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Advanced applications of solar energy in agricultural greenhouses

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A R T I C L E I N F O

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A B S T R A C T

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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1. Introduction

The increase of world population and energy consumption has directed researchers and scientists to provide a sufficient amount of food and energy technology by using alternative sources. In addition, climate changes and poor water resources reveal that protected cultivation in greenhouses has become the favored way to develop the agricultural sector. Greenhouse production is carried out by taking advantage of favorable climate (air temperature, relative humidity and lighting) while keeping the operational cost at a minimum [1,2]. Heating and cooling systems are two major costs involved in greenhouses production. Heating is usually provided by burning fossil fuels (diesel, fuel oil, liquid petroleum, gas) which increase carbon dioxide (CO_2) emission, or by using electric heaters, which consume more energy [3]. Tong et al. [4] conducted an experiment in Japan and reported that the hourly energy consumption for heating from January to March in the greenhouse with heat pumps was in the range of 0.22 to 0.56 MJ m^{-2}, while

Abbreviations: PVs, Photovoltaic array for straight-line shading; PVc, Photovoltaic array for checkerboard shading; APV, Agrophotovoltaic; HETS, Horizontal Earth Tube System; PEM, Polymer Electrolyte Membrane; EAHE, Earth-to-Air Heat Exchanger; LLP, loss-of-load probability; SWHS, Solar Water Heating System; NIR, Near Infrared Radiation; SAH, Solar Air Heater; SATE, Surplus Air Thermal Energy; UWTE, Underground Water Thermal Energy; SAHLSC, Solar Air Heater With Latent Heat Storage; PVWP, Photovoltaic water pumping; PV-GHP, Photovoltaic-Geothermal Heat Pump

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heating with a kerosene heater was in the range of 0.42–0.76 MJ m^{-2}.Concurrently, the hourly CO_2 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 CO_2 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 CO_2 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 ºC, 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 CO_2, which are as close as possible to optimal growth conditions for plants by using heating, cooling, ventilation, variable shading, and CO_2 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. Yano 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