Advanced applications of solar energy in agricultural greenhouses

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Abstract

Energy is the largest overhead cost in the production of agricultural greenhouse crops in temperate climates. Moreover, the initial cost of fossil fuels and traditional energy are dramatically increasing. The negative environmental impacts, limited sources of fossil fuels and a high consumption of energy and food have caused the increase in demand for solar energy as a green and sustainable choice. Therefore, this paper reviews the solar energy application technologies in the environmental control systems of greenhouses (cooling, heating and lighting) mainly the generated energy of photovoltaic (PV) and solar collectors, as well as the PV water pumping for irrigation. Furthermore, this paper briefly discusses the economic analyses and the challenges for this technology.

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heating with a kerosene heater was in the range of 0.42–0.76 MJ m⁻². Concurrently, the hourly CO₂ emissions in the greenhouse with heat pumps were in the range of 9.5–24 g m⁻², while that in the greenhouse with the kerosene heater was in the range of 31–55 g m⁻². The prices of fossil fuels are rising rapidly [5] thereby, the major challenge for agricultural greenhouses is to find ways that improve energy efficiency combined with an absolute reduction of the overall energy consumption and related CO₂ emissions of the greenhouse industry [6]. Energy is the backbone of the modern world in terms of economic growth and solar energy is the main source of other renewable energies applied in agricultural and industrial sectors. Subsequently, concerns over energy security are mandating the use of green energy, such as solar energy sources, to reduce both CO₂ emissions and heating costs. On the other hand, paying more attention to food, environment and energy is more urgent than ever for sustainable greenhouse crop production. In the last few decades, solar energy has been developed intensively due to both technological improvements and government policies supportive of renewable energy development and utilization [7]. Nevertheless, solar energy technologies have a relatively high initial cost; they do not require fuel, they have low carbon emission, long term solar resources, less payback time, and they often require little maintenance [8,9]. The main purpose of greenhouses is to provide ideal growth conditions sustainable of microclimate for optimum plant growth and for early marketing of ornamental and vegetable crops [10] or early/year-round production. Most hot-season greenhouse vegetable plants grow rapidly at daily temperatures between 20–30 °C and 14–18 °C at night. In those areas of the world where winters are cold, with ambient temperatures less than 0 °C, heating systems are required to provide certain internal air temperatures for greenhouses [11]. Conversely, in tropical climates, where ambient temperatures in summer exceed 40 °C, cooling systems are required to prevent crops in greenhouses from high air temperature or the accumulation of heat during daytime higher than the optimal level [12]. There are numerous interrelated parameters that could influence the environmental control system in greenhouses such as the size of the greenhouse, its location, the type of covering material, heat storage method, quantity and quality of materials used, type of cultivation, desired day and night temperature of the inside air, and outside ambient conditions. The low valued energy, which is delivered by sustainable energy sources such as heat pumps, solar collectors and energy storage, has been successfully used in heating and cooling systems and is still being used in sustainable buildings [13,14]. As a consequence, the barriers to solar energy utilization in the agricultural sector require urgent attention and further research [15]. Recently, the conversion of cropland into PV plants has been increased. Thereby, combining PV panels and crops on the same area unit of land could alleviate the increasing competition for land between food and energy production. Out of all the reviewed papers, this paper briefly reviewed and discussed numerous new and feasible technologies for solar energy applications in the environmental control of greenhouses microclimate and its irrigation systems.

2. Environmental control systems in greenhouses

Environmental control in greenhouses is meant to achieve indoor temperatures, relative humidity, light and CO₂, which are as close as possible to optimal growth conditions for plants by using heating, cooling, ventilation, variable shading, and CO₂ enrichment and lighting systems as shown in Fig. 1. A greenhouse is a structure covered with transparent materials that utilize solar radiant energy and provide optimum growing conditions for plants [16]. The cover materials (plastic, glass and fiberglass) allow the short waves of solar irradiation to enter the greenhouse. The materials inside the greenhouse then re-radiate these waves as infrared radiation (IR), which is then detained inside the greenhouse by the transparent cover materials [17–20]. The solar irradiation inside the greenhouse depends upon its orientation as the East-west oriented greenhouse is more efficient in collecting solar radiation in winter than in summer [21,22]. The energy conservation in greenhouses could be improved by “Double thermal screen” and “Double glazing” with 60% reduction in energy demand. However, the highest improvement (80%) was observed by using a fully closed greenhouse without ventilation [23,24]. Solar cooling and solar heating applications in buildings have been intensively conducted and reviewed [25–35]. Nevertheless, certain studies have been implemented in agricultural greenhouses. Those studies were performed to develop the environmental control systems in greenhouses by thermal, dynamic and energy prediction modules to reduce energy consumption [36–40], a few applications have been conducted e.g. Vano et al. [41] developed a prototype of a microspherical semi-transparent solar module for greenhouse roof applications by using two modules. Firstly, they used 1500 spherical solar microcells (1.8 mm diameter, crystalline silicon) with 15.4 cells cm⁻² density in (108 mm × 90 mm) area; 39% of the area of this module was covered with the spherical solar microcells and the remaining 61% was transparent to allow the most sunlight to enter the greenhouse for promising plant photosynthesis. Secondly, 500 cells with 5.1 cells cm⁻² density when 30% of the area of this module was covered with the cells. They concluded that according to the annual electrical energy production per unit of greenhouse land area, the semi-transparent PV modules were potentially suitable for greenhouses with basic electrical environmental control systems in high-irradiation regions where electricity production could be high and winter demand low. The experiences in the integration of PV and greenhouse carried out in South Eastern Spain have been investigated in a greenhouse roof with 9.8% coverage area by means of 24 flexible thin film PV modules. The results indicated that the yearly electricity production normalized to the greenhouse ground surface was 8.25 kWh m⁻². The effect of flexible solar panels mounted on top of a greenhouse for electricity production on yield and fruit quality of tomatoes has been also revealed that there were no differences found in terms of total or marketable production under solar panels and control greenhouses [42]. Subsequently, solar panels did not affect the yield and price of tomatoes despite their negative effect on fruit size and color. The simulation of PV energy to predict its performance in greenhouses indicated that the panel with two axes provided the best performance, and both sensors supplied their best returns in the case of a dark blue sky. Moreover, the total satisfaction of the load was the only determining factor in choosing the components of an installation [43]. Van Beveren et al. [44] proposed an energy minimizing module to minimize the energy consumption of a commercial rose greenhouse especially for heating and cooling systems. They found that the energy saving potential as compared to the actual grower’s practice was substantial because of less natural ventilation on colder days and more natural ventilation and less heating on warmer days. Concurrently, relaxing the temperature and humidity decreases the energy input to the greenhouse.

2.1. Heating systems

It has been confirmed that the growth, yield and quality of greenhouse plants were affected when temperatures were below 12 °C or above 30 °C and the optimal temperature range is between 22 and 28 °C in the daytime and 15–20 °C at night [45]. The structure of a greenhouse is usually not sufficient to keep the inside air temperature at an appropriate level for the optimum
growth especially in cold climate. In addition, the shortage of
heating systems has adverse effects on the yield, cultivation time,
quality and quantity of the products in greenhouses; thereby,
auxiliary heating systems are required. Nevertheless, due to high
relative cost of energy, only a small number of greenhouse owners
will be able to use auxiliary heating systems. There are two types
of agricultural solar greenhouses which utilize solar energy for
heating purposes. Firstly, the passive greenhouses, which are uti-
lized as collectors and designed for maximizing the solar heat
gains by using a special cover and structure materials [2]. Sec-
ondly, the active greenhouses, which are equipped with solar
systems that utilize a separated collecting system from the
greenhouse with an independent heat storage system, such as
adding thermal energy inside the greenhouse from an air heating
system in addition to direct thermal heating [36,46–48]. The free
energy from the sun can be used to heat the greenhouse by col-
cecting and storing heat in summer in a semi-closed greenhouse
and in winter for heating. On top of that, it can be used to generate
electricity by integrating PV panels on the roof of the greenhouse
[49]. It has been predicted by a simulation model that the monthly
solar heating fraction may be correlated with a dimensionless
variable which involved mean daily solar radiation, total capture
factor of the greenhouse cover, and night-time heat load [50].

The performance of a demonstrated 2304 m² solar-heated greenhouse
equipped with a seasonal thermal energy storage system in China
was better than the performance of common heat pump heating
system [51]. The energy storage system was utilizing 4970 m³ of
underground soil to store the heat captured by a 500 m² solar
 collector in non-heating seasons through U-tube heat exchangers.
It was found that solar energy covered all the heating loads
directly or indirectly and no auxiliary heating equipment was
installed. Concurrently, this system was capable of maintaining an
interior air temperature 13 °C higher than that of the ambient
temperature. In another study, a seasonal thermal energy storage
using paraffin wax as a Phase Change Material (PCM) with the
latent heat storage technique had been investigated to heat a
greenhouse with a 180 m² floor area [52]. The system consisted of
flat plate solar air collectors of 27 m², latent heat storage (LHS)
tank of 11.6 m³, experimental greenhouse, heat transfer unit and
data acquisition unit. The LHS unit was filled with 6000 kg of
paraffin, equivalent to 33.33 kg of PCM per square meter of the
greenhouse ground surface area as shown in Fig. 2. PCM is a
substance with a high heat of fusion which melting and solidifying
at a certain temperature. It is capable of storing and releasing large
amounts of energy, PCMs are classified as latent heat storage (LHS)
units. Therefore, it was indicated that the average net energy and
exergy energy efficiencies were 40.4% and 4.2%, respectively.

It has been reported that using geothermal energy by earth-
tube heat exchanger systems, heat pipe heating systems and
ground source heat pumps systems could reduce the heating loads
by 20–70% at various locations [36,53]. The effective use of ground source heat pumping systems with suitable technology in the modern greenhouses could play a leading role in the future for heating, cooling and dehumidification of greenhouses. Recently, there is a composite system; same system could be used for heating the greenhouses in winter and cooling them in summer [54,55]. Yang et al. [56] developed a heating and cooling system to utilize surplus air thermal energy (SATE) and underground water thermal energy (UWTE) as heat sources. The system consisted of a heat pump system including high and low temperature heat storage tanks, fan coil units (FCU) in the greenhouse, and an underground water source. They successfully recovered and utilized SATE and UWTE for cooling and heating when operating this system in February and March. On a clear day, the SATE and UWTE were measured to be 878.2 MJ and 603.1 MJ, respectively. SATE and UWTE are natural and sustainable energy sources which save energy and increase agricultural benefits. Various renewable energy sources (biogas, soil and sun) have been investigated for heating a greenhouse in Turkey including a flat plate solar collector with water antifreeze solution (20%), aluminum plate, and expansion tank [57]. Results illustrated that solar energy can be stored underground and then used to raise soil temperature and to heat biogas reactors. Moreover, solar energy system as a standalone solution could be feasible with high storage temperatures. The efficiency of a photovoltaic-geothermal heat pump integrated system (PV-GHP) as a greenhouse heating system and a conventional hot air generator using liquefied petroleum gas (LPG-HG) were compared in terms of environmental impact analysis in Italy [58]. The microclimatic conditions, the thermal energy produced and the electricity consumption were analyzed. Consequently, the PV-GHP was preferable because it has a good impact on the environment. Due to the plant with the PV-GHP reduces carbon emissions by 50%. Subsequently, to assess the sustainability of the geothermal heat pump plant, the estimated payback-time for energy and for carbon emissions were 1 year and 2.25 years, respectively. A solar air heater (SAH) system was investigated experimentally for heating a greenhouse in Iraq [59]. Six solar air heaters with a single glass cover and a V corrugated absorber plate connected in parallel were mounted on the greenhouse roof. The mass flux of air through the collectors was varied from 0.006 to 0.012 kg s\(^{-1}\) m\(^{-2}\). An air mass flux of 0.012 kg s\(^{-1}\) m\(^{-2}\) was found to provide about 84% of the daily heat demand to keep the inside air temperature of greenhouses at 18 °C during winter, SAH could cover all the daily heating demand with an excess of approximately 46%. Additionally, the thermal performance of a new solar air heater using a packed bed of spherical capsules with the latent heat storage system has been investigated in east–west orientated greenhouses in Tunisia [60]. It was observed that the nocturnal temperature inside the heated greenhouse was higher than that of the conventional greenhouse by 5 °C. The relative humidity decreased at night time inside the heated greenhouse from 10–20%. Therefore, the solar air heater system attained 31% of the total heat requirements at nighttime and reduced CO\(_2\) emissions. Benli et al. [61] analyzed and discussed the thermal performance of a PCM thermal storage unit consisting of a 10-pieces solar air collector for space heating of a greenhouse and charging of PCM as CaCl\(_2\)H\(_2\)O with a melting temperature of 29 °C. The hot air delivered by ten-piece solar air collector passed through the PCM to charge the storage unit then to heat the ambient air before being admitted to a greenhouse. They reported that the proposed size of collectors integrated PCM provided about 18–23% of the total daily thermal energy requirements of the greenhouse for 3–4 h compared to the conventional heating device. Moreover, the nocturnal temperature inside a greenhouse equipped with a solar air heater collector with latent heat storage and nocturnal shutter was higher than that of the outside temperature by approximately 7 °C [62,63]. The solar air collector stores solar energy during daytime by reducing the internal temperature during the day and supplies it for heating at night. On top of that, it has been observed that the temperatures of greenhouse air can be increased by around 7–8 °C during winter season, when the photovoltaic/thermal (PV/T) operated and coupled with the earth air heat exchanger (EAHE) at night [64]. Mehrpooya et al. [65] investigated the optimum performance of the combined solar collector and geothermal heat pump system to meet the heat load for greenhouses in terms of economic and technical points of view. Results indicated that the selected model has mean seasonal coefficient of performance of 4.14, borehole length of 50 m, and 3 boreholes. Moreover, the total collector area of the gained model was 9.42 m\(^2\). Sonneveld et al. [66] studied the performance of a new type of greenhouse, which combines reflection of near infrared radiation (NIR) with electrical power generation using hybrid PV/T collector modules as shown in Fig. 3. In addition to the generation of electrical and thermal energy, the reflection of the NIR resulted in improved climate conditions in the greenhouse. The typical yearly yield of this greenhouse system was as a total electrical energy of 20 kWh m\(^{-2}\) and a thermal energy of 160 kW h m\(^{-2}\). Thus, the heating system could operate independent of fossil fuels for this greenhouse.
Moreover, decreasing the exchanger inlet green temperature at a capillary polypropylene heat exchanger integrated in the houses according to Tunisian weather. Results of simulation revealed that the temperature at the collector outlet decreases when the tank volume increases. Moreover, decreasing the exchanger inlet flow rate was a good solution to reduce heating losses. They suggested a flat plate collector and a 200 L tank as the best storage system to increase the inside air temperature of the greenhouse by 5 °C and provide suitable conditions for growing tomatoes. Additionally, Kryan et al. [68] developed a mathematical model (Matlab/Simulink) to investigate the thermal behavior of a greenhouse, which is heated by a hybrid solar collector system. This hybrid system contains an evacuated tube solar heat collector unit, an auxiliary fossil fuel heating unit, a hot water tank, control unit and piping units. This model has been developed to predict the storage water temperature, the indoor temperature and the amount of auxiliary fuel, as a function of various design parameters of the greenhouse such as location, dimensions and meteorological data of the region. Results of simulations indicated that revising the existing fossil fuel system with the proposed hybrid system was economically feasible for most cases and it has a positive environmental impact; however, it requires a slightly longer payback period than expected.

2.2. Cooling systems

A greenhouse cooling system is used to decrease the accumulated heat energy from inside to outside the greenhouse by various techniques such as ventilation (natural and forced), shading/reflection, evaporative cooling (fan-pad system, mist/fog and roof cooling). Subsequently, a PV hybrid system for cooling a tropical greenhouse has been investigated in Selangor, Malaysia [69]. This system included 48 solar PV Panels with 18.75 W for each, one inverter, 1 charge controller and a battery bank (including 12 batteries). The load consisted of two misting fans for cooling a greenhouse with 400 W electric power at a five hours daily operation. It was found that the PV system could be suitable in supplying electricity to cover the loads requirement demands without using extra energy from the grid. Moreover, the passive cooling system has been used as a low energy consuming technique. Consequently, solar chimney (SC) and underground earth to air heat exchanger (EAHE) have been used for the cooling and ventilation of solar houses [70]. The results revealed that the solar chimney can be perfectly used to power the underground cooling system during the daytime, without any auxiliary electricity. Therefore, the comparison of optical and thermal behavior of a solar PV greenhouse and a similar glass greenhouse, devoted to the production of soil-less tomatoes in three different Italian areas have also been investigated with computational aspects and methods of the TRNSYS simulation [71]. It was observed that the integrated PV roof saved energy in air conditioning for all three locations with an average of 30% for summer cooling and 11% for winter heating. In another study, the energy performance of a solar PV system-assisted earth-to-air heat exchanger (underground air tunnel) for greenhouse cooling has been investigated. It was found that the average value of temperature difference between inlet and outlet of earth-to-air heat exchanger system (EAHE) was 8.29 °C. The total electric energy consumption of this system was 8.10 kWh by operating it for about 11 h/day, when 34.55% of this energy demand was provided from PV cells [13]. In an Indian study, Ganguly et al. [72] modulated and analyzed a greenhouse-integrated power system consisting of solar PV panels, electrolyzer bank and polymer electrolyte membrane (PEM) fuel cell stacks. They found that 51 PV modules, each of 75 Wp along with a 3.3 kW electrolyzer and 2 PEM fuel cell stacks, each of 480 W, can support the energy requirement of a 90 m² floriculture greenhouse with a fan-pad ventilated system. Whereas, under the Saudi Arabian arid climate, the solar radiation availability and the demand for electricity were studied and quantified to optimize the PV greenhouse for desert climate operation [73]. The PV greenhouse system consisted of the 14.72 kW PV arrays, a 3000 A h battery storage system, a 15 kW power conditioning system and data measurement collection system in a 9 m wide and 39 m length of fiberglass greenhouse. Results showed that the PV greenhouse subsystem met the required load of the cooling and pumping equipment. Moreover, its performance was satisfactory. In a Japanese study, a greenhouse side window ventilation controller, driven by PV energy, has been developed for saving power [74]. The side window controller was moved using power from a combination of an amorphous silicon PV module of 0.078 m² with rated maximum power of 3.2 W and a battery capacity of 28 A h in a 5 h rate (12V). The greenhouse side windows were well operated according to the greenhouse temperature without outage. Consequently, the interior temperatures of the greenhouse were concentrated between the side-vent opening and shutting temperatures. Therefore, PV power systems are applicable for a greenhouse environmental control system. An experiment was performed by Mongkon et al. [75] which investigated the cooling performance of the horizontal earth tube system (HETS) when placed horizontally at a depth of 1 m in loam soil under the lawn surface to the North of the agricultural greenhouse under the tropical climate. They found that increasing tube diameter and air velocity could enlarge the coefficient of performance more than other parameters. Moreover, operating the HETS during day time with a clear sky could decrease the temperature and lead to better results in the greenhouse during summer months. On the other hand, the feasibility for combining cooling and high grade energy production in

Fig. 3. Greenhouse concept (A) with a spectral selective cylindrical mirror and a collector in the focal line (Yellow line indicates visual light and red line indicates NIR radiation). (B) The complete greenhouse (with permission of the copyright owner) [66].
a new design for solar greenhouses has been investigated [76] as a solution for energy supply in winter and cooling in summer by applying seasonal storage of excess solar energy and exploiting this for heating in winter. Meanwhile, the excess solar energy was directly converted to high grade electric energy for heating. Therefore, this system was cheaper with energy savings of about 35% compared to heating by furnace.

There are a number of solar driven cooling technologies such as solar-PV-driven air conditioning technologies and solar-thermal systems. The PV-driven air conditioning uses a conventional vapor compression air conditioning cycle in which the electrical input is provided by PV panels. The solar-thermal system has three different types. The first is based on a solid desiccant. The second type of thermally driven system is absorption cooling and the third is the adsorption cycle [77, 78] as shown in Figs. 4 and 5.

2.3. Lighting systems

Plant growth requires an appropriate light intensity. Excessively high or low intensity could disrupt photosynthesis in the plant. In addition, light not only has effects on plant morphology, physiology and microstructure but also has an important impact on the plant production, because plants produce food for themselves and others when plant use the energy from light to convert CO₂ and water into carbohydrates and oxygen [79–84]. Normally, different plants require different amounts of light for optimal growth. Plants are classified into high energy and long-day (LD) or low energy and short-day (SD) plants, depending on the intensity of light they need.

Supplemental lighting is essential to produce greenhouse crops during cloudy, low-light days, to increase total daily light levels during short days of natural light and to extend the day length or photoperiod to initiate or prevent flowering. However, adding supplemental lighting to a greenhouse is a relatively expensive investment. Operational costs are relatively high, approaching or surpassing the cost of heating in some applications, and different sources of light produce different amounts of light at different wavelengths. Nevertheless, supplemental lighting is usually not required in greenhouses in many regions from May through November. The minimum recommended light intensity for floriculture crops is 2 μmol m⁻² s⁻¹ (100 lux) at plant height. Furthermore, the movable shade curtains can reduce the energy load in the greenhouse crop during warm and sunny conditions and they reduce heat radiation losses at night. Under the sunny conditions of winter seasons, the structures covered with shading materials are suitable for growing crops that can grow at photosynthetically active radiation (PAR) less than 150 W m⁻². However, under cloudy conditions few plants can grow at PAR less than 30 W m⁻² [85]. Therefore, integrating the transparent PV modules on the roof of greenhouses not only decreases the energy load, but
also generates appropriate energy for artificial lighting in winter and forced ventilation in summer. Additionally, agrivoltaic or Agrophotovoltaic (APV) is to produce agricultural commodities under the photovoltaic modules in open fields such as, potatoes, onions, vegetables, salads, herbs, oil plants, fruits (grapes, apple, pear, cherry, etc.) and animals (sheep, chicken, cattle, etc.). Agrophotovoltaic could protect the crops against high temperatures, or increased water availability for the crops if the rainfall is concentrated and infiltrated on a limited cropped area. The height level of the solar panels has no impact on the total quantity of radiation available at the soil level but the low level has a very large impact on the heterogeneity of radiation at ground level. Agri-voltaic systems could maximize land use and productivity efficiency by a 35–73% under shading density of 50% from the incoming radiation of PV panels [86,87]. Crops can achieve high yield under the fluctuating shade of PV panels. Subsequently, under a dry Mediterranean climate, microclimate measurements at crop level below PV panels indicated that these systems could contribute to alleviate climatic stress and to save water [88]. PV systems require land to intercept incoming solar radiation. Consequently, the area required for both food and energy supply depends on land use benefits per square meter [89]. There are a number of opportunities for APV in the agricultural sector such as protection from radiation stress, lower water demand, less salinization due to less irrigation, soil quality improvement, higher crop yields, different species adapted to lower radiation conditions can be cultivated, existing PV structures can be used for shading, product diversification for farmers and higher income security. Moreover, APV can be used for water desalination of groundwater in the poor land [90]. Cossu et al. [91] investigated the effects of shading from the PV array on tomato plants in an east-west oriented greenhouse of which 50% of its roof area was replaced with PV modules. Meanwhile, they integrated the natural radiation with supplementary lighting powered by PV energy as shown in Fig. 6A. They found that PV array reduced the availability of solar radiation inside the greenhouse by 64%. However, the supplementary lighting, powered without exceeding the energy produced by the PV array, was not enough to affect the crop production, whose revenue was lower than the cost for heating and lighting. Therefore, designing PV greenhouses is useful for both energy and crop production. Solar-LED was used alternatively to fuel-based lighting for night fishing in Tanzania [92]. Subsequently, solar energy could be used in greenhouses for supplementary lighting at night for growing long-day floriculture crops. Yano et al. [93] investigated the generated electrical energy of different tilt angles for four amorphous-silicon PV modules arranged in an arch formation at the Northern end of the Gothic-arch style roof of a north-south oriented greenhouse. Two were attached to the inner surface of the East roof with tilted angles of 20° and 28°. The other two were attached to the inner surface of the west roof with tilted angles of 20° and 28°. The total area of PVs was 1.7 m², which were 1.5% of the roof area as shown in Fig. 6B. The results illustrated that the low tilt angle module generates more electrical energy when it was mounted inside the roof of a north–south oriented greenhouse. Furthermore, Kadowaki et al. [94] used PV arrays to supply electricity for a greenhouse. The PV array was mounted inside the South roof of an east-west oriented single-span greenhouse, with a hydroponic Welsh onion (Allium fistulosum L.) as shown in Fig. 6C. Meanwhile, effects of PV array shading (straight-line and checkerboard of array distribution 12.9% of the roof area for each) on the onion growth were investigated. The results showed that the PV array for straight-line shading decreased the fresh weight (FW) and dry matter weight (DW) of the Welsh onion comparing to the checkerboard and control. Nevertheless, the electrical energy generated in the shading of greenhouses by PV arrays was more beneficial than that of the control greenhouse. Concurrently, the distribution of sunlight energy in an east-west oriented single-span greenhouse equipped with a PV array (12.9% of the roof area) inside a Gothic-arch style roof and the electrical energy generated by the PV array were studied [95] when the PV array was straight-line (PVs array) and checkerboard (PVc array) with 30 PV modules facing the southern sky for each. It was found that under the assumption of a cloudless sky, the PVs and PVc arrays are estimated to generate electricity of 4.08 GJ y⁻¹ and 4.06 GJ y⁻¹, respectively. Additionally, the checkerboard arrangement improved the unbalanced spatial distribution of received sunlight energy in the greenhouse. Moreover, a greenhouse shading screen control system has been developed and operated by a stand-alone power system with 4.8 W amorphous silicon PV module and a battery of 28 A h capacity in a

![Fig. 6. Integration of PV panels with greenhouses. (A) 50% of its roof area covered with PV in Italy [91]. (B) 1.5% of the greenhouse roof area. (C) the PV array covered 12.9% of the greenhouse roof area. B and C, respectively in Japan (with permission of the copyright owner) [93–95].](image-url)
5 h rate [96]. It was observed that the capacity of this system was sufficient for shading screen operation.

In recent years, Liu et al. [97] reported that the Chinese government has supported many projects for the applications of the thin film PV solar greenhouses at different provinces in China such as Hebei project in an area of 6687 hm² for generating electric power of 120 MW Fig. 7.

The intensive study of solar energy applications in greenhouses worldwide showed that cooling and lighting systems were conducted by the stand alone/ integrated PV technologies and both systems were more viable in hot climates than in moderate climates. Using PV on the roof of greenhouses for shading in hot climate not only decreases the inside air temperatures of greenhouses and the high solar radiation, but also generates energy for operating the cooling equipment. On the other hand, a heating system was applied by the integrated systems of flat plates or evacuated tubes as solar heaters and a hybrid PV cells with thermal collectors as shown in Table 1.

3. The photovoltaic water pumping in irrigation systems

Historically, solar water pumps have not been widely used in greenhouses. Nevertheless, the utilization of PV systems in all irrigation applications has increased in the last decades especially in remote and desert areas, where no reliable electricity supply is available. The studies of PV-water pumping systems related to irrigation applications were extensively reported and the water flow rate has been predicted to achieve an efficient management of water demand in remote and desert areas [101–110], and the whole possible methods for developing this system have been reviewed [111] as shown in Figs. 8 and 9. The prediction of water flow rate by theoretical and experimental analysis in a PV water pumping system has been investigated for achieving the optimal sizing of PV-based water pumping system and optimum utilization of solar energy and water management in remote and desert areas. It was indicated that developed models can predict accurately the hourly flow rate based on measured hourly air temperature and solar irradiation [103,112–115]. On the other hand, it was reported that the PV

![Fig. 7. Photos of solar energy applications in agricultural greenhouses. a. Thin film PV solar glass greenhouses (with permission of the copyright owner) [97], b. solar collector of evacuated tube, China.](image)

<table>
<thead>
<tr>
<th>Environmental control systems in greenhouses</th>
<th>Solar energy applications</th>
<th>Country</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating and cooling</td>
<td>A semi-transparent PV modules</td>
<td>Japan</td>
<td>[41]</td>
</tr>
<tr>
<td>Heating</td>
<td>A flexible thin film PV modules (9.8 % of the roof area)</td>
<td>Spain</td>
<td>[42,98]</td>
</tr>
<tr>
<td>Heating</td>
<td>A flat plate solar air collectors with the latent heat storage technique</td>
<td>China</td>
<td>[51]</td>
</tr>
<tr>
<td>Heating</td>
<td>Earth-tube heat exchanger systems ( thermal energy)</td>
<td>Turkey</td>
<td>[52]</td>
</tr>
<tr>
<td>Heating</td>
<td>A flat plate solar collector with water antifreeze solution (% 20); aluminum plate</td>
<td>India</td>
<td>[53]</td>
</tr>
<tr>
<td>Heating</td>
<td>A Photovoltaic-geothermal heat pump integrated system (PV-GHP)</td>
<td>Turkey</td>
<td>[57]</td>
</tr>
<tr>
<td>Heating</td>
<td>Solar air heaters on the roof</td>
<td>Iraq</td>
<td>[59]</td>
</tr>
<tr>
<td>Heating</td>
<td>Solar air heater using a packed bed of spherical capsules with the latent heat storage system</td>
<td>Tunisia</td>
<td>[60]</td>
</tr>
<tr>
<td>Heating</td>
<td>A phase change thermal storage unit consisted of ten pieced solar air collectors</td>
<td>Turkey</td>
<td>[61]</td>
</tr>
<tr>
<td>Cooling</td>
<td>Hybrid PV/T collector</td>
<td>Netherlands</td>
<td>[66]</td>
</tr>
<tr>
<td>Cooling</td>
<td>PV hybrid system</td>
<td>Malaysia</td>
<td>[69]</td>
</tr>
<tr>
<td>Cooling</td>
<td>A solar flat-plate collector</td>
<td>Morocco</td>
<td>[99]</td>
</tr>
<tr>
<td>Cooling</td>
<td>Solar chimney (SC) and underground (EAHE)</td>
<td>Iran</td>
<td>[70]</td>
</tr>
<tr>
<td>Cooling</td>
<td>PV greenhouse</td>
<td>Italy</td>
<td>[71]</td>
</tr>
<tr>
<td>Cooling</td>
<td>A greenhouse-integrated power system with PV-greenhouse</td>
<td>India</td>
<td>[72]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>Side ventilation driven by PV energy</td>
<td>Saudi Arabia</td>
<td>[73]</td>
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<tr>
<td>Lighting and shading by shading</td>
<td>HETS bedded underground of 1 m</td>
<td>Japan</td>
<td>[74]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>PV array (50% of the roof area)</td>
<td>Thailand</td>
<td>[75]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>PV array (1.5% of the roof area)</td>
<td>Netherlands</td>
<td>[76]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>PV array (12.9% of the roof area)</td>
<td>France</td>
<td>[86,87,100]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>A stand-alone PV for shading screen control</td>
<td>Italy</td>
<td>[91]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>Thin film PV solar glass greenhouses</td>
<td>Japan</td>
<td>[93]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>Thin film PV solar glass greenhouses</td>
<td>Japan</td>
<td>[94,95]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>Thin film PV solar glass greenhouses</td>
<td>China</td>
<td>[96]</td>
</tr>
<tr>
<td>Lighting and shading by shading</td>
<td>Thin film PV solar glass greenhouses</td>
<td>China</td>
<td>[97]</td>
</tr>
</tbody>
</table>
array and the storage tank are the most important elements for the optimal designing of the PV water pumping [105,116]. The loss-of-load probability (LLP) of a PV water pumping system has been estimated by drawing LLP maps with normalized parameters using long term observed or generated sequences of meteorological data, which provides a generalized and practical graphical tool for systems sizing [117]. Therefore, a poor design of the PV array and/or the storage tank could affect system reliability and create a deficit of daily water demand for the population. On the other hand, the effect of pumping head on solar water pumping system by using the optimum PV array configuration, adequate to supply a DC Helical pump with an optimum energy amount, under the outdoor conditions of the Madinah site in Saudi Arabia has been conducted [118]. The experimental results revealed that the efficiency increased with the increasing of solar radiation until the pump reached their maximum power. Furthermore, the system efficiency increased with decreasing pumping heads during low solar radiation, and the optimum pumping head corresponds to the best average system efficiency at the head of 80 m. A solar water pumping system has numerous advantages; for example, besides no cost for fuel and maintenance, it has no noise and pollution for the environment. Meanwhile, many parts of the world are rural in nature and consequently do not have electrical distribution lines in many parts of villages, farms, and ranches. Thereby, using small scale applications of PV powered water pumping is more cost effective in these areas and in its greenhouses [119]. Recently, the Governments of some developing countries such as Egypt started to support the applications of solar energy in the desert areas to increase the reclamation of agricultural lands and to maximize the utilization of solar energy, as well as to guarantee the sustainability of food and energy production.

The performance of the directly coupled PV water pumping system has been investigated at different conditions of varying solar irradiance values and two static head hydraulic system configurations [110]. The system consisted of a 1.5 kW PV array, DC motor and a centrifugal pump as shown in Fig.8. It was observed that the system is suitable for low delivery flow rate applications and it was a low cost design, without any complex electronic control and auxiliary systems. The performance of four submersible PV water pumping systems in Tunisia has been investigated [120] and results showed that the maximum overall efficiency of the system was 3.7% and the mean efficiency of the whole system was 2.5% at constant head pumping. Whereas, the potential of solar irrigation systems for sustaining pasture lands in arid regions in China [121] reported that PV pumping could cover about 8.145 million ha appropriately for the grasslands.

4. Economic analyses

The economic analyses include the initial costs, energy cost and payback period in comparison with the expected service life cycle of any solar system installation [122–125]. Subsequently, to size the solar energy for cooling, heating and lighting systems, a number of parameters should be considered such as the energy

![Fig.8. Schematic diagram of PV water pumping system (with permission of the copyright owner) [110].](image1)

![Fig.9. Layout of PV irrigation system (with permission of the copyright owner) [106, 107].](image2)
consumption for a single system and equipment for environmental control, the required air temperature and relative humidity inside the greenhouse, ambient temperature, and daily use. Consequently, in order to evaluate the economic analysis, the solar energy applications in the environmental control systems of greenhouses should be compared to conventional systems. For example, the heating cost in Tunisia and payback times of solar air heater with latent heat storage collectors and the conventional systems revealed that the payback period of solar air heater with latent storage was 5 years if the system operates only 3 months per year as shown in Table 2. Furthermore, it has been reported that PV module prices have had dramatic reductions in the past decade by 80%, while the prices for competing gasoline or diesel fuel have been increased by over 250% [126]. PV water pumping technology is the most cost-effective for steady pumping needs such as community water supply or livestock watering, and it is considered as a sustainable and economical solution to provide water for land irrigation [127]. In a word, the clean environmental impact of solar energy could also be considered as a great benefit.

The economic study of solar thermal cooling systems which covered most climatic regions worldwide showed that solar thermal cooling is more viable in hot climates than in moderate European climates. The specific costs per kWh cooling in German locations vary between 0.25 and 1.01 €/kWh, in Spanish locations between 0.13 and 0.30 €/kWh. In hot climates like Jakarta and Riyadh, the specific costs were as low as 0.09–0.15 €/kWh. Furthermore, the maximum investment costs were calculated and got a payback time of 10 years [128]. Fathioni et al. [129] studied the technical and economic potential of solar energy application in Indonesia. They found that Makassar got the shortest payback period for 11 years and Banjarmasin got the longest payback period of 17.6 years. Similar results were found in Spain which indicated that the payback time to return the investment capital of integrated PV panels on greenhouses would be about 18 years [42]. Furthermore, solar energy application can reduce the greenhouse gas emission by up to 243,252 tons per year as shown in Table 2. Furthermore, it has been reported that the total annual heating requirement was between 3,592,848 and 10,459,688 MJ/ha. The calculated total annual and hourly costs per ha were 65,891.5–151,220.6 $/year and 23.8–34.2 $/h, respectively. Whereas, the energy requirements for seasonal heating (October 15th to March 15th) at Turin and Remo, in Italy ranges from 134 kW h m−2 to 209 kW h m−2 which included the losses of air infiltration and the heating cost can be valued into 15.7 € m−2 for Turin and 10.56 € m−2 for Sanremo [8]. Furthermore, in [4,6,8,41] a collected literatures survey of annual electrical energy consumption per unit greenhouse area at different locations with electrical load as shown in Table 3 reported that energy consumption deviated from (0.1–528 kW h m−2 yr−1) according to the location of greenhouses and the level of applied technology, e.g. for maintaining the optimal microclimatic conditions, cooling and heating systems are required. Therefore, solar energy applications in agricultural greenhouses should be given a high priority in future studies to reduce energy consumption. Nevertheless, the solar energy technologies in agricultural greenhouses have significant advantages; a lot of challenges are remaining. Firstly, PV water pumping operation and maintenance, as well as the distances to the grid, the water elevation, and water storage, are critical factors when determining the economic feasibility of PV pumping technologies [131,132].

Secondly, the high humidity rates and the agrochemicals could affect the long-term life of the PV arrays integrated on the greenhouse roofs. Additionally, the variability of the microclimatic conditions in PV greenhouses, particularly the reduction of light and solar radiation under PV panels could also have an effect. Since shading not only influences the amount of light received by plants but also changes microclimatic conditions, such as air and ground temperature, humidity and CO2 concentrations, which are important factors for plant growth [137,138]. Subsequently, to integrate PV arrays with greenhouses, a specific and new PV greenhouse design or adaptation of existing structures are required. It has been reported that the position and orientation of PV modules on greenhouses roofs must be considered carefully to provide a sufficient electrical energy with minimum shading of plants [93–95]. Consequently, for a north-south oriented greenhouse in the Northern hemisphere, a PV module mounted on the North end of the greenhouse roof casts the smallest shadow in the greenhouse. Whereas, for an east-west oriented greenhouse, the South-facing roof is suitable for generating electricity by PV modules, but the effects of shading by the PV modules will be.

### 5. Conclusion and challenges of solar energy in greenhouses

This paper has reviewed state-of-the-art solar energy applications in agricultural greenhouses, with the focus on the environmental control systems, particularly heating, cooling, lighting and irrigation systems. A variety of solar energy heating systems have been discussed, including solar air heaters and solar thermal collectors. Among solar heating systems, the solar air heaters show the best overall performance. Furthermore, the integrated photovoltaics in greenhouse roofs have also been presented, in terms of energy generated, shading effects on plants, and the environmental impact by decreasing CO2 emissions.

Subsequently, studies from various regions of the world have conducted many experimental applications and theoretical investigations of solar energy on the agricultural greenhouses. Thus, different types of solar application systems in the environmental control of greenhouses were discussed. The previous studies revealed that PV systems and/or solar thermal system would be the suitable options in greenhouse application especially for remote and desert areas. Moreover, solar technologies are environment friendly, low maintenance, have no fuel cost, and increase the overall land productivity by integrated PV panels in agricultural land or greenhouses such as APV systems. The decrease of PV module prices will make the PV greenhouses and PV powered water pumping systems more feasible in the near future and it can pay back the initial cost in a short time. Climate changes increase the energy consumptions in greenhouses along with the increasing of the conventional fuels prices (coal and diesel). Canakci et al. [5] estimated the heating requirements and their costs for a gothic roofed and coal heated, plastic model greenhouse located in an area with 1 ha representing modern greenhouses in Turkey. They reported that the total annual heating requirement was between 3,592,848 and 10,459,688 MJ/ha. The calculated total annual and hourly costs per ha were 65,891.5–151,220.6 $/year and 23.8–34.2 $/h, respectively. Whereas, the energy requirements for seasonal heating (October 15th to March 15th) at Turin and Remo, in Italy ranges from 134 kW h m−2 to 209 kW h m−2 which included the losses of air infiltration and the heating cost can be valued into 15.7 € m−2 for Turin and 10.56 € m−2 for Sanremo [8]. Furthermore, in [4,6,8,41] a collected literatures survey of annual electrical energy consumption per unit greenhouse area at different locations with electrical load as shown in Table 3 reported that energy consumption deviated from (0.1–528 kW h m−2 yr−1) according to the location of greenhouses and the level of applied technology, e.g. for maintaining the optimal microclimatic conditions, cooling and heating systems are required. Therefore, solar energy applications in agricultural greenhouses should be given a high priority in future studies to reduce energy consumption. Nevertheless, the solar energy technologies in agricultural greenhouses have significant advantages; a lot of challenges are remaining. Firstly, PV water pumping operation and maintenance, as well as the distances to the grid, the water elevation, and water storage, are critical factors when determining the economic feasibility of PV pumping technologies [131,132].

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### Table 2

Comparison of the cost and the payback times between solar air heating and the fuel boiler [60].

<table>
<thead>
<tr>
<th>System cost ($)</th>
<th>Hybrid systems (SAHSC + Fuel boiler)</th>
<th>Conventional systems (Fuel boiler)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Operation cost ($)</td>
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<tr>
<td></td>
<td></td>
<td>3600</td>
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<tr>
<td></td>
<td></td>
<td>1800</td>
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<tr>
<td></td>
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<td>Annual energy (kWh)</td>
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<td></td>
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<td></td>
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<td>150</td>
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<td></td>
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<td>Gain of energy (kWh)</td>
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<td></td>
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<td>1800</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Total cost ($)</td>
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<tr>
<td></td>
<td></td>
<td>4014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2717.8</td>
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</tbody>
</table>
great. Thereby, a specific crop management for choosing the most suitable crops or vegetables can be suggested particularly in hot seasons such as, lettuce, spinach carrot, turnips, cabbage and broccoli as well as the indoor ornamental plants and floriculture which need low light intensities. Furthermore, using semi-transparent PV panels can provide sufficient light intensity for plants and maximize the annual electrical energy production per unit greenhouse land area especially in high-irradiation regions. Concurrently, it was indicated that a microspherical transparent solar cell has an isotropic ability for photoreception and it can provide constant quantities of electricity over widely differing sunlight incident angles [139]. Thus, it can be suitable for greenhouse-roof and greenhouse-wall embedded applications. Finally, the length of pipelines between the solar collectors and heat storage tanks for cooling or heating systems may cause heat losses. Nevertheless, the future prospects expect that solar electric cooling will require the lowest capital investment in 2030 due to the high coefficient of performances (COPs) of vapor compression refrigeration and the strong cost reduction targets for PV technology [78]. In conclusion, solar energy can provide cheap and clean energy for agricultural greenhouses (cooling, heating, lighting, and irrigation) applications all over the world. In recent years, the optimum utilization of food, water and energy resources has become an essential issue especially in rural areas of high solar potential and no grid electricity. Additionally, the utilization of green energy and the sustainability for food production in agricultural greenhouses are the most important challenges for humanity in this century. Therefore, further experiments and studies addressing this technology must be performed for supporting the agricultural greenhouses and the applications of solar energy. Meanwhile, the governments should create a number of opportunities and energy policies to develop this technology.

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