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ENERGY SAVING AND CLIMATE CONTROL FOR GREENHOUSES





DEWANTO HARJUNOWIBOWO

Energy Saving and Climate Control for Greenhouses

First edition

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Preface

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, the research main aims 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 any system.

Author

Dewanto Harjunowibowo, Ph.D.

A COMPREHENSIVE REVIEW

ENERGY SAVING AND CLIMATE CONTROL FOR GREENHOUSES

First Edition

Chapter 1

What is the review topic about?

1. Introduction

In 2016, 130 countries produced greenhouse vegetables commercially on a total area of more than 1.1 million acres [1]. The majority of greenhouses face the challenge of high operational costs due to their high energy requirements. The high energy demand in greenhouses [2], [3] is attributable to the high rate of heat loss caused by greenhouse envelope materials (which have low U-values) [4], [5].

In countries with a warmer climate, however, cooling has a greater energy demand [3], [6]. In addition, regions with different climates, such as those in countries with a cold climate, may have unique requirements, which in turn affect their heating demand [7]–[10]. These factors cause the energy required for heating to dominate the total energy demand of a greenhouse [4]; up to 80 percent of the total greenhouse energy demand [11].

Numerous references demonstrate the effectiveness of heat pump technology for heating and cooling [12]–[14]. Zhang et al. [15] simulate the effectiveness of a solar seasonal soil heat storage system aided heat pump. Consequently, the greenhouse space could be maintained at 12 °C during the winter.

In addition, Xu et al. [9] have demonstrated that a system with seasonal soil-based thermal energy storage can improve heating performance. Without a heat pump, the greenhouse air space could be maintained at 13°C throughout the winter using a U-type heat exchanger, water storage, and vacuum tube solar collector.

In this regard, the combination of a ground-source heat pump, buffer tank, underground pipe heat exchanger, and solar collector could be effective in meeting the greenhouse's heat demand [16]–[19]. Even so, heat loss in the soil should be minimised, as should the cost of pipe installation.

Therefore, Harjunowibowo et al. examined the utilisation of soil insulation and shallow pipe heat exchanger beneath a greenhouse aided heat pump. They discovered that the system could maintain an indoor temperature of 16 degrees Celsius year-round, with the exception of winter [20].

In addition, to protect the environment, the United Kingdom [21] and the European Union [22] have issued a policy to reduce greenhouse gas emissions by 80 percent by the year 2050. Consequently, increasing energy efficiency and utilising renewable energy are the optimal solution.

Therefore, it is crucial to provide a greenhouse with a low energy requirement. Innovations in thermal storage and grid independence are crucial for minimising the total energy demand of greenhouses, particularly during heating season.

2. Aim and Objective

In light of the problems mentioned in the introduction, the primary objective of a future project should be to propose a low-cost energy-

saving and climate control system that could provide a long-term solution to the inherent issues of greenhouses used in the protected cropping industry. The project should present an innovative integrated strategy to improve the energy efficiency of greenhouses and the yield of various protected crops through the use of a seasonal underground thermal energy store with innovative insulation panels, heat-insulating solar PV glass as greenhouse glazing, natural ventilation wind-catchers, and innovative LED lighting.

"Developing a low-cost, energy-saving, and climate control system can provide a sustainable and innovative solution to the current high fossil fuel consumption and related high carbon emissions of the protected cropping (greenhouse) industry."

The proposed solution should improve the indoor conditions of greenhouses, increase productivity, and reduce reliance on conventional fuels for energy provision, thereby reducing carbon emissions and high operating costs. A successful implementation of the project will benefit the entire community, including protected crop growers and industry, customers, and the economy.

Developing a low-cost, energy-saving, and climate control system can provide a sustainable and innovative solution to the current high fossil fuel consumption and related high carbon emissions of the protected cropping (greenhouse) industry.

An objective has been identified in order to achieve the goal, and a good starting point would be to highlight the gap in the literature regarding the technologies used in greenhouses in different climates, particularly in energy conservation and climate control.

Recommendations for future work related to the innovative energy savings improvement in greenhouses are derived from this point of departure.

3. Scope

By decreasing the greenhouse industry's dependence on fossil fuel, carbon emissions and operating expenses can be reduced. Thus, a sustainable and energy-efficient system can be proposed by employing a variety of innovative technologies, such as heat insulation panels, wind-catchers, and LED lights, in addition to a seasonal thermal energy storage system based on underground soil.

In order to optimise the nutrient content and production rate of food in a particular facility, production was increased by establishing complete control over key factors that affect plant productivity, such as light levels, temperature, carbon dioxide, humidity, and exclusion of pests/diseases. Dynamic control of the technologies enables the system to be adapted to the varying requirements of different crops.

Year-round production will permit crops to be grown in the cold country, thereby avoiding the "food-mile" carbon emissions associated with importing crops from warmer climates, particularly during the winter. Despite the anticipated increases in productivity, energy consumption and resulting carbon emissions were reduced, particularly as a result of the efficient and sustainable utilisation of PV solar energy and seasonal heat/cool storage.

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Chapter 2

Photovoltaic Integrated Greenhouse System

1. Introduction

Global energy demand increases by 2.2% in 2017 [1] and by 30% between 2017 and 2040 under the New Policies Scenario [2], with the heating, cooling, and transportation sectors accounting for approximately 80% of the global total final energy demand [3]. The greenhouse structure contributes 30 percent of the world's greenhouse gas emissions and 40 percent of the world's total energy consumption [4]. Twenty to forty percent of the building's energy loss occurs through its windows and roof [5]. It could be worse if commercial greenhouses, whose number is increasing to 1.1 million acres of greenhouses [6] globally, continue to use conventional facades.

As a rule, greenhouses utilise glass [7], [8], plastic/polyethylene [9], [10], semi-rigid plastic [11] and plastic film [12], [13] for their covers. While these materials have a high thermal conductivity that permits easy heat dissipation to the atmosphere [14]. Therefore, the majority of the energy consumed in the greenhouse is used for heating [15]. In this regard, definitive measures are necessary for the minimization of global energy consumption and the sincere reduction of carbon emissions.

In addition to the physical structure, the types of cultivation and location play an important role in energy consumption. The purpose

of greenhouse cultivation is to prepare land for the development and maturation of vegetables and organic products [16], to protect them from severe weather [17], pests and disease [18], and to improve crop quality [19]. Therefore, the growing demand for energy in a greenhouse is a crucial factor in ensuring the sustainability of cropping and harvesting [20], [21].

However, in an effort to preserve the environment, some developed nations have issued a new standard to reduce carbon emissions from buildings. For instance, the United Kingdom issued a policy in 2008 to reduce greenhouse gas emissions by 80 percent from 1990 to 2050 [22]. In addition, the European Union issued the same policy to reduce greenhouse gas emissions by 40%, 60%, and 80% below 1990 levels by 2030, 2040, and 2050, respectively, while increasing energy efficiency and bolstering renewable energy sources [23]. Therefore, it encourages researchers and scientists to seek additional energy sources, eco-friendly technologies, and energy-saving solutions.

2. Energy Saving

Each region has different requirements for greenhouse temperature, lighting, and humidity in terms of energy conservation [18]. Consequently, the technology utilised in greenhouses in various regions varies as well [24].

Countries with four distinct seasons typically have a greater need for a technology that can provide year-round heating. For example, British Columbia [21], the Netherlands [25], China [17], and several countries in the Mediterranean [26] and Middle East [8], which are predominantly cold, require a greater amount of energy for heating. In such climates, therefore, soil-based thermal energy storage

systems are preferable. The energy that is stored in water or soil can be used to heat the greenhouse at night according to its needs [27].

Passive solar heating technologies on existing greenhouses vary by thermal storage medium, such as water [28], rock [29], [30], phase change material [31], isolation moves (thermal screen /curtains) [32], soil water collector [10], and north wall and mulching [33]. With these systems, it is possible to keep the air temperature 2 to 4 degrees Celsius above the ambient temperature.

In the meantime, tropical and subtropical nations have a greater need for cooling technology to reduce the excessive midday heat in greenhouses [10], [12]. Countries such as Indonesia [34], Malaysia [35], India [36], Turkey [37], and Thailand [38] receive an abundance of sunlight intensity, resulting in greenhouse overheating. It promotes the spread of disease and pests. In tropical and subtropical climates, passive cooling ground heat exchangers based on horizontal earth tube systems (HETS) are strongly recommended.

Meanwhile, the majority of hot-season greenhouse vegetable plants grow rapidly at daily temperatures of 20–30 °C and nighttime temperatures of 14–18 °C [39]. Moreover, external local climate, structural materials, exposure, slope, soil, altitude, wind conditions, and cultivated plant species significantly impact energy demand [40].

In the region of Mediterranean climates, which are typically extreme, the greenhouse relies primarily on ventilation without a heating system [41]. In contrast, inadequate cooling during the summer will cause poor crop conditions on extremely hot days, albeit for brief periods. Especially in Tunisia, the annual sunshine can reach 3,288 kWh/m^2, causing crops to wither.

Hence, solar power systems are required to reduce the operational costs of greenhouses in extreme climates. Furthermore, heat pumps, solar collectors, and energy storage appear suitable for heating and cooling [42]. Since combining PV panels and crops on the same acreage could reduce reliance on the electricity grid or fossil fuels, the conversion of cropland into PV plants is on the rise [43]. However, there are obstacles that must be overcome when applying solar energy in the agricultural sector.

3. Adapted Technologies

The use of eco-friendly PV modules to generate energy for heating, cooling, and lighting is strongly recommended [35], [44]–[47]. PV system thermodynamic analysis is of paramount importance for a dependable performance evaluation of such technologies.

Nayak & Tiwari provide an excellent example [48]. An exergy analysis of the Photovoltaic Thermal (PVT) integrated greenhouse system reveals an approximate 4 percent efficiency level. The annual net electrical energy savings is 716 kWh and the annual exergy thermal energy is 12.8 kWh for the greenhouse temperature range of approximately 25 to 45 degrees Celsius.

Similarly, Yildiz et al. report that the average exergy efficiency of PV was approximately 5% at a reference temperature of 15 ^{o}C [49]. However, the majority of greenhouses still rely on the grid because PV-assisted earth-to-air heat exchangers (EAHEs) are only capable of supplying approximately 31 to 34 percent of the greenhouse's total electricity demand [42], [49].

Since PVT is inefficient, some enhancements have been made using a concentrator known as Concentrator Photovoltaic Thermal

(CPVT). Recently, CPVT collector has greater overall efficiency than PVT collector [50]. CPVT can generate thermal energy and electricity with a 65 percent and 11,3 percent efficiency, respectively [51]. Under Dutch weather conditions, the prototype produces 20 $kWhm^{-2}$ of electrical energy annually and 161 $kWhm^{-2}$ of thermal energy annually at temperatures of 17.5 ^{o}C in winter and 19.5 ^{o}C in summer. To increase the electricity supply for the heat pump and well-insulated greenhouse with seasonal storage, however, certain improvements were required. After improvement, the system's electrical and thermal outputs reached 31 $kWhm^{-2}$ and 270 $kWhm^{-2}$, allowing it to operate without fossil fuel.

In addition to temperature control, a good greenhouse must also consider adequate ventilation, light transmission, construction cost, and low energy consumption [52]. On the facades of the greenhouse, it is necessary to employ materials with low thermal transmittance, low weight and low cost, and high light transmittance. Visible light, also known as Photosynthetically Active Radiation (PAR) [7], [31], [53], is a crucial factor for photosynthesis [54]–[56]. Thus, the facade material, particularly the roof, must not obstruct the sun, as shading the plant will diminish the crop's quality [44].

Kadowaki et al. found that covering the greenhouse roof area by 12.9 percent causes the dry-matter weight (DW) and fresh weight (FW) of Welsh onion dropped significantly. In this context, the design of the greenhouse's facade and roof is also crucial for improving performance.

The primary focus of this chapter is, therefore, the retrofitting of an existing conventional greenhouse. Location determines the plantation's energy requirements for maintaining temperature and humidity. For that reason, technology retrofitting is crucial to the

greenhouse's operation. This effort has a direct impact on operational cost, ease of operation, overall performance, and return on investment, which must be considered from a business perspective. The state-of-the-art in greenhouse technology is consequently discussed in order to provide a clear description of the technology used to minimise the energy requirement and cost.

4. Photovoltaic Modules

Electric energy is one form of energy that can be utilised in the greenhouse for a variety of purposes, including heating, cooling, and lighting. Utilizing renewable energy in a greenhouse will reduce carbon emissions and operational costs. Therefore, dependence on the grid should be gradually reduced. The remaining section of the chapter will examine what can be done to retrofit existing greenhouses with more energy-efficient and environmentally friendly technology and materials.

Sunlight is the primary energy source that is the simplest and least expensive to use and convert into electricity. However, photovoltaic module has a low efficiency of 10 to 25 percent for the Si type [46], 18 to 28 percent for the GaAs type, 17 to 19 percent for the Thin-film chalcogenide type, 10 percent for the a-Si type, 9 to 12 percent for the Photochemical type, and 8 to 11 percent for the Organic type [57], [58], and it is also very heat sensitive. Upon receiving excessive heat energy, the photovoltaic system's efficiency will gradually diminish [47], [59]–[61]. Therefore, numerous efforts are made to obtain an abundance of the sun's visible light energy while maintaining a low photovoltaic temperature.

Conventional Photovoltaic modules

Recent widespread use of photovoltaic technology has prompted numerous industries to compete to develop a more durable and efficient panel. Since the technology is superior in terms of durability, high efficiency, and, most importantly, affordability, as production increases the price will decrease [62]. In addition, photovoltaic can convert the visible light energy of sunlight into electricity for direct current (DC) or alternating current (AC) devices via inverters, as well as stored in batteries [47].

On the market, mono and poly-Silicone types (Si) account for approximately 36% and 54.9%, respectively [63]–[65]. Despite the fact that, as shown in Table 2. 1, crystalline silicon is the most commonly used material in greenhouses for renewable energy generators, it is also the most expensive. In addition, the use of PV modules improves the greenhouse's ideal temperature and enables significant energy savings and carbon emission reduction.

Table 2. 1. Type of PV used for heating, cooling and lighting on Greenhouse

Ref.	Type of PV	Country	Result
[66]	Crystalline silicon (c-Si) semi-transparent	India	The highest energy consumption is 1.9 kWh/d.
[53]	Crystalline silicon spherical solar microcells semi-	Japan	The maximum power output is 540mW when exposed to 1213 Wm^{-2}. The conversion rate is 4.5 percent efficient.

	transparent		
[67]	Crystalline silicon solar cells (CEL-PM75)	India	Maximum power is 3825 Wp. The module improves the grid-independent greenhouse's viability (Simulation)
[68]	Crystalline Silicon (c-Si)	India	The annual electrical energy savings amount to 1,185 kWh. 2.04 is the electricity production factor (EPF).
[40]	Mono-crystalline silicon	Italy	Energy savings of approximately 30% for summer cooling and 11% for winter heating.
[69]	Mono-crystalline Si-cells	Nether lands	A peak output electrical power of 38Wm^{-2}. Annual electrical energy consumption will be 29 $kWhm^{2}$. 11 percent electric efficiency yield
[42]	Poly-crystalline silicon	Turkey	The total amount of electricity consumed is 8.10 kWh. 34.55 percent is provided by PV cells, the remainder by the grid. The interior temperature could be decreased by 19.9 degrees Celsius, as the outdoor temperature is 49.9 degrees Celsius.
[9]	Multi-crystalline silicon	Italy	The annual production of electricity is 107,885 kWh. 11.4 percent is the overall conversion efficiency of the PV system. The average annual temperature inside the greenhouse is 19.8 ^{o}C, with a range of 12 to 30 ^{o}C.
[19], [70]	a-Si thin film	Spain	Electricity generates 8.25 $kWhm^{-2}$, with 9.79% cover occupancy.
[44], [71]	a-silicon (FPV1024S)	Japan	The straight-line PVs and checkerboard PVc arrays produce

	4.08 and 4.06 GJy^{-1} of electricity, respectively. However, straight-line PVs reduce the onion's fresh weight (FW) and dry matter weight (DW).

Table 2. 2 displays the evolution of PV and its efficiency. The most efficient PV available on the market are multi-junction devices [57], [63]. However, as a result of its high cost, it is generally not used in greenhouses. The PV application in a greenhouse is primarily used to supplement the greenhouse's electric heating and lighting needs. However, the amount of electricity generated is contingent on the PV area, module efficiency, and location.

Table 2. 2. Multiple types of PV cells utilised in greenhouses and their efficiency measured under standard conditions [57], [58]

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

It has been stated previously that photovoltaic often experiences a sharp rise in temperature, particularly in regions with high solar radiation intensity, such as Italy [9]. Due to the conversion of fifty percent of the sun's energy into heat, the solar cell temperature will rise by fifty degrees Celsius above the ambient temperature [61].

In four-season countries, the average temperature difference between the inside of a photovoltaic module and its surrounding environment is approximately 18 degrees Celsius. While the module reaches its highest temperature peak of 76 °C in the summer, it reaches its lowest temperature of 25 °C in the winter. Therefore, it is recommended to use passive or active cooling systems to reduce the thermal excess in PV applications in a greenhouse.

Concentrating Photovoltaic (CPV)

Due to the low efficiencies of conventional PV, a large area of PV panels is typically required to meet the demand for green energy. Growers are compelled to install the PV module on the greenhouse's roof due to limited space. However, this method prevents sunlight from reaching the crops, affecting their harvest quality [9], [44], [53], [71]. Consequently, in order to avoid these losses, a number of researchers employed sunlight concentrators to increase the PV's power output. Multiple concentrators such as Fresnel lenses [72], [73] and Parabolic trough concentrator [51] are used in greenhouses,

as shown in Fig. 2. 1. These concentrators have numerous benefits and drawbacks.

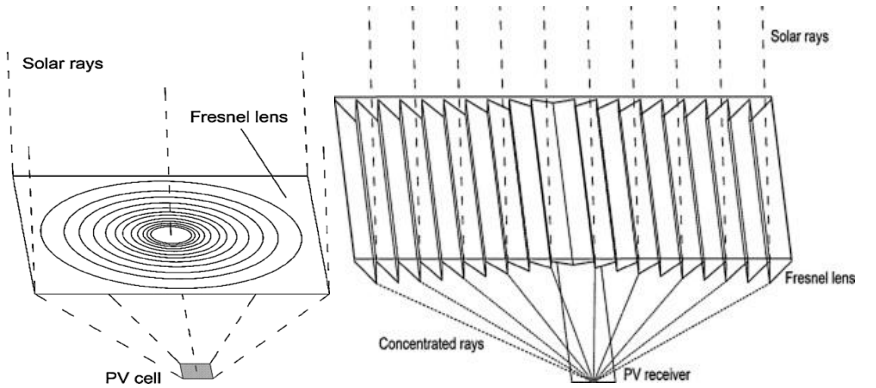


Fig. 2. 1. Aspheric/spot and Linear Fresnel lens diagrams [75]

The primary benefit is the diminution of PV module size, which automatically reduces the capital cost [63], [74]. Concentrating PV modules increase efficiency without requiring a great deal of space. In addition, a high concentrator can increase the amount of sunlight by up to 100 times more than a PV module of the same size [75]. In addition, recent reports indicate that CPV modules can achieve efficiencies of up to 38.9 percent under Concentrator Standard Test Conditions (CSTC) [76].

However, if they are not properly managed, module concentrator PV overheating could be a fatal drawback [61]. According to previous discussion, the temperature of the PV reaches 120 ˚C at 20 ˚C ambient temperature and 1000 W/m^2 of solar radiation intensity. Moreover, in extreme climates such as the Middle East in the summer (50 °C), the temperature of PV modules exceeds 200 °C. As shown in Fig. 2. 2 and Table 2. 3, such a high temperature will reduce the PV's efficiency to 8 percent from roughly 14 percent.

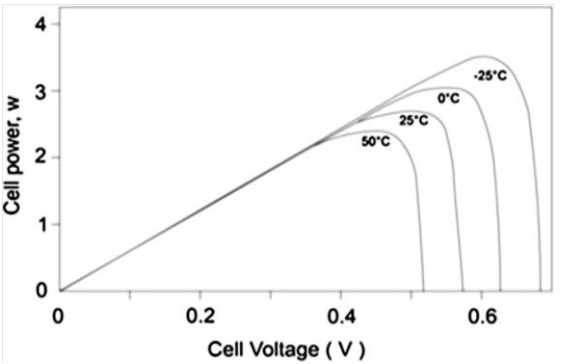


Fig. 2. 2. The impact of Si cell temperature on output power [77]

Table 2. 3. A temperature dependent crystalline silicon PV electrical conversion efficiency [60]

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

Table 2. 4 displays the concentrators typically utilised in greenhouses along with their efficiencies. The maximum safe temperature for a solar panel is approximately 80 degrees Celsius. More than that can result in irreparable harm and failure. Therefore, a cooling system is required to maintain the panel's temperature. Several techniques described in the literature can be used to utilise it as a greenhouse heat source or for other purposes [51], [73], [78]. Such efforts not only increase the electrical efficiency of PV

modules, but also allow greenhouses to reduce their heating needs significantly.

Table 2. 4. Type of concentrator used in a greenhouse

Concentrator	Greenhouse Temperature (°C)	Electricity Efficiency (%)	Ref.
Linear Fresnel lens	N/A	69.0	[72]
Concave/curve glass	17.5 and 19.5	12.52	[51]
cylindrical trough concentrator	20.8-31.2	15.7	[79]

Photovoltaic Thermal (PVT)

Due to the negative effects of the extreme heat generated by the PV system, another innovation is implemented to reduce the temperature of PV. The method is implemented in a variety of ways and even employs the excessive heat as the greenhouse's heat source [12], [42], [48], [51], [67], [68], [78], [80]. In addition to harvesting electrical energy from renewable sources, the heat produced by the PVT module [81] simultaneously reduces greenhouse heating requirements.

The architecture of a water-based PVT module is depicted in Fig. 2. 3. In general, the PVT configuration consists sequentially of a solar cell, heat sink, ventilation, and insulation. Several studies aimed at increasing the efficiency of solar PV panels by lowering the temperature of the solar cell have employed air conditioning and water [61], [82]–[84]. In recent years, PVT modules for greenhouse applications have garnered significant attention [85], [86].

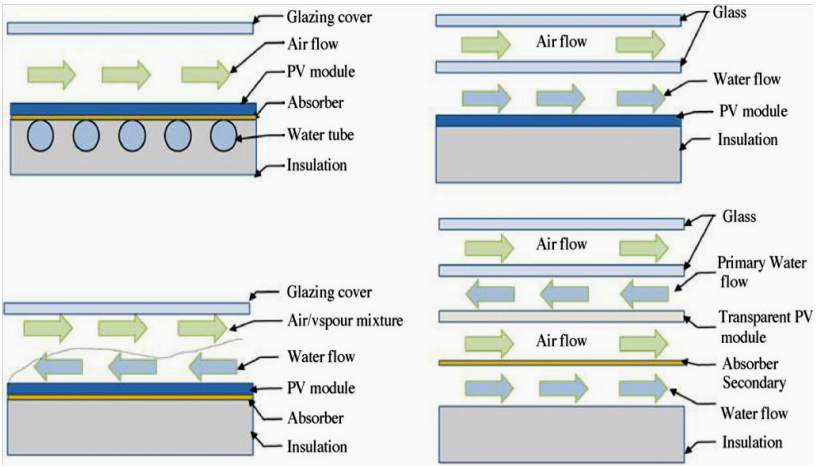


Fig. 2. 3. Perspective section of the PVT module [87].

For instance, Nayak and Tiwari [48] theoretically and experimentally investigate a PVT system in a greenhouse in the climate of New Delhi. They mention that the system could recover 12.8 kWh annually of waste heat from PV modules. In addition, the remarkable annual electrical energy savings achievable is 716 kWh. Table 2. 5 reveals the application of PVT technologies and their impact on greenhouses.

Table 2. 5. PVT technologies used in greenhouse construction

Ref.	PV	Country	Cooler	Result
[48]	0.605m^2 75W	India	Water	Annual energy savings amount to 716 kWh. 12.8 kWh of waste heat is recovered annually. 4% is the energy efficiency of a PVT integrated greenhouse.

[89]	8 PV modules connected in series.	India	Air	The waste heat recovery causes 7–8 °C daytime and nighttime increases in greenhouse temperature during the winter season. The annual exergetic efficiency of the greenhouse is 5%. The annual thermal energy is approximately 24,729 kWh. The annual thermal exergy is approximately 1006 kWh. Annual energy savings amount to 805,9 kWh.
[68]	1200 Wp 1.62mx 6.5m	India	Water	Annual total thermal energy consumption is 29,157 kWh. Annual energy savings amount to 1,185 kWh. The yearly thermal exergy is 1,366 kWh.
[85]	Semi-transparent PV double pass facade 0.6 m^2	India	air	The annual thermal energy consumption is 480.81 kWh. Annual energy consumption is 469.87 kWh. 5–6 °C increases in indoor temperature for a typical New Delhi winter day.

				The thermal efficiency is 42% and the electrical efficiency is 8.4%.
[66]	Semi-transparent PV modules 280Wp electricity 1.2m x 0.54 m	India	Water	Daily thermal energy totals 20,5 kWh. Return is 3.74 and 4.10 years for load and no load conditions, respectively (CFD Simulation)

In extreme weather, water as a heat exchanger appears to be the optimal material for reducing the PV temperature in greenhouses [61]. The PVT-based air conditioner is more modest and suitable for moderate climates, but its efficiency is still inferior to that of PVT-based water cooling [87], [88]. As shown in Fig. 2. 4, the efficiency of amorphous silicon BiPVT to produce heat and electrical energy in India is 1,531 kWh and 16,220 kWh per year, respectively, for air-cooled solar panels [82]. BiPVT that uses water (BiPVW) as a cooling medium for solar cells achieves 2,257.6 kWh of thermal energy and 3,229.9 kWh of electrical energy [83].

Concentrating Photovoltaic Thermal (CPVT)

CPVT modules are preferred in rural areas where grid electricity is costly to access for greenhouse applications. Consequently, the integration of a concentrator module and a PVT module is one of the additional innovations that can increase thermal and electrical energy output [90]–[93]. Typical CPVT module depicted in Fig. 2. 5 [94], [95].

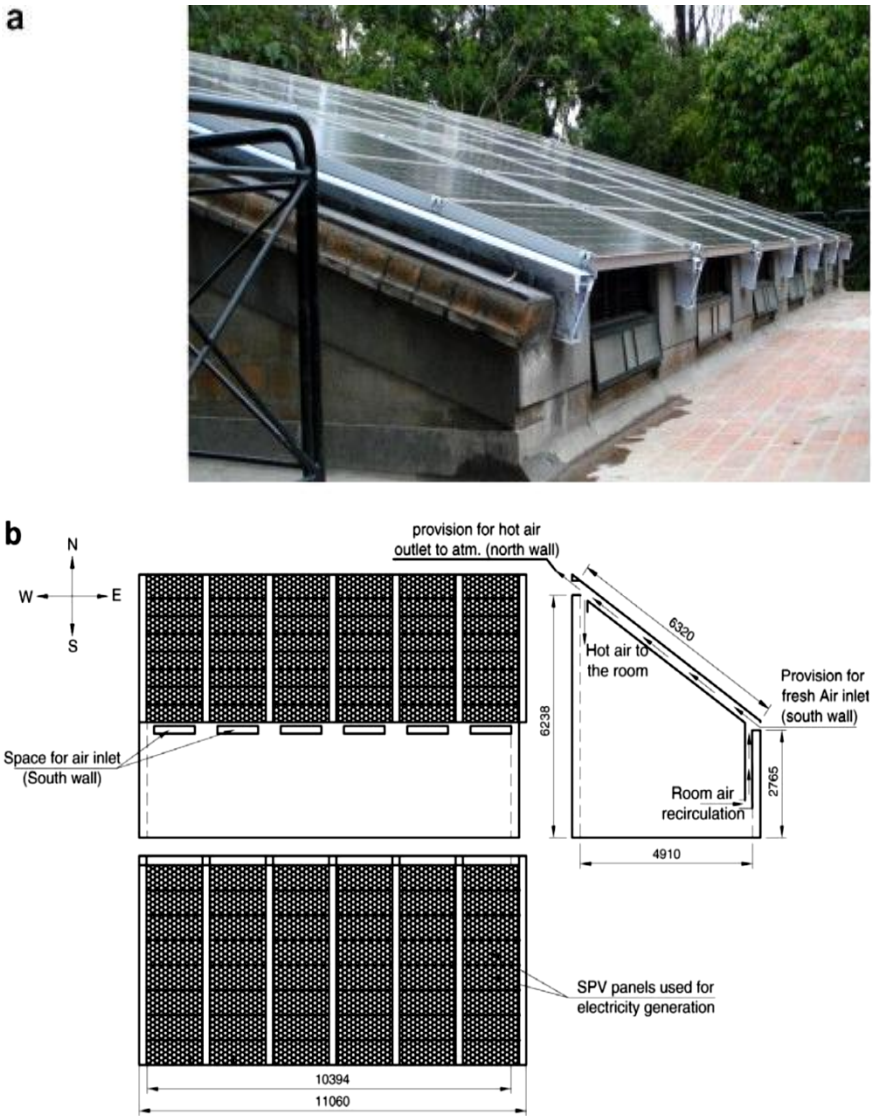


Fig. 2. 4. (a) Rooftop perspective view of PVT systems and (b) waste heat recovery from PV modules [82]

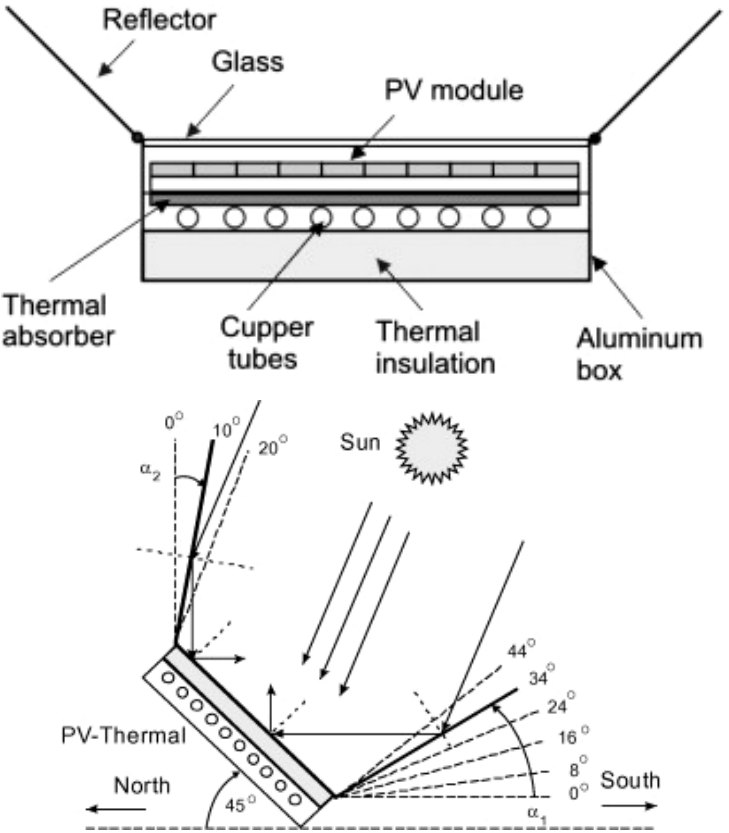


Fig. 2. 5. A typical CPVT system that may be utilised in greenhouses [50], [94]

In order to concentrate sunlight on the PV module, reflectors are installed on the system's perimeter so that sunlight can be easily reflected and concentrated. The effect of these techniques on thermal and electrical output relative to the conventional method is depicted in Fig. 2. 6 and Table 2. 6.

A.

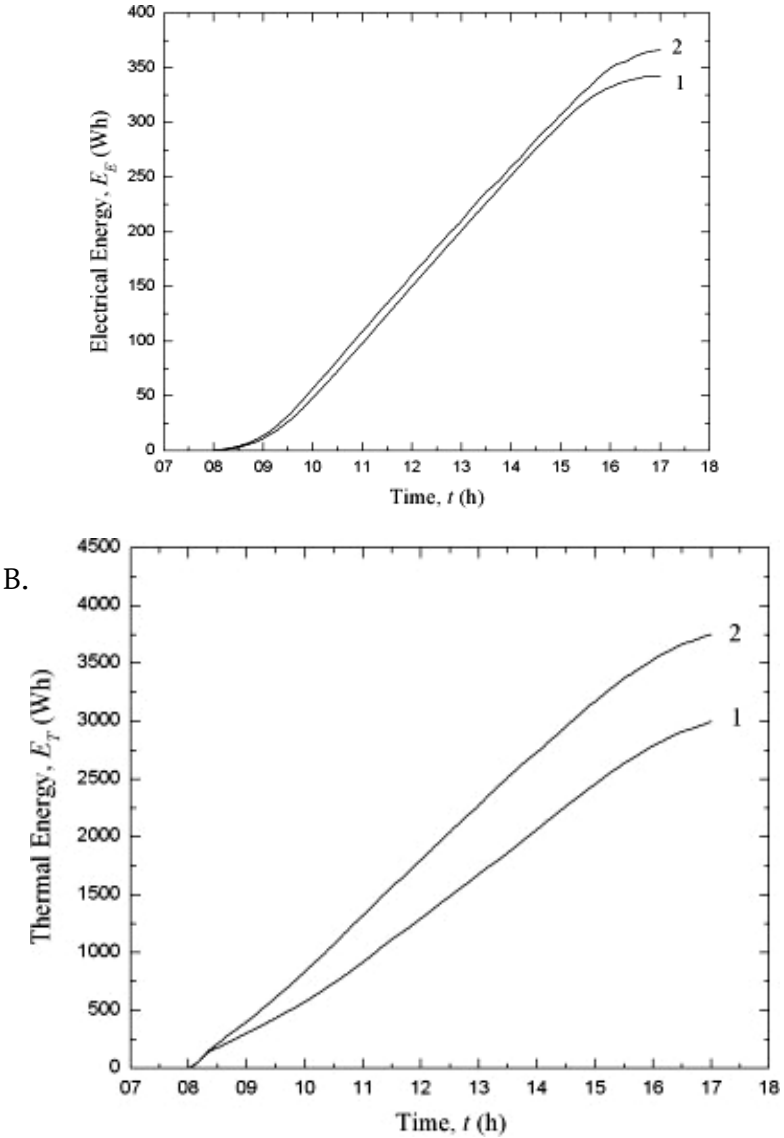


Fig. 2. 6. Changes in the total amount of A. electrical energy and B. thermal energy generated by a PVT collector with (2) and without (1) reflectors [50]

Furthermore, innovation is ongoing to make the CPVT module more concise and compact by employing Fresnel lens, as shown in Fig. 2. 7, so that it can be easily mounted on the greenhouse's roof [69]. Due to the superior Fresnel lens on the CPVT, this module is frequently used in greenhouses. The incidence angle of sunlight on the reflector or collector has a substantial impact on the CPVT performance of various concentrator designs [50], [69], [94]. CPVT applications on greenhouses are widespread and effective at supporting the supply of electricity and thermal energy, particularly at night or during cold weather [69], [73], [96].

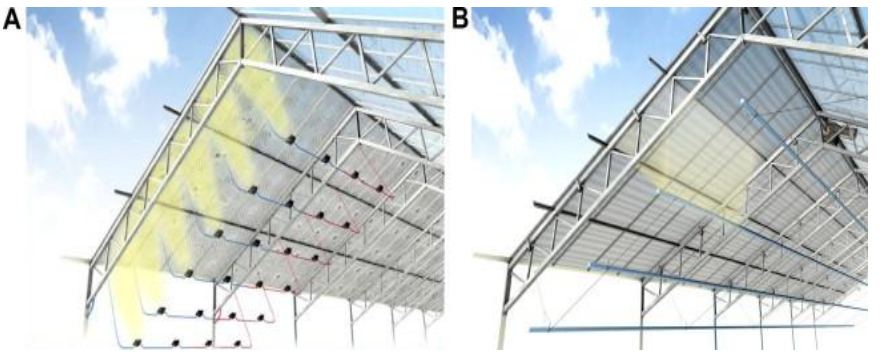


Fig. 2. 7. Integration of a greenhouse hood with (A) standard Fresnel lenses and PVT modules and (B) linear Fresnel lenses and PVT modules [69].

Table 2. 6. CPVT is commonly employed in Greenhouses

Ref.	PV/T module	Country	Cooler	Result
[96]	PV modules with Parabolic and tracker	Netherlands	Water	Annual electrical energy per square metre is 20 kWh Annual thermal energy is 160 kWh m^{-2} η_{ex} PV: 11.3%. η_{ex} T :

				65%
[97]	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%
[69]	PV modules with Linier Fresnel lenses	Netherlands	Water	Annual electrical energy is 29 kWh/m². Annual thermal energy is 143.89 kWh/m².
[98]	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%

5. An overview of PV modules for greenhouse

In general, previous research indicates that PV modules hold great promise for partially meeting the energy requirements of greenhouses (heating, cooling, lighting, and ventilation) [28], [39], [99]–[103] due to their renewable energy resources. Thus, the use of PV modules becomes extremely prevalent due to their adaptability and shorter payback period [45], [80], [104]–[108]. However, the most common problems with PV modules, such as overheating, reduce their efficiency and lifespan, particularly in hot and extreme climates [9], [109], if an appropriate cooling system is not utilised. In addition, PV modules installed on the greenhouse roof could reduce the PAR required for photosynthesis by the plantation.

Insufficient lighting and shading have a negative impact on the quality, size, colour, and flavour of the plants [9], [44], [53], [71], [110]. Concentrating PV modules offer significant energy production [75], space savings, and the ability to solve the greenhouse lighting issue. However, they must be performed in conjunction with a suitable cooling system. Consideration should be given to plant production and energy production via solar panels and intensive farming systems in order to solve this issue. The construction of expansive photovoltaic greenhouse farms that generate large-scale energy savings with some openings would be promising. This method could stabilise the interior temperature by reducing heat loss through the walls and roof.

Consequently, the semi-transparent PV (STPV) Module may be a suitable option for the rooftop. The PV modules are typically covered with transparent glass to protect them from adverse weather conditions, such as dust and overheating. PV is positioned above the air filling of the double glazing. Recent research indicates that semi-transparent PV modules are more efficient than opaque PV modules [85]. This is because a semi-transparent PV module will transmit the incoming sunlight; consequently, the PV module will not cast a shadow on the leaves. In addition, this type of PV module will not be exposed to excessive heat, so its efficiency will be relatively stable and comparable to its efficiency at its operating temperatures. Additionally, semi-transparent amorphous silicon PV could save up to 30 percent of a building's annual energy costs, or about $12,000 [111].

Chow et al. reported that in Hong Kong, natural-ventilated PV double-glazing could reduce air-conditioning power consumption by 28% compared to conventional single absorptive glazing [112]. Moreover, PV glazing can transmit incoming light that is nearly

identical to the spectrum of incident light [113] and also reduce radiation, making it an excellent greenhouse insulator [114].

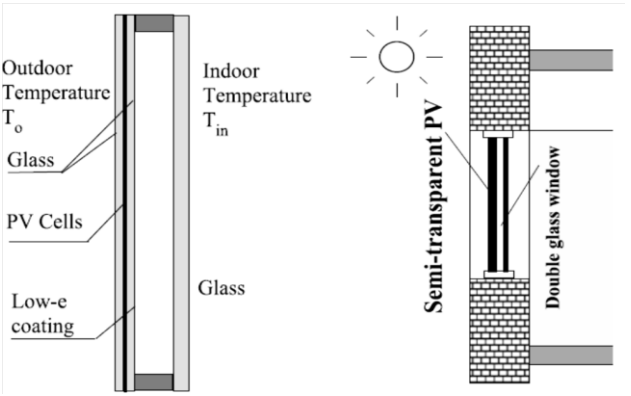


Fig. 2. 8. Diagrammatic representation of PV double glazing with low-e coating [114]

Fig. 2. 8 demonstrates that a PV cell is tested in direct sunlight. It aims to reduce the excess heat within the room, thereby reducing the cooling demand. The U-value of the glazing is determined by the low-e coating because a substantial amount of long-wave radiation can be reflected. Using this method, the STPV's excess heat could be reduced, thereby increasing the energy conversion efficiency. As a result of the double glazing's low U-value, the greenhouse's heat energy could be maintained considerably better and heat loss significantly reduced. Consequently, the demand for heating at night or during the winter will decrease.

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Chapter 3

Solar Thermal Collector Integrated Greenhouse System

1. Introduction

Benli et al [1] 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 [2] 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 et al. [3] 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. [4]. 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 [5] and the results show that solar air heaters provide more than 60% of the heating load.

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 [6]–[8]. 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 [1], [9].

2. Flat Plate Solar Collector

Flat Plate Solar Collector (FPSC) is one of solar collector modules which is 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. 3. 1), this system is able to provide 18-23% of thermal energy every day for 3-4 hours [10].

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[11].



Fig. 3. 1. Air circulation lines and solar collectors [10]

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. [12] 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. 3. 2). 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.

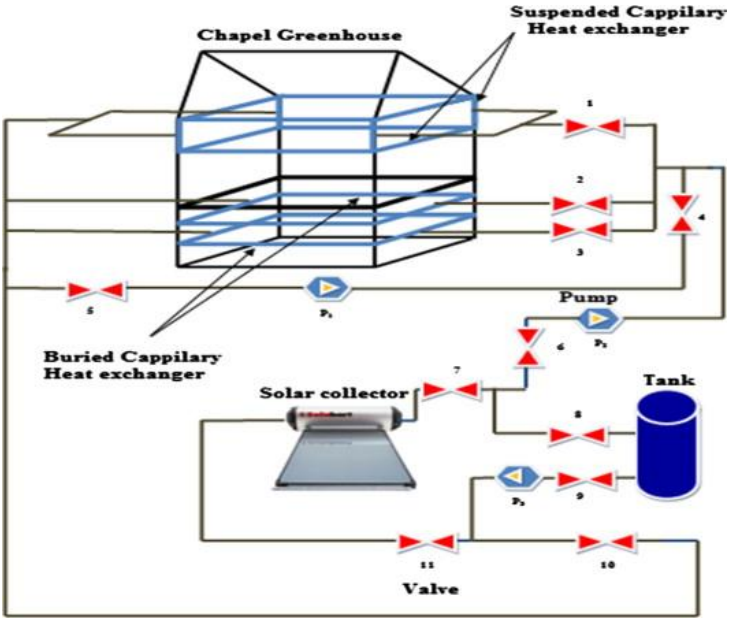


Fig. 3. 2. A greenhouse control system equipped with flat plate solar collector [12]

3. 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. 3. 3. The inner tube is coated with thermal absorber hence could produce temperatures of 80°C up to 120°C [13].

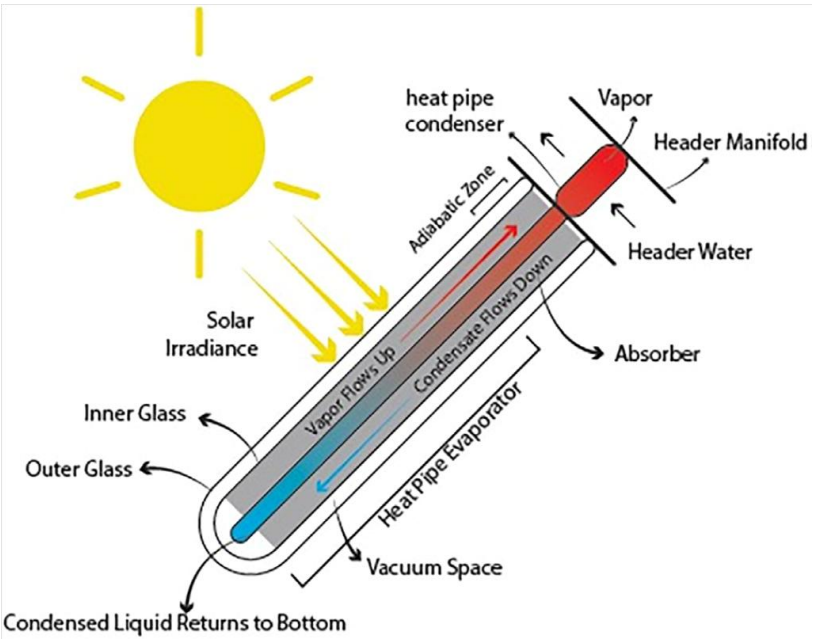


Fig. 3. 3. An evacuated tubes schematic [14]

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 [13]. Therefore, some improvement have recently done such as adding fin arrays to the heat pipe condenser [15], adding more heat tubes [16], and vary the back surface emissivity [17].

The solar evacuated tube mainly used in solar absorption cooling, adsorption cooling, desalination and desiccant dehumidification systems [14]. Mostly the range inlet water temperature are near ambient 20-40 °C for water heating application [18], [19].

4. 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 [20], even can produce temperature outlet up to 45°C [21]. This technology generally used as solar wall and classified into opaque type [22] and glazed (Trombel wall) [23].

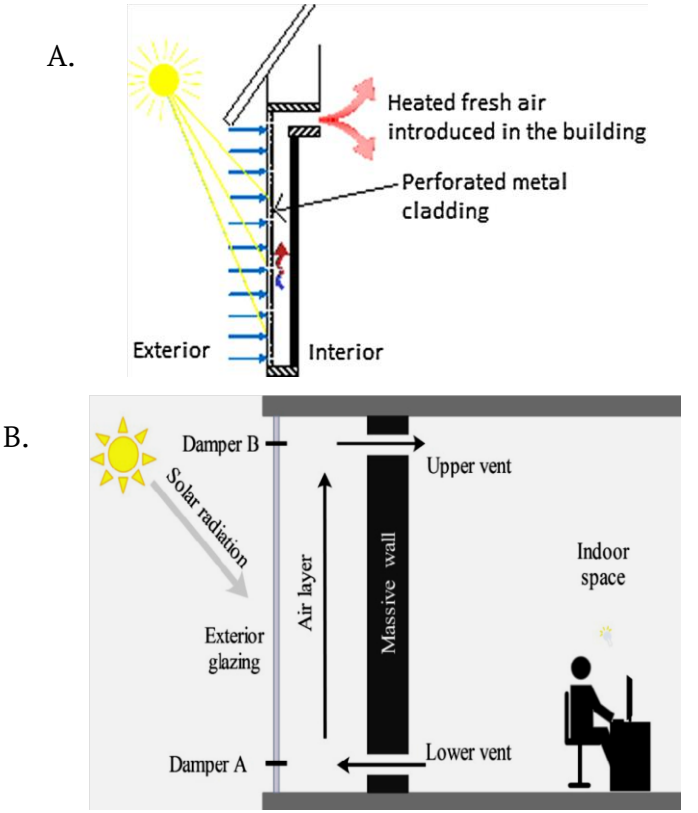


Fig. 3. 4. A. Opaque solar collector [22], and B. Solar glazed solar collector model [23]

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. 3. 4b.

Meanwhile, as seen in Fig. 3. 4a, the unglazed transpired solar collector principle is when the sun's radiation heats the perforated metal cladding, 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 [23], such as in Canada, US and Europe [24]. When direct outdoor air heating is desired, this technique is recommended to be applied due to high efficiency un to 72% [25].

5. 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 [26]. 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 [27]. The type of concentrator is also an important parameter on the overall system efficiency. For instance, Hussain et al. [8] 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. 3. 5). 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. 3. 6).

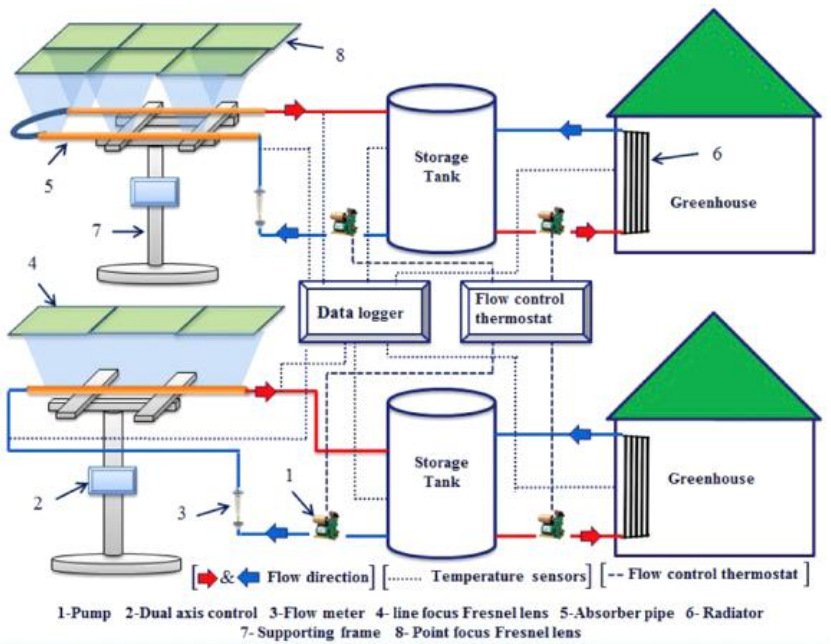


Fig. 3. 5. Schematic diagram for SFL and LFL collectors [8]

The use of solar tracker on the solar collector is very beneficial to increase the efficiency of solar collectors, although only one axis [28], [29]. Solar tracking application in greenhouses can maximize the solar radiation directly, especially if it has dual-axis tracker [8]. In addition to its small size, heat loss from the Fresnel lens

concentrator is also small [30] so it seems suitable to apply it in greenhouses in cold climate.

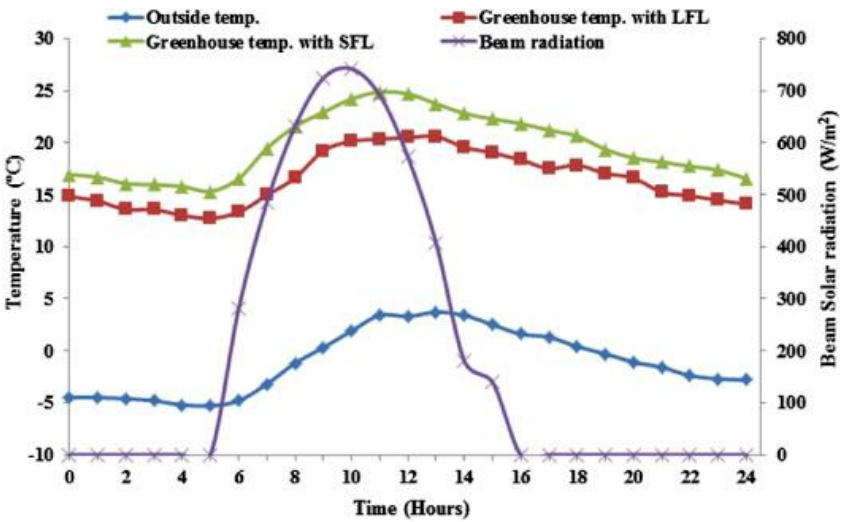


Fig. 3. 6. Daily temperature variation and solar radiation [8]

Reference [31] 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.

6. An overview on greenhouse solar thermal collectors

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 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 potential to be applied for temperate climate. Even though, concentrating collectors are more suitable for greenhouse heating [32] 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 [33].

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 [34]. 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 [30]. 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 [8], [35], [36].

Furthermore, Fresnel lenses can also be integrated with PVT modules for thermal and electric power generation, whereas for lighting the vegetable crops use the separated diffuse solar radiation [31]. 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 [26]. In terms of energy and price, Fresnel lens collector are

cheaper and better compared with those of a parabolic trough collector [37]. 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 [27].

7. References

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Chapter 4

Thermal Energy Storage Integrated Greenhouse System

1. Introduction

Benli [1] examines the performance of a ground-source heat pump (GSHP) greenhouse heating system integrated with a horizontal closed-loop ground heat exchanger and phase change materials (PCM) for energy conservation and greenhouse management. This method yields an overall Coefficient of Performance (COP) of 2–3.5, which is observable. It is also noted that an additional heat source may be required during sudden temperature drops and freezing temperatures.

Therefore, Esen et al. [2] investigate experimentally greenhouse heating by biogas, solar, and geothermal energy. Consequently, 2,231.83 l of biogas could be produced to maintain a greenhouse temperature of 23 degrees Celsius during the winter. Bouadila et al. report that solar air collectors with PCM assistance are a common technology in the Mediterranean region [3]. The nighttime heat recovery of the solar system meets 31% of the total heating requirements at 12 degrees Celsius.

When integrated with PCM, these kinds of systems become much more cost-effective and efficient. The annual energy gain is 1,800 kWh, and the payback period is approximately five years. Iraq also

utilised a similar system for heating [4], and the results indicate that solar air heaters provide more than sixty percent of the heating load.

Consistent microclimate must be maintained in a greenhouse to sustain the natural environment of plantations. This consistency is difficult to achieve in many regions without the use of technology. In order to maintain the stability of temperature, humidity, and lighting in a greenhouse, technology that provides both heat and cold must be utilised.

Likewise, electricity is required to maintain the humidity and artificial lighting, particularly at night. Therefore, various combinations of technologies, including heat storage, have been implemented. The following technologies are derivatives of heat source collectors used for thermal energy storage and greenhouse cooling.

The efficiency of thermal heat storage is strongly influenced by the storage material and container employed. Researchers have used a variety of heat storage materials, including gaseous substances like air [3]–[5], liquid substances like water [6]–[9], and solid substances like Phase Change Material (PCM) [1], [10], [11]. To maintain the thermal energy content throughout the day and night, thermal energy storage that is adequately insulated is essential. Consequently, the storage typically employs a tank with a heat insulator or a pipe buried in the ground [1], [12], [13].

2. PCM for thermal energy storage

Since the 1980s, PCM has been used as a thermal energy storage material and is considered one of the most promising thermal

energy storages. Solar air heater combined with PCM is capable of providing 18-23 percent or 3-4 hours of daily thermal energy to the greenhouse. $CaCl_26H_2O$, $Na_2SO_210H_2O$, Polyethylene glycol (PEG), and paraffin are the most common PCMs [11]. Benli reported that by utilising calcium chloride hexahydrate type PCM in Greenhouse with 30m^2 ground area (Fig. 4. 1) in Turkey, the overall COP system could be controlled between 2.0 and 3.5 [1].

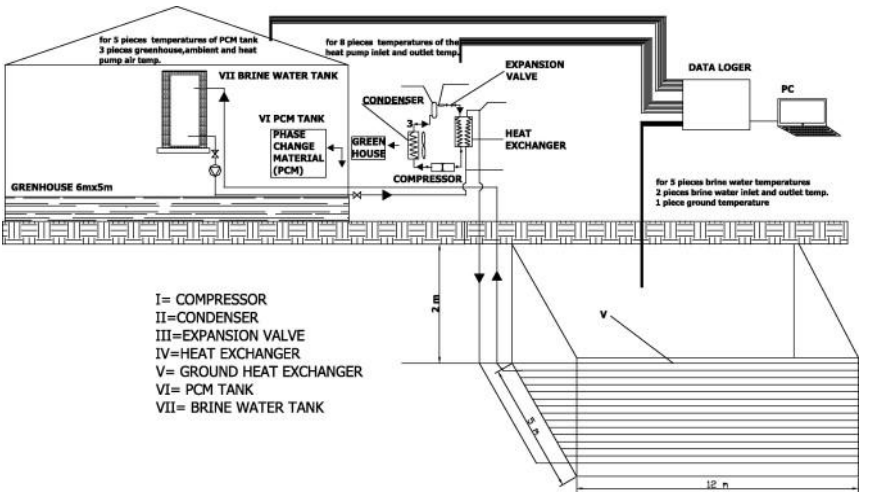


Fig. 4. 1. The primary component of the GSHP, including the PCM and schematic [1]

Moreover, PCM is used as a thermal energy storage to maintain the interior temperature of a greenhouse at 15 °C at night when the ambient temperature is 13 °C, as shown in Fig. 4. 2 [5]. This tomato greenhouse has shutters to reduce heat loss at night and raise the room temperature by 2 degrees Celsius compared to a greenhouse without shutters. PCM commonly used along with solar heat collector as shown in Table 4. 1 and characteristics is shown in Table 4. 2.

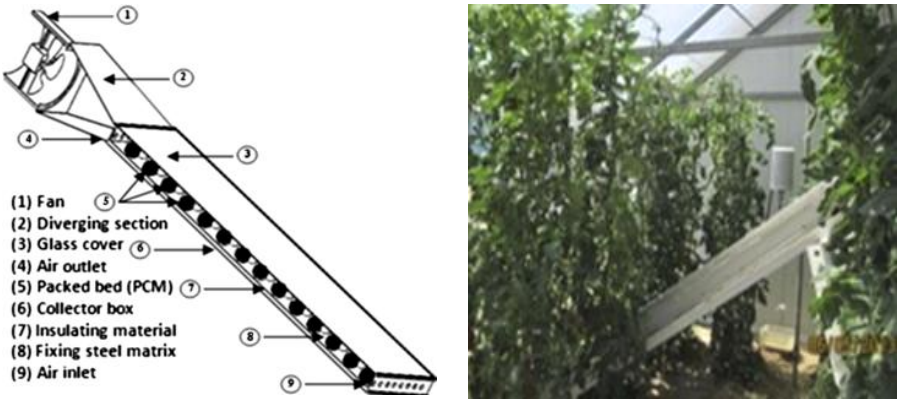


Fig. 4. 2. Schematic depiction of the SAHLSC and its location within the greenhouse [5]

Table 4. 1. PCM utilisation with other greenhouse heat collectors

Countries	Demand		Combination Technology	Ref.
	Heating	Cooling		
Turkey	18–23% of total heating for 3-4h, DT=6-9 °C	-	solar air collectors	[11]
Turkey	1.7kW, 18.6 °C for 7h	-	ground-source heat pump	[1]
Tunisia	13.7 MJ, 12°C for 10h, 31% of total heating	-	solar air collectors	[3]
Tunisia	123W, 15°C for 17h from 13°C	-	solar air collectors	[5]

Table 4. 2. PCM Thermal Properties [5].

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

3. Storage of thermal energy in the soil

In addition to PCM in the storage tank, the ground has its own unique property that allows it to store thermal energy throughout the year in a stable manner. Numerous researchers have utilised the ground as a heat exchanger or heat sink in an effort to reduce the greenhouse's temperature. In addition, as shown in Table 4. 3, the ground has the potential to store thermal energy generated by a solar collector [14], [15] and other active cooling [16], [17].

As a result of its low energy consumption and environmental friendliness, the ground heat exchanger is widely used in tropical nations with a high demand for cooling. In Thailand, for example, the greenhouse's cooling system is a horizontal earth tube system (HETS). A 38.5-meter-long iron pipe is buried approximately 1 metre deep with a centrifugal blower to blow air on the shaded north side of the greenhouse. As a result, the COP during the summer, monsoon, and winter are respectively 3.56, 2.04, and 0.77. It has been determined that the summer cooling efficiency is approximately 74.84 percent [16].

In addition, Xu et al. [18] have successfully utilised the earth as a thermal energy storage location in the U-tube heat exchanger.

According to reports, the winter heating of a 2,304-square-meter greenhouse in China could be provided by 500-square-meter solar collectors. The total amount of energy produced was 331.9 GJ, of which 208 GJ was used for greenhouse space heating (Fig. 4. 3). The electrical coefficient of performance (ECOP) system is estimated to have a value of 8.7, which is superior to conventional heat pump heating systems.

Table 4. 3. Storage underground for Greenhouse

Countries	Demand		Combination Technology	Area (m^2)	Ref.
	Heating	Cooling			
China	208.9 GJ	-	solar water collectors	2304	[18]
China	$4.60 \cdot 10^7$ kJ	-	solar water collectors	231	[15]
Thailand	-	COP: 0.77–3.56	Blower fan	15	[12], [16]
Turkey	-	$\dot{Q}_r$= 4.74kW	Fan and PV	48.51	[17]
India	11.55MJ	18.87MJ	Fan	34.32	[19]

Fig. 4. 3 depicts the major components of a solar heating system equipped with a seasonal thermal energy storage system in a greenhouse. This seasonal thermal energy storage is comprised of a vacuum tube solar collector array, water tanks, a borehole thermal energy storage (BTES) unit, and a heat distribution pipe. Table 4. 4 displays the system's equipment specifications.

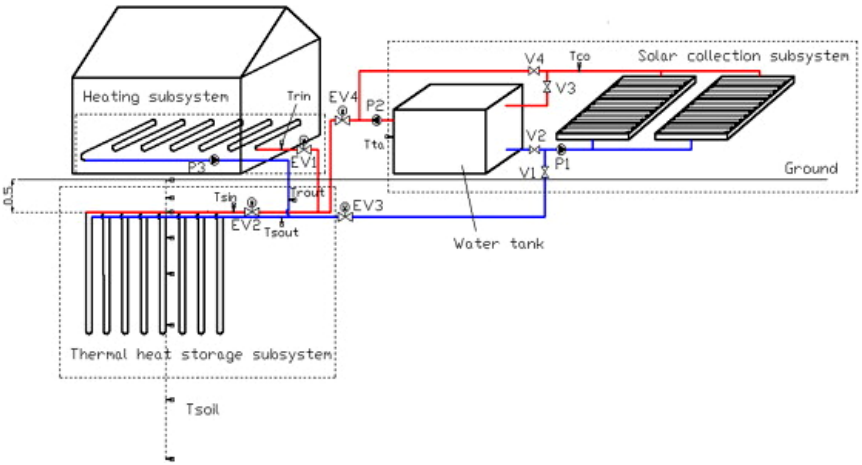


Fig. 4. 3. Solar heating system diagram in schematic [18]

Table 4. 4. Detail of the Solar Heating System's Design [18]

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 thermal energy storage are intended to be directly beneath the greenhouse, approximately 10 metres below the surface of the ground. The total volume of soil is 4,979 m^3, and 130 UHX (U-type heat exchanger) pipes are planted vertically and parallel to a depth of 10 m. It is not insulated between the UHX pipes so that the

surrounding ground can be heated by conduction. The surface is partially covered with concrete at ground level. The thermal heat storage unit's heat is transferred to a heat exchange tube, which is placed on shelves above the ground and distributes heat into the greenhouse through convection and radiation. As shown in Fig. 4. 4, in addition to space heating, heat from the thermal heat storage beneath the ground is also distributed in the greenhouse's floor.

Fig. 4. 4 demonstrates that the temperature of borehole thermal energy storage (BTES) varies with different ground depth measurements used to store seasonal heat energy. It appears that the temperature change will be more sensitive to the ambient temperature in the more superficial layers of the ground. Using this system, the interior temperature of the greenhouse can be maintained between 13 and 15 degrees Celsius throughout the winter.

Other researcher [15] conducts simulations using TRNSYS and designs a solar seasonal storage solar soil (SSSHS) system to heat greenhouse. As depicted in Fig. 4. 5, the system consists of an underground U-pipe connected to a solar collector, while the greenhouse heating diffuser consists of capillary radiators. Using the design parameter calculated in Table 4. 5, the thermal energy dissipated into the groundwater storage tank is 92.8% and the annual energy loss is 12.7%. There is a significant difference in soil temperature when heat storage is utilised versus when it is not (Fig. 4. 6).

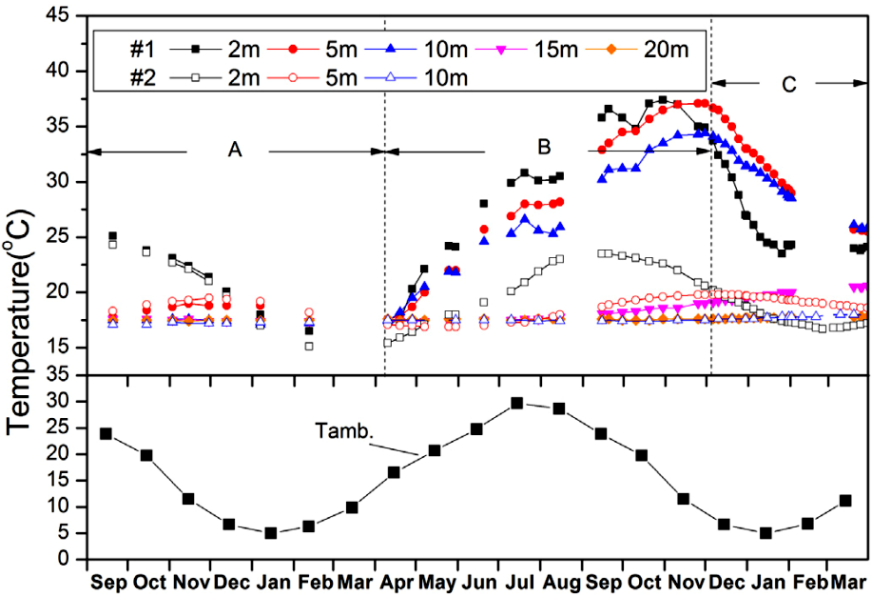


Fig. 4. 4. Temperature change in the underground storage facility: A – Before charging; B – Charging process; C – Discharging process [18].

In addition, the wintertime greenhouse temperature could be maintained at 12 degrees Celsius. However, justification required load heating of the greenhouse is crucial for achieving the precise and optimal balance between temperature requirements and employed technology. The load heating must be less than the amount of heat received or absorbed by the solar collectors, heat stored in the ground, and heat loss through the ground.

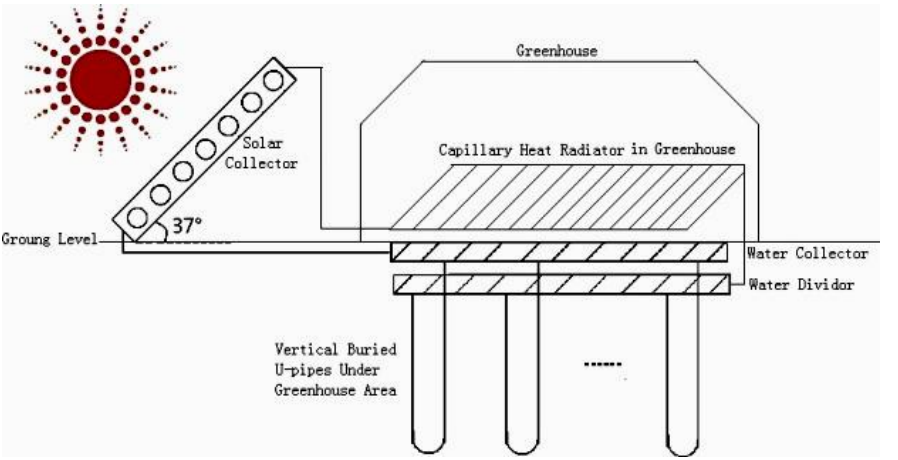


Fig. 4. 5. Schematic of the solar seasonal soil heat storage system [15]

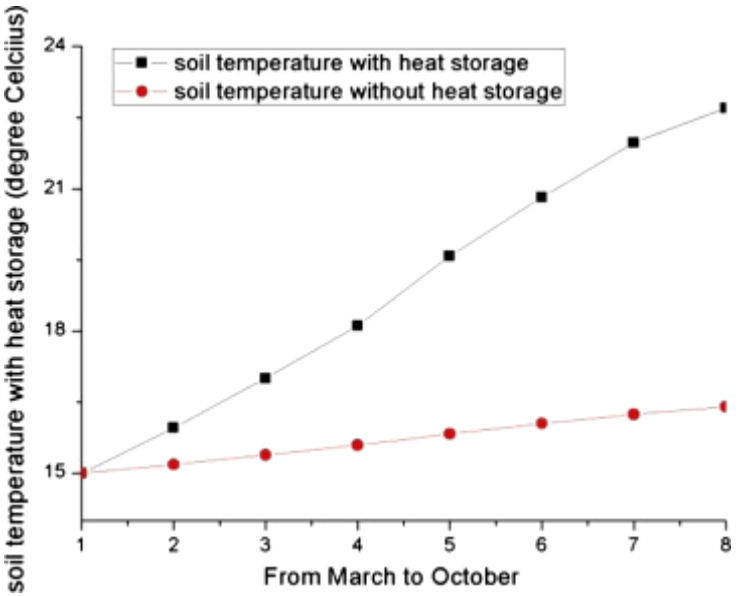


Fig. 4. 6. Comparison of soil temperature without heat storage and with heat storage [15].

Table 4. 5. Experiment-specific System Parameters [15]

Spesification	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

4. Solar air heaters in thermal energy storage

Solar air heaters-aided PCM are widely used and have demonstrated the ability to maintain the greenhouse temperature at 15 °C in Tunisia [3]. Additionally, this system can meet 31% of the nighttime heating demand. This result is in good agreement with Kooli et al. [5] in that the system increases the overall system's effectiveness to maintain an indoor temperature of 15 °C when the temperature outside is 8 °C.

In tropical climates, air can also be used for cooling purposes in addition to providing thermal energy. Cooling with air and Horizontal earth tube system (HETS) was able to reduce the greenhouse temperature to the ambient conditions required by Dahlia and head lettuce plants, which require a temperature range of 10 to 24 degrees Celsius and a relative humidity range of 40 to 50 percent [12]. Increasing the wind velocity in HETS tubes improves the system's performance. The COP cooling for wind speeds of 9 m/s and 12 m/s was determined to be 1.91 and 2.87, respectively.

5. Solar water heaters in thermal energy storage

In addition to air, water is a well-known material that can be used to store thermal energy. Due to its fluidity, water is not easily converted into a hazardous compound, but it is corrosive to certain metals. Zhang et al. [15] use ordinary water as the heat conductor from the collector to the heat exchanger pipe. The hot water flows through the heat storage tank to the greenhouse's underfloor heating system. As depicted in Fig. 4. 5, the water in the tank serves as a buffer for the system to improve its overall performance.

6. An overview on thermal energy storage for greenhouse

The literature indicates that the use of ground heat storage is capable of regulating the greenhouse temperature so that it is suitable for the majority of plants. A soil-filled heat exchanger is assembled around the walls of a greenhouse (capillary buried heat exchanger). For instance, the system could keep the greenhouse temperature constant at 20 degrees Celsius [20]. It agrees with Xu et al. that by utilising ground thermal energy storage, the greenhouse

temperature can be maintained between 13 and 15 °C, even during the winter months [18]. The deeper the borehole to a certain depth, the more stable and unaffected by ambient temperature the ground temperature. This stability is advantageous as a source of stable heat for greenhouse heating. However, heat naturally dissipates due to the conduction process, so the annual heat loss from seasonal heat storage in the soil is approximately 12.7% [15]. Therefore, it is recommended to insulate land used as a heat reservoir in order to reduce heat loss.

In addition to greenhouse space heating, earth–air heat exchangers (EAHE) may be utilised for greenhouse cooling. Al-Ajmi et al. [21] demonstrate conclusively that the indoor temperature decreases by 2.80 degrees Celsius during summer peak hours. It is remarkable that greenhouses with EAHE have the potential to reduce cooling demand by 30 percent during the height of summer. Increasing the pipe's diameter rather than its length or depth will significantly improve the coefficient of performance [12].

Length and depth of the pipeline will cause a significant pressure drop along the pipeline and increase the blower's energy consumption. However, piping is costly in soil-based thermal energy storage systems. Consequently, by employing a conventional borehole method, this expense can be reduced. However, the injection method is only possible with a single pipe, necessitating innovation to replace the U-tube loop method.

7. References

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Chapter 5

Lighting Integrated Greenhouse System

1. Introduction

Since a greenhouse is designed to grow plants, it is customary to employ a cover that allows sunlight to pass through. Sunlight contains the photosynthetically active radiation (PAR) [1]–[3] required for photosynthesis [4]. Too much shade on the plant will significantly diminish the fruit's quality [5]. In addition to adequate ventilation, light transmission, construction cost, and low energy consumption, a quality greenhouse must also consider the following: sufficient ventilation, light transmission, construction cost, and low energy consumption [6].

Typically, vegetable and fruit plants have specific lighting; wavelength spectrum of 400-700 nm known as Photosynthetically Active Radiation (PAR) [3], [7], [8]; temperature [7], [9]; and humidity [7] requirements for optimal growth. For instance, Pepper (Piper) requires a temperature of approximately 20^{o}C [10]. The temperature ranges required by Orchid (*Dendrobiums*), Edamame (*Glycine max L.*), and Lemongrass (*Cymbopogon citratus*) are 18-30^{o}C, 20-25^{o}C, and 22-38^{o}C, respectively.

In addition, these plants require specific humidity levels between 30 and 90 percent in order to optimally grow and produce fruit [11]. In providing a good seedling environment in a greenhouse, lighting becomes one of the most important factors [12], [13]. However,

there are a number of plant species whose growth is not significantly affected by excessive sunlight, such as Lulo or Naranjilla fruit (*Solanum quitoense Lam.*) and Panax ginseng [14]. In this regard, research on the efficacy of lamp types and wavelength of light emitted by artificial lighting in greenhouses is crucial [15]–[17].

It is already known that sunlight provides the optimal lighting for crops. Sunlight is essential for photosynthesis in greenhouse-grown plants. For photosynthesis, plants absorb sunlight, particularly wavelengths of visible light [17], [18]. Given the significance of lighting to the overall yield of vegetables and fruits in greenhouse agriculture, a number of studies are conducted [16], [19]–[21].

Therefore, in terms of visible light transmittance, the facade material of greenhouses is crucial for providing natural light. Some recommended cladding materials, including glass, polycarbonate (twin wall), polyethylene (single layer), and acrylic, have PAR transmission rates of 90%, 75%, 88%, and 86%, respectively [22].

2. Sodium lamps

In greenhouses, High Pressure Sodium (HPS) lamps are commonly used to prevent ornamental plants from flowering. *Chrysanthemum*, *pot chrysanthemum*, and *velvet sage* [23] respond positively to HPS lighting. Such a lamp is easily manipulated to determine the flowering time of plants for efficient market adaptation.

Kim et al. investigate *Cymbidium orchids* grown under different intensities of night interruption lighting [24]. Low-intensity HPS light bulbs increase the photosynthesis activity of plants, according to the researchers. However, the quantity of chlorophyll in its leaves

decreases with prolonged exposure. To preserve the quality of the flowers, it is necessary to combine the use of HPS lamps for artificial lighting with good fertiliser.

Wojciechowska et al. [25] compare the impact 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*) grown in a greenhouse in Poland during the winter season. In 2012/13, relative humidity and temperature in the greenhouse environment were measured as 58 ± 2%, ± 17 °C, and 54 ± 2%, ± 16.3 °C, respectively. The average CO_2 concentration ranges between 380 and 400 parts per million.

Tabel 5. 1 demonstrates that exposure to 90R / 10B LED lamps results in the highest growth and quality, whereas HPS lamp exposure results in the lowest growth (control).

Tabel 5. 1. Average plant height in cm [25]

	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

In Fig. 5. 1 are depicted the spectral characteristics of the test lamps in the research. Control (HPS), 100R (100 percent red LED), 50R/50B, 70R/30B, 90R/10B (various percentages of red (R) and blue (B) LED), and white LED are the light treatments used in this experiment.

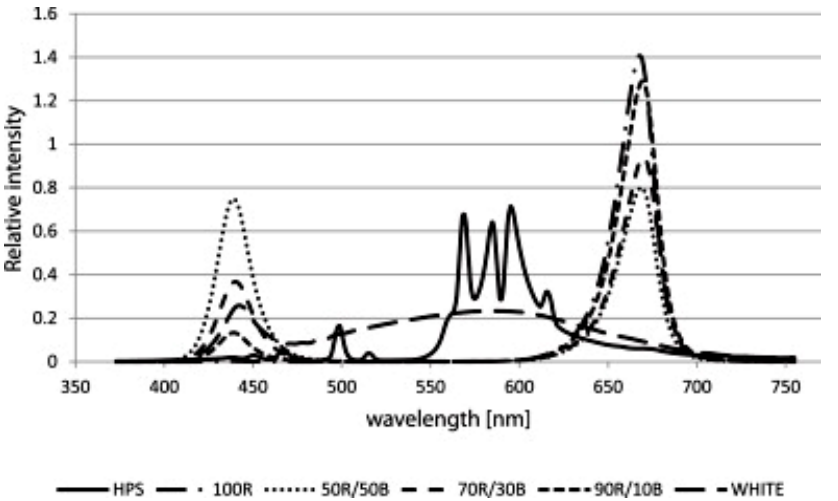


Fig. 5. 1. Spectral characteristics of lamps used in greenhouse production of lamb's lettuce [25]

3. LED

The most effective and efficient alternative lighting technology used in greenhouses is Light Emitting Diode (LED). They do not generate an excessive amount of heat, so they are extremely long-lasting, have monochromatic colours at specific wavelengths, and are inexpensive [26]. LED emits a specific wavelength that satisfies the PAR requirements for photosynthesis [16]. Therefore, LED is capable of having a positive effect on plant growth, thereby increasing crop yield and quality.

The wavelength of blue (448 nm), red (634 and 661 nm), or a combination of blue and red (3:7) has the greatest influence on the growth of plants [17], [25], [27]. Fig. 5. 2 depicts wavelengths with a total photon flux of 100 mol $m^{-2} s^{-1}$ in any light source. LEDs enhance plant growth more than artificial light sources [25], [28].

For example, red leaf lettuce prefers green LED over white fluorescent lighting (FL) [29].

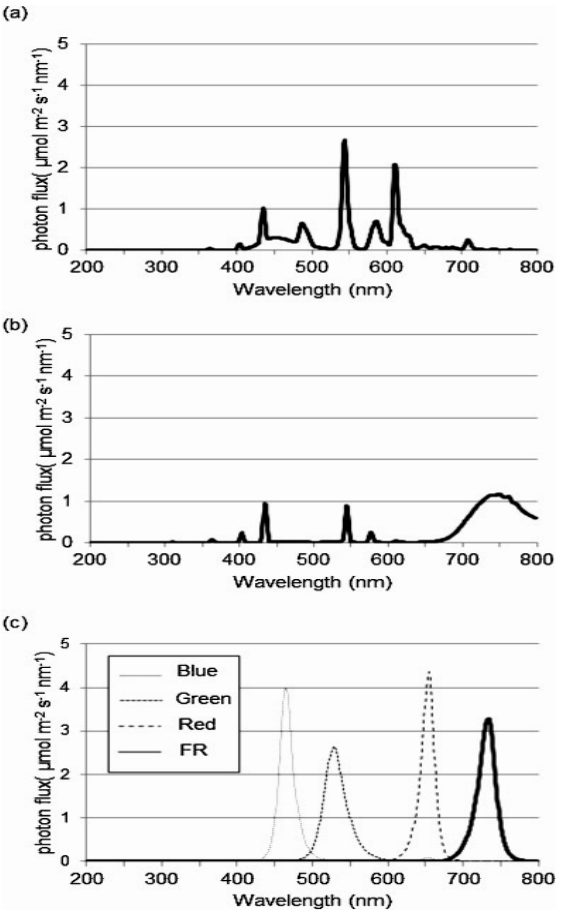


Fig. 5. 2. Photon flux distributions based on (a) White-FL; (b) FR-FL; (c) LEDs [27]

However, for certain plants, another type of lamp, such as a fluorescence lamp, is more effective than LED. As shown in Fig. 5. 3 for instance, sprouts [27] exhibit the quickest growth under fluorescent lamps emitting a far-red spectrum. The figures depict

(a) and (b) sprouts grown under white fluorescent lighting for four days prior to far-red irradiation, (c) irradiation with far-red fluorescent from above and white fluorescent lighting from the side for two days, (d) irradiation with white fluorescent from above and far-red LED from the side for two days, (e) and (f) irradiation with far-red fluorescent from above for two days. In terms of durability and cost-effectiveness, LED has advantages [18].

LED uses very small energy therefore the growers could maximise the crops and benefits [26]. LEDs' lifetime shown in Fig. 5. 4 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. Moreover, retrofitting a greenhouse with LEDs can provide energy-efficient lighting that costs up to 75 percent less per year than other artificial lights [30]. Fig. 5. 4 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. Tabel 5. 2 depicts the comparison effect of artificial light source to plantation.

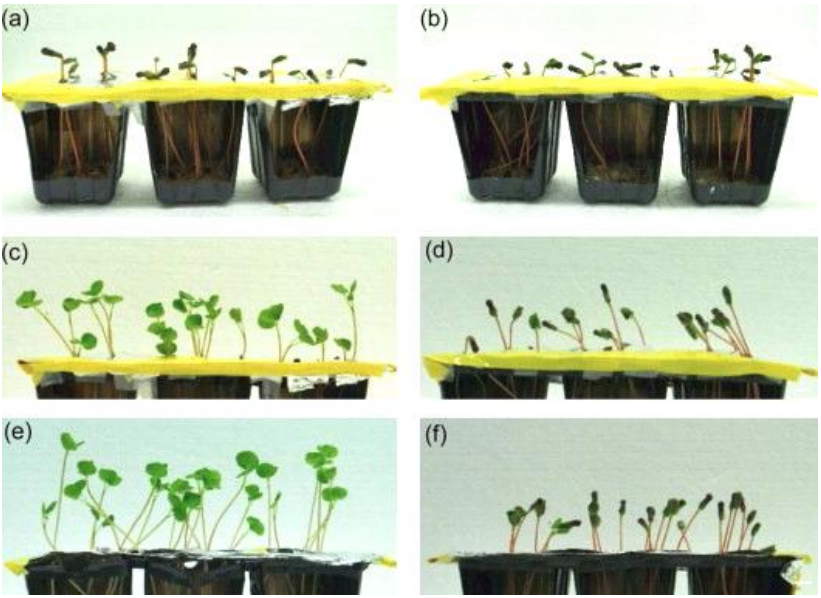


Fig. 5. 3. The effect of far-red irradiation on sprout organs on cotyledon emergence [27]

Tabel 5. 2. The effectiveness of artificial light sources on plant growth

Ref.	Lamps	Plants	Note
[27]	fluorescent	Sprouts	-
[29]	green LED	red leaf lettuce (*Lactuca sativa L.*)	in comparison to white LED
[25]	90R/10B	lamb's Lettuce (*Valerianella Locusta*)	-
[24]	low-intensity of HPS	Cymbidium hybrids 'Red Fire' and 'Yokihi'	The amount of chlorophyll decreases when plants are exposed to an HPS lamp for too long

[21]	HPS Plantastar 400 W	Tomato	-
[31]	RB20 (red/blue : 8/2)	Gynura bicolor DC (*Asteraceae, perennial herb*)	Examine the essential oil profile and accumulation of terpenes.

4. An overview on lighting for greenhouse

As previously stated, crops require sufficient light of a specific wavelength for photosynthesis. As long as there is sufficient light, plants will produce their own food and continue to grow regardless of the time [17], [25], [26], [31], [32] In this regard, in order to achieve sustainable harvesting and high quality, a greenhouse must employ the most effective and energy-efficient daily practises.

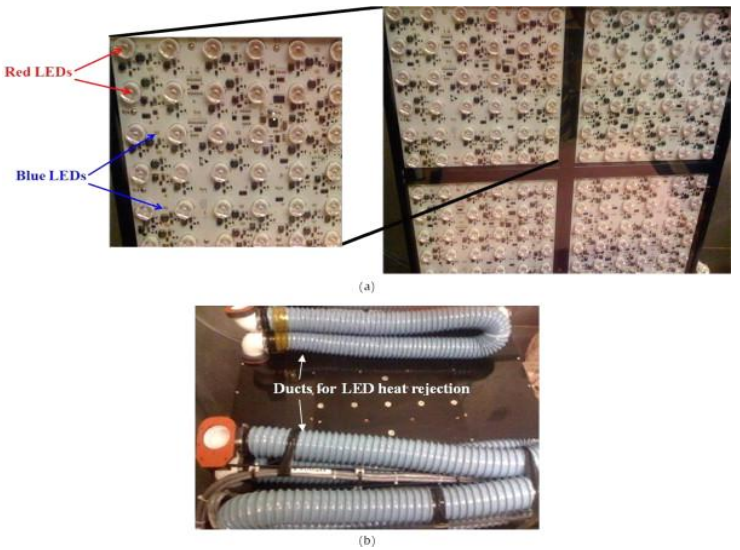


Fig. 5. 4. LED array available for purchase [26]

LEDs can reduce annual lighting-related energy consumption by up to 75 percent compared to HPS. LEDs have three colours (red, blue, and green) that are typically used in greenhouses because they positively affect plant growth [18] and have an exceptionally long lifetime [33]. In addition to its colour, it has been shown that a plant's growth rate is also affected by its intensity. Therefore, it is necessary to ensure that the LEDs provide sufficient light intensity by adjusting the distance between lamps and leaves.

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Chapter 6

Insulation Integrated Greenhouse System

1. Introduction

The greatest heat loss in a building occurs at the window, as well as in a greenhouse; even worse, it occurs in all wall and roof components [1]–[5]. Almost all greenhouses employ plastic or glass with high power transmission but a low overall heat transfer coefficient [6]. Therefore, forty percent of a building's total energy consumption is for heating [7]. From this perspective, insulation for greenhouse facades is crucial for cost and energy management.

Consequently, polycarbonate sheet is favoured for installation in the majority of existing greenhouses due to its energy efficiency and high sunlight transmittance [8]. Polycarbonate is lighter, less expensive, has the highest fire rating among plastic products, and has superior insulating properties compared to other materials commonly used for greenhouse construction. These factors result in energy-efficient, simple, and safe agricultural structures. Moreover, polycarbonate twin wall types with low thermal transmittance, as shown in Table 6. 1, are more energy-efficient.

The effectiveness of insulation is crucial for storing energy for an extended period of time [9]–[13]. In this regard, selecting the best glazing products for energy-efficient and environmentally friendly greenhouse applications is crucial.

Table 6. 1.. optical and thermal properties of panels and a sample of double glazing units [14]

	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. Glazing

As previously stated, a greenhouse's facade plays a significant role in minimising heat loss. Many types of glazing can be used for this purpose, those with a lower U-value reducing heat loss more effectively, as illustrated in Table 6. 2. A hybrid vacuum glazing with an air gap and low-e coating has also been developed as a result of an improvement. As shown in Fig. 6. 1, the U-value for the sample with three low-e coatings [15] reaches 0.24 W/m^{2}K. According to another study on vacuum glazing [16], the U-value of vacuum tube windows can fall below 0.40 W/m^{2}K. Fig. 6. 2 depicts the schematic of the aforementioned window technology for vacuum tubes.

In addition to this innovative glazing, the heat insulation solar glass (HISG) depicted in Fig. 6. 3 can be considered. This modern technology allowed the technology to reduce the noticeable heat loss. Additionally, it is self-cleaning and can generate electricity for energy conservation. Due to the nanolayer TiO_2 coating, heat-insulating solar glass could generate more electricity than conventional PV glazing, according to a study. Typical PV power output is approximately 34.1W, whereas heat-insulating solar glass

produces approximately 36.6W. In addition, HISG offers numerous advantages in terms of optical properties, as shown in Table 6. 3.

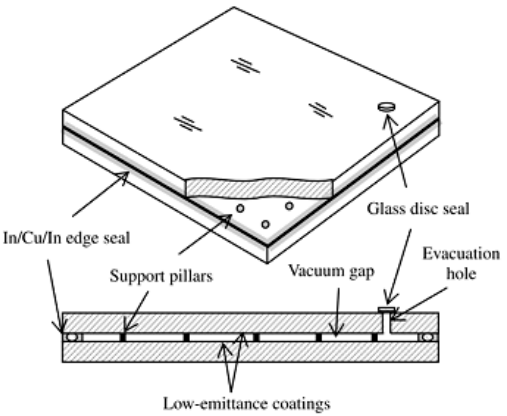


Fig. 6. 1. Cross-sectional diagram of double pane evacuated glazing [17]

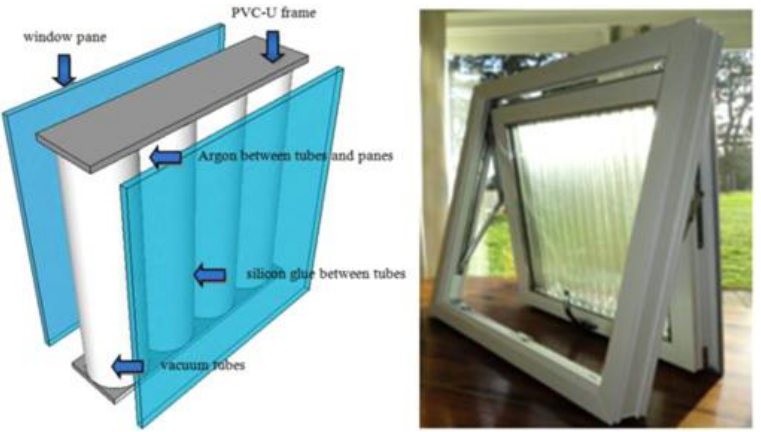


Fig. 6. 2. Diagram of the vacuum tube window and the developed sample [18]

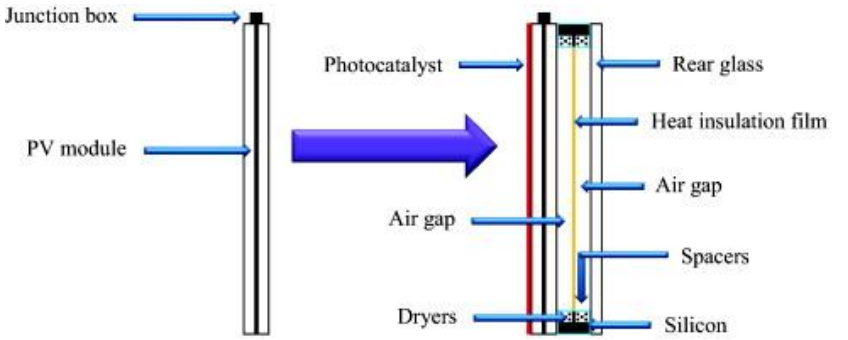


Fig. 6. 3. HISG cross-sectional view [19]

Table 6. 2. Thermal performance comparison of various types of glazing systems [6]

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 6. 3. The optical and thermal characteristics of common glass and HISG curtain walls [19]

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^2K))	5.97	1.10
Shading coefficient	0.87	0.144

3. An overview on thermal insulation for greenhouse

Due to inadequate thermal insulation, the greenhouse heating load is significantly greater than that of other types of structures. The covers of commercial glasshouses are made of plastic or a single pane of glass [3], [4]. Consequently, the application of suitable insulation materials to walls and roofs is a crucial issue that must be addressed.

In comparison to other types of plastics, polycarbonate may be the best option for greenhouse facades. Polycarbonate has a low U-value range, is durable, lightweight, and complies with European energy efficiency regulations. Moreover, it is inexpensive and simple to install, and its solar factor is comparable to that of other glazing products [14]. In Italy, Low-E solar glazing costs between 50 and 80 euros per square metre, while polycarbonate panels cost between 25 and 35 euros per square metre.

Another option for facade materials is solar glass with heat insulation. In addition to its ability to prevent heat loss, it can generate electricity and clean itself thanks to a special coating. The

U-value is also very competitive with triple-glazed Argon-filled low-e windows. In addition, its current manufacturing cost of approximately 250 euros per square metre will be reduced when produced in mass quantities. In this regard, heat-insulating solar glass can play a significant role in reducing greenhouses' heating and cooling needs in any climate zone [16].

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Chapter 7

Control System and Greenhouse Concept

1. Introduction

Manually controlling a greenhouse system's humidity, temperature, lighting, and CO_2 levels may appear simple, but it is actually quite complicated; therefore, an automatic control system is more cost-effective and worthwhile. Utilizing adaptive climate control, integrating control algorithms, installing an insulating cover, and employing optimal energy management techniques can result in a greenhouse with a low energy demand [1].

A system that controls soil moisture, temperature, and humidity in a greenhouse has many advantages. Comparatively, manually operated systems are likely to have many disadvantages, in addition to being expensive and providing inaccurate control. Consequently, control systems that take advantage of the declining cost and size of sensors have been employed to automate systems that have the potential to increase the efficiency and yield of greenhouses; such systems have already been implemented in Kenya [2].

It has been stated that energy savings by greenhouses in northern climates (achieved through passive technology such as a closed concept and double glazing) could provide up to fifty percent of the total energy demand [3]. These passive technologies have been described as the most innovative and promising heating-cooling technologies for both northern and tropical nations.

2. Control System

Utilizing an insulating cover, adaptive climate control, integrating control algorithms, and optimal energy management can reduce the greenhouse's energy demand [1]. A system that controls the soil moisture, temperature, and humidity of a greenhouse automatically has numerous advantages [4]. Manual operation will result in significant losses, high costs, and inaccurate control. Therefore, control systems play a significant role in reducing greenhouses' costs and improving their productivity and yield quality in Kenya [5]. This type of remote control strategy has been shown to significantly increase productivity and decrease labour requirements.

In addition, the use of a solar tracker on a solar collector is highly advantageous for increasing the efficiency of solar collectors used in greenhouses [6], [7]. Solar tracking application in greenhouses will directly maximise solar radiation, thereby enhancing performance [8]. In addition, its tracker system requires less than 2% of the total electrical energy per m^2 per year [7].

Liu and Ying used Bluetooth technology to monitor and control the greenhouse's microclimate [9]. A sensor network collects and transmits the greenhouse's environment data to a central control system. Zhou et al. use an open source control system to simultaneously maintain the greenhouse's temperature and humidity, soil water content, and carbon dioxide concentration [10]. ZigBee technology with Bluetooth and wireless is used for communication.

In addition, the control system could store the data in a database that can be used for future enhancements. In addition, it possesses

low complexity, low power consumption, low data rate, low cost, and ad hoc networks [11]. Fig. 7. 1 depicts the implementation of a ZigBee multi-powered wireless data acquisition network.

Utilizing a wireless protocol to control the microclimate of a greenhouse has many more advantages than using a conventional protocol. In terms of efficiency, wireless transmission reduces and simplifies wiring and maintenance significantly [12]. Thus, it can reduce operational costs and save money very efficiently. Additionally, wireless control systems can be monitored remotely via the internet. Therefore, it is likely that a greenhouse wireless control system will be implemented in the near future.

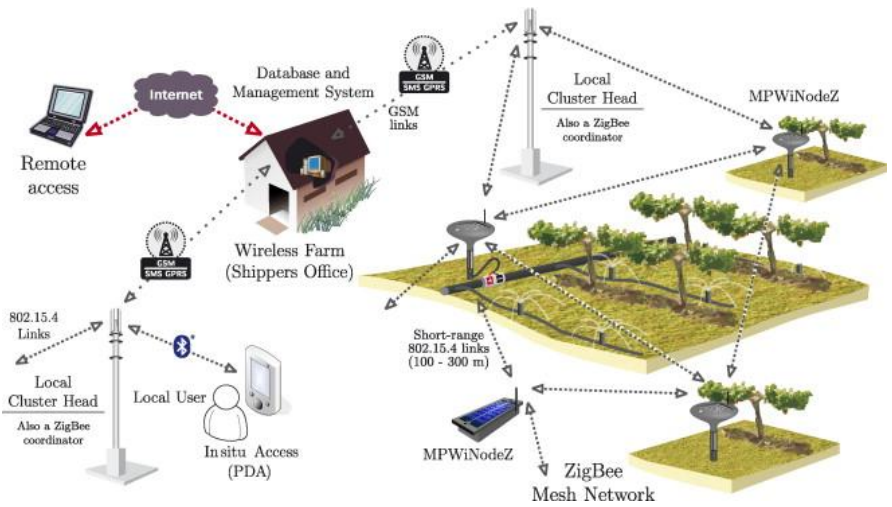


Fig. 7. 1. Implementation of a field data acquisition network using a ZigBee network of MPWiNodeZ devices [11]

3. Concept Opening System of Greenhouse

The concept of a closed greenhouse is characterised by the absence of a ventilation window, and the sensible and latent heat surplus is

harvested and stored for later use in meeting the greenhouse's heating demand (Fig. 7. 2). In addition, a closed greenhouse system may be superior to the others [13]. Since on areas with high solar radiation, a substantial amount of excess heat will be stored.

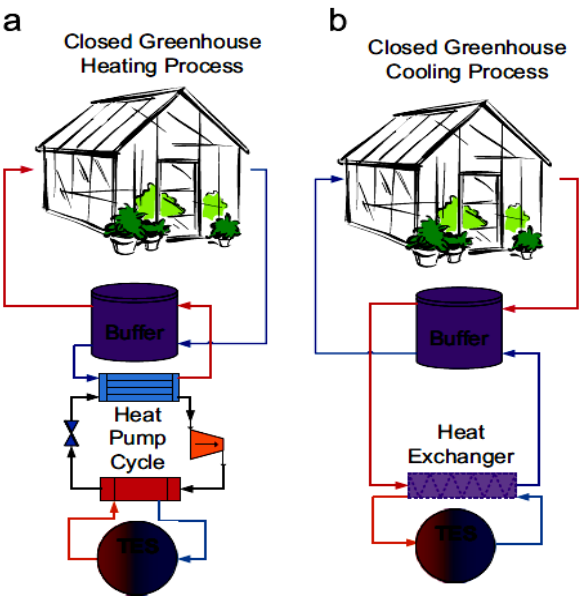


Fig. 7. 2. a. Heating, and b. Cooling in closed-concept greenhouse opening [13]

Opdam et al. demonstrate that this concept can decrease energy consumption by 20 percent and increase energy efficiency by 50 percent [14]. In addition, in 2006, the concept can collect 80 percent of incident solar radiation or 2.5 HJ/m2y in northern Europe [15]. Vadiee and Martin also claim that by utilising TRNSYS, the payback period for the ideal closed greenhouse could be halved [16].

In a separate study, they use TRNSYS simulation to evaluate the possibility of reducing external energy demand and maximising

solar energy utilisation in a commercial greenhouse under Northern climate conditions. The results indicate that a solar blind system employing glazing Polycarbonate with a thermal screen and a closed concept could reduce the heating and cooling energy demand by 80% and 60%, respectively, when compared to the conventional system [17].

The most expensive retrofitting option is to install a double-layer thermal screen with a 5-year PBP. Utilizing "Double polyethylene" (6 months PBP) and "Double ply IRAC" are low-cost alternatives (10 months PBP). In contrast, the concept of a closed greenhouse offers the greatest improvement (80 percent), with a potential payback of 5–6 years under favourable conditions.

In addition, Fig. 7. 3 displays the net energy reduction resulting from energy performance improvement opportunities. It demonstrates that the concept of a closed greenhouse with double glazing has the greatest impact (50 percent), while double thermal screens account for nearly 40 percent [18]. The results suggest that a closed concept can be used to produce tomatoes in a sustainable manner, where water use and energy use efficiency can be improved by 71% and 43%, respectively, compared to existing greenhouse systems [19].

In spite of the fact that fully closed greenhouses can capture more solar thermal energy, semi-closed greenhouses are more practical [13]. Since the greenhouse must deal with fresh air as a rapid response for humidity control, it must be ventilated frequently. In addition, there is no ventilation in a fully closed concept, which necessitates the removal of excess sensible and latent heat in subtropical climates [20]. Thus, cooling and humidity present difficulties in a closed-concept greenhouse [21].

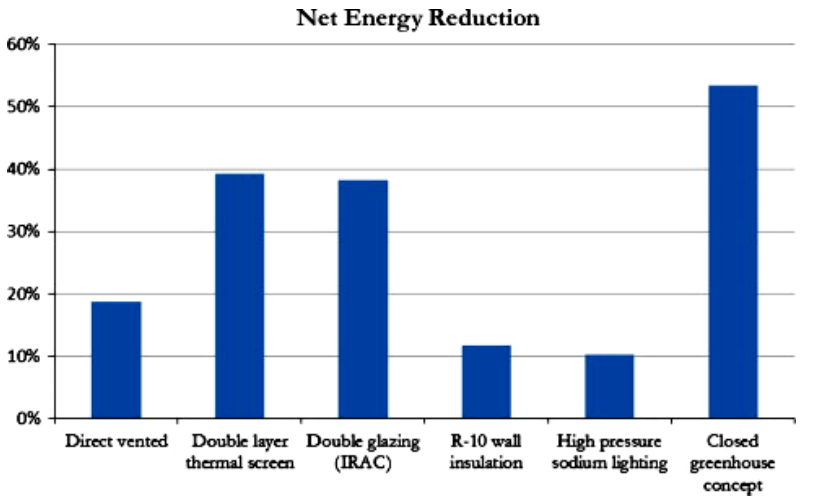


Fig. 7. 3. Energy efficiency improvement in a commercial greenhouse [18]

Table 7. 1 displays the advantages of three greenhouse design concepts. A partially closed greenhouse is one in which the excess heat energy from the closed greenhouse portion is also used to heat the open greenhouse portion. The semi-closed greenhouse, meanwhile, is a nearly closed greenhouse with open ventilation windows supplying a portion of the cooling demand.

Table 7. 1. Experimental report comparing opening concept system to experimental report [13]

	Closed	Semi-closed	Partly-closed
Benefits	- can provide heat for itself and nearby buildings - 17 percent higher yield and 30 percent	- 30–45% CO_2 emission reduced	- 50 percent improvement in energy efficiency; - 20 percent increase in

	reduction in fossil fuel use - Increase production yield by up to twenty percent while reducing total primary energy demand by thirty to forty percent [14]	production; - 50 percent reduction in water consumption
Weaknesses	25% greater annual capital expenditures than conventional	

4. An overview on System Control and Concept for greenhouse

Greenhouses with automatic control systems would produce a consistent and cost-effective microclimate, thereby ensuring the yield's quality and quantity. In northern climates, double glazing polycarbonate in conjunction with a thermal screen and a closed greenhouse concept can reduce the heating demand by 80% and the cooling demand by 60% respectively.

In addition, natural ventilation/wind catchers on the roof (semi-closed concept) may significantly reduce the temperature in a greenhouse due to the fact that daytime heat in a closed greenhouse can be excessive. Therefore, the semi-closed concept is more applicable to climates in the Mediterranean and sub-/tropical regions.

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Chapter 8

Conclusion and challenges of technologies in Greenhouse

1. Introduction

Greenhouses are specialised structures designed to provide a particular climate for the cultivation of particular plants. The vast majority of existing greenhouses are constructed with conventional materials and have facades that are as inexpensive as possible. In addition, they used traditional technology for heating, cooling, ventilation, and lighting, which resulted in high operational costs but was ineffective in achieving the ideal microclimate required by the crops.

In this regard, it is evident that novel greenhouses with innovative energy-efficient, inexpensive, and environmentally friendly solutions are required for growers to minimise expenses and maximise profits. Consequently, this review identifies a number of technologies that can be considered for enhancing the efficiency of existing greenhouse systems.

2. Conclusion and challenges

The following are examples of significant findings from this study:

- The most appropriate glazing for the facade and roof material is multifunctional, semi-transparent PV modules. As well as

transmitting sufficient natural sunlight, minimising heat loss, and generating electricity efficiently.

- To meet heating demand during the heating season, seasonal underground thermal energy storage and vertical ground heat exchanger can be used effectively. To reduce investment costs by employing the shallow-embedded method, an innovation in pipe design is necessary. In addition, polyethylene insulation can be used to prevent heat transfer to the soil and thereby reduce heat loss from storage facilities.
- Solar assisted heat pump systems can efficiently meet the heating and cooling needs of greenhouses. Typically, these systems have COP values greater than 3.0, which is very encouraging.
- Windcatcher is an ideal device for passively cooling a greenhouse in the summer and ventilating it at the same time. It is easily installed without electricity, which reduces the greenhouse's operating expenses.
- Vacuum tube windows are another promising glazing for greenhouse envelopes. It has a U-value of less than 0.40 W/m^2K to reduce greenhouse gas emissions and energy consumption.
- A combination of blue and red LED has proven to be an effective artificial light source for plants' photosynthesis throughout the day. These lighting devices are both affordable and promising in terms of energy efficiency.
- The use of PCM in conjunction with solar thermal collectors to increase the amount of heat energy saved, particularly for greenhouses in regions with extreme climatic conditions, has a significant impact on reducing the amount of energy used for heating.
- Automation system in greenhouse increases the effectiveness of microclimate-controlling devices demonstrably. With precision

control, it is possible to reduce labour costs, conserve energy, reduce human error, and shorten the payback period, among other advantages.

- Closed-concept increases energy efficiency, water efficiency, and yield production. A combination of closed and open concepts would be more adaptable for each season and would protect crops from excessive heat during the summer.
- The payback period for energy-efficient greenhouse systems ranges from four to eight years, based on the type of energy used and climate data.

The review suggests that the significant role of heating demand in greenhouses is primarily attributable to poor constructional characteristics and inadequate thermal resistance of the envelope material. In many countries, traditional greenhouse heating energy is typically derived from coal, which is environmentally hazardous due to its pollution. Thus, natural gas is used to modify coal because it is more efficient and cleaner; however, there is a consensus among scientists not to further investigate this fuel due to its limited lifetime and carbon emission problems.

Therefore, renewable and sustainable energy technologies are the best solution, as they are more eco-friendly and reduce greenhouse gas emissions. As the energy is abundant and free, the investment generates a positive cash flow between 4 and 8 years later, depending on the climate and plant type.

About the Author



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