Applied Energy 113 (2014) 32–40

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Mirror symmetrical dielectric totally internally reflecting concentrator for building integrated photovoltaic systems

Firdaus Muhammad-Sukki [a,b,*], Siti Hawa Abu-Bakar [a,c], Roberto Ramirez-Iniguez [a], Scott G. McMeekin [a], Brian G. Stewart [a], Nabin Sarmah [d], Tapas Kumar Mallick [d], Abu Bakar Munir [e], Siti Hajar Mohd Yasin [f], Ruzairi Abdul Rahim [g]

[a] School of Engineering & Built Environment, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, G4 0BA Scotland, United Kingdom
[b] Faculty of Engineering, Multimedia University, Persiaran Multimedia, 63100 Cyberjaya, Selangor, Malaysia
[c] Universiti Kuala Lumpur British Malaysian Institute, Batu 8, Jalan Sungai Pusu, 53100 Gombak, Selangor, Malaysia
[d] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn, Cornwall TR10 9EZ, United Kingdom
[e] Faculty of Law, University of Malaya, 50603 Kuala Lumpur, Malaysia
[f] Faculty of Law, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia
[g] Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81300 UTM Skudai, Johor, Malaysia

HIGHLIGHTS

- A novel type of solar concentrator is presented.
- The geometrical properties and the optical concentration gain are analysed.
- It provides significant gain within its acceptance angle, as high as 13.54×.
- The MSDTIRC is a better alternative design for the BIPV systems.

ARTICLE INFO

Article history:
Received 29 January 2013
Received in revised form 28 June 2013
Accepted 3 July 2013
Available online 31 July 2013

Keywords:
Solar photovoltaic
Solar concentrator
Mirror symmetrical dielectric totally internally reflecting concentrator

ABSTRACT

This paper describes a novel type of solar concentrator – a mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC). This new concentrator type has been designed to satisfy the following objectives: (i) to provide optimum gain in two different planes, therefore increasing the electrical output of a solar photovoltaic (PV) system, and (ii) to reduce the amount of the PV cell material needed, hence minimising the cost of the system. The concentrator is capable of having two different acceptance angles on different planes. The procedure of designing an MSDTIRC is explained and the geometrical properties are analysed in detail. In addition, the optical concentration gain is presented for various angles of incidence. Through simulation results, it is demonstrated that the MSDTIRC provides significant optical concentration gain within its acceptance angle, as high as 13.54× when compared with non-concentrating solar cell. It can be concluded that the MSDTIRC can be a way to produce a low cost solar PV system and can be chosen as an alternative design for the BIPV systems.

1. Introduction

Solar photovoltaic (PV) is one of the renewable energy technologies that has great potential in supplying the world's energy needs. According to a statistic from BP Global [1], the total installed capacity of solar PV around the globe in 2012 reached 100.1 GW, as presented in Fig. 1. Around 68.4% of the installations were carried out in Europe, 8.2% in North America with the remaining balance found in other parts of the world. The rising trend of solar PV installation in many countries is mainly catalysed by the implementation of a financial incentive known as the feed-in tariff (FiT) scheme, which is currently enacted in more than 80 countries [2].

The International Energy Agency (IEA) identified potential in integrating solar PV into the architectural design of roofs and facades for all types of building. A study [3] was conducted by the IEA to assess the prospect of building integrated photovoltaic (BIPV) systems in 14 selected countries. The study concluded that there is a BIPV area potential totalling approximately 23 billion m^2 and could generate about 3 PW h annually. According to another

* Corresponding author at: School of Engineering & Built Environment, Glasgow Caledonian University, 70 Cowcaddens Road, Glasgow, G4 0BA Scotland, United Kingdom. Tel.: +44 (0)141 331 8938; fax: +44 (0)141 331 3690.

E-mail addresses: firdaus.muhammadsukki@gcu.ac.uk, firdaus.sukki@gmail.com (F. Muhammad-Sukki).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.07.010

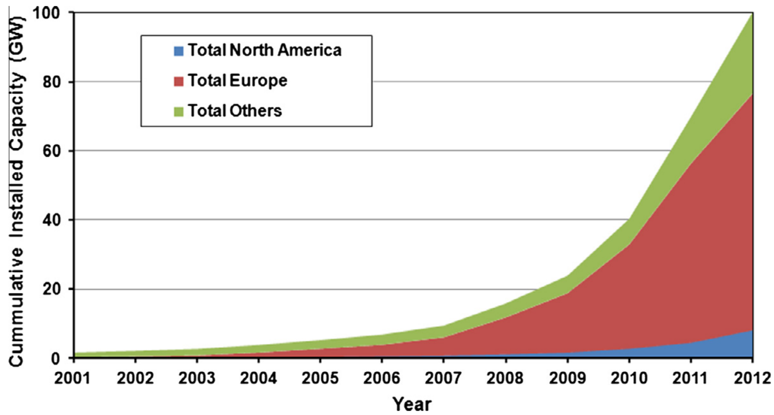

Fig. 1. Cumulative installed capacity of solar PV worldwide in 2011. Adapted from [1].

study by Oliver and Jackson [4], BIPV systems could offer additional advantages when compared with centralised solar PV plant which include the following:

i. Eliminate the cost of land acquisitions and the cost of support structures since the PV panels are mounted/replacing the building structure. The cabling cost could also be reduced since all buildings have access to the grid, unlike an isolated PV site.
ii. The electricity generated by BIPV systems could be consumed in the building itself, which minimises the losses due to the transmission and distribution of electricity. A reduction in the electricity bill could be achieved since the electricity generation coincides with the peak electricity demand during the day.
iii. The integration of PV panel substitutes parts of the building (e.g. roof, window, facade), eliminating the need for other building materials, which can be costly.

In the last decade, there has been a significant rise in the use of solar concentrators for BIPV applications, including sky lights, double glazing windows and solar blinds [5–7]. A solar concentrator is a device that allows the collection of sunlight from a large area and focuses it on a smaller receiver or exit [8]. The concentrator is aimed at reducing the usage of expensive PV material, hence reducing the overall cost of the system [5].

One example is the luminescence solar concentrator (LSC). With the ability to make full use of direct and diffuse sunlight, LSCs have the potential to replace windows and building facades. However, their low efficiency (the highest conversion efficiency is only 7.1% [9]) makes them less attractive for electricity generation, particularly if a homeowner wants to take full advantage of the FiT scheme.

Another concentrator type, called the asymmetrical compound parabolic photovoltaic concentrator (ACPPVC), was demonstrated by Mallick et al. [10]. These concentrators are made from reflective materials with strips of solar cell connected in series and attached at the exit aperture of the concentrators. Their experimental results indicate that this concentrator managed to increase the maximum electrical output power by 62% when compared with a similar system without a concentrator [10]. The panel could also be mounted on the roof or replace the wall of a building.

The asymmetrical compound parabolic concentrator (CPC) extrusion is another example employed by the Photovoltaic Facades of Reduced Cost Incorporating Devices with Optically Concentrating Elements (PRIDE) project which was carried out in the late 1990s [7,11]. The asymmetrical CPC is made from dielectric material. The first generation of PRIDE technology concentrators produced 2.3 times more electrical output when compared with a flat plate conventional solar PV [11]. However, it has disadvantages in terms of durability and instability of the dielectric material under long term outdoor characterisation [12]. This is because the concentrators were produced from casting processes which are prone to UV degradation [12]. With the aim of large scale production, durability and reduction in weight and cost, the second generation PRIDE design was developed in 2006 [12]. The prototype of the improved design was a 3 kWp PV concentrator module and was built using injection moulding processes. This design is suitable for building facade integration. When compared with a non-concentrating system, this prototype achieves a 2.01 output power gain. It is projected that the second generation PRIDE technology system could reduce the module cost by approximately 40% [12].

Recently, Sellami et al. developed a novel static 3D concentrator called the Square Elliptical Hyperboloid (SEH) for BIPV applications [5]. This concentrator has an elliptical entry aperture, hyperbolic side profiles and a square or rectangular exit aperture where a PV cell is attached. It has the potential to be integrated into double glazed windows. With a concentration value of $4\times$ and acceptance angle of 120° ($\pm 60^\circ$), an optical efficiency of 40% was recorded [5]. The large value of acceptance angle helps to eliminate the need for mechanical solar tracking.

Clive has also proposed an alternative design for BIPV systems known as SolarBrane which comprises of extrusions of dielectric totally internally reflecting concentrators (DTIRCs) [13]. SolarBrane can reduce the usage of PV material by 70% while maintaining the same output power when compared with a traditional solar panel [14]. The use of DTIRCs has the potential of reducing the cost of implementation of conventional solar PV systems by 40% [14].

Chemisana et al. [15] on the other hand investigated a holographic solar concentrator for the BIPV applications. This concentrator is capable of diffracting light in the spectral bandwidth to which the cell presents the highest sensitivity – allowing the PV cell to be protected from overheating [15]. It is reported that the holographic concentrator managed to increase the efficiency of the PV cell by 3% [15].

This paper proposes a new type of solar concentrator for use in BIPV systems. This concentrator is known as a mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC). Section 2 explains the steps involved in producing the design, and the geometrical properties of the MSDTIRC are presented in Section 3. The optical concentration gain analysis is carried out in Section 4 prior to presenting the experimental result of the optical gain of the concentrator in Section 5. The annual output prediction of