flat plate collectors (Belessiotis, Kalogirou and Delyannis, 2016). Therefore, some improvement have recently done such as adding fin arrays to the heat pipe condenser (Brahim, Dhaou and Jemni, 2014), adding more heat tubes (Azad, 2018), and vary the back surface emissivity (Zheng *et al.*, 2014).

The solar evacuated tube mainly used in solar absorption cooling, adsorption cooling, desalination and desiccant dehumidification systems (Elsheniti, Kotb and Elsamni, 2019). Mostly the range inlet water temperature are near ambient 20-40 °C for water heating application (Ayompe and Duffy, 2013; Bracamonte *et al.*, 2015).

2.2.2.3. Air-based solar collector

Another promising system which is potentially used in greenhouse is air-based solar collector. It could be used to preheat the fresh air for heating, drying, and maintain a minimum temperature during winter with a lower

investment cost (Bejan *et al.*, 2018), even can produce temperature outlet up to 45°C (Goyal and Tiwari, 1999). This technology generally used as solar wall and classified into opaque type (Croitoru *et al.*, 2016) and glazed (Trombel wall) (Zhang *et al.*, 2016).



a. b.

Fig. 2-12. a. Opaque solar collector (Croitoru *et al.*, 2016), and b. Solar glazed solar collector model (Zhang *et al.*, 2016)

The work principle of the Trombel wall is to absorb solar radiation and convert its energy for heating, ventilating to provide thermal comfort in buildings. The Trombel wall usually consists of a massive wall, an exterior glazing cover, and an air channel between the massive wall and the cover. The massive wall is used to absorb the heat and release it by heat convection, conduction and radiation between the massive wall and room air and distribute also via ventilation to the indoor space as seen in Fig. 2-12b.

Meanwhile, as seen in Fig. 2-12a, the unglazed transpired solar collector principle is when the sun's radiation heats the perforated metal cladding, the heat will be transferred to passing airflow. A fan can be placed on the top outlet side in order to create a negative pressure, forcing the air circulation. Perforated opaque solar collectors are often used in buildings due to the low cost and efficient (Zhang *et al.*, 2016), such as in Canada, US and Europe (Leon and Kumar, 2007). When direct outdoor air heating is

desired, this technique is recommended to be applied due to high efficiency un to 72% (Gunnewiek, Hollands and Brundrett, 2002).

2.2.2.4. Linear and Spot Fresnel lens

Fresnel lens is frequently utilized in solar thermal collectors. Besides the high light concentration ratio and lower heat loss, its inexpensive and good impact to the thermal efficiency cause Fresnel lens useful for greenhouse applications (Imtiaz Hussain & Lee 2014). In addition, cost optimization and analysis between a concentrated and non-concentrated solar collectors in terms of design system, application, and turnover period shows that concentrated solar collectors is better (Sait *et al.*, 2015). The type of concentrator is also an important parameter on the overall system efficiency. For instance, Hussain et al. (Imtiaz Hussain et al. 2015) comparing the performance of Linear solar collector and Spot Fresnel Lens (LFL and SFL) for heating in two identical greenhouse in South Korea. Both solar collectors have dual-axis solar trackers to ensure that sunlight will exactly fall vertically with solar collector (Fig. 2-13). Experiment results shows that the SFL had 7-12% higher performance compared to LFL collector. Besides, the availability of energy per unit area and thermal efficiency of SFL are also higher than the LFL (Fig. 2-14).

The use of solar tracker on the solar collector is very beneficial to increase the efficiency of solar collectors, although only one axis (Chemisana et al. 2009; Sonneveld et al. 2011). Solar tracking application in greenhouses can maximize the solar radiation directly, especially if it has dual-axis tracker (Imtiaz Hussain et al. 2015). In addition to its small size, heat loss from the Fresnel lens concentrator is also small (Wu et al. 2012) so it seems suitable to apply it in greenhouses in cold climate.

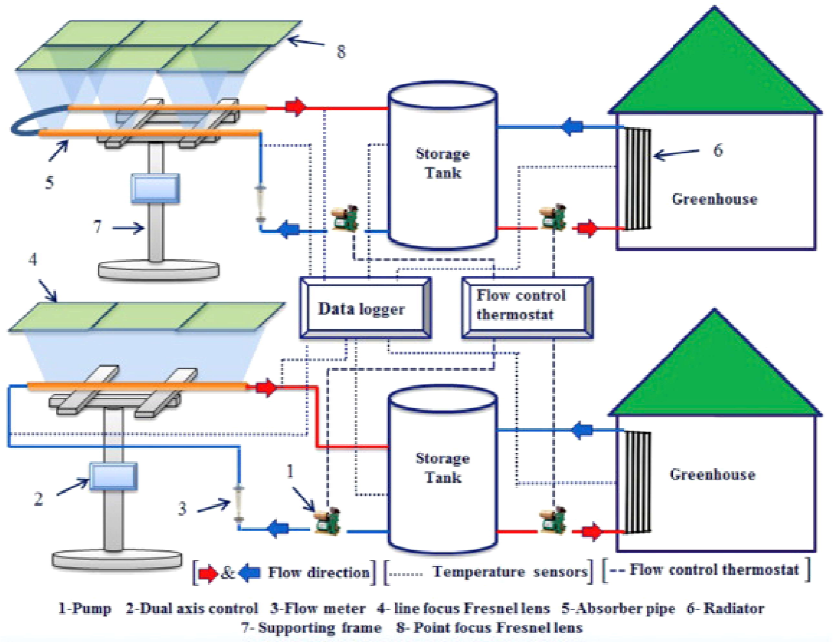


Fig. 2-13. Schematic diagram for SFL and LFL collectors (Imtiaz Hussain et al. 2015)

Reference (Sonneveld et al. 2011) uses Linear Fresnel lens with a factor 25 to obtain thermal energy and electrical energy to meet the needs of a greenhouse measuring 36 m^2 (Fig. 2-7.b). LFL is placed inside the double glass to protect the lens from dirt and damage due to the weather. The LFL covers the entire roof of the greenhouse. In this case heat energy is more needed than the electrical energy so that the use of solar collector depends on the needs of the system. The system is able to generate 29 kWh/m^2 electrical energy and 143.89 kWh/m^2 heat energy, annually. Moreover, the electrical energy needs for its tracker system requires only less than 2% of the total electrical energy per year.

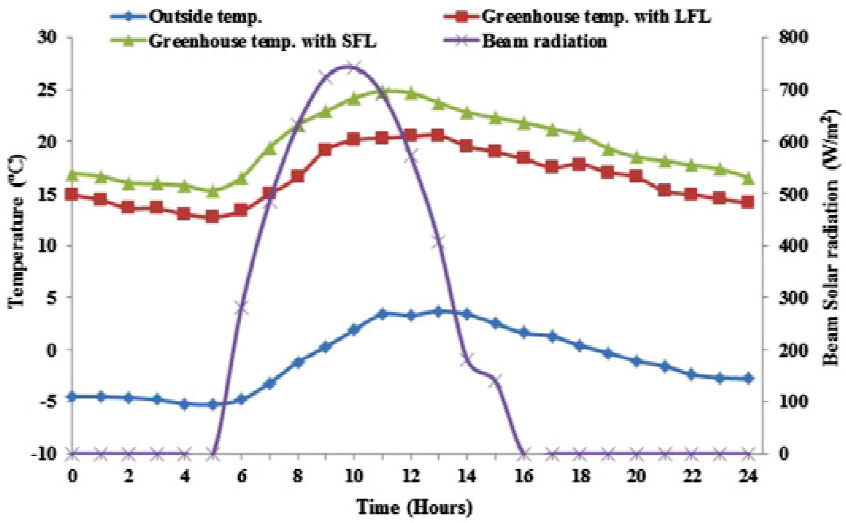


Fig. 2-14. Daily temperature variation and solar radiation (Imtiaz Hussain et al. 2015)

2.2.2.5. Brief findings on solar thermal collectors for greenhouse applications

Concentrating solar collectors are the best option for delivering energy at high temperatures which is not achievable with flat plate collectors nor evacuated tube solar collectors and air-based solar collectors. However, evacuated tube collectors are potential to be used in cold climate due to their low heat loss leading to higher efficiency and low cost. Moreover air-based solar collectors are also potential to be applied for temperate climate. Even though, concentrating collectors are more suitable for greenhouse heating (Kalogirou, 2004) because of their higher temperature outputs. Among all concentrating collectors, Fresnel lens seems to be the most appropriate choice due to its high precision, excellent optical efficiency, and low-cost (Leutz *et al.*, 2000).

The invention of Fresnel lens from polymethyl methacrylate (PMMA) has a big impact on the solar energy industries because of its high thermal stability and refractive index (Xie et al. 2011). Basically, Fresnel lens could be categorised based on the concentration ratio like a line and point focus

with lower and higher concentration ratio, respectively. The point focus type are more preferred due to its small receiver results in lower heat losses (Wu et al. 2012). For application in a greenhouse, Fresnel lens can easily supply the thermal energy required for space heating when utilising a single/dual-axis tracking receiver (Sonneveld, Swinkels, Campen, et al. 2010; Imtiaz Hussain et al. 2015; Sonneveld & Swinkels 2010). Furthermore, Fresnel lenses can also be integrated with PV/T modules for thermal and electric power generation, whereas for lighting the vegetable crops use the separated diffuse solar radiation (Sonneveld et al. 2011).. The average thermal efficiencies of Fresnel lens and other concentrating collectors are higher than non-concentrator collectors due to their higher concentration ratios and lower heat losses (Imtiaz Hussain & Lee 2014). In terms of energy and price, Fresnel lens collector are cheaper and better compared with those of a parabolic trough collector (Simms, 1987). Linear power density, measured in kW per longitudinal linear meter of the receiver for parabolic trough collectors is 5 kW/m whereas in Fresnel receivers it is between 10 and 15 kW/m. The amount of available energy per unit aperture area of Fresnel lens collector for dual axis tracking system is higher than single axis tracking of the parabolic trough collector (Sait *et al.*, 2015).

2.2.3. Thermal Energy Storage

In a greenhouse, microclimate needs to be maintained consistently to support the natural environment of plantations. In many regions, this consistency is hard to achieve naturally without the presence of technology. Therefore, the stability of temperature, humidity, and lighting that meets the greenhouse need must use technology which provides hot and cold to maintain temperatures. Similarly, electricity is needed to maintain the moisture and artificial lighting, especially at night. Therefore

the combinations of various technologies have been conducted including heat storage. The following are derivative technology of heat source collector which is used as thermal energy storage as well as for cooling in greenhouse.

The thermal heat storage efficiency is strongly affected by material of the storage and the container that is used. Researchers have used various type of heat storage materials such as gaseous material like air (Kooli et al. 2015; Joudi & Farhan 2014; Bouadila et al. 2014), liquid like water (Redpath 2012; Tang et al. 2011; Dagdougui et al. 2011; Ziapour et al. 2016), as well as solid material such as Phase Change Material (PCM) (Silva et al. 2016; Benli 2011; Benli & Durmuş 2009). To maintain the thermal energy content for day and night, well-insulated thermal energy storage is a crucial factor. Thus, the storage commonly uses tank with heat insulator or else such as pipe buried in the soil (Bansal *et al.*, 2010; Benli, 2011; Mongkon *et al.*, 2014).

2.2.3.1. PCM for thermal energy storage

PCM is used as a thermal energy storage material since the 1980s, and to be one of the promising thermal energy storage. Solar air heater combined with PCM capable of providing a total daily thermal energy in the greenhouse at 18-23% or 3-4 hours per day. Most likely used PCM are $CaCl_2{\cdot}6H_2O$, $Na_2SO_2{\cdot}10H_2O$, Polyethylene glycol (PEG) and paraffin (Benli & Durmuş 2009). Benli reported that by utilising *calcium chloride hexahydrate* type PCM in Greenhouse with $30m^2$ ground area (Fig. 2-15) in Turkey could manage overall COP system of 2.0-3.5 (Benli, 2011).

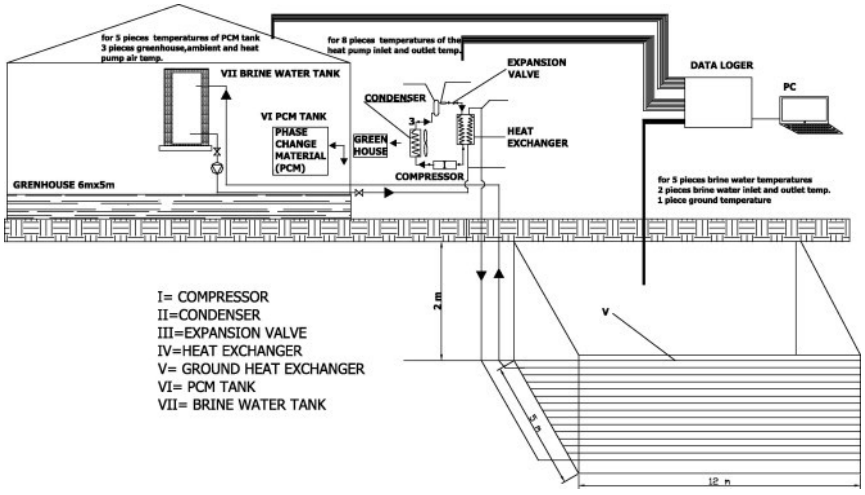


Fig. 2-15. The main component including PCM and schematic of the GSHP (Benli, 2011)

Moreover, PCM utilisation as a thermal energy storage is also done to keep the room temperature of a greenhouse at the level of 15 °C at night while the temperature outside reaches 13 °C as shown in Fig. 2-16 (Kooli *et al.*, 2015). This tomatoes greenhouse uses shutter to minimise heat loss at night and to increase the room temperature by 2 °C higher than one without the shutter. PCM commonly used along with solar heat collector as shown in Table 2-7 and characteristics is shown in Table 2-8.

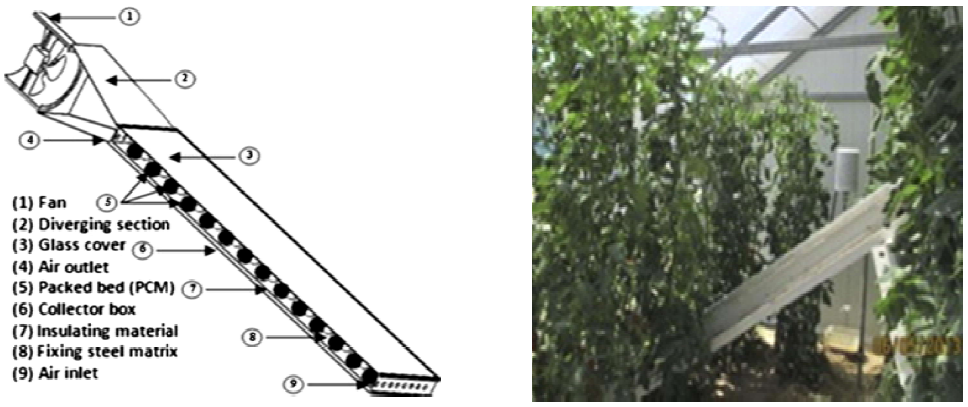


Fig. 2-16. Schematic view of SAHLSC and its placement inside the greenhouse (Kooli *et al.*, 2015)

Table 2-7. PCM utilization with other heat collector in greenhouse

Countries	Demand		Combination Technology	Reference
	Heating	Cooling		
Turkey	18–23% of total heating for 3-4h, DT=6-9 °C	-	solar air collectors	2009 (Benli & Durmuş 2009)
Turkey	1.7kW, 18.6 °C for 7h	-	ground-source heat pump	2011 (Benli, 2011)
Tunisia	13.7 MJ, 12°C for 10h, 31% of total heating	-	solar air collectors	2014 (Bouadila *et al.*, 2014)
Tunisia	123W, 15°C for 17h from 13°C	-	solar air collectors	2015 (Kooli *et al.*, 2015)

Table 2-8. Thermal Properties of PCM (Kooli *et al.*, 2015).

Material	Melting point (°C)	Heat of fusion (kJ/kg)	Specific heat (kJ/kg °C)		Density (kg/m^3)		Thermal conductivity (W/m °C)	
			Liquid	Solid	Liquid	Solid	Liquid	Solid
Capsule (AC27)	27	192.6	2.22	1.42	1710	1530	0.58	1.05

2.2.3.2. Soil for thermal energy storage

In addition to PCM in the storage tank, ground has its own very specific characteristic which has capability of storing thermal energy throughout the year in stable way. Many researchers have used ground as heat exchanger in its efforts to cool down the temperature of greenhouse, or use it as a heat sink for the heat pump. In addition, ground has well

potential to deposit thermal energy generated by a solar collector (Xu et al. 2014; Zhang et al. 2015) and other active cooling (Yildiz, Ozgener and Ozgener, 2011; Mongkon *et al.*, 2013) as seen in Table 2-9.

Meanwhile, in tropical country where the cooling demand is high, the ground heat exchanger is one of passive cooling widely used because it consumes low energy and environmental-friendly. For instance, in Thailand, the cooling system in the greenhouse uses horizontal earth tube system (HETS). An iron pipe of 38.5m length is buried about 1m depth with a centrifugal blower to blow the air on the north side of the greenhouse which is covered from the sunlight. As the results, the COP in the summer, monsoon, and winter are 3.56, 2.04 and 0.77, respectively. It is found that in the summer, the cooling efficiency is about 74.84% (Mongkon *et al.*, 2013).

In addition, Xu et al. (Xu *et al.*, 2014) have successfully used ground as a place to store thermal energy in the U-tube heat exchanger. It is reported that in the winter, the greenhouse heating in area of 2304 m^2 in China could be provided by utilise the heat from 500 m^2 of solar collectors. The total energy produced achieved 331.9 GJ, and 208.9 GJ used for greenhouse space heating (Fig. 2-17). The electrical coefficient of performance (ECOP) system is calculated to be 8.7 better than conventional heat pump heating system.

Table 2-9. Underground storage for Greenhouse

Countries	Demand		Combination Technology	Area (m^2)	Reference
	Heating	Cooling			
China	208.9 GJ	-	solar water collectors	2304	(Xu *et al.*, 2014)
China	$4.60 \cdot 10^7$ kJ	-	solar water collectors	231	(Zhang et al. 2015)
Thailand	-	COP: 0.77–3.56	Blower fan	15	(Mongkon *et al.*, 2013, 2014)
Turkey	-	$\dot{Q}_r$= 4.74kW	Fan and PV	48.51	(Yildiz et al. 2011)
India	11.55MJ	18.87MJ	Fan	34.32	(Tiwari *et al.*, 2006)

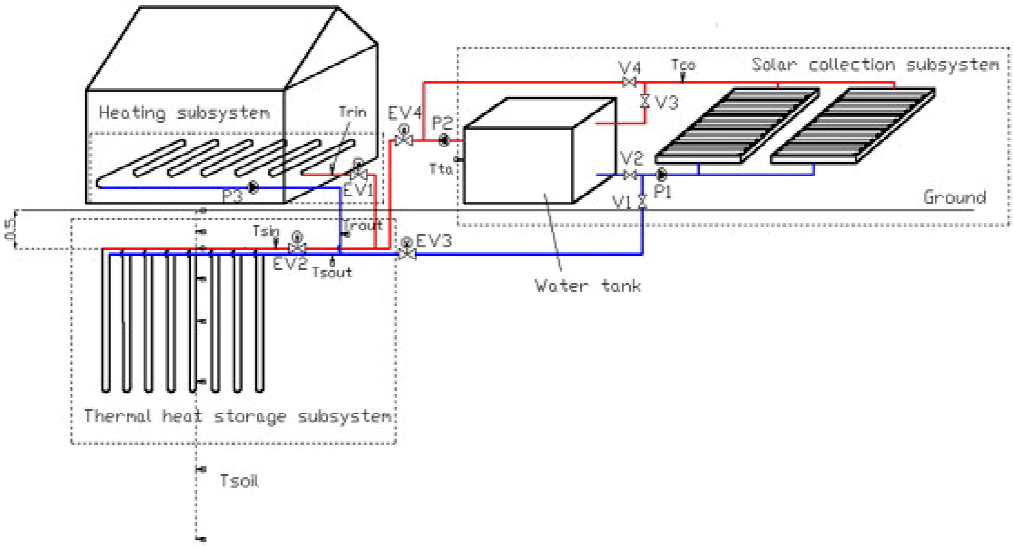


Fig. 2-17. Schematic diagram of a solar heating system (Xu *et al.*, 2014)

Fig. 2-17 shows the major components of a solar heating system in the greenhouse equipped with a seasonal thermal energy storage system. This seasonal thermal energy storage uses vacuum tube solar collector array,

water tanks, borehole thermal energy storage (BTES) unit, and heat distribution pipe. Table 2-10 shows the specification of equipment used in the system.

Table 2-10. Design Detail of The Solar Heating System (Xu *et al.*, 2014)

Specification	Number
Surface area of the greenhouse (m^2)	2304
The solar collection surface area (m^2)	500
The water tank capacity (m^3)	20
Circulating pump power for the collector tank loop (W)	1500
Circulating pump Power for the tank-BTES loop (W)	400
U-tube heat exchanger (UHXs) specification:	
Number	130
Diameter (mm)	32
Depth (m)	10
Distance between two adjacent boreholes (m)	1.4

The boreholes for storage thermal energy are designed to be directly beneath greenhouse around 10 m below the ground surface. The total soil volume is 4979 m^3 with 130 pieces of UHX (U-type heat exchangers) pipes which are planted vertically and parallel as deep as 10 m. Between the UHX pipes, it does not use insulation so that the surrounding ground can be heated by conduction. At the ground level, it is partially covered with concrete. The heat, from the thermal heat storage unit, is flowed into heat exchange tube which is placed on the shelves above the ground and distributed into the greenhouse by convection and radiation. Besides the space heating, heat from the thermal heat storage under the ground is also distributed in the greenhouse's floor as shown in Fig. 2-18.

Fig. 2-18 shows that the temperature of borehole thermal energy storage (BTES) changes with various levels of measurements in ground depth use for storing seasonal heat energy. It seems that the more superficial layers

of ground to the surface, the temperature change will be more sensitive to the ambient temperature. Moreover, by utilising this system the interior temperature of the greenhouse can be maintained at 13-15 °C throughout the winter.

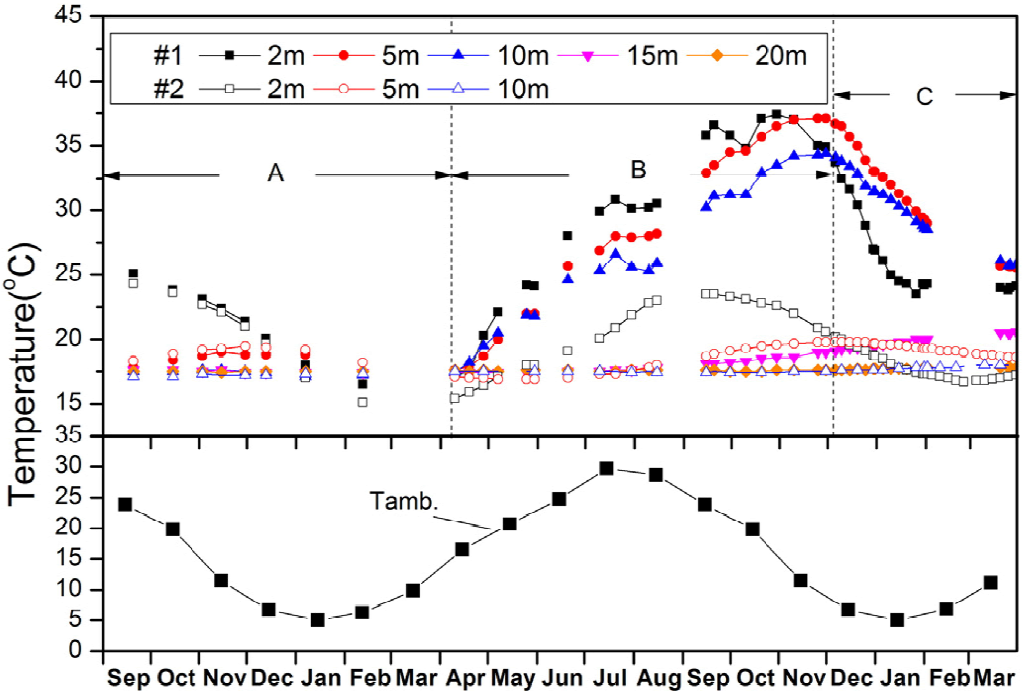


Fig. 2-18. Temperature evolution of the underground storage unit: A – Before charging; B – Charging process; C – Discharging process (Xu *et al.*, 2014).

Other researcher (Zhang et al. 2015) performs simulations using TRNSYS and designing a system of solar seasonal storage solar soil (SSSHS) to heat greenhouse. The schematic of the system as shown in Fig. 2-19, uses underground U-pipe and connected to a solar collector whereas the greenhouse heating diffuser is capillary radiators. By using the design parameter figured in Table 2-11, the thermal energy dissipated into the groundwater tank is 92.8% and 12.7% of annual energy loss. There is a big difference in the soil temperature when using heat storage with no heat storage (Fig. 2-20). In addition, the greenhouse temperature could be maintained at 12 °C in the wintertime. Nevertheless, to get the exact and

fit composition between temperature needs and technology used, justification required load heating of the greenhouse is important. The load heating must be less than the amount of heat received or absorbed by the solar collectors plus heat stored in the ground and reduced by heat loss on the ground.

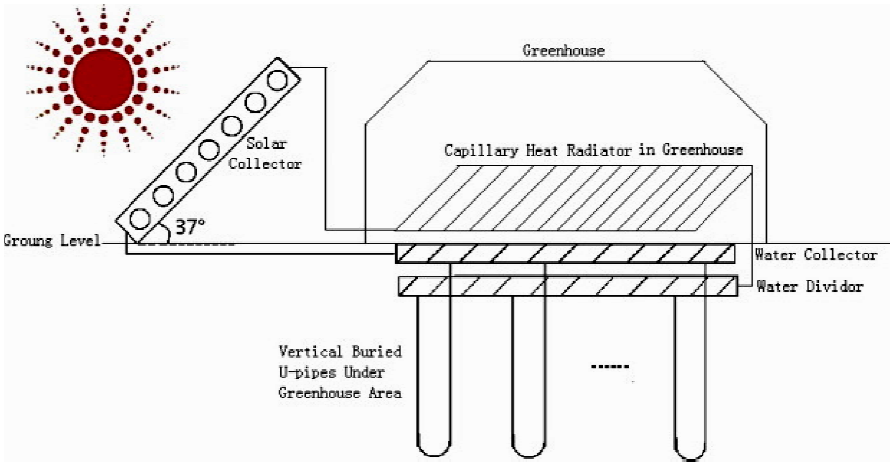


Fig. 2-19. The diagram of the seasonal solar soil heat storage system (Zhang et al. 2015)

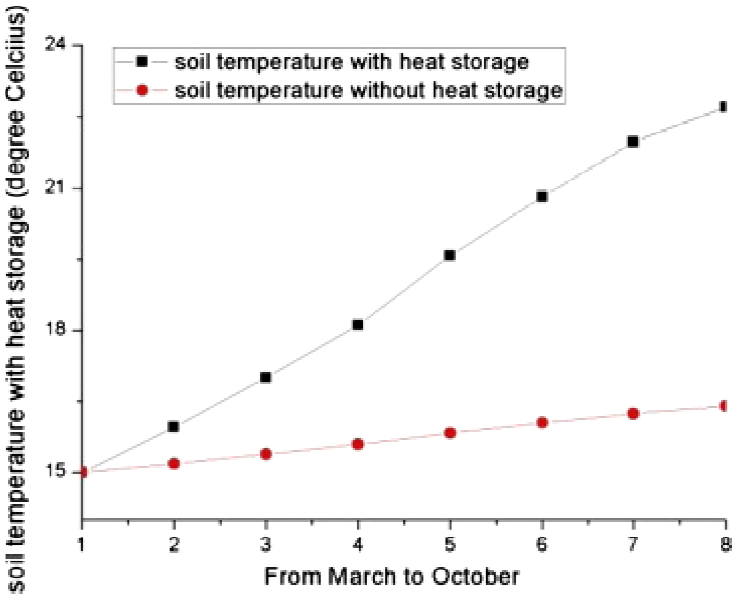


Fig. 2-20. Comparison of the soil temperature without and with heat storage (Zhang et al. 2015).

Table 2-11. System Parameters (Zhang et al. 2015)

Specification	Size
Size of greenhouse	38.5 m(L) × 6 m(W) × 3 m(H)
Envelop structure	Metal stand and bi-layer plastic membrane
Solar collector subsystem:	
Solar collector area	30 m^2
Type	Vacuum-tube
Orientation and tilt angle	South, 37°
Capacity of the water tank	1000 kg
Capillary radiators:	
Tube diameter	2 mm
Coverage area	77 m^2
U-pipe heat exchangers:	
Tube diameter	32 mm
Well depth	15 m
Number of the wells	25
Distance between wells	3 m
Hydronic subsystem:	
Pipe diameter	80 mm
Actual average flow rate	7.1 m^3/h

2.2.3.3. Solar air heaters in thermal energy storage

Solar air heaters aided PCM is widely used and proven can maintain the greenhouse temperature at 15 °C under Tunisia climatic (Bouadila *et al.*, 2014). Besides, this system can meet the 31% of heating demand at night. This result have a good agreement with Kooli et al. (Kooli *et al.*, 2015) that the system increases the effectiveness overall system to keep the indoor temperature at 15 °C, whereas the outside temperature is 8 °C.

In addition to providing thermal energy, air can also be used for cooling purposes, especially in tropical climates area. Cooling using air and Horizontal earth tube system (HETS) is able to lower the temperature of the greenhouse which is equal to ambient conditions required by Dahlia and head lettuce plants that require a temperature of 10-24 °C and relative

humidity of 40-50% (Mongkon *et al.*, 2014). The system performance is better when the wind speed in HETS tubes increased. It was found that the COP cooling for wind speed at 9 m/s and 12 m/s to be 1.9 and 2.87, respectively.

2.2.3.4. Solar water heaters in thermal energy storage

Besides air, water is a well-known material that can be used as thermal energy storage too. Water owing a characteristic fluid property which does not easy to react become a dangerous compound but corrosive to some metals. Zhang et al. (Zhang et al. 2015), utilise common water as the conductor material for the collected heat from the collector into the pipe heat exchanger. The hot water flows through the heat storage tank to under floor heating of the greenhouse The water in the tank serves as buffer for the system to improves the overall system performance applied as illustrated in Fig. 2-19.

2.2.3.5. Brief findings on thermal energy storage for greenhouse applications

The literatures show that the use of ground heat storage is able to control the temperature in the greenhouse which is appropriate for most of the plants. Heat exchanger is backfilled with soil and assembled around the walls of a greenhouse (capillary buried heat exchanger). For instance, the system could maintain the greenhouse temperature stable at 20 °C (Attar *et al.*, 2014). It has a good agreement with Xu et al. that by utilising ground thermal energy storage, the greenhouse temperature can be maintained at a temperature of 13-15 °C although in winter (Xu *et al.*, 2014). It is found that the deeper of the borehole to a certain depth, the more stable ground temperature and not affected by ambient temperature. This stability has benefits as a stable heat source for greenhouse heating.

However, naturally, the heat spreads because of conduction process therefore the heat loss from seasonal heat storage in the soil for a year is large enough around 12.7% (Zhang et al. 2015). Thus, it is recommended to use insulation on tha land used as a store of heat in order to reduce the heat loss.

Besides for greenhouse space heating, earth–air heat exchangers (EAHE) are potential for greenhouse cooling applications. Al-Ajmi et al. (Al-Ajmi, Loveday and Hanby, 2006) clearly reveal that an indoor temperature reduction of 2.8 °C during summer peak hours. Greenhouses having EAHE are expected to have the potential for reducing cooling demand by 30% over the peak summer season, which is remarkable. Enlarging the diameter of the pipe will improve the COP significantly rather than increasing the length of pipe or depth (Mongkon *et al.*, 2014). As the length of the pipeline and depth will lead to high pressure drop along the pipeline and increase the energy consumption for the blower.

However, in soil based thermal energy storage systems, piping is expensive. Thereby, using a conventional borehole method, this cost can be reduced. But the injection method is only possible if using single pipe thus some innovation is needed to substitute method of loop on U-tube.

2.2.4. Heat Pump

Recently, heat pump become a famous technology in providing heating and cooling at once in a building. This characteristic led to a widespread application, particularly for greenhouse (Awani et al. 2015; Mehrpooya et al. 2015; Russo et al. 2014; Chou et al. 2004). In addition, heat pump also can provide cooling at greenhouse when the weather is too hot (Valiño et al. 2010; Benli 2013; Benli 2011; Benli & Durmuş 2009). Moreover, heat pumps can also be used to control the relative humidity of the air in the

greenhouse. Heat pump can be functioned as the producer of heat effect in the winter by utilising electrical energy. Because of its double functions, heat pump is widely used in maintaining the temperature stability in the greenhouse.

2.2.4.1. Ground source heat pumps (GSHP)

Compare to other types of heat pump, Ground source heat pumps are favoured by the growers for greenhouses due to its high performance. the ground heat exchanger pipes could be installed horizontally (Benli, 2011) or vertically (Benli, 2013) or slinky (Esen & Yuksel 2013) . Fig. 2-21 shows the installation of ground heat exchanger horizontally. But the system of ground-source heat pump should meet the requirement that the ground temperature must be greater than the ambient temperature to produce heat (Benli, 2011).



Fig. 2-21. The greenhouse and the ground heat exchangers buried 2 m depth (Benli, 2011)

The installation of vertical ground source heat pump (VGSHP) and horizontal ground source heat pump (HGSHP) is illustrated in Fig. 2-22 (Benli, 2013). Both vertical and horizontal system of ground-source heat pump mounted on two models-sized glass greenhouses which are identical and each has an area of 30 m^2. The HGSHP is planted as deep as 2 m, while VGSHP is planted as deep as 60 m by drilling. Types of crops used in

the greenhouse are cucumber and tomato. The heat pump use R-22 refrigerant and to avoid the freezing of the circulating pump, 25%-30% of ethylene glycol water mixture is used. From the experimental results, the COP values of HGSHP and VGSHP are determined to be 3.3 and 3.5, respectively. It is concluded that VGSHP is more efficient than HGSHP. However, it is noted that the first installation cost of VGSHP is higher than that of HGSHP.

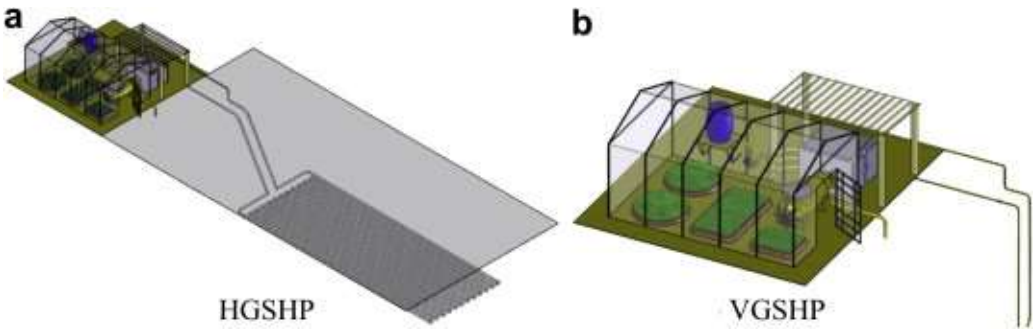


Fig. 2-22. The greenhouse with; a) the horizontal ground heat exchangers, (b) vertical ground heat exchanger (Benli, 2013).

Solar and ground coupled heat pumps can be used to improve the system performance for heating and cooling purposes (Esen, Inalli and Esen, 2006). A computational prediction of a flat plate solar collectors assisted heat pump system with seasonal thermal energy storage in hemispherical surface tanks is investigated annually by Yumrutas and Unsal (Yumrutaş and Ünsal, 2000). The storage tank is embedded 1 meter below the ground surface. They find that for small burial depths, the temperature of the storage tank and the annual COP improved reasonably.

Furthermore, Badescu (Badescu, 2002) investigates the performance of parallel circular tubes thermal energy storage (TES) united into solar air heaters assisted heat pump for heating. The said work results that the COP of heat pump and exergy efficiency decline with increasing TES unit length.

Meanwhile, the electrical energy-saving found to be 50% when the thermal energy storage unit is charged.

Additionally, energetic and exergetic efficiencies of ground-coupled heat pump systems as a function of depth trenches for heating season is investigated by Esen et al. (Esen *et al.*, 2007). The results show that energetic and exergetic efficiencies of the system increase when increasing the heat source (ground) temperature. Moreover, Zhai et al. (Zhai *et al.*, 2011) that a combination of geothermal heat pump and thermal solar collectors is suitable for heating. Another work is done by Xi et al. (Xi, Lin and Hongxing, 2011) that these kinds of combination system can increase the annual efficiency by 26%.

Wang et al. (Wang *et al.*, 2010) evaluate a combined solar collector-geothermal heat pump system with seasonal storage too. The storage is done in winter seasons while in the summer the ground acts as storage to absorb the excess heat from the building. In winter, solar collectors are given priority over heat pump and the building is heated by combined system. As the results, the heat extracted from the ground by the heat pump is found to be around 75% of the heat stored by solar seasonal thermal storage. The combined system has several characteristic benefits. It is suitable from both economic and technical points of view and can be used instead of conventional systems (Bakirci *et al.*, 2011).

2.2.4.2. Air source heat pump (ASHP)

Compared to ground source heat pump, air source heat pump is rarely used in greenhouse because of the low performance due to ambient air temperature fluctuation (Safa, Fung and Kumar, 2015). However, improvements on ASHP technology in terms of performance, installation simplicity, and low-cost make it interesting. For instance, Tong et al. (Tong

et al., 2010) successfully applied multiple (ten) ASHP on a greenhouse with a floor area of 151.2 m^2 at night in winter. In order to keep the indoor greenhouse temperature at 16 ^oC when the outside temperature reach 6 ^oC, the average hourly COP determined to be 4. Even though the system consumes high energy, the energy consumption is up to 65% lower than a kerosene heater (Tong *et al.*, 2012).

Yang and Rhee use ASHP for greenhouse cooling and heating device supplemented with electrical heater (Yang and Rhee, 2013). The work principle of the system is storing the excess heat in the greenhouse utilising ASHP to the storage water tank. In cold season, the heat from the storage is taken and distributed to the greenhouse space. As the result, the energy conservations are determined to be maximum of daily 76.3% and monthly 25.7%.

2.2.4.3. Water source heat pump (WSHP)

Another type of heat pump is water-source heat pump which is branch of ground source heat pump type. Water-source heat pump uses ground water as the heat source. Zhou et al. utilise water-source heat pump for heating in a cold climate school building in Zhangye, China (Zhou *et al.*, 2017). The system mainly consists of two sets of heat pump systems in parallel and each system includes a small-capacity heat pump in series with a high-capacity heat pump. As the results, with inlet water temperature stable at 11°C the indoor temperature could be maintained at 18°C with COP of small and high capacity heat pump were 6.24 and 3.67, respectively.

Even though, the water-source heat pump has a high efficiency the cost is still high especially for the borehole part. Therefore, the application should be calculated carefully to meet the need and budget. Moreover,

optimisation of the heat pump system needs to be improved. Kang et al. optimised their new water-source heat pump and calculated the energy saving (Kang *et al.*, 2017). They compared the design method of the new system to the traditional water-source heat pump. Based on the experiment, it was found that the traditional heat pump's compressor power consumption was higher than the new one lead to reduction operating cost achieved 17%. Likewise, Subić et al. (Subić, Nastić and Bekić, 2015), also found that using geothermal waters in growing flowers and vegetables in their glasshouses enables the realization of a production cycle during the whole year and decrease the energy cost in Serbia.

Furthermore, Moon et al. (Moon *et al.*, 2014), used ground water-source heat pump to heat the greenhouse in Korea. A greenhouse area of 3.185 m^2 was supplied with 320.000 kcal/h resulting COP of the heat pump around of 3.4-4.0 and COP of the system represented as 3.0-3.5. In addition, the system could recharge up to 63% of intake water and maintained the indoor temperature at 20°C where the intake water temperature was 12-18°C during all year.

2.2.4.4. Brief findings on Heat pump for greenhouse applications

Heat pump technology still more expensive compared to conventional heating, however in terms of cost, performance, and payback period heat pump are highly preferred due to its dual features, heating and cooling. Air-source heat pump (ASHP) is potentially used in temperate climate, however ASHP frequently severed with cold ambient air temperature. Hence, hybrid air-water-source heat pump (HSHP) could be used as the alternative.

Besides, water-source heat pump (WSHP) become a good option since the water-source temperature is more stable and higher COP but having high

cost investment when using deep ground water and freezing. Therefore, among these types of heat pumps, GSHP is the most widely used in greenhouses due to lower operational costs and higher COP ranges compared to conventional heat pumps.

Consequently, GSHP is the most widely utilised in greenhouses due to higher COP ranges and low cost in operational compared to another type of heat pumps. Since compressor become the most higher energy consumption by 84% of total power consumption (Benli, 2011). Hence, utilising low power compressor should be a priority consideration to reduce the electricity consumed. Besides, to increase the heat pump efficiency there are some aspects should be taken into accounts such as defrost cycle, losses due to non-continuous operation, external temperature fluctuation, refrigerant fluids mixture, and complexity due to heat exchanger between condenser and evaporator (Mempouo, 2011).

2.2.5. Lighting

Usually vegetable and fruit plants have specific growing requirements in terms of lighting; wavelength spectrum of 400-700 nm known as Photosynthetically Active Radiation (PAR) (Benli & Durmuş 2009; Yano et al. 2014; Benli 2011); temperature (Benli & Durmuş 2009; Russo et al. 2014); and humidity (Benli & Durmuş 2009). For example, Pepper (*Piper*) needs a warm condition of about 20^{o}C (Attar *et al.*, 2014). In sequence, Orchid (*Dendrobiums*), Edamame *(Glycine max L.),* Lemongrass *(Cymbopogon citratus)* need the temperatures between 18-30^{o}C, 20-25^{o}C, and 22-38^{o}C. Also, those plants need specific humidity between 30-90% in order to be able to grow and bear fruit optimally such as being reviewed by (Chou *et al.*, 2004). Therefore, in providing a good seedling place in a greenhouse, lighting becomes one of the primary concern (Sun et al. 2012;

Vidyavathi et al. 2012). Nevertheless, there are several types of plants whose growth are not overly influenced by too much sunlight such as Lulo or Naranjilla fruit (*Solanum quitoense Lam*.), and Panax ginseng (Jang *et al.*, 2015). In that respect, investigation on the effectiveness of lamp types used and wavelength of the light emitted from artificial lighting in greenhouse is crucial (Lamnatou & Chemisana 2013b; Choi et al. 2015; Ilieva et al. 2010).

It has already known that the best light for crops is sunlight. Sunlight is very needed for photosynthesis which is planted inside greenhouse. Plants absorb sunlight especially wavelength of visible light for photosynthesis (Singh et al. 2015; V et al. 1989; Ilieva et al. 2010). Given the importance of lighting to the total production of vegetables and fruits in greenhouse farming, then some numbers of studies are conducted (Trouwborst et al. 2011; Cuce, Riffat, et al. 2015; Messinger & Lauerer 2015; Choi et al. 2015; Singh et al. 2015; Ilieva et al. 2010; Cossu et al. 2014).

Therefore, in providing the natural light facade material is vital in greenhouses in terms of visible light transmittance. Some recommended cladding materials such as glass, polycarbonate (twin wall), polyethylene (single layer) and acrylic can transmit PAR of 90%, 75%, 88% and 86%, respectively (Both, 2013).

2.2.5.1. Sodium lamps

Most often, High Pressure Sodium (HPS) lamp is used in greenhouses to prevent the ornamental plants flowering. Chrysanthemum, pot chrysanthemum, and velvet sage (Blanchard & Runkle 2009) having a good response to HPS lamp. Such a lamp is easy to be manipulated lead to determine the time of flowering plants for adapting to market needs efficiently.

Cymbidium orchids grown under different intensities of night interruption lighting is investigated by Kim et al. (Kim *et al.*, 2015). They find that the activity of photosynthesis in plants increases as radiated under low-intensity of HPS light bulbs. However, the amount of chlorophyll in its leaves decreases as too long exposure period. Therefore, utilising HPS lamp for artificial light must be applied along with good fertiliser to maintain the quality of the flowers.

Wojciechowska et al. (Wojciechowska *et al.*, 2015) compare the effect of LED and HPS light exposures (200 μmol m^{-2} s^{-1} PPFD; 16 h photoperiod) on the growth and quality of lamb's Lettuce (*Valerianella Locusta*) within the greenhouse in a winter season of Poland. Relative humidity and temperature in the greenhouse environment are measured in the range of 58 ± 2%, ± 17 °C in 2012/13, and 54 ± 2%, ± 16.3 °C in 2013/2014 term. The average CO_2 concentration is in the range of 380-400 ppm.

Table 2-12 shows that the highest growth and the quality is obtained from exposure of 90R / 10B LED lamps whereas the poorest growth is observed under HPS lamp (control). Spectral characteristics of the said lamps utilized in testing are shown in Fig. 2-23. Light treatments used in this experiment are control (HPS), 100R (100% red LED), 50R/50B, 70R/30B, 90R/10B (various percentage of red (R) and blue (B) LED) and white LED.

Table 2-12. Average growth of plants in cm (Wojciechowska *et al.*, 2015)

	2013	2014	Mean
Control	2.75	1.6875	2.21875
100R	2.0625	2.5	2.28125
White	1.625	3.25	2.4375
70R/30B	4.875	3.4375	4.15625
50R/50B	3.9375	4.875	4.40625
90R/10B	5.75	5.25	5.5

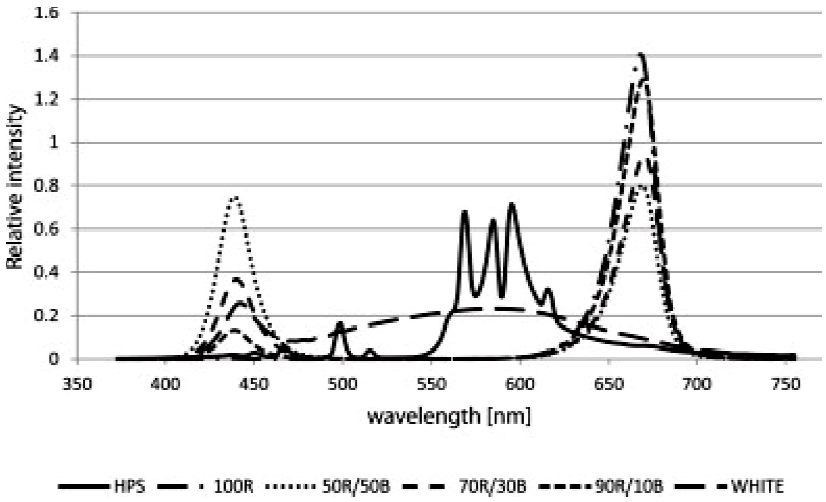


Fig. 2-23. Spectral characteristics of lamps utilized in lamb's lettuce greenhouse cultivation (Wojciechowska *et al.*, 2015)

2.2.5.2. LED

The most effective and efficient technology used in greenhouses as alternative lighting is Light Emitting Diode (LED). They do not generate too much excessive heat thus it is very durable, having specific monochromatic colours at certain wavelengths, and low-cost (Poulet *et al.*, 2014). The specific wavelength owing by LED able to fulfil the PAR required for photosynthesis (Choi et al. 2015). Therefore, LED capable to provide a positive impact on plant growth hence increase the crop production and its quality.

The greatest influence on the growth of plants is the wavelength of blue (448 nm), red (634 and 661 nm) or combination of blue and red (3:7) (Kitazaki et al. 2015; Choi et al. 2015; Wojciechowska et al. 2015; Ilieva et al. 2010; Singh et al. 2015). Wavelengths can be seen in Fig. 2-24 with total photon flux of 100 μmol m^{-2} s^{-1} in any light source. LEDs provide better plant growth compared to artificial light sources (Islam *et al.*, 2012; Wojciechowska *et al.*, 2015). For instance, red leaf lettuce likes green LED the most compared to white fluorescent (Johkan *et al.*, 2012).

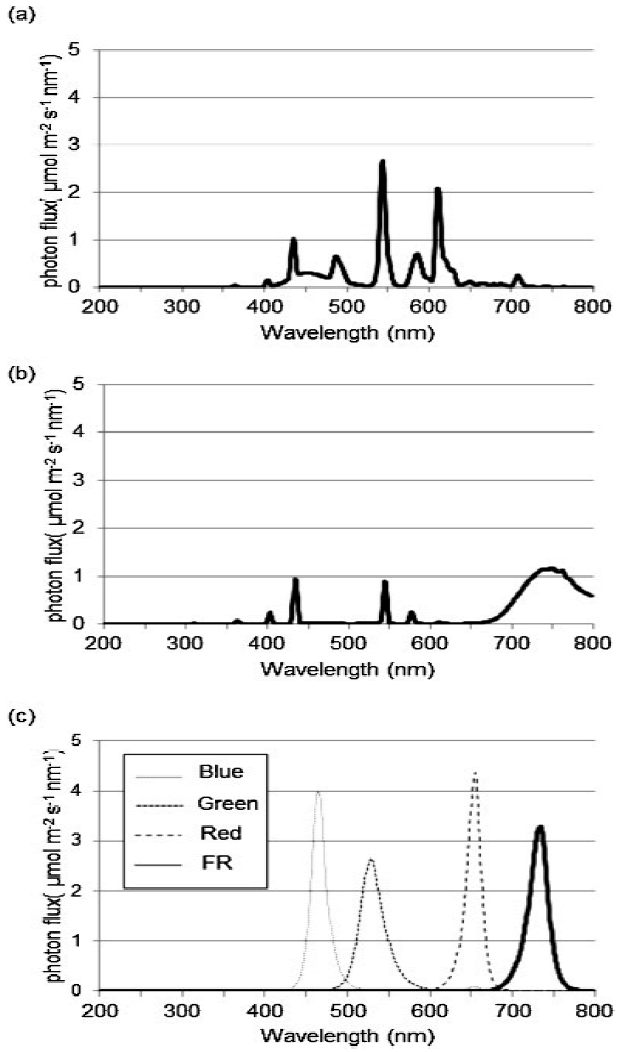


Fig. 2-24. Spectral photon flux distributions of (a) White-FL; (b) FR-FL; (c) LEDs (Kitazaki *et al.*, 2015)

However for some plants, another type of lamps such as fluorescence lamp having better results rather than LED. For example, under far-red fluorescent lamps, it is found that the fastest growth is demonstrated by sprouts (Kitazaki *et al.*, 2015) as illustrated in Fig. 2-25. The figures show (a), (b) sprouts that are grown under white fluorescent lighting for 4 days before far-red irradiation, (c) irradiation with far-red fluorescent from above and white fluorescent lighting from the side for 2 days, (d) irradiation with white fluorescent from above and far-red LED from the side for 2 days, (e) irradiation with far-red fluorescent from above for 2 days,

(f) irradiation with white fluorescent from above for 2 days. In terms of durability and economic, LED has longevity and inexpensive (Singh et al. 2015).

Besides, LED uses very small energy therefore the growers could maximise the crops and benefits (Poulet *et al.*, 2014). LEDs' lifetime shown in Fig. 2-26 is reported up to 100,000 h. In simple calculation, in a daily use of 14 h, LEDs are expected can be used of 19 year lifetime. Fig. 2-26 describes of (a) bottom view of the combined four panels, each containing nine LED clusters with each cluster composed of four red LEDs and one blue LED, and zoom on one panel showing the position of red and blue LEDs, and (b) top view showing ductwork for fan-driven heat rejection from the back of the LED array. Table 2-13 depicts the comparison effect of artificial light source to plantation.

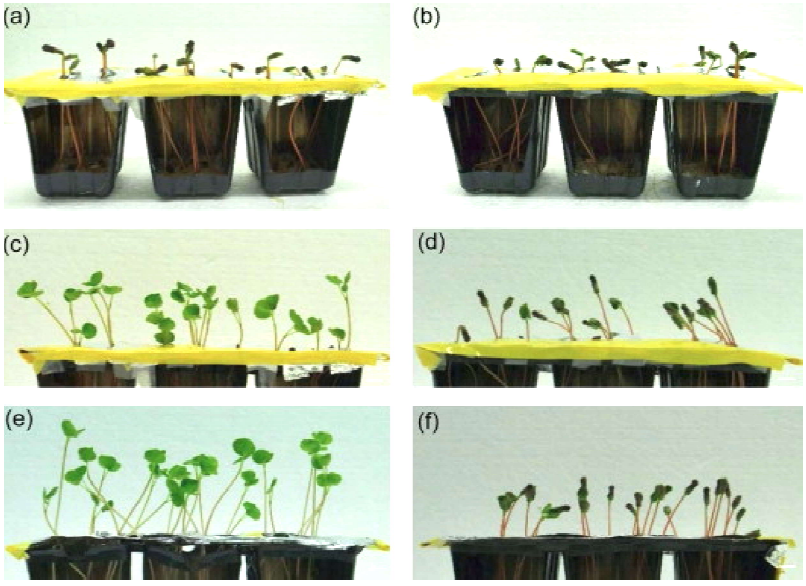


Fig. 2-25. The effect of far-red irradiation of different organs of sprouts on cotyledon opening (Kitazaki *et al.*, 2015)

Table 2-13. The effectivity of artificial Light Source to Plants

Reference	Lamps	Plants	Note
(Kitazaki *et al.*, 2015)	fluorescent	Sprouts	-
(Johkan *et al.*, 2012)	green LED	red leaf lettuce (*Lactuca sativa L.*)	Compared with white LED
(Wojciechowska *et al.*, 2015)	90R/10B	lamb's Lettuce (*Valerianella Locusta*)	-
(Kim *et al.*, 2015)	low-intensity of HPS	Cymbidium hybrids 'Red Fire' and 'Yokihi'	the amount of chlorophyll decreases due to too long exposure of HPS lamp
(Cossu *et al.*, 2014)	HPS Plantastar 400 W	Tomato	-
(Ren, S. Guo, et al. 2014)	RB20 (red/blue=8/2)	Gynura bicolor DC (*Asteraceae, perennial herb*)	investigate the essential oil profile and terpenes accumulation

2.2.5.3. Brief findings on lighting for greenhouse applications

As the aforementioned, crops need enough light with a certain wavelength for their photosynthesis. As long as there is a suitable light, the plants will produce their own food and keep growing no matter the time is (Ren, S.-S. Guo, et al. 2014; Ouzounis et al. 2014; Poulet et al. 2014; Ren, S. Guo, et al. 2014; Choi et al. 2015; Wojciechowska et al. 2015; Ilieva et al. 2010). In that respect, in order to attain sustainable harvesting and good quality, a greenhouse must use the most effective and energy-saving for daily purpose.

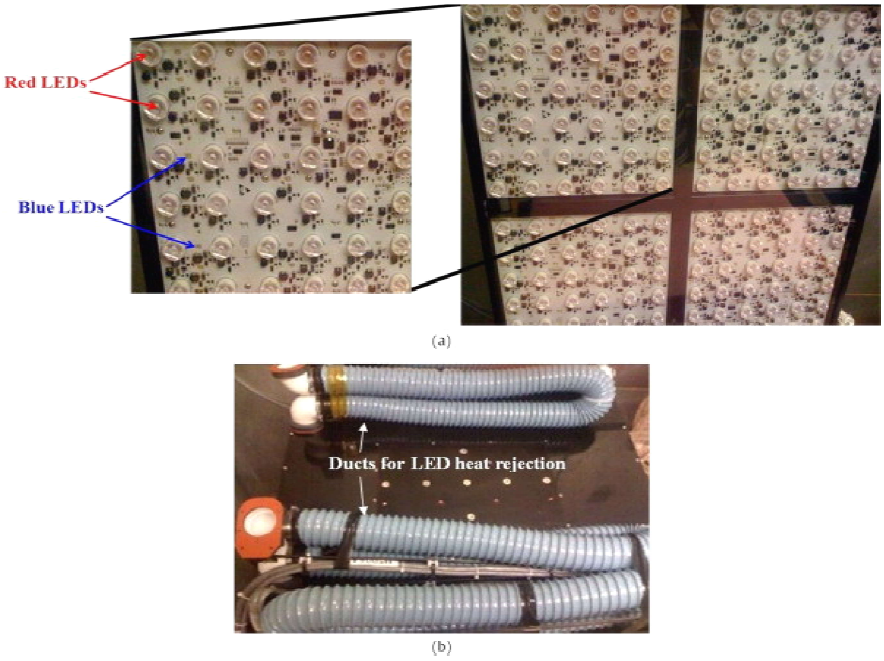


Fig. 2-26. LED array available in the market (Poulet *et al.*, 2014)

Compared to HPS, LEDs can provide lighting related energy saving up to 75% per year. LEDs have three colours (red, blue and green) which are commonly utilized in greenhouses as they positively affect the plant growth (Singh et al. 2015) and have remarkably long lifetime (Principi & Fioretti 2014). Besides of its colour, it is also proved that intensity effects to the crops growth rate. Therefore, it has to be ensured that the crops should get enough intensity from the LEDs by set the distance between lamps to the leaves.

2.2.6. Windcatcher

Windcatcher is a wind control system for ventilation purpose. The purpose of the windcatcher is to decrease the temperature inside a building. The wind is captured from the roof and then cascaded down to the whole room of the building (Esfeh et al. 2012; Khan et al. 2008). The incoming wind temperature is lower than the air in the room causes a difference pressure inside the space, so that the warm air pushed upward and out of the roof

of the building as shown in Fig. 2-27. Windcatchers can be designed for multi-functional purposes as illustrated in (Suleiman & Himmo 2012).

Windcatchers do not need electricity for its operation, only fully mechanical (Afshin *et al.*, 2016). Hence, windcatchers are eco-friendly system and widely used in Middle East countries to ensure the immediate air circulation in the building. In addition, this kind of technology is cheaper and healthier than AC and Hiller. Windcatcher are commonly installed on the roof with a high variation and has vary opening system on it (one-sided, two-sided, four-sided and polyhedral sided).

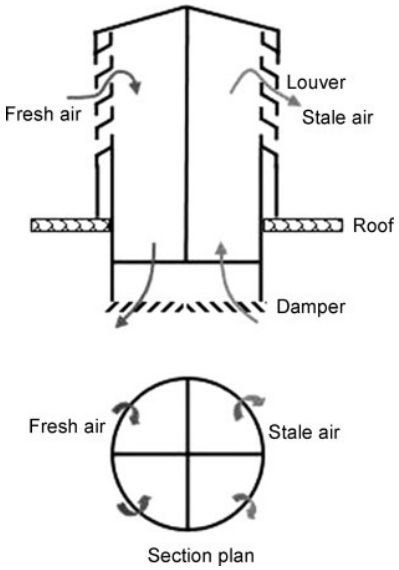


Fig. 2-27. Architecture view of Monodraught™ windcatchers (Su *et al.*, 2008)

Monodraught™ windcatchers is a commercial product that is normally mounted on the roof of the building. The simulation and experiment results show that the effect occurs because of the pressure of the opening room wall. In addition it is shown also that the installation over the roof top have a good effect rather than mounted on a flat roof where there is a larger region of flow separation exists (Su *et al.*, 2008).

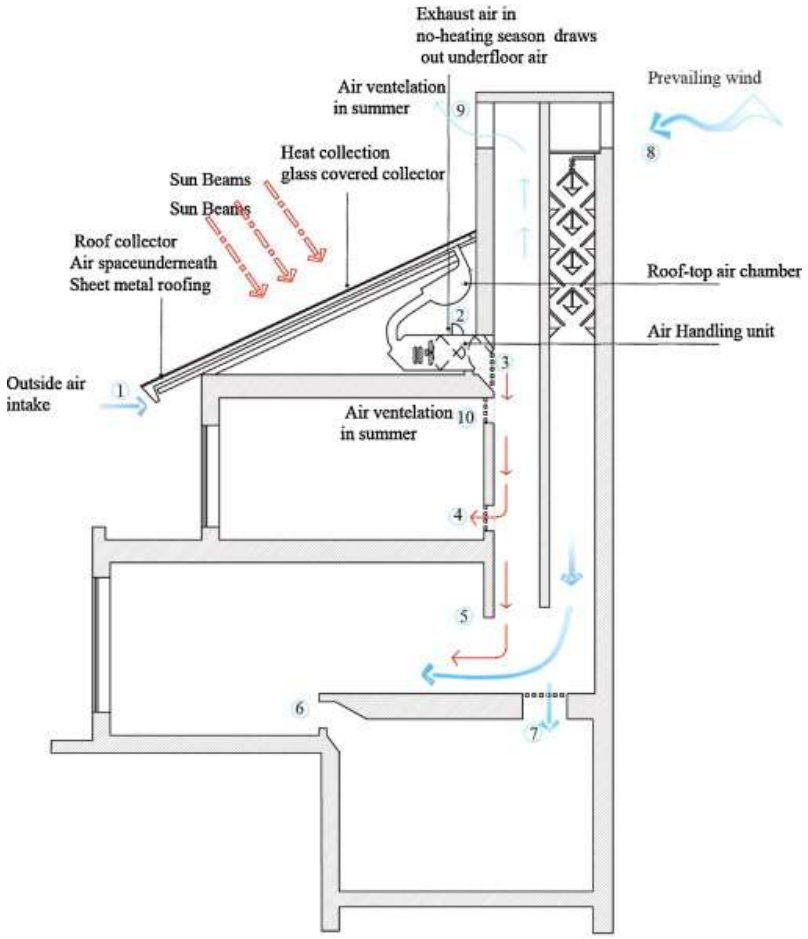


Fig. 2-28. Alternative windcatcher installation for summer by (Suleiman & Himmo 2012)

Due to its advantages, windcatchers might be used to dissipate the excess heat inside the greenhouse. Thus, they can reduce the HVAC energy consumption particularly in extreme climatic region (Suleiman & Himmo 2012; Saadatian et al. 2012; Heidarinejad et al. 2008; Attar et al. 2014).

The performance of windcatchers is influenced by the number of opening owned toward the room net airflow generated as illustrated in Table 2-14. The table shows that the sensitivity of the performance of different wind catchers related to the wind angle reduces by increasing the number of openings (Montazeri, 2011). The use of natural ventilation in greenhouses may be appropriate because the heat from the plant during summer or

during the day will flow out above the roof as a result of differences in the density of hot and cold air (Mongkon *et al.*, 2014).

Table 2-14. The effects of different opening and airflow to Windcatcher (Montazeri, 2011).

Windcatcher Type	Wind angle Degree	Rate of net air flow (m^3/s)	
		Experiment	CFD
Two opening	0	0.029	0.031
Two opening	15	0.028	0.029
Two opening	30	0.17	0.019
Two opening	45	0.022	0.023
Two opening	60	0.014	0.016
Two opening	75	0.015	0.017
Two opening	90	0.015	0.017
Three opening	0	0.026	0.030
Three opening	15	0.026	0.029
Three opening	30	0.025	0.026
Three opening	45	0.017	0.018
Three opening	60	0.016	0.019
Four opening	0	0.024	0.029
Four opening	15	0.018	0.026
Four opening	30	0.018	0.028
Four opening	45	0.027	0.029
Six opening	0	0.021	0.024
Six opening	15	0.027	0.029
Six opening	30	0.028	0.029
Twelve opening	0	0.025	0.026
Twelve opening	15	0.027	0.027

Even though the opening should be installed along with protection, otherwise pest and diseases could enter into the greenhouse due to high humidity and high temperatures (Mongkon *et al.*, 2014). Therefore it needs

surrounding environment protection by using insect-proof nets (Kumar et al. 2009).

2.2.7. Insulation system for greenhouse application

The greatest heat loss occurred in building is on the window part, as well as in greenhouse, even worse, occurred in all parts of the walls and roof (Konroyd-Bolden & Liao 2015; Hee et al. 2015; Imtiaz Hussain et al. 2015; Russo et al. 2014). Almost all of greenhouses using plastic or glass which have high-power transmission, but poor overall heat transfer coefficient (Ghoshal & Neogi 2014). Therefore, 40% of the total energy used in a building is for heating (International Energy Agency, 2013). From that perspective, insulation for greenhouse facades plays a key role in terms of cost and energy control.

Thereby, in most existed greenhouses, polycarbonate sheet becomes a favourite to be installed due to its energy-saving and high sunlight transmissivity (Fabrizio, 2012). Among others type of materials commonly used for greenhouses, polycarbonate is more lightweight, cheap, boasts the best fire rating among plastic products and has excellent insulation properties. These are lead to energy-efficient agricultural buildings, simple design and safe construction. Moreover, polycarbonate twin wall type having low thermal transmittance as seen on Table 2-15 which led to more effective in energy-saving.

The effectiveness of insulation is therefore of vital importance to keep the energy stored for a long time (Joudi & Farhan 2015; Ziapour et al. 2016; Tang et al. 2011; Kooli et al. 2015; Benli 2011; Benli & Durmuş 2009; Dagdougui et al. 2011; Joudi & Farhan 2014; Bouadila et al. 2014; Zhang et al. 2015). Therefore, glazing products best choice is very critical in this respect for energy-efficient and eco-friendly greenhouse applications.

Table 2-15. Optical and thermal properties of panels and some typical double glazing units (Moretti et al. 2014)

	Transmittance		U-value
	Light	Solar	[W/m^2 K]
Polycarbonate	0.72	0.69	1.84
Conventional double glass unit	0.81	0.72	2.70
Double glass unit with Low-e	0.74	0.52	1.70
Double glass unit with low-e, argon filling	0.74	0.43	1.10

2.2.8.1. Glazing

As previously stated, facade plays a significant role in minimising heat losses from a greenhouse. Many types of glazing can be used for this purpose, lower U-value better heat loss reduction such as shown in Table 2-16. An improvement has also been made to create a hybrid vacuum glazing integrated with an air gap and low-e coating. The U-value reaches 0.24 W/m^{2}K for the sample integrated with three low-e coatings (Fang *et al.*, 2013) as illustrated in Fig. 2-29. Another work on vacuum glazing (Cuce and Riffat, 2015) reveal that the U-value of vacuum tube window can achieve below 0.40 W/m^{2}K. The schematic of the said vacuum tube window technology is figured in Fig. 2-30.

Besides that novel glazing, heat insulation solar glass (HISG) which is illustrated in Fig. 2-31 can be considered. This modern technology permitted the technology to reduce the heat loss which is noticeable. Moreover, it is self-cleaning and can produce electricity toward energy-saving. According to an investigation, heat insulation solar glass could generate electrical power more than conventional PV glazing since nanolayer TiO2 coating applied. For instance, regular PV power output is around 34.1W while heat insulation solar glass is about 36.6W. In addition,

in terms of optical properties, HISG offers many benefits as shown in Table 2-17.

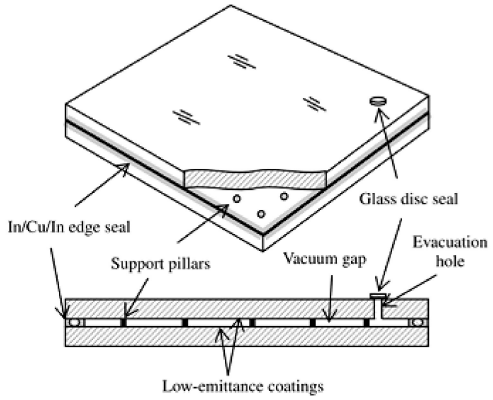


Fig. 2-29. Schematic cross section of double pane evacuated glazing (Fang *et al.*, 2009)

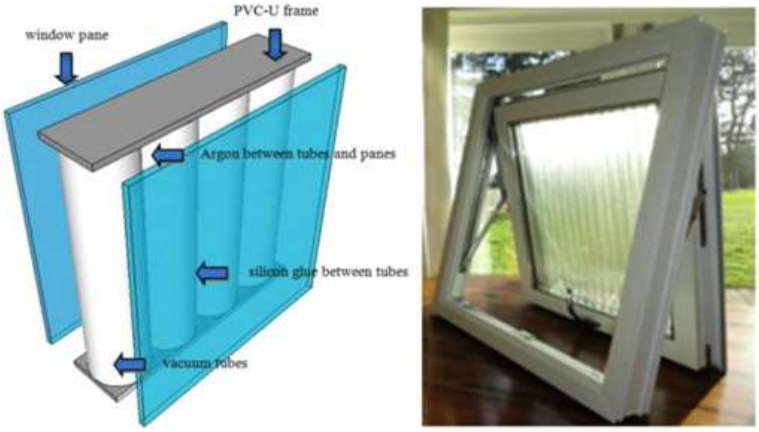


Fig. 2-30. Schematic of the vacuum tube window and the sample developed (Cuce & Riffat 2015b)

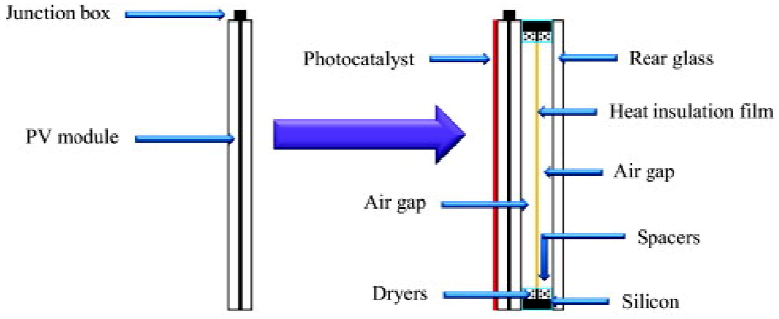


Fig. 2-31. Cross-sectional view of HISG (Cuce, Riffat, et al. 2015)

Table 2-16. Comparison of thermal performance of different types of glazing systems (Ghoshal & Neogi 2014)

Type of Glazing	Description	U-Value (W $m^{-2}K^{-1}$)
Single	One glass sheet	5.79-6.3
Double	Air filled	2.78-3.24
Double	Argon filled	2.61-2.95
Double	Argon filled and night insulation	1.5-1.99
Double	Vacuum	0.86
Double	Monolithic aerogel filled	0.63
Double	Granular aerogel filled	1.69
Electrochromic vacuum	Two glass pane forming evacuated glazing with a third pane having EC layer	Slightly less than 1
Triple evacuated	Three glass panes with two evacuated space in between	0.26

Table 2-17. Optical and thermal properties of ordinary glass and HISG curtain walls (Cuce, Riffat, et al. 2015)

Properties	Ordinary glass	HISG
Visible light transmittance (%)	87.00	7.15
Solar thermal transmittance (%)	60.00	2.60
Absorption rate (%)	5.75	79.35
Thermal conductivity (W/mK)	1.05	0.032
Overall heat transfer coefficient (W/m^2)	5.97	1.10
Shading coefficient	0.87	0.144

2.2.8.2. Brief findings on thermal insulation for greenhouse applications

Compared to other types of building, greenhouse heating load is much higher due to poor thermal insulation used. On commercial glasshouse, the covers are made of plastics or a single glass (Imtiaz Hussain et al. 2015; Russo et al. 2014). For that reason, applying proper insulation material as walls and roof is a very important issue have to be noted and solved.

Among other type of plastics, polycarbonate could be the best choice to be applied as the facades for greenhouse. Polycarbonate has a low U-value range, strong, light-weight and fulfils the European legislation on energy efficiency. Besides, it is inexpensive with easy installation and the solar factor is competitive with the other glazing products (Moretti, Zinzi and Belloni, 2014). For instance, in Italy Low-E solar glazing price is in 50–80 €/m^2 range, whereas polycarbonate panels is about 25–35 €/m^2.

Another option of facade materials is heat insulation solar glass. Besides its ability to suppress the heat loss, it is also able to generate electricity and self-cleaning due to a special coating applied. The U-value also very competitive with Argon filled triple glazed windows with low-e. Moreover, its current manufacturing cost is about 250 €/m^2 and will be reduced when mass-produced. In this respect, heat insulation solar glass can play a significant role in reducing heating and cooling demand of greenhouses for any type of climatic region (Cuce and Riffat, 2015).

2.2.8. Control System

A low energy demand of greenhouse can be realized by utilising an insulating cover, adaptive climate control, integrating control algorithms, and optimal energy management (Bot *et al.*, 2005). An automatic system has many benefits to control soil moisture, temperature, and humidity of greenhouse (Khan *et al.*, 2016). While, manually operative will cause a lot of losses, high-cost, and inaccurate control. Therefore, control systems take a significant role on decreasing cost and to increase the efficiency and yield's quality of greenhouses in Kenya (Groener *et al.*, 2015). It is showed that this type of remote control strategy could greatly improve productivity and reduce labour requirement.

Moreover, the use of solar tracker on the solar collector is very beneficial to increase the efficiency of solar collectors which is applied in greenhouse (Chemisana et al. 2009; Sonneveld et al. 2011). Solar tracking application in greenhouses will maximize the solar radiation directly which increase the performance (Imtiaz Hussain et al. 2015). Additionally, the electrical energy needs for its tracker system requires only less than 2% of the total electrical energy per year m^2 (Sonneveld et al. 2011).

Liu and Ying used the Bluetooth technology to monitor and to control the microclimate in a greenhouse (Liu & Ying 2003). The data of environment in the greenhouse is collected by a sensor network and transmitted to a central control system. Zhou et al. use an open source control system to maintain the temperature and humidity, soil water content, and concentration of carbon dioxide in greenhouse at once (Zhou *et al.*, 2013). They use ZigBee technology which has Bluetooth and wireless for the communication. Furthermore, the control system could save the data to database which can be used for further improvement. It also has low complexity, low power consumption, low data rate, low cost, and ad hoc networks (Morais *et al.*, 2008). Fig. 2-32 shows the implementation of data acquisition network using a ZigBee multi-powered wireless.

The wireless protocol usage to control the micro-climate of greenhouse has much more benefits compared to conventional protocol. In terms of effectiveness, wireless transmission has significant reduction and simplification in wiring and maintenance (Wang et al. 2006). Thus, it can cut the operation cost and very efficient to save money. Moreover, wireless control system is possible to be monitored from anywhere using internet. Thereby, it is very promises to implement greenhouse wireless control system in the future.

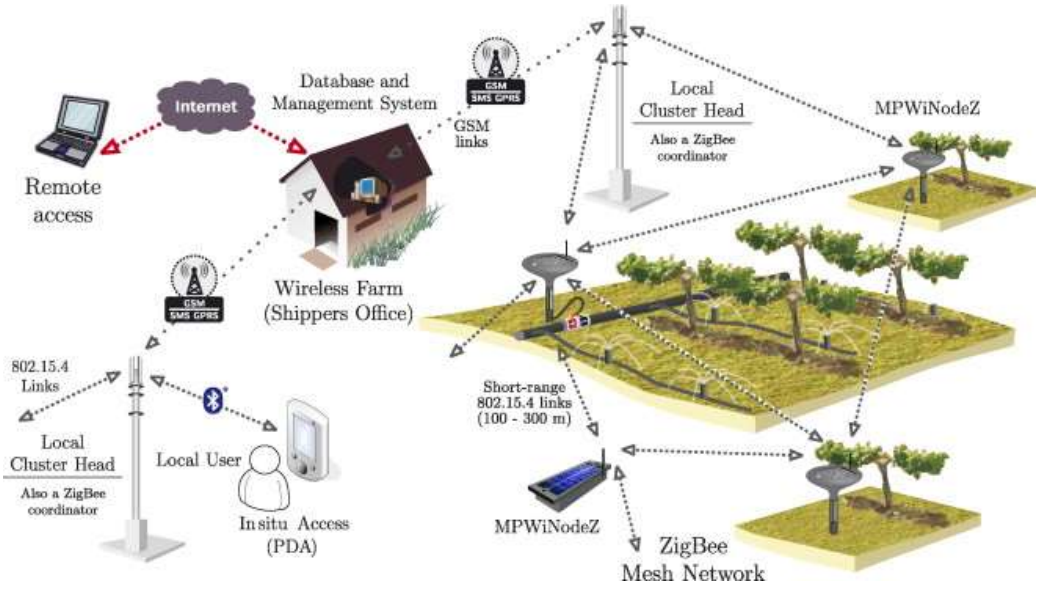


Fig. 2-32. a ZigBee network of MPWiNodeZ devices implementation of an *in-field* data acquisition network (Morais *et al.*, 2008)

2.2.9. Concept Opening System of Greenhouse

A closed greenhouse is a concept with no ventilation window and the excess heat in both forms of sensible and latent heat is harvested and stored for covering the heating demand at a later time. Besides, a closed greenhouse type could be a good system than the others (Vadiee & Martin 2012). Since on high sun radiation area, a large part of the available excess heat will be stored.

Opdam et al. show that this concept can reduce energy use by 20 and improve the energy efficiency by 50% (Opdam *et al.*, 2005). Moreover, in 2006, the concept can collect the incident solar radiation by 80% or 2.5 HJ/m^2y in north Europe (Campen et al. 2006). Vadiee & Martin also state that using TRNSYS, the payback period for the ideal closed greenhouse might be reduced by 50% (Vadiee & Martin 2013).

Furthermore, in another work, they use TRNSYS simulation to assess the potential of cutting external energy demand as well as maximizing solar

energy utilization in a commercial greenhouse for Northern climate condition. The results reveal that solar blind system use glazing Polycarbonate with thermal screen and closed concept could reduce the heating and cooling energy demand by 80% and 60%, respectively compared to the conventional one (Vadiee & Martin 2014b).

The most expensive opportunity of retrofitting is by applying the double layer thermal screen with 5 years PBP. The low cost opportunities are using the "Double polyethylene" (6 months PBP) and "Double ply IRAC" (10 months PBP). Whereas, the highest improvement (80%) by using the closed greenhouse concept, with a potential payback of 5–6 years under favourable conditions.

Additionally, the net energy reduction due to energy performance improvement opportunities is presented in Fig. 2-34. It depicts that the closed greenhouse concept with double glazing has the highest impact (50%), and double thermal screen for almost 40% (Vadiee & Martin 2014a). Compared to existing greenhouse systems, the results suggest that a closed concept can be used to produce tomatoes in a sustainable way, where the water use and the energy use efficiency can be improved by 71 % and 43 %, respectively (Dannehl *et al.*, 2014).

Even though, fully closed greenhouse have a higher amount of solar thermal that can be harnessed but in reality a semi-closed greenhouse is more useable (Vadiee & Martin 2012). Since the greenhouse must to deal with fresh air as a rapid response for humidity control. Besides in fully closed concept, there is no ventilation which means that excess sensible and latent heat must be removed which is happen in subtropical climate (Katsoulas *et al.*, 2015). Therefore, cooling and humidity are challenging points in a closed concept greenhouse (Buchholz *et al.*, 2006).

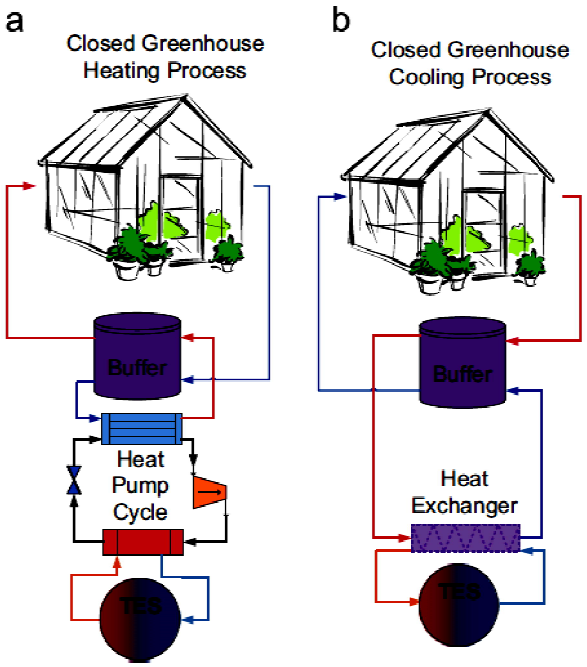


Fig. 2-33. a. Heating, and b. Cooling in closed-concept opening in Greenhouse (Vadiee & Martin 2012)

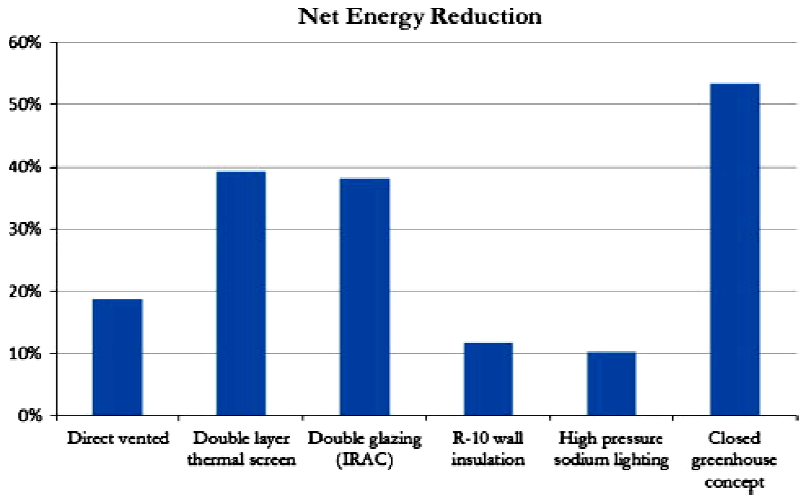


Fig. 2-34. Net Energy reduction in a commercial greenhouse (Vadiee & Martin 2014a)

Table 2-18 shows the benefits from three types of greenhouse concept. Partly closed greenhouse means the surplus in heat energy from the closed greenhouse portion is used also for heating the conventional greenhouse portion. Meanwhile, the semi-closed greenhouse is an almost closed greenhouse where part of the cooling demand will be supplied by open ventilation windows.

Table 2-18. Comparison opening concept system based on experimental report (Vadiee and Martin, 2012)

	Closed	Semi-closed	Partly-closed
Benefits	- can supply heat for itself and other nearby buildings - 17% higher yield & 30% fossil fuel reduction - increase production yield up to 20% while the total primary energy demand will reduced by 30–40% (Opdam *et al.*, 2005)	- 30–45% CO_2 emission reduced	- 50% energy efficiency improvement; - 20% more Production; - 50% less water consumption
Weaknesses	25% higher annual capital cost than conventional		

2.2.10. Conclusion and challenges of technologies in greenhouses

Greenhouses are special building made to provide a specific climate for specific plants cultivation too. The vast majority of existed greenhouses utilise conventional materials for its construction and facades as cheap as possible. Besides, for heating, cooling, ventilation, and lighting they used traditional technology causes high operational cost but not efficient to tackle the ideal microclimate required by the crops. In this respect, it is obviously can be asserted that novel greenhouse equipped with novel energy-efficient, inexpensive, and eco-friendly solutions are needed for the growers to minimise their cost and maximise their profits. Therefore, this review reveals several technologies that can be considered to enhance the effectiveness of the existed greenhouse systems. Some characteristic findings from the work can be given as follows:

- The most suitable glazing for the facade and roof material is semi-transparent PV modules which have multi-functional benefits. Like transmitting enough natural sunlight, reducing heat losses as well as generating electricity in an efficient way.

- To meet the heating demand at the heating season, seasonal underground thermal energy storage can be used effectively along with vertical ground heat exchanger. An innovation on the pipe design is needed to reduce the investment cost by using the shallow-embedded method. Besides, for suppressing the heat loss from the storage can be done by using polyethylene insulation surrounding it so that no heat transfer to soil..

- Solar assisted heat pump systems can meet the heating and cooling demand of greenhouses in a cost-effective way. Those systems usually have COP values greater than 3.0, which is very promising.

- Windcatcher is an ideal device for passive cooling in summer and ventilation at once in a greenhouse. It is easily installed without electricity so that reduce the operational cost of the greenhouse.

- Another promising glazing for greenhouse envelope is vacuum tube windows. It has very low U-value below 0.40 W/m^2K to reduce greenhouse oriented energy consumption and carbon emissions.

- Combination of blue and red LED is proven effective as artificial light to meet the plants need for their photosynthesis along the day. These lighting devices are inexpensive and also promising in terms of energy-saving.

- The application of PCM with solar thermal collectors to enhance the amount of saving heat energy especially for greenhouse in an extreme

climatic region has a noticeable impact on reducing the spent energy for heating.

- Automation system in greenhouse obviously increases the effectiveness of devices which is utilised to control the microclimatic. Therefore, with precision control many benefits can be achieved such as lowering labour cost, energy efficient, diminishing human error, and shortening payback period.

- Closed-concept improves the energy saving, water saving, and yields production. Closed-open concept combination would be more adaptable for every season and reduce the crops severe from an excess heat in hot period.

- The payback period of energy-efficient greenhouse systems varies from 4 to 8 years depending on the energy type utilized and climatic data.

The review indicates that the remarkable role of heating demand in greenhouses is mainly caused by poor constructional features and insufficient thermal resistance of the envelope material. In many countries, the heating energy of traditional greenhouse is commonly produced from coal which dangerous for environmental due to its pollution. Thereby, natural gas is used to alter the coal since it is more efficient and cleaner, however there is a consensus among scientist not to explore further this fuel because it has a limited lifetime and carbon emission issues.

Therefore, renewable and sustainable energy technologies are become the best solution which is more environmental-friendly and reduce the energy consumed for greenhouse. As the energy is free and abundant, the

investment provides a positive cash flow after a particular time between 4 to 8 years depending on the climatic condition and plant type.

CHAPTER 3 – Methodology

Outline of the Chapter:

This chapter discusses the mathematical modelling and simulation used to investigate the performance of the greenhouse. The objective of the present work is to demonstrate the design system, the material properties, the working principle, measurements method and analyses method. In order to evaluate the performance of the PV assisted Heat Pump system with a seasonal soil-based thermal energy storage system for greenhouse applications.

3.1. INTRODUCTION

The methods used in this research include a review of works of literature of the aspects related to this study. Such aspects include heating and cooling technologies used in greenhouses around the world, as well as the advantages of closed-concept greenhouses in order to reduce heat losses and water wastes, which in turn enhances the energy saving. The literature review helped the research by providing insights on the issues related to the heating and cooling demand in different weather conditions and the primary methods to improve the greenhouse system's performance.

The review shows that the proposed appliances need to be efficient and should prioritize the need of the greenhouse to maintain the microclimate in terms of heating and cooling energy. The most appropriate method to reduce energy consumption in different regions is by utilising passive technology, namely the use of façade material with low U-value. Even though it reduces the incoming natural light, artificial light from LED could be very effective and efficient to assist. The review also covers some other important methods to optimise the greenhouse performance, namely the utilisation of control system to accurately manage the devices' performances, heat pumps to provide heating and cooling, photovoltaic to generate electricity, and windcatcher to help managing temperature and humidity.

Other methods were also used in the research, such as simulations study and a number of experimental works. Firstly, building simulations were carried out, using DesignBuilder –dynamic simulation software based on Energyplus. The simulations were conducted to establish the variation of the system's behaviour when different façade materials configurations were used and different sizes capacity of heating-cooling units were used under various conditions. These simulations were also used to predict its heating-

cooling capacity range and performance for the building before being applied on site. A laboratory based experimental for soil-based heat exchanger has been done to support the simulation. Based on the results of both kinds of simulations, a greenhouse with high technologies has been built and tested.

Secondly, based on the test results, some improvement was conducted experimentally and theoretically. Experimental works for mitigating the heat loss from the façade was carried out using high-quality materials such as aerogel. The flowchart of these methods is well figured in Fig. 3-2.

To the author's knowledge, the innovation of ground source heat pump with shallow coaxial pipes vertical borehole for heating and cooling in a greenhouse is very rarely discussed in works of literature. Therefore, the experiment of the novel system will provide a new, clear contribution to this field of science. Future work should focus on the improvement of the thesis' outcomes.

Mathematical modelling and simulation were used to evaluate the performance of the systems in various ways and under different operating conditions, including different radiations. In addition, the sensitivity analysis of the effects of the materials' characteristic used in the building also been investigated.

3.2. PROPERTIES

The simulation and the greenhouse building uses the type of material as mentioned in Table 3-1 and the main materials for piping and utilities for the heating-cooling system as summarised in Table 3-2.

3.3. MODELLING

The mathematic modelling for the system of seasonal soil-based thermal energy system assisted greenhouse follows Fig. 3-1. In this project, there are approximately 200 m^3 of soil directly under the greenhouse, embedded in which are 24 vertical U-type heat exchangers at a depth of 2.5 m. These heat exchangers are used to store the excess solar heat captured in non-heating periods. In a greenhouse application, the underground soil usually acts as an important heat source during the night (Baille *et al.*, 2006). In this project, the underground soil is utilised not only as a heat storage unit but also as a heat distribution unit during the wintertime. The heat released from the soil can be significantly increased, thus enhancing the overall heating efficiency. The electricity is consumed by the Heat pump, circulating pumps, lamp, and the control system.

The objective of the present work is to demonstrate the potential and evaluate the performance of the PV assisted Heat Pump system with Borehole Thermal Energy Storage (BTES) for greenhouse applications. Experiments were initiated in September 2016 and a year long-term performance was monitored. The heat-charging process of the first-year operation was evaluated and the heating performance in the wintertime was presented according to the Nottingham weather conditions. The operation strategy of the greenhouse is also analysed. The results of this work will be useful for the optimisation of the management of greenhouses as well as of the design and control the seasonal soil-based thermal energy storage system.

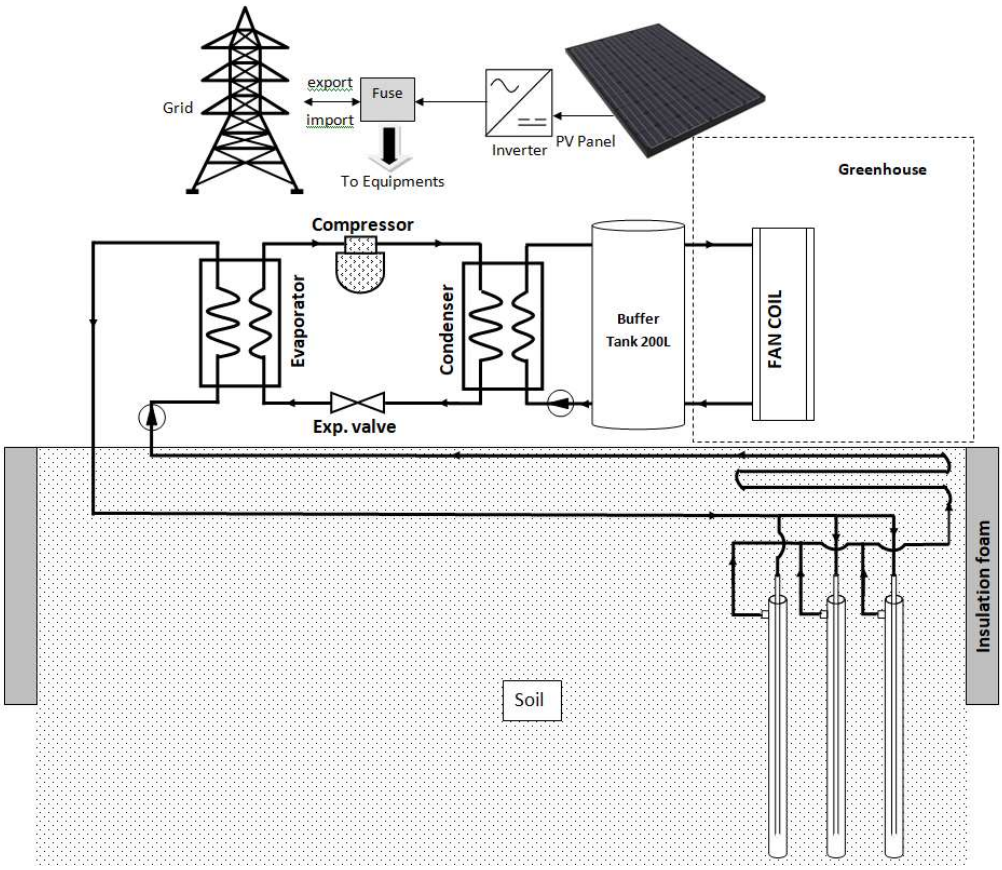


Fig. 3-1. The diagram workflow of system purposed

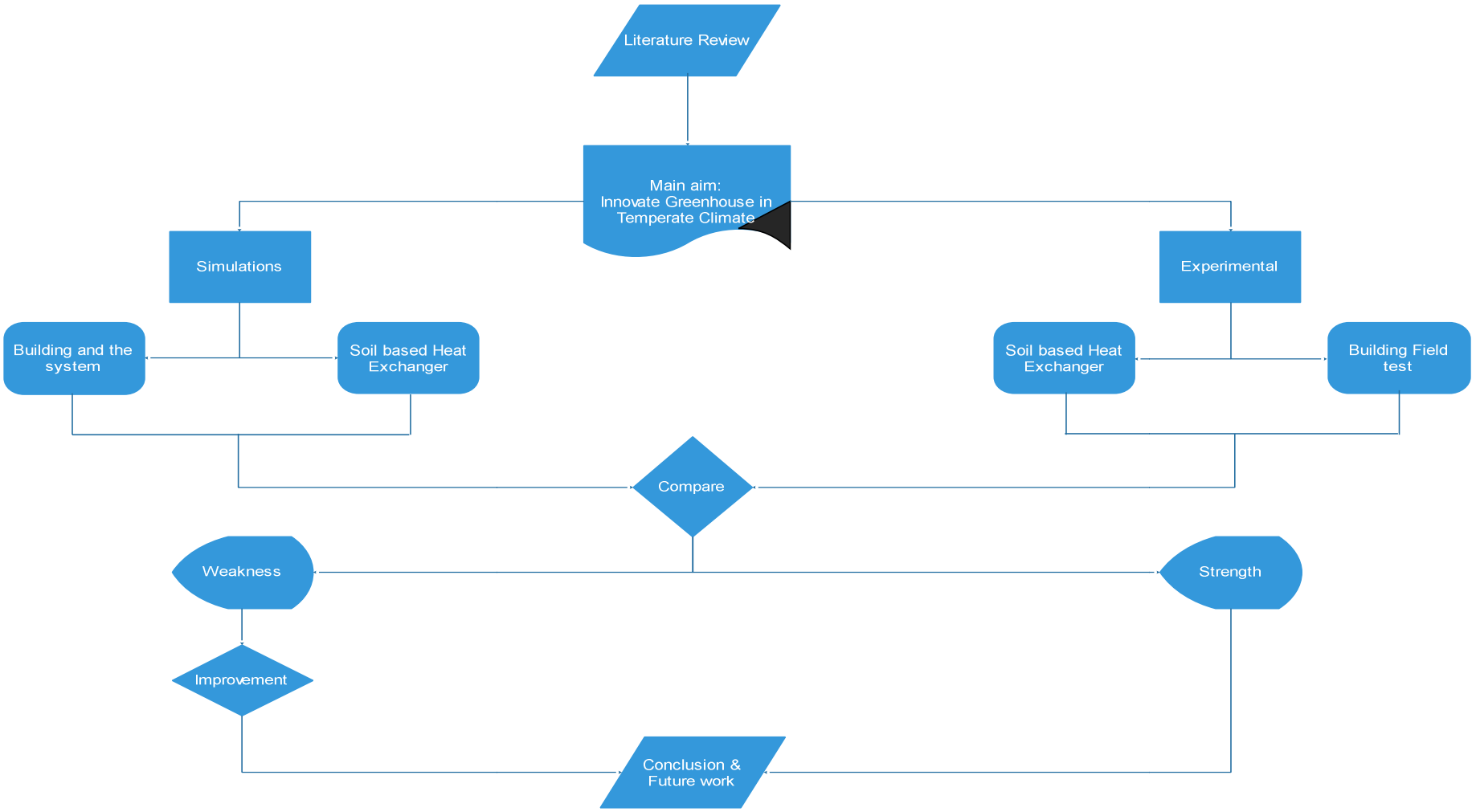


Fig. 3-2. The research methodology adopted in the thesis

Table 3-1. Properties of envelope materials

Materials	Total Solar transmittance / SHGC	Light Transmittance	U-Value (W/m^{2}K)	Life span	Thickness (mm)
Single PE	0.70-0.95 (Papadakis *et al.*, 2000)	0.86 (Sangpradit, 2014)	6.53 (Resources, 2004) (max 5.84 for DB) 6-8 (Papadakis *et al.*, 2000)	12 M (Alhamdan & Al-Helal 2009) 3-4 Y (Anon 2012)	0.5-1
Twin-wall PC	0.77 (Papadakis *et al.*, 2000) 0.69 (Moretti et al. 2014) 0.73 (DB) Solar absorptance: 0.27	0.78 (Papadakis *et al.*, 2000) 0.72 (Moretti et al. 2014) 0.75 (DB) Visible absorptance :	4.2-5.0 (Papadakis *et al.*, 2000) 1.2-1.84 (Moretti et al. 2014) 4.2 DB	10-15 years Emissivity : 0.9 (Bash, 2015)	10

		0.25			
Polycarbonate 5X-walls (PC) (Industrial, 2015)	0.64	0.62	2.0	10-15 years Emissivity : 0.9 (Bash, 2015)	16
Opaque PV + air gap	0	0	3.86 (The Scottish Government, 2009; Ozgener, Ozgener and Goswami, 2011)	17.75 (Canadian Solar, 2015)	4
Semi-Transparent PV double glazed	0.42-0.5 (Wong *et al.*, 2008; Polysolar, 2015a)	0.2 (Polysolar, 2003)	1.2 (Polysolar, 2015a)	8 (Polysolar, 2015b)	17
Clear Single glass (Guardian, 2017)	80	90	5.8	18	6

3.4. SYSTEM DESCRIPTION

3.4.1. Working principle

As schematically illustrated in Fig. 3-1, the entire solar heating system for the greenhouse is divided into three subsystems: a PV solar collection subsystem, a charging thermal heat storage subsystem, and a discharging subsystem. In summer, the charging process is scheduled for the seasonal soil-based thermal energy storage system. In winter, the stored heat is retrieved to meet the heating loads using a reverse process; this reverse process is also called the discharging process. However when heating or cooling is needed, the three processes might happen alternately.

Therefore, solar energy in the summer compensates the insufficient heating capacity in the low-temperature seasons. Moreover, the details analysis was done for a certain time only.

3.4.2. Main components of the system

The main components of this proposed seasonal thermal energy storage system are solar PV panels, water tank, BTES unit and heat distribution pipes, and fan coil unit (FCU). Table 3-2 gives the main design parameters of the system. With respect to the system design, a steady-state calculation was made compliant to the building code. Solar radiation condition of the location, heating load and heat loss of the greenhouse was taken into consideration. Despite the received passive heat due to the transparent envelope of the greenhouse, the rest of the heating loads need to be met by the active heating system, which is aimed to be supplied by the underground stored heat in this project. Based on the required amount of thermal energy to keep the greenhouse set temperature, the design

parameters of the PV solar energy system (such as PV solar collector area, its power peak and efficiency, inverter), and underground storage volume was determined based on its manual specification product (Polysolar, 2003; Canadian Solar, 2015; Fronius, 2017).

3.4.3. The Greenhouse

The area of the greenhouse is 46.94 m^2 and volume 142.87 m^3, located in Nottingham, UK (Lat. 53.48°, Longitude -1.0°). The building gross wall area is 98.22 m^2, and gross roof area is 77.01 m^2. It is covered with Semi-transparent PV rooftop double glazing and opaque PV on all side walls. The plantations were placed above the ground.

3.4.4. Thermal Energy Storage

The thermal energy storage unit is the key component of the entire system, consisting of hot water storage tank and glycol solution circulated in borehole underground thermal energy storage pipes.

3.4.5. Buffer Storage Tank

According to Charlick and Summerfield (Helen Charlick and Iain Summerfield, 2013, p. 62), they found that for heat pump power 4kW, the minimum system volume at hysteresis of 4°C to 2°C is 143.5 to 287.1 litres for the buffer tank. Therefore, a buffer storage tank with a capacity of 200 L is used as STTES (short term thermal energy storage) in the system with heat pump of 5kW, serving as a buffer between the collection loop, the SSBTESS, and the horizontal pipe, and the heat distribution (Fan coil) subsystem. The water flow rate nominal is 0.35 l/s. A buffer tank is a critical part of the system because it is capable of keeping the solution at a high-temperature level before transferring it into the SSBTESS, decrease

short cycling of the heat pump (Sarbu and Sebarchievici, 2016, p. 63), and it might help to accept and dispense heat at a much higher rate than the SSBTESS subsystem, thus improving the overall performance of the system.

3.4.6. Borehole Soil Based Thermal Energy Storage Bed

The boreholes thermal energy storage bed is designed right under the central area of the greenhouse, and it is 0.2 m below the ground surface. Totally 200 m^3 soil embedded with 24 vertical SVHXs (Single Vertical type heat exchangers) which are connected in parallel way, each stretching down to the depth of 2.5 m, and will be used as an underground storage bed. The brine flow rate of the circulation was determined nominal at 0.2 L/s. It is intended to store heat that produced in summer and transition seasons and serves as one of the heat sources in low-temperature season. The underground boreholes are arranged in orderliness, forming a cubic structure, with 0.5 to 1 m space between adjacent ones as seen in Fig. 5-6. Surrounding insulation is built to the soil storage unit so that the heat loss could be minimized (adiabatic). At the surface below, a long heat radiant floor is covered by concrete as heat extractor or injector unit in the greenhouse underground.

Table 3-2. Main design parameters of the greenhouse system

System	Number
Floor area of the greenhouse (m^2)	46.94
Power of the opaque PV (W) (Canadian Solar, 2015)	7670
Volume of the water tank UKV (m^3) (NIBE, 2016b)	0.2
Power of circulating pump for the BTES loop (W) (Grundfos, 2010)	185

V-tube heat exchanger specification:	
Number of the VHXs	24
Diameter of the VHXs (mm)	25
Depth of the VHXs (m)	2.5
Distance between two adjacent boreholes (m)	0.5-1
Power of circulating pump for the collector tank loop (W) (Grundfos, 2015)	48
Power of circulating pump for the brine (W) (Grundfos, 2015)	185
Power of the Semi-transparent PV (W) (Polysolar, 2003)	2880
Power of circulating pump for fan coil unit (W) (Grundfos, 2015)	48
Fan coil Unit (heating capacity 21.15 kW Cooling capacity 18.3 kW) (W) (N.V., 2008)	1197
Heat pump NIBE F1145-5 power (kW) (NIBE, 2016a)	1.23
Inverter Fronius 2.0 capacity (kW) (Fronius, 2017)	2

3.4.7. Heat Distribution Unit

During high-temperature periods, the heat withdrawn from the indoor excess heat to buffer tank seasonal thermal heat storage unit via fan coil and delivered the heat produced by the heat pump to the ground through the vertical heat exchanger pipes and the horizontal tubes placed on the ground by means of conduction. In addition, the soil itself serves as a heat distribution unit due to its relatively high temperature and thermal conductivity. While in low-temperature periods, the heat is withdrawn from the buffer tank which is produced by the heat pump through circulating pumps to the fan coil unit. The heat was delivered to the greenhouse in convective way.

3.4.8. Control Strategy

The operation of the entire system is controlled automatically by a control panel. The circulation pumps are switched ON/OFF based on the monitored temperature and the preset working principle. In this section, detailed descriptions of the charging and discharging processes are given (refers to Fig. 3-1):

- Charging process (summer)
- Discharging process (winter)

In summer or in the cooling season, when the inside temperature of the greenhouse above 20 °C then the control system will open the windcatcher automatically and closes it when the temperature is back at set value. Otherwise, if the temperature gets higher than 25 °C, the heat pump active cooling mode is operated by adsorbing the indoor excess heat through the fan coil and stores it to the ground through the buffer tank and heat pump.

While in the winter or in heating seasons, when the external temperature of the greenhouse is reduced to or below a certain value, heating is required to keep the interior temperature at 16 °C and higher than the set value of 18 °C in summer. Whenever the brine intake drops to -5 °C, the heat pump will stop working to avoid freezing which may cause harm to the heat pump system.

3.5. MEASUREMENT

For the underground storage soil, the temperatures at about 1 m in several observation wells were measured by thermocouples with accuracies of ±0.5 °C. Observation will be located in each wall side of the BTES site to monitor the temperature variation of the heat carrier fluid. Temperature probes are also installed at the inlet and outlet of each loop in the system

for differential controllers. The interior air temperature and relative humidity were measured at a position of 1.5 m from the ground level. The data were automatically recorded at 15-min intervals on charging and discharging process. Electricity consumption is measured by a power meter. The flow rates of the solar collection loop, SSBTESS loop, and heating distribution loop are measured by heat meter Sharky 775 with an error rate of 1%. At the same time, environmental climate data were recorded every 5 minutes with a weather station that included ambient temperature (±1°C), humidity (±3%) and pyranometers sensors to measure solar radiation (±5%).

3.6. ANALYSIS METHOD

Heat pumps have great potential for saving energy, particularly in cold climates. They are the only heat recovery systems that enable the temperature of waste heat to be raised to more useful levels. Principally, a heat pump is a heat engine operating in reverse. The principle work is illustrated in Fig. 3-3. A heat pump principle follows the second law of thermodynamics, the amount of heat delivered (Q_D) at the higher temperature (T_D) is related to the amount of heat extracted (Q_S) at the low temperature (T_S) and the amount of high-grade energy input W by the Equation (3-1).

$$Q_D = Q_S + W \tag{3-1}$$

The heat pump coefficient of performance (COP) can be defined as Equation (3-2).

$$COP = \frac{Q_D}{W} \tag{3-2}$$

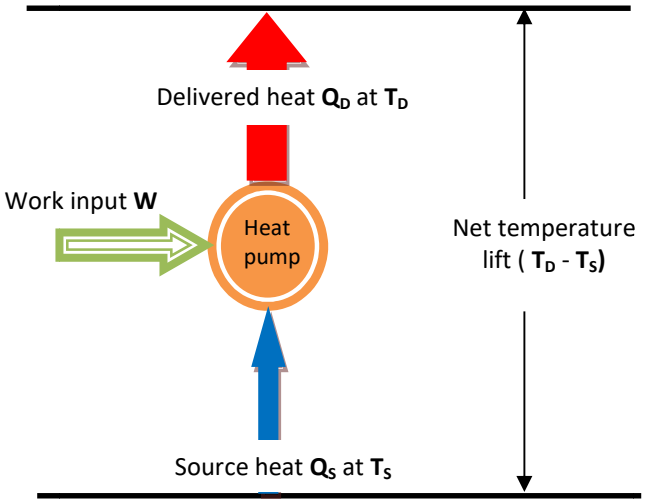


Fig. 3-3. Heat pump principle work

Theoretical maximum thermodynamic efficiency (η) of a heat engine operating between a higher temperature (T_D) and a lower temperature (T_S) known as Carnot efficiency. While a heat pump can be considered as a heat engine operating in reverse. The ideal Carnot efficiency defined by Equation (3-3) (Bhatia, 2014), represents the upper theoretical value obtainable in a heat pump system.

$$\eta = (T_D - T_S)/T_D \tag{3-3}$$

Practically, a heat pump coefficient of performance (COP) is significantly less than COP which is shown in Equation (3-4).

$$COP = T_D/(T_D - T_S) \tag{3-4}$$

Fig. 3-4 illustrates a primarily conventional mechanical vapour compression heat pump, consists of two heat exchangers, a compressor, an expansion valve, and a working fluid. In the evaporator heat exchanger, the working fluid evaporates at a temperature (T_{EV}) by extracting heat from the source.

After that, it is compressed and releases its latent heat as it condenses at a higher temperature (T_{CO}) in the condenser heat exchanger. The condensed liquid flows through an expansion valve to be expanded and is returned to the evaporator to complete the cycle.

The temperature distinction between the condensing and evaporating (T_{CO} - T_{EV}) is the gross or most extreme conceivable temperature lift. The net temperature lift (T_D - T_S) is less than the gross temperature lift by the sum of the temperature difference driving forces in the evaporator and condenser heat exchangers.

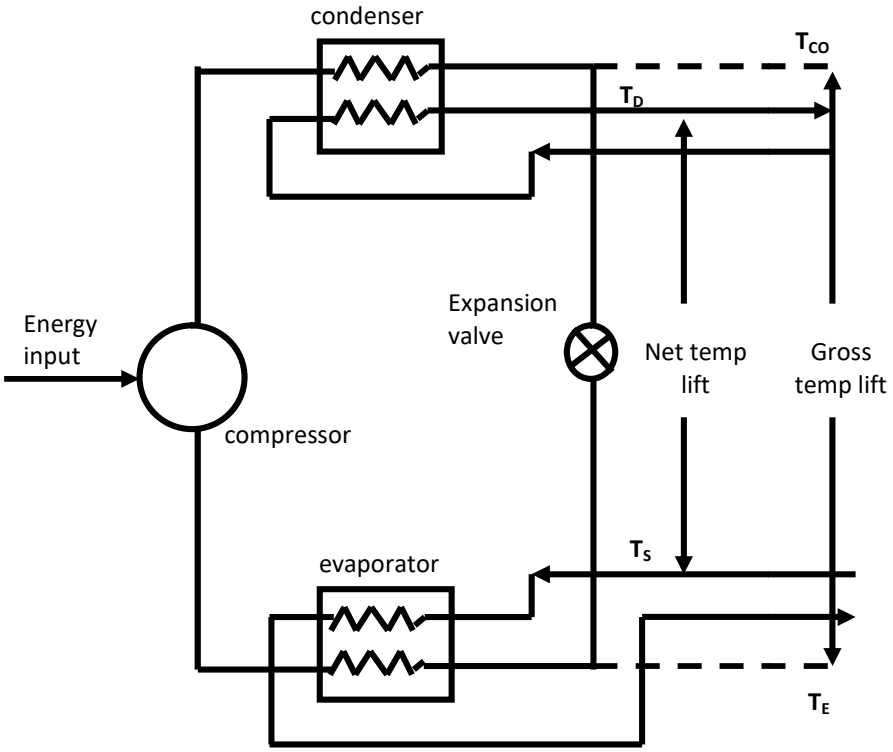


Fig. 3-4. General heat pump mechanical vapour compression

The ratio of the corresponding pressures in the condenser and evaporator P_{CO}/P_{EV} is the compression ratio (CR). (T_{CO} - T_{EV}), (CR) and the condensing temperature (T_{CO}) are the critical parameters that determine the feasible operating range of a heat pump operating on a specific working fluid.

In general, a simple mathematical model of a heat pump can be developed from psychometric processes. In practice the operation of a mechanical vapour compression heat pump approximates more closely to the Rankine heat pump cycle than to the theoretical Carnot cycle (F.A.Holland *et al.*, 1999). The ideal Rankine heat pump cycle is the reverse of the Rankine power cycle and can be illustrated with reference to the R407C pressure enthalpy diagram shown in Fig. 3-5. The theoretical Rankine coefficient of performance of a heat pump can be defined as in Equation (3-5).

$$(COP)_R = (H_{D1} - H_{D3})/(H_{D1} - H_{S2}) \tag{3-5}$$

where H is the enthalpy per unit mass. Since the compression from point S_2 to point D_1 is at constant entropy, $\Phi_{S2} = \Phi_{D1}$, where Φ is the entropy per unit mass. The enthalpy per unit mass of superheated vapour at point D_1 is related to the enthalpy per unit mass at the saturated vapour point D_2 by the equation Equation (3-6).

$$H_{D1} = H_{D2} + C_p (T_{D1} - T_{D2}) \tag{3-6}$$

where C_p is the heat capacity per unit mass at constant pressure.

Equation (3-6) can be approximated with accuracy sufficient for design purposes by

$$H_{D1} = H_{D2} + (\phi_{S2} - \phi_{D2}) T_{CO} \tag{3-7}$$

The error involved in using this method can be shown to be less than 1 percent, which is within the probable error of the data and equations on which the thermodynamic tables in the appendices are based (Holland, Watson and Devotta, 1982).

A heat pump effectiveness compared to the theoretical Rankine cycle can be defined as

$$(HPE)_R = (COP)_A/(COP)_R \tag{3-8}$$

which is the ratio of the actual coefficient of performance $(COP)_A$ to the calculated ideal Rankine coefficient of performance $(COP)_R$. The $(HPE)_R$ is effectively the ratio of work required in an ideal Rankine cycle to that in an actual cycle in order to transfer a given amount of heat to the condenser.

The coefficient of performance of a mechanically driven heat pump defined by Equation (3-2) is the ratio of the heat output to the work input to the compressor. Equation (3-2) takes no account of the efficiency of usage or the method by which this work is produced.

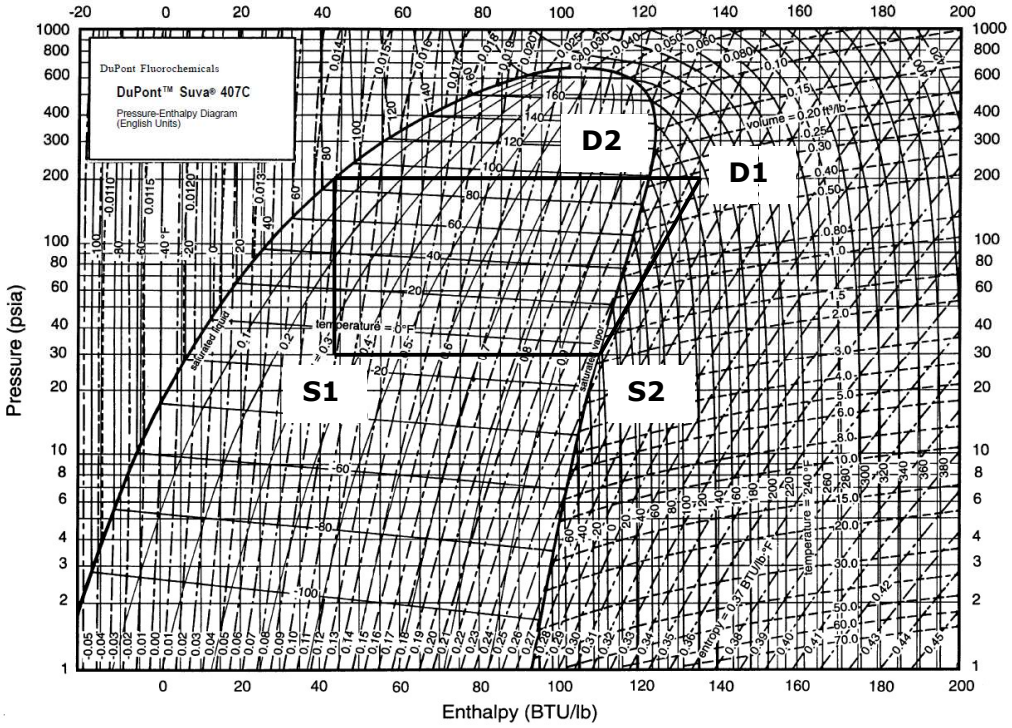


Fig. 3-5. Pressure against Enthalpy (p-H) per unit mass graph (DuPont, 2004)

When comparing heat pump systems driven by different energy sources it is more appropriate to use the primary energy ratio (PER) (Holland, Watson and Devotta, 1982) defined as

(PER) = useful heat delivered /primary energy input (3-9)

Equation (3-9) can be related to the coefficient of performance by Equation (3-10).

$$(PER) = \eta(COP)_A \tag{3-10}$$

where η is the efficiency with which the primary energy input is converted into work up to the shaft of the compressor.

Heating efficiency for air-source heat pumps is indicated by the heating season performance factor (HSPF). The HSPF tells the ratio of the seasonal heating output in Btu's divided by the seasonal power consumption in Watt-hours (Mustafa Omer, 2008). HSPF also defined as SCoP and mathematically follows Equation (3-11) and (3-12).

$$SCoP = \frac{seasonal\,heat\,delivered}{seasonal\,power\,consumption} \tag{3-11}$$

$$SCoP = \frac{Q_{output}}{W_{HP} + W_{pump} + W_{fan}} \tag{3-12}$$

CHAPTER 4 – Designing the heating and cooling of the greenhouse and potential of the soil-based TES

Outline of the Chapter:

This chapter sums up the up to date result from the simulation of the novel greenhouse with its HVAC system. The chapter begins with the prediction of the heating-cooling demand in the building based on the thermal transmittance of the claddings. It is followed by the prediction of the heat energy stored in the soil based on the solar energy generated by PV panels installed and the Heat pump in different COPs. These predictions were done analytically. Finally, EnergyPlus simulation was used to validate the analytical investigation on thermal performance of the greenhouse.

4.1. ANALYTICAL INVESTIGATION

4.1.1. Introduction

Various aspects need to be considered in planning a greenhouse building, such as the size of greenhouse, the thermal resistance of the cladding, and the site's location. These aspects are important in predicting the energy demand of the greenhouse. Thus, in this present study, a simple calculation of energy demand was conducted. The aim of the study is to calculate the heating-cooling load of the proposed greenhouse and the SSBTESS for a greenhouse, theoretically.

There are two scenarios for the greenhouse interior; high-temperature set point (20 °C) as the worst-case scenario, and low-temperature set point (15 °C) as the best-case scenario. The specific size of the greenhouse has been determined in the methodology, as shown in Fig. 4-1. The heating and cooling energy demand are going to be provided using electric water heater which is powered by solar PV panel surrounding the building's facades and distributed through cost-effective shallow underground pipes. In order to reduce the heat loss from the SSBTESS edges, the boundaries are well-insulated with high grade thick Polyurethane panels. The particular soil used to store the heat is placed underneath the building and the heat will be used as the heat source for a ground source heat pump (GSHP) to provide heating and cooling in the building.

4.1.2. Methodology

The first aim of the research is to determine the monthly heating cooling energy demand of the greenhouse. The overall heat transfer coefficient and the temperature difference between outdoor and indoor greenhouse are independent variables in this analysis. The energy demand is determined

by calculating the heat loss (U-value) based on the main governing equation (4-1)

$$\mathrm{Q} = \mathrm{UA}\Delta\mathrm{T} \qquad (4\text{-}1)$$

where $\Delta T = T_f - T_i$, T_i is initial indoor temperature, and T_f is the final indoor temperature (℃), Q is heat loss of the greenhouse in W, U is the overall heat transfer coefficient of claddings in W/m^{2}K, A is the cladding's surface area in m^2, and ΔT is the temperature difference between indoor and outdoor the greenhouse in ^{o}C. To simplify the calculation, hence some assumptions were used:

i. Air infiltration is neglected
ii. Surface area = 47 m^2
iii. Walls area = 98 m^2
iv. Roofs area = 77 m^2
v. The roof angle = 27.1^{o}
vi. U-value for all facades are made to be similar (vary from 1 to 5 W/m^{2}K)

The U-value is varied to investigate its effect to the energy demand needed by the greenhouse. The previous review reveals that a commercial greenhouse commonly used facade materials with U-value vary from 1 to 5 W/m^{2}K for polycarbonate to plastic film. Thereby in this investigation, the heat loss from the facades is calculated by varying the U-value at these ranges. The results shall be used to determine type of facades materials available and affordable in the market.

The second aim is to determine the energy capacity of soil-based TES, analytically. Many pieces of research have proven that GSHP has high efficiency compared to the other heating-cooling devices. One of the reasons for it is that the GSHP utilising heat ground which is available free

and unlimited as the heat source. In order to determine the amount of energy can be saved to the ground from pipes heat exchangers that are installed vertically, an analytical investigation was conducted, with the assumption that the electric water heater utilise electricity from the PV panels. The governing equation to determine the soil-based thermal energy storage capacity and its temperature are given by equation (4-2), and (4-3) resulted equation (4-4).

$$\mathrm{Q_{wh}} = \mathrm{Q_{SE}}\,\eta_{wh} S_p \qquad (4\text{-}2)$$

$$\mathrm{Q_H} = m_s c_s \Delta T \qquad (4\text{-}3)$$

$$T_{fs} = \frac{\mathrm{Q_H}}{m_s c_s} + T_{is} \qquad (4\text{-}4)$$

Where $\mathrm{Q_{wh}}$ is energy produced by the water heater in Joule, $\mathrm{Q_{SE}}$ is ideal solar energy per solar panel area in Joule/m^2, $\mathrm{Q_H}$ is output energy yielded by the water heater in Joule, η_{wh} is electric water heater efficiency, S_p is PV panel surface area in m^2, specific heat capacity c_s is 1800 J/kg°C m^2, clay soil density ρ is 1700 kg/m^3, soil mass m_s is in kg, initial soil temperature T_{is} is 16.7 °C based on the thermal response result in summer which is explained further in Section 5.1, and the final soil temperature T_{fs} is in °C.

Since the greenhouse is located in the rural side of Nottingham, UK –a place that has abundant enough solar irradiance in summer, the solar power generated by PV panels can be calculated by equation (4-5) (Chen, Gooi and Wang, 2012; Nguyen, Le and Member, 2014).

$$\mathrm{P^s_{p,t}} = \eta_p \mathrm{S_p} \Phi^s_t \left(1 - 0.005(\mathrm{T^{s,a}_t} - 25)\right) \qquad (4\text{-}5)$$

where $P^s_{p,t}$ is rated PV power in kW, Φ^s_t is solar irradiance in kW/m^2, $T^{s,a}_t$ is outdoor temp °C at time t in ambient temperature a, η_p is PV efficiency in percentage. This measurement is assumed being conducted under ambient

temperature of 25 °C. Some assumptions were made to simplify the calculation:

1. The surface area of the greenhouse will determine the varying mass that potential to be used: 100, 150, 200, 250, 300, 350, 400, 450, and 500 tonnes,
2. Solar energy is obtained from the solar irradiance in Nottingham and calculated per month,
3. The heat is injected to the soil and never been extracted for a year,
4. The electric water heater efficiency η_{wh} is 90%,
5. The heat source comes from the electric water heater and the power is from the PV panel with 15% efficiency (η_p),
6. The solar power is calculated per square meter of PV panel and exposed by the sunlight perpendicularly.

The stored energy yielded by the electric water heater was compared to the heat produced by a heat pump. Hence, to get the information on the amount of energy which can be stored by the heat pump, the investigation yielded by the heat pump with efficiency (η_{hp}) of the compressor (75%) and vary coefficient of performance follows the governing equation (3-2). Thus, the equation used to calculate the heat produced by the heat pump ($\mathrm{Q_{HP}}$) follows:

$$\mathrm{Q_{HP}} = \mathrm{COP} \cdot \mathrm{W}, \text{ where } W = \eta_{wh} Q_{SE} \qquad (4\text{-}6)$$

By equalising equation (4-3) and (4-6), thus the final soil temperature is shown in equation (4-7).

$$T_{fs} = \frac{\eta_{hp} \mathrm{Q_{SE}}\, \mathrm{COP}}{m_s c_s} + T_{is} \qquad (4\text{-}7)$$

4.1.3. Results and Discussion

In the assumption that the proposed greenhouse is built with an area limit of 47 m^2 in a rural area in the UK, energy sustainability must be taken into consideration. Hence, to support the UK government to cut the greenhouse gases emission solar power was chosen and become the most appropriate one. Besides the renewable energy, the need of sophisticated technology is inevitable.

4.1.3.1. Heating-Cooling Energy Demand

In the present study, preliminary research to predict the heating cooling energy demand has been done based on thermal transmittance of the claddings. By assuming that the U-value of the greenhouse claddings and floor are the same, the energy demand can be calculated. Moreover, by utilising PV panels surrounding the greenhouse facades, the monthly power needed by two scenarios of worst and best conditions for the indoor temperature can be predicted. However, the power generated by the PV's was based on assumption that has been aforementioned.

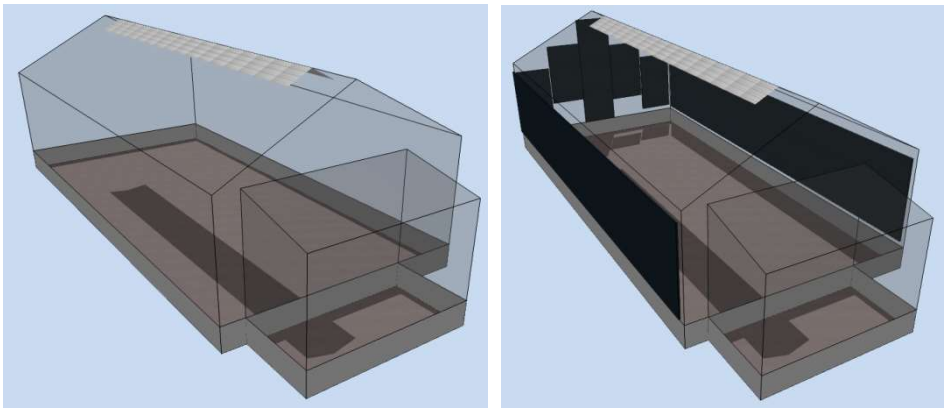


Fig. 4-1. The greenhouse design in 3D; typical and proposed system

With respect to heating and cooling load, the energy demand of the greenhouse in various thermal transmittances was calculated analytically. Fig. 4-2 and Fig. 4-3 show the heating and cooling energy demand for

different temperature targets for the inside of the greenhouse 20 °C and 15 °C, respectively. Obviously, it can be seen that for highest expected indoor temperature, all of the energy is used for heating. While for lower indoor temperature, the energy is predominantly used for heating and the rest is for cooling.

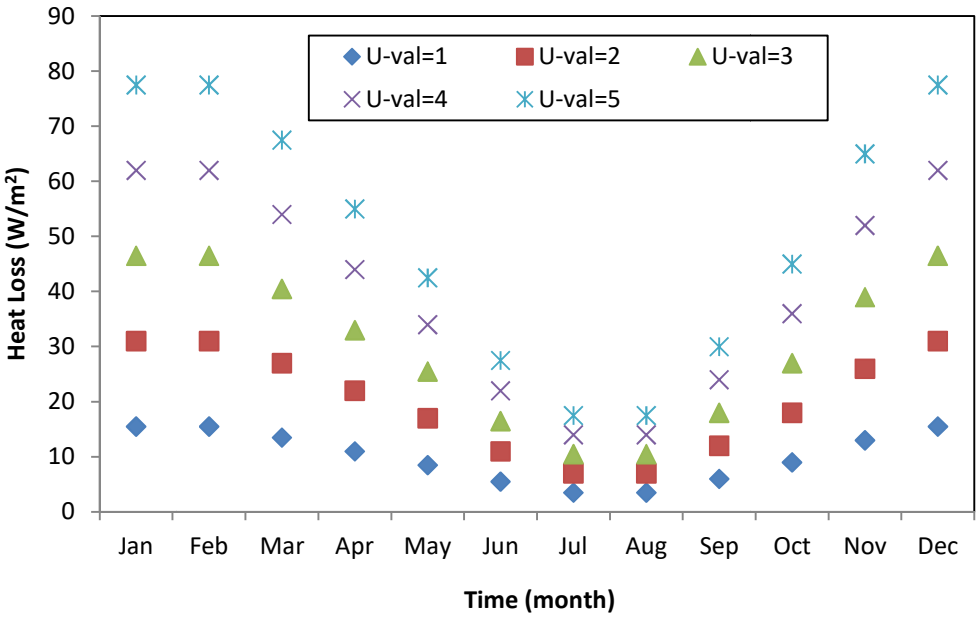


Fig. 4-2. Monthly Heat loss for 20 °C as the target indoor temperature (worse case)

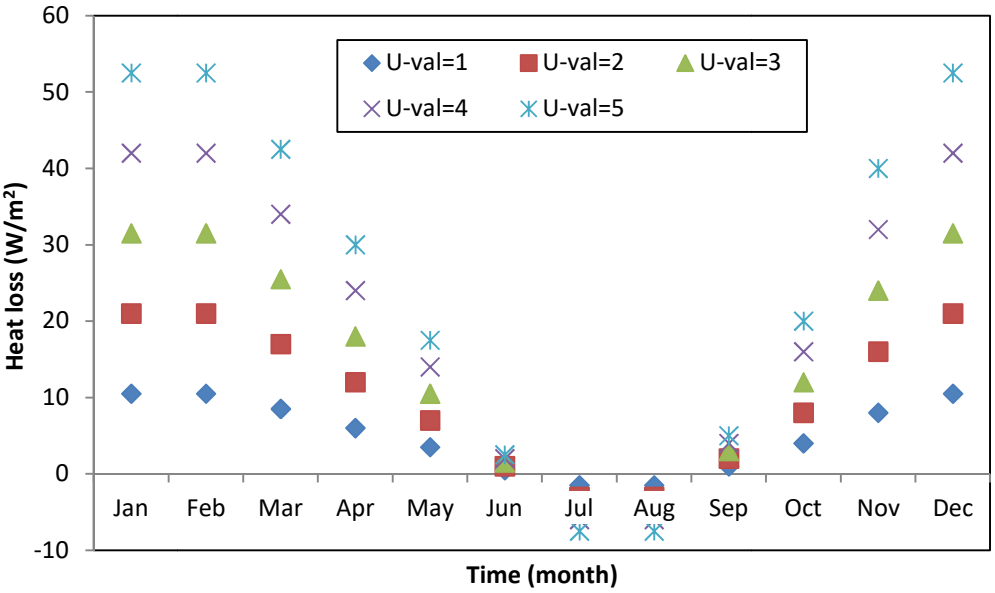


Fig. 4-3. Annual Heat loss prediction for 15 °C as the target indoor temperature (best case)

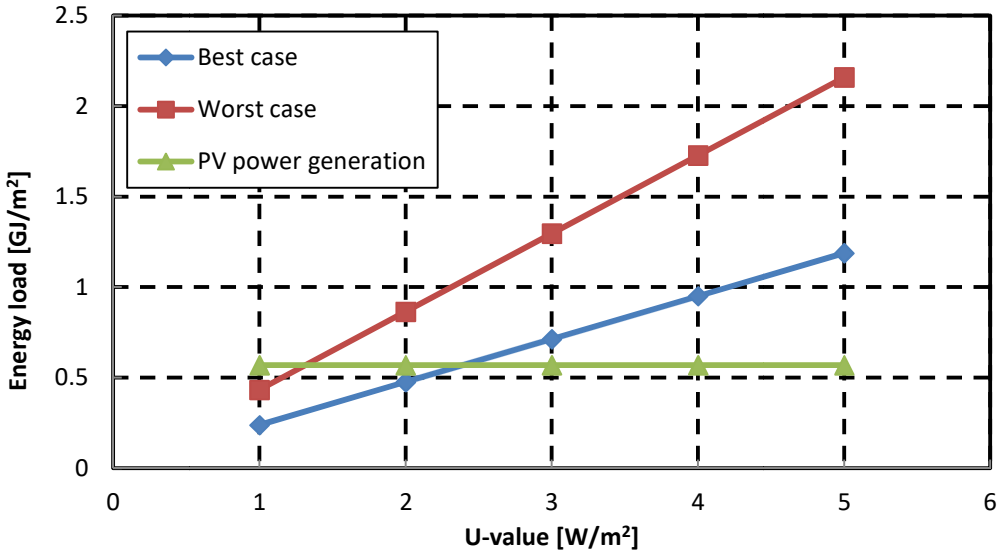


Fig. 4-4. Annual Energy building load prediction for best and worst case

Fig. 4-4 shows the typical greenhouse annual energy demand for heating and cooling purposes only on average. The temperature difference and overall heat transfer coefficient between indoor and outdoor environments are considered to be independent variables in the analysis. The yearly total energy demand is depending on the aforementioned independent variables. Obviously it can be seen that the higher U-value the higher heating-cooling demand.

4.1.3.2. The Potential of Solar Power

Fig. 4-5 shows the soil temperature fluctuation at Eastbourne, UK. The black line is the temperature at 30 cm depth and the grey line is from 100 cm depth. The fluctuation gets narrow when shifting to deeper soil. Therefore, if the heat injection could be started at a high level of temperature, it is very beneficial for seasonal thermal energy storage.

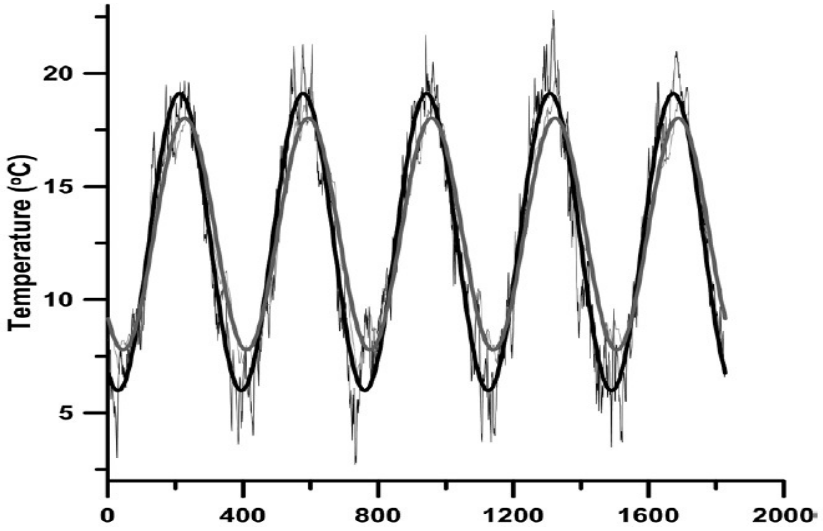


Fig. 4-5. The daily soil temperature at a depth of 30 cm and 100cm from 2000-2005 (Busby, 2015)

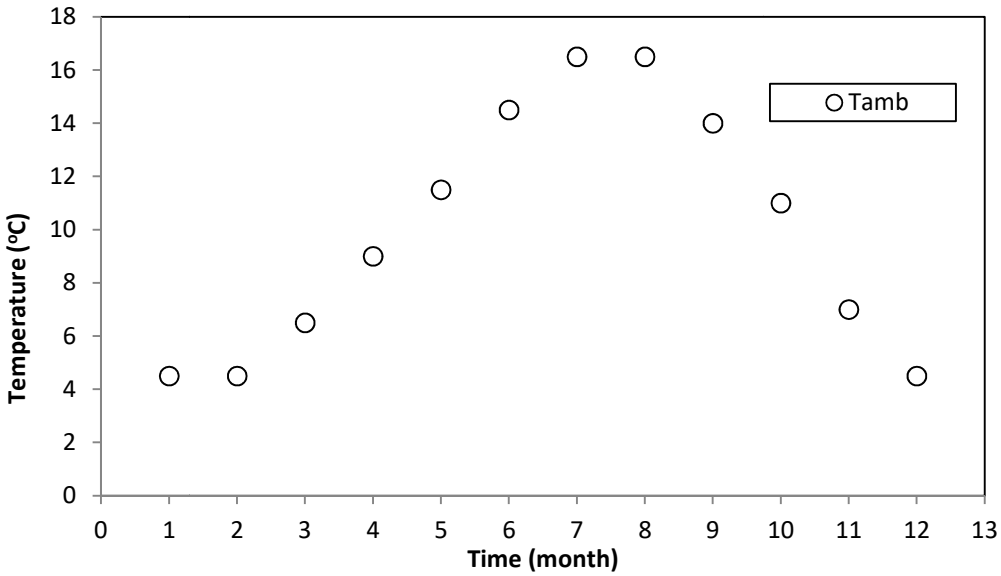


Fig. 4-6. The average ambient temperature for Nottingham in 1985-2015 (Timeanddate, 2016)

Fig. 4-6 show the annual weather averages in Nottingham, UK of past 30 years which is used as the ambient temperature and solar irradiance in 2015, respectively. Burnett, et al. said that solar energy resource in the UK offers a huge potential, especially in the south of England and Wales. The average daily solar irradiance is often in excess of 130 W/m^2 due to climate change (Burnett, Barbour and Harrison, 2014).

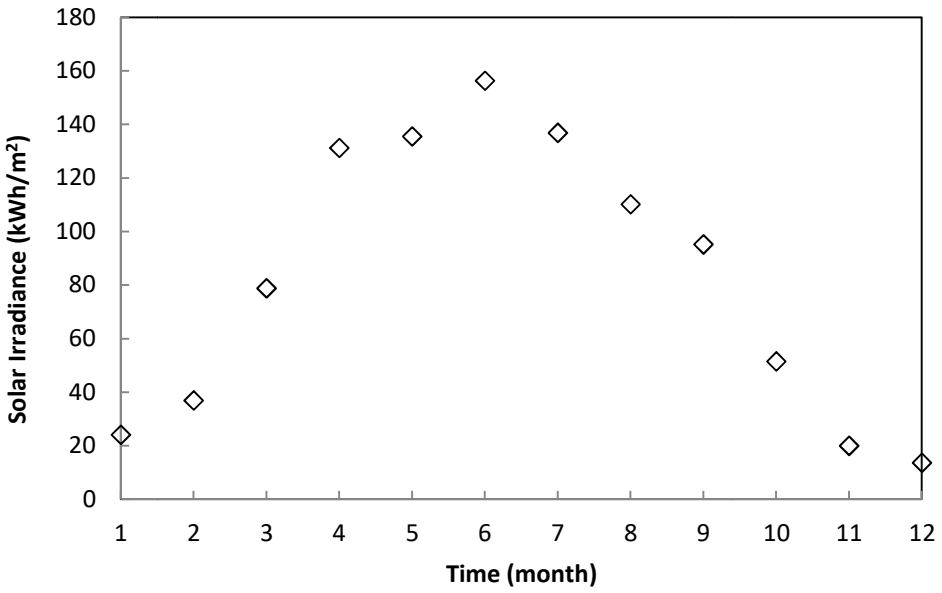


Fig. 4-7. The average solar irradiance for Nottingham in 2015 (Nasa, 2016)

Fig. 4-7 shows the monthly average solar irradiance which is potential to be used by solar photovoltaic as a power or even directs used as heat source and natural light at once for the greenhouse. The solar irradiance achieves the highest peak power in June and lowest in December. Hence, it will lead to high soil temperature in June and build a shallow soil-based seasonal heat storage will be better at that time.

4.1.3.3. Solar PV Power Generated

In order to investigate the soil temperature distribution of SSBTESS, some graphs show the potency of renewable energy. Fig. 4-8 shows the monthly average solar energy generated by the solar PV panel per square meter. The solar energy was calculated based on the assumptions made. By utilising PV panels surrounding the greenhouse facades, the monthly energy needed by the two scenarios of worst and best conditions for the indoor temperature obviously can be covered.

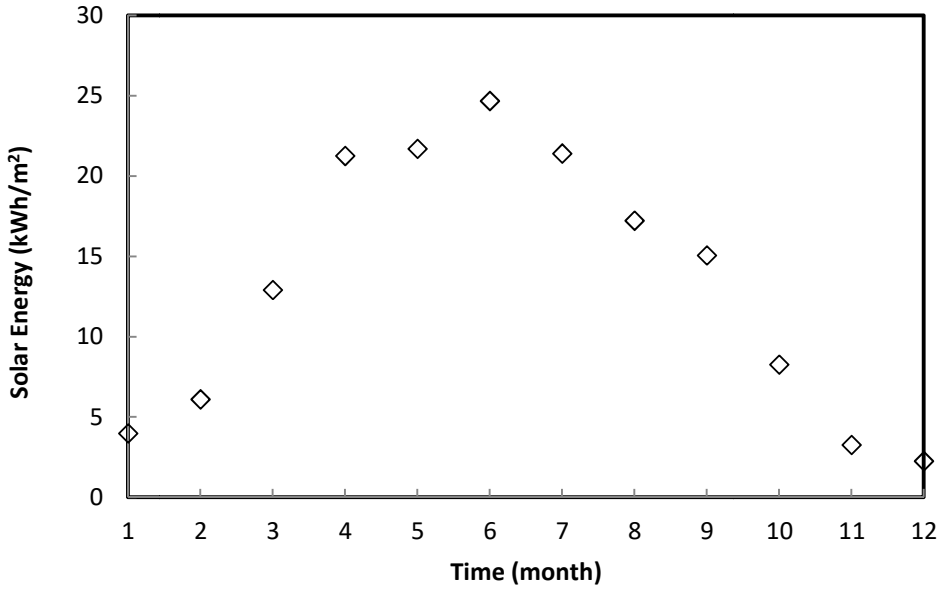


Fig. 4-8. Monthly average solar energy prediction generated by the PV panels

To have a big picture regarding the amount of energy that can be stored in the soil beneath the building, the energy calculation is conducted by varying the soil volume. Later, the information is used to determine how deep the pipe heat exchanger and the insulation are should be.

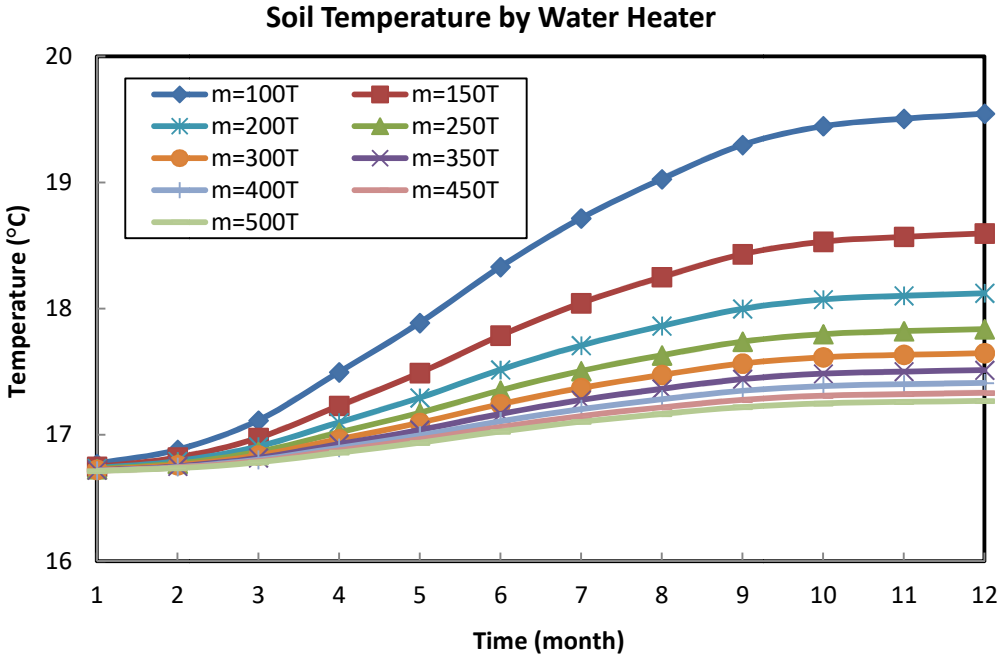
Based on solar energy calculation, the annual average electric energy generated by solar PV was 0.6 GJ/m^2 (166.67 kWh/m^2), which is remarkable and sufficient to cover the best case's energy demand for U-value by 2 W/m^{2}K, as revealed in Fig. 4-4. It shows the annual average heat loss from the facades including floor, rooftop, and walls of the design greenhouse for vary U-value of 1-5 W/m^{2}K whereas indoor temperature target is set on 20 °C (worst case) and 15 °C (best case), respectively.

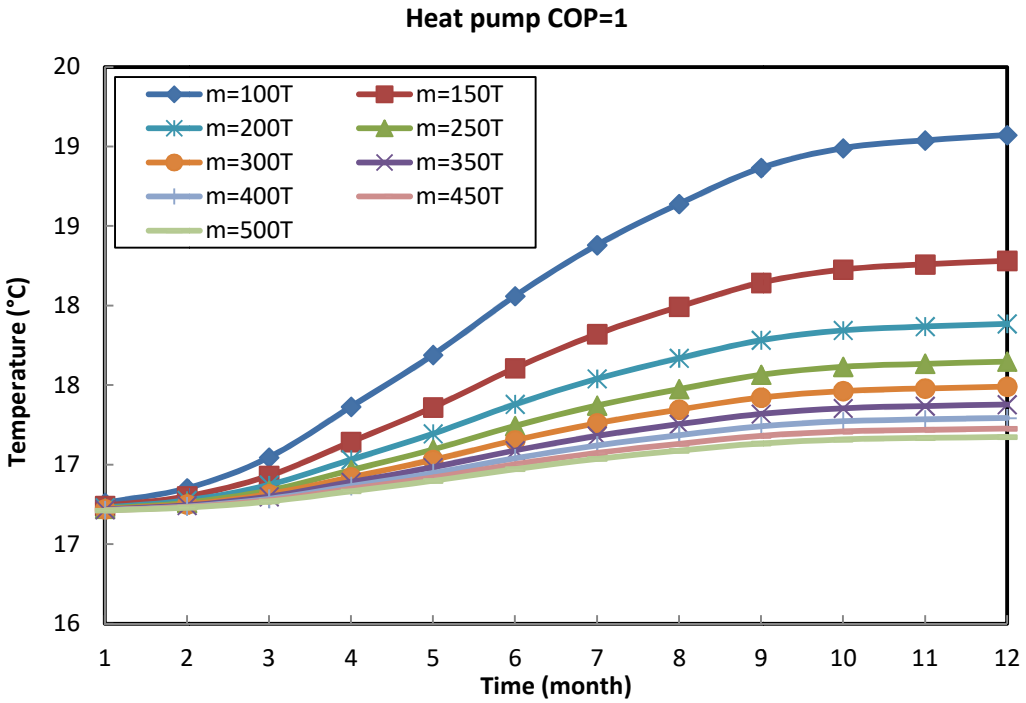
4.1.3.4. Soil Temperature Distribution

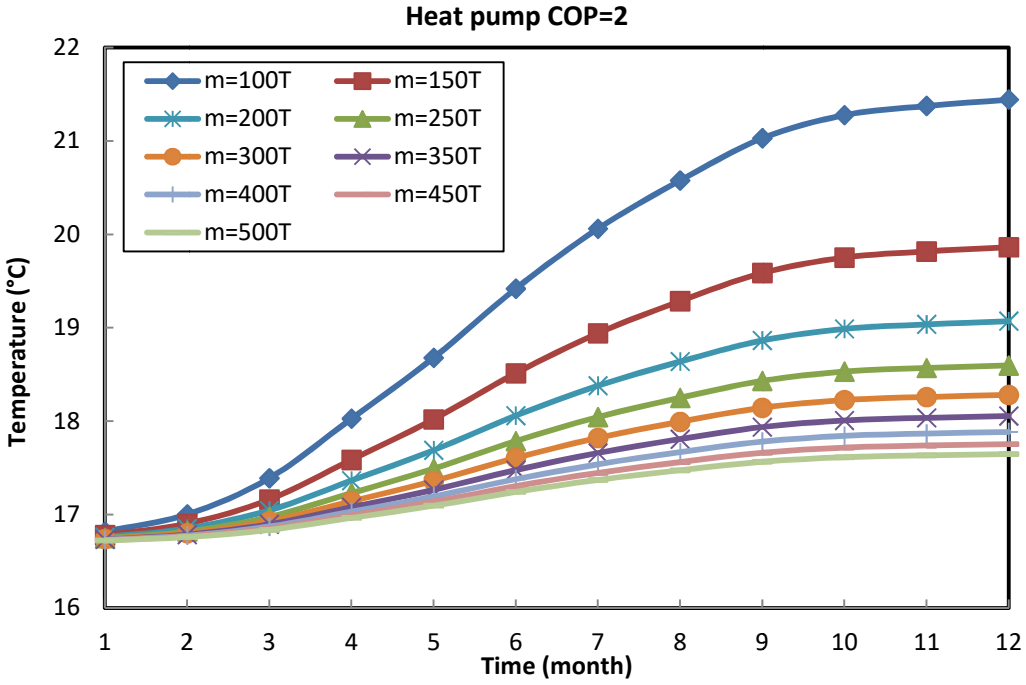
In order to investigate the soil temperature distribution of SSBTESS, the graphs in Fig. 4-9 shows the potential of renewable energy. It is obviously revealed that lower soil mass has higher temperature distribution and higher COP yields high soil temperature. The amount of energy that can be

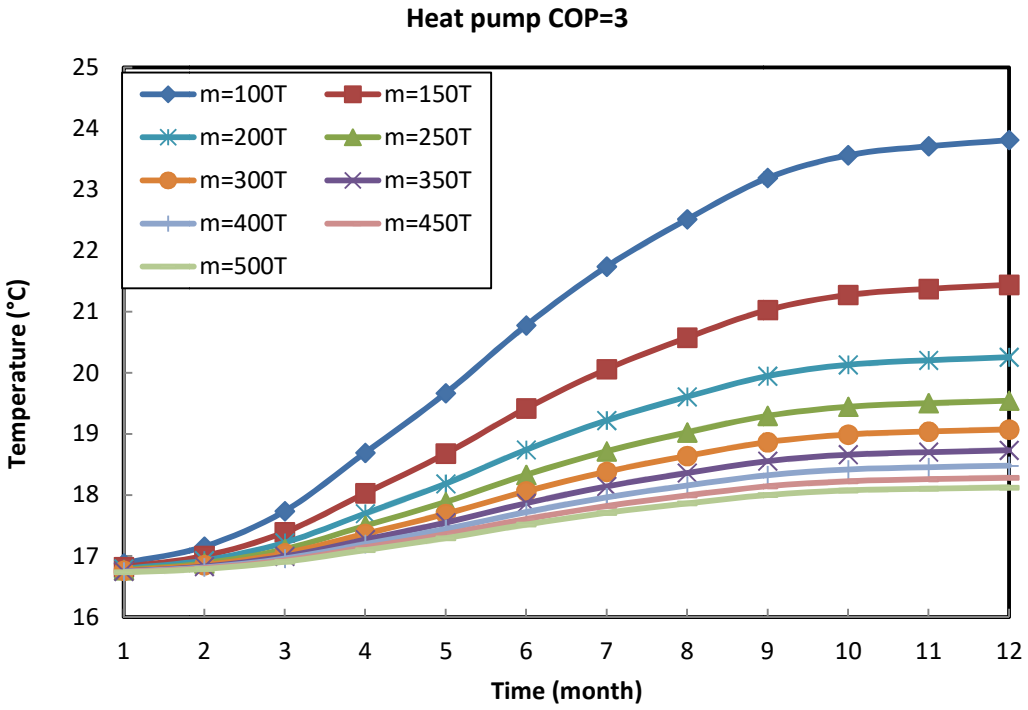
stored in the soil beneath the building was calculated by varying the soil volume can be seen in Fig. 4-10.

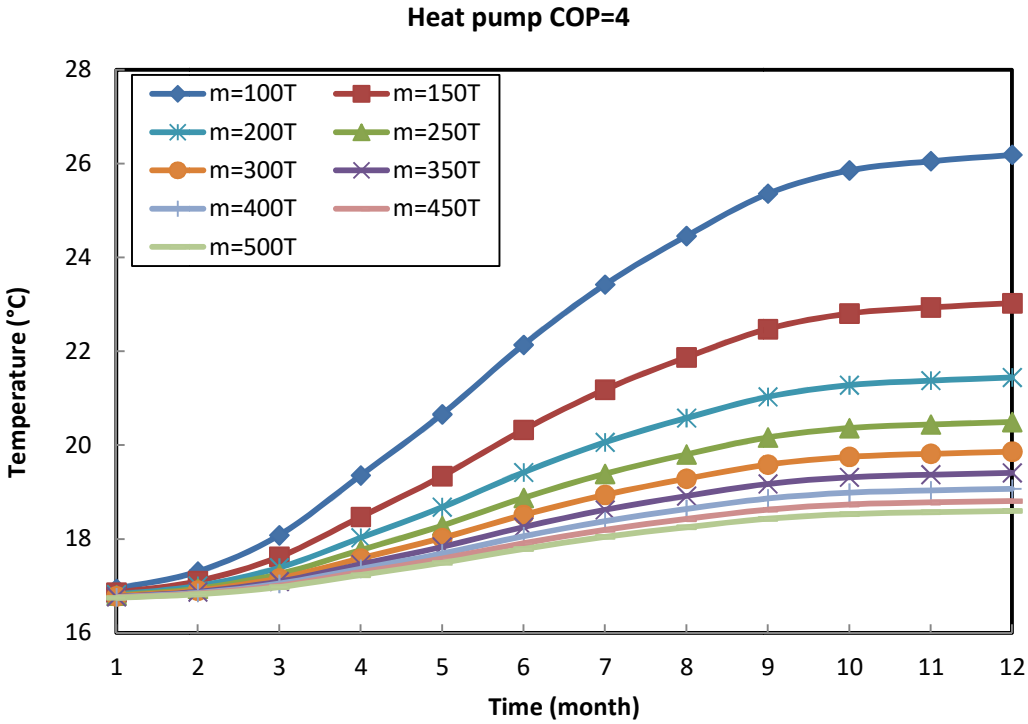
Based on equation (4-4) and (4-7), the soil temperature that was successfully injected by electric water heater and heat pump with various COP has been calculated and can be seen in Fig. 4-9. The initial soil temperature of 16.7 °C for the site was used. The undisturbed ground temperature was determined based on the thermal response test result which is explained further in Section 5.1. This value is in the range of average shallow UK soil temperature of 8.8-17.7 °C for 1m depth (Busby, 2015). The highest soil temperature was achieved by the lowest soil mass and highest COP of heat pump that is used.




Heat pump COP=1
m=100T
m=150T
m=200T
m=250T
m=300T
m=350T
m=400T
m=450T
m=500T
Temperature (°C)
Time (month)
20
19
19
18
18
17
17
16
1
2
3
4
5
6
7
8
9
10
11
12


Heat pump COP=2
m=100T
m=150T
m=200T
m=250T
m=300T
m=350T
m=400T
m=450T
m=500T
Temperature (°C)
Time (month)
22
21
20
19
18
17
16
1
2
3
4
5
6
7
8
9
10
11
12


Heat pump COP=3
m=100T
m=150T
m=200T
m=250T
m=300T
m=350T
m=400T
m=450T
m=500T
Temperature (°C)
Time (month)


Heat pump COP=4
m=100T
m=150T
m=200T
m=250T
m=300T
m=350T
m=400T
m=450T
m=500T
Temperature (°C)
Time (month)

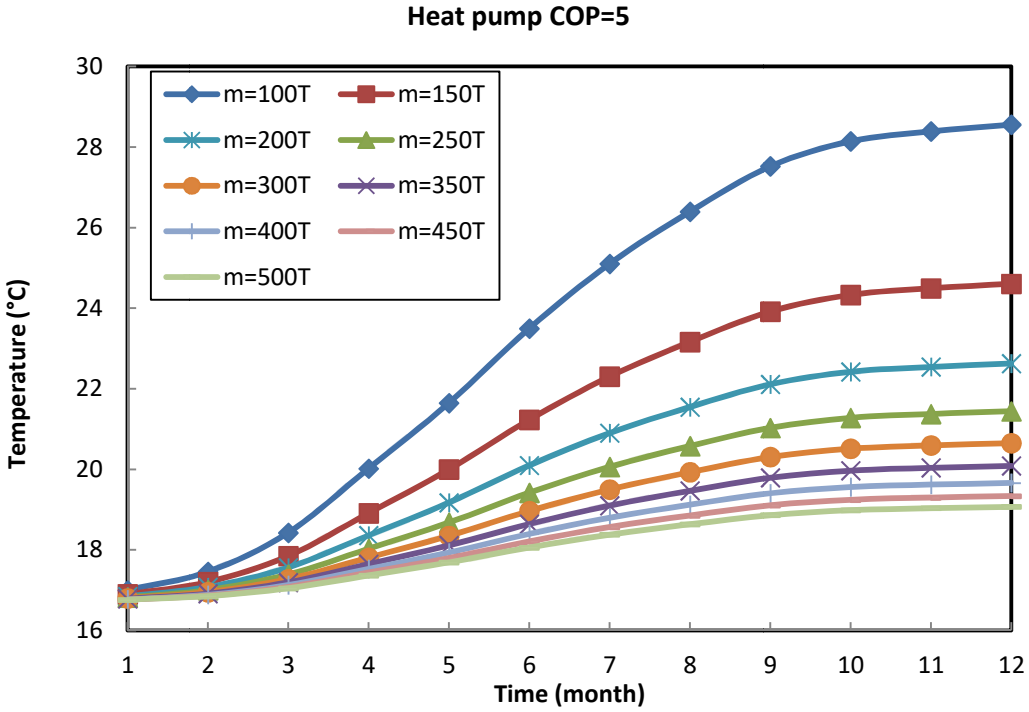


Fig. 4-9. Monthly soil average temperature distribution as seasonal thermal energy storage system yielded by electrical water heater and heat pump with varying COP's

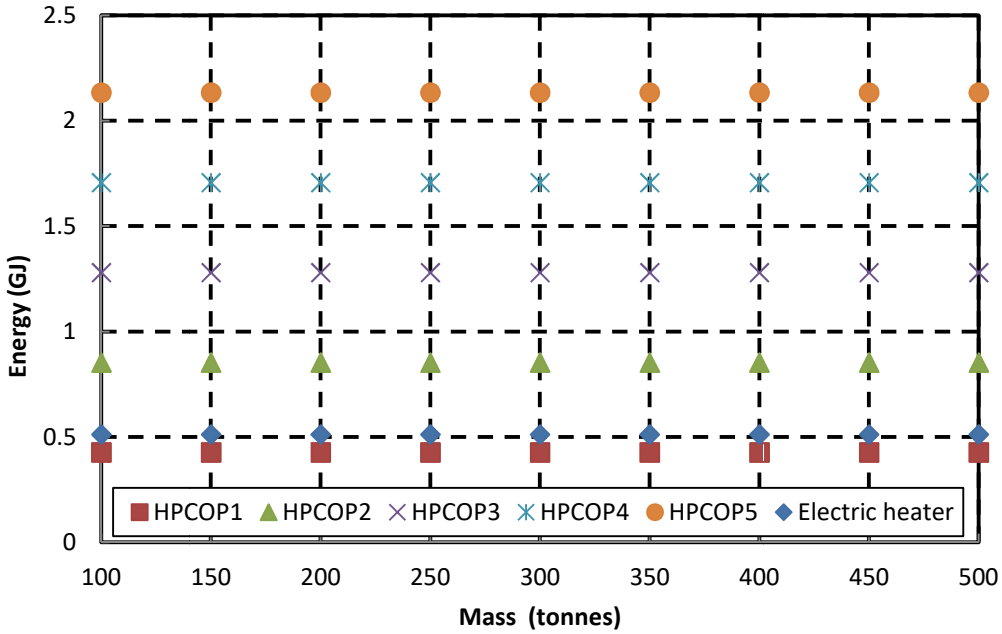


Fig. 4-10. The analytical annual soil energy stored with mass variation yielded by the electrical water heater and heat pump at different COPs

Fig. 4-10 shows the annual energy that can be stored to the ground in the different soil mass. This information is used to determine the potential of

seasonal underground heat storage for the heat pump by determining the depth of the pipe heat exchanger and the insulation. By comparing the soil volume and the soil density, the surface area and the soil depth can be calculated. As result, the soil-based underground TES is capable of annually saving 0.4-2.1 GJ per square meter of PV panel area and cover both type set point temperature needed. As it is clearly seen from the results that the soil mass is a dominant parameter in soil temperature and hence the thermal energy storage capacity.

Table 4-1. Soil volume configuration for seasonal thermal energy storage system

	insulation soil depth (m)					
	1.5	2	2.5	3	3.5	4
m (tonnes)	**Surface area A (m^2)**					
100	39.22	29.41	23.53	19.61	16.81	14.71
150	58.82	44.12	35.29	29.41	25.21	22.06
200	78.43	58.82	47.06	39.22	33.61	29.41
250	98.04	73.53	58.82	49.02	42.02	36.76
300	117.65	88.24	70.59	58.82	50.42	44.12
350	137.25	102.94	82.35	68.63	58.82	51.47
400	156.86	117.65	94.12	78.43	67.23	58.82
450	176.47	132.35	105.88	88.24	75.63	66.18
500	196.08	147.06	117.65	98.04	84.03	73.53

In order to understand to design the parameters variable needed in designing the seasonal thermal energy storage for novel greenhouse, therefore Table 4-1 was made. The table shows the possibility soil volume and soil surface area that could be used to design the greenhouse building. In addition, to reduce the heat loss of the seasonal underground heat storage, the surrounding soil heat storage needs to be well-insulated. With respect to those results, for an example the depth of soil-based TES for 47

m^2 of 200 tonnes with soil temperature distribution of 17.9-22.6 °C per square meter of PV panel surface area and COP=1-5 at least must be in 2.5 m depth, likewise for the insulation would be enough to cover the heating-cooling energy demand.

4.1.4. Conclusion

To design a greenhouse building, heating-cooling demand should be considered to ensure an appropriate place for protected plantations. An analytical investigation may give a good start to describe the energy demand needed. Therefore, this preliminary research was aimed to investigate the energy demand of a proposed greenhouse and show the capability of the soil beneath the greenhouse to be used as heat storage. The heat was injected to the ground by utilising electric water heater and heat pump with varying COP and distributed via pipe heat exchanger. There are two scenarios for the greenhouse; indoor high temperature as the worst-case scenario and indoor low temperature as the best-case scenario.

Based on the results, it is shown that the annual power generated by PV panels is 0.6 GJ per square meter, capable of covering the heat loss of the best-case building which has facades thermal transmittance of 2 W/m^2 by power up an electric water heater or a heat pump to inject the heat into the ground. The injected heat could be used as a heat source for a ground source heat pump to maintain the heating and cooling demand for both cases in the greenhouse.

In addition, an example case of the greenhouse system with seasonal TES must consider using higher COP heat pump than 3, utilising lower thermal transmittance of facades, and install solar PV's panel with high efficiency

more than 15% on the building facades surface area. Besides solar power, the soil properties should be designed better than has been assumed. For 47 m^2 surface area, the insulation depth must be no less than 2.5 m beneath the floor.

However, since the calculations were conducted with some assumptions that are ideal for the PV solar panel, it is recommended that the greenhouse use a low thermal transmittance (U-value) for the facades as the best effort to minimise the heat loss. By using high PV panels efficiency surrounding the claddings could beneficial to increase power generation. In addition, well-insulated soil-based TES will provide adiabatic condition thus no heat loss from the edges. Furthermore, a dynamic building simulation is needed to validate the analytical results.

4.2. SIMULATION INVESTIGATION

4.2.1. Introduction

This section aims to investigate the performance of the novel greenhouse equipped with semi-transparent PV, LED lights, Ground source heat pump, and well-insulated soil-based underground thermal energy storage. The investigation was conducted by using the EnergyPlus energy building simulator whereas DesignBuilder was used as the user interface. The results were used to support the analytical investigation of the novel greenhouse in Section 4.1 and to find the most reliable results in terms of energy demand and soil-based energy saving.

4.2.2. Methodology

The simulation will refer to some assumptions and the properties of envelope materials used for the greenhouse are shown in Table 3-1. The

dimension of the greenhouse as previously mentioned and can be seen in (Harjunowibowo et al., 2017). While the soil crosses section beneath the greenhouse can be found in Fig. 4-11.

The simulation software DesignBuilder which uses the EnergyPlus algorithm as its basis was used to assess the dynamic thermal and energy conventional of the greenhouse building. DesignBuilder provides a 3D architectural modelling tool and the simplicity in inputting numerous parameters. Moreover, DesignBuilder could produce the graphs of energy consumption, carbon emissions, occupant comfort and daylight based on the EnergyPlus output (DesignBuilder, 2011).

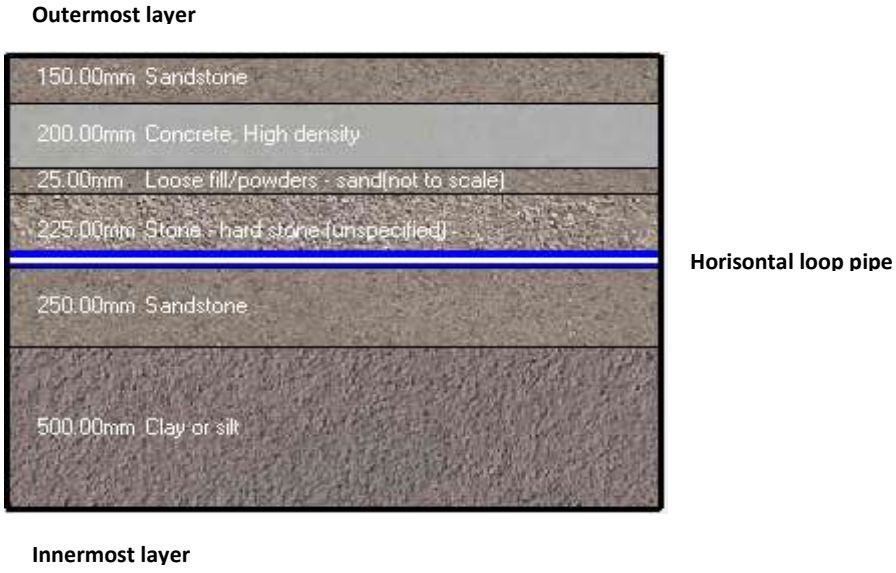


Fig. 4-11.The cross-section of soil TES

EnergyPlus has three integrated simulation parameters; building, system, and plant all of which need to be simultaneously run and solved in order to get results. The sequential solution began with a zone air heat balance to renovate the zone conditions and determine the heating-cooling loads at all times. This information is then supplied to the air handling simulation in order to determine the system response. Similarly, the system information

produced is passed to the plant simulation with no feedback. This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space. The analytical method based on Energyplus engineering reference (EnergyPlus, 2016).

4.2.2.1. Greenhouse Description

The greenhouse was built in Loughborough, UK (Latitude 53.48°, Longitude -1.0°) with the specification mentioned in chapter theoretical investigation. The semi-transparent double glazing PVs were used as the rooftop. The double glazing walls were made of Polycarbonate 5X wall type and opaque PVs were installed on the east, south, and west-facing façade walls. The investigations were conducted for two different materials to make better comparison regarding the heat loss and energy-saving.

4.2.2.2. HVAC Modelling

This system utilised a ground source heat pump to provide heating and cooling for the greenhouse. The HVAC system can be seen in Fig. 4-12. The greenhouse was equipped with natural ventilation which is controlled by an automation machine to open the wind-catcher on the rooftop when needed. A fan coil was used to distribute the heating air and cool air in heating and cooling mode. The simulation carried out in 365 days to get a comprehensive behaviour of the proposed system.

The proposed GSHP-PVT system is schematically illustrated in Fig. 3-1. The system is mainly designed to provide heating and cooling. The system consists of PV collectors, a water-to-water heat pump unit, water circulation pumps, ground heat exchanger loop tube, vertical heat

exchanger pipe and an indoor air-handling unit (AHU). The water-to-water heat pump model was trained using the manufacturing catalogue data. The key parameters of the PV, Ground heat exchanger (GHE), and water pumps were determined using the available product specifications in Table 4-2.

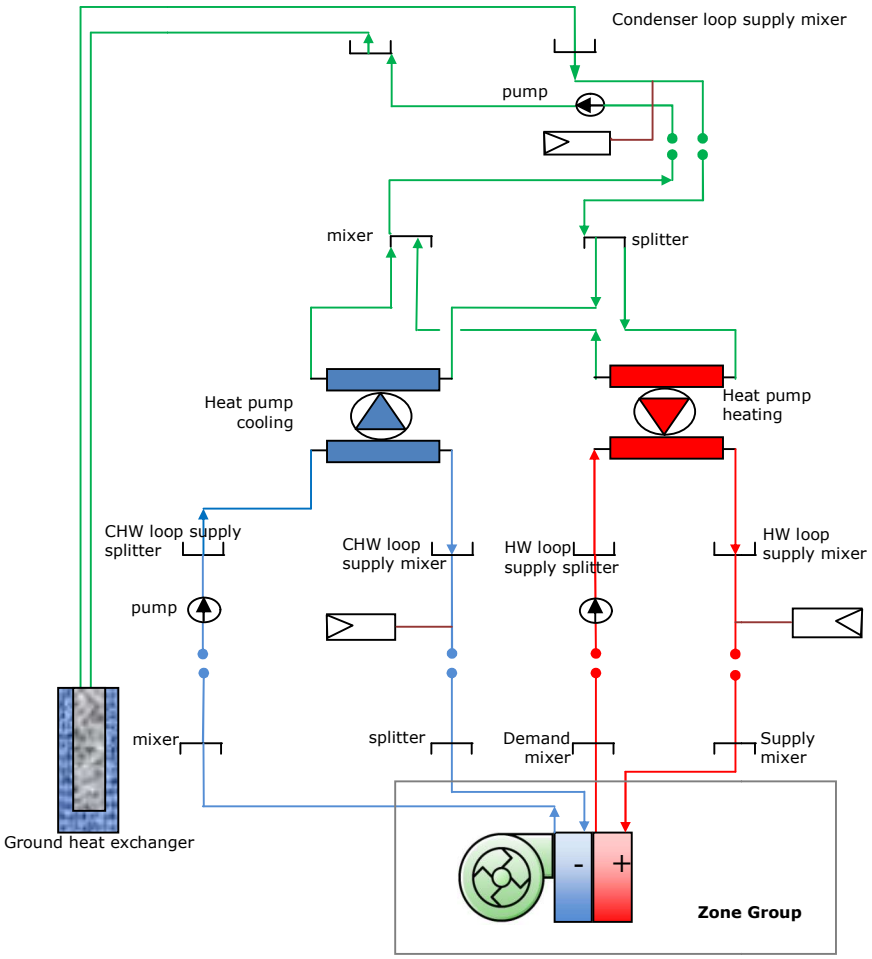


Fig. 4-12. The Energyplus HVAC scheme system for the greenhouse simulation

The annual heating and cooling demands of the greenhouse were simulated using DesignBuilder based on the weather data from International Weather for Energy Calculations (IWEC) of East Midland and are presented in Fig. 4-14.

4.2.2.3. Photovoltaic Array

The usable electrical powers produced by a PV surface were calculated using equation (4-8):

$$P = A_{surf} \cdot f_{activ} \cdot G_T \cdot \eta_{cell} \cdot \eta_{invert} \quad (4\text{-}8)$$

P is PV Electrical power produced by photovoltaic [W], A_{surf} is Net area of surface [m^2], f_{activ} is Fraction of surface area with active solar cells [dimensionless], G_T is Total solar radiation incident on PV array [W/m^2], η_{cell} Module conversion efficiency [dimensionless], η_{invert} DC to AC conversion efficiency [dimensionless].

Table 4-2. Specifications of the GSHP system

Parameter	Value
Ground Heat Exchanger system	
Ground thermal conductivity (W/mK)	1.5
Ground heat capacity (J/m^3K)	880.00
Borehole diameter (m)	0.08
Outer diameter of U-tube (m)	0.025
Initial ground temperature (°C)	16.7
Pipe thermal conductivity (W/mK)	344.00
Pipe thermal heat capacity (W/mK)	158
Heat pump unit ((NIBE, 2010)**)**	
Rated cooling/heating capacity (kW)	2.62 /3.85
Rated water flow rate (m^3/h)	0.65

On the right-hand side of this equation, only G_T is calculated by EnergyPlus and the rest are user inputs. Power levels are assumed constant over the time step to arrive at energy production. Incident solar radiation on the PV or collector surface is calculated using the same algorithms used for all

exterior surfaces and is calculated separately for beam, sky, and ground reflected components based on surface geometry.

4.2.2.4. Soil-based energy saving

The energy yielded by the PV panels in the simulation was used to investigate the performance of energy stored in soil which was placed beneath the building. The governing equation to reveal the soil temperature and energy stored was outlined in Equation (4-3) and (4-4) in the previous section. In this simulation, the impact of ground temperature on the performance of the system was discussed. The COP was calculated based on the heat output from the condenser over the power supplied (Cho and Mirianhosseinabadi, 2013).

4.2.3. Results and Discussion

Fig. 4-13 reveals the yearly energy demand for heating and cooling on a single glass greenhouse found to be 133.6 GJ. The total annual of building loads for heating and cooling was 104.0 GJ and 29.6 GJ, respectively. The heating peak load was 295kWh or 22.6 MJ/m^2 in January and the cooling peak load was 164kWh or 3.5 MJ/m^2 in August. The graph was derived from dynamic building simulation by DesignBuilder. The properties of the facades were shown in Table 3-1.

Compared to heating-cooling demand with a single glass greenhouse in Fig. 4-13, the declination of the heating-cooling load was very significant. The total heating-cooling energy demand found to be 76.6 GJ where heating and cooling loads are 76.5 GJ and 0.083 GJ, respectively. There was energy saving by 42.7% due to heat loss from the facades and in accordance with Bailey and Harjunowibowo et al. that double glazing could

reduce the heat loss to 35-60% (Bailey, 1981; Harjunowibowo *et al.*, 2017).

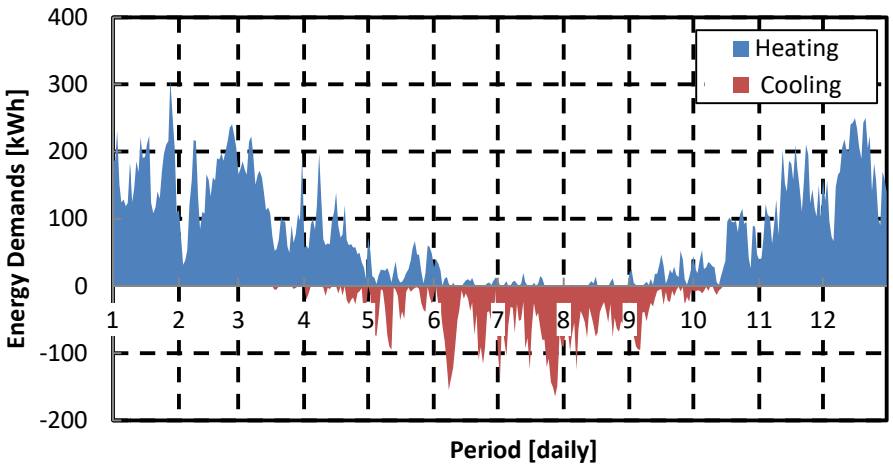


Fig. 4-13. The annual heating-cooling demand of a single glazing greenhouse

In addition, Tantau et al., and Vadiee and Martin found that replacing single glazing with double glazing may reduce the total energy demand by 45% to 60% (Tantau *et al.*, 2011; Vadiee and Martin, 2014a). However, Harjunowibowo et al. found that converting the single glass with double glazing sandwiched with opaque PV and semi-transparent solar PV glazing on roof top resulting the energy saving by only 35% (Harjunowibowo *et al.*, 2017).

Fig. 4-14 shows the energy demand for heating and cooling in a year which has to be fulfilled to achieve desired temperature. In addition, the air temperature in the novel greenhouse was targeted to be stable at 16 $^{\circ}$C to 18 $^{\circ}$C as shown in Fig. 4-15. However, based on the simulation, the novel system used has a fluctuating indoor temperature, ranging from 16 $^{\circ}$C to 21.6 $^{\circ}$C. Also, relative humidity could be maintained in the range of 36% to 55 % compared to the outside relative humidity as can be seen in Fig. 4-16.

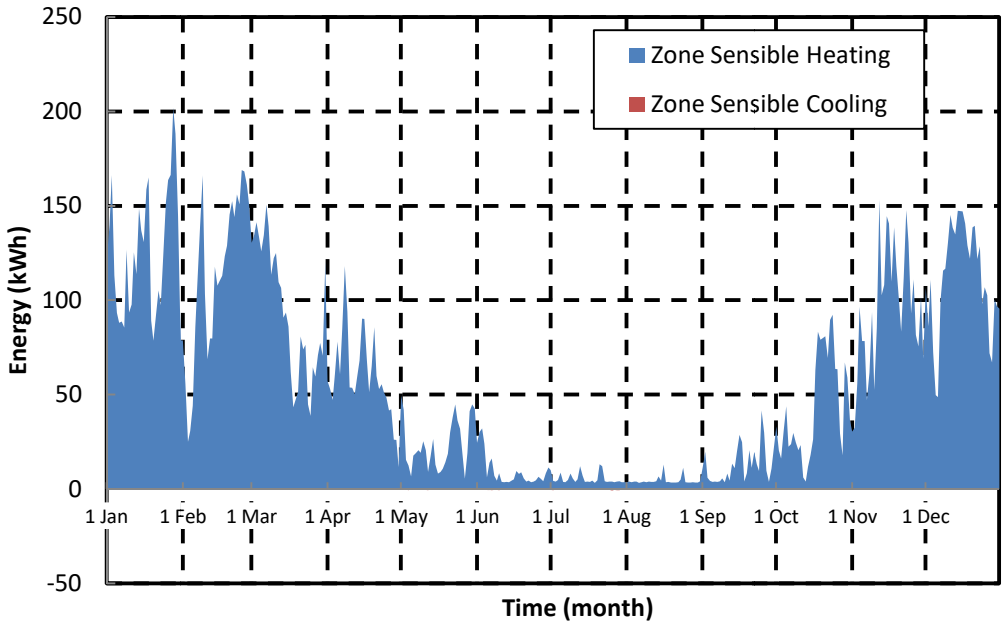


Fig. 4-14. The daily heating-cooling demand of the novel greenhouse

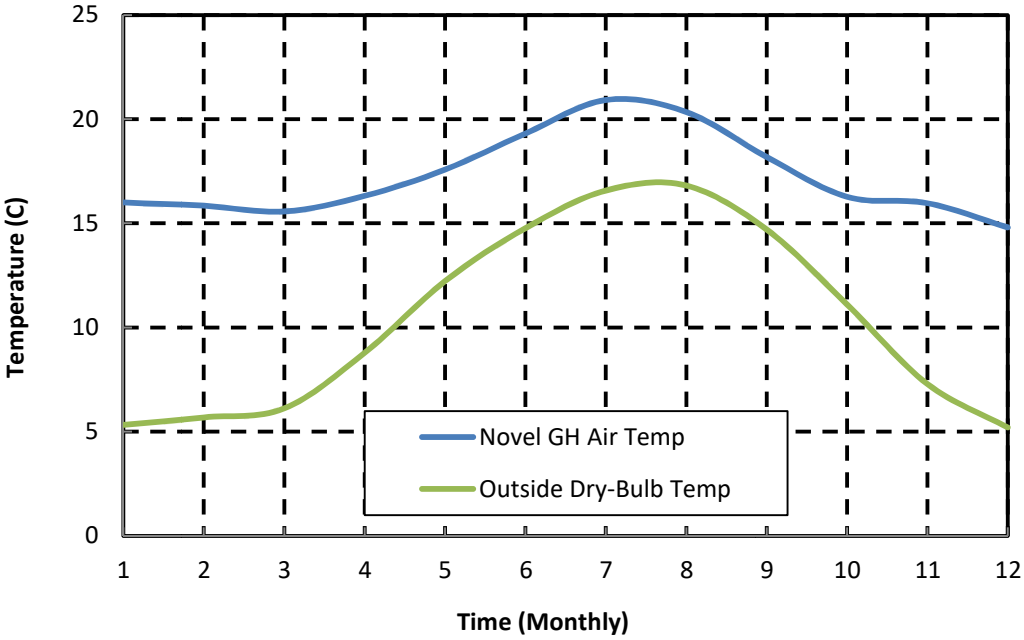


Fig. 4-15. The average inside and outside air temperature of the novel greenhouse

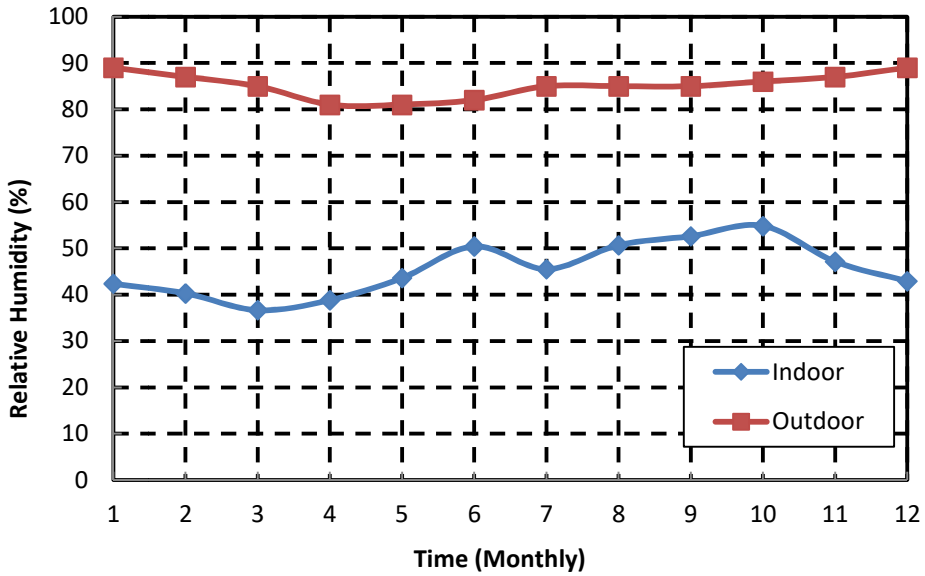


Fig. 4-16. The relative humidity of the novel greenhouse

Regarding the energy used by the HVAC to distribute heating and cooling of the greenhouse, the zone sensible heating and cooling demand per surface floor area indicates that heating energy demand was superior, as predicted. The behaviour of the energy consumption was revealed in Fig. 4-17. The results of the simulation indicate that the total energy demand for heating-cooling load was about 0.81 GJ/m^2. In addition, there was also 0.99 GJ/m^2 energy demand for HVAC, 0.18 GJ/m^2 for lighting and 1.33 MJ/m^2 for control system. However, up to 62.25 % of the energy needed by the site could be provided by the PV panels with total power of 29.13 MJ. Therefore, the net total energy consumption found to be 0.41 MJ/m^2.

The zone sensible heating is the overall sensible heating effect of any air introduced into the zone through the HVAC system including any 'free heating' due to the introduction of relatively warm outside air and the heating effects of fans. In other words, zone sensible heating shows the overall HVAC heating contribution to the zone heat balance (DesignBuilder, 2011).

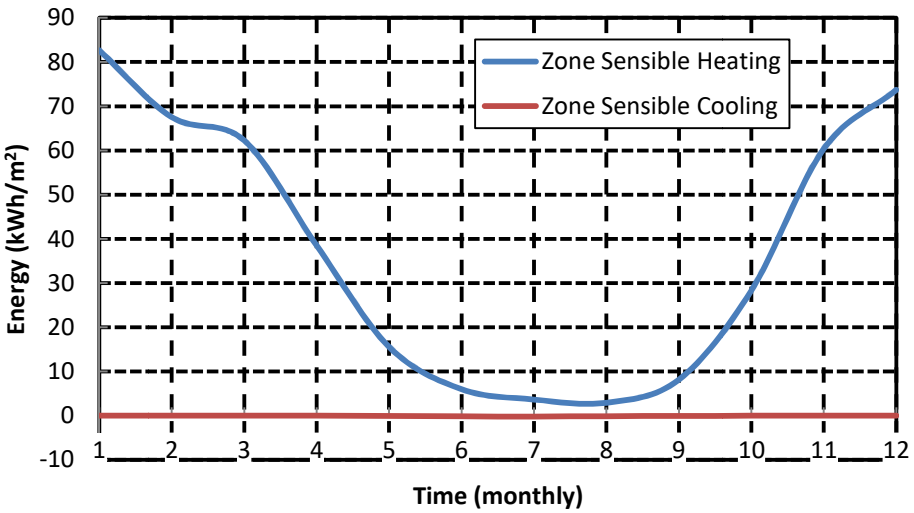


Fig. 4-17. The average zone sensible heating and cooling energy demand of novel greenhouse

Likewise, zone sensible cooling is defined as the overall sensible cooling effect on the zone of any air introduced into the zone through the HVAC system. It includes any free cooling due to introduction of relatively cool outside air and the heating effect of any fans present. Cooling always shows as a negative heat gain in the results. Simply, zone sensible cooling shows the overall HVAC cooling contribution to the zone heat balance (DesignBuilder, 2011).

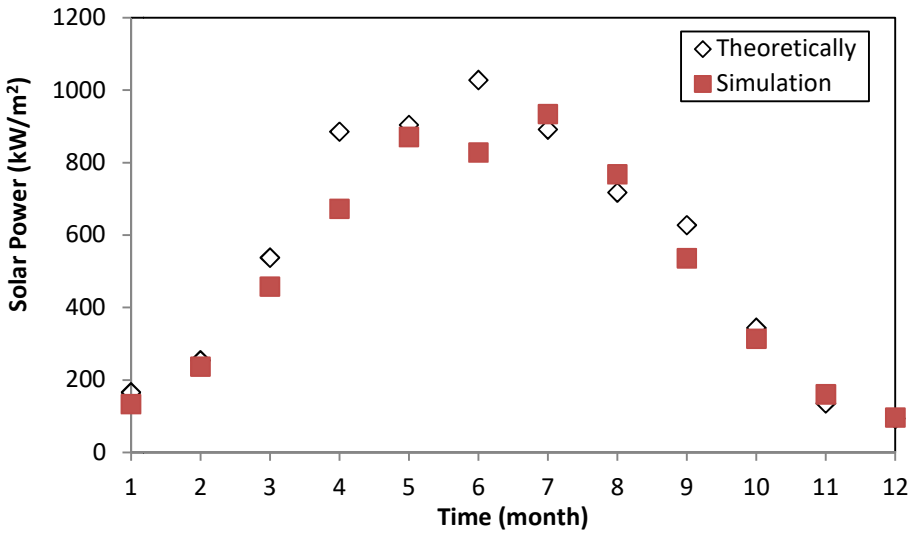


Fig. 4-18. The comparison of power produced by PV panels based on the EnergyPlus simulation and theoretical

Power generation of the PV panels installed on the greenhouse envelopes was calculated based on the diffuse horizontal solar irradiance. The electricity generated from the PV panels as seen in Fig. 4-18 was obviously remarkable. The energy per surface area of PV panels was utilised to power up the electrical water heater. The resultant heat was then injected into the soil as mentioned in the introduction section.

Fig. 4-19 shows that the energy demand for various greenhouse systems remains stable for orientation changes. It can be seen that the proposed greenhouse (GHPCSTPV) has the lowest energy consumption compared to other types with different facades layers. Furthermore, in order to understand the orientation effect of PV power generation, Fig. 4-20 shows the result. To have maximum benefit in terms of electricity generated by the PVs, it is recommended for the northern area to build the proposed greenhouse with PV facing west-south-east. Since the PV will be exposed by the sunlight much more and hence produce maximum power.

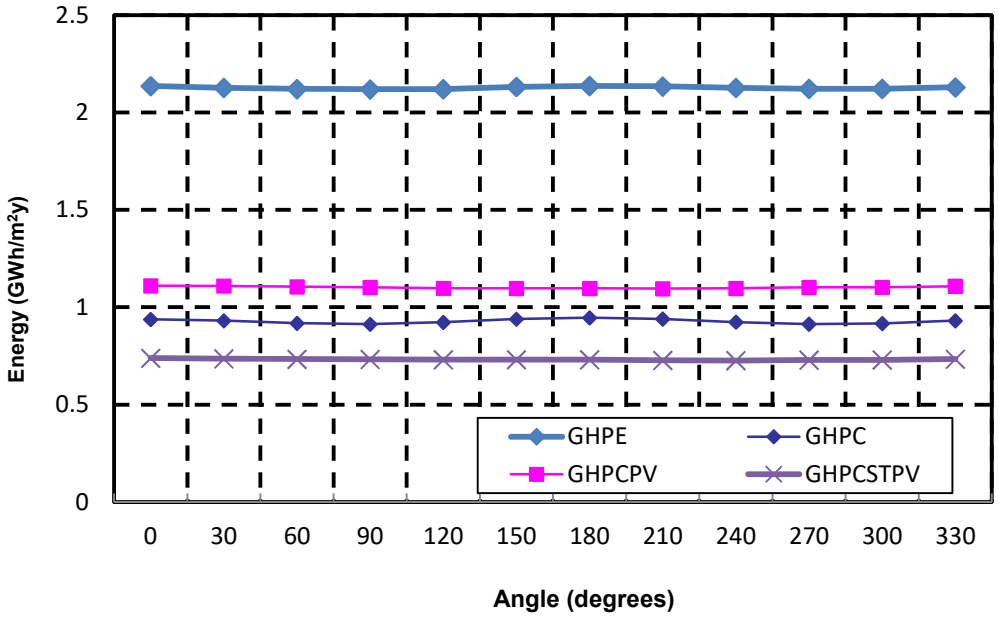


Fig. 4-19. The effect of greenhouse orientation against the Net Source Energy (Harjunowibowo *et al.*, 2017)

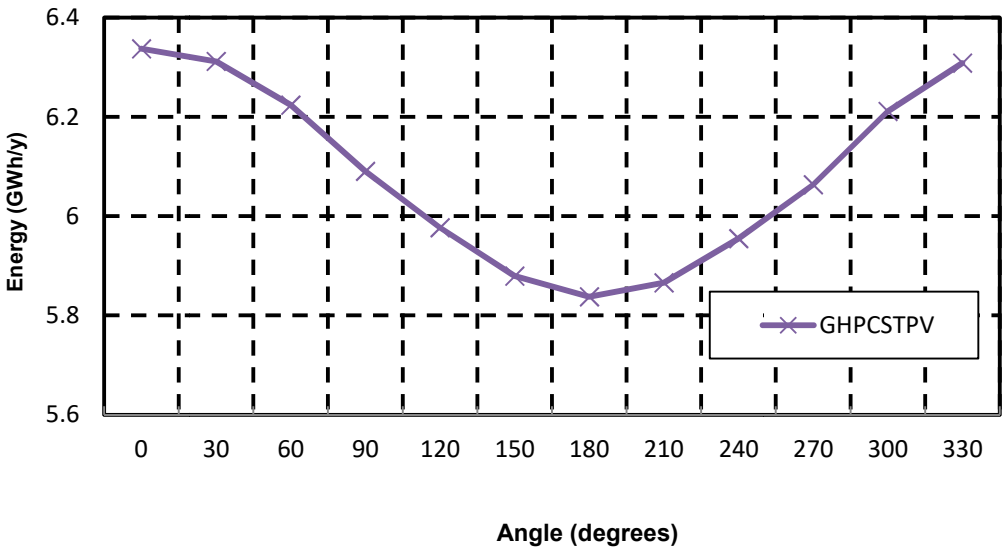


Fig. 4-20. The effect of Greenhouse orientation against the PV energy generation (Harjunowibowo *et al.*, 2017)

The solar energy results are in agreement with the EnergyPlus simulation result. Hence, the soil temperature in the soil was lower compared to the typical greenhouse due to the lower electric water heater efficiency as clearly seen in Fig. 4-21. Based on the results, the energy demand for the proposed novel greenhouse could be fulfilled by heat pump with COP of 3.

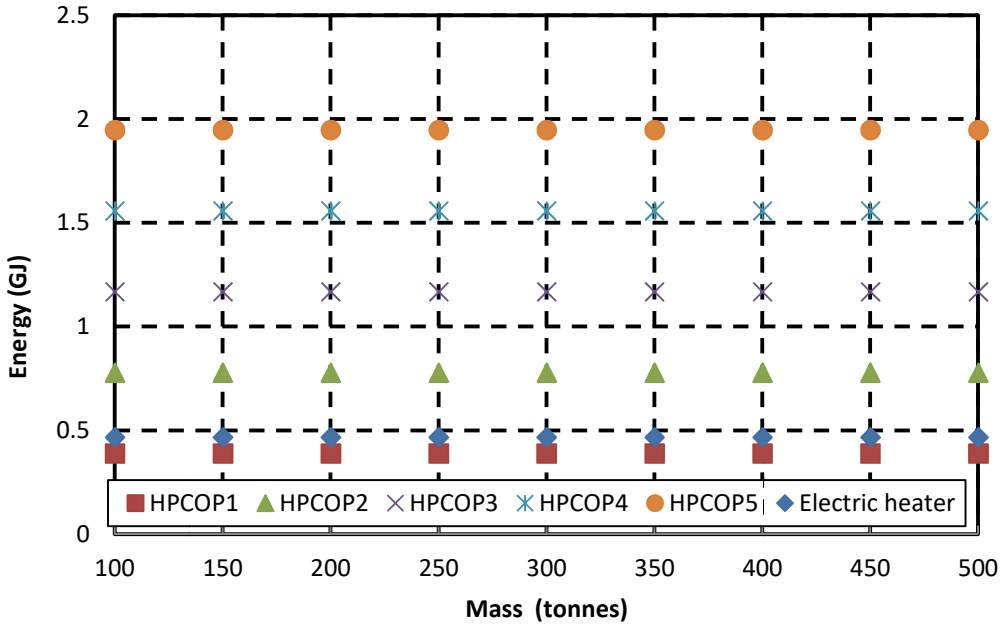


Fig. 4-21. The annual total energy stored in the soil based on the simulation

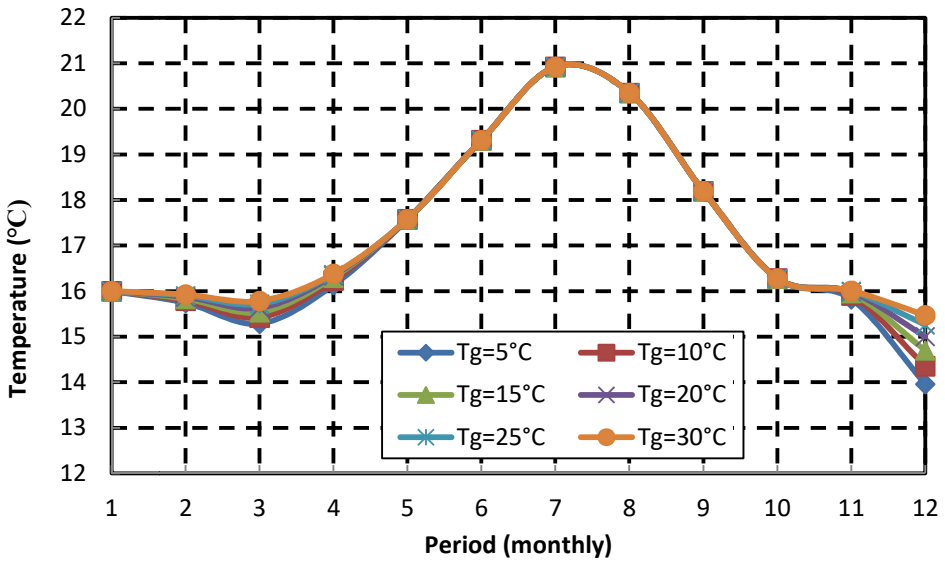


Fig. 4-22. The ground temperature impact to the indoor temperature

Fig. 4-22 shows the ground temperature as the thermal source for the heat pump. The ground temperatures vary between 5°C to 30 °C –at a temperature below 5°C, the brine was reported to freeze and the simulation could not be run. It can be seen that the indoor temperature was better when having higher ground temperature. Even though the ground temperature getting high, the indoor temperature difficult to rise significantly. As a result, the COP of the system found to be very low, at 1.61, 1.64, 1.66, 1.67, 1.69, and 1.70 respectively.

Besides temperature a greenhouse needs sunlight containing PAR for plants photosynthesis wavelength of visible light (Gislerod, Eidsten and Mortensen, 1989; Benli and Durmuş, 2009; Ilieva *et al.*, 2010; Benli, 2011; Yano, Onoe and Nakata, 2014; Singh *et al.*, 2015). PAR wavelength spectrum is around 400-700nm. Daylight is free energy and cost-effective for sustainable building design (Yu and Su, 2015). It provides a more pleasant and attractive indoor environment for human visual response and plants as well, much better than an artificial light source. Therefore, the

cladding material is an important factor related to the PAR that enters a greenhouse's interior space.

In this respect, EnergyPlus is a well-known simulation tool for lighting, heating and cooling energy consumption in the building, which builds on the strength of two widely used programs: BLAST and DOE-2. When calculating the lighting energy consumption, the hourly schedules for lighting-related settings could be generated in lighting simulation program such as Daysim and read as input file into EnergyPlus. The accuracy of the software has been tested and validated by another simulation program (Witte *et al.*, 2001) and field measurement (Yun *et al.*, 2012). Thus EnergyPlus is used to analyse the daylighting of the greenhouse in this research.

Daylight Factor is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies. Daylight Factor is typically calculated by dividing the horizontal work plane illumination indoors by the horizontal illumination on the roof of the building being tested and then multiplying by 100. Based on the simulation, the average DF from the novel greenhouse was 18.9% where the uniformity of the light distribution only 36.5%. The illuminance of the daylighting was in range of 535-1465 lux as seen in Fig. 4-23. However, the daylight passes the BREEAM Health and Wellbeing Credit HEA 01 status due to requirements can be fulfilled. The BREE Environmental Assessment Method is an assessment method used to describe buildings' environmental performance originated in the UK (Star, 2019). The average daylight factor was at least 2.0% and the uniformity ratio of at least 0.3 or a minimum point daylight factor of 0.8%. Even though, in order to achieve minimum requirement for good distribution to improve the photosynthesis

of 200 μmol m^{-2} s^{-1} (10.800 lux) (Apogee Instruments, 2016), artificial lighting is needed.

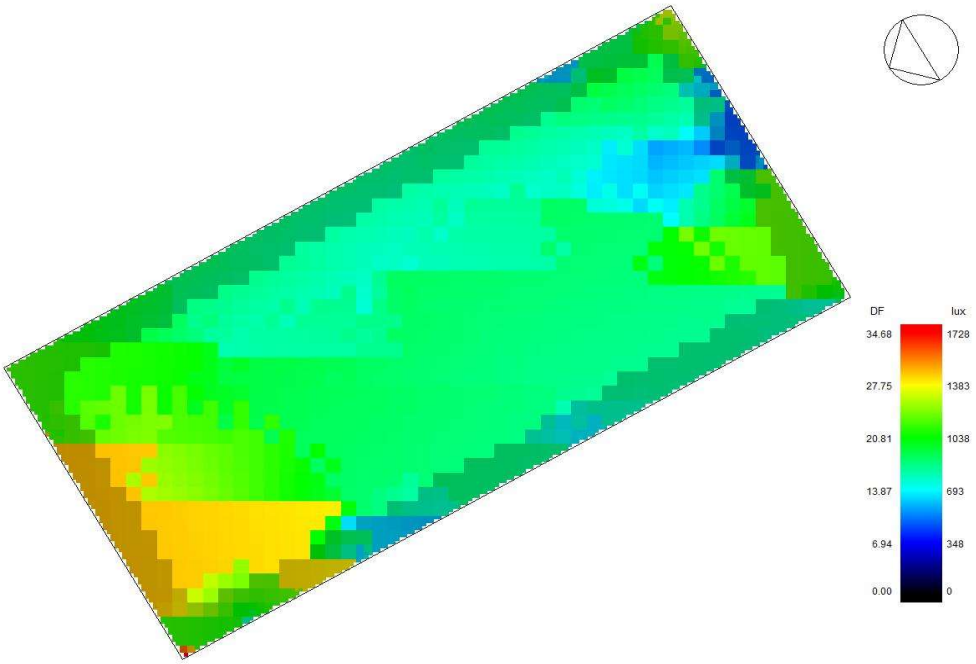


Fig. 4-23. The daylighting distribution map in the main greenhouse

4.2.4. Conclusion

This research was carried out to investigate the performance of the novel greenhouse. Secondly, it was used to validate the analytical investigation of the soil-based thermal energy storage performance in the previous chapter. The results show that the novel greenhouse could maintain its indoor temperature within the range of 16 °C to 21.6 °C, with annual energy consumption for heating-cooling load of 0.81 GJ/m^2. In addition, the light distribution is only 36.5%. The illuminance of the daylighting was in range of 535-1465 lux of 10.800 lux, therefore artificial light is important.

Therefore, the design recommendation for the proposed greenhouse was by using thermal transmittance 1.2 W/m^2 and 2.0 W/m^2. As previously mentioned, it was very crucial to consider heat pump with COP of 3 as the

heating-cooling energy provider. Likewise, preventing the freezing of the brine by using glycol is urgent and more importantly keeping the ground temperature above 5 °C. Also, to achieve lighting for photosynthesis requirement, utilising LED lamp which has a long life span and low wattage was required in order to gain more energy saving. Due to the similar results regarding the energy demand on specified U-value, COP of heat pump, therefore the simulation investigation of soil-based energy storage verifies the analytical investigation from Section 4.1.

CHAPTER 5 – Experimental Work Results and Its Analysis

Outline of the Chapter:

This chapter summarises the up to date result of the experimental fieldwork and proposes some recommendations for the future. The chapter begins with several tests on thermal responses to determine the undisturbed ground temperature, soil thermal conductivity, and borehole thermal resistance. Secondly, seasonal COP of the Heat pump and the system were also calculated. Finally, the thermal performance of the greenhouse is analysed; including the annual temperature inside and outside the greenhouse, the soil temperature, and the PV performance. Moreover, some findings also been discussed.

5.1. THERMAL RESPONSE TEST

5.1.1. Introduction

The information about the undisturbed ground temperature while designing and modelling a system related to underground heat transfer is very important. The ground temperature experiences interactions with many aspects especially atmospheric conditions such as ambient temperature, solar exposure, humidity, and subsurface layer.

It is well known that ground temperature changes with depth; the amplitude of change decreases in deeper ground level. Moreover, ground temperature varies in different locations and times (Li *et al.*, 2017). Therefore, in order to support the modelling of greenhouse with shallow soil-based thermal energy storage, this section was focused on soil thermal properties.

The aims of the experiment were to determine the undisturbed ground temperature, the thermal conductivity of the soil and the borehole thermal resistance. The information was used to determine the performance of GSHP for the greenhouse in the previous investigations in Chapter 4. Furthermore, the results were used to be validated with the field test in Chapter 5.

5.1.2. Methodology

The distributed thermal response test pipe-in-pipe coaxial can be calculated using the equation (5-1) (Acuña and Palm, 2013; Sarbu and Sebarchievici, 2016, p. 92). The principal analysis was determined with a line-source, representing the borehole as a heat line-source.

$$T_b - T_g = \frac{q}{4\pi k_g}\int_{r_b^2/4at}^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta$$

$$= \frac{q}{4\pi k_g}E_i\left(\frac{r_b^2}{4at}\right) \quad (5\text{-}1)$$

Where T_g is undisturbed ground temperature [°C], q is injected/extracted specific power [W/m], L is pipe length [m], T_b is borehole wall temperature [°C], r_b is borehole wall radius [m], $a = {k_g}/{c_g} = 1.44 \cdot 10^{-6}\, m^2/s$ is ground diffusivity, t is time period [h], c_g is ground volumetric heat capacity [J/m^3°C], k_g is soil thermal conductivity in W/m°C, and E_i is exponential integral. Thus for

$$E_i\left(\frac{r_b^2}{4at}\right) = ln\left(\frac{4at}{r_b^2}\right) - \gamma, \qquad \text{for } \frac{at}{r_b^2} \leq 5 \text{ and} \quad (5\text{-}2)$$

$$T_f - T_b = R_b q \quad (5\text{-}3)$$

where R_b is borehole thermal resistance [mK/W], $T_f = (T_{in} + T_{out})/2$ is the average fluid temperature [°C], and γ is Euler constant = 0.5772. The equation (5-1) becomes.

$$R_g q = \frac{q}{4\pi k_g}\left(ln\left(\frac{4at}{r_b^2}\right) - \gamma\right) \quad (5\text{-}4)$$

where R_g is the thermal resistance of the ground, in [mK/W]. For injected/extracted heat from the ground, the equation (5-4) can be expressed by

$$T_f = \frac{Q}{4L\pi k_g}ln(t) + \left(\left[\frac{Q}{L}\left(\frac{1}{4\pi t}ln\left(\frac{4a}{r_b^2}\right) - \gamma\right)\right] + R_b\right) + T_g \quad (5\text{-}5)$$

where Q is the injected/extracted total power in W. For constant heat flux in the cylinder with line-source model, the soil conductivity k_g can be

calculated from the slope $\bar{m}$ of the graph (Mattsson, Steinmann and Laloui, 2008; Sarbu and Sebarchievici, 2016). Hence, the equation (5-5) can be simplified as a line form:

$$T_f = \bar{m} ln(t) + c \quad (5\text{-}6)$$

$$\bar{m} = \frac{Q}{4L\pi k_g} \quad (5\text{-}7)$$

$$k_g = \frac{Q}{4\bar{m}L\pi} \quad (5\text{-}8)$$

The uncertainty of measurement follows equation (5-11).

5.1.3. Experimental system

A 1 m pipe-in-pipe copper was installed with a system control for the water pump, and electric water heaters. The specifications of the materials were presented in Table 5-1. The pipe was buried in 1 m depth from the surface soil as seen in Fig. 5-1. The data experiments were recorded by a data taker DT85 with an interval of 5 seconds for 7 days. Austin et al. (Austin, 2000) recommend a minimum duration of 50 h.

The thermocouples were installed on the water inlet and outlet. The thermocouples used were T-type and assumed has been calibrated by the company. Day 1 is to measure the undisturbed ground temperature. At this stage, the water was circulated to the pipe through an insulated tube until the input and output temperature of the water was the same. Day 2 to 7 is to measure the thermal conductivity of the ground and the borehole thermal resistant. For these goals, the electric water heater was turned on and controlled around 30 °C. The flow rate was stabilised at 0.033 kg/s.

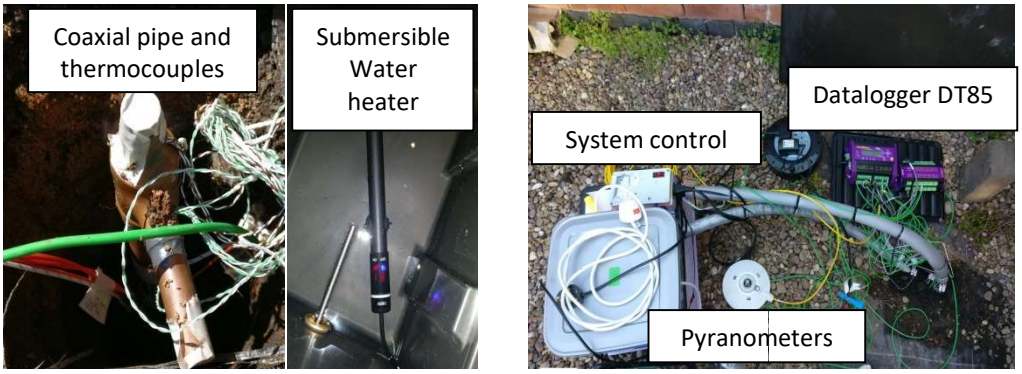


Fig. 5-1. The thermal response test schematic

Table 5-1. Specifications of the TRT system

Equipment	Unit
Inside and outside diameter copper pipe	15 mm;25 mm
Inside and outside length copper pipe	980 mm; 1000mm
Electric water heater	100 W ; 300 W
Thermocouples Type-T	± 0.5 °C
Pyranometer CMP22(Kipp & Zonen, 2015)	7 to 14 V/Wm^2
Datalogger	DT85
Humiditymeter Ellitech RC-4HC (Metrology, 2017)	±3%RH(25°C,20~90%RH), others,±5%RH

5.1.4. Results and Discussion

The experiment was conducted in the site location of the greenhouse from 21 to 27 May 2016. The type of soil was clay with coarse gravels and approximate moisture of 78%. To minimise the effect of solar exposure and rain, the surface of soil was covered with a 1mm thick HDPE layer and 30mm rocks layer surrounding the pipe. When the data experiment was taken, the upper pipe was covered with a sheet of plywood. Furthermore, to minimise temperature changes due to the environmental condition and the heat loss from the water tank and along the circulation tube, they were insulated with 20mm thick extruded polystyrene (XPS) board and 0.8mm pipe insulation, respectively.

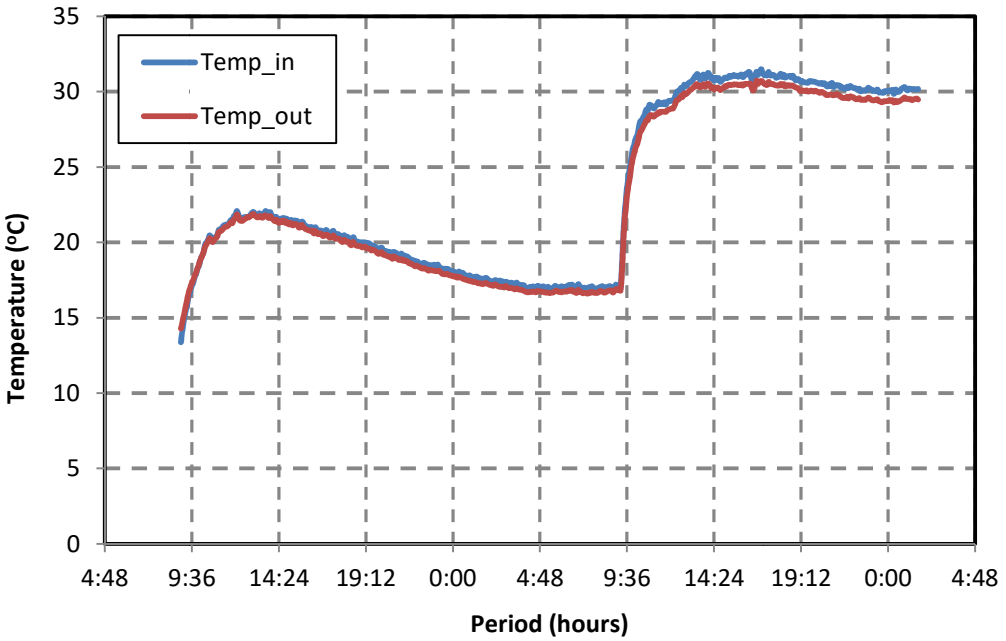


Fig. 5-2. The undisturbed ground temperature at 1 m depth

Fig. 5-2 shows the fluctuation temperature of the inlet and outlet unheated water to measure the undisturbed ground temperature. The experiment was carried out from 21st to 23rd until the soil temperature remains stable which could be obtained in 24 hours. Based on the recorded temperature during the non-heated part of the test, the undisturbed ground temperature could be estimated to be (16.7 ±0.3) °C. This range of temperature at shallow depth (1 m) was in agreement with the measurement conducted by Busby (Busby, 2015) at Eastbourne, UK.

Furthermore, Fig. 5-3 shows the ground thermal conductivity which can be used to determine the real thermal resistance of the borehole (Sarbu and Sebarchievici, 2016). The soil thermal conductivity found to be (1.7 ± 0.4) W/m°C which is in agreement with (Amanzholov *et al.*, 2016) and borehole thermal resistance (R_b) was considered equal to (0.20 ± 0.06) m°C/W.

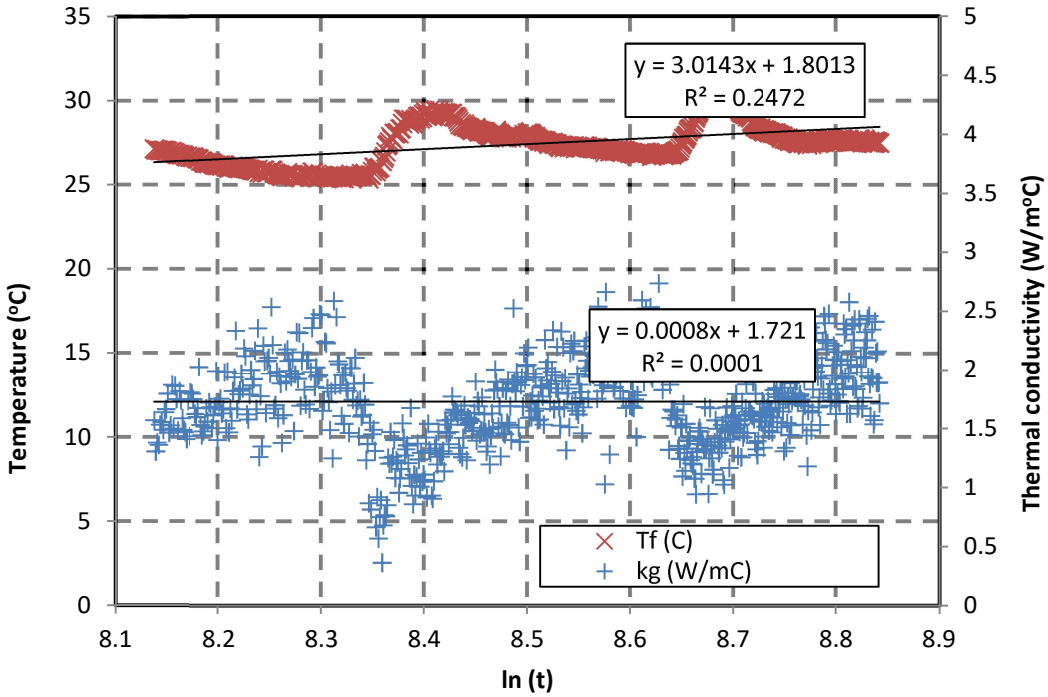


Fig. 5-3. The thermal conductivity (k_g) of the ground temperature at 1 m depth

5.1.5. Conclusion

An experiment on-site to determine soil thermal properties which were very important for designing the greenhouse aided shallow vertical borehole pipe thermal heat exchanger has been done. The undisturbed ground temperature, soil thermal conductivity, and borehole thermal resistant on-site were found to be (16.7 ±0.3) °C, (1.7 ± 0.4) W/m°C, and (0.20 ± 0.06) m°C/W, respectively. These results were used in Chapter 4 to design and simulate the proposed novel greenhouse.

5.2. IN SITU U-VALUE MEASUREMENT OF GREENHOUSE FAÇADES

5.2.1. Introduction

Since the thermal transmittance (U-value) of a building's facades is a crucial aspect in determining the heating-cooling demand (Cuce, Harjunowibowo and Cuce, 2016; Harjunowibowo *et al.*, 2016, 2017), this

section was dedicated to investigating the U-value of the wall and roof facades. In order to find the heat loss from façades, U-value measurement was conducted based on International Standard ISO 9869-1, using a method named the 'average method (ISO9869-1, 2014)' therein.

5.2.2. Methodology

A heat flux sensor installed inside the double glazed roof with two thermocouples, both of them were placed inside and outside. To shield the sensor from sunlight, the outer face of the rooftop was protected by aluminum heat reflectors as shown in Fig. 5-4. Due to the standard recommendation, the minimum test duration was 72 hours (3 days) if the temperature is stable around the HFM, otherwise this duration may extend beyond 7 days. DT85 Datataker data-logger was utilised for time-dependent data triggering. The time step for data acquisition was selected to be 30 s. The accuracy of measurement was rechecked utilising the uncertainty analysis. The uncertainty of the average method (ΔU) determined by the standard error formula in equation (5-11) based on standard deviation (s) in equation (5-10), respectively (Harjunowibowo *et al.*, 2019).

The average method assumes that the conductance or transmittance can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference, the average was taken over a sufficiently long period of time. The electrical data from the heat flow meter (HFM) and the temperature sensors have been recorded continuously using Heat Flukse sensor. The U-value measurement of wall façades was also measured with the same method. The thermocouples used were T-type and assumed has been calibrated by the company.

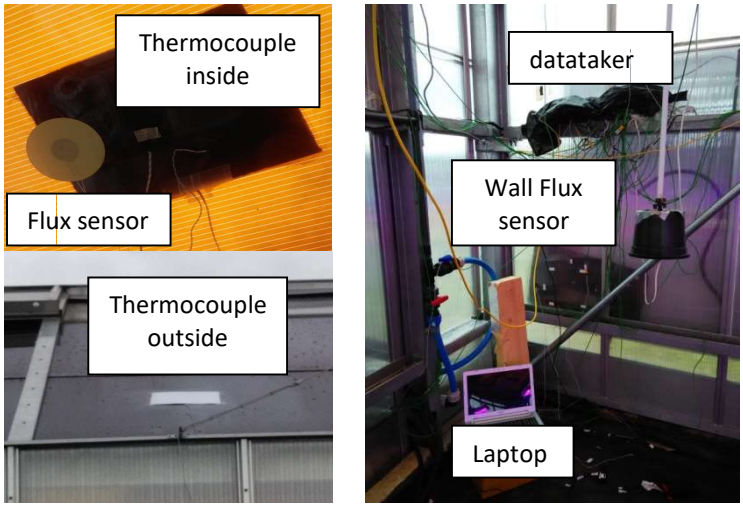


Fig. 5-4. The heat flux measurement in the cold season

The thermal transmittance (U-value) was calculated according to the following equation:

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{ij} - T_{ej})} \tag{5-9}$$

where U is the thermal transmittance (W/m^{2}K), q_j is heat flux density, i.e., heat flux on a unit area, measured in (W/m^2), T_{ij} is internal ambient temperature, while T_{ej} is external ambient temperature. The uncertainty of measurement follows equation (5-11).

$$s = \sqrt{\frac{\sum(U_i - \overline{U})^2}{n-1}} \tag{5-10}$$

$$\Delta U = \frac{s}{\sqrt{n}} \tag{5-11}$$

where $T^i_{air,I}$ and $T^i_{air,E}$ respectively that are internal and external air temperature (^{o}C), and n is the number of the data population.

5.2.3. Result and Discussion

Measurement of the U-value of an existing building can be done by measuring the heat flow on an element using heat flux meter. In addition, measuring the inside and outside air temperature should be done simultaneously. All of these measurements have to be conducted in a steady-state condition. Since the steady-state condition was hard to achieve, there was a method that could be used, provided in BS ISO 9869-1:2014.

The in-situ experiments were conducted in no less than 7 days. The data collection was taken for both walls and rooftop double glazing at once by utilising heat flux sensors, thermocouples, and data loggers. As previously mentioned, the outside sensors were covered from sunlight with aluminium thermal sheets.

As a result, the U-value for wall was found to be 2.47 W/m^{2}K, higher than the technical datasheet of 2.0 W/m^{2}K (Industrial, 2015). Meanwhile, the U-value for the double glazing rooftop was found to be 1.34 W/m^{2}K, higher compare to the factory datasheet of 1.2 W/m^{2}K (Polysolar, 2015a), as can be seen in Fig. 5-5. The uncertain measurement of the walls and roof U-value were found to be ±0.15 W/m^{2}K and ±0.20 W/m^{2}K, respectively. Whereas, for floor U-value, based on reference for 20 cm thickness sand and gravel aggregate, was found to be 0.99 W/m^{2}K (Sizes, 2015).

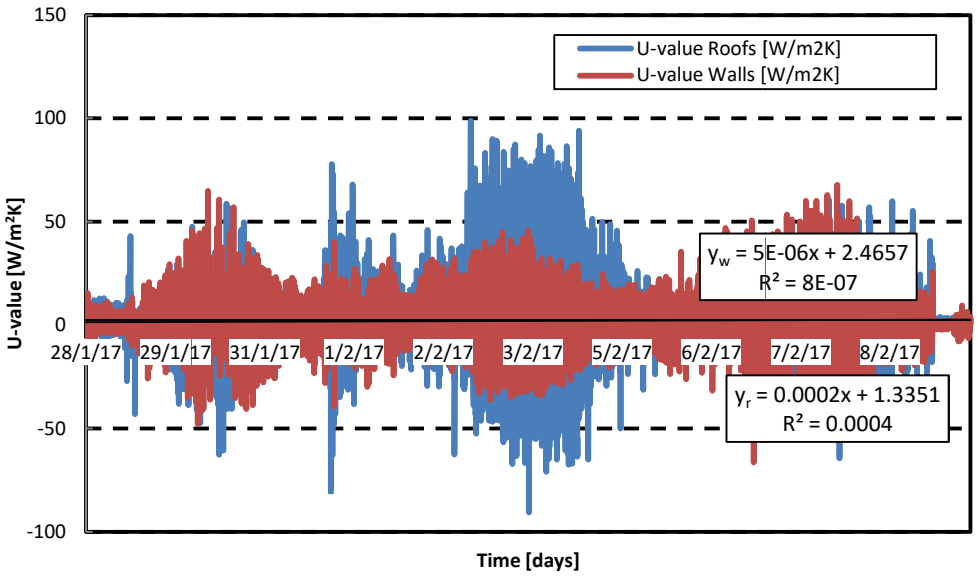


Fig. 5-5. The U-value of facades material

The graph of facade U-value fluctuates in response to the changing weather condition. Solar exposure on the facades affects the double glazing heat flux measurement. The greenhouse effect was happening inside the double-wall causing the heat flux reverse to fluctuate sharply between external and internal glazing (Cuce, 2017a). The high fluctuation probably caused by large amount of sun radiation penetrated from the uncovered glazing causing greenhouse effect. Thereby, for better result on the future experiment, it is recommended to use wider sun protector that could cover the whole surface area of measured glazing.

5.2.4. Conclusion

In order to determine the heat loss from the façade, an in situ experiment based on BS ISO 9869-1:2014 method was conducted. Based on the data analysis, the U-value for the walls and roof double glazing were found to be (2.47 ± 0.15) W/m^{2}K and (1.34 ±0.20) W/m^{2}K, respectively. By using the U-values for the façades, the heat loss from the façades can be calculated.

5.3. EXPERIMENTAL INVESTIGATION OF GROUND-SOURCE HEAT PUMP SYSTEM FOR GREENHOUSE HEATING

5.3.1. Introduction

Many pieces of research have been conducted to investigate the performance of GSHP heating for greenhouse. The system described in those researches requires a very large area or a very deep borehole to keep the heat-exchanger pipes, which are too expensive for end-users. Moreover, the soils used as the thermal storage do not have good insulation to minimize heat loss. Meanwhile, in the soil, the heat losses are very huge especially during winter and on days where the weather is cloudy and cold.

Therefore, in the present study, all of these aspects were put into account; in terms of initial cost and energy saving from the system utilizing renewable energy and well-insulated soil thermal energy storage. This chapter aims to investigate the performance of innovative GSHP system in the greenhouse with well-insulated shallow vertical pipes heat exchanger.

5.3.2. System Description

The description of the system has been described in Section 3.4.

5.3.3. Experimental setup

The system was installed at East Leake, Loughborough, UK. The system has been installed and operated for 1 year. The constructed experimental system was illustrated in an outline diagram in Fig. 3-1. This system mainly consists of four separate circuits: (i) the GSHP, (ii) the vertical and horizontal ground heat exchanger, (iii) the buffer water tank, and (iv) heat distribution (fan-coil unit) for the greenhouse heating. The main

specifications of each element were described in Table 5-2. The greenhouse building and the HVAC design system can be seen in Fig. 5-6 and Fig. 5-7, respectively.

Inside the main building, a fan coil unit was installed with a rated air outlet of 1 m/s (1753.84 m^3/h). The main area was about 47 m^2 surrounded with multi-wall X type polycarbonate and on the outside layer were installed PVs solar panel. For the rooftop, double glazing semi-transparent PVs were installed. The inverters were installed on the building's front façade and the electric current was controlled by the electrical control panel. The control panel was responsible for the PV generated feed-out to the grid and HVAC as well as lighting power consumption for the greenhouse system.

A commercial 5kW F1145 NIBE Heat pump was integrated with HPAC40 to manage the heating and cooling mode. Twenty four vertical heat pipe exchangers and horizontal tube polyethylene heat exchanger (PHE) installed underground of the building and insulated with 400mm polyurethane foam-HDPE sandwiched to avoid water absorption surrounding the ground vertically. To increase the system efficiency, a 200L water thermal storage tank was connected to the condenser heat exchanger. A fan coil unit and floor heating pipes were connected to the buffer tank and placed inside the greenhouse and 20cm underneath the floor covered with sand, gravel, and concrete.

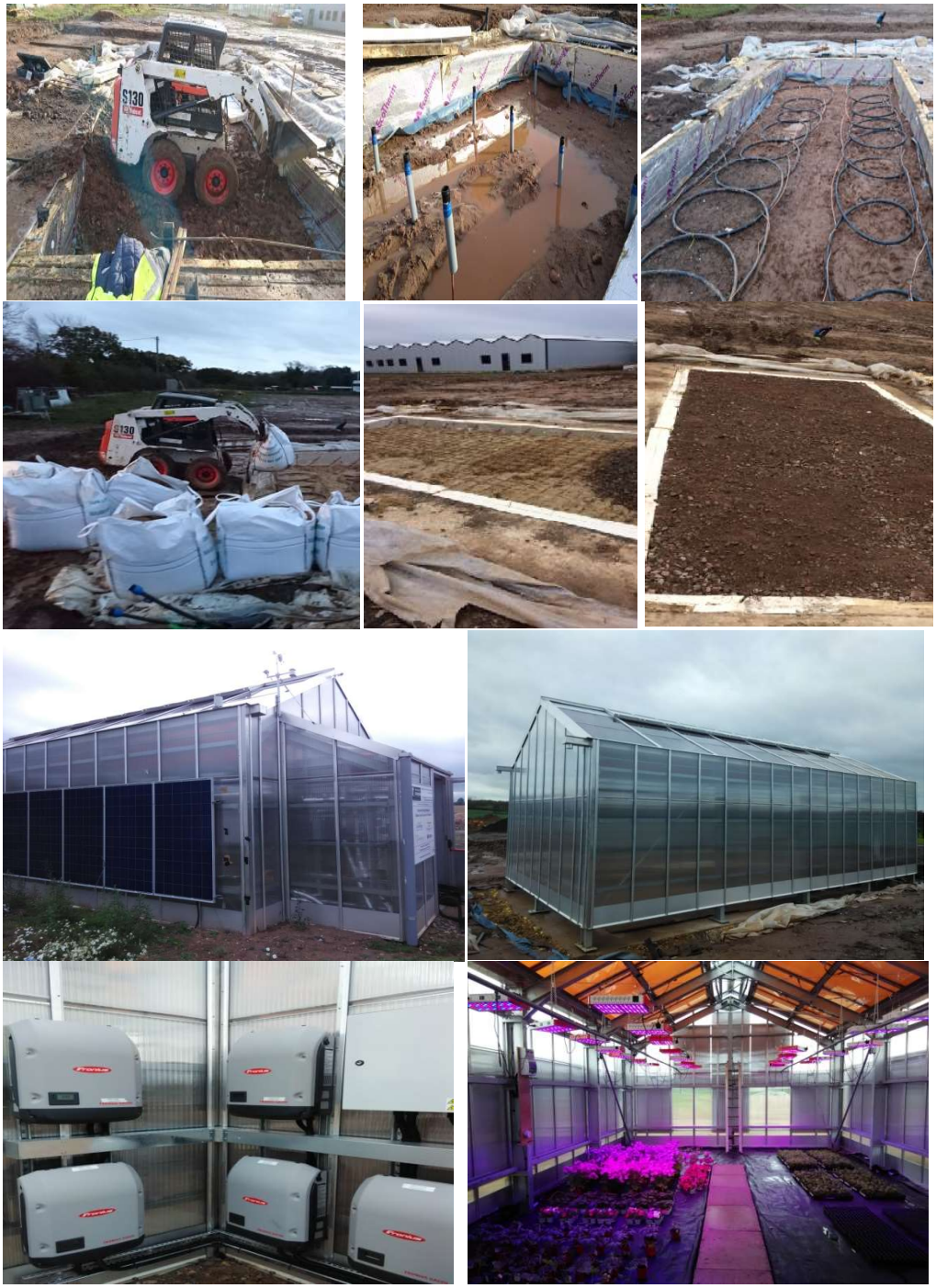


Fig. 5-6 Soil-based thermal energy storage systems and the greenhouse building's construction

The heat demand of the greenhouse was set at 16 °C in autumn, winter and spring, while in the summer was set at 18 °C. The annual heating and cooling demand were produced by dynamic simulation building software Energyplus using the third party DesignBuilder (DesignBuilder, 2011) and

can be seen in Fig. 4-14. The weather data used in the simulation were obtained from the East-Midland data station and ground soil temperature from CEDA (Office, 2019). The building façade properties are described in Table 3-1. Based on the simulation result from the previous chapter, a 5 kW capacity of heat pump was selected. Moreover, the PVs solar panel indirectly supports the sustainability of electricity needed.

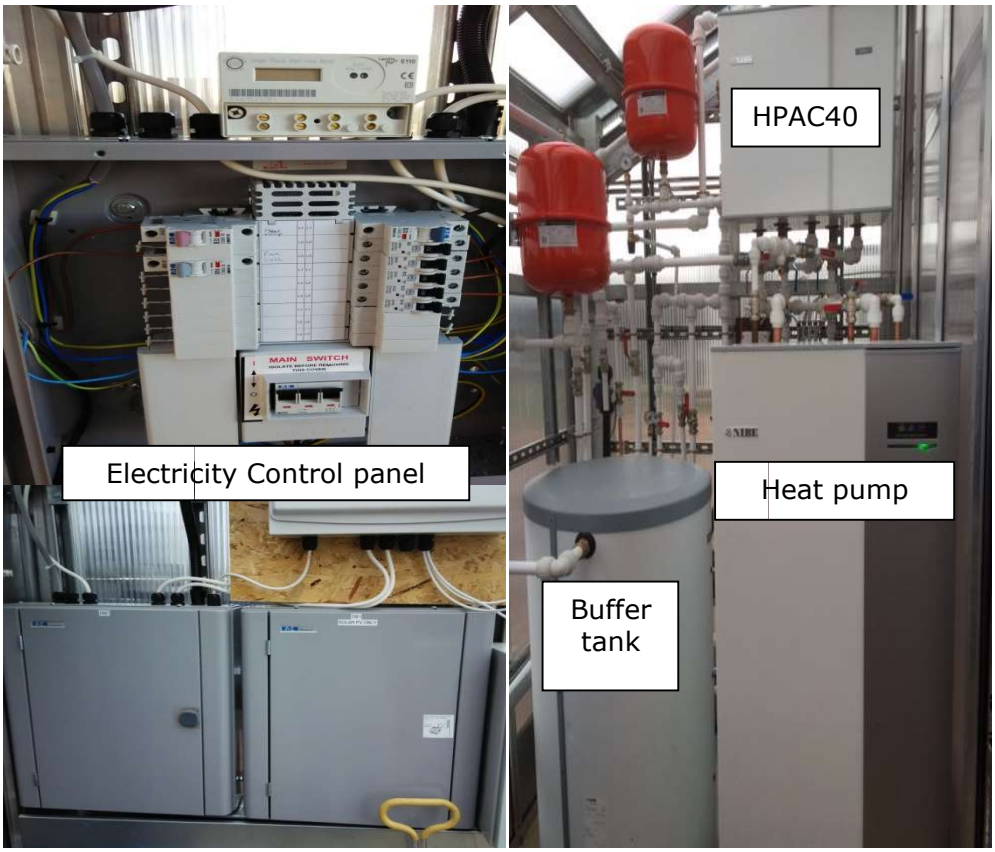


Fig. 5-7 The control panel and Heat pump system installed

5.3.4. Development of Units

To avoid freezing, the brine from the ground pipe heat exchanger and the heating medium to the storage heat tank until the FCU and floor heating are utilizing 32% ethylene glycol solution. The systems were installed in a greenhouse facing north. The greenhouse was conditioned during the summer and winter seasons where flowers and fruits were cultivated. The

field pre-test was carried out starting from May 2016 to October 2016 due to the project report requirement; however the data for this analysis was taken from 29th of September 2016 till 23rd of August 2017. The data were recorded at 5 minutes intervals and analysed at 15 minutes intervals. The summary of the main circuits is given in Table 5-2.

There were two active cooling modes, e.g. passive cooling and active cooling. The operation mode (active cooling - passive cooling - heating) of the commercial heat pump was determined by the outdoor temperature sensor (BT1) and any room temperature sensors or room units (BT50). Whenever active cooling was needed, the cooling reversing valve and the circulation pump were activated (NIBE, 2016a). In this system, the passive cooling and opening will be activated when the room temperature achieved 25 °C, and above 25 °C the active cooling was activated until the room temperature drops to normal set point (18 °C).

Table 5-2. The main specification of the SHXGSHP (NIBE, 2010)

Main circuit	Element	Technical Specification
Heat Pump NIBE F1145-5kW	Compressor	Rated voltage 230 V, Max operating current of with control system and circulation pump 9.5 A
	Refrigerant	R407C, 1.4 kg
	Brine pump	35-185 W, flow rate: 0.19-0.30 l/s, ext. diam. Cu Connection pump 22mm, max 3bar
	Circular pump	7-72 W, flow rate: 0.08-0.40 l/s, ext. diam. Cu Connection pump 28mm. Grundfos UPS2 15-50/60, max 4 bar
Ground coupling	Ground heat exchanger	Vertical coaxial pipe type, ext. diam.: 25mm, int. diam.:15mm, 24 pipes connected in parallel, 3 m length per pipe, material: copper, the distance among pipes: 1 m and 2 m. Horizontal ground collector pipe;

		Diameter: 32mm, 60m long, material: polyethylene
Storage heat water tank	UKV200	Double jacket insulation with heat loss 75W, capacity: 200L
	Fan coil unit	Daikin FWD04-18A 2 pipes, Power: 1.197kW, cooling/heating capacity: 18.30/21.15 kW, water flow rate: 3.14 l/h, airflow rate:3000 m^3/h
Heating distribution	Heating medium pump (Grundfos, 2010)	Grundfos UPS2 15-50/60, Power: 7-48 W, mass flow rate:0.35-2.4 m^3/h, Liquid temp.: 2-95 °C, pressure max:4bar, pipe connection diam.:3/4 in.
	Greenhouse	Surface area:47m^2, wall: Polycarbonate 16mm X-5 walls, U-value:2.0 W/ m^2K Roof top: double glazing PV; U-value:1.2 W/ m^2K.
Artificial light	LED grow lamps	RGB LED 210 W (10 pcs) RGB LED 150 W (14 pcs)

5.3.4.1. PV Array

The PVs system comprised of 26 opaque PV panels installed outside the wall and 32 semi-transparent double glazing installed as the roof. The electrical efficiencies were 17.75 % (Canadian Solar, 2015) and 8 % (Polysolar, 2015b), respectively. There are 3 inverters for the opaque PVs circuit on the south-side wall, east-side wall, also west-side wall, and 2 inverters for the semi-transparent PV of west-roof-side and east-roof-side. The optical properties of the PVs panel were summarized on previous chapter in Table 3-1.

5.3.4.2. The Ground Pipe Array

The ground pipeline array system comprised of 24 vertical coaxial copper pipes (25mm in diameter) connected in parallel and a horizontal pipe (32mm in diameter). These pipes were used to extract and inject heat from

and to soil. The vertical coaxial pipes were 2.5 m in length and installed in depth of 0.5 m on 47 a surface area at low-cost.

5.3.4.3. The Heat pump-Buffer Tank-Fan coil

A commercial NIBE F1145 5kW heat pump was utilised to maintain the temperature of the greenhouse between 16 °C to 18 °C depending on the season. The set temperature in the summer was at 18°C and the others were at 16 °C. The refrigerant used in the Heat pump was R407C. The heating medium produced by the condenser was sent to the highly insulated water buffer tank of 200L NIBE UKV located between the heat pump and FCU. This system allowed more heat could be stored and stabilised the heat medium distributed to the room through the FCU. Vice versa at passive cooling mode, when the room is overheating, the wind-catcher opened automatically and if it is not enough to decrease the temperature, the active cooling mode is activated. The excess heat inside the room was adsorbed by the fan coil unit, sent to the buffer tank and used by the heat pump to inject the soil with heat generated by the heat pump.

5.3.5. Measurements

The test was conducted under heating mode over the period in autumn 2016 to summer 2017. The following data were regularly recorded with a time interval of 5 min:

(a) Measurement of mass flow rates of the water/antifreeze solution by a Sharky 775 Heatmeter.

(b) Measurement of temperature of the water/antifreeze solution entering and leaving the GHE and solar collector by log set feature from the heat pump.

(c) Measurement of outdoor and greenhouse air temperatures and humidity by using Carel duct mount sensor.

(d) Measurement of inlet water temperature to and exit water temperature from the fan-coil unit by copper–constantan thermocouples.

(e) Measurement of surface temperatures of glass-reinforced plastics (GRP) greenhouse by copper–constantan thermocouples.

(f) Measurement of solar flux inside and outside the greenhouse by pyranometers.

(g) Measurement and monitoring on an LCD display of instantaneous power consumptions of the heat pump compressor, the pumps, and all electrical parameters by using electricity meter.

(h) Measurement of illumination inside and outside the greenhouse by lux meter logger.

5.3.6. Analysis

5.3.6.1. Solar greenhouse

When designing a heating system for a greenhouse, the first step was calculating how much heat energy must be supplied. The amount of heat necessary to keep the greenhouse warm can be determined by adding up the amount of heat loss must be replaced. The calculation was made for heat loss under the average highest heat loss conditions. The average

winter low temperature for the coldest month was used. The rate of heat loss from the greenhouse was calculated by equation (4-1).

5.3.6.2. The ground-source heat pump system

The second step was selecting an economical and efficient heating system to supply heat energy. The present work was geared towards studying the performance of a ground-source heat pump coupled to a model-sized greenhouse to meet its heating, and cooling requirements.

During the cycle calculations for the GSHPS, the following assumptions were made: (i) the volumetric efficiency of the compressor was taken to be 85%; (ii) compressor isentropic efficiency was taken to be 71%, and (iii) there were no pressure losses in the cycle. The rate of heat extracted (absorbed) by the unit in the heating mode (GHE load) $\mathrm{Q_e}$ was calculated from the following equation (5-12).

$$\mathrm{Q_e} = m_b c_b \Delta T \qquad (5\text{-}12)$$

where m_b and m_w is the mass flow rate of the antifreeze solution/water, c_w and c_b is the specific heat of the water–antifreeze solution, and ΔT is the temperature difference between the outlet and inlet of the GHE. The heat rejection rate in the condenser ($\mathrm{Q_{co}}$) was calculated with equation (5-13)

$$\mathrm{Q_{co}} = m_w c_w \Delta T \qquad (5\text{-}13)$$

Hence, if $\mathrm{W_{comp}}$ is the work input rate to the compressor, the COP of the GSHP can be calculated as

$$COP_{HP} = \frac{\mathrm{Q_{co}}}{\mathrm{W_{comp}}} \qquad (5\text{-}14)$$

The coefficient of performance of the overall heating system (COPs); which is the ratio of the condenser load to total work consumptions of the compressor, the brine and water circulation pumps, and the fan-coil unit, is computed by the following equation

$$COP_s = \frac{\mathrm{Q_{co}}}{\mathrm{W_{comp}} + \mathrm{W_{pumps}} + \mathrm{W_{fc}}} \quad (5\text{-}15)$$

5.3.6.3. Thermal Imbalance Ratio

Underground thermal balance determines the annual heat injected into the ground by GSHP through the ground heat exchanger. For long term GSHP operation, the injected heat should be equal to the extracted heat. The high imbalance thermal can affect the performance of the GSHP since the heat source keeps decreasing. Therefore, determine the imbalance ratio is very important to describe the soil thermal condition. The imbalance ratio can be calculated by studying the building load and heat pump performance.

The thermal imbalance ratio was defined as follows (Zhao *et al.*, 2018):

$$IR = \frac{Q_{ahi} - Q_{ahe}}{Q_{ahi} + Q_{ahe}} \times 100\% \quad (5\text{-}16)$$

Where IR is the thermal imbalance ratio, Q_{ahi} is the accumulated heat injected [kW], and Q_{ahe} is the accumulated heat extracted [kW].

$$Q_{ahi} = \sum_{1}^{n} Q_i\left(1 - \frac{1}{COP_{c,i}}\right) \quad (5\text{-}17)$$

$$Q_{ahe} = \sum_{1}^{n} Q_i\left(1 + \frac{1}{COP_{h,i}}\right) \quad (5\text{-}18)$$

Where Q_i is hourly heating or cooling load [kW], $COP_{c,i}$ and $COP_{h,i}$ are COP for cooling and heating load at time i.

5.3.6.4. The Electric Schematic System

The greenhouse system was equipped with solar energy which was harvested by using photovoltaic (PV) solar panel. The PVs were used to decrease heat loss and generate electricity. The opaque PV was installed on the walls whereas the double glazing semi-transparent PV was installed as the rooftop. The electricity generated was injected to the grid while the greenhouse building with its system takes electricity from the grid. The scheme of the electricity system in the greenhouse is shown in Fig. 5-8.

5.3.7. Results and Discussion

In the present study, the results obtained from the experiments over the heating period from 29th of September 2016 till 23rd of August 2017 were evaluated to determine the performance characteristics of the system studied. Fig. 4-14 reveals the average heating and cooling load of the proposed solar greenhouse considered were obtained to be 1.63 GW/m^2 and 0.02 GW/m^2 per month at design conditions. In this calculation, the overall heat transfer coefficient of Greenhouse cladding was in range of 1.2 W/m^{2}K to 2 W/m^{2}K and the highest temperature difference between greenhouse inside and outdoor temperatures T_i & T_o is 10.8 °C.

Fig. 5-9 shows the variation of average values of ground surface temperatures outside and inside the greenhouse. The ground surface temperatures at the inside and outside of the greenhouse ranged from 8 to 24 °C, and from 5°C to 18 °C, respectively. Obviously, the outside ground surface was influenced by seasonal temperature fluctuations. The ground surface is exposed to the natural environment thereby the soil temperatures are affected by outdoor temperatures with daily and seasonal terms below 15 m depth (Survey, 2011).

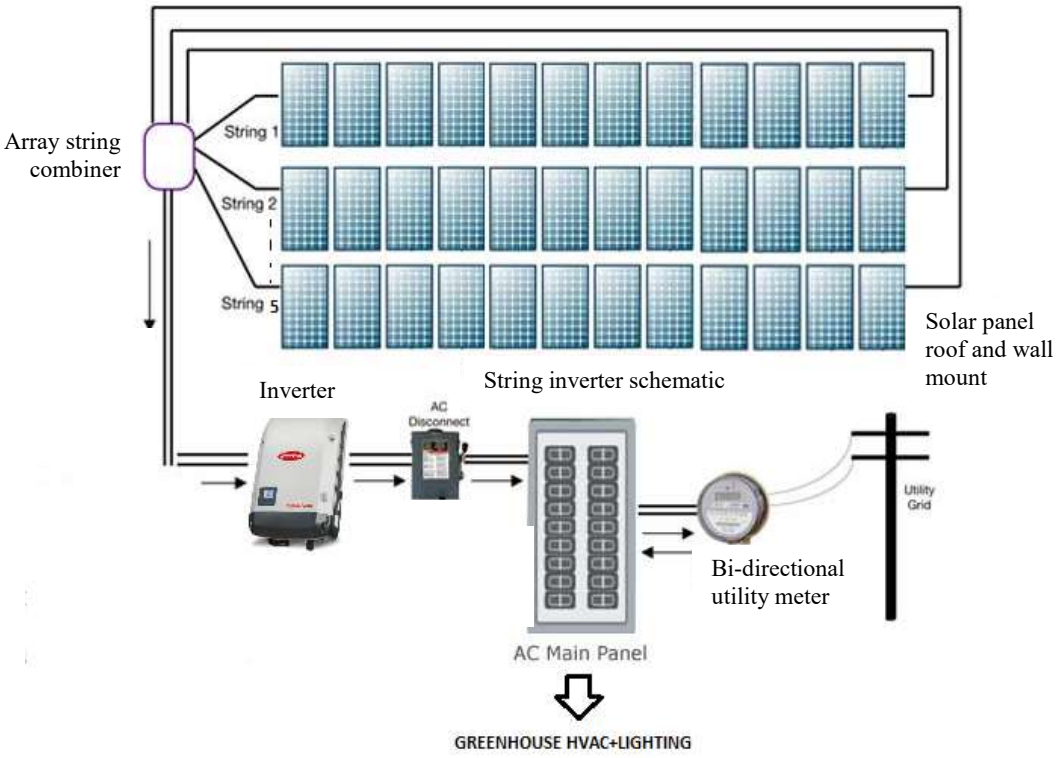


Fig. 5-8. The electricity diagram of the system

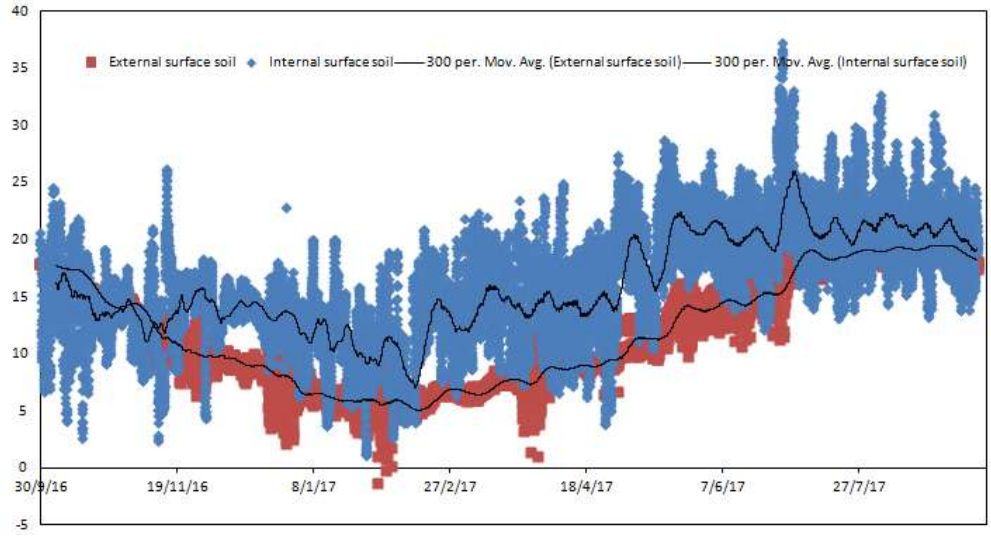


Fig. 5-9. The surface soil temperature inside and outside the greenhouse

Fig. 5-10 show the average values of outside air and inside air greenhouse temperatures. The ambient air temperatures varied from -5 to 28.05 °C, and the greenhouse average temperatures fluctuate from -2 to 29.05 °C.

The values for COP_{HP} Heating to be in a range of 1.48–2.97 and the COP_{HP} Cooling were found to be 1.20–3.45 as can be seen in Table 5-3. The COP getting low when the output condenser set on high 60 °C with low brine input as seen in Fig. 5-11.

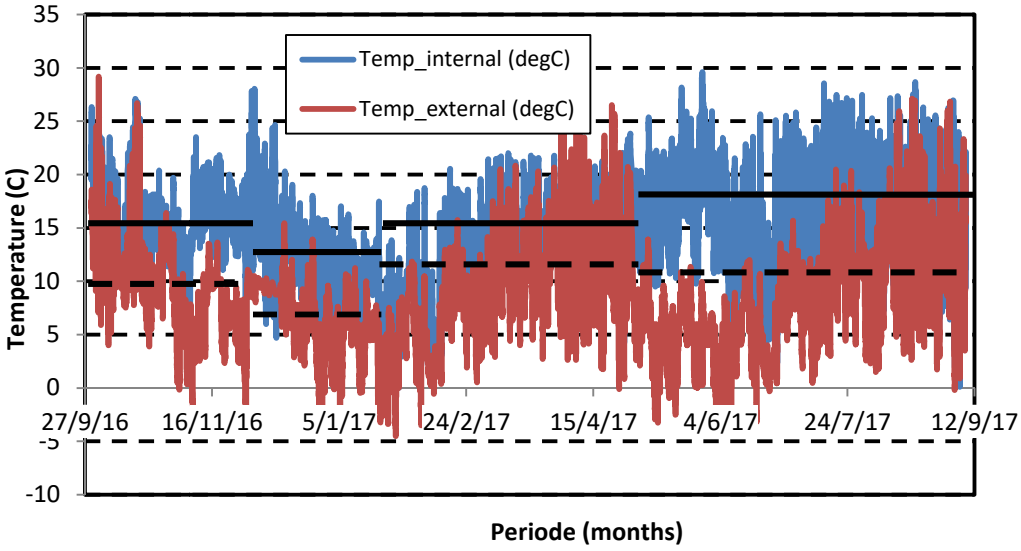


Fig. 5-10. The Temperature inside and outside the greenhouse

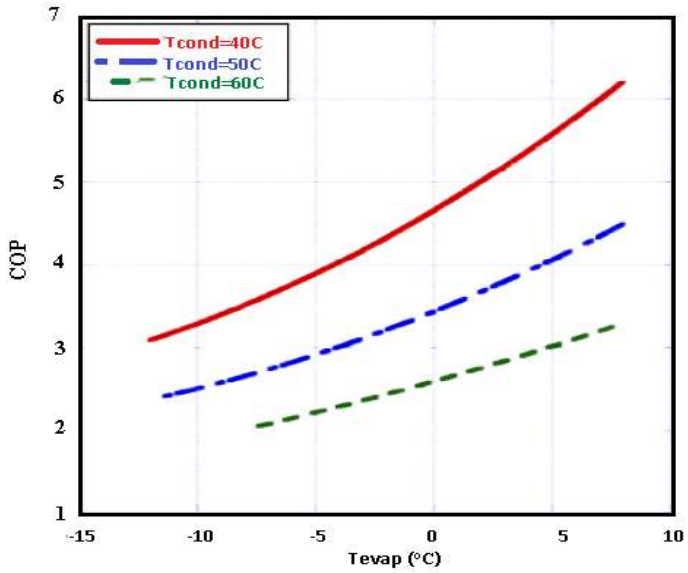


Fig. 5-11. The NIBE F1145-5 COP on different Tevap and Tcond using R407C (Silversand and A.B., 2010)

While, the COP_{sys} heating and cooling was found to be 1.51 and 1.55, respectively. However, it is obviously seen that in summer the system could maintain at 18 °C, in autumn and spring the system could achieve the desired temperature at 16 °C, but not in winter since the soil temperature reached the lowest temperature as shown in Fig. 5-14. Further, it is reported that the heat pump frequently became faulty during those times as the brine in the pipeline freezes at -10 °C. It indicates that the heat transfer between the pipe and soil very low, which means that the soil thermal conductivity too low and needs to be improved. Some improvements might be done by injecting nano-particles metal-based or carbon-based (Sweet, Chesser and Singleton, 2012), and encapsulated PCM solution for trench (Bottarelli, Bortoloni and Su, 2015).

Table 5-3. The heat pump Seasonal COP

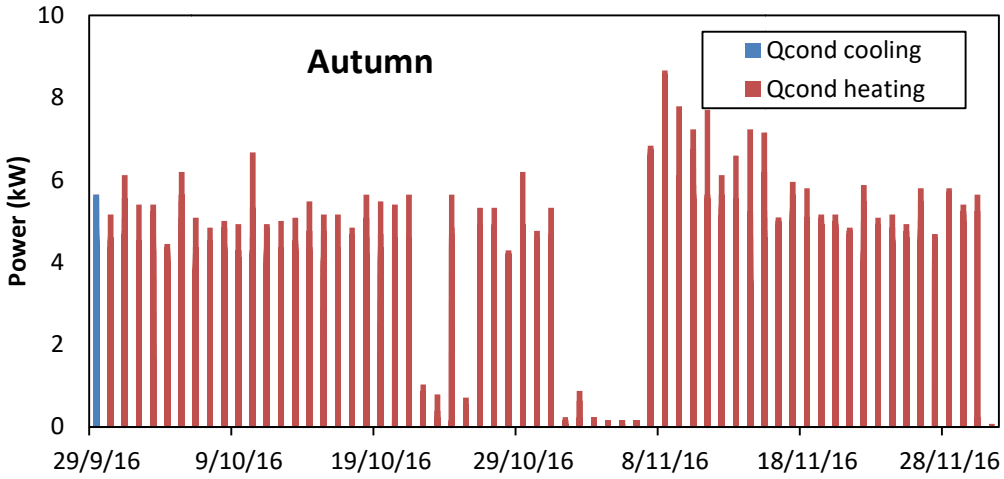
	COP	
Seasons	Heating	Cooling
Autumn	2.97	3.45
Winter	2.1	1.2
Spring	1.48	1.65
Summer	2.15	2.41

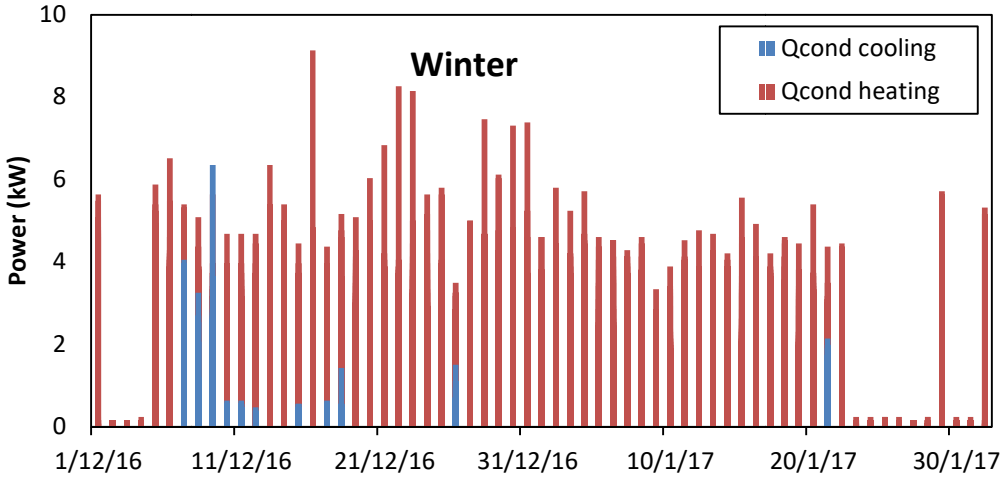
Fig. 5-12 shows the seasonal heat delivered for air heating in cold seasons and heat delivered for active cooling in the hot season. It can be seen that heating mode was more dominant than cooling mode in all seasons but summer. The annual summary of the power delivered for heating and cooling mode -as depicted in Table 5-4, were 5175.92 kWh and 3997.82 kWh, respectively. It is definitely unable to fulfil the heating requirement needed by the greenhouse. This, in turn, causes the indoor air temperatures to sometimes drop below the set temperature. Furthermore, the cooling power produced by the system also below the required power

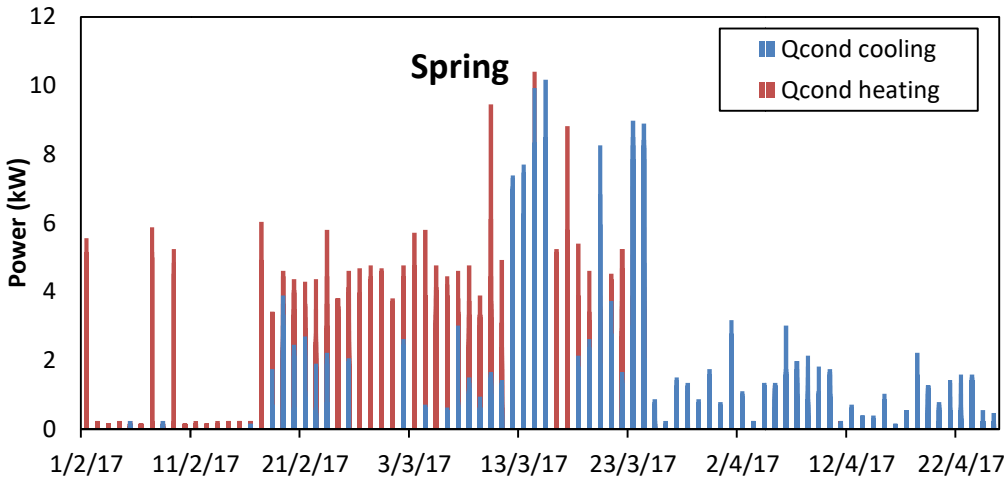
of the previous design cooling. It makes the indoor temperature risen more than being expected. Even though, it does not make a big problem for the greenhouse due to the highest temperature was still within the tolerance range.

The lower cooling power resulted in the system affecting the heat injection to the ground as is revealed in Fig. 5-13. When the annual injected power is lower than the extracted power, it will cause instability on the ground temperature and result in imbalance of the ground temperature environment. There were solutions which have the potential to be adapted, such as ground source heat pump system with heat recovery (Zhao *et al.*, 2018).

Zhao et al simulated their system in transient simulation software and found that the thermal imbalance ratio and soil temperature decreased with increasing heat recovery ratio. The soil thermal imbalance ratios decrease from 29.2% to 5.2% and the soil temperature raises decrease from 8.78 °C to 0.34 °C while the heat recovery ratios increase from 0.8 % to 53%. However, the proposed system has adapted the heat recovery in practice and successfully reduces the soil thermal imbalance by 2378.85 kWh annually. The ratio of soil thermal imbalance achieved 32.76% which means the novel proposed system could gain soil heat recovery by 67.24% which is remarkable.


Autumn
Qcond cooling
Qcond heating
Power (kW)
10
8
6
4
2
0
29/9/16
9/10/16
19/10/16
29/10/16
8/11/16
18/11/16
28/11/16


Winter
Qcond cooling
Qcond heating
Power (kW)
10
8
6
4
2
0
1/12/16
11/12/16
21/12/16
31/12/16
10/1/17
20/1/17
30/1/17


Spring
Qcond cooling
Qcond heating
Power (kW)
12
10
8
6
4
2
0
1/2/17
11/2/17
21/2/17
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13/3/17
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12/4/17
22/4/17

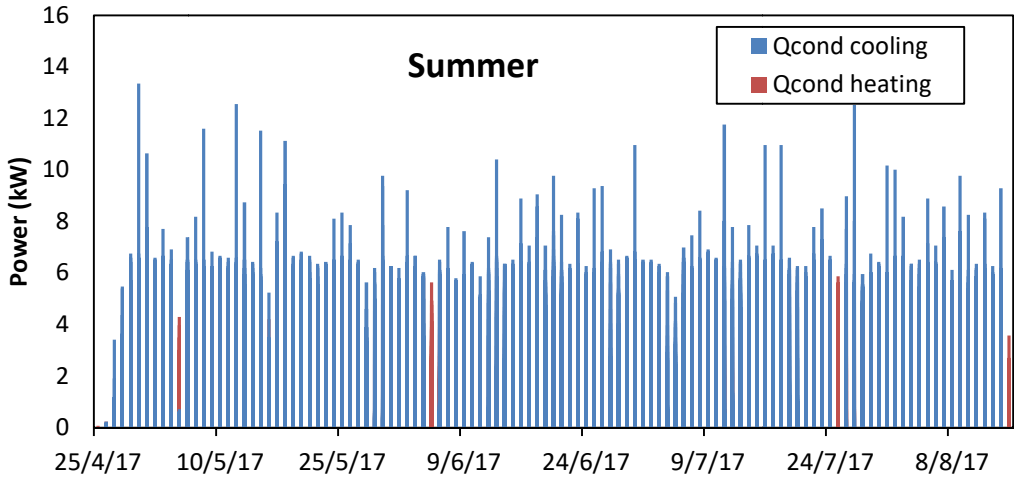
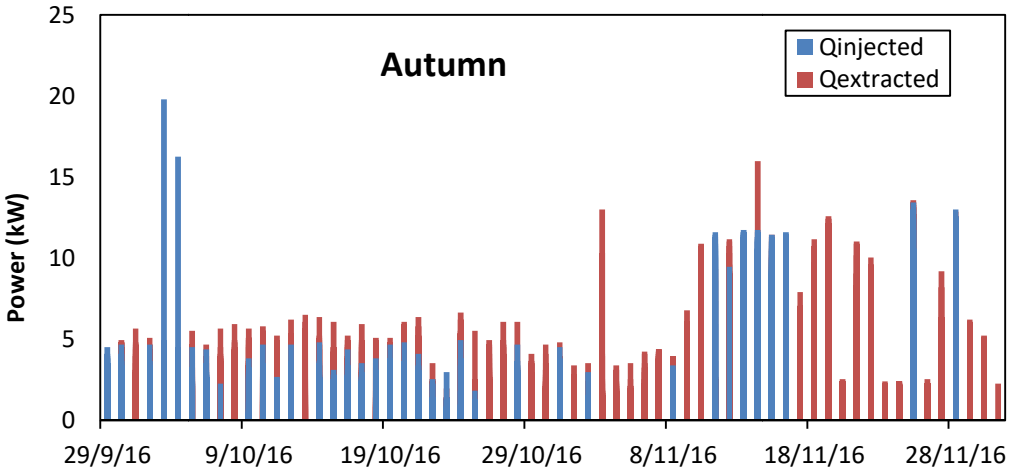
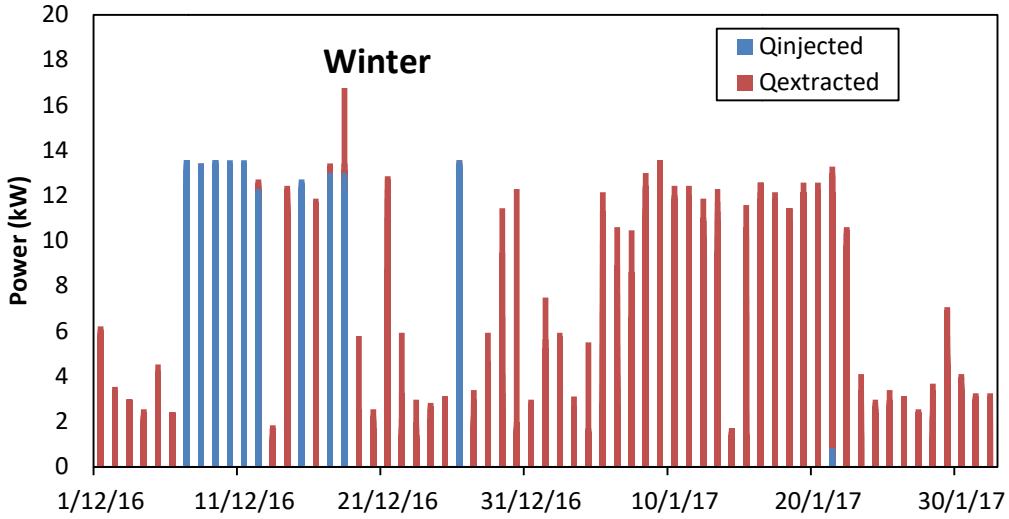


Fig. 5-12 The seasonal heat produced in heating and cooling mode





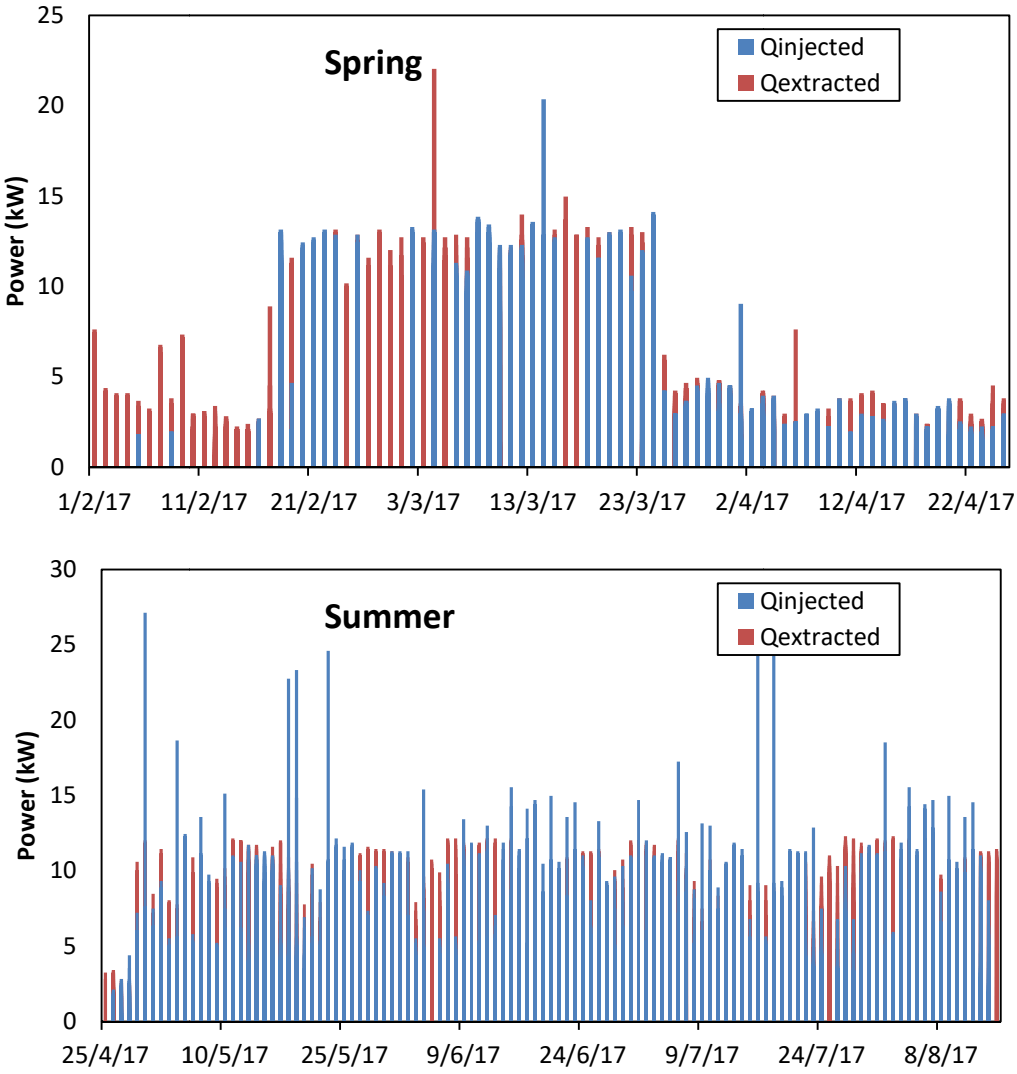


Fig. 5-13 The seasonal heat extracted from the ground and injected to the ground

Fig. 5-14 shows the comparison between the SSBTESS, outside soil temperature at 1 m depth, and the ambient temperature. The average temperature of SSBTESS was started at a high temperature found to be 22 °C and fluctuates down to 9 °C. It is different from the outside soil temperature which fluctuates back to 17 °C higher than the SSBTESS temperature. The graphs lines were cut due to the data logger error, but it does not impact the behaviour of the graphs. The dropping SSBTESS temperature was caused by the low heat injection and insulation that is act

as adiabatic side. The adiabatic condition prevents the heat transfer between underground thermal energy storage with the environmental soil.

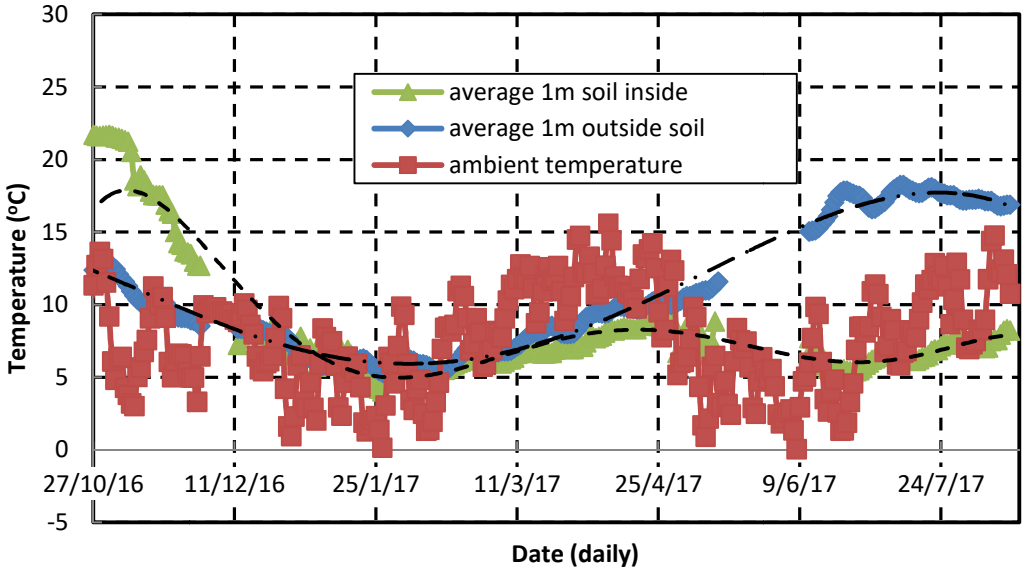


Fig. 5-14 The soil thermal energy storage temperature fluctuation

The SSBTESS temperature increased in winter but then dropped in spring due to the high heat extraction from the ground as shown in Table 5-4. Afterward, the temperature inclined up slightly when the heat injection was happening in summer. From the graph line, the SSBTESS temperature keeps declining without any heat recovery by the system and causing imbalance ground temperature. Therefore, some actions should be done to improve the system performance.

The power system was made to make the measurement of what was the electricity produced and injected into the grid and what was the electricity needed by the system. There are 5 strings connected to the 5 inverters, i.e., West wall PV, South Wall PV, East Wall PV, West Roof PV, and East Roof PV.

Table 5-4. The heat delivered for each season

	seasonal heat delivered			
Season	heating (kWh)	cooling (kWh)	extracted (kWh)	injected (kWh)
autumn	2740.00	501.50	2485.99	626.39
winter	220.59	39.91	2808.49	458.18
spring	1161.67	327.53	3814.24	2138.65
summer	1053.65	3128.88	3920.90	6292.17
total	5175.92	3997.82	13029.62	2378.85

As a result, in Fig. 5-15 obviously it can be seen that the power electricity generated by the PVs has a good agreement pattern compared to the simulation results based on the technical specification. Annual electricity generated by PVs panel found to be 59.63 GJ (16.56 kWh) while the energy used was 223.54 GJ (62.09 kWh). This means that solar PV could contribute to the utility of 26.7%.

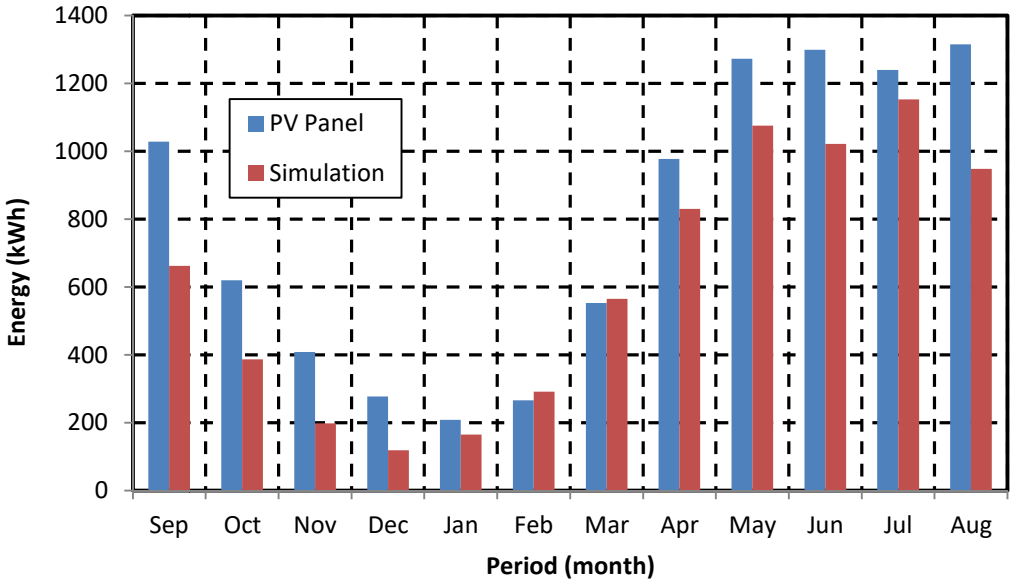


Fig. 5-15. The PV energy generated annually

Regarding the daylighting inside the greenhouse, Fig. 5-16 shows the daily illumination on average. It can be seen that the daylighting inside the greenhouse found to be around 1000lux which is three times lower than

outside. There were 24 LED lamps at full power hanged 2m above the floor. It seems that hanging down the LED to 1m above the floor and about 0.7m above the leaves could increase the illumination.

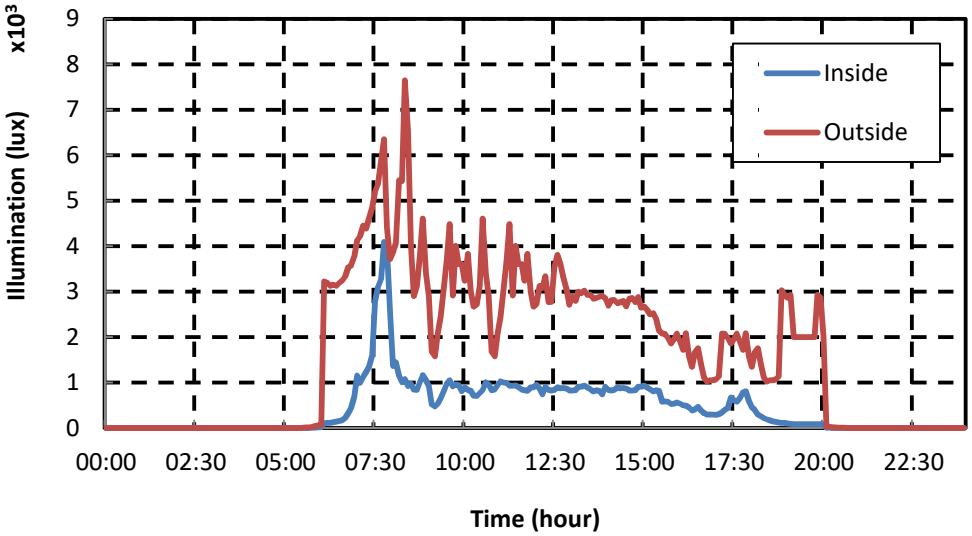


Fig. 5-16. The daily average daylighting of the greenhouse

5.3.8. Conclusion

This section aims to investigate the field test of innovative greenhouse system heating cooling with soil based thermal energy storage heat recovery in the UK. In conclusion, there are three findings based on the analysis. First of all, the overall system could maintain the desired air temperature except during winter. The problem could be solved by lowering the air infiltration by changing the procedure (below 25°C-turn on the active cooling directly, higher 25°C- turn on the windcatcher/opening). With this procedure, power injection could be increased significantly.

The second is that the heat extraction causes ground temperature imbalance as reported by many researchers. Thanks to the heat recovery system, the proposed system successfully reduces the soil thermal imbalance by 2378.85 kWh annually. Thirdly, there were problems caused by low thermal conductivity of the soil. Enhancing the thermal conductivity

could be done by injecting the nano-particles carbon or metal-based, water moisture addition, and adding encapsulation phase change material solution for shallow underground thermal energy storage. In addition, utilising higher thermal capacity of heat pump could improve the system performance.

CHAPTER 6 – Methods and Experiments to Improve the Greenhouse Performance

Outline of the Chapter:

This chapter discusses the improvement methods that could be used to enhance the performance of the novel greenhouse in terms of minimizing the building's heat losses and improving the underground energy storage's performance. It is found that airtightness plays a key role in energy saving, followed by lower thermal transmittance of facades, and thermal conductivity of the underground storage. However, the high visible transmittance must be taken into account in order to fulfil the photosynthesis requirement. A combination of these treatments could make a significant impact on fulfilling the greenhouse energy demand.

6.1. INTRODUCTION

Based on the previous experiments, it obviously can be seen that the highest heat loss transpires on the envelopes of the greenhouse. They are caused by the low airtightness surrounding the building and the poor U-value from the facades. It is well known that low airtightness and poor U-value of facades have negative impact to building energy consumption (Cuce, 2017b; Harjunowibowo *et al.*, 2019). Airtightness is very important as the novel greenhouse system adopts natural ventilation. Moreover, the joints between frames and envelopes are prone to leakage. Therefore, this chapter is focus on lowering the thermal transmittance from the double glazing walls. In addition, some simulations are used to predict the potential of some techniques that could improve the system performance of the greenhouse which in the later potential for energy-saving.

6.2. METHODOLOGY

This research will use experimental works and simulations to see the improvement that can be achieved by the proposed material used in the experimental if it is implemented in the novel greenhouse.

6.2.1. Experimental work

This experimental work aims to investigate the thermal performance of polycarbonate (PC) which is integrated into silica aerogel with different types; granular, fine powder, blanket bio-aerogel, and blanket aerogel. The thermal performance will be represented by the U-value of each material and the measurement was carried out using hot box in the University of Nottingham (Jarimi *et al.*, 2018) as seen in Fig. 6-1.

The hot box contains 3 parts that are hot side box, sample box, and cold side box. There are two control panels, to control the hot and cold temperature source and also the wind speed. One central control panel is placed in the middle with a PC to adjust and collect the data from the data loggers. More than 100 thermocouples were installed to observe the temperatures of inside air temperatures and sample panel surface temperatures.

The scheme of panels used in this study is shown in Fig. 6-2. It contains 3 layers, on the bottom is the Polycarbonate 9X walls, in the middle is the aerogel type, and on the top is a polycarbonate sheet. These constructions were the easiest way to refurbish the existing building. The materials' properties of the samples were shown in Table 6-1.



Fig. 6-1. The hot box and the sample panel

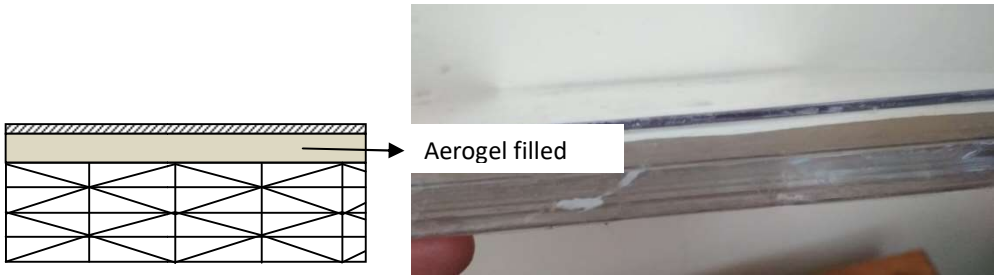


Fig. 6-2. The schematic sandwiches sample panels

6.2.2. Simulation

To have a comprehensive understanding, the experimental results were used in simulation to find the impact of the claddings refurbishing against the building energy consumption. The DesignBuilder software was utilised to perform the heat loss reduction from the envelope and energy consumption therefore, energy saving can be known accurately. The simulations were focused on the effect of U-value of facades, soil thermal conductivity, and airtightness against energy consumption.

Table 6-1. Materials' properties

Sample	Thickness (mm)	Properties
PC 9X	16	U-value: 1.77 (W/m^{2}K) (Sabic, 2008)
Powder Aerogel (PA)	10	Bulk density :20 - 100 kg/m^3 @ 20°C, size: 2–1200 lm (Cabot Corporation, 2012)
Granular Aerogel (GA)	10	U-value: 0.75 W/m^{2}K per 25 mm (Cabot, 2013)
Marlon polycarbonate sheet	2	U-value: 5.56 W/m^{2}K (Brett Martin, 2011)

6.3. RESULTS AND DISCUSSION

6.3.1. The Effect of Facades Thermal Transmittance

Before the samples were measured, the calibration for the hot box has been done and performed in (Jarimi *et al.*, 2018) therefore, the experimental results were reliable. The calibration for the polycarbonate double walls used in the study also was carried out. It is in accordance with the U-value that is conducted by the company based on ISO 10077 (EN673) as revealed in Table 6-2. Fig. 6-3 shows the environmental guarded hot box in the cold and hot side which were maintained in temperature difference of 20 °C for 2 hours. The temperature deviation for hot air and cold air were 0.26 and 0.07, respectively.

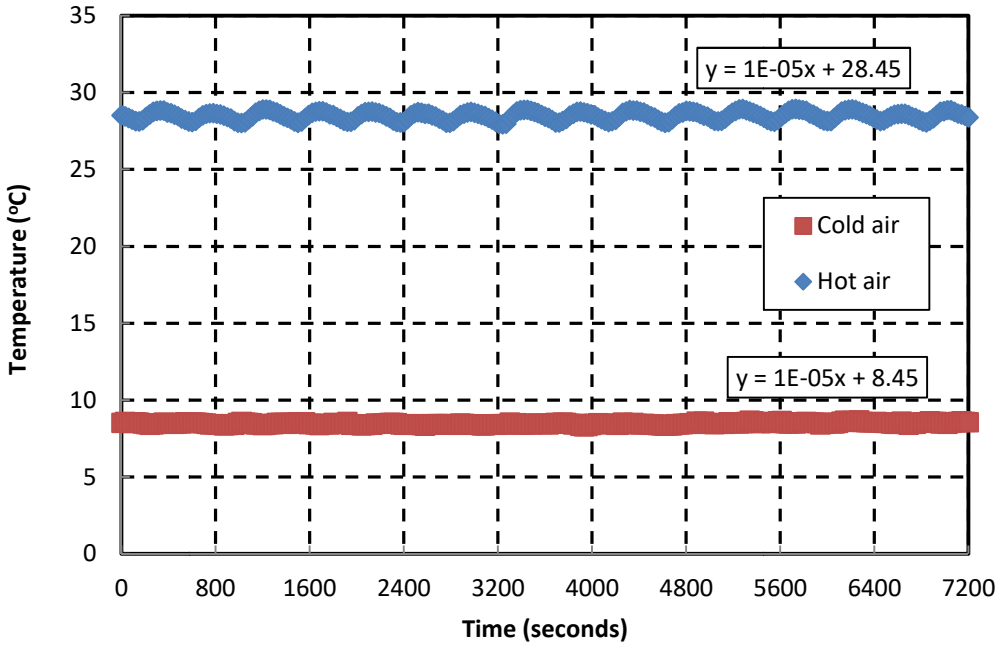


Fig. 6-3. The environmental guarded hot box

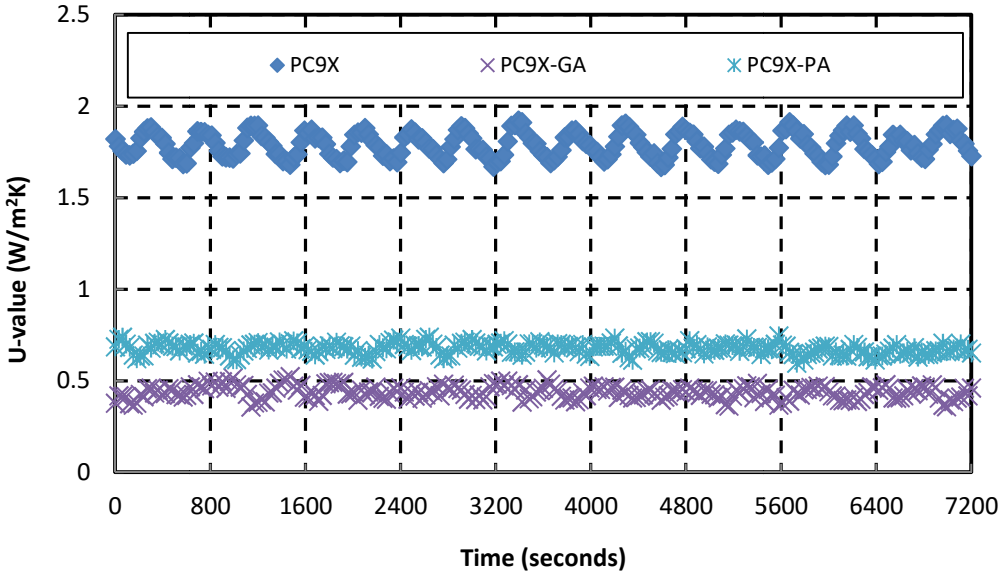


Fig. 6-4. The U-value summary from the samples

Based on the experimental results, we can see from Fig. 6-4 that granular aerogel achieved the lowest thermal transmittance of 0.44 W/m^{2}K followed by Powder aerogel, and polycarbonate 9X walls, respectively. The uncertainties of the measurements were found to be 0.03 W/m^{2}K. This granular type has some benefits if being applied to refurbish the existed building. Besides its high transparency compared to the others, the thicknesses were only 1 cm.

Table 6-2. The samples U-value measurement results

Sample	Thickness (mm)	U-value (W/m^{2}K)	Density (gr cm^{-3})
PC 5X	16	2.00	-
PC 9X	16	1.78	1.2
PC 9X-PA	28	0.68	0.07
PC 9X-GA	28	0.44	0.13

A simulation with DesignBuilder has been conducted regarding the impact of aerogel refurbishment to the greenhouse cladding based on the properties material in Table 6-3. Since the sample with high thermal resistant has low light transmittance, the granule aerogel provides better energy saving due to the better distribution of the useful daylight (Berardi,

2015) compared to the others. Buratti and Muretti proved that granular aerogel windows showed 25% reduction in heat losses and 66% in light transmittance (Buratti and Moretti, 2012).

Table 6-3. The properties of material refurbishment and the simulation results

Sample	LT	emissivity	SHGC	Energy consumption [kWh/m^2/y] Airtightness =0 ac/h	Ratio improvement [kWh/m^2/y]/ (W/m^{2}K)
PC 5X	0.62	0.9	0.64	297.71	-
PC 9X	0.54	0.9	0.54	297.29	1.91
PC 9X-PA	0.01	0.9	0.01	295.11	1.41
PC 9X-GA	0.08	0.9	0.02	292.12	3.58

Moreover, Reim et al. found that silica aerogel granule window has a low U-value of 0.4 W/m^{2}K with SHGC of 35% (Reim *et al.*, 2005). In summary, the annual energy consumption using the refurbishment panels has a slight improvement by 1.9% as shown in Fig. 6-5.

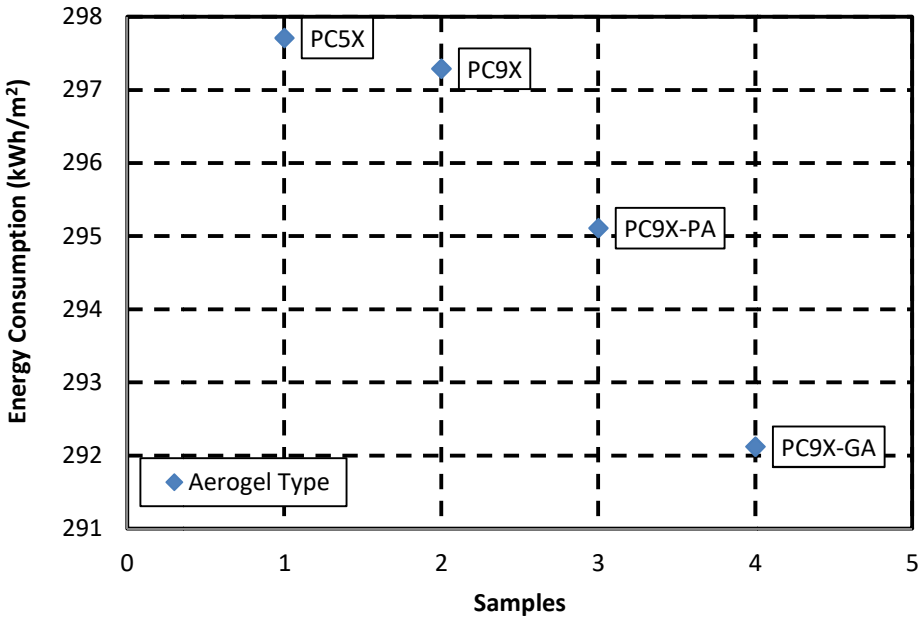


Fig. 6-5. The impact of the refurbishment of the facade against the greenhouse energy consumption for airtightness =0.05 ac/h

6.3.2. The Effect of Air Infiltration

The air infiltration of the building has the biggest impact on energy saving. Air infiltration on a glazing window plays a key role in improving thermal comfort (Cuce, 2017a; Harjunowibowo *et al.*, 2019). Therefore, ensuring that the building has airtightness is imperative. Table 6-4 and Fig. 6-6 shows the effect of air infiltration on energy consumption of the greenhouse building.

It is obvious that the improvement ratio gets bigger when the air infiltration decreases. The energy consumption can be reduced by 8%. This airtightness proved to be paid attention to any building to reduce energy demand. Combining airtightness, low thermal transmittance and high light transmittance of the envelopes may be a good solution of passive technologies for the greenhouse to get high energy saving.

Table 6-4. The air infiltration effect on energy consumption

Air infiltration (ac/h)	Energy consumption [kWh/m^2/y]	Improvement ratio [kWh/m^2/y]/[ac/h]
4	323.44	0
3	319.38	4.06
2	313.39	10.05
1	305.73	17.71
0	297.26	26.18

Improvement ratio describes the ratio of energy consumption per decrease in air infiltration of buildings. Whenever the air infiltration is high and then decreased to almost zero, the energy consumption saving considerably increases. However, when the cladding's thermal transmittance was refurbished without paying attention to air infiltration, the energy-saving becomes negative, as shown in Table 6-5 and Fig. 6-7.

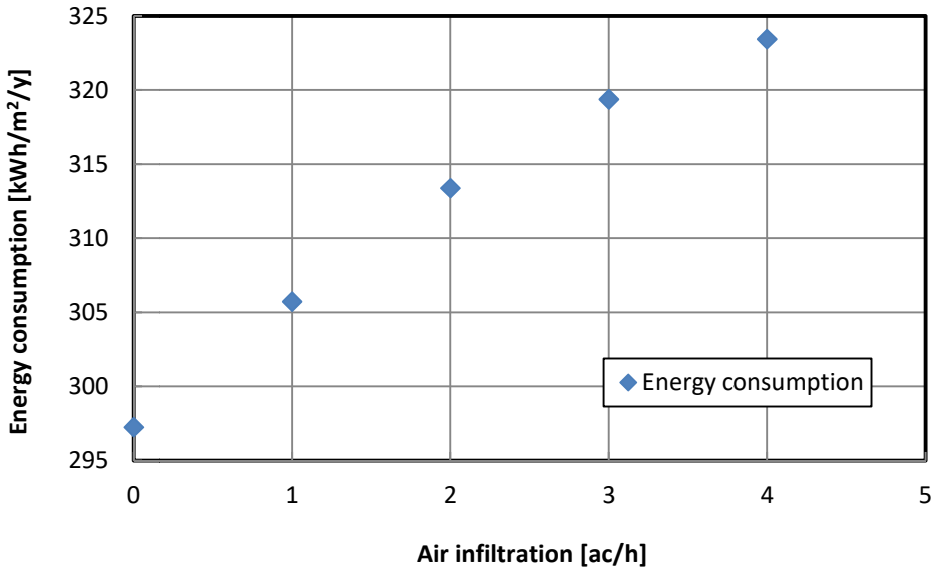


Fig. 6-6. The impact of air infiltration on greenhouse energy consumption

This happens due to the lower solar internal gains from the refurbishment materials which have low SHGC and light transmittance (LT). The internal heat gain covers general lighting, occupancy, solar gain interior, and exterior windows. Therefore, due to low these aspects on refurbishing sample, the heating demand and lighting increased which in turn increase the energy demand (Harjunowibowo *et al.*, 2017).

Table 6-5. The Solar heat gain coefficient effect on energy consumption

Sample	LT	emissivity	SHGC	Energy consumption [kWh/m²/y] Airtightness =4 ac/h
PC 5X	0.62	0.9	0.64	323.58
PC 9X	0.54	0.9	0.54	323.93
PC 9X-PA	0.01	0.9	0.01	326.67
PC 9X-GA	0.08	0.9	0.02	324.48

6.3.3. The Effect of Soil Thermal Conductivity

It is reported from the field test that the brine in pipe freezes when the soil temperature surrounding the pipe heat exchanger drops. The average soil temperature was above zero, which indicates that the thermal conductivity of soil is too low for the system. Therefore, improving the underground thermal conductivity is urgently required.

Based on the literature study, there are treatments that can be done, such as increasing the moisture of the soil, adding salt contents, increasing the bulk density and organic matters (Abu-Hamdeh and Reeder, 2000), nano-particles carbon or metal-based (Rizvi *et al.*, 2016), and also mixing the soil with another type of soil or rocks or PCM with higher thermal conductivity (Bottarelli, Bortoloni and Su, 2015).

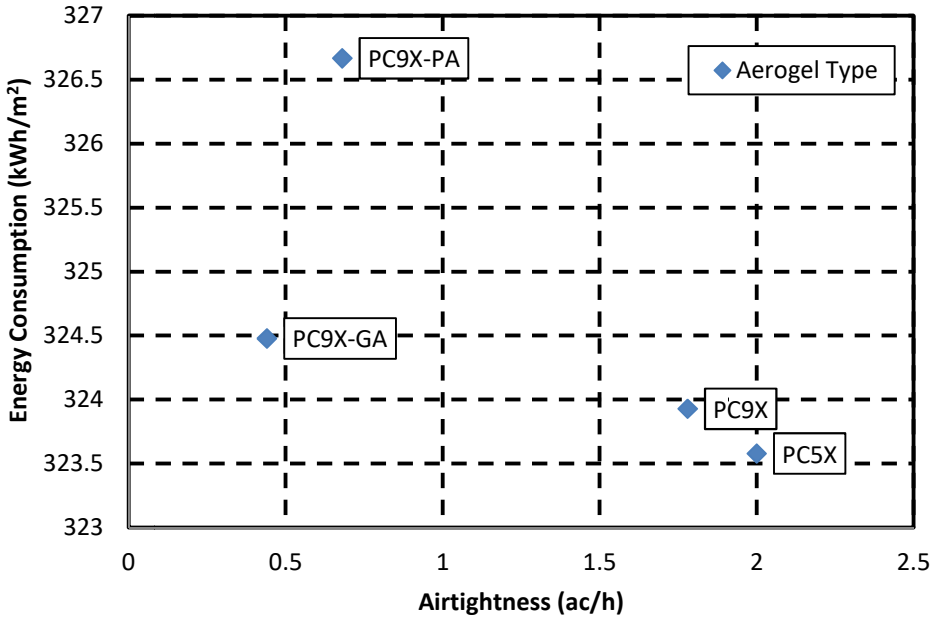


Fig. 6-7. The impact of the refurbishment of the facade on the greenhouse energy consumption for airtightness =4 ac/h

In the present greenhouse case, refurbishing the underground thermal conductivity by adding the moisture with water and nano-particles injection is the most feasible option. Increasing the soil moisture by 22% of the

volumetric water content could increase the thermal diffusivity (Roxy, Sumithranand and Renuka, 2015). Increasing thermal conductivity and diffusivity may, in consequence, decrease the length of the borehole by up to 30% (Sailer, Taborda and Keirstead, 2015). However, investigating the effect of thermal conductivity enhancement to increase the greenhouse system performance through a dynamic simulation is very important. By varying the thermal conductivity of soil on the original facade, the greenhouse's energy consumption can be analysed.

Table 6-6 shows that the soil thermal conductivity has very little impact on energy consumption saving. Thermal conductivity of underground increase results a trivial effect on energy saving by only 0.1%.

Table 6-6. Soil thermal conductivity on energy consumption

λ (W/mK)	Energy consumption [kWh/m^2/y]	Ratio improvement [kWh/m^2/y]/ (W/mK)
1.5	297.71	-
2.0	297.59	0.24
2.5	297.5	0.21
3.0	297.43	0.19
3.5	297.38	0.16

However, enhancing the soil's thermal conductivity might smooth the thermal waves resulted from the heat pump (Bottarelli, Bortoloni and Su, 2015). Hence, considering soil thermal conductivity enhancement, in this case, is worthwhile. Table 6-7 reveals the potential materials to increase the underground thermal conductivity through injecting method.

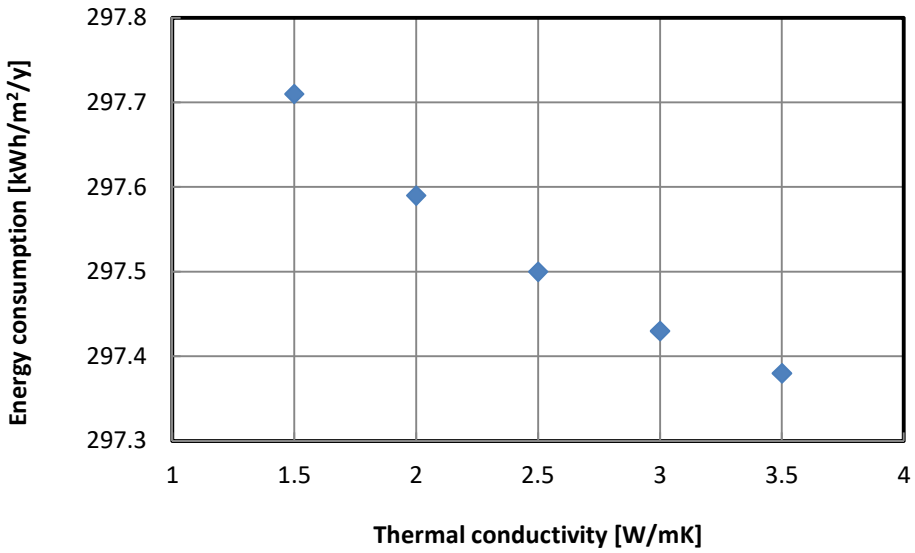


Fig. 6-8. The impact of the refurbishment of the facade on the greenhouse energy consumption for airtightness =0.05 ac/h

Table 6-7. Materials properties for soil thermal conductivity enhancement (Holman, 2010)

Material	Density kg/m^3	Specific heat J/kgK	Thermal conductivity W/mK	Thermal effusivity Ws$^{0.5}$/m^{2}K
Copper	8,954	384	398.00	1,368,458
Aluminium	2,707	905	237.00	580,611
Graphite	1,730	710	3,000.00 (Yu *et al.*, 2006)	3,684,900
Wet soil	1,890	878	0.78-2.20	2,473
Quartz	2,640	743	6.21	12,181

Thermal effusivity is the ultimate indicator of how fast the materials conduct and release thermal energy. In order to determine the value, thermal conductivity is required to be measured. It is obvious that mixing highly conductive materials, as seen in Table 6-7, is expected to improve the performance of the underground heat transfer.

Quartz is the most common mineral on the planet and consists of silicon dioxide. It is partially crystallised and the use for semi-conductor has been popular. Due to the unique crystals inside, the thermal conductivity values have a wide range from 6.21 W/mK to 11.6 W/mK (Holman, 2010).

However, carbon-based materials have the highest thermal conductivity among studied materials at moderate temperatures (Chang, Han and Zettl, 2005). Though both diamond and graphite are representative materials, graphite is far more economically viable. Thermal conductivity of diamond, graphite and graphite fibres can be high as much as 3,000 W/m/K at 27 °C (Yu *et al.*, 2006). Furthermore, the numerical study comes to the conclusion that carbon nano-tube potentially has thermal conductivity of 6,600 W/mK at ambient temperature (Chang, Han and Zettl, 2005).

The use of graphite particles seems to be harmless to the environment. Carbon fibres have strong resistance against corrosion and chemicals (Fukai *et al.*, 2000); therefore, directly mixing the substance into the soil may be feasible. There is an industrial method to inject fluid into the soil (Fig. 6-9). Injecting substances with hot air or stream is carried out to chemically neutralise polluted soil or to fill air voids for underground reinforcement (URETEK, 2010). Uretek USA provides a service to inject a high-density polymer into a depth of more than 9 m and the technique has been already industrialised.

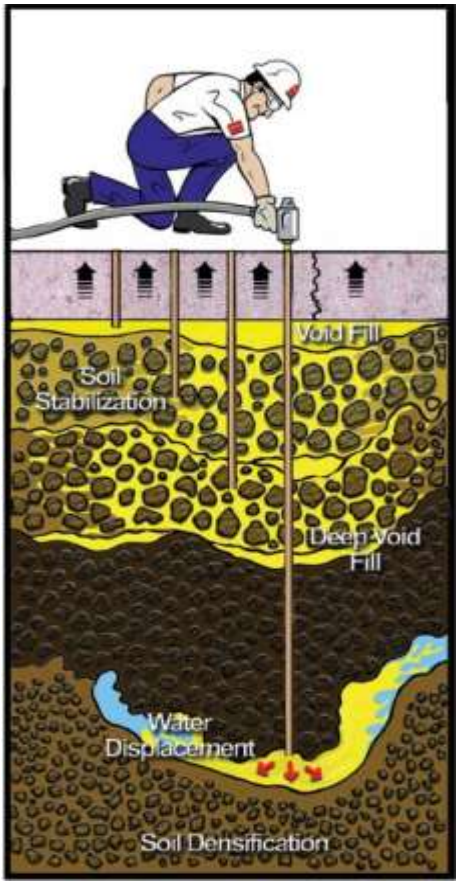


Fig. 6-9. Uretek USA injection technique (URETEK, 2010).

6.3.4. The Effect of Heat Pump Heating Capacity

Fig. 6-10 shows the effect of the thermal capacity of heat pump against indoor temperature and energy consumption. The heat pump capacities of heat pump were taken from data technical of NIBE F1145 (Nibe, 2006). Obviously, it can be seen that the higher heat pump capacity has good potential to provide heating and cooling. Converting the 5kW heat pump to 8kW heat pump capacity could improve the system performance. However, this potency has to be paid due to increasing HVAC energy consumption.

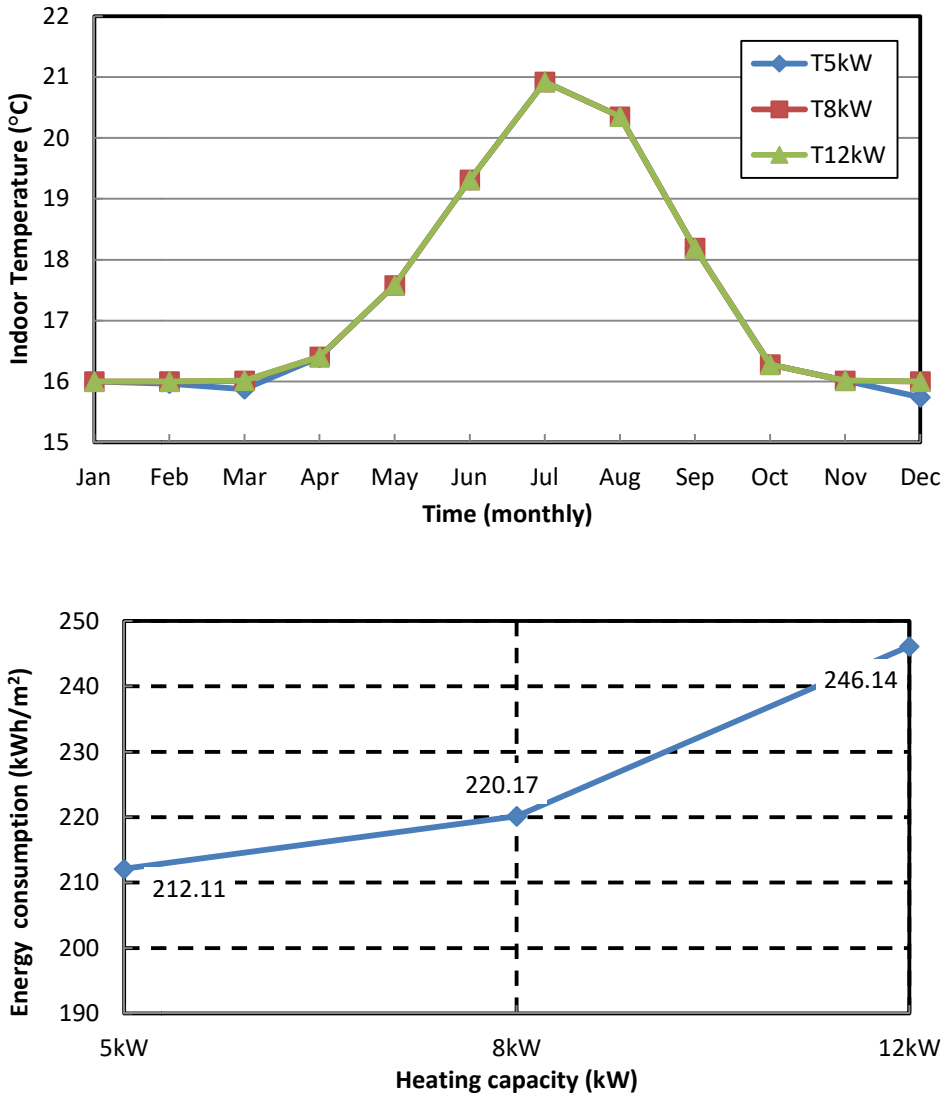


Fig. 6-10. The impact of the heat pump capacity on the indoor temperature and HVAC consumption, respectively for airtightness =2 ac/h

6.4. CONCLUSION

The effect of refurbishing the envelope of the building of the novel greenhouse with granular aerogel, improving the underground thermal conductivity, and airtightness of building is the focus of this chapter. It has been found that airtightness becomes the better option to reduce energy consumption in comparison to other treatments –providing a reduction of 8%. Lowering the thermal transmittance of facades could decrease energy

consumption by about 1.9% as long as the building is airtight. Utilising silica aerogel granule has the highest energy saving without losing too much daylight. Otherwise, converting the higher thermal capacity of the heat pump could enhance the system performance and maintenance the indoor temperature. Meanwhile, improving the soil's thermal conductivity has the potential to increase the energy stored, prevent freezing, and smoothen the output temperature of heat pump. Particularly if the nano-particles carbon-based can be injected and saturate the soil moisture with water thus enhances the soil thermal conductivity and improves the heat transfer of soil significantly.

CHAPTER 7 – Techno-economics of The Greenhouse

Outline of the Chapter:

This chapter calculates the Discounted and Non-Discounted Payback Period of Greenhouse proposed system and its environmental impact. Due to the superiority of the Discounted Cash Flow (DCF) method in considering inflation and future cost changes, the payback period achieved will be closer to reality.

It was found that the discounted and non-discounted payback period was 14th year and 11th year respectively, with an Internal Rate of Return (IRR) greater than the loan discount rate. Moreover, the greenhouse gas emission could be cut up to 68% compared to the conventional greenhouse.

7.1. INTRODUCTION

An undertaking's monetary investigation is envisioned to determine the profit of an investment; appraising many alternatives to find the optimum use of resources while weighing its profit-cost ratio. Determining the behaviour of two types of costs, fixed and variable, in a greenhouse business is an ordinary way to find the relation between investment and profitability. Fixed costs are associated to the spent whether or not there is production, such as the investment building, equipment, property taxes, and legal bills. Whereas, variable costs in an economic analysis of a greenhouse are related to the production cycle, for instance, seeds, fertilizers and perlite bags.

Compared to the Return of Investment (ROI) method, DCF method is superior since the time value of money is incorporated. Moreover, DCF can estimate the future cash flow of the investment (Sinclair, 2010). The DCF development analysis requires the need to describe the scheme within which investment prices, operating cash flow in. Besides, the in-activity costs are calculated over the time period under scrutiny and processed in conjunction with various related. It means cash flow identification is needed. Therefore, some performance and economic analysis of cultivation greenhouses have been done.

A discounted life cycle cash flow analysis has been used on two solar kilns design for over 20 years' service life (Hasan *et al.*, 2016). This financial analysis could determine the most profitable and environmentally beneficial of two different solar kilns. While another reference used the DCF analysis for an indoor sports arena building for 27 years (Copiello, 2016).

Additionally, DCF analysis for the yield of crop inside the modified net house, Polyethylene (PE) covered greenhouse, and conventional net house-white screen net covered greenhouse has been done for 20 years lifetime (Sethi, Dubey and Dhath, 2009). It was found that modified net house produces the highest yield and the fastest payback period (5.2 years) compared to the conventional net house (6.5 years) and PE covered greenhouse (10.5 years).

Furthermore, a financial analysis of a greenhouse and its modification has also been conducted in India (Banik and Ganguly, 2017). A novel scheme system of a desiccant assisted distributed fan-pad ventilated greenhouse to decrease the humidity was proposed for tropical and subtropical country. The net present value (NPV) and payback period calculation for 15 years resulted in $9090 and about 6 years, respectively.

NPV is the value of cash flow in the future over the life span of an investment discounted to the present. There are some advantages attached to using NPV in a financial investigation, which are (Žižlavský, 2014):

(i) it calculates the money value in the future, and

(ii) it considers all the future net cash flows related to the innovation occasion, but not for payback period which only take into account the initial cash flow.

At least, there are two serious disadvantages of the non-discounted Payback method of financial assessment are:

(i) it does not take any attention of returns following the payback period and,

(ii) it neglects the timing of the returns (Lefley, 1996).

Another analysis of greenhouse dryer with thermal energy storage operating under passive mode and active mode was done (Prakash, Kumar and Laguri, 2016). The active mode is operated to utilise DC fans as the exhaust fan is powered by a 6 W of photovoltaic (PV) panels with battery backup. The energy payback time calculation for 35 years lifespan shows that the modified small greenhouse dryer under passive and active mode payback period is found to be 1.11 years and 1.89 years, respectively.

The aforementioned greenhouse financial investigation merely assesses energy dependent building and its production. However, it is hard to find an investigation of financial on a greenhouse project which is purposed to be more independent in energy by using solar PV panel and seasonal underground heat storage. Therefore, the main focus of this analysis is to find the direct reimbursement of the investment in renewable technologies, thermal storage, and electrical saving benefit. Hence, the technologies considered for cost were not only photovoltaic panels and double glazing modules but also the Heat pump and the heat exchanger too.

The financial analysis uses DCF and non-DCF to find NPV, IRR, and the Payback period of the new system compared to the conventional greenhouse. Linked to this analysis, an environmental study was also performed to observe the reduction of carbon dioxide emissions with the utilization of renewable technologies. As described in energy efficiency section of the introductory chapter, the main strategy for climate change is directly related to the efficiency of energy. When improving the performance of some process, not only economical savings are being

obtained but also fewer resources are being consumed, therefore, the emission of pollutants is minimal.

Regarding the environmental analysis, life-cycle assessment (LCA) is one of the effective methods to analyse the greenhouse gas (GHG) emissions of a particular heating system throughout its life cycle (Zheng, Fang and Yu, 2016). LCA is a standard assessment methodology for potential environmental and the impacts of the products and resources used against human health (Bartzas, Zaharaki and Komnitsas, 2015). LCA could assist decision-making, marketing by identifying the product improvements to the environmental performance in different life cycle stages (Curran, 2013; Islam, Ponnambalam and Lam, 2016; Brandão, 2017).

7.2. METHODOLOGY

The selected method of study was to determine the profitability of implementing passive and active technologies for production in agriculture industry (more specifically production using greenhouses) to determine the efficiency of the energy produced, against the cost of conventional energy resources.

7.2.1. Population/sample of the study

From the population of a full economic analysis, this study was performed only analysing the main mechanisms involved in the renewable energy production. Some variable costs and some fixed cost such as insurance for all building materials and its equipment were also been neglected. Also, costs of installation and transportation were avoided to facilitate the comparison between technologies. But consider the costs of maintenance annually for all system i.e. fan coil, Heat pump, while others vary such as

inverter every 16 years, and cladding per 10 years as described in Table 7-4.

7.2.2. Location

For location purposes, all prices were presented in sterling British pound (GBP) currency. According to prices of electricity, the E.ON Company of electricity was considered for the city of Loughborough.

7.2.3. Limiting conditions

The analysis was performed comparing two types of greenhouses with different configuration systems. Firstly, the conventional greenhouse using single glazing (SG), HPS lamps, and electric heaters, while the proposed greenhouse using double glazing (DG), Ground Source Heat Pump, solar photovoltaic panels, seasonal underground thermal storage, LED, and the supporting elements and equipment.

As observed in a review (Peng, Lu and Yang, 2013), previous examples of studies developed for Photovoltaic panel technology showed a high advantage of using this technology given the short time to pay back the investment. Moreover, the types of those modules could overpass the 20-30 years lifetime period in locations with favourable solar radiation.

In order to be fair, the electrical loads of both buildings are taken by Energyplus simulation for a year using Nottingham weather data which is close to Loughborough. The design of the building can be found in Harjunowibowo et al. (Harjunowibowo *et al.*, 2017). The indoor temperature setting is 18 ^{o}C. Whereas, the PV's electrical generation is taken from the real annual data field.

7.2.4. Electricity pricing

The price of electricity presents a wide variation between countries, and even between localities in the same country. In the case of UK, the price of electricity varies according to the location and provider. The cost of electricity is given by kWh and is determined by the cost of production.

The tariff chosen for this analysis was E.ON Energy plan with a variable price given the inconstancy of the energy required according to the production obtained by PV installation. The unit normal rate is 14.140p per kWh for the city of Loughborough (EON, 2018). Given that all previous analysis was performed under climatologically conditions of Loughborough, costs of this city were also considered for this study.

7.2.5. Evaluation of electricity cost and GHG emissions per kWh

Three stages of the study were followed in order to find all costs of electricity to compare. SG load refers to the electricity load required when the greenhouse cladding material is clear single glazing 6mm without thermal insulation and renewable electricity generation. DG load is the analysis case where the building has a double glazing insulation, in this case, it is triple wall Polycarbonate equipped with solar PV panels. The PV panels are installed around surrounding walls and rooftop.

The amount of GHG emitted to the atmosphere from electricity generated also present variations not only of its location but also according to the resources used, whether it is from coal, oil or natural gas, the amount emitted varies. In the case of the UK, most of the electricity is generated from fossil fuel burning a 30% of natural gas, 23% of coal and less than 1% from oil (DBEIS, 2017b). For the exact case of Loughborough, a total electricity price of £0.1440/kWh according to E.ON is the value used for

this analysis (EON, 2018). E.ON said its standard dual fuel bill will increase by 8.8% from the end of April 2018. In this calculation, a total amount of greenhouse gas factor of 0.38443 was used (BEIS., 2017). Gas rates will go up by 3.8% and its electricity prices will rise by a whopping 13.8% (UKPower, 2018). The UK discount rate is assumed 6.9% for 8 years payback of loan (uSwitch, 2018).

7.2.6. Economics assessment

The Net Present Value (NPV) expresses the sum of all the ingoing and outgoing cash flows, once they have been discounted at a given discount rate. The NPV formula is governed by equation (7-1) (Osborne, 2010):

$$NPV = CF_o + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^n} \qquad (7\text{-}1)$$

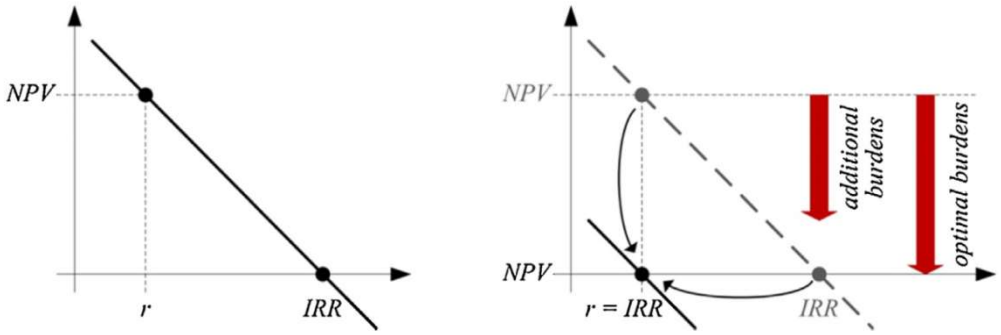
where CF is the sum of the net cash flow or cash balances, which in turn overall form the cash flow in order to be discounted at the rate r, while i reflects each time unit of analysis throughout the time span n.

Moreover, the Internal Rate of Return (IRR) represents a relative measure of the profitability has the property to make null the NPV (Copiello, 2016). In other words, the IRR is the highest possible discount rate when NPV=0 at the end of the lifecycle. The IRR formula is governed by equation (7-2) (Osborne, 2010):

$$NPV = CF_o + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^n} = 0 \qquad (7\text{-}2)$$

IRR is also crucial for the estimate of the upper level of interest rate for the loan. Appropriately, the higher the IRR value, the more possibilities exist to determine the requisite amount of investment expense on the market.

Besides, the higher the value of IRR and the difference (IRR – r), the higher value of NPV and the more stable is the project (lesser risks) (Kharitonov and Kosterin, 2017).



a. b.

Fig. 7-1. NPV, IRR, and discount rate relationship; (a). profit prediction, and (b). Discounted Payback Period (Copiello, 2016)

Fig. 7-1a shows that if NPV > 0 and IRR > r meaning the investment generates profit and is feasible to do. Additional burdens may be charged to the project until the NPV close to zero as shown in Fig. 7-1b. Therefore, it reflects the condition where the project does not generate profit; NPV = 0 and IRR = r, so-called discounted cash flow payback period. Furthermore, if NPV < 0 and IRR < r then the project is not recommended to be funded since it losses.

7.2.7. Cost analysis of equipment

The renewable energy production equipment of the greenhouses is shown in Table 7-1. The prices were obtained from the manufacturer companies and distributors in 2015, therefore prices are subject to variation.

Table 7-1. Greenhouse cost analysis

Greenhouse Cost Analysis					
Unitary prices					
	Sterling Pounds £	Unit	Area	Quantity	Total £
NIBE Ground-source Heat Pump F1145 5 kW	6,631	Piece		1	6,631
Flexi type fan coil unit FDW04-18A-018 4 pipes	1,762	Piece		1	1,762
200 litres premium direct heat pump water tank storage	1,080	Piece		1	1,080
Pump Grundfos UPS2 15-50/60 (130) A+ 240V	240	Piece		2	480
278W LED grow lights - Aluminum	299.95	Piece		20	5,999
ValuTek™ HPS Poultry/Greenhouse Light - 150 Watt	86.91	Piece		20	1,738
Polysolar a-Si Photovoltaic Module PS-C-901 20%	165	m^2	49	34	5,610
Fronius Galvo Inverter 2.5-1 165-440V 50/60Hz 2.5KW	1,530	Piece		4	6,120
CanadianSolar CS6P-265 W Solar Panel	150	Piece		26	3,900
Clarke Devil 6005 5Kw portable industrial electric fan heater	119	Piece		2	238
Structure					
Seasonal Heating: Insulation foam, 24 pcs double pipe heat exchanger, piping					1,000

Stainless Steel Structure with 10" beams, Stainless steel T section 25mmx25mx3mm, Aluminium Box Square tubes 76.2mmx50.8mmx3.2mm, Mill finish aluminium wallboard lining section 60mm, Aluminium T section 50.8mm x50.8mm x 3.2mm, Aluminium Channel 50.8mmx50.8mmx3.2mm				21,642
Cladding				
Macrolux® Multiwall LL 5X - 16 mm clear Polycarbonate sheet	32.26	m^2	86	2,774
Single Glazing - Clear - 6mm	70.20	Panel	48	3,370

Total cost (excluding labour)	5X polycarbonate Total	56,998
	Single Glazing walls Total	26,988
Building maintenance (5%) - discount fee for commercial product of 25%(profit)	5X polycarbonate Total	17,099.51
	Single Glazing walls Total	8,096.35
VAT (20% of profit)	5X polycarbonate Total	3,419.90
	Single Glazing walls Total	1,619.27
Total capital cost + Labour (assume 10% total cost)	5X polycarbonate Total	51,868.51
	Single Glazing walls Total	24,558.93

7.3. RESULTS AND DISCUSSION

7.3.1. Economic analysis

This economic study was performed for both configurations and presented in two results. Firstly, time of investment payback comparing the cost of technology against the savings occurred from electricity output. Secondly, the total amount of profit obtained from the implementations made after paying the equipment; considering a lifetime of 25 years according to the literature review.

In Table 7-2, it shows the prices related to the first two cases of load requirement, the amount of electrical load required to achieve comfort temperatures for both cases and the cost of electricity that should be paid. The SG load case represents a case where an owner of a greenhouse without any thermal improvements has to pay. The second, DG is the amount of electricity that is required to fulfill from the renewable PV modules in order to evaluate the electricity production.

Table 7-2. Cost analysis of kWh for cases SG and DG load

	SG load			DG load		
Month	**Electrical load**	**Cost**	**GHG**	**Electrical load**	**Cost**	**GHG**
	kWh	GBP	Kg/kWh	kWh	GBP	Kg/kWh
Jan	3,006.76	£425.16	1,155.89	839.73	£118.74	322.82
Feb	2,508.36	£354.68	964.29	699.43	£98.90	268.88
Mar	2,035.08	£287.76	782.34	601.16	£85.00	231.11
Apr	1,507.79	£213.20	579.64	459.86	£65.02	176.79
May	835.18	£118.09	321.07	337.13	£47.67	129.60
Jun	595.45	£84.20	228.91	258.61	£36.57	99.42
Jul	282.32	£39.92	108.53	225.87	£31.94	86.83
Aug	407.63	£57.64	156.70	257.11	£36.36	98.84
Sep	854.13	£120.77	328.35	347.53	£49.14	133.60
Oct	1,582.89	£223.82	608.51	506.87	£71.67	194.85
Nov	2,343.56	£331.38	900.93	690.01	£97.57	265.26
Dec	2,927.85	£414.00	1,125.55	831.62	£117.59	319.70
Total	18,886.98	£2,670.62	7,260.72	6,054.92	£856.17	2,327.69

Table 7-3, it shows the breakdown of elements analyses observing that the benefit of applying PV has a total saving of £2,487.32 in the first year. When considering a lifetime of 25 years, the implementation of this renewable technology can produce an annual gain of £672.87 from electricity generated by the greenhouse cladding elements. For the total

capital cost of £51,868.51 for the proposed system, the discounted payback period could be achieved in 14.3 years. While for non-discounted payback period takes 11 years only as can be seen in Table 7-4.

Table 7-3. Money saving analysis

	Unit	Amount
The energy required for initial loads	kWh	18,886.98
Annual cost from conventional GH	GBP	2,670.62
· Annual electricity purpose greenhouse		
The annual energy required for loads	kWh	6,054.92
Annual energy supplied by PV	kWh	4,758.60
Total annual energy is taken from the grid	kWh	1,296.32
· Cost of electricity		
Cost of electricity per KWh	GBP	0.14
Total paid for electricity from the grid without renewable energies	GBP	856.17
Total paid for electricity from the grid with renewable energies	GBP	183.30
Annual total saved	GBP	672.87
Annual saved compare to conventional GH	GBP	2,487.32

The bar chart in Fig. 7-2 reveals the monthly electrical bill produced by the conventional and renewable system for heating and cooling. Since the high U-value of single glazing, it has a big impact on the energy consumption of the conventional system. Compared to the renewable system which is equipped with low U-value double glazing and high-efficiency ground source heat-pump, there is a big difference.

Table 7-4. Payback period calculation based on UK loan discount rate (r=6.9%)

Year	Cash flow in (£)	Cash flow out (£)	Net Cash flow (FV) (£)	Present Value (£)	Discounted Payback period Cash flow (£)	Non-discounted Payback Cash flow (£)
0	-51,868.51	0.00	-51,868.51	-51,868.51	-51,868.51	-51,868.51
1	2,487.32	209.00	2,278.32	2,131.26	-49,737.25	-49,590.19
2	2,830.57	209.00	2,621.57	2,294.07	-47,443.18	-46,968.62
3	3,221.19	209.00	3,012.19	2,465.75	-44,977.43	-43,956.43
4	3,665.71	209.00	3,456.71	2,646.99	-42,330.44	-40,499.72
5	4,171.58	209.00	3,962.58	2,838.50	-39,491.94	-36,537.14
6	4,747.26	209.00	4,538.26	3,041.05	-36,450.89	-31,998.88
7	5,402.38	209.00	5,193.38	3,255.41	-33,195.48	-26,805.50
8	6,147.91	209.00	5,938.91	3,482.45	-29,713.03	-20,866.60
9	6,996.32	209.00	6,787.32	3,723.05	-25,989.98	-14,079.28
10	7,961.81	2,983.36	4,978.45	3,978.16	-23,435.41	-9,100.83
11	9,060.54	209.00	8,851.54	4,248.78	-19,186.63	-249.29
12	10,310.90	209.00	10,101.90	4,535.97	-14,650.66	9,852.61
13	11,733.80	209.00	11,524.80	4,840.87	-9,809.79	21,377.41
14	13,353.06	209.00	13,144.06	5,164.66	-4,645.13	34,521.47
15	15,195.79	581.00	14,614.79	5,371.89	726.75	49,136.26
16	17,292.80	710.00	16,582.80	5,701.84	6,428.59	65,719.06
17	19,679.21	209.00	19,470.21	6,262.53	12,691.12	85,189.27
18	22,394.94	209.00	22,185.94	6,675.43	19,366.55	107,375.21
19	25,485.44	209.00	25,276.44	7,114.42	26,480.97	132,651.66
20	29,002.44	3,463.36	25,539.08	7,454.84	33,205.33	158,190.73
21	33,004.77	209.00	32,795.77	8,077.67	41,283.00	190,986.50
22	37,559.43	209.00	37,350.43	8,605.70	49,888.70	228,336.93
23	42,742.63	209.00	42,533.63	9,167.38	59,056.08	270,870.56
24	48,641.11	209.00	48,432.11	9,764.92	68,820.99	319,302.68
25	55,353.59	209.00	55,144.59	10,400.64	79,221.64	374,447.27
NPV				79,221.64		
IRR				13.83%		
Discounted Payback period					14.32 Years	
Non-Discounted Payback period						11.02 Years

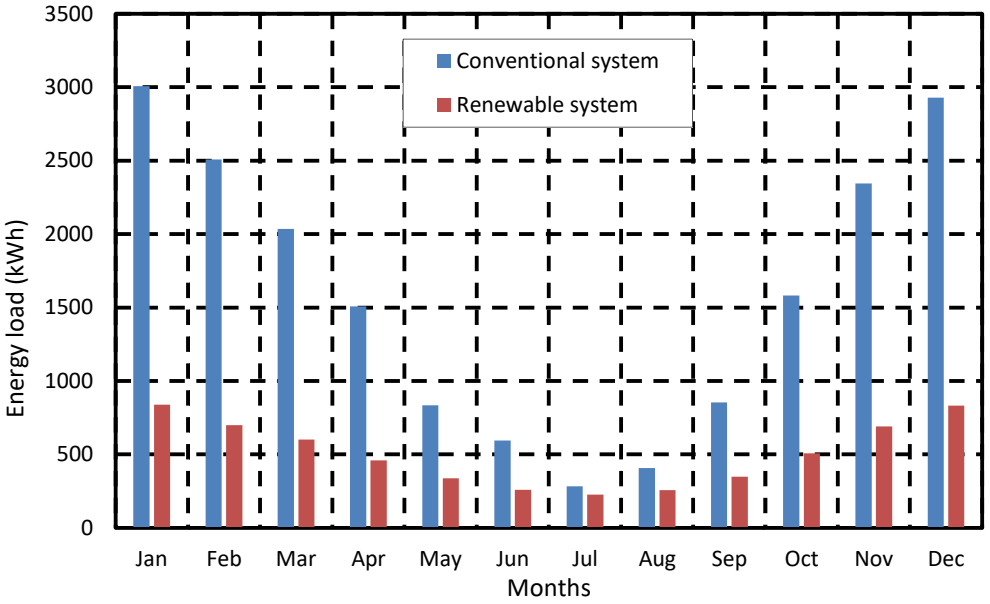


Fig. 7-2. Average electrical loads needed by the buildings per year

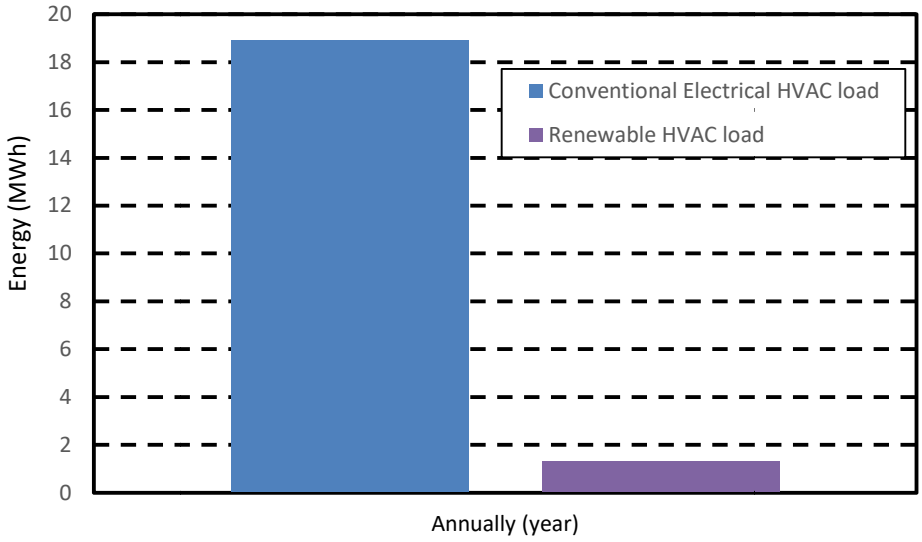


Fig. 7-3. The annual average power consumption of the buildings

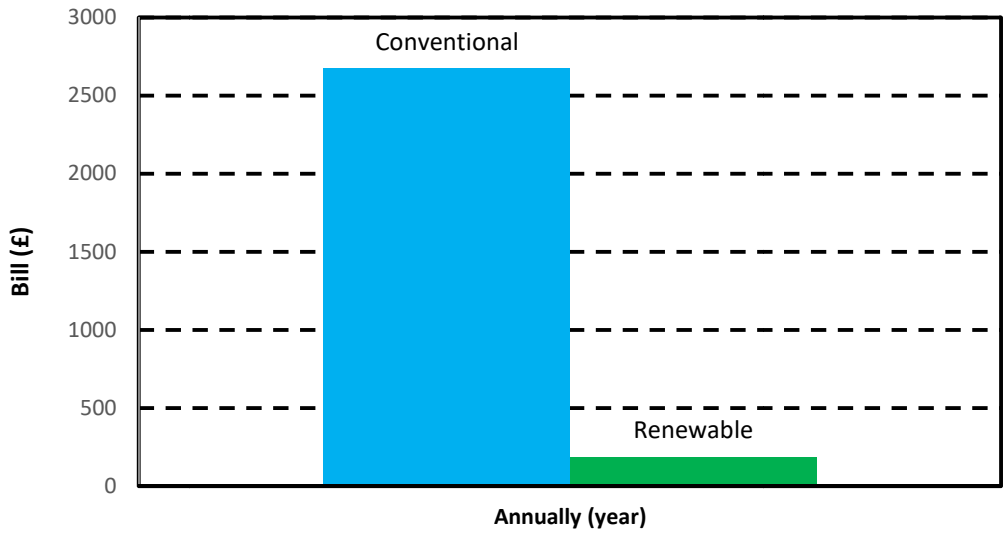


Fig. 7-4. Electric bills paid by both buildings per year

The electricity intake from the PV panels adds a remarkable saving as shown in Fig. 7-3 and Fig. 7-4. The energy saving gained by using renewable technology achieved 93% compared to the conventional greenhouse. Moreover, Fig. 7-5 shows that the payback period for both methods have rocketed exponentially. For the 25 lifespan, the proposed system could gain profit higher than the investment cost. Since the payback period is calculated with not taken into account of crops yield, then a shorter payback period could be achieved.

7.3.2. Environment analysis

The UK Government issued policies at earth protecting by diminishing GHG by means of 80% up to 2050 (DECC, 2015). Therefore, the LCA is conducted to assess the impact of the renewable greenhouse system to its environmental and human health. The LCA calculation is based on the desired temperature by utilizing electrical power and natural gas resource.

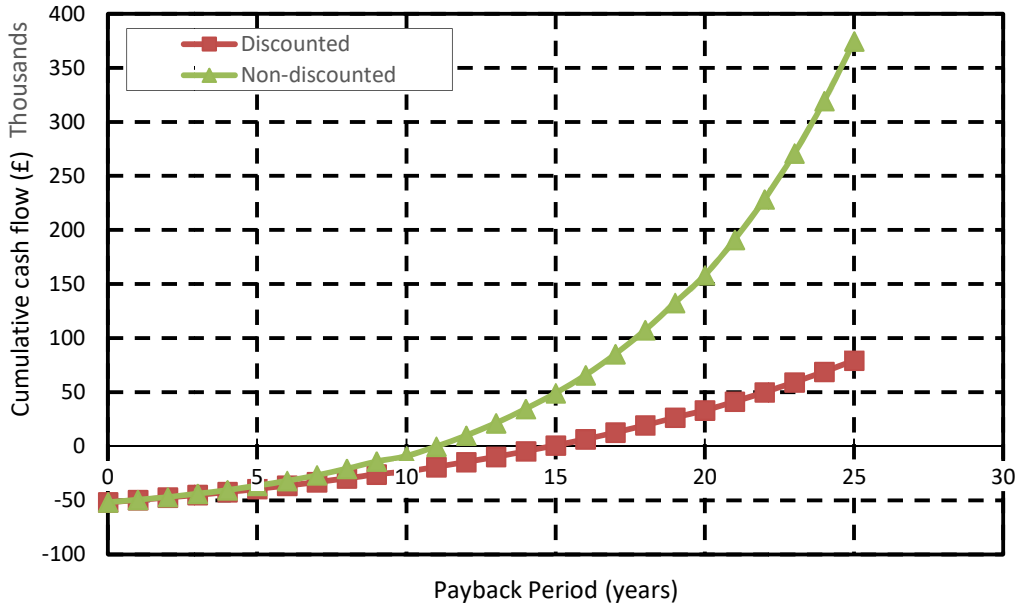


Fig. 7-5. The payback period for the proposed greenhouse in 25 years lifespan

In that respect, for the environmental analysis of the novel greenhouse the electricity consumed (includes grid losses), the electricity generation emission factors respectively from CO_2, CH_4, N_2O, are 0.39108, 0.00070, and 0.00234 (BEIS., 2017). In this calculation, a total amount of greenhouse gas factor of 0.38443 was used. While for natural gas, the heat generation emission factor from CO_2e, CO_2, CH_4, and N_2O are 0.20463, 0.20423, 0.00029, and 0.00011, respectively. Therefore, the total amount of the emission factor for the calculation is 0.40925 (DBEIS, 2017a). Based on the calculation, a reduction of 68% GHG can be achieved for the greenhouse's second configuration as shown in Table 7-2.

7.4. CONCLUSIONS

The observed results are in substantial agreement with the expected from the difference in costs of both technologies, given that the greenhouse proposed systems have a considerably reduced price. In an industry which

main cause of money outflow is constituted by variable costs, the implementation of renewable technologies with a short payback time economically is attractive.

Furthermore, it can be observed that the feasibility to generate electricity for the greenhouse has not only an economic profit but also allowing optimizing land by locating the electricity generation technologies in the cladding elements of the greenhouse.

It was found that the discounted and non-discounted payback period can be obtained in the 14th year and 11th year respectively, with an IRR greater than the loan discount rate. Moreover, the greenhouse gas emission could be cut up to 68% compared to the conventional greenhouse. Therefore, the proposed greenhouse has potential to be a zero-energy greenhouse in terms of energy, environmental-friendliness, and reduce the greenhouse gas emission in harmony with government policy.

CHAPTER 8 – Overall Conclusion and Future Works

Outline of the Chapter:

This chapter summarise the whole thesis work, including problems of the research, solutions approaching and the findings. Also, the future works that are recommended from the research findings are mentioned in the final section.

8.1. OVERALL CONCLUSION

In general, Greenhouse is a special building dedicated to plants cultivation which creates a particular environment needed by the plants to grow and flourish. For any type of plant to grow, it requires an appropriate environmental condition, which includes temperature, relative humidity, lighting, and soil nutrients. However, more than a cumulative 1.1 million acres of commercial greenhouses in 130 countries are facing the problem of low energy-efficient greenhouse, high operational costs, low environmental-sensitivity, and durability. To overcome the aforementioned problems, this work proposed a system that delivers a high-efficiency greenhouse that is low-cost and environmentally friendly using renewable technologies, especially for northern hemisphere countries that have high heating demand.

The literature study in Chapter 2 reveals that a thermal energy storage technique based on shallow seasonal soil thermal energy storage could help the system in a greenhouse to keep the indoor temperature at 13-15 °C throughout the winter without a heat pump. In addition, renewable solar energy harvested using PV panels can be used to minimise the grid dependency, especially in a rural-urban setting. Furthermore, installing the PV panels as the walls and roof top layers could reduce the heat loss while simultaneously producing electricity. Semi-transparent PV panels can be used a rooftop to allow natural light from the sunlight into the greenhouse while generating electricity using the energy, efficiently reducing excessive heat. The electricity resulted could be used to power lighting, irrigation, and heat pump.

Utilization of blue and red LEDs have been proven to be a good alternative light that is able to maintain photosynthesis in the day, evening or

nocturnal efficiently, energy-saving, and inexpensive. In order to reduce the excess temperature in a hot area or summer season, wind-catcher was potentially used as passive cooling. It has energy efficient because it only uses the system mechanically to work to decrease the temperature in the greenhouse.

Therefore, in the proposed system, a greenhouse with a new thermal energy storage technique based on shallow seasonal soil thermal energy storage equipped with well-insulated on its boundaries provides an adiabatic condition for yielding no heat loss on the edges was built. Horizontal tubes and coaxial vertical heat exchangers were used to make the installation easier and cheaper. To decrease the heat loss from the facades, opaque PV panels were installed in layer with double glazing X type polycarbonate. High-efficiency semi-transparent PV double glazing was used to make up the entirety of the rooftop. In order to fulfil the lighting requirement for photosynthesis, LED grow lights were utilised. Additionally, a commercial heat pump with high thermal capacity of 5kW was used to provide heating and cooling equipped with a well-insulated buffer tank and a fan coil unit as the heat distributor. All of the systems were controlled automatically with a control system.

The preliminary analytical and simulation investigation in Chapter 4 was done to determine the heating-cooling energy demand from the new greenhouse with specific materials properties needed. Both analytical and dynamic simulation resulted in similar, important points. They recommended facades with low thermal transmittance no more than $2W/m^2$, soil thermal energy storage surface area of $47m^2$ with at least 2.5m depth insulation, and artificial light addition. A closed-open concept was used because it is adaptable for every season.

Simulations have been conducted in order to find the best orientation to maximise the PV electricity generation and day lighting. It is found that build a greenhouse should take into account the PV surface facing west-south-east to get the optimum solar radiation. Furthermore, building a greenhouse with opaque PVs addition to the Polycarbonate and using semi-transparent PV as the roof altogether could reduce the energy demand by almost 43% compared to single glazing. The PV solar panels are capable of generating electricity by 62.25 %.

Based on the theoretical and dynamic simulation results, the greenhouse was built and analysed in Chapter 5. The system performance was observed and analysed for one year. The investigation results show that the seasonal COP heating and cooling of the heat pump varied between 1.48–2.97 and 1.20–3.45, respectively. While the COP_{sys} heating and cooling was found to be 1.51 and 1.55, respectively. These have been predicted by the simulation. However, the system successfully maintained the indoor temperature at 18°C in summer and 16°C in other seasons except for winter. In winter, the average indoor temperature dropped to 13.5°C due to very low brine-in less than -5°C (the heat pump automatically shut down for safety reason) whereas it was found that the indoor underground temperature was at 5-9°C. It indicates a problem with the ground property, such as low thermal conductivity which caused a slow heat transfer, high thermal transmittance of the facades, excessive air infiltration, a change in the control system setting, and the probability of altering the heat pump to higher thermal capacity heat pump. Therefore, some treatments should be done to fix the problems. Nevertheless, the proposed system could achieve soil thermal imbalance ratio of 32.76% so that the soil heat recovery attain by 67.24%.

Some experiments were conducted to acquire some information regarding the problems. In situ thermal performance measurement of facades used as walls and rooftops were carried out successfully in Section 5.2. It was found that the U-value for the walls and roof double glazing were found to be (2.47 ± 0.15) W/m^{2}K, and (1.34 ±0.20) W/m^{2}K, respectively. The wall u-value found to be higher than the data technical of 2.0 W/m^{2}K. It can be caused by the installation that not so well thus break the airtightness tape surrounding the double-wall polycarbonate. Hence, it made the heat loss from the wall higher than was expected. Thus, a laboratory experiment was taken on new polycarbonate-aerogel sandwiches to measure the U-value improvement and use the result in a building dynamic simulation. There were three samples measured that are an original multi-wall 9X type polycarbonate (PC9X), the 9X PC-aerogel powder sandwich (PC9X-PA), and the 9X PC-aerogel granule sandwich (PC9X-GA). These U-values found to be (1.78±0.03) W/m^{2}K, (0.68±0.03) W/m^{2}K, and (0.44±0.03) W/m^{2}K, respectively. The simulation results showed that the annual energy consumption using the refurbishment panels has a slight improvement by 1.9%.

In addition, the high air infiltration when the heating process was happening in cold seasons. This aspect is very hard to guarantee since the proposed greenhouse accommodates mechanical ventilation that was closed and opened when the heat excess indoor is too high which has gap along with the opening edges and the rooftop construction. While airtightness is well-known become the biggest problem facing low energy buildings in cold countries. The air infiltration may be lower by changing the procedure (below 25°C-turn on the active cooling directly, higher 25°C-turn on the windcatcher/opening), with this procedure changing the

injection power could be increased significantly. Therefore, the simulation proved that diminishing air infiltration could decrease the energy demand highest of 8% among the other treatments.

Moreover, a simulation regarding the effect of thermal conductivity of soil against energy consumption was done. The results show that shows that the soil thermal conductivity has very little impact on energy consumption saving. Increasing the thermal conductivity of underground resulting a trivial effect on energy saving by only 0.1%. However, enhancing the soil's thermal conductivity might smooth the thermal waves resulted from the heat pump (Bottarelli, Bortoloni and Su, 2015) and vanishing the frozen hence could extract more heat from the ground.

Furthermore, another option can be done is altering the low heat capacity heat pump to a higher one. Converting the 5kW heat pump to 8kW heat pump capacity could improve the system performance. However, this potency has higher cost investment due to increasing HVAC energy consumption.

The observed results are in substantial agreement with the expected from the difference in costs of both technologies, given that the greenhouse proposed systems have a considerably reduced price. To generate electricity for the greenhouse has not only an economic profit but also allowing optimizing land by the farmer. It was found that the discounted and non-discounted payback periods were in the 14^{th} year and 11^{th} year respectively, with an IRR greater than the loan discount rate. Moreover, the greenhouse gas emission could be cut up to 68% compared to the conventional greenhouse.

8.2. FUTURE WORKS

There are some recommendations that are very potential to improve the proposed system performance based on the discussion above. The experimental system demonstrate low COP both heat pump and overall system. This is primarily due to poor airtightness and low soil thermal conductivity. As a result, future work should focus on minimising the unwanted air infiltration of the facades and improving the thermal conductivity of the soil. Additionally, more extensive soil-based thermal energy storage system testing should be conducted to further investigate the relationship between connection type of pipe heat exchanger in serial and buffer tank volume on overall performance.

As highlighted in Chapter 6, lowering the air infiltration and retrofit the facades with lower U-value materials have a significant impact to decrease the heat loss. Besides, enhancing the underground thermal conductivity would be a very good investment to diminishing freezing that turns the heat pump off and smoothing the temperature output of heat pump. Therefore, future works could focus on injecting nano-particle carbon-based solution into the soil pores and investigate the best composition to achieve the highest performance of the greenhouse. It could be very challenging but will not destroy the building construction.

In addition, the suitable set up on how the control system work most probably could improve the overall system performance. Hence, optimisation of the control system set up for further work could be worth effort to significantly enhanced the system performance including lowering the ratio soil thermal imbalance.

Another future work should be done is investigating the potency of underground heat storage system with more suitable methods. Approaching methods as close as possible with the real condition would be giving more information in detail, theoretically and numerically. By using many vertical pipes heat exchanger can be very useful to see the soil temperature characteristic.

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