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Research Paper

Prototype semi-transparent photovoltaic modules for greenhouse roof applications

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Improved energy efficiency and the increased use of renewable energy are important objectives for sustainable greenhouse crop production. Two prototypes of semi-transparent-bifacial photovoltaic modules intended for greenhouse roof applications were developed. A module (PV_1) using 1500 spherical solar microcells (1.8 mm diameter, crystalline silicon) with 15.4 cells cm^{-2} density in 108 mm × 90 mm area was produced. Thirty-nine percent of the area was covered with the cells. The remaining 61% was transparent to allow the most sunlight to enter the greenhouse for promising plant photosynthesis. Similarly, a module (PV_2) was made using 500 cells with 5.1 cells cm^{-2} density. Thirteen percent of the area of this module was covered with the cells. The peak power output was 540 mW when the PV_1 module was irradiated with 1213 W m^{-2} sunlight coming directly from the sky and via ground reflection. The peak power output was 202 mW when the PV_2 module was irradiated with 1223 W m^{-2} sunlight. The conversion efficiencies from sunlight energy irradiated on the 108 mm × 90 mm area into electrical energy were 4.5% for the PV_1 module and 1.6% for the PV_2 module. Calculations of the annual electrical energy production per unit greenhouse land area indicated that these modules are potentially suitable for greenhouses in high-irradiation regions where electricity production could be high and winter demand low.

1. Introduction

Greenhouse plant production improves the yield and quality of crops through control of the growth environment in terms of light, water, temperature, relative humidity, CO_2 concentration, and ventilation. Greenhouse environment control often entails the consumption of fuel and electricity. Consequently, important aims for sustainable greenhouse crop production are to minimise energy consumption and to compensate, or partly compensate, the consumed energy with renewable energy (Bot et al., 2005; Yano et al., 2009, 2010).

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Nomenclature

d	distance between the PV module and an observation point in the PV cell shadow, m
e_1	solar eclipsing percentage by PV_1 cells, %
e_2	solar eclipsing percentage by PV_2 cells, %
I	electric current, A
I_{HT}	global irradiance on a horizontal plane, W m^{-2}
I_{HS1}	horizontal global irradiance in the PV_1 cell shadow, W m^{-2}
I_{HS2}	horizontal global irradiance in the PV_2 cell shadow, W m^{-2}
I_T	global irradiance on the inclined PV top surface, W m^{-2}
$I_{T\rho}$	ground-reflected irradiance on the inclined PV bottom surface, W m^{-2}
p	atmospheric transmissivity, %
P_{max}	peak power value of a P_{pv}–V characteristic curve of the PV modules, W
P_{pv}	power output of the PV modules, W
s_0	shading percentage of the PV-module's transparent cover materials, %
V	voltage, V
β	tilt angle of the PV modules, °
γ	angle between direct sunlight incidence and the sky-directing PV-module's normal, °
η	module efficiency, %
ψ_p	azimuth of the PV module's normal from the south, °

Crop yields depend strongly on the availability of light. Nearly 1% yield loss is expected to occur with a 1% reduction in light (Kläring & Krumbein, 2013; Marcelis, Broekhuijsen, Meinen, Nijs, & Raaphorst, 2006). Nevertheless, in some high-irradiation regions or during summer for some crop species, solar radiation is often too intense. Accordingly, screens and coating applications are used to moderate the intensity of radiation in greenhouses (López-Marín, Gálvez, González, Egea-Gilabert, & Fernández, 2012). This fact implies that the excessive sunlight irradiating greenhouses could be useful to provide an electrical energy source for the operation of environment-control equipment after conversion into electricity using photovoltaic (PV) modules.

Yano et al. (2005b) and Yano, Tsuchiya, Nishi, Mariyama, and Ide (2007) developed a ventilation window controller driven solely by electrical energy supplied from a greenhouse-roof-mounted 0.078 m^2 PV-module with a conventional 28 Ah car battery used for PV energy storage. The stand-alone ventilation-window controller was operated successfully and greenhouse temperature was regulated appropriately. This implies that a PV module size could be extended to cover more of the greenhouse roof and that heavier electrical loads than the ventilation window controller could be driven using PV generated electricity. If the electrical energy consumed by some heavy loads, such as heating and cooling, could be replaced, or partially replaced, by PV generated energy, then the consumption of grid-supplied electricity in greenhouses could be reduced. Yano et al. (2010) studied electricity gain and shading in an east–west oriented greenhouse on which a 720 W maximum-rated-power PV array covering 12.9% of the roof area was mounted. Two PV array configurations were tested: a straight-line and checkerboard arrangements. The two arrangements created quite different sunlight distributions in the greenhouse, although the electrical energy generated by these two arrangement PV arrays was comparable. The annual solar-irradiation distribution in the checkerboard PV greenhouse was more uniform than that of the straight-line PV greenhouse because the checkerboard PV array intermittently cast shadows in the greenhouse. Kadowaki, Yano, Ishizu, Tanaka, and Noda (2012) studied how plants grew in the greenhouse equipped with the PV arrays. The growth of welsh onions under the straight-line arranged PV array shadows was inhibited significantly because the PV array cast shadows on the plants continuously during cultivation. However, the inhibitory growth effects of the shading were diminished with the checkerboard array. The PV results were not generalised because the balance between the amount of electricity produced and the allowable shading rate varies according to plant species, geography, meteorology, season, and greenhouse characteristics. Ureña-Sánchez, Callejón-Ferre, Pérez-Alonso, and Carreño-Ortega (2012) tested PV modules with a checkerboard arrangement for greenhouse tomato production with nearly 10% coverage. The results showed that PV shading did not affect the yield or the price of tomatoes despite some negative effects on fruit size and colour.

The use of sunlight can be shared by plants and PVs by separating the sunlight spectrum with respect to plant photosynthesis and PV electricity production. The sunlight spectrum in the 400–700 nm wavelength range is designated as the photosynthetically active radiation (PAR) because it is particularly important for crop cultivation. Radiation with wavelengths longer than 700 nm could be useful for purposes other than plant cultivation. Consequently, Sonneveld, Swinkels, Bot, and Flamand (2010) and Sonneveld, Swinkels, Campen, et al. (2010) developed a greenhouse roof PV system that allowed the penetration of PAR for plant growth but captured near-infrared radiation for electricity production and heat storage. Another aspect of solar radiation is beam density: i.e. direct and diffused irradiance. Fresnel-lens greenhouse roofs have been developed to concentrate the direct radiation onto a photovoltaic and thermal collection module, while diffused radiation remains unchanged and reaches the plants (Sonneveld et al., 2011; Souliotis, Tripanagnostopoulos, & Kavga, 2006).

These studies showed that although conscientious design is necessary, it is possible to generate enough electricity for the control of greenhouse environment appliances using PV systems that are compatible with plant cultivation (Kadowaki et al., 2012; Sonneveld et al., 2011; Ureña-Sánchez et al., 2012; Wenger & Teitel, 2012).

Past PV greenhouse studies commonly used conventional flat hard or planar flexible PV modules (Al-Ibrahim, Al-Abbadi, & Al-Helal, 2006; Kadowaki et al., 2012; Pérez-Alonso, Pérez-García, Pasamontes-Romera, & Callejón-Ferre, 2012; Sonneveld, Holterman, Swinkels, van Tuijl, & Bot, 2008; Sonneveld, Swinkels, Bot, et al., 2010; Sonneveld, Swinkels, Campen,