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RECENT ACTIVE TECHNOLOGIES OF GREENHOUSE SYSTEMS – A COMPREHENSIVE REVIEW

DEWANTO HARJUNOWIBOWO[1,2]*; YATE DING[1]; SIDDIG OMER[1]; SAFFA RIFFAT[1]
[1] *University of Nottingham, Department of Architecture and Built Environment, Faculty of Engineering, University Park, NG7 2RD Nottingham, UK*
[2] *Sebelas Maret University, Department of Physics Education, Surakarta 57126, Indonesia*

Abstract

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Recent innovations in greenhouses for energy-saving purposes have included developments in heat-pump technology, semi-transparent Photovoltaic (PV), lighting technology, and control systems. In addition, retrofitting greenhouse with Light Emittance Diode (LEDs) can provide energy-saving lighting, which costs up to 75% less per year compared to the cost of other artificial lights. Moreover, combining heat pump and underground thermal storage could cut energy demands by 25%, and semi-transparent or checkerboard PVs on rooftops could simultaneously reduce the cooling energy demand and generate electricity. Finally, an automatic control system in greenhouses would both ensure energy efficiency and accurately control the microclimate within the greenhouse, resulting in suitable conditions for the crops.

Key words: control system; energy demand; greenhouse; lighting, retrofitting

Introduction

In 2008, the UK Government produced policies aimed at protecting the earth by diminishing greenhouse gas emissions (GHG) by means of 80% over a period from 1990 to 2050 (DECC, 2015). The policies urge researchers to scan for elective wellsprings of vitality other than petroleum derivatives; specifically, to seek sources that are both energy saving and environmentally friendly (Surahmanto et al., 2017). Fuels derived from fossils are still a major supplier of the energy consumed on the planet, their use being the reason behind the worldwide temperature alteration and environmental changes (Harjunowibowo et al., 2016; Zeinelabdein et al., 2017). Most of the total energy used in building such as greenhouses is for heating, making up 65-85% of the total energy demand (Runkle & Both, 2012).

Since a greenhouse is built to grow plants, it is common practice to use a transparent cover that allows sunlight through. Sunlight contains photosynthetically active radiation (PAR) (Benli & Durmuş, 2009; Benli, 2011; Yano et al., 2014) which is necessary for photosynthesis (Singh et al., 2015). Too much shade on the plant will significantly reduce the quality of the fruit (Kadowaki et al., 2012). Unfortunately, it is known that the most significant contribution of energy loss within buildings comes from windows and roofs, contributing about 20-40% of the total energy loss (Hee et al., 2015). Existing greenhouses primarily use glass (Joudi & Farhan, 2014), plastic/polyethylene (Cossu et al., 2014), semi-rigid plastic (Esen & Yuksel, 2013), and plastic film (Sonneveld et al., 2010a), all of which easily release heat energy into the environment (Ghoshal & Neogi, 2014).

To reduce the costs associated with greenhouses and to control the greenhouse microclimate in the most

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**Corresponding author:* dewanto.h@nottingham.ac.uk

extreme climates, solar power systems are needed. In Tunisia, solar radiation is potential to be one of the most remarkable energy resources. In this country, the annual sunshine can reach 3,288 kWh/m^{2}y, while a greenhouse using active conventional heating consumes one litre of fuel/m^{2}y. Furthermore, Tunisian greenhouses cover about 1,000 ha, which corresponds to 10 kL of fuel/year (Attar et al., 2013). Thus, switching to an electric boiler (from a gas/wood/coal boiler or from propane) saves between 15% (Steenis, 2009) and 22% (Manitoba, 2016) in terms of the respective amounts of energy consumed.

As a consequence, the handicaps to solar energy utilisation in the agricultural sector require both imperative attention and further study. The conversion of cropland into PV plants is a recent occurrence (Mekhilef et al., 2013). In terms of its utilisation in a greenhouse, PV is used to produce the power used for heating, cooling, and lighting (Kumar et al., 2015; Zimmermann et al., 2015). Therefore, combining PV boards and harvests on a similar regional unit of land could reduce the reliance on the power network or on petroleum derivatives.

In order to increase the PV's energy-efficiency conversion rates, the performance of photovoltaic-thermal (PVT) collectors has been observed. The exergy analysis calculations, when applied to the PVT integrated greenhouse system, show an exergy efficiency level of approximately 4% (Nayak & Tiwari, 2008). As the efficiency of PVT is demonstrably low, some improvements have been made using a concentrator (a so-called CPVT). Recently, the total efficiency of a CPVT has been shown to be greater than that of a PVT collector (Kostić et al., 2010b). CPVT system can produce heat and electricity at once with an efficiency rating of 65% and 11.3%, respectively (Sonneveld et al., 2010b).

Even tough, it has been mentioned that the energy saving by greenhouses in the northern climate (achieved using passive technology such as a closed concept and double glazing) potentially provides up to 50% of the total energy demand (Harjunowibowo et al., 2016). These passive technologies have been described as the newest and most promising heating-cooling technology for both northern and tropical countries. However, the need for energy to be used for temperature, lighting, and humidity varies between regions (Yang et al., 2014) and the technology used in greenhouses across the various regions is also different (Qoaider & Steinbrecht, 2010).

Therefore, this paper will examine the latest active technology classifications in existent greenhouses (Figure 1). This review will provide clear key plans that will demonstrate the efficiency of the active technology and the potential budget savings that could be used in operational greenhouses and which, therefore, could be retrofitted in existing greenhouses. Additionally, were the technology to be appropriately retrofitted to 1.1 million acres of greenhouses (Cuesta Roble Greenhouse Vegetable Consulting, 2016) this would then significantly reduce both the greenhouses' operational costs and world energy consumption.

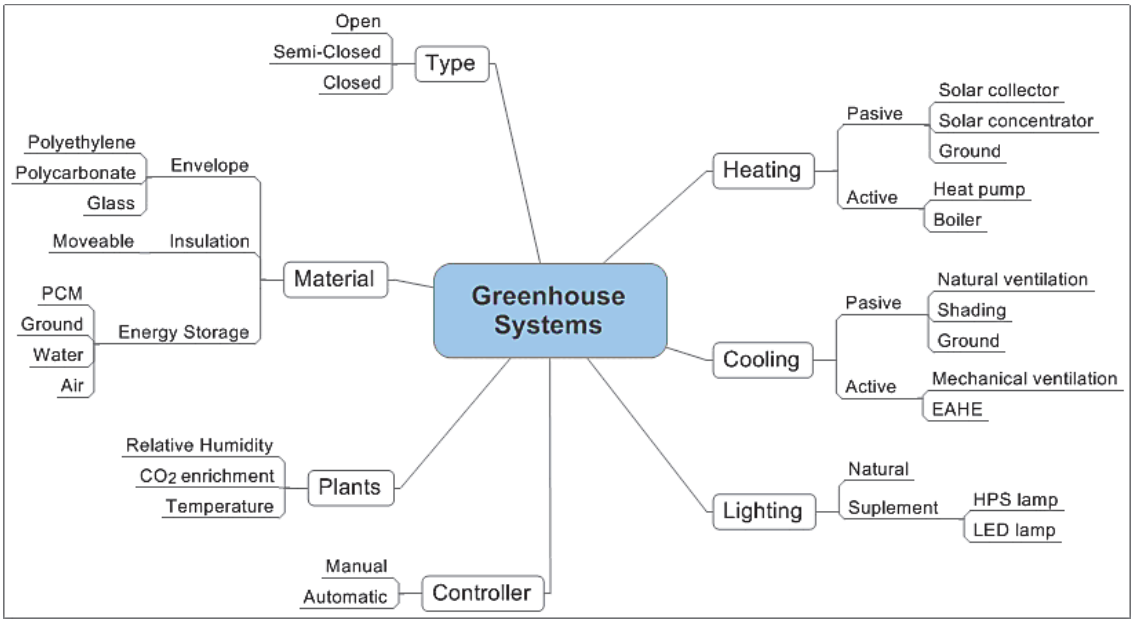

Fig. 1. Agricultural Greenhouse Technologies classification

Recent Technologies of Greenhouses and Recommendations

The technologies used in greenhouses have been experiencing rapid growth. Everything is geared to meet the appropriate and most optimal conditions for both plant growth (Pérez-Alonso et al., 2012) and protection from pests (Yang et al., 2014). This section will review the development of each technology that is used in greenhouses. It will also mention the type of technologies used in various countries, each with varying climates.

Heat pumps

One technology that can be utilised to produce both a heating and cooling effect is the heat pump (HP) (Awani et al., 2015; Mehrpooya et al., 2015; Mohamed et al., 2017). The use of a heat pump in a greenhouse offers advantages that are not possessed by other technologies; for example, to control the relative humidity in the greenhouse. Because of its multi-functional abilities, the heat pump is widely used to maintain the microclimate in the greenhouse.

Heat pumps are often used in conjunction with the ground. The ground serves as the source of thermal energy, which is then absorbed by the heat pump and used to heat the indoor air. The coefficient of performance (COP) of the COPHP ground-source heat pump (GSHP) is 2.3-3.8, and it is able to maintain an indoor temperature between 5-10 °C (Benli & Durmuş, 2009). However, the ground-source heat pump system requires that the ground temperature is higher than the ambient temperature, if it is to produce heat (Benli, 2011).

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Figure 2 shows the installation of a heat pump. The ground heat exchanger pipes could be installed vertically (Benli, 2013), or horizontal slinky (Esen & Yuksel, 2013). The advantages and disadvantages offered by the ground heat exchanger installation should be considered well before selecting the installation method. Vertical GSHP (VGSHP) is more proficient compared to horizontal GSHP (HGSHP); however, the cost of a VGSHP installation is a bit expensive than that of a HGSHP installation. Experimental results have established that the heat pump performance of a HGSHP (COPHP-H) and a VGSHP (COPHP-V) are 3.3 and 3.5, respectively. In comparison, the performance of the system horizontally (COPsys-H) and vertically (COPsys-V) returns 3.0 and 3.3, respectively (Benli, 2013).

Table 1 shows the energy efficiency of a heat pump and seasonal soil thermal storage. It can be seen that the heat pump, combined with underground heat storage, gives an excellent performance compared with that of a boiler, being 25% more efficient (Bot et al., 2005). Xi et al. studied a geothermal heat pump solar collector combined model, which was utilised with a heat storage system to provide

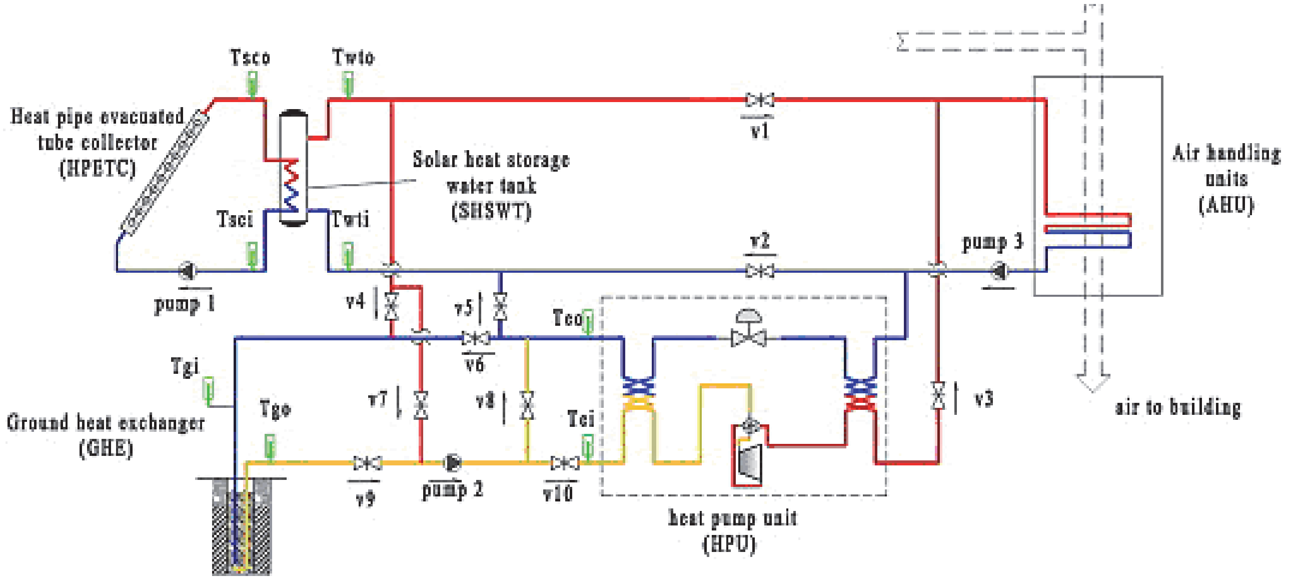

Fig. 2. Schematic diagram of the Heat pump utilisation (Dai et al., 2015)

Table 1
Annual energy consumption of greenhouse (NGE: Natural Gas Equivalence) (Bot et al., 2005)

Envelope	Energy Consumption with			
	Boiler		Underground and heat pump	
	NGE	%	NGE	%
Single	53	100	-	-
Double	40	75	26	49
Double/Triple with thermal screen	33	62	20	38

domestic hot water and heat load. The results confirm that confirm that there is increasing average annual efficiency for environmental heating increased by 26%. This is because the solar collectors are used to increase the energy that is stored in the soil, while the environmental heating is reserved using this heat (Xi et al., 2011). The advantages of the combined system are that it is proper from both an economic and technical point of view, and that it could replace the conventional systems used in Turkey (Bakirci et al., 2011).

Lighting

There are not many references to the types of lighting used in greenhouses. This is, perhaps, because the source of the light energy is not as significant as that used for heating or cooling. However, a specific growing required by vegetable and fruit plants has to be fulfilled is the lighting. The photosynthesis process needs photosynthetically active radiation (PAR) wavelength or visible light for photosynthesis (Singh et al., 2015). Lack of PAR negatively affects the colour and the size of the harvested fruits (Yano et al., 2014).

For this reason, several studies have been conducted to overcome the lack of natural lighting. Artificial lighting is used in many ways, and takes forms such as intra-canopy lighting (Trouwborst et al., 2011), photoperiodic lighting (Messinger & Lauerer, 2015), and lighting using different wavelength combinations (Choi et al., 2015). In addition, in greenhouses, research into the lamp types effectiveness and the light wavelength emitted from artificial lighting is one of majors considered in greenhouse farming (Lamnatou & Chemisana, 2013a; Choi et al., 2015).

High-Pressure Sodium (HPS) lamps

High-pressure sodium (HPS) lamps are oftenly used to prevent the flowering of ornamental plants in greenhouses. Some plants that respond to this type of lamp are the chrysanthemum ‘Bianca’, the pot chrysanthemum ‘Auburn’, and the velvet sage (*Salvia leucantha L.*) (Blanchard & Runkle, 2009). The ability to control the level of radiation allows farmers to decide the time at which a plant flowers, permitting them to effectively adapt to market needs.

However, a study into the effects of HPS light intensity on the process of photosynthesis in plants indicates a disadvantage (Kim et al., 2015). The experimental results demonstrate that the low-intensity of HPS light bulbs has the possibility of increasing photosynthesising activity in plants.

However, too long an exposure to the HPS lamp can cause chlorophyll levels to decrease. Wojciechowska et al. have conducted a comparison of the effect of LED and HPS light exposures (200 μmol $m^{-2}s^{-1}$ PPFD; 16 h photoperiod) on the growth and quality of lamb’s lettuce (*Valerianella Locusta*) within a greenhouse in the winter. Their observations, (Table 2) show that the highest growth and quality of the harvest is obtained from an exposure that uses 90R/10B LED lamps, followed by white LED light, 100% red LED light, before finally employing the HPS lamp (control) (Wojciechowska et al., 2015).

Fig. 3. Cultivation of plants with unique illumination of LEDs lights in a growth chamber (GC, A) and a plastic greenhouse (PG, B). (1) Blue + Red LED, (2) Blue LED, (3) Red LED, (4) incandescent bulbs (Choi et al., 2015).

LEDs

Following the low-cost and excellent effect of LED compared to HPS lamps, Johkan et al. have compared LED to fluorescence lamps (FL). A comparison of the green LED and the white FL against the plant growth of the red leaf lettuce (*Lactuca sativa L.*) shows that the green LED has a better effect than the white FL (Johkan et al., 2012). This result agrees with another study, which shows that (comparing the artificial light sources provided by these types of HPS and LED lamps) the LED light radiation produces a better outcome (Islam et al., 2012; Wojciechowska et al., 2015).

Additionally, Choi et al. have compared the effects of LED light on strawberry farming in a plastic greenhouse and a growth chamber (Figure 3). Cultivation was carried out in two separate locations; namely, a growth chamber (GC) lit with LED lights, and a plastic greenhouse (PG) that used supplemental LED light in addition to ambient light. The results show that the use of LED light as a supplemental light results in a better yield (in terms of both quality and quantity) than does a sole light source. Furthermore, a remarkably higher fruit production has been achieved when ambient light is combined with blue or red LED light, or with a red and blue LED combination (Choi et al., 2015). Additionally, the best wavelength influence on the growth of plants is shown in response to blue (448 nm), red (634 and 661 nm), and a combination of blue and red (3:7) (Ilieva et al., 2010; Choi et al., 2015; Kitazaki et al., 2015; Singh et al., 2015; Wojciechowska et al., 2015). Table 3 depicts a comparison of the effects of artificial light sources on a plantation.

However, high-intensity lighting should be avoided, as it has a harmful effect on plants. Ilieva et al. use monochromic LEDs emitting light in the red, green, and blue regions of the spectrum. Their experiments with plants (including lettuce and radicchio) were carried out at 400 μmol $m^{-2}s^{-1}$ PPFD and 220 μmol $m^{-2}s^{-1}$ PPFD, using 70% red, 20% green, and 10% blue light compositions. The biochemical indicators revealed a higher sensitivity to photo-damage in lettuce and radicchio plants grown in a high-intensity light (specifically, showing a photosynthetic rate that was two times lower than that shown by plants grown in low light). Furthermore, low light conditions have been shown to result in a more positive functioning of Photosystem II (compared to that resulting from high-intensity light conditions) when the plants were grown in a 70% red, 20% green, and 10% blue light composition (Ilieva et al., 2010).

Table 2
Growth rate of plantations in cm (Wojciechowska et al., 2015)

	2013	2014	Mean
Control (HPS)	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 addition to the effectiveness, LEDs have both a lower cost and a long lifespan. Moreover, LEDs use minimal energy, so their use would be advantageous in terms of allowing farmers to maximise their greenhouse crops (Poulet et al., 2014). Calculations show that the use of red and blue LEDs requires 39% less energy per unit of dry biomass (energy per unit of dry biomass). Moreover, a white LED uses 23% less energy than do sole-source intra-canopy (vertical) red and blue LEDs, which consume 1.02 kWh/g of dry biomass. The total coverage provided by red and blue LEDs uses 14% less energy per unit of dry biomass. Therefore, the use of LEDs would save costs associated with the lighting system, compared to those required by other types of light, by 75% per year (Singh et al., 2015).

Photovoltaic Modules

Nowadays, many researchers use PV panels as an electric energy provider in greenhouses, resulting in various capacities (Al-Shamiry et al., 2007; Agricola et al., 2012; Carlini et al., 2012; Pérez-Alonso et al., 2012; Urena-Sanchez et al., 2012; Yildiz et al., 2012; Cossu et al., 2014; Yano et al., 2014; Fatnassi et al., 2015). PV applications can support active heating, cooling, and lighting in a greenhouse.

Table 3
The effectivity of artificial Light Source to Plants

Reference	Lamps	Plants	Note
(Kitazaki et al., 2015)	fluorescent	Sprouts	Energy consumption need to be considered
(Wojciechowska et al., 2015)	90R/10B	*Valerianella locusta*	
(Kim et al., 2015)	low-intensity of HPS	Cymbidium hybrids ‘Red Fire’ and ‘Yokihi’	too long exposure causes a number of chlorophyll decreases
(Ren et al., 2014)	RB20 (red/blue=8/2)	Asteraceae, perennial herb	
(Cossu et al., 2014)	HPS Plantastar 400 W	Tomato	
(Johkan et al., 2012)	green LED	*Lactuca sativa* L.	PPF 200 μmol m^{-2} s^{-1} is the optimum

Conventional Photovoltaic

PV usage in greenhouses has recently started to become feasible, as the price of PVs is becoming lower while their efficiency is increasing (Global Trends in Renewable Energy, 2014). Additionally, PV panels can serve as the walls or the roof of the greenhouse, thereby decreasing levels of heat loss. As a result, demands for heating and cooling energy will go down, thereby reducing grid dependence on the electrical grid. This then means that the operative cost will decrease as well.

Table 4 depicts how electrical energy from PVs is mostly used to power cooling fans and lighting; these require little energy, especially in the hot arid climatic regions. A conventional PV has a low conversion efficiency. The electricity production depends on the PV width, the efficiency of the employed module, and the geographical location. Kadowaki et al. and Yano et al. use PVs to produce up to 4.06 GJy^{-1} of electricity (Yano et al., 2010; Kadowaki et al., 2012) and have generated a massive income from PV energy (Cossu et al., 2014).

However, some disadvantages occur due to the use of PV rooftops; for example, shading to the plants decreases the quantity and quality of the fruits yielded (Kadowaki et al., 2012; Cossu et al., 2014; Yano et al., 2014). In addition, PV efficiency decreases markedly in excess heat (Chow, 2010; Wu et al., 2012; Kumar et al., 2015; Herrando & Markides,

Table 4
Kind of PV utilised on Greenhouse to power up heating, cooling and lighting

Reference	Type of PV	Country	Result
PVT (Shyam et al., 2015)	(c-Si) semi-transparent	India	Dryer. The highest electricity energy is 1.9 kWh/d
PVT (Nayak and Tiwari, 2010)	(c-Si)	India	Heating. The annual overall annual electrical energy savings is at 1185 kWh. Electricity production factor (EPF) is 2.04.
PV (Ganguly et al., 2010)	(c-Si) (Specifications of PM-75 Module of Central Electronics Ltd 2016) (CEL-PM75)	India	Cooling fan. The peak power is 3825 Wp. The module strengthens the viability of a greenhouse grid-independent (Simulation)
PV (Yildiz et al., 2012)	Multi-cSi	Turkey	Cooling. 34.55% of the total electricity energy consumption is provided from PV cells. Temperature inside decrease by 19.9°C, outside is 49.9°C.
PV (Fatnassi et al., 2015)	Mono-cSi	France	Solar radiation is more evenly distributed in the Venlo greenhouse than in the Asymmetric greenhouse. The checkerboard PV panel setup improved the balance of the spatial distribution of sunlight received than straight-line arrangement in the greenhouse (simulation)
PV (Urena-Sanchez et al., 2012; Pérez-Alonso et al., 2012)	a-Si thin film	Spain	Extra income. Electricity produces 8.25 kWh m^{-2}, with 9.79% of cover occupation
PV (Yano et al., 2014)	(c-Si) spherical solar microcells semi-transparent	Japan	Electrical consumption. The peak power output is 540mW when irradiates with 1213 Wm^{-2}. The conversion efficiency is 4.5%
PV (Yano et al., 2010; Kadowaki et al., 2012)	a-silicon (FPV1024S)	Japan	Electrical appliances. The straight-line PVs and checkerboard PVc arrays generate electricity of 4.08 GJy^{-1} and 4.06 GJy^{-1}, respectively. However, straight-line PVs decrease the fresh weight (FW) and dry matter weight (DW) of the onion.
PV (Cossu et al., 2014)	Multi-cSi	Italy	Lighting. The annual electricity production is 107,885 kWh. The overall conversion efficiency of the PV system is 11.4%. Yearly average temperature inside the greenhouse 19.8°C and the range is 12-30°C
PV (Russo et al., 2014)	N/A	Italy	Heating. Temp set of 10°C. Estimate payback-time for energy and carbon emissions are 1 year and 2.25 years, respectively.
PV (Carlini et al., 2012)	Mono-cSi	Italy	Heating and cooling. Saving energy approximately 30% for summer cooling and 11% for winter heating
CPVT (Sonneveld et al., 2011)	Mono-cSi	Netherlands	Heating and cooling. The annual electrical energy to be 29 kWh m^{-2}. Electric efficiency yield of 11%. The annual thermal yield of 56% at 518 MJ m^{-2}
CPV (Sonneveld and Swinkels, 2010)	N/A	Netherlands	Electrical purpose. The annual electricity output is over 26 kWh/m². Reducing the heat load, blocking harmful direct radiation.

2016) especially in hot regions (in India, for example) (Shyam et al., 2015). It has been observed that more than 50% of sunlight radiation will be converted into heat; this causes the temperature of the solar cell to rise to 50°C above the ambient temperature (Chow, 2010). For that reason, semi-transparent PVs and checker-checkerboard positioning could offer a solution because utilising semi-transparent PV could decrease the energy demand by 65% (Harjunowibowo et al., 2017). However, the layout PV in building should be considered to reduce the solar heat gain, increase the energy saving and optimise the daylighting (Eltaweel & Su, 2017).

Concentrating photovoltaic (CPV)

To counter the low efficiency of PV panels, researchers have previously focused a sunlight concentrator on the PV; such concentrators include the Fresnel lens (Wu et al., 2012; Imtiaz Hussain et al., 2015), parabolic trough concentrators (Sonneveld et al., 2010b), and Fresnel mirrors (Sonneveld & Swinkels, 2010). Sonneveld and Swinkels report that CPV using near-infrared (NIR) reflecting lamellae integrated onto a greenhouse could produce electricity at a rate of 26 kWh/m2y-1 and could reduce the amount of energy required for heating and cooling while also blocking the direct radiation that can be harmful to the plants (Sonneveld & Swinkels, 2010). Figure 6 shows the type of concentrator that is used to increase the electricity energy gain in greenhouses. Such concentrators have many advantages and disadvantages.

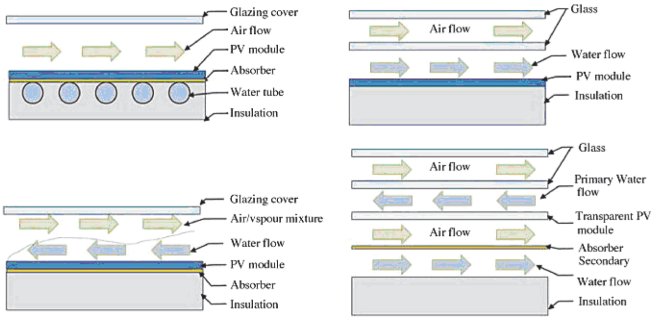

Fig. 4. A cross-sectional view of the PVT module (Zhang et al., 2012).

A high concentrator can double the quantity of sunlight, making it up to 100 times more effective than the number of light received by a PV of the same size (Chemisana, 2011). Recently, CPV efficiency reached up to 38.9% under Concentrator Standard Test Conditions (CSTC) (Philipps et al., 2015). However, the module concentrator PV has a fatal disadvantage: if it is not well-managed, it is in danger of overheating (Chow, 2010). Therefore, a cooling technology for PVs (whether they use a concentrator or not) is needed, especially when they are used in tropical countries.

Due to the unconstructive impact on the PV that can be caused by extreme heat, innovations have been aimed at reducing the temperature decreasing the PV efficiency. Such innovation has taken various forms, even utilising the excessive heat as the heat source for the greenhouse (Nayak & Tiwari, 2008, 2009, 2010; Ganguly et al., 2010; Sonneveld, 2010b; Yildiz et al., 2012; Aste et al., 2015). This particular method can harvest electrical energy from sunlight and simultaneously heat the greenhouse using the photovoltaic/thermal (PV/T) module (Buker & Riffat, 2015).

Photovoltaic thermal (PVT)

Figure 4 shows the architecture of a water-based PVT module. Commonly, the PVT arrangement consists of a solar cell, heat sink, ventilation, and insulation sequentially. Several studies have been performed that aim to enhance the efficiency of solar PV panels by lowering the temperature using an air conditioner and water (Nayak & Tiwari, 2008, 2009, 2010; Chow et al., 2009; Chow, 2010; Agrawal & Tiwari, 2010; Kamthania et al., 2011; Rekha et al., 2013; Shyam, 2015). One researcher has managed to obtain heat energy and electricity at 12.8 kWh and 716 kWh, respectively (Nayak & Tiwari, 2008).

Table 5 demonstrates the use of PVT technologies and the results when applied to greenhouses. Water (as the heat

Table 5
PVT technologies used for Greenhouses

Reference	Country	Cooler	Result
2008 (Nayak and Tiwari, 2008)	India	Water	E_e: 716 kWh/y, E_t : 12.8 kWh/y, η_{ex} PV: 4%.
2009 (Nayak and Tiwari, 2009)	India	Air	T_{gh}: 7–8°C during winter at night, T_{amb}: 9°C, η_{ex} PV: 5.5% with EAHE, E_{tfb}: 24,728.8 kWh/y, E_e: 805.9 kWh/y, E_{tex}: 1006.2 kWh/y
2010 (Nayak and Tiwari, 2010)	India	Water	E_t : 29,156.8 kWh /y, E_e: 1185 kWh/y, E_{tex}: 1366.4 kWh/y
2011 (Kamthania et al., 2011)	India	air	E_t: 480.81 kWh /y, E_e: 469.87 kWh/y, T_{gh} :5-6°C > T_{amb} winter, T_{amb}: 10-30°C
2015 (Shyam et al., 2015)	India	Water	E_t: 20.5 kWh/d (CFD Simulation)

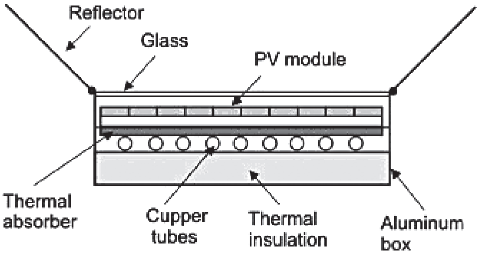

Fig. 5. Schematic diagram of CPV/T collector (Kostić et al. 2010)

exchanger) seems to be the appropriate substance with which to decrease the PV temperature and extract the heat that is to be sent to the heat storage. The technology using an air conditioner-based PVT (PVT/air) is more modest compared to water based, but its efficiency is still below that of the water cooling-based PVT (PVT/water) (Zhang, 2012). Nevertheless, there is no rule applied to the use of PVT coolers; all depends on the geographical area and the applications that are to be used. An area with low-level solar radiation and a low ambient temperature will require more heating; thus, a PVT/air could be cost-effective and offer the most uncomplicated option. However, PVT/water could be more efficient when used to provide pre-heating services in an area with high solar radiation and a higher ambient temperature (Chow, 2010).

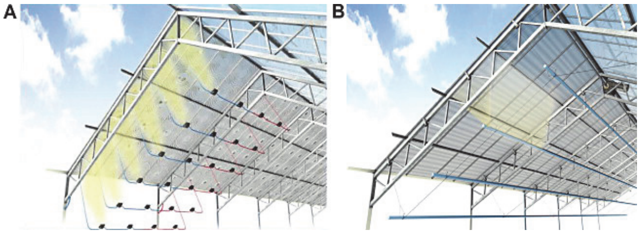

Fig. 6. Integration of a PV/T greenhouse rooftop with: (A) normal Fresnel lenses, and (B) linear Fresnel lenses (Sonneveld et al. 2011)

The efficiency of amorphous silicon when used to produce heat and electrical energy in India has reached 1.531 kWh and 16.209 kWh respectively in a year, when employed with PVT/air (Agrawal, 2010). In comparison, a building integrated photovoltaic thermal (BiPVT) that uses water for solar cell cooling (BiPVW) reaches 2,257.6 kWh for thermal energy and 3,229.9 kWh for electrical energy (Chow, 2009).

Concentrated photovoltaic thermal (CPVT)

PVT is able to increase the level of module efficiency for electric energy and can use heat energy for anything; despite this, the energy requirements needed to make a greenhouse independent from the electric grid have still not quite been met. Therefore, the integration of the sunlight concentrator module and the PVT module in greenhouses is a further innovation that has been employed by many researchers (Sonneveld, 2010a; Tyagi et al., 2012; Lamnatou, 2013a; Lamnatou & Chemisana, 2013b; Chou et al., 2004;). This integration is referred to as a concentrating photovoltaic thermal (CPVT) module, and is used to increase the efficiency of PVT in a multiple times.

The array configuration CPVT module is shown in Figure 5. The use of reflectors on the edge of the PVT module allows the sunlight coming from all directions to be reflected towards the PV module. A comparison of the efficiency of PVTs (that is, PVTs without a reflector) and CPVTs (PVTs with a reflector) has been conducted shows that the total efficiency of a CPVT is greater than that of a PVT collector (Kostić et al., 2010b).

Continuous innovative efforts aim to make the CPVT module more lighter and compact by using a Fresnel lens, as shown in Figure 6. A CPVT using a Fresnel lens is the module most often used in greenhouses. In addition to its high-efficiency factor, the module structure is also more compact and thus is easily mounted on the roof of the greenhouse (Sonneveld et al., 2011). In addition to its small size, heat loss from the Fresnel lens concentrator is also minimal (Wu et al., 2012) which makes it suitable to use in greenhouses.

The efficiency of CPVTs in conjunction with various concentrator models is strongly influenced by the incidence angle of sunlight on the reflector or collector (Kostic et al., 2010a; Kostić et al., 2010b; Sonneveld, 2011). CPVT applications on greenhouses are widely employed (Table 6) and have been successful in supporting the provision of both electricity and thermal energy, especially at night or in cold weather (Sonneveld

Table 6
CPVT frequently used in Greenhouses

Reference	GH Area	Concentrator	Country	Result
(Sonneveld et al., 2010)	1075.2 m^2	Parabolic reflector	Netherlands	E_t: 160 kWh m^{-2}/y, E_e: 20 kWh m^{-2}/y, η_{ex} PV: 11.3%. η_{ex} T: 65%
(Sonneveld et al., 2011)	36 m^2	LFL	Netherlands	η_{ex} PV: 11%. η_{ex} T: 56%, E_t: 518 MJ m^{-2}/y. E_e: 29 kWh m^{-2}/y
(Imtiaz Hussain et al., 2015)	9.89 m^2	LFL and SFL	South Korea	LFL: η_{ex} T: 69.6%, SFL: η_{ex} T : 71.7%

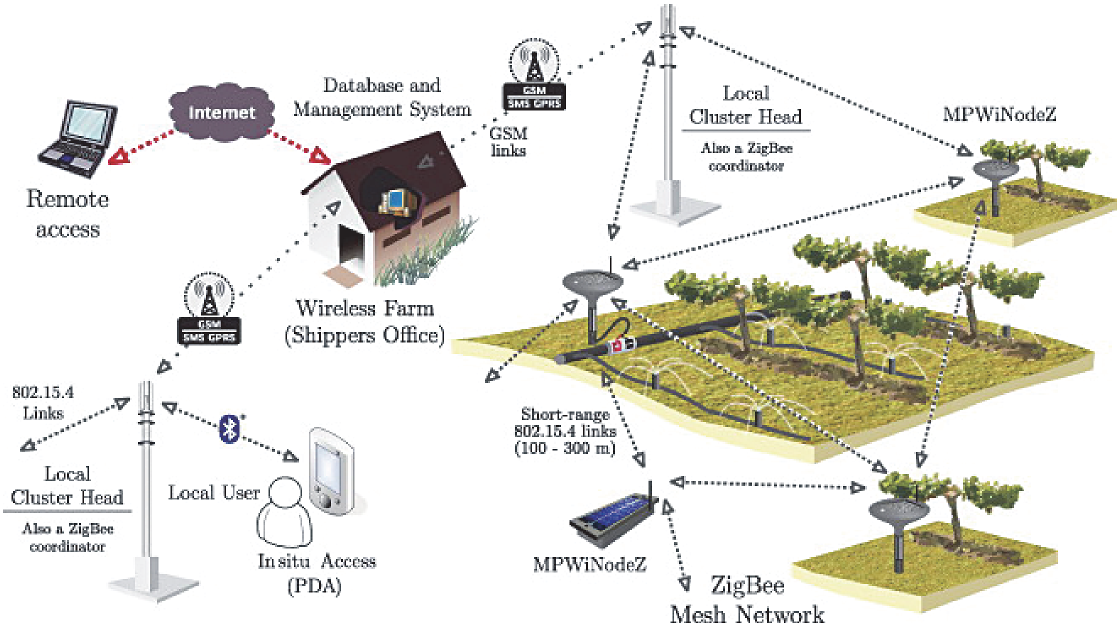

Fig. 7. A ZigBee network of MPWiNodeZ devices operation of an in-field data acquisition network (Morais et al. 2008)

et al., 2010a, 2011; Lamnatou & Chemisana, 2013a; Imtiaz et al., 2015).

Control system

In spite control a greenhouse system in terms of humidity, temperature, lighting, and CO_2 needed manually look easy, but actually, it is very complicated, therefore an automatic control system is much cheaper and worthy. A greenhouse with a low energy demand can be realised by using adaptive climate control, integrating control algorithms, installing insulating cover, and utilising optimal energy management techniques (Bot et al., 2005). An automatic system has many benefits: it controls soil moisture, temperature, and humidity within a greenhouse. In comparison, manually operated systems are likely to have a lot of disadvantages, as well as being high-cost, and offering inaccurate control. Therefore, control systems that take advantage of the declining cost and size of sensors have been used to automate systems that can potentially increase the efficiency and yield of greenhouses (Wang et al., 2006); such systems have already been utilised in Kenya (Tang et al., 2011).

A pepper (Piper) needs warm conditions of about 20°C (Attar et al., 2014), while orchid, edamame, and lemongrass need the temperatures to be between 18-30°C, 20-25°C, and 22-38°C, respectively. Additionally, these plants need specific humidity (between 30-90%) in order to be able to grow and bear fruit optimally (Chou et al. 2004). Therefore, a control system will provide a good place for the seedlings of each crop; this stage is the primary concern of greenhouse operators, especially in terms of temperature, lighting, and relative humidity.

Additionally, the use of solar trackers on the solar collector is very beneficial, as it increases the efficiency of solar collectors even when used only on one axis (Sonneveld et al., 2011; Groener et al., 2015). This is because a solar tracking application in greenhouses maximises solar radiation directly, especially if it has a dual-axis tracker (Imtiaz et al., 2015). Besides, the electrical energy needed for a tracker system is less than 2% of the total electrical energy requirements per year (Sonneveld et al., 2011).

Zhou et al. use an open source control system (ZigBee technology) (Zhou et al. 2013). This communicates via Bluetooth and other wireless technologies in order to maintain the soil water content, temperature, and humidity, at the same time as monitoring the concentration of carbon dioxide in the greenhouse (Chemisana et al. 2009). Moreover, the control system can save data to a database. It also has low complexity, a low power consumption, low data rate, is low-cost and can use ad hoc networks (Zhou et al. 2013). Figure 7 shows the implementation of a data acquisition network using a

ZigBee multi-powered wireless. The system collects the data environment simply by using a wireless protocol.

Before this, many researchers have tried to use different techniques to control the greenhouse microclimate. Liu and Ying use Bluetooth technology to monitor a control system in a greenhouse (Morais et al. 2008). The data from the greenhouse environment is collected using a sensor network and is transmitted to a central control system. It is believed that this type of remote control strategy could significantly improve productivity and reduce labour requirements.

Conclusion and recommendations

Recently, there has been several innovations in active technology in an attempt to overcome the Heating-Ventilation and Air Conditioner (HVAC) energy demand made by greenhouses. The use of a heat pump and seasonal underground heat storage reduces the energy demand up to 25% on an annual basis, compared with the energy requirements made by a conventional boiler. In addition, semi-transparent PV can be used to simultaneously reduce the high irradiation of sunlight and to generate electricity for greenhouses; its use could be very viable and less costly to maintain. Furthermore, the use of LEDs in retrofit HPS lamps would save energy and reduce costs by 75% annually. In addition, greenhouses equipped with automatic control systems would generate a consistent and cost-effective microclimate, thereby guaranteeing the quality and quantity of the yield.

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References

Agrawal, B. and G. N. Tiwari, 2010. Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions. *Applied Energy*, **87** (2): 417-426. http://doi.org/10.1016/j.apenergy.2009.06.011

Agricola, S., R. Ureña-Sánchez, Á. J. Callejón-Ferre, J. Pérez-Alonso and Á. Carreño-Ortega, 2012. Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. *Scientia Agricola*, **69**(4): 233-239.

Al-Shamiry, F.M.S., D. Ahmad, A.R.M. Sharif, I. Aris, R. Janius and R. Kamaruddin, 2007. Design and development of a photovoltaic power system for tropical greenhouse cooling. *American Journal of Applied Sciences*, **4**(6): 386-389. http://doi.org/10.3844/ajassp.2007.386.389

Aste, N., F. Leonforte and C. Del Pero, 2015. Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector. *Solar Energy*, **112**: 85-99. http://doi.org/10.1016/j.solener.2014.11.025

Attar, I., N. Naili, N. Khalifa, M. Hazami and A. Farhat, 2013. Parametric and numerical study of a solar system for heating a greenhouse equipped with a buried exchanger. *Energy Conversion and Management*, **70**: 163-173. http://doi.org/10.1016/j.enconman.2013.02.017

Attar, I., N. Naili, N. Khalifa, M. Hazami, M. Lazaar and A. Farhat, 2014. Experimental study of an air conditioning system to control a greenhouse microclimate. *Energy Conversion and Management*, **79**: 543-553. http://doi.org/10.1016/j.enconman.2013.12.023

Awani, S., R. Chargui, S. Kooli, A. Farhat and A. Guizani, 2015. Performance of the coupling of the flat plate collector and a heat pump system associated with a vertical heat exchanger for heating of the two types of greenhouses system. *Energy Conversion and Management*, **103**: 266-275. http://doi.org/10.1016/j.enconman.2015.06.032

Bakirci, K., O. Ozyurt, K. Comakli and O. Comakli, 2011. Energy analysis of a solar-ground source heat pump system with vertical closed-loop for heating applications. *Energy*, **36** (5): 3224-3232. http://doi.org/10.1016/j.energy.2011.03.011

Benli, H., 2011. Energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating. *Energy Conversion and Management*, **52**(1): 581-589. http://doi.org/10.1016/j.enconman.2010.07.033

Benli, H., 2013. A performance comparison between a horizontal source and a vertical source heat pump systems for a greenhouse heating in the mild climate Elaziğ, Turkey. *Applied Thermal Engineering*, **50**(1): 197-206. http://doi.org/10.1016/j.applthermaleng.2012.06.005

Benli, H. and A. Durmuş, 2009. Performance analysis of a latent heat storage system with phase change material for new designed solar collectors in greenhouse heating. *Solar Energy*, **83**(12): 2109–2119. http://doi.org/10.1016/j.solener.2009.07.005

Blanchard, M.G. and E.S. Runkle, 2009. Use of a cyclic high-pressure sodium lamp to inhibit flowering of chrysanthemum and velvet sage. *Scientia Horticulturae*, **122**(3): 448-454. http://doi.org/10.1016/j.scienta.2009.06.016

Bot, G., N. Van De Braak, H. Challa, S. Hemming, T. Rieswijk, G.V. Straten and I. Verlodt, 2005. The solar greenhouse: State of the art in energy saving and sustainable energy supply. *Acta Horticulturae*, **691**: 501-508.

Buker, M.S. and S.B. Riffat, 2015. Building integrated solar thermal collectors – A review. *Renewable and Sustainable Energy Reviews*, **51**: 327-346. http://doi.org/10.1016/j.rser.2015.06.009

Carlini, M., T. Honorati and S. Castellucci, 2012. Photovoltaic greenhouses: Comparison of optical and thermal behaviour for energy savings. *Mathematical Problems in Engineering*, http://doi.org/10.1155/2012/743764

Chemisana, D., 2011. Building integrated concentrating photovoltaics: A review. *Renewable and Sustainable Energy Reviews*, **15**(1): 603-611. http://doi.org/10.1016/j.rser.2010.07.017

Chemisana, D., M. Ibáñez and J. Barrau, 2009. Comparison of Fresnel concentrators for building integrated photovoltaics.

Energy Conversion and Management, **50**(4): 1079-1084. http://doi.org/10.1016/j.enconman.2008.12.002

Choi, H.G., B.Y. Moon and N.J. Kang, 2015. Effects of LED light on the production of strawberry during cultivation in a plastic greenhouse and in a growth chamber. *Scientia Horticulturae*, **189**: 22-31. http://doi.org/10.1016/j.scienta.2015.03.022

Chou, S.K., K.J. Chua, J.C. Ho and C.L. Ooi, 2004. On the study of an energy-efficient greenhouse for heating, cooling and dehumidification applications. *Applied Energy*, **77**(4): 355-373. http://doi.org/10.1016/S0306-2619(03)00157-0

Chow, T.T., 2010. A review on photovoltaic/thermal hybrid solar technology. *Applied Energy*, **87**(2): 365-379. http://doi.org/10.1016/j.apenergy.2009.06.037

Chow, T.T., A.L.S. Chan, K.F. Fong, Z. Lin, W. He and J. Ji, 2009. Annual performance of building-integrated photovoltaic/water-heating system for warm climate application. *Applied Energy*, **86**(5): 689-696. http://doi.org/10.1016/j.apenergy.2008.09.014

Cossu, M., L. Murgia, L. Ledda, P.A. Deligios, A. Sirigu, F. Chessa and A. Pazzona, 2014. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. *Applied Energy*, **133**: 89-100. http://doi.org/10.1016/j.apenergy.2014.07.070

Cuesta Roble Greenhouse Vegetable Consulting, 2016. International Greenhouse Vegetable Production - Statistics, 2016 ed., http://cuestaroble.com/statistics.htm (retrieved February 11, 2016)

Dai, L., S. Li, L. DuanMu, X. Li, Y. Shang and M. Dong, 2015. Experimental performance analysis of a solar assisted ground source heat pump system under different heating operation modes. *Applied Thermal Engineering*, **75**:325-333. http://doi.org/10.1016/j.applthermaleng.2014.09.061

DECC, 2015. Government Response to the Committee on Climate Change. Progress on meeting carbon budgets and preparing for climate change - Summary Document. London.

Eltaweel, A. and Y. Su, 2017. Parametric design and daylighting: A literature review. *Renewable and Sustainable Energy Reviews*, **73**(October 2016): 1086-1103. http://doi.org/10.1016/j.rser.2017.02.011

Esen, M. and T. Yuksel, 2013. Experimental evaluation of using various renewable energy sources for heating a greenhouse. *Energy and Buildings*, **65**: 340-351. http://doi.org/10.1016/j.enbuild.2013.06.018

Fatnassi, H., C. Poncet, M.M. Bazzano, R. Brun and N. Bertin, 2015. A numerical simulation of the photovoltaic greenhouse microclimate. *Solar Energy*, **120**: 575-584. http://doi.org/10.1016/j.solener.2015.07.019

Ganguly, A., D. Misra and S. Ghosh, 2010. Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse. *Energy and Buildings*, **42**(11): 2036-2043. http://doi.org/10.1016/j.enbuild.2010.06.012

Ghoshal, S. and S. Neogi, 2014. Advance Glazing System – Energy Efficiency Approach for Buildings a Review. *Energy Procedia*, **54**: 352-358. http://doi.org/10.1016/j.egypro.2014.07.278

Global Trends In Renewable Energy, 2014. *Global Trends In Renewable Energy*.

Groener, B., N. Knopp, K. Korgan, R. Perry, J. Romero, K. Smith and J. Henriques, 2015. Preliminary design of a low-cost greenhouse with open source control systems. *Procedia Engineering*, **107**: 470-479. http://doi.org/10.1016/j.proeng.2015.06.105

Harjunowibowo, D., D.N. Adilah, D. Teguh, D.S. Wijayanto, F. Surahmanto and P. Teguh, 2016. The Effect of Different Ambient Temperature To Solar Cooling Performance. *Jurnal Teknologi*, **5**: 51-56.

Harjunowibowo, D., E. Cuce, S.A. Omer and S.B. Riffat, 2016. Recent passive technologies of greenhouse systems - a review. In: 15th International Conference on Sustainable Energy Technologies – SET 2016, Singapore, pp. 1-10.

Harjunowibowo, D., D. Yate, S.A. Omer and S.B. Riffat, 2017. Reducing greenhouse energy consumption using Novelty Rooftop: A simulation. In: 16th International Conference on Sustainable Energy Technologies – SET 2017, Bologna, pp. 1-10.

Hee, W.J., M.A. Alghoul, B. Bakhtyar, O. Elayeb, M.A. Shameri, M.S. Alrubaih and K. Sopian, 2015. The role of window glazing on daylighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews*, **42**: 323-343. http://doi.org/10.1016/j.rser.2014.09.020

Herrando, M. and C.N. Markides, 2016. Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations. *Applied Energy*, **161**: 512-532. http://doi.org/10.1016/j.apenergy.2015.09.025

Ilieva, I., T. Ivanova, Y. Naydenov, I. Dandolov and D. Stefanov, 2010. Plant experiments with light-emitting diode module in Svet space greenhouse. *Advances in Space Research*, **46**(7): 840-845. http://doi.org/10.1016/j.asr.2010.05.009

Imtiaz Hussain, M., A. Ali and G.H. Lee, 2015. Performance and economic analyses of linear and spot Fresnel lens solar collectors used for greenhouse heating in South Korea. *Energy*, **90**: 1522-1531. http://doi.org/10.1016/j.energy.2015.06.115

Islam, M.A., G. Kuwar, J.L. Clarke, D.R. Blystad, H.R. Gislerød, J.E. Olsen and S. Torre, 2012. Artificial light from light emitting diodes (LEDs) with a high portion of blue light results in shorter poinsettias compared to high pressure sodium (HPS) lamps. *Scientia Horticulturae*, **147**, 136-143. http://doi.org/10.1016/j.scienta.2012.08.034

Johkan, M., K. Shoji, F. Goto, S. Hahida and T. Yoshihara, 2012. Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in Lactuca sativa. *Environmental and Experimental Botany*, **75**: 128-133. http://doi.org/10.1016/j.envexpbot.2011.08.010

Joudi, K.A. and A.A. Farhan, 2014. Greenhouse heating by solar air heaters on the roof. *Renewable Energy*, **72**: 406-414. http://doi.org/10.1016/j.renene.2014.07.025

Kadowaki, M., A. Yano, F. Ishizu, T. Tanaka and S. Noda, 2012. Effects of greenhouse photovoltaic array shading on Welsh onion growth. *Biosystems Engineering*, **111**(3): 290-297. http://doi.org/10.1016/j.biosystemseng.2011.12.006

Kamthania, D., S. Nayak and G.N. Tiwari, 2011. Performance evaluation of a hybrid photovoltaic thermal double pass facade for space heating. *Energy and Buildings*, **43**(9): 2274-2281. http://doi.org/10.1016/j.enbuild.2011.05.007

Kim, Y.J., D.J. Yu, H. Rho, E.S. Runkle, H.J. Lee and K.S.

Kim, 2015. Photosynthetic changes in Cymbidium orchids grown under different intensities of night interruption lighting. *Scientia Horticulturae*, **186**: 124-128. http://doi.org/10.1016/j.scienta.2015.01.036

Kitazaki, K., S. Watanabe, A. Okamoto, M. Matsuo, S. Furuya and K. Sameshima, 2015. Far-red light enhances removal of pericarps in tartary buckwheat (*Fagopyrum tataricum* Gaertn.) sprout production under artificial lighting. *Scientia Horticulturae*, **185**: 167-174. http://doi.org/10.1016/j.scienta.2015.01.022

Kostic, L.T., T.M. Pavlovic and Z.T. Pavlovic, 2010a. Influence of reflectance from flat aluminum concentrators on energy efficiency of PV/Thermal collector. *Applied Energy*, **87**(2): 410-416. http://doi.org/10.1016/j.apenergy.2009.05.038

Kostić, L.T., T.M. Pavlović and Z.T. Pavlović, 2010b. Optimal design of orientation of PV/T collector with reflectors. *Applied Energy*, **87**(10): 3023-3029. http://doi.org/10.1016/j.apenergy.2010.02.015

Kumar, A., P. Baredar and U. Qureshi, 2015. Historical and recent development of photovoltaic thermal (PVT) technologies. *Renewable and Sustainable Energy Reviews*, **42**: 1428-1436. http://doi.org/10.1016/j.rser.2014.11.044

Lamnatou, C. and D. Chemisana, 2013a. Solar radiation manipulations and their role in greenhouse claddings: Fluorescent solar concentrators, photoselective and other materials. *Renewable and Sustainable Energy Reviews*, **27**: 175-190. http://doi.org/10.1016/j.rser.2013.06.052

Lamnatou, C. and D. Chemisana, 2013b. Solar radiation manipulations and their role in greenhouse claddings: Fresnel lenses, NIR- and UV-blocking materials. *Renewable and Sustainable Energy Reviews*, **18**: 271-287. http://doi.org/10.1016/j.rser.2012.09.041

Manitoba, 2016. Greenhouse Energy Calculations. http://www.gov.mb.ca/agriculture/crops/production/print,energy-calculations.html (Retrieved December 1, 2015)

Mehrpooya, M., H. Hemmatabady and M.H. Ahmadi, 2015. Optimization of performance of Combined Solar Collector-Geothermal Heat Pump Systems to supply thermal load needed for heating greenhouses. *Energy Conversion and Management*, **97**: 382-392. http://doi.org/10.1016/j.enconman.2015.03.073

Mekhilef, S., S.Z. Faramarzi, R. Saidur and Z. Salam, 2013. The application of solar technologies for sustainable development of agricultural sector. *Renewable and Sustainable Energy Reviews*, **18**: 583-594. http://doi.org/10.1016/j.rser.2012.10.049

Messinger, J. and M. Lauerer, 2015. Solanum quitoense, a new greenhouse crop for Central Europe: Flowering and fruiting respond to photoperiod. *Scientia Horticulturae*, **183**: 23-30. http://doi.org/10.1016/j.scienta.2014.11.015

Mohamed, E., S. Riffat and S. Omer, 2017. Low-temperature solar-plate-assisted heat pump: A developed design for domestic applications in cold climate (Pompes à chaleur assistées par panneaux solaires à basse température: conception d'un modèle pour des applications domestiques dans les climat). *International Journal of Refrigeration*, **81**: 134-150. DOI: 10.1016/j.ijrefrig.2017.05.020.

Morais, R., M.A. Fernandes, S.G. Matos, C. Serôdio, P.J.S.G. Ferreira and M.J.C.S. Reis, 2008. A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. *Computers and Electronics in Agriculture*, **62**(2): 94-106. http://doi.org/10.1016/j.compag.2007.12.004

Nayak, S. and G.N. Tiwari, 2008. Energy and exergy analysis of photovoltaic/thermal integrated with a solar greenhouse. *Energy and Buildings*, **40**: 2015-2021. http://doi.org/10.1016/j.enbuild.2008.05.007

Nayak, S. and G.N. Tiwari, 2009. Theoretical performance assessment of an integrated photovoltaic and earth air heat exchanger greenhouse using energy and exergy analysis methods. *Energy and Buildings*, **41**(8): 888-896. http://doi.org/10.1016/j.enbuild.2009.03.012

Nayak, S. and G.N. Tiwari, 2010. Energy metrics of photovoltaic/thermal and earth air heat exchanger integrated greenhouse for different climatic conditions of India. *Applied Energy*, **87**(10): 2984-2993. http://doi.org/10.1016/j.apenergy.2010.04.010

Pérez-Alonso, J., M. Pérez-García, M. Pasamontes-Romera and A.J. Callejón-Ferre, 2012. Performance analysis and neural modelling of a greenhouse integrated photovoltaic system. *Renewable and Sustainable Energy Reviews*, **16**(7): 4675-4685. http://doi.org/10.1016/j.rser.2012.04.002

Philipps, S.P., A.W. Bett, K. Horowitz and S. Kurtz, 2015. Current Status of Concentrator Photovoltaic (cpv) Technology. *National Renewable Energy Laboratory.* 1-25. http://www.ise.fraunhofer.de/en/ publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/ current-status-of-concentrator-photovoltaic-cpv-technology.pdf.

Poulet, L., Massa, G.D., Morrow, R.C., C.M. Bourget, R.M. Wheeler and C.A. Mitchell, 2014. Significant reduction in energy for plant-growth lighting in space using targeted LED lighting and spectral manipulation. *Life Sciences in Space Research*, **2**: 43-53. http://doi.org/10.1016/j.lssr.2014.06.002

Qoaider, L. and D. Steinbrecht, 2010. Photovoltaic systems: A cost competitive option to supply energy to off-grid agricultural communities in arid regions. *Applied Energy*, **87**(2): 427-435. http://doi.org/10.1016/j.apenergy.2009.06.012

Rekha, L., M. M. Vijayalakshmi and E. Natarajan, 2013. Green house saving potential of a Photovoltaic Thermal Hybrid Solar System for residential applications. *International Journal of Innovative Research in Science, Engineering and Technology*. **2**(1): 370–376.

Ren, J., S. Guo, Q. Cheng, Y. Shen and H. Feng, 2014. Synergistic effects of CO_2 and LED lighting on accumulation of terpenes in roots of *Gynura bicolor*. *Chinese Herbal Medicines*, **6**(3): 228-236. http://doi.org/10.1016/S1674-6384(14)60033-2

Runkle, E. and A. Both, 2012. Greenhouse energy conservation strategies. *Michigan State University-Extension Buletin*, (February), 1. http://www.biggrower.com/sites/default/files/54_TechnicallySpeaking_GPN0212 FINAL.pdf

Russo, G., A.S. Anifantis, G. Verdiani and G.S. Mugnozza, 2014. Environmental analysis of geothermal heat pump and LPG greenhouse heating systems. *Biosystems Engineering*, **127**: 11-23. http://doi.org/10.1016/j.biosystemseng.2014.08.002

Shyam, Al-Helal, I.M., A.K. Singh and G.N. Tiwari, 2015. Performance evaluation of photovoltaic thermal greenhouse dryer and development of characteristic curve. *Journal of*

Renewable and Sustainable Energy, **7**(3), 33109. http://doi.org/10.1063/1.4921408

Singh, D., C. Basu, M. Meinhardt-Wollweber and B. Roth, 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews*, **49**: 139-147. http://doi.org/10.1016/j.rser.2015.04.117

Sonneveld, P. and G.J. Swinkels, 2010. A CPV system based on NIR reflecting lamellae integrated into a greenhouse: optimizing of optics. *Advances in Science and Technology*, **74**: 297-302. http://doi.org/10.4028/www.scientific.net/AST.74.297

Sonneveld, P.J., G.L.A.M. Swinkels, G.P.A. Bot and G. Flamand, 2010a. Feasibility study for combining cooling and high grade energy production in a solar greenhouse. *Biosystems Engineering*, **105**(1): 51-58. http://doi.org/10.1016/j.biosystemseng.2009.09.012

Sonneveld, P.J., G.L.A.M. Swinkels, J. Campen, B.A.J. van Tuijl, H.J.J. Janssen and G. P. A. Bot, 2010b. Performance results of a solar greenhouse combining electrical and thermal energy production. *Biosystems Engineering*, **106**(1): 48-57. http://doi.org/10.1016/j.biosystemseng.2010.02.003

Sonneveld, P.J., G.L.A.M. Swinkels, B.A.J. van Tuijl, H.J.J. Janssen, J. Campen and G.P.A. Bot, , 2011. Performance of a concentrated photovoltaic energy system with static linear Fresnel lenses. *Solar Energy*, **85**(3): 432-442. http://doi.org/10.1016/j.solener.2010.12.001

Specifications of PM-75 Module of Central Electronics Ltd., 2016. Modules_Central Electronics Limited.

Steenis, E. Van, 2009. Greenhouse energy consumption alternative fuels. In: USDA Forest Service Proceedings, pp. 7-9.

Surahmanto, F., H. Saptoadi, H. Sulistyo and T.A. Rohmat, 2017. Biofuels Investigation of the slow pyrolysis kinetics of oil-palm solid waste by the distributed activation energy model by the distributed activation energy model. *Biofuels*, 1-8. http://doi.org/10.1080/17597269.2017.1387750

Tang, R., Y. Yang and W. Gao, 2011. Comparative studies on thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt-angles. *Solar Energy*, **85**(7): 1381-1389. http://doi.org/10.1016/j.solener.2011.03.019

Trouwborst, G., A.H.C.M. Schapendonk, K. Rappoldt, S. Pot, S.W. Hogewoning and W. van Ieperen, 2011. The effect of intracanopy lighting on cucumber fruit yield - model analysis. *Scientia Horticulturae*, **129**(2): 273-278. http://doi.org/10.1016/j.scienta.2011.03.042

Tyagi, V.V., S.C. Kaushik and S.K. Tyagi, 2012. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renewable and Sustainable Energy Reviews*, **16**(3): 1383-1398. http://doi.org/10.1016/j.rser.2011.12.013

Urena-Sanchez, R., A. Jesus Callejon-Ferre, J. Perez-Alonso and A. Carreno-Ortega, 2012. Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. *Scientia Agricola*, **69**(4): 233-239. http://doi.org/10.1590/S0103-90162012000400001

Wang, N., N. Zhang and M. Wang, 2006. Wireless sensors in agriculture and food industry - Recent development and future perspective. *Computers and Electronics in Agriculture*, **50** (1): 1–14. DOI: 10.1016/j.compag.2005.09.003.

Wojciechowska, R., O. Długosz-Grochowska, A. Kołton and M. Żupnik, 2015. Effects of LED supplemental lighting on yield and some quality parameters of lamb's lettuce grown in two winter cycles. *Scientia Horticulturae*, **187**: 80-86. http://doi.org/10.1016/j.scienta.2015.03.006

Wu, Y., P. Eames, T. Mallick and M. Sabry, 2012. Experimental characterisation of a Fresnel lens photovoltaic concentrating system. *Solar Energy*, **86**(1): 430-440. http://doi.org/10.1016/j.solener.2011.10.032

Xi, C., L. Lin and Y. Hongxing, 2011. Long term operation of a solar assisted ground coupled heat pump system for space heating and domestic hot water. *Energy and Buildings*, **43**(8): 1835-1844. http://doi.org/10.1016/j.enbuild.2011.03.033

Yang, N.-W., L.-S. Zang, S. Wang, J.-Y. Guo, H.-X. Xu, F. Zhang and F.-H. Wan, 2014. Biological pest management by predators and parasitoids in the greenhouse vegetables in China. *Biological Control*, **68**: 92-102. http://doi.org/10.1016/j.biocontrol.2013.06.012

Yano, A., M. Kadowaki, A. Furue, N. Tamaki, T. Tanaka, E. Hiraki and S. Noda, 2010. Shading and electrical features of a photovoltaic array mounted inside the roof of an east-west oriented greenhouse. *Biosystems Engineering*, **106**(4): 367-377. http://doi.org/10.1016/j.biosystemseng.2010.04.007

Yano, A., M. Onoe and J. Nakata, 2014. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. *Biosystems Engineering*, **122**: 62-73. http://doi.org/10.1016/j.biosystemseng.2014.04.003

Yildiz, A., O. Ozgener and L. Ozgener, 2012. Energetic performance analysis of a solar photovoltaic cell (PV) assisted closed loop earth-to-air heat exchanger for solar greenhouse cooling: An experimental study for low energy architecture in Aegean Region. *Renewable Energy*, **44**: 281-287. http://doi.org/10.1016/j.renene.2012.01.091

Zeinelabdein, R., S. Omer and G. Gan, 2017. Critical review of latent heat storage systems for free cooling in buildings. *Renewable and Sustainable Energy Reviews*, (July): 0-1. http://doi.org/10.1016/j.rser.2017.10.046

Zhang, X., X. Zhao, S. Smith, J. Xu and X. Yu, 2012. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. *Renewable and Sustainable Energy Reviews*, **16**(1): 599-617. http://doi.org/10.1016/j.rser.2011.08.026

Zhou, J., X. Wang, X. Wang, W. Zou and J. Cai, 2013. Greenhouse monitoring and control system based on zigbee. Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering (ICCSEE 2013), Iccsee, 2361-2364. http://doi.org/10.2991/iccsee.2013.591

Zimmermann, S., H. Helmers, M.K. Tiwari, S. Paredes, B. Michel, M. Wiesenfarth and D. Poulikakos, 2015. A high-efficiency hybrid high-concentration photovoltaic system. *International Journal of Heat and Mass Transfer*, **89**: 514-521. http://doi.org/10.1016/j.ijheatmasstransfer.2015.04.068

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