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The integration of semi-transparent photovoltaics on greenhouse roof for energy and plant production

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ABSTRACT

The aim of this study was to investigate the effect of semi-transparent building integrated photovoltaics (BIPV) mounted on top of a greenhouse, on the growth of tomatoes and microclimate conditions as well as to estimate the generated energy and the payback period of this system. Three modules were settled at 20% of the greenhouse roof area at a tilt angle of 30° facing south at a distance of 0.08 m between the plastic cover and the BIPV. Each module has a peak power of 170 W_p and efficiency of 8.25%. Results revealed that the annual generated electric energy of the BIPV was 637 kWh. Furthermore, there were no significant differences ($P < .05$) in the growth of tomatoes between shaded greenhouse by the BIPV and the un-shaded greenhouse. The reduction of solar radiation under the BIPV was 35%–40% more than the Polyethylene covers on clear days. The BIPV shading decreases the air temperature by (1 °C–3 °C) on clear days and has no effect on relative humidity. The payback period was found to be 9 years. Moreover, this system can provide most of the annual energy demands for the greenhouse environmental control systems.

1. Introduction

Projections for population growth and food demand through 2050 result in a clear increase of food and energy demands [1]. In addition, the continuously increasing scarcity of conventional fuel, particularly fossil fuel resources, the need for greenhouse gas emissions reduction and the global climate changes call for urgent actions to implement more sustainable technologies to move towards climate-smart agriculture for food security and energy production [2]. Consequently, photovoltaics panels (PV) are an attractive renewable energy technology because they avoid significant carbon emissions during their usage, have a long useful lifetime estimated at 20–30 years, and they take advantage of a stable and plentiful energy resource [3]. Djevic and Dimitrijevic [4] studied the influence of greenhouse construction on energy consumption in winter lettuce production for four greenhouses in the Serbia region. They reported that the multi-span greenhouse had the lowest energy consumption (i.e., 2.71 kWh/m^2). The energy use pattern for tomato production in greenhouses indicated that diesel, electricity and chemical fertilizers are the major energy consuming inputs in Iran [5] and the energy consumption (direct and indirect) per unit floor area of greenhouse in Indonesia for tomatoes was 47.62, GJ/ha [6]. Canakci and Akinci [7] also reported that tomatoes cultivation is the most profitable crop among the greenhouse vegetables in Turkey. Recently, a number of studies have been conducted on the integration of PV panels on the agricultural greenhouses [8–11]. Integration of PV with cropland can partially decrease the water consumption in irrigation [12,13], alleviate the increasing competition for land between food and energy production [14], reduce, or replace part of the electrical energy consumption [15,16] and decrease the greenhouse gas emission by 243,252 tons per year on Caribbean islands [17]. Additionally, it has been reported that PV module prices have been reduced in the past decade by 80% [18]. Furthermore, the costs of off-grid hybrid PV systems were 19% cheaper compared with electricity generation by diesel generators in most rural parts of Indonesia, whereas stand-alone PV systems were 3% cheaper than stand-alone diesel generators on average [19]. Kadowaki et al. [10] found that the straight-line (PVs) array shading significantly decreased the fresh weight and dry-matter weight of welsh onions compared to the checkerboard (PVc) and control as well as decreased the annual crop yield by 25% in Japan. The effect of flexible solar panels mounted on top of a

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greenhouse for electricity production on yield and quality of tomatoes has been investigated in southeastern Spain [15]. Results revealed that there was no effect found in yield and price of tomatoes despite their negative effect on the fruits size and color. Cossu et al. [20] introduced a novel algorithm to estimate the cumulated global radiation (GGR) inside photovoltaic (PV) greenhouses. They found that the yearly GGR increased with the canopy height on the zones under the plastic cover from 59% at 0.0 m to 73% at 2.0 m, and decreased under 50% PV cover ratio on the roof from 57% at 0.0 m to 40% at 2.0 m. Fatnassi et al. [21] predicted the distributed microclimate inside greenhouse equipped with photovoltaic panels by the Computational Fluid Dynamic (CFD) model. They reported that the mean solar radiation transmission in asymmetric greenhouse, which covered an area of 1 ha, composed of six Asymmetrical modules, and equipped with a six continuous openings on the roof, was 41.6% whereas that of the Venlo greenhouse, which had a 10 Venlo type module, covered an area of 1.4 ha, equipped with three continuous openings in the roof, was 46%. On the other hand, the integration of the BIPV with buildings can serve as a shading device for a window, a semi-transparent glass facade, a building exterior cladding panel, a skylight, and parapet unit or roofing system [22]. Li et al. [23] reported that the semi-transparent PV facade in the sub-tropical climate of Hong Kong was able to reduce the annual building energy use and peak cooling load by 1203 MWh and 450 kW, respectively for a room located at the 20th floor of a residential building facing close to west (260°). Moreover, BIPV can generate electricity at a building's peak usage times and reduce the building's peak grid electricity demand [24]. Meanwhile, the heat from solar radiation in the air channel between the BIPV panels or glazing and the building façade could be helpful to decrease the heating load in winter at temperate and cold climates [25,26].

The environmental control in summer is one of the major challenges faced by greenhouse growers in the tropical and subtropical climates. Thus, shading the agricultural greenhouses in hot and sunny regions along with cooling systems reduces water consumption by 25%, reduces greenhouse air temperatures below the outside temperatures by 5–10 °C and increases the relative humidity by 15%–20%. Moreover, shading reduces the solar radiation by 30%–50%, and decreases the energy consumption for cooling by 20% and 15% for heating [27]. Li et al. [28] reported that the annual return of the integrated photovoltaic and agricultural greenhouses in China was varied from 9% to 20% with a payback period of 4–8 years. The previous studies [29–33] which conducted in the integration of PV array on greenhouses commonly used conventional opaque PV or planar flexible PV modules directly above the roof or under the roof. However, the internal integration (under the plastic cover) could decrease the efficiency and lifespan of BIPV panel due to the high humidity rates, air temperatures and the agrochemicals inside the greenhouses. Meanwhile, the high reduction of solar radiation may affect the plant growth and lead to pathogen development [21]. In addition, no experimental data reported to date has shown how tomato plants grow under semi-transparent BIPV shading conditions. Therefore, the aim of this study is to find out the effect of semi-transparent BIPV panels on the growth of tomatoes (*Solanum lycopersicum L., cv. cherry*). Furthermore, to estimate the generated electrical energy at different tilted angles and areas of the roof and the payback period for achieving a sustainable greenhouse crop production.

2. Materials and methods

2.1. The greenhouse structure and PV configuration

This experiment has been conducted in Kunming, China (longitude 102.68°E and latitude 25.07°N), in two greenhouses of a single stand-alone structure with an equal gable roof in east-west orientation to maximize the utilization of solar energy on the south roof in winter. The dimensions of each greenhouse were 7.5 m (length), 3.5 m (width), 3 m (maximum height) and 2 m (gutter height), with a roof slope of 30°. The material covering the greenhouses was 0.12 mm plastic Polyethylene (PE) film with light transmittance of 80%. The ventilation vents were along the side walls (7 m × 1 m) with net curtains of white saran. Ventilation was provided by manually opened side windows. The first greenhouse was considered as shading treatment with semi-transparent BIPV and the second greenhouse with Polyethylene cover only was as a control. Three semi-transparent BIPV of mono-crystalline silicon double glazed were fixed on the south west roof of one greenhouse at tilted angle of 30 ° and settled on top of the plastic cover with a vertical distance of 0.08 m as an isolation air channel between the plastic cover and the BIPV to reduce the heat stress and to avoid the high internal air temperatures and relative humidity from the greenhouse to the modules as well as from the BIPV to the greenhouse. Each module (1985 mm × 1038 mm) had a peak power of 170 W_p and efficiency of 8.25%. The transmittance ratio of each module was 47% (64 cells, 12 cm × 12 cm) and the total area was 6.1 m^2, which occupied 20% of the greenhouse roof area as shown in Fig. 1. The peak rated power of the three modules was 510 W_p. The electrical and mechanical characteristics of the BIPV and Micro-inverters are shown in Table 1.

The environmental control parameters such as air temperature, solar radiation, and relative humidity were measured both outside and inside the greenhouse. The greenhouse roof of 30 m^2 area, had a supporting structure consisted of 7 north-south oriented steel pipes of 0.03 m thicknesses, which shaped gable roof. These were mutually separated by 1.25 m. The total coverage area of the pipes on the roof was 3 m^2, which occupied 10% of the roof area. Two white light-emitting Diode (LED 30 W, China) lamps were attached to horizontal steel bars at a height of 2 m, providing light intensity of 2700 lm. A small circulation fan with a discharge of 3000 m^3/h was fixed in the center of the greenhouse (0. 370 kW and 220 V).

The greenhouse transmissivity was calculated as the ratio between the internal global radiation measured under the plastic cover and the external global radiation [15]. The solar panels were connected in a series and fed into the grid by a three DC/AC Micro-inverters APS YC250A, (Zhejiang Yu energy technology, Limited, China). The energy consumed by the greenhouse (e.g., for ventilation and lighting) and the AC real power output of the Micro-inverters were also measured using smart electric meters DrF-AVC-485 (Beijing Hanwei Borch technology Limited, China) and smartPV software at 4 s intervals. In addition, PolySun program was used to simulate and predict the annual generated energy at different angles and covering area of the greenhouse roof. The simulation of the BIPV was done before the installation. However, the tilt angle was chosen to be 30° to fit the length of the BIPV panel with the greenhouse structure and the experiment was conducted to cover only part of the south roof to save the initial cost of the experiment. Subsequently, the cost of the BIPV panels and the payback period were calculated in terms of energy self-provision and the income from the sale of the remaining energy to the grid.

2.2. Plants measurements

Tomato seedlings (*Solanum lycopersicum L., cv. cherry*) were transplanted in pots at plant spacing in each row of 0.5 m and distance between rows of 1 m. There were 42 pots for each greenhouse, each pot housing one plant. All plants had the same soil, irrigation and fertilization systems. The experimental design was a randomized block design with two treatments (shading and un-shading greenhouses) and four replicates in each greenhouse.