Applied Energy 162 (2016) 1042–1051

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Advances on the semi-transparent modules based on micro solar cells: First integration in a greenhouse system

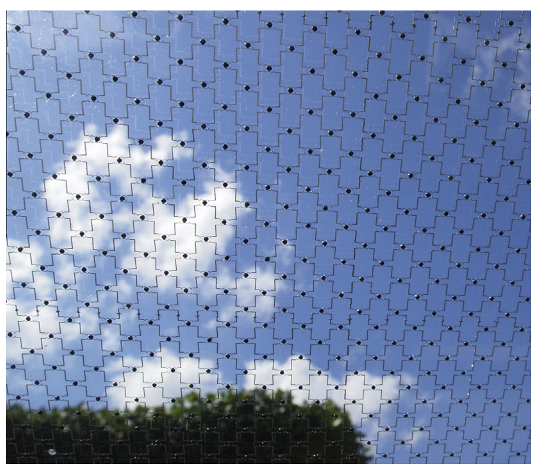
Marco Cossu [a], Akira Yano [a,*], Zhi Li [a], Mahiro Onoe [a], Hidetoshi Nakamura [b], Toshinori Matsumoto [b], Josuke Nakata [c]

[a] Faculty of Life and Environmental Science, Shimane University, 1060 Nishikawatsu, Matsue, Shimane 690-8504, Japan
[b] Sphelar Power Corporation, 2F Karasuma-Nijo bldg. 267 Makieya-cho Nakagyo-ku, Kyoto 604-0857, Japan
[c] Kyosemi Corporation, 949-2 Ebisu-cho Fushimi-ku, Kyoto 612-8201, Japan

HIGHLIGHTS

- A semi-transparent photovoltaic module was developed for greenhouse applications.
- Spherical micro-cells with 1.2 mm diameter were embedded in the module.
- The module size matches the roof panel and the sunlight eclipsing level was 9.7%.
- The module conversion efficiency was 0.2% over wide incident angles of sunlight.
- The semi-transparent module allows the co-production of crops and energy.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 30 September 2015
Accepted 4 November 2015

Keywords:
Sunlight
Shading
Renewable energy
Sustainability
Crop

ABSTRACT

The spherical micro-cells are a semi-transparent photovoltaic (PV) technology which can contribute to improve the sustainability of greenhouse systems. Previous prototypes were tested in laboratory conditions, but the size was not suitable for the greenhouse roof application. In this work, a new prototype has been developed and tested on a real greenhouse roof. The semi-transparent PV module (STM) was composed by 4800 spherical silicon micro-cells (1.2 mm diameter) sandwiched between glass plates and integrated on a greenhouse roof with 26.5° slope. The STM was 910 mm long and 610 mm wide to match the size of the greenhouse framework. The percentage of the STM area covered with micro-cells was 2.3%, reaching 9.7% considering the metallic conductors. The cell density was 2 cells cm^{-2} and the measured perpendicular light transmissivity of the semi-transparent area was 73%. The characteristics of the prototype were compared with those of a conventional planar multi-crystalline silicon module (CPM). The module conversion efficiency was steadily around 0.2% over wide incident sunlight angle. The micro-cells never completely eclipse the incident sunlight when observed from more than 1 m distance from

* Corresponding author. Tel./fax: +81 852 32 6543.
E-mail address: yano@life.shimane-u.ac.jp (A. Yano).

http://dx.doi.org/10.1016/j.apenergy.2015.11.002

the roof, keeping the eclipsing level at 9.7%. The yield factor of the STM was slightly higher than the CPM because of the isotropic properties of the spherical cells, which are able to use both the sky-incident and the ground-reflected irradiation for energy production, irrespective of the module slope. The prototype STM is promising for greenhouse roof applications and its performance can be improved by increasing the conversion efficiency.

1. Introduction

A greenhouse improves the yield and quality of crop productions by means of micro-climate optimisation. The environment control in greenhouse systems is an energy-demanding technique affecting the profit and loss of greenhouse crop production [1–3]. The economic competitiveness of the greenhouse depends also on the capability of saving and self-producing energy to partly or completely cover the demand. Photovoltaic (PV) energy is the most popular renewable source in Europe [4, 5], already examined in the greenhouse sector for powering various climate control applications [6–10]. The same area on which the greenhouse is located can be partly used for installing PV systems, thereby producing energy without consuming additional land for agricultural activities or restricted by regulations. Accordingly, the PV greenhouse integrates a PV array on the roof, with the attempt of finding the best compromise between energy and food production on the same area, thus optimising the integrated system [11, 12].

The solar radiation available inside a PV greenhouse decreases with the ratio of the roof area covered with panels and it is distributed with a high variability over the greenhouse area, depending on the sun position, the portion of the area considered, and the roof panel configurations [13]. The yield is strictly related to the light availability [14–16], decreasing by nearly 1% for every 1% reduction of solar radiation for a large variety of greenhouse crops including vegetables and flowers [17]. As a consequence, the irregular distribution of the solar radiation in a PV greenhouse affects crop growth and productivity differently depending on the position of the plants on the cultivation area. The uniformity of the light distribution can be improved by increasing the gutter height, installing the PV array on both roofs, or arranging the PV panels using a checkerboard pattern [18–20].

The crop response is essentially related to the species considered and the characteristics of the PV greenhouse. Yield reduction of tomato was not observed inside a greenhouse with a 9.8% PV coverage, despite negative effects observed on the fruit size and colour [21]. A crop yield loss of 25% was observed for Welsh onion, when the PV coverage was 13% [22]. The biomass production and yield of basil and zucchini were not affected significantly by a PV coverage of around 20% [23]. Most PV greenhouses in southern Europe have been realised with the specific purpose of maximising energy production. The structures have often been built following an east–west orientation, with the entire south-oriented roofs (50% of the total roof area) covered with conventional planar multi-crystalline silicon panels and roof slopes around 22° [24]. In this case, the solar radiation is distributed following a north–south gradient at the canopy level. The greenhouse areas under the PV roof receive 82% less solar energy than a conventional greenhouse without PV array, whereas the reduction under the plastic cover is 46%, on average.

The semi-transparent PV technology is considered a good compromise between electrical production and light transmissivity in greenhouse systems because they usually shade only a fraction of the incident solar radiation and can maintain the uniformity of light distribution over the greenhouse area. The products based on multi-crystalline or amorphous silicon have already been tested and applied on residential, commercial and office buildings [25–27]. They can be based on conventional planar silicon PV cells, flexible thin films, CIS or CIGS semiconductors [18, 28–30].

Other semi-transparent panels are based on spherical silicon micro-cells, as described already by Yano et al. [31]. The first prototype was based on spherical cells with 1.8 mm diameter with a sunlight eclipsing percentage of 39%. The solar radiation would be distributed homogeneously over the greenhouse area because the dimension of the small cells was not enough to completely eclipse the sun observed from plants. This feature can be distinguished from the semi-transparency of PV modules based on conventional cells, where the sun is completely eclipsed. Furthermore, they can use the sun-rays coming from any spatial direction, thereby producing a constant amount of energy over a wide range of sunlight incident angles. The prototype demonstrated the advantage of the spherical micro-cells, but the module still needed to be tested on the field and it was too small (97 cm^2) and thick (11 mm) for greenhouse roof applications.

In this study, a new prototype of semi-transparent module (STM) covered with spherical micro-cells and conductors was designed. The sunlight eclipsing percentage was calibrated referring to the light requirements of tomato, which is considered the most light-demanding greenhouse crop [32, 33]. As a reference concerning tomato cultivation inside PV greenhouses, Ureña-Sánchez et al. [21] reported no yield loss when the PV cover was 9.8% of the greenhouse roof area. Therefore, the new STM prototype has been designed with a similar sunlight eclipsing percentage of 9.7%, thus providing a transparency about four times potentially higher than the previous prototype. The module size was compatible with the dimensions of common greenhouse glass panels. Therefore, it has been integrated and tested on the roof of a real greenhouse. The shading of the PV panel over the greenhouse area has been measured and the electrical performance of the prototype has been compared with that of a conventional planar multi-crystalline silicon module (CPM).

2. Materials and methods

2.1. Spherical solar micro-cells and the semi-transparent PV module

Mono-crystalline silicon spherical PV cells of 1.2 mm diameter (Sphelar®; Sphelar Power Corp., Kyoto, Japan) were used (Fig. 1a). The PV cells were composed of a *p*-type semiconductor as the inner core and an *n*-type semiconductor as the outer shell [34, 35]. The power output is drawn through electrodes.

The STM was assembled using 4800 cells with a density of 2 cells cm^{-2} (Fig. 1b and c). The module was 910 mm × 610 mm to match the size of the greenhouse roof framework size. The cells were distributed across a 501 mm × 480 mm area, of which 2.3% was covered with the cross-sectional area of the cells and 7.4% with 0.3 mm wide metallic conductors, connecting the cells to feed current to the output terminals of the module. The 4800 cells were sandwiched between 3-mm-thick glass plates after they were embedded in 2-mm-thick transparent resin. Thereby, the STM was optically bifacial. The thickness of the module was 8 mm