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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.

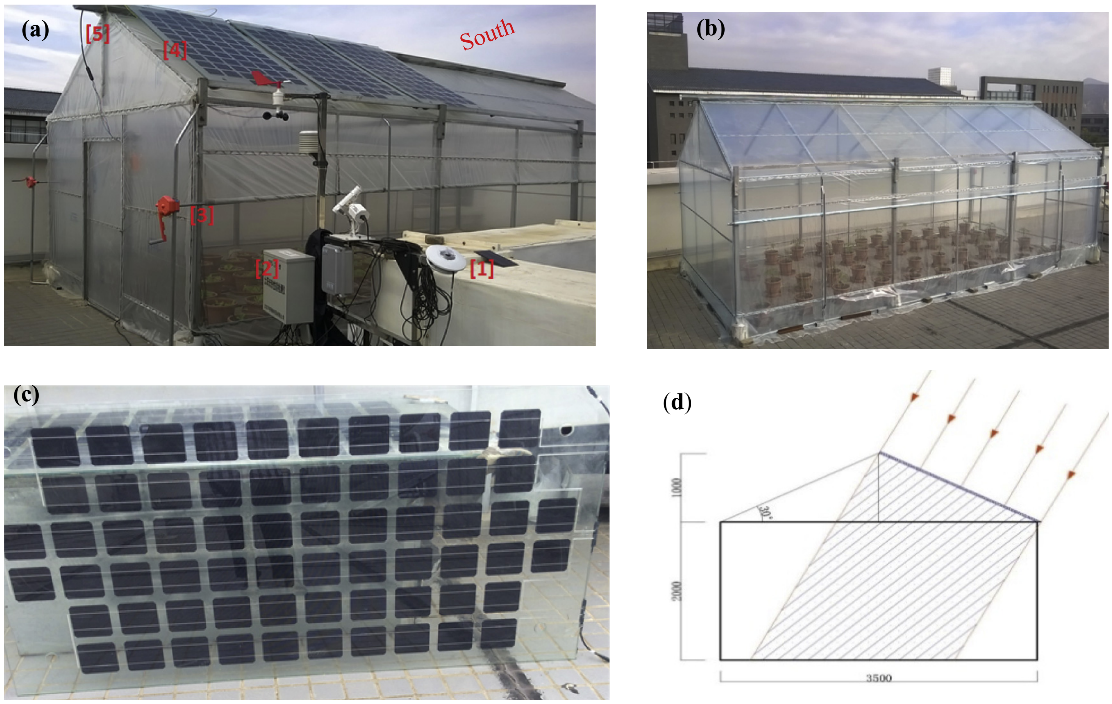


Fig. 1. Photo of the greenhouses (a): Shaded greenhouse [1]: pyranometer [2], Recording station [3], Side ventilation system [4], The distance between the BIPV panels and plastic cover [5], Micro-inverter's cable. (b): Un-shaded greenhouse, (c): BIPV panel, (d): greenhouse diagram.

Table 1
Specifications of the solar panels and the DC/AC inverter system.

Solar panels		DC/AC micro inverter system	
Name and type	CD-BIPV-64/5M170	Name	YC250
		AC Power(max)	250 W
Peak power (Wp)	170 W	AC Vol tage	230-270 VAC
Peak voltage (V)	33.2 V	Frequency	50-55 HZ
Peak current (A)	5.12 A	Max. Efficiency	95.5%
Open circuit voltage (V)	39.6 V		
Short circuit current (A)	5.65 A		
Layer structure	Toughened glass(6 mm)+ PVB(2.28 mm)+(125 × 125 mm) sc-Si cells+ toughened glass(6 mm)		
Weight per piece (kg)	63 kg		

The plant measurements were plant height, number of leaves, leaves area, chlorophyll contents on 37, 47, 67 and 87 days after shading treatments. The relative chlorophyll concentration of the leaves was measured by a portable chlorophyll meter (or SPAD meter) and leaf area by a portable leaf area meter, both instruments from Shanghai Rong Yan instruments. Co., Ltd, China. Four different experiments with four different plants (such as lettuce, strawberry, cucumber, and tomato) have been conducted in these integrated BIPV greenhouses. However, only results for tomato plants were presented in this manuscript. The experimental data were analyzed using the statistical software SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Data and results from each sampling were analyzed separately by one-way analysis of variance (ANOVA). The data were given as the mean ± Standard errors and the level of statistical significance was set at $P < .05$.

2.3. Microclimate monitoring

Mean daily relative humidity and air temperature were measured. Relative humidity was recorded each hour by an Accurate TH12R-EX recorder from Xin yada instrument Co., Ltd, China. The light intensity was measured by a digital portable lux meter from Taiwan, Tai Pei TES electronic industry. Ltd., China. The solar radiation at crop level was measured each minute in each treatment with pyranometers sensors connected to a data logger (model TRM-2, Beijing Tianyu technology, Ltd., China). Two sensors for solar radiation were installed at two levels of plants and fixed in the southwest under the BIPV and in the middle of the un-shaded greenhouse at the same height. Two sensors for air temperatures were distributed in each greenhouse at 1.0 m and 1.5 m above the ground level and at 1.5 m apart as shown in Fig. 2. The specifications of all sensors are shown in Table 2 and the monthly averaged weather variables in Kunming are shown in Table 3.

3. Results and discussions

3.1. Effect of BIPVs on the greenhouse air temperature and relative humidity

Climate distribution in greenhouses can greatly influence the growth and development of crops, particularly the air temperature distributions. It was observed that air temperature under the shaded greenhouse by BIPV was lower than that of the un-shaded greenhouse during the period from 12:00 noon to 2: 00 p. m. in the range of (1 °C–3 °C). Consequently, the average temperature differences between the shaded and un-shaded greenhouses were high only on sunny days and the variation started from 9 a. m. to 3 p. m. The average air temperature inside the shaded greenhouse with natural ventilation was higher than that of the ambient air temperature by (5 °C–8 °C) and the average air temperature inside the un-shaded greenhouse was higher than the ambient temperature by (8 °C–10 °C) as shown in Fig. 3a. Furthermore, the average air temperature in the air channel between the plastic cover and the BIPV on top of the greenhouse roof was lower than the internal air temperature of greenhouse by (3 °C–6 °C) on sunny days

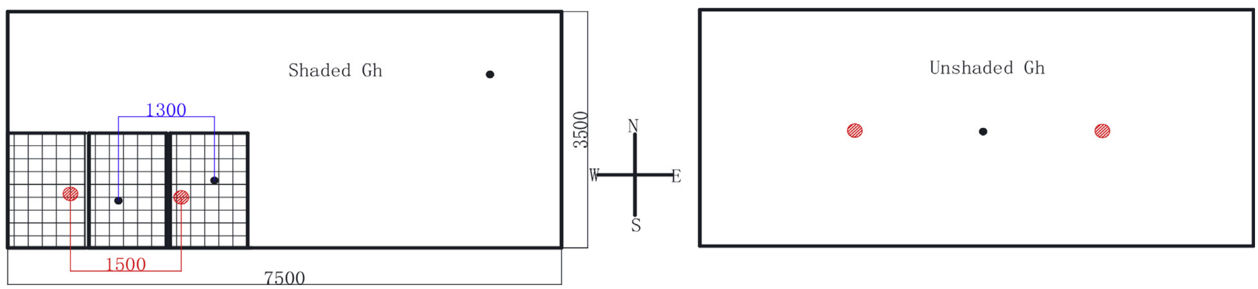


Fig. 2. Sensors position and distributions. This bullet ● represent the solar radiation, light intensity and relative humidity sensors. Meanwhile, this bullet ⊗ represent air temperature sensors in shaded and un-shaded greenhouses (units in mm).

Table 2
The specification of the instruments.

Instrument name	Measurement range	Accuracy
Thermocouple	0–150 °C	± 0.1 °C
Pyranometers	0–2000 W/m^2	± 2%
Wind speed sensor	0–70 m/s	0.5 m/s
Digital portable lux meter	(0–200000 lx).	±1lx
Accurate TH12R-EX	0–100%	± 0.2 °C and ±2%

meanwhile, higher than the ambient air temperature by (3 °C–5 °C) as shown in Fig. 3b.

Fig. 4 shows that the temperature of the BIPV was higher than the internal air temperatures of the greenhouse by an average of 8 °C, while the difference between the module temperature and the ambient temperature was 14 °C. The maximum and minimum temperatures of the BIPV were 48.3 °C and 23 °C, respectively while the maximum and minimum temperatures of the greenhouse under the natural ventilation were 38 °C and 23.3 °C, respectively. These results illustrated that the integration of the BIPV outside the greenhouse could alleviate the over-heating inside the greenhouse in summer.

Data here in Figs. 3 and 4 were presented to show the shading effect on a certain sunny days of hot months from April to July, due to the fact that there were obvious differences in air temperatures during those months. Results revealed also that air temperature decreased in the un-shaded greenhouse compared to the shaded greenhouse from 5 p. m. to 7 p. m. as shown earlier in Fig. 3a, which means that the un-shaded greenhouse was losing heat faster comparing to shaded greenhouse due to the lower solar radiation in late afternoon. Furthermore, integrating the BIPV on the greenhouse could decrease the heat losses at night in winter due to the BIPV and air channel between the plastic cover and the BIPV could serve as a thermal cover to maintain the internal air temperature. In contrast, it decreases the internal air temperatures during the daytime in summer, these results are in agreement with Ahmed et el. [27].

Air temperatures inside greenhouses were always observed higher than that of the ambient temperatures. In contrast, the relative humidity was lower inside the greenhouse on yearly basis particularly during the day time on sunny days. It was clear that using the natural ventilation all day long could decrease the internal air temperature and relative humidity however, on rainy days the relative humidity increased to 99.9%. Thus, the mechanical ventilation operated only on hot days when the internal temperature exceeded 25 °C and the relative humidity 85%. It was observed that relative humidity increased gradually at night from 6:00 p. m. to 6:00 a. m. inside the greenhouse compared to the outside. The average relative humidity in the shaded greenhouse was insignificantly higher than that of the un-shaded greenhouse by 2% during the day in summer. The maximum internal relative humidity was 99.9 at night and on rainy days and the minimum was approximately 23% in the un-shaded and 25% in the shaded greenhouse during the daytime particularly afternoon on sunny days at high dry bulb temperatures as shown in Fig. 5a and b.

3.2. Effect of semi-transparent PV on solar radiation

Results showed that the solar radiation under the shaded greenhouse by the plastic cover of Polyethylene (PE) along with BIPV panels was lower than that of PE cover only. Accordingly, the plants under the PE cover always received a higher amount of solar radiation compared to those under the BIPV with PE cover.

Fig. 6a shows the results of a primary experiment which was conducted in the shaded greenhouse only to compare between the shaded (west) and un-shaded (east) parts. It was observed that the solar radiation in the morning was lower under the shaded part. Subsequently, the variation in the solar radiation changed at 3:00 p. m. due to the shaded area moves in the same greenhouse from the west to the east direction in terms of time and the solar radiation sensors were in a fixed position. Nevertheless, there was an extra shading from 11:00 a. m. to 1:00 p. m. which caused by the greenhouse structure, due the shading of greenhouse structure was very difficult to be avoided. Subsequently, it was found that solar radiation in the shaded greenhouse increased from 1:30 p. m. to 2:45 p. m. due to the movement of most of the shaded area away from the solar radiation sensor during this period (Fig. 6b). Meanwhile, the solar radiation decreased in the un-shaded greenhouse at 1:00 p. m. as a result of the greenhouse structure.

The PE cover reflected more direct-beam radiation during afternoon. Consequently, it was found that solar radiation under the PE cover with the partial shading of the BIPV on the greenhouse was 30%–35% at 12:00 noon whereas, under the plastic cover it was

Table 3
Monthly-averaged of meteorological data for Kunming city [34].

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temperature(°C)	5.8	7.9	12.2	16.4	18.2	19.3	19.2	18.9	16.6	13.0	9.41	6.20
Average relative humidity (%)	75.8	66.9	55.8	50.6	60.5	71.7	74.9	75.5	77.9	82.3	81.2	80.4
Daily solar irradiation - horizontal (kWh/m^2/d)	4.38	5.13	5.71	6.23	5.61	5.04	4.57	4.59	4.03	3.77	3.92	3.97

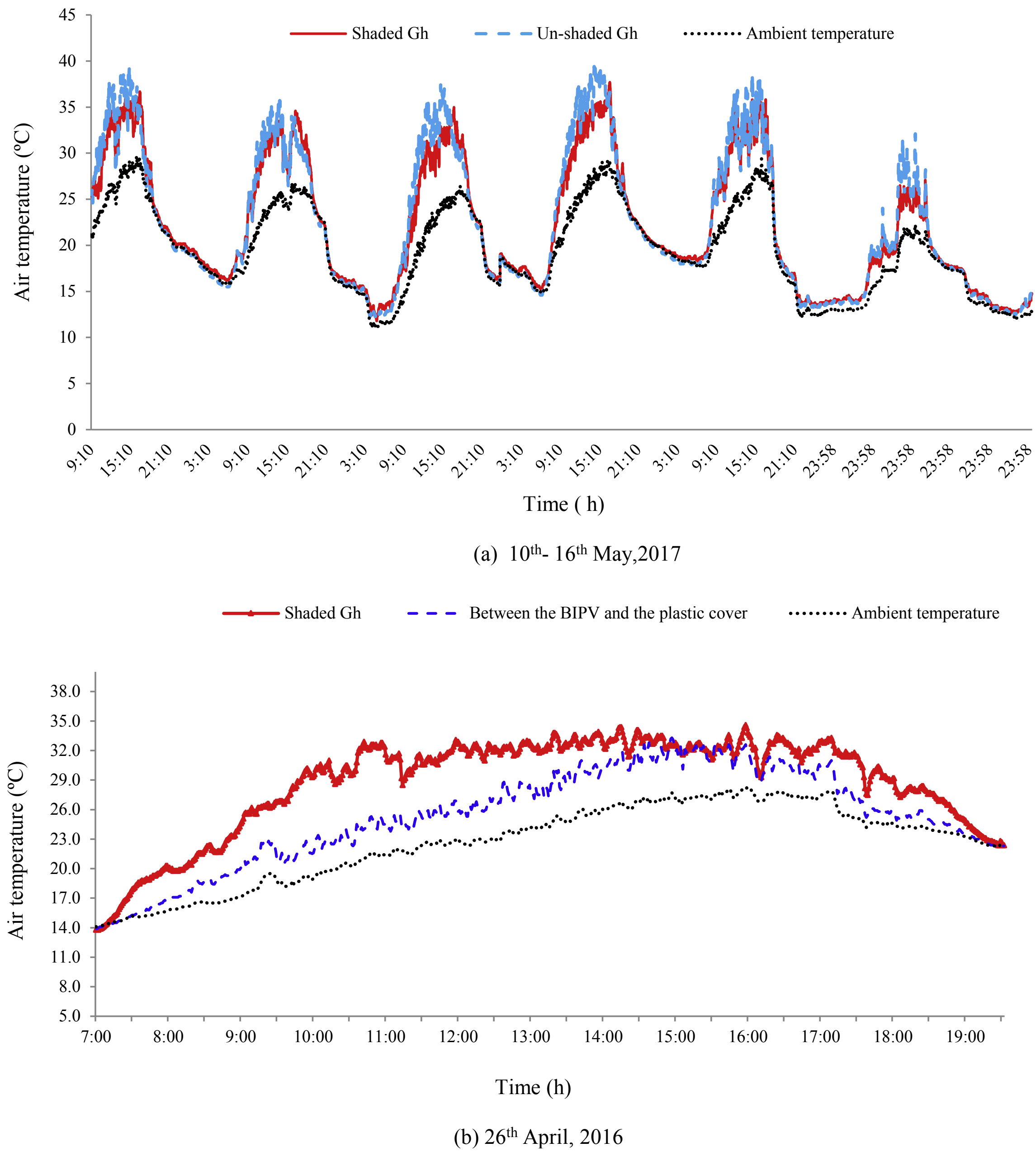


Fig. 3. Average air temperature inside and outside the greenhouses under natural ventilation.

only 75%–80% compared to the direct sunlight outside the greenhouse on sunny days at a tilt angle of 30°. On the other hand, there was no observed variation of solar radiation on the cloudy days between the shaded and un-shaded greenhouses. It can be also observed that the solar radiation in the shaded greenhouse in the middle of the shaded area (shaded1) was lower than that of the east shaded area (shaded 2) by an average of 100 W/m^2 due to the movement of the shading area away from it, and the effect of the unshaded half of the greenhouse (Fig. 7a). The peak values of solar radiation on clear and sunny days during the afternoon were high outside the greenhouse ranging from 0.5 to 1.15 kW/m^2 while, inside the greenhouse under the PE cover (Control) it ranged from 0.4 to 0.700 kW/m^2 and low under the PE with the BIPV ranged from 0.10 to 0.56 kW/m^2 as shown in Fig. 7b, these results are in agreement with Cossu et al. [20]. The greenhouse cover can absorb and reflect the solar radiation. Accordingly, attaching PV panels inside greenhouses can decrease the generated electric energy [9,35]. Cossu et al. [8] reported that the shading of opaque PV modules reduced the availability of solar radiation inside the greenhouse by 64% up to 82% for the areas under the non-transparent PV covers. Meanwhile, they reported that the income derived from the energy production was considerably higher than that resulting from the tomato crops. It was reported that using the flexible PV and thin films, the semi-transparent PV panels, and the spherical micro-cells, can increase the amount of solar light entering the greenhouse [32,36,37]. Accordingly, the BIPV can be considered as a moderate technology between the opaque PV and the plastic cover, due to the light transmission of the semi-transparent PV being higher than that of the non-transparent PV and lower than the single plastic cover and it can fit some of greenhouse crops. Results

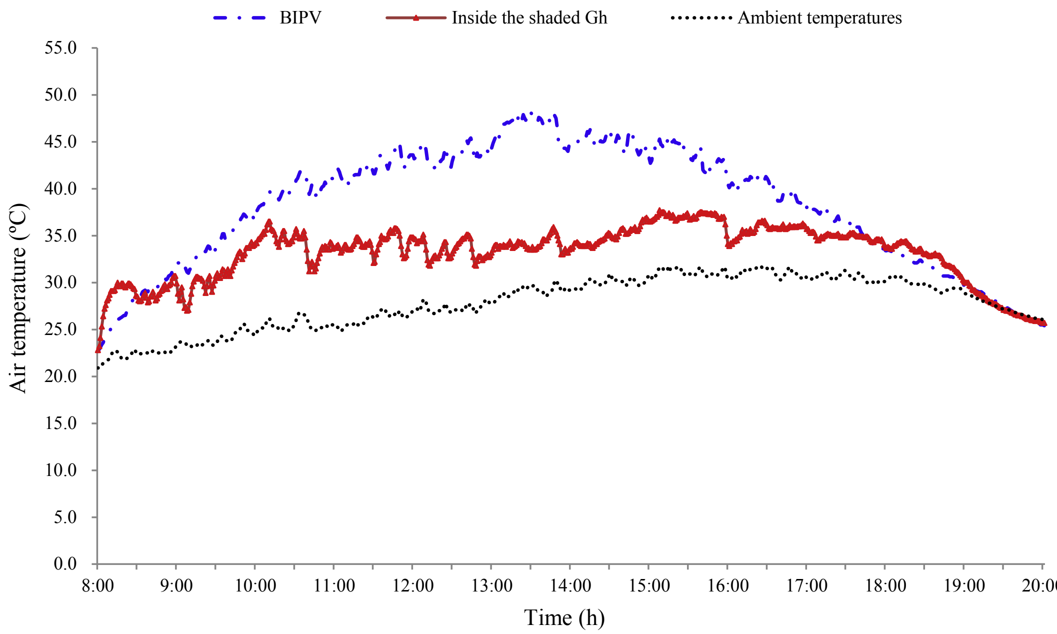


Fig. 4. Average air temperatures inside and outside the shaded greenhouse compared to the BIPV temperature on 10th July 2016.

revealed that when the average light intensity outside the greenhouses was 86.3 klx (on a sunny day of November at 1 m from the ground), the average light intensity under the plastic cover was 64 klx. Meanwhile, light intensity under the plastic cover with the BIPV was 27 klx. These results revealed that the plastic cover transmittance was about 75% and the transmittance of the plastic cover with the BIPV was about 30% compared to the outside light intensity. Thereby, the combination of the BIPV and plastic cover decreases the light intensity inside the greenhouse by approximately 35%–40% compared to the single plastic cover.

The amount of light in the wavelength range of 400–700 nm can be defined as Photosynthetically Active Radiation (PAR) and it can be measured in either micromoles of photons per square meter per second (μmol/m^2/s) or in watts per square meter (W/m^2). Results showed that the solar radiation under the BIPV shading in the peak period during daytime was higher than or equal to 200 W/m^2 from 10:00 a. m. to 5:00 p. m. The minimum amount of irradiation necessary to ensure sufficient growth and flowering corresponds to a daily global radiation of 2.0–2.3 kWh/m^2 days, (200 W/m^2 equal to 1000 μmol/m^2/s).

Consequently, the small reduction in light transmitted through the PE cover compared to the combination of the PE with the BIPV did not affect the growth of the tomato plants.

The position and orientation of PV modules on greenhouse roofs must be considered carefully to provide a sufficient electrical energy with minimum shading [9–11]. Thereby, 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 great. Moreover, it was observed that lots of dust accumulates on the plastic cover of the greenhouse and under the BIPV, this dust could prevent the light from entering the greenhouse. Thus, a regular cleaning system is recommended to clean the dust on the BIPV and the plastic cover.

3.3. *Electric energy production of BIPV on greenhouse*

Fig. 8 illustrates that the average of the generated electric energy of BIPV increased gradually with the increasing of solar radiation on sunny days. The generated electric power at 10:00 a. m. was 240 W and reached the peak value at 1:00 p. m. with 414 W eventually decreasing again to 235 W at 5:00 p. m.

The daily total greenhouse power consumption of ventilation and lighting systems in a typical day of July was 1.85 kWh/day. According to the meteorological data as shown earlier in Table 3 and the reported data that the optimal temperature range for most plants is between 22 and 28 °C in the daytime and 15–20 °C at night [38], the annual required energy for heating greenhouses in Kunming is only required in December, January and February. While, the cooling is only required in May, June and July along with natural ventilation and shading as well as no need for lighting. Accordingly, this integrated system can provide most of the annual energy demand for heating and cooling systems. The semi-transparent BIPV could produce enough electricity to meet the power consumption during the period from March through November. Nevertheless, the required energy for heating demand will be higher than the generated electric energy from the BIPV from December to February.

Results of the PolySun simulation showed that the best tilt angle to generate more electric energy of the BIPV when it faced the South direction was 25° and the best tilt angle when it faced the North direction was 20°. Meanwhile, the CO_2 savings at those angles was higher than the other angles. The annual generated electric energy of the BIPV facing south at 25° and roof area of 20% was 638 kWh and the CO_2 savings were 342.1 kg whereas, at 20° and roof area of 20% facing north was 493 kWh and the CO_2 savings were 264.5 kg. It was reported that the specific CO_2 emission of the rooftop grid-connected PV systems was in the range of 50–100 g/kWh $_{generated}$ while the CO_2 emissions of burning fossil fuels could be 504–900 g/kWh $_{generated}$ [39,40]. Therefore, the BIPV has a great impact on the reduction of CO_2 emissions.

On the other hand, by increasing the occupied south roof area to be 40% at tilt angle of 25° it produced 1247 kWh while, at the north roof area of 40% and tilt angle of 20° it produced 968 kWh as shown in Tables 4 and 5.

The generated electric energy of the system facing the South direction from May to October was less than that from November to

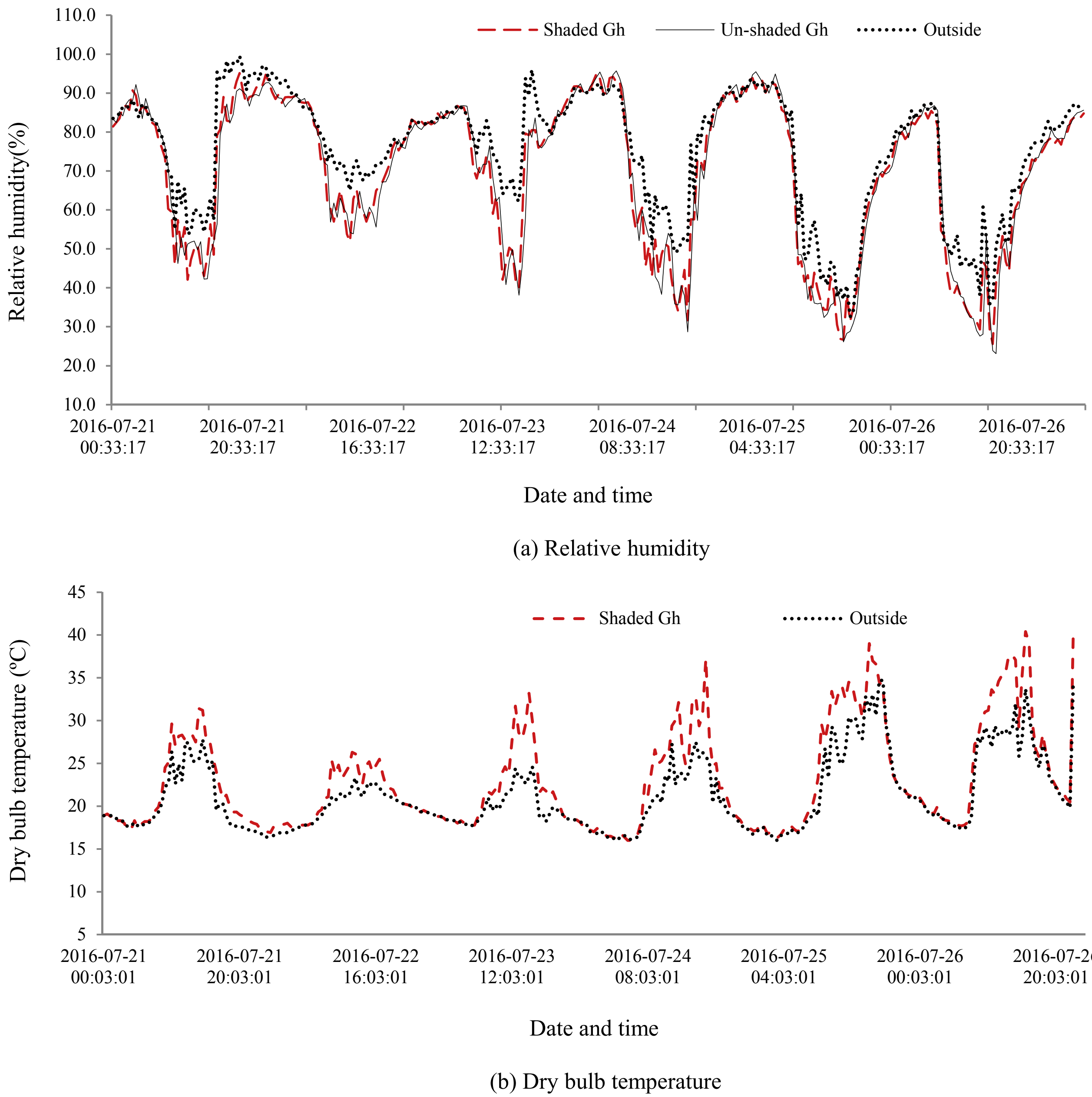


Fig. 5. Relative humidity and dry bulb temperature inside and outside the greenhouses under the natural ventilation.

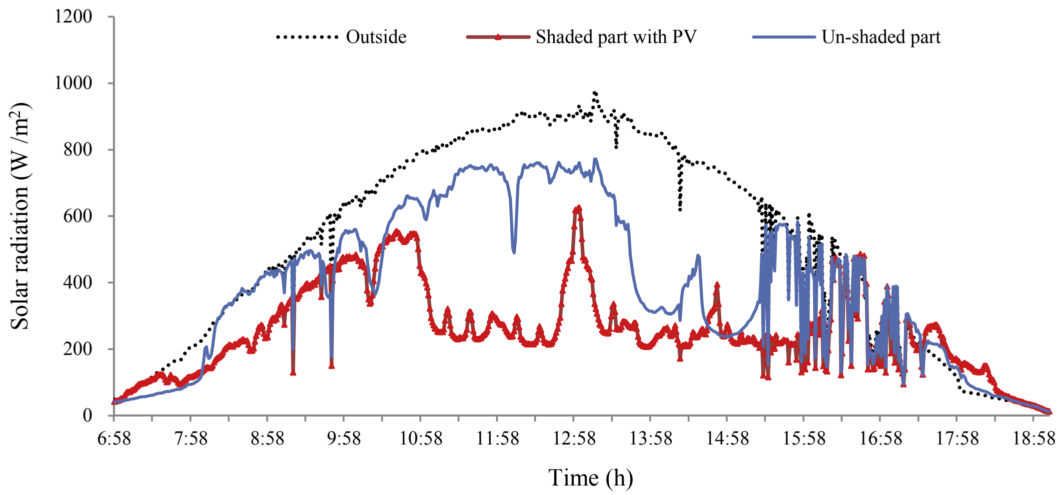
April. This is may be due to the lower attitude angle of the sun in this period, which can cause more shading on the panels and resulted in varies irradiation levels on the surface of BIPV modules. Therefore, the monthly peak production of electric energy from the south roof at covering area of 20% and tilt angle of 30° was reached in March, with 68 kWh and the lowest was found in July at 41 kWh. In contrast, the generated electric energy of the system facing the north direction from March to September was higher than that from November to February. Thereby, the peak production of electric energy from the North roof at tilt angle of 20° was reached in April with 59 kWh and the lowest was found in December at 25 kWh as shown in Fig. 9.

It was reported that the annual electric energy consumption per unit greenhouse area in different countries was deviated from 0.1 to 528 kWh/m^2 for heating, cooling, lighting, and irrigation systems according to the location and the environmental control technology in the greenhouse [16]. Thus, the results of this experiment will be applicable for many regions around the world.

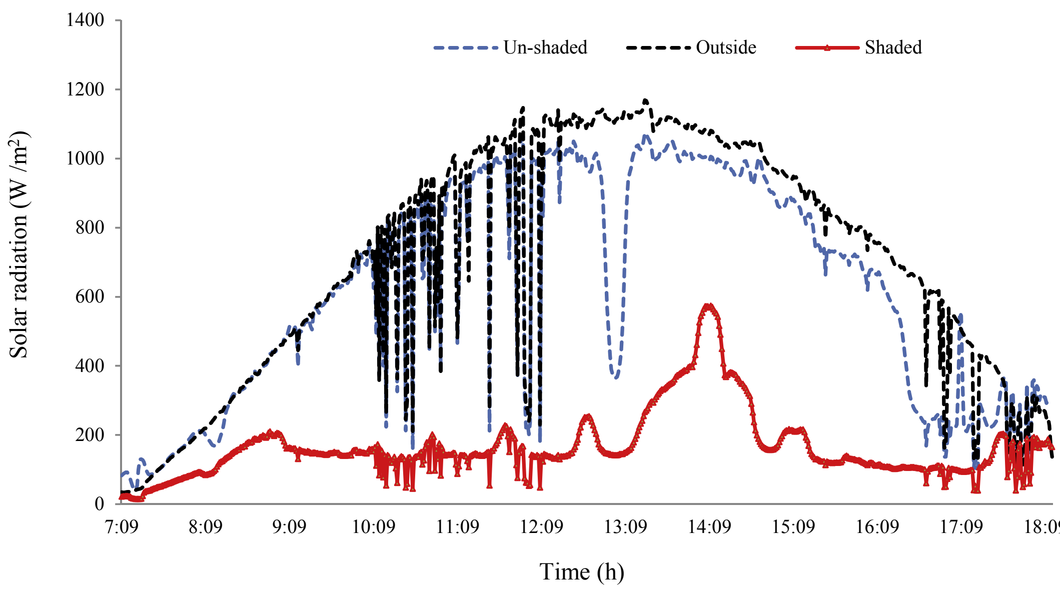
In this study a semi-transparent mono-crystalline silicon double glazed PV panels were used for a high transmittances, which was at the same price of the opaque PV modules. Thus, using a high efficiency BIPV can be recommended and the extra income from the sale of the remaining energy to the grid could recover the extra costs after a period of time.

3.4. Effect of BIPV shading on tomato

Normally, different plants require different amounts of light for optimal growth. The movable shading curtains can reduce the energy load in the greenhouse crop during warm and sunny conditions and they reduce heat radiation losses at night [41]. Shading not only affects plant morphology, physiology and microstructure



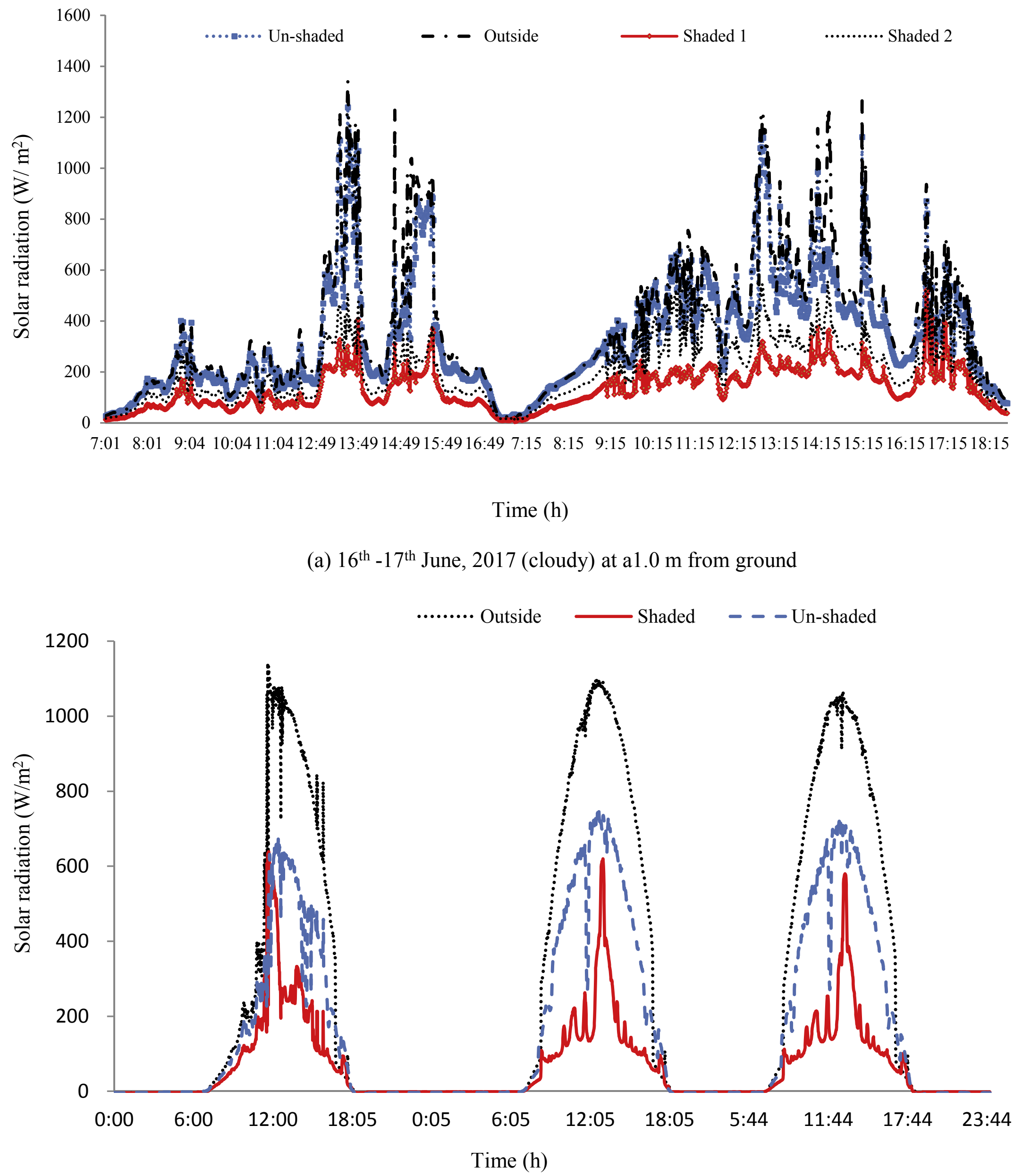
(a) 26th May 2015, inside the shaded greenhouse (plastic and plastic with the BIPV panels) and outside the greenhouse at a 0.60 m from ground



(b) 22nd May, 2017, Inside the shaded and un-shaded greenhouses at 2.0 m from ground.

Fig. 6. Solar radiation inside two parts of the shaded greenhouse, and un-shaded greenhouse compared to the outside radiation.

but also has an important impact on the total biomass production. Plant growth requires appropriate photosynthetic photon flux density (PPFD); excessively high or low intensity will prevent photosynthesis in the plant [42,43]. Mashonjowa et al. [44] reported that shading a greenhouse by whitening reduced the transmission coefficients for photosynthetically active radiation, total solar and thermal radiation of the greenhouse cover from 0.75 to 0.53; 0.74 to 0.55 and 0.45 to 0.43, respectively. The plant height and number of leaves under BIPV shading were insignificantly higher than those of the un-shaded plants. In addition, it can be clearly seen that the chlorophyll contents of leaves in shading were higher than those of the control. However, the differences were not significant in chlorophyll contents between plants in control and shading greenhouses. The relative chlorophyll content in leaves estimated by the SPAD-502 chlorophyll meter can be an efficient way to evaluate plant nitrogen (N) status in many crops and some tree species [45]. Therefore, it can be confirmed that there were no differences in the chlorophyll contents and nitrogen concentration in tomato leaves under BIPV shading and the control as shown in Fig. 10. It was observed that the air temperatures and solar radiation in the un-shaded greenhouse were higher than that in the shaded greenhouse with the BIPV. Consequently, the tomato pots were dried quickly and more water was consumed because the tomato transpiration rate increased with the increasing of air temperature. These results are consistent with the previous studies of [46]. On the other hand, tomato plants grown in hot climates for the entire season under a shade of 30%–40% had a higher yields and more fruit than those grown without shade [47]. It was found that the light intensity of 300 $\mu mol/m^2/s$ was more suitable for the culture of tomato seedlings in terms of the fresh weight, dry weight, stem



(a) 16th -17th June, 2017 (cloudy) at a1.0 m from ground

(b) 15th -17th Febraury, 2016 at 2.0 m from ground

Fig. 7. Average solar radiation, inside the shaded greenhouse with the BIPV, un-shaded greenhouse and outside the greenhouse.

diameter and health index [48]. Consequently, the integration of BIPV and greenhouses could be more applicable in hot climates to grow tomatoes. Similar results were reported by Raual et al. [15].

In addition, the leaf area of shading plants under the BIPV was insignificantly bigger than those leaf areas without shading after 37 days and 47 days of shading, respectively (Fig. 11).

The photovoltaic systems can be evaluated by the economic and environmental issues when the genereated energy used for internal electric consumption or for sale to the grid [49]. The payback period can be calculated by dividing the amount of the initial investment by the cumulative net cash flow for each period. The total costs of the photovoltaic systems include the cost of the structure, PV panels, inverters, handling system, and storage batteries as well as the maintenance and insurance costs (1%) of the initial cost [50]. In the present study, the BIPV panels, the structure, micro-inverters, wirings and the system maintenance and insurance costs were 5000 RMB ($720) and the annual electric energy production of the BIPV system at 20% of the greenhouse roof area, was 637 kWh (24.5 kWh/m^2) of greenhouse floor area). The price of 1 kWh in China is about 0.50 RMB [51]. Thus, the annual income of BIPV system will be 319 RMB. This income could be increased by increasing the BIPV covering area and efficiency. The reduction of the annual energy production was set at 1%, due to the reduction of the BIPV efficiency, the lifespan of the BIPV panels is assumed to be 25 years and the rate of increase in energy prices was assumed to be 3% as well as the inflation of 2% and interest of 3%. Consequently, the payback period of using the BIPV system was nine years and this period of time could be shortened by choosing the most suitable

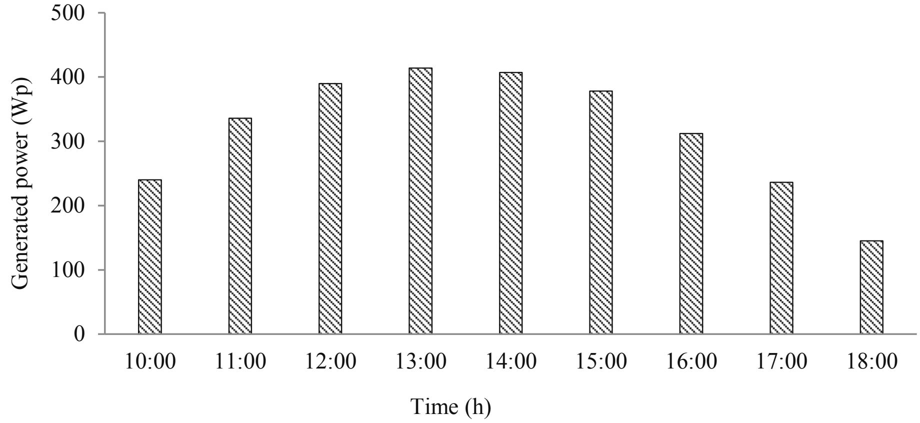


Fig. 8. Average of the generated electric energy from BIPV on 14th February 2016.

Table 4
The annual generated electric energy (kWh) of the PV modules at different tilted angles and directions at 20% of the greenhouse roof area.

Tilted	20°	25°	30°	35°	40°	45°	50°	55°
Facing South	635	638	637	632	624	612	597	579
CO_2 savings)kg(	340.8	342.1	341.5	339	334.6	328.4	320.5	310.8
Facing North	493	462	430	396	362	332	306	282
CO_2 saving)kg(	264.5	248	230.4	212.3	194.3	178.2	164.4	151.5

Table 5
The annual generated electric energy (kWh) of the PV modules at different tilted angles and directions at 40% of the greenhouse roof area.

Tilt angle	20°	25°	30°	35°	40°	45°	50°	55°
Facing South(kWh)	1242	1247	1244	1235	1219	1197	1168	1133
CO_2 savings)kg(	666.3	668.6	667.4	662.4	653.9	641.9	626.5	607.7
Facing North(kWh)	968	908	844	778	713	654	604	557
CO_2 savings	519.1	486.9	452.8	417.5	382.3	351	324	298.9

plants to increase the annual yield production. On top of that, the environmental benefits of using the BIPV panels are considerable, due to the reduction of CO_2 emission. Therefore, the integration of semi-transparent PV with greenhouses would be an appropriate system in subtropical regions. Nevertheless, the PV panel's technologies have been specifically developed for greenhouse applications; further investigation for testing the performance on the field and the impact on the crops still needed. It was indicated in 2012 that the payback period to return the investment capital of integrated PV panels on greenhouses would be about 18 years in Spain [15]. While, in 2016 Marucci and Cappuccini [52] reported that the calculated payback period of a dynamic photovoltaic greenhouse was 6 years in clear sky conditions in Italy. Subsequently, the combination of BIPV and greenhouses could be a beneficial option for the remote areas in the near future due to the reduction of PV prices and governmental support.

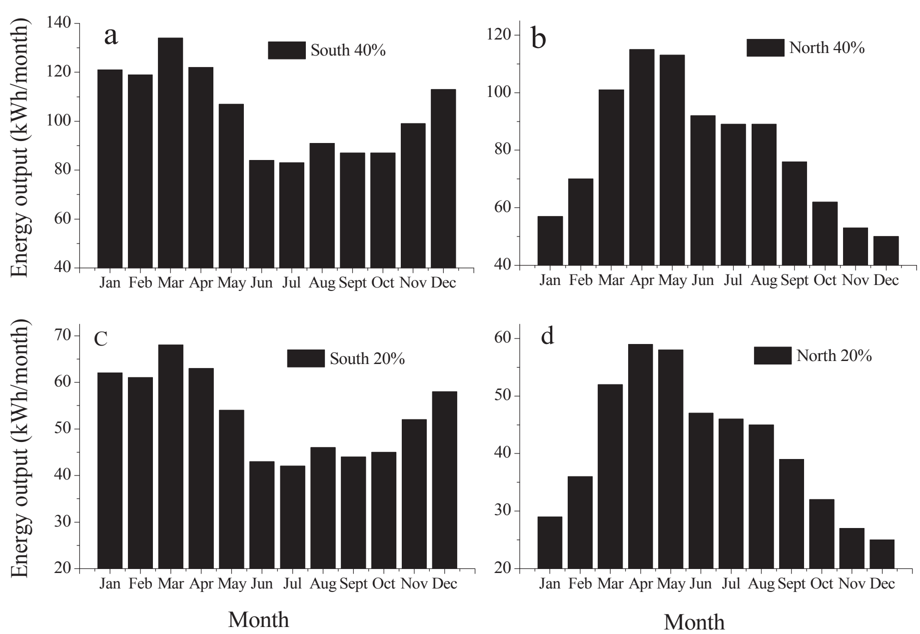


Fig. 9. Average of the monthly generated electric energy at different roof area and tilt angles. (a)Roof area 40% facing South at tilt angle of 25°, (b) Roof area 40% facing North at tilt angle of 20°, (c) Roof area 20% facing South at tilt angle of 25°, (d) Roof area 20% facing North at tilt angle of 20°.

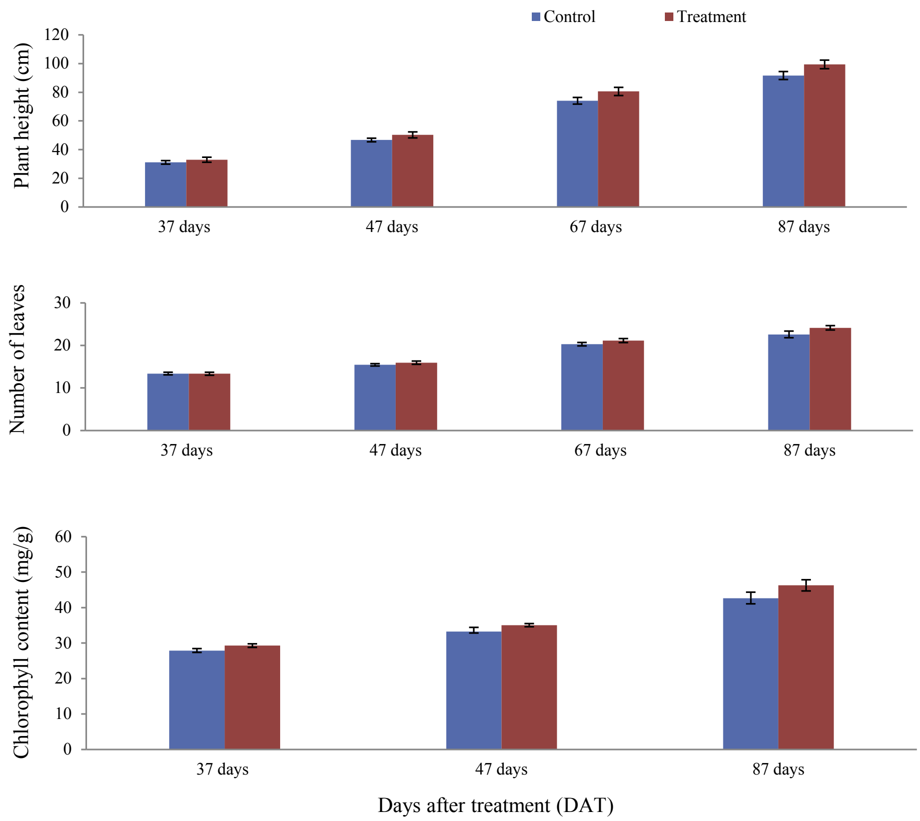


Fig. 10. Plant height, number of leaves chlorophyll content of tomato. Vertical bars represent mean ± standard errors at $P < .05$, (n = 20 and n = 50 for chlorophyll samples).

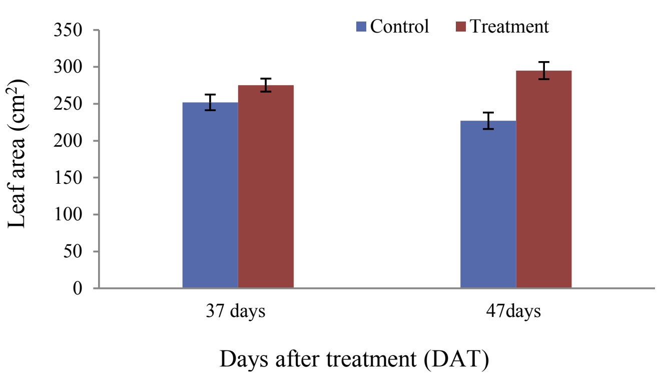


Fig. 11. Leaves area. Vertical bars represent mean ± standard errors at $P < .05$, (n = 20).

4. Conclusion

The integration of semi-transparent BIPV panels with a transmittance ratio of 47% on the roof of greenhouses not only decreases the energy load, but also generates appropriate energy for the supplemental lighting and heating in winter as well as forced ventilation in summer. The annual generated electric energy of the BIPV panels per unit floor area of greenhouse was ranged from 24.5 kWh/m^2 to 47.5 kWh/m^2 at 20%–40% of greenhouse roof covering area. Furthermore, the proper tilt angle for generating more electric energy of the BIPV on the South roof of greenhouse was 25° and the best tilt angle in the North roof was 20°. The BIPV shading decreases the air temperature by approximately (1 °C–3 °C) on clear days and insignificantly increases the relative humidity by 2% as well as decreases the solar radiation by 35%–40% compared to un-shaded greenhouse. Moreover, The BIPV insignificantly affected the growth of tomato. Results also revealed that the payback period of using the BIPV system was 9 years for only 20% of the greenhouse roof area. The annual electric energy production of The BIPV can be increased particularly in high-irradiation regions and remote areas. Therefore, it can be recommended that the most suitable crops, vegetables and ornamental plants under the BIPV system those which need low light intensities. Furthermore, an external integration of a mobile BIPV with a high efficiency or spherical micro-cells as a semi-transparent photovoltaic (PV) technology on the greenhouse roof are highly recommended in the subtropical regions. In addition, further studies should be conducted to explore the optimal integration of a new PV panels with different plants in agricultural greenhouses.

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