Shading and electric performance of a prototype greenhouse blind system based on semi-transparent photovoltaic technology

Zhi LI^a, Akira YANO^{b,†}, Marco COSSU^b, Hidekazu YOSHIOKA^b, Ichiro KITA^b and Yasuomi IBARAKI^c

^aThe United Graduate School of Agricultural Sciences, Tottori University, 4-101 Koyama-Minami, Tottori, Tottori 680-8553, Japan

^bFaculty of Life and Environmental Science, Shimane University, 1060 Nishikawatsu, Matsue, Shimane 690-8504, Japan

^cFaculty of Agriculture, Yamaguchi University, 1677-1 Yoshida, Yamaguchi, Yamaguchi 753-8515, Japan

Abstract

Photovoltaic (PV) energy is emerging in the greenhouse industry to compensate energy demands for cultivation. Because both crops and PVs need sunlight, their compatibility on the same land unit often conflicts. To overcome this difficulty, we prototyped a venetian-blind-type shading system comprising semi-transparent bifacial PV modules that concurrently function for greenhouse shading control and electricity production. The PV blind installed in a test greenhouse was operated automatically according to the external solar irradiance. When the solar irradiance was higher than a predetermined threshold level, the PV modules were oriented parallel to the roof with sunlight shading of 42%. The PV modules were oriented to be perpendicular to the roof when the irradiance level was low, prioritizing the sunlight intake into the greenhouse. The blind system operations were managed completely by the electrical energy generated by the PV modules. Actually, the PV-produced electricity was surplus to the blind system operations, suggesting that additional greenhouse appliances can be operated by the PV-produced electricity. This system might be applicable to greenhouses in high-insolation regions as an energetically stand-alone dynamic shading system to produce a better light environment for crops.

Key words: Irradiance; Renewable energy; Solar cell; Stand-alone; Venetian blind

1. Introduction

Shading plays an important role for crop cultivation in greenhouses, particularly during summer (Hanan, 1998; Ishii *et al.*, 2001; Castilla, 2013; Martínez *et al.*, 2016). Appropriate shading mitigates the excessive temperature rise which can occur in greenhouses (Yano *et al.*, 2007; García *et al.*, 2011; López-Marín *et al.*, 2012). It can also contribute to the improvement of crop growth and development (Lorenzo *et al.*, 2003; Dai *et al.*, 2009; Kittas *et al.*, 2009; Deng *et al.*, 2012), as well as extension of the culture period and regulation of ripening (Teitel and Segal, 1995). Practical and inexpensive means of providing greenhouse shading commonly involve nets or reflective coatings (Hanan 1998; García *et al.*, 2011; López-Marín *et al.*, 2012; Castilla, 2013). Actually, these simple shading methods are beneficial. The sunlight on the canopy is moderated properly by virtue of the reflection of partial sunlight to the outside. Nevertheless, the sunlight energy is not exploited completely in a greenhouse with such conventional shading methods.

The use of photovoltaic (PV) systems is emerging in the greenhouse industry to mitigate fossil fuel dependence. Installing PV modules on part of the greenhouse roof area can be a strategy when crops require moderate shading in high-insolation regions. Unlike simple shading nets or reflective coatings, appropriate shading and electricity production can be realized concurrently in a greenhouse with installed PV. However, excessive shading

by enlarged PV panels on the greenhouse roof conflicts with the sunlight requirements of crops below (Castellano, 2014; Cossu *et al.*, 2014; Castellano *et al.*, 2016; Cossu *et al.*, 2017). Accordingly, some works have been undertaken to improve light transmittance of PV installed roofs by contriving the shapes or arrangement of PV panels (Yano *et al.*, 2010; Kadowaki *et al.*, 2012; Pérez-Alonso *et al.*, 2012; Tani *et al.*, 2014; Yano *et al.*, 2014; Fatnassi *et al.*, 2015; Buttaro *et al.*, 2016; Cossu *et al.*, 2016). In this way, inhibitory effects of shading on crop growth can be mitigated (Kadowaki *et al.*, 2012; Ureña-Sánchez *et al.*, 2012; Tani *et al.*, 2014; Buttaro *et al.*, 2016).

Another concept related to the application of PVs to greenhouses is the separate use of wavelength ranges of the solar radiation spectrum for cultivation and for electrical energy generation. Sonneveld *et al.* (2010a; 2010b) developed and assessed a PV system based on this concept. In their systems, photosynthetically active radiation (PAR) is delivered into the greenhouse. Near infrared radiation (NIR) is reflected on a straight focal line above the concavely curved roof, the surface of which was coated with NIR reflective film. The PV modules positioned on the focal facing downward can receive the concentrated NIR and can generate electricity. The cooling load in the greenhouse can thus be reduced by the NIR reflection. Exploiting translucent organic solar cells on the greenhouse roof represents another solution based on use of separate sunlight spectrum components for electricity generation and crop cultivation (Emmott *et al.*, 2015; Yang *et al.*, 2015).

Another system was developed using a greenhouse roof made with Fresnel lenses to collect direct sunlight onto PV modules to generate electricity and to use scattered sunlight for crop production (Souliotis *et al.*, 2006; Sonneveld *et al.*, 2011; Hemming *et al.*, 2014). Recently, new ideas have been proposed

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[†]Corresponding Author: yano@life.shimane-u.ac.jp

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to regulate irradiance in greenhouses dynamically using PV blind systems (Vadiee and Martin, 2014; Marucci *et al.*, 2015; Marucci and Cappuccini, 2016a, 2016b; Vadiee and Yaghoubi, 2016), although improvement of the blind mechanism and shading controllability is expected.

Applications of PVs on portions of the greenhouse roofs enable moderate shading and electricity production on the same land unit, as summarized above. However, most of them are ineluctable to shade crops from low level sunlight unnecessarily during winter or cloudy days. This problem was implied by Tani *et al.* (2014), who reported that the dry weight accumulation of lettuce plants grown under partial PV cover was unaffected during summer and autumn, but suppressed in winter.

For this study, we prototyped a venetian-blind-type greenhouse shading system that incorporates bifacial semi-transparent PV-modules as blind blades. The system changes the PV module inclination autonomously according to the solar irradiance level. The blind control system orients the PV modules to make them parallel to the greenhouse roof to generate electricity with moderate shading when solar irradiance is intense or to make them perpendicular to the roof when the irradiance level is low. Thereby, solar irradiance intake in the greenhouse is ensured during cloudy days or low-insolation times. Moreover, this stand-alone system was operated using electricity generated by the PV blind itself. Details of the prototype PV blind system are reported herein along with data supporting the validity of the shading and electricity-producing performance.

2. Materials and methods

2.1 Bifacial semi-transparent PV module as a venetian-blind blade for greenhouse shading application

The bifacial semi-transparent PV-module (Fig. 1a) used as a blind blade was 500 mm × 200 mm × 11 mm, weighing 2.23 kg. The module structure comprised three layers sandwiching 3.0-mm thick resin between two 3.8-mm-thick glass plates. In transparent resin, 13,764 mono-crystalline-silicon PV cells with 1.2-mm-diameter (Sphelar[®]; Sphelar Power Corp., Kyoto, Japan) were embedded with conductor wires connecting the cells. Between the 0.38-mm-wide and 0.1-mm-wide conductors, PV cells were aligned (Fig. 1b). Each cell consisted of a p-type semiconductor inner sphere and an n-type semiconductor outer shell. The PV cells were spherical, enabling them to generate electrical energy using sunlight from all directions (Biancardo *et al.*, 2007; Taira and Nakata, 2010; Yano *et al.*, 2014; Cossu *et al.*, 2016). The produced electricity was drawn from electrodes in contact with the respective semiconductor types (Fig. 1b). The

Fig. 1. Semi-transparent PV module as a venetian-blind blade for the greenhouse shading application: overview of the PV module (a), cross-sectional structure of the spherical Si-PV cell (b), overlap of the sun and the PV cells photographed using a digital camera with a solar eclipse observation filter 1 m below the module (c).

spherical PV cell is smaller than the apparent diameter of the sun seen from an observer below the PV module. Therefore, the PV cells cannot eclipse the direct solar radiation completely (Fig. 1c). The rated output power of the PV module was 1.2 W (1 kW m⁻² single side irradiation at 25° C with air mass 1.5). The percentage of the opaque area, which included the 0.38 mm width conductors and the cells, was 31% when the module was visible from the direction of the module normal. This percentage corresponds to the ideal value with a perfect transparency of the glass plates and resin.

The PV module rim was covered by a 2-mm-thick aluminum frame. Iron shafts were fixed respectively to the two short sides of the module frame to rotate the PV module around the shaft axis (Fig. 2). Two PV modules were aligned on the common rotation axis and were mounted on a 1250 mm × 825 mm aluminum frame. Only two PV modules were manufactured for this study because of the difficulty of hand assembly of the unique PV module and the consequently high manufacturing costs. Their electrical output terminals were connected in parallel. The module shaft was connected to a geared DC motor (SS23F-LH-860-DC12V; Sawamura Denki Ind. Co., Ltd., Kanagawa, Japan) with rated voltage, current, torque, and rotation speed of 12 V, 0.3 A, 2.0 N m, and 4 rpm, respectively. Two pyranometers P_{PVT} and P_{PVB} (ML-01; Eko Instruments Co. Ltd., Tokyo, Japan) were positioned proximally at the bottom long side of one PV module. The P_{PVT} normal coincided with the PV module normal. The P_{PVB} faced 180° opposite. The global irradiances on the top surface I_{PVT} and on the bottom surface I_{PVB} of the PV modules were measured respectively by P_{PVT} and P_{PVB} . A pyranometer P_{Cell} was positioned 0.2 m below the PV module, facing the eastern sky with its normal direction aligned to the normal of the eastern roof of a north–south oriented greenhouse, to measure the sunlight shading percentage of the semi-transparent PV module. The distance of 0.2 m was chosen to avoid collision of P_{Cell} and the PV module during module rotation and to ensure positioning of P_{Cell} in the PV module shadow when the sun was in the eastern sky.

2.2 Motor drive circuit for PV-blind rotation control

A motor drive circuit was developed to rotate the PV modules in response to irradiance (Fig. 3). A pyranometer P_{Signal} (ML-01)

Fig. 2. Block diagram of the prototype PV blind system: P_{PVT} and P_{PVB} are pyranometers respectively facing to the sky and the ground when the PV module is set parallel to the greenhouse roof. S_1 and S_2 are mechanical switches to stop the blind position at a parallel (S_2) or perpendicular (S_1) position.

transformed horizontal global irradiance I_H into the input signal voltage of the motor drive circuit. P_{SIGNAL} was positioned at the top of the greenhouse. The P_{SIGNAL} voltage was amplified linearly using an operational amplifier (LM358; Texas Instruments Inc., Texas, USA). The output voltage of the operational amplifier was voltage V_{CW} at the IN_1 terminal of a DC motor full bridge driver (TA7267BP; Toshiba Corp., Tokyo, Japan). Therefore, V_{CW} was proportional to I_H . The amplification factor can be regulated by an R_0 value. The motor rotation direction can be changed according to the amplitude balance of the voltages at the input terminals IN_1 (V_{CW}) and IN_2 (V_{CCW}) of the DC motor full bridge driver. The PV blind rotation from the perpendicular to the parallel position to the roof surface was defined as clockwise (CW). The reverse rotation was defined as counter-clockwise (CCW). The R_0 value determines a threshold irradiance value of the CW blind rotation.

Two diodes D_1 and D_2 (BY329-1200; NXP Semiconductors, Eindhoven, The Netherlands) and two mechanical switches S_1 and S_2 (DB1C-A1LB; Cherry GmbH, Auerbach, Germany) were used to achieve automatic reshuffling rotations CW and CCW (Fig. 2). S_1 and S_2 were installed respectively at the perpendicular and parallel positions relative to the roof surface (Fig. 2). When the PV module touched one of the switches, the motor was disconnected from the circuit and was stopped. When $V_{\text{CW}} > V_{\text{CCW}}$, motor current i_M was supplied from terminal OUT_1 of the full bridge driver, then passed D_2 , S_2 , the motor, and finally arrived at terminal OUT_2 . The motor rotated the PV module CW during this process. Subsequently, the motor was disconnected from the circuit when the PV module touched S_2 . Thereby, the PV module stopped at the position parallel to the roof (Fig. 4a). By contrast, when $V_{\text{CCW}} > V_{\text{CW}}$, a reversed current $-i_M$ flowed. Thereby, the PV module turned to the position perpendicular to the roof (Fig. 4b). A voltage gap separating the CW and CCW rotations existed to avoid motor rotation instability in the proximity of the threshold I_H . This function was included in the DC-motor full-bridge driver (TA7267BP).

The terminals of the motor control circuit, a 28 Ah battery (40B19R; Panasonic Inc., Osaka, Japan), and the PV modules were connected with a charge-discharge controller (SA-MN05-8; Denryo Co. Ltd., Tokyo, Japan) to complete the stand-alone power system (Fig. 2).

A MOS FET relay (G3VM-21AR; Omron Corp., Kyoto, Japan) was added at the drive circuit inlet to eliminate the standby energy consumption of the motor drive circuit during nighttime. The relay was operated according to the experimental

Fig. 3. DC motor control circuit for rotating the semi-transparent PV modules: M denotes the DC motor; charge-discharge is abbreviated to C/D. PV_N denotes a conventional PV module used for detecting the test site brightness to disconnect the control circuit from the charge-discharge controller during nighttime, thereby reducing the standby energy loss.

site brightness, which was monitored by the output current of an additional PV module (KD03; Kyocera Corp., Kyoto, Japan; PV_N in Fig. 3) with current-regulating diodes.

2.3 Verification of PV blind performance at the test greenhouse

The PV blind was installed underneath the east-sky-facing glass roof (tilt angle of 26.5°) of the north-south oriented greenhouse ($8.20 \text{ m} \times 4.25 \text{ m}$) at the Shimane University campus ($35^\circ 29' \text{ N}$, $133^\circ 04' \text{ E}$) (Fig. 4). It was positioned below the roof because the prototype system was not water resistant. The north end of the long axis of the north-south oriented greenhouse deviated 6° to the west. The greenhouse floor was concrete without crop cultivation. The 0.1 mm conductor was positioned on the upper side of the PV module, with the 0.38 mm conductor positioned on the bottom side (see Fig. 1b) when the PV module was parallel to the roof. The external horizontal global-irradiance I_H was measured using pyranometer P_H (ML-01). Pyranometer P_T (ML-01) was used to measure the global irradiance on the inclined greenhouse roof-surface I_T (26.5° inclination and 6° to the north from true east). P_H , P_T , and P_{SIGNAL} were positioned on the top of the greenhouse roof at 3.5 m height. The CW threshold I_H was set at 500 W m^{-2} by adjusting the R_0 value at $3 \text{ k}\Omega$.

The irradiance, the electrical power output, and the operations of the PV blind were measured at 1 min intervals during 26–29 April and 1–8 May 2017 using a data acquisition unit (34972A; Keysight Technologies Inc., California, USA) and a voltage and current source/meter (6241A; ADC Corp., Tokyo, Japan). Data were stored in a computer after transmission through a GPIB interface. Data obtained during two sunny days (28 April and 4 May) and one cloudy day (26 April) are presented in the results section to demonstrate the electrical and shading performance of the PV blind system.

Fig. 4. Semi-transparent PV modules installed underneath the greenhouse glass roof facing the eastern sky: PV modules positioned as parallel (a) or perpendicular (b) to the roof surface.

The angle γ between direct sunlight incidence and the PV-module's normal (Fig. 2) was calculated using the following geometric formula (Yano *et al.*, 2009).

$$\cos \gamma = \sin h \cos \varphi + \cos h \sin \varphi \cos (|\alpha - \beta|) \quad (1)$$

In that equation, h , φ , α , and β respectively represent the solar altitude, the PV module tilt angle, the azimuth of the sun, and the azimuth of the PV module normal.

2.4 Energy balance of the PV blind system

The energy flow of the PV blind system was measured continuously from 21 February through 23 April 2017. The CW threshold I_H was set at 600 W m^{-2} . Three shunt resistors of 0.1Ω were connected respectively to the PV module, the battery, and the load terminals of the charge–discharge controller (SA-MN05-8) to measure the PV generated current i_{PV} , the charging current into the battery i_C , and the current supply to the motor drive circuit i_D . In addition to the current values, I_H , I_T , I_{PVT} , I_{PVB} , as well as voltages at the PV module, battery, and circuit terminals were measured at 10 s intervals using the data acquisition unit (34972A). By integrating the product of the voltage, current, and duration, the respective cumulative energies generated by the PV module E_{PV} , charged into the battery E_C , and supplied to the motor drive circuit E_D were calculated. The total cumulative energy consumption E_i at the charge–discharge controller, conducting wires, shunt resistances, and the internal resistance of the battery were calculated using the following formula.

$$E_i = E_{PV} - E_C - E_D \quad (2)$$

3. Results

3.1 Shading performance of the PV blind

The global irradiance on the eastern greenhouse roof-surface I_T , the global irradiances on the PV top surface I_{PVT} and on the PV bottom surface I_{PVB} , and the irradiance I_{Cell} measured by the pyranometer P_{Cell} behind the PV module on 28 April and 4 May sunny days are depicted in Figs. 5a and 5b. Morning data of 28 April were lost because of a data-logging computer freeze. I_T peaked before 11:00. I_{PVT} generally followed the course of I_T with slightly attenuated values according to partial sunlight scattering at the greenhouse glazing. I_{PVT} was greater than I_{PVB} during most of the daytime, but I_{PVB} sharply increased in the late afternoon when the PV modules turned to the position perpendicular to the roof. Thereby, the angle γ values jumped up (Figs. 5d and 5e). Direct sunlight irradiated the bottom of the PV module and therefore also irradiated the pyranometer P_{PVB} from the western sky at that time. P_{Cell} was shaded by the semi-transparent area ($154 \text{ mm} \times 158 \text{ mm}$ square area presented in Fig. 1a) of the PV module from 8:40 to 11:20. Direct sunlight reached P_{Cell} without passing through the PV module for the remaining hours. I_{Cell} decreased sharply when the metal roof beams of the greenhouse or the aluminum PV-module rim blocked the

direct sunlight from reaching the P_{Cell} . The sunlight transmittance of the greenhouse roof glass was calculated using the values of I_{PVT} over I_T when the PV modules positioned parallel to the roof and the pyranometer P_{PVT} were not shaded by any metal frame during 9:00–11:00. The average sunlight transmittance of the greenhouse glass roof was 91% (Table 1). The sunlight shading percentage of the PV module was calculated from I_{Cell} over I_{PVT} during 9:00–11:00. The average sunlight shading was 42% (i.e. transmittance of 58%, Table 1). During the period, the angle γ between the PV module normal and incident direct sunlight was 20° – 25° on 28 April (Fig. 5d) and 18° – 23° on 4 May (Fig. 5e). I_{Cell} over I_T during 9:00–11:00 presents the total transmittance of the solar irradiance by the greenhouse glazing and the PV blind (Fig. 5g). The average value of I_{Cell}/I_T was 53% (Table 1). This value estimates the transmittance of irradiance to be reached at canopy level when numerous PV modules cover the entire greenhouse roof at the inclination parallel to the roof. When the PV blind was perpendicular to the roof, the direct sunlight was mostly unaffected by the PV blind. Thereby, I_{Cell}/I_T can be approximated as 90% according to the transmittance of the greenhouse glazing. This condition was observable during 6:54–7:45 on 4 May, as presented in Fig. 5b.

On 26 April, a cloudy day (Fig. 5c), the PV blind mostly retained at the perpendicular angle to the roof to prioritize the sunlight intake into the greenhouse. The sky condition was overcast throughout the day. Therefore, direct sunlight was unavailable. At 13:59 the PV blind rotated CW to the parallel position to the roof. The average I_{Cell}/I_T during 14:00–15:10 was 45% (Fig. 5h, Table 1) when the PV blind was parallel to the roof (Fig. 5f). The shading performance of that period approximates a cloudy-day sunlight level in the test greenhouse, the roof of which is assumed to be covered entirely with the semi-transparent PV modules at the parallel inclination to the roof. Before and after the period, I_{Cell}/I_T were greater than 60% (Fig. 5h) by virtue of the perpendicular orientation of the PV blades.

3.2 Electrical characteristics of the PV modules

The power output P_o of the twin PV modules under the greenhouse glazing measured at 1 min intervals on 28 April and 4 May are depicted in Figs. 6a and 6b. The maximum value of P_o was 2.04 W at 10:39 on 28 April. The P_o curve generally followed the course of bifacial incident irradiance $I_{PVT} + I_{PVB}$, but it was suppressed around the peak of $I_{PVT} + I_{PVB}$ (Figs. 6a and 6b) because of the PV module microstructure. The spherical cells were interconnected by conductor wires (Fig. 1b) positioned at the top and bottom surface sides of the PV module. The top wires shaded the cells from sunlight irradiating from the top of the PV modules when the module normal was directed to the sun in the eastern sky. Thereby, P_o was suppressed around the peak of $I_{PVT} + I_{PVB}$.

The PV module efficiency η was calculated using the value of P_o per two-PV module single-side-areas ($500 \text{ mm} \times 200 \text{ mm} \times 2$) over $I_{PVT} + I_{PVB}$ (Fig. 6c). The greenhouse metal beams sometimes

Table 1. Sunlight transmittance of the PV blind and greenhouse glazing.

	PV blind	Greenhouse glazing	PV blind + Greenhouse glazing (sunny)	PV blind + Greenhouse glazing (overcast)
Sunlight transmittance (%)	58	91	53	45

Fig. 5. Global irradiance on the easterly inclined greenhouse roof-surface I_T , global irradiances on the PV top surface I_{PVT} and on the PV bottom surface I_{PVB} , and irradiance behind the PV module I_{Cell} on 28 April (a), 4 May (b), and 26 April (c); angle γ between direct sunlight incidence and the PV module normal on 28 April (d), 4 May (e), and 26 April (f); total transmittance of greenhouse glass and the PV module on sunny days (g, 28 April and 4 May) and on a cloudy day (h, 26 April).

separately shaded P_{PVT} , P_{PVB} , and PV modules as the sun position moved from east to west. Efficiency η decreased sharply when only the PV module was in beam shadow, and increased sharply when only the pyranometers were in shadow. For example, η decreased suddenly at 14:16 on 28 April and at 14:20 on 4 May (Fig. 6c). At the times of those events, P_o dropped suddenly while $I_{PVT} + I_{PVB}$ retained the slope of the continuous curve (Figs. 6a and 6b). Only the PV module was shaded by the greenhouse beam during those events. The average η during 9:00–14:00, when direct sunlight impinged on the PV modules and the pyranometers were not shaded by any opaque structure, was 1.1% on both 28 April and 4 May. The relation between η and γ during 9:00–14:00 is depicted in Fig. 6d. The values of η were greater than 1% over the wide incident angle of direct sunlight.

3.3 Energy balance of the PV blind system

The PV blind operated without outage for two months during 21 February to 23 April (Figs. 7a and 7b). The PV modules rotated 391 times in the CW direction when $I_H = 657.7 \pm 159.2 \text{ W m}^{-2}$ (mean $\pm$ standard deviation), and 391 times in the CCW direction when $I_H = 249.9 \pm 47.0 \text{ W m}^{-2}$. On sunny days such as 3, 4, and 23 April, the PV blind operated once CW in the morning and once CCW in the late afternoon. On heavily cloudy days such as 23 February, 21 and 31 March, 6, 9, 11, and 17 April, the PV modules did not rotate, but instead retained their position perpendicular to the roof, that enabled a better sunlight passage into the greenhouse.

The cumulative energy generated by the PV module E_{PV} ,

Fig. 6. Power output P_o curves of the twin PV modules installed underneath the greenhouse roof, horizontal global irradiance I_H , and total PV incident irradiance $I_{PVT} + I_{PVB}$ measured on 28 April (a) and 4 May (b). Module efficiencies η calculated based on $I_{PVT} + I_{PVB}$ (c) and relation between γ and η during 9:00–14:00 (d).

supplied to the motor drive circuit E_D , charged into the battery E_C , and the internally dissipated energy E_i were, respectively, 1257.5 kJ, 998.6 kJ, 207.5 kJ, and 51.4 kJ at the end of the operation test (Fig. 7c). E_i was 0.83 kJ d⁻¹ almost constantly. The daytime average current of the motor drive circuit i_D was 0.03 A. The system operation was supported by the energy

stored preliminarily in the battery during February through 22 March. At the maximum discharge ($E_C = -39.0$ kJ) on 10 March, 3.2% of the battery full capacity (28 Ah) had been discharged. The battery capacity recovered after the day. Finally, surplus electrical energy $E_C = +207.5$ kJ was stored.

4. Discussion

The prototype PV blind system operated reliably and continuously in response to the sunlight levels for two months. The operations were automatic and energetically stand-alone. Sunny-day intense sunlight was attenuated under the PV blind according to the semi-transparency of the PV modules. Because of its photovoltaic effect, some of the blocked sunlight by the PV cells was converted into electricity, unlike conventional shading materials such as nets or paint. The PV-produced electrical energy ensured the operation of the blind system. The PV blind had produced 207.5 kJ of surplus electrical energy by the end of the two-month test. System operations were supported by the energy stored preliminarily in the battery in late winter. At the maximum discharge, the battery supported the system operation using 3.2% (= 0.9 Ah) of the full battery capacity (28 Ah). The results suggest that sufficient energy should be stored in the battery before winter to ensure annual operation.

The annual energy balance of the PV blind system operation was estimated using the experimental data and local meteorological statistics. The orientation of the greenhouse's long axis was regarded as exactly the north-south. The roof was assumed to be covered with replications of the PV blind system installed underneath the glazing roof. For that estimation, the cumulative energy consumption at the motor drive circuit E_D was calculated using the values of motor drive-circuit current $i_D = 0.03$ A and voltage of 12 V during daytime (sunrise and sunset time data from National Astronomical Observatory of Japan). In addition, $E_i = 0.5$ kWh m⁻² yr⁻¹ was determined from experimentally obtained data. Accordingly, the annual energy consumption of the PV blind system per unit of greenhouse area was estimated as 9.4 kWh m⁻² yr⁻¹ (= $E_D + E_i$). On the other hand, the cumulative electrical energy production of the PV blind was estimated based on local insolation data obtained during the prior 9 years (2009–2017, from Japan Meteorological Agency) and exterior sunlight to electrical energy conversion efficiency η_0 of the PV blind installed underneath the greenhouse roof. The value of η_0 was determined from the equation 3 according to the percentage of the integrated PV-generated electrical energy against the integrated sunlight energy received by the greenhouse ground area of the PV-blind horizontal occupation ($S_{PV} \cos 26.5^\circ$).

$$\eta_0 = \frac{\int_{21 \text{ Feb}}^{23 \text{ Apr}} P_o dt}{S_{PV} \cos 26.5^\circ \int_{21 \text{ Feb}}^{23 \text{ Apr}} I_H dt} \times 100\% = 0.88\% \quad (3)$$

In this formula, S_{PV} represents the PV blind area (0.2 m²). The value of η_0 (= 0.88%) represents the realistic efficiency of the PV blind because both P_o and I_H were experimentally obtained throughout the test period under actual sunlight affected by the greenhouse structure and surrounding university buildings. The calculated value of the annual electrical energy production per unit of greenhouse area was 11.4 kWh m⁻² yr⁻¹. The cumulative

Fig. 7. Horizontal global irradiance I_H and the angle between roof surface and PV module's surface (a, 21 February–23 March; b, 24 March–23 April); cumulative energies generated by the PV module E_{PV} , charged into the battery E_C , and supplied to the motor drive circuit E_D (c).

amount of charging capacity was calculated from the difference of the produced and consumed electrical energy (Fig. 8). It was also depicted equivalently as surplus electrical energy per unit greenhouse area (kWh m⁻²). The surplus electrical energy can be estimated as 2.0 kWh m⁻² yr⁻¹ (= 11.4–9.4 kWh m⁻² yr⁻¹). Therefore, some additional greenhouse power demands can be met using this electrical energy. Campiotti *et al.* (2008) reported that electrical energy demands range from 2 kWh m⁻² yr⁻¹ for very low-technology climate control to a maximum of 9 kWh m⁻² yr⁻¹ with advanced climate control (heating, cooling or ventilation) in Mediterranean greenhouses. Sato *et al.* (2013) investigated the electrical energy demands of a heat pump and an oil-fired heater in a 1000 m² rose greenhouse in Shizuoka, Japan. According to their report, 3.43 and 0.37 kWh m⁻² yr⁻¹ (12.34 and 1.32 MJ m⁻² yr⁻¹) of electrical energy were demanded respectively for heating and cooling by the heat pump. Also, 0.31 kWh m⁻² yr⁻¹ (1.13 MJ m⁻² yr⁻¹) of electrical energy was demanded by the oil-fired heater. The surplus of electrical energy (2.0 kWh m⁻² yr⁻¹) producible by the present PV system would meet the electrical energy demands for the Mediterranean greenhouses with simpler controls or exceed the demands of the heat pump cooling and the oil-fired heater used in the study by Sato *et al.*, if the present PV blinds could cover the entire greenhouse.

The low energy efficiency of the PV module is ascribed to the low PV-cell density that was intended to ensure adequate sunlight transmissivity to the crops below the PV module. To overcome this conflict of electrical energy production and sunlight transmissivity, increasing the PV cell density, decreasing the conductor wire width,

and increasing the transparency of the conductor wire (Dalapati *et al.*, 2018) remain as topics to be tackled in future.

On sunny days the greenhouse interior irradiance was maintained as around 500 W m^{-2} when the exterior irradiance was greater than 800 W m^{-2} (Figs. 5a and 5b). For the natural sunlight spectrum, 500 W m^{-2} is approximated as $900 \mu\text{mol m}^{-2} \text{ s}^{-1}$ of photosynthetic photon flux density (PPFD) (Larcher, 1995). PPFD exceeds $2000 \mu\text{mol m}^{-2} \text{ s}^{-1}$ on sunny summer days, although the photosynthetic light saturation points of major agricultural C3 plants are $1000\text{--}1500 \mu\text{mol m}^{-2} \text{ s}^{-1}$ (Larcher, 1995) or less (Fu *et al.*, 2012; Hidaka *et al.*, 2013). The yield and quality of some crop species might be improved if only excessive sunlight were moderately shaded by the semi-transparent PV blinds, which can be rotated to a less-shading position when irradiance is less than a photosynthetically optimal level. Based on their data obtained from well-designed experiments, Kläring and Krumbein (2013) reported that the quality of tomato fruit might be unaffected by partial shading if shading were to occur only during high irradiation hours. López-Marín *et al.* (2013) reported that some sweet pepper crops in Spain might be producible under 40% shading. High-quality rocket was cultivated in Italy with PV panel installation on 32% of the greenhouse roof (Buttaro *et al.*, 2016). Tani *et al.* (2014) demonstrated that lettuce can be cultivated appropriately under 50% solar cell coverage of a greenhouse roof during summer and autumn in Japan. They used light-scattering film underneath the PV cells, which were arranged in a checkerboard formation on the test greenhouse. The lettuce plants received $700 \mu\text{mol m}^{-2} \text{ s}^{-1}$ of PPFD at the peak on 4 September. These results of earlier studies show that the present dynamic blind control with less than 42% shading of the PV modules might be beneficial for greenhouse cultivation of moderate-light demand crops in high-insolation seasons or regions.

Cloudy day irradiance was adequately introduced into the greenhouse by virtue of the blind orientation to the perpendicular position relative to the roof. This improvement of the sunlight intake

Fig. 8. Calculated annual cumulative charging capacity (left ordinate axis) and cumulative surplus electrical energy of the PV module blinds per unit greenhouse area (right ordinate axis) estimated based on local meteorological data. The surplus electrical energy of $2.0 \text{ kWh m}^{-2} \text{ yr}^{-1}$ corresponds to the subtraction of the system consumed energy of $9.4 \text{ kWh m}^{-2} \text{ yr}^{-1}$ from the PV generated energy of $11.4 \text{ kWh m}^{-2} \text{ yr}^{-1}$. The battery charging capacity of the PV blind system measured from 21 February to 23 April is also depicted.

in the greenhouse on cloudy days is a particular advantage of this PV blind system. As depicted in Figs. 7a and 7b, the PV blind retained a perpendicular ($\theta = 90^\circ$) position relative to the roof without any rotation on overcast days. This behavior is also beneficial for conserving electrical energy consumption by the blind operations.

Sunlight energy received at the ground level at the center in the greenhouse, the roof of which was covered with the replication of the PV blinds, was estimated assuming two different blind angles ($\theta = 0^\circ$ and 90°) using exterior I_H data measured on 4 May (Fig. 9). The values reported in Table 1 were used as the sunlight transmittance of glazing and the PV blind. The atmospheric transmittance during the day was determined as 0.65. The sunlight energy in the test greenhouse was estimated to be $20.6 \text{ MJ m}^{-2} \text{ d}^{-1}$ without the PV blinds (Fig. 9 a and b). It

Fig. 9. Estimated greenhouse interior irradiance on 4 May assuming that the PV blinds were not installed (a, b) or the greenhouse roof was covered with the semi-transparent PV blinds, the tilt angle of which were parallel ($\theta = 0^\circ$; c, d) or perpendicular ($\theta = 90^\circ$; e, f) to the roof. Exterior horizontal global irradiance I_H measured on 4 May is depicted with black bold lines (b, d, and f). Numerous gray lines in (a), (c), and (e) represent opaque frames (5 cm width of north–south oriented beams and 4 cm width of east–west oriented beams) of the greenhouse roof and the PV blind rim superimposed on the angular coordinate of the sun path (green line in (a), red line in (c), and blue line in (e)). The observation point of the sun path was set at the center of the greenhouse on the floor level. A positive azimuth corresponds to a western direction. The azimuth at 0 rad indicates the true south. Sky blue areas in (c) and (e) represent the semi-transparent PV blinds. Calculated interior irradiances under the respective PV blind conditions are depicted with green (b), red (d), and blue (f) lines.

would be $17.0 \text{ MJ m}^{-2} \text{ d}^{-1}$ if the PV blinds were oriented at $\theta = 0^\circ$ (Fig. 9 c and d). The interior sunlight energy would be increased to $18.1 \text{ MJ m}^{-2} \text{ d}^{-1}$ if the PV blinds were kept at $\theta = 90^\circ$ to prioritize sunlight intake into the greenhouse (Fig. 9 e and f).

This study confirmed the physical feasibility of a PV blind system for greenhouse applications. Although the shading controllability presents new possibilities of greenhouse environment control, the small scale of the prototype is insufficient for deployment to conventional greenhouses. To extend the system scale, the cost of manufacturing specific semi-transparent PV modules represents the salient difficulty. There are some possibilities to design a semi-transparent PV blind using substitute PV cells through low-cost automated manufacturing processes. The glass plates used in the present PV modules were superior in terms of transparency, thermal stability and mechanical hardness. These characteristics were necessary to fabricate the special semi-transparent PV modules. However, gaining this benefit necessitated the sacrifice of light weight. The weight restricts the number of PV modules that are controllable by a single motor. The lighter the weight is, the more connectable PV modules are controllable by a single motor, which boosts the energy efficiency of the total blind system. Substituting the module matrix material from glass to plastic might reduce weight and costs considerably. Further studies should be conducted to attract agricultural and industrial attention to greenhouse applications of PV systems and to achieve benefits for large-scale production of greenhouse PV materials.

5. Conclusions

For application to greenhouse shading, a stand-alone venetian-blind-type system was prototyped using bifacial semi-transparent PV modules. The maximum power output of the twin PV modules was 2 W when they were operated underneath the greenhouse glazing roof. The sunlight-to-electricity conversion efficiency of the PV module was 1.1% based on the reference area of the PV module single-side, 69% of which was transparent material to transmit sufficient sunlight to the greenhouse. The stand-alone PV blind system was operated autonomously according to the level of the external irradiance. The PV modules were oriented parallel to the greenhouse roof with 42% sunlight shading when the irradiance was intense. When the irradiance level was low, the PV modules were oriented perpendicular to the roof to increase the sunlight intake into the greenhouse. The cumulative energy balance of the PV blind system became positive after a two-month test of operation conducted during early spring in Japan, suggesting that the surplus energy can be supplied to electrical appliances for greenhouse environment control to achieve better crop yield and quality. Further studies must be undertaken to expand the blind coverage area to some model experimental greenhouses and to test plant reactions to a modified light environment.

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