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Design, fabrication and outdoor performance analysis of a low concentrating photovoltaic system

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Abstract

A prototype concentrating photovoltaic (CPV) module was designed and constructed with a low concentrating dielectric compound parabolic concentrator (DiACPC) for outdoor characterisation. The designed concentrator has acceptance half angles of 0° & 55° with a concentration ratio of 2.8. This concentrator design is suitable for building facade integration in higher latitude (>55°) locations. A small prototype CPV module of 300 mm × 300 mm was constructed with 2 strings of 14 solar cells in series. The prototype CPV module was characterised in Edinburgh for different weather conditions and the performance is compared with a similar non-concentrating counterpart (i.e. a flat-plate module with the same PV cell area and technology) in real time. The electrical output results for a cloudy day, rainy day and a day with sunny intervals have been reported to evaluate the performance of the concentrating system with direct and diffuse irradiance. The maximum power output of the CPV module on the day with sunny intervals was found to be 5.88 W for a solar radiation input of 943 W/m^2, which is 2.27 times higher than that for the flat-plate module. The average short circuit current of the CPV module was found to be 2.22 times higher than that of the flat-plate module. The average open circuit voltage and fill factor of the CPV module were also found to be 2.5% and 1.6% higher than that for the flat-plate module. The CPV module is found to be very effective on the rainy day with an average power output of 0.13 W, which is 2.17 times higher than the average output power for the flat-plate module.

Keywords: Concentrating photovoltaics; BIPV; Low concentration; Dielectric concentrator

1. Introduction

Solar energy has the potential to fulfil the world's electricity demand without negative impact on the environment. However harvesting the abundant solar energy efficiently and in a cost effective way is still a challenge to the scientific community. With the development in solar photovoltaic (PV) technologies, it is expected that the grid parity with large scale PV implementation can be achieved by 2020, depending on the energy policy. However this requires increase in deployment of PV system both as commercial power plants and building integrated systems. It was reported that building integrated photovoltaics (BIPV) have potential of generating 3PWh energy annually considering current buildings around the world. BIPV systems do not need land space unlike PV systems and can also replace building components, for example a solar tile can be used instead of a conventional roof tile. Furthermore, in recent times it has been found that concentrating photovoltaic systems can be a potential option for BIPV. A low concentrating system with a wider range of acceptance angle can significantly increase the power output with reduced area of solar cell.

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From early days different stationary concentrator designs for different applications have been reported. The primary design objective of the stationary low concentrating systems is to collect the solar irradiation with the diurnal and seasonal variation of sun position without tracking the sun unlike the high concentrating systems. Especially for BICPV systems in higher latitudes, the concentrator should have a wide range of acceptance angles while mounted on building roof and facades. So it was found that asymmetric design is the most appropriate approach for the concentrator in BICPV system. Semi-Nonparabolic (SNP) concentrator (Mills and Giutronich, 1978), Extremely Asymmetric Concentrator (EAC) (Mills and Giutronich, 1979), sea shell concentrators (Rabl, 1976a, b) were a few early asymmetric concentrator designs proposed and reported for BICPV systems. However these concentrators were not suitable for deployment as they required seasonal tracking and had integration difficulties on the building walls. Non-imaging static concentrator designs were reported as another approach for BICPV system with roof tiles (Bowden etal., 1993; Wenham et al., 1997) and flat-plate static concentrators (Uematsu et al., 2001). However these concentrators are not capable of collecting solar radiations effectively with diurnal and seasonal variation of sun position in higher latitudes. For higher latitudes three different designs with asymmetrically truncated parabolic concentrators for stand-alone, building roof and wall integration have been reported by (Adsten et al., 2005, 2004). However the maximum optical efficiency is found to be only 56%, even though they are capable of collecting solar radiation effectively over the year.

Recent studies show the asymmetric compound parabolic concentrator (ACPC) design as a more promising choice for building integration compared to the other stationary concentrators (Zacharopoulos et al., 2000). This type of low concentrating ACPC can be designed with a wide range of acceptance angles for a specific concentration ratio to integrate on building façade in higher latitudes which can collect solar radiation effectively with diurnal and seasonal variation of solar altitude angle. Study shows that these types of concentrators can collect 40% solar radiation even outside the range of acceptance angles. A BICPV module with reflective type ACPC and acceptance half angles (0° and 50°) is reported to achieve a 62% increase in power output compared to that of a similar non-concentrating counterpart, while designed with a concentration ratio of 2 (Mallick et al., 2004). The range of the acceptance angle can be increased by manufacturing the ACPC with clear dielectric material. The solar radiation is collected to the receiver from the parabolic sides of the ACPC due to total internal reflection, hence reducing the reflection losses from the system (Mallick and Eames, 2007). The PRIDE concentrating system fabricated with this concept is reported to achieve an effective concentration ratio of 2.01, while designed for the concentration ratio of 2.45. A dielectric concentrator for Edinburgh and higher latitudes (>55°) is designed with acceptance half angles (0° and 55°) and geometric concentration ratio 2.8 (Sarmah et al., 2011). A CPV module with this kind of contractor has been reported with reduced optical losses in the module to increase overall system efficiency of the CPV system.

In current research, there are few other concentrator designs reported to achieve higher concentration ratios and a range of acceptance angles. To achieve higher optical efficiency for a wider range of acceptance angles compared to the reflective type counterpart, a lens walled CPC system has been proposed (Guiqiang et al., 2013). For a symmetrical CPC design of concentration ratio 4, the lens walled design can achieve optical efficiency of more than 40%, while the reflective counterpart has only 7% for incidence angle 20°. However, reduced optical efficiency within the range of acceptance angles is the major drawback of this kind of design. A Window Integrated Concentrating Photovoltaic (WICPV) has been reported with different configurations of hyperbolic concentrator design (Sellami and Mallick, 2013). This kind of system designed with 4X concentration ratio can achieve optical efficiency of 60% for a wide range of acceptance angle. While this kind of system has advantages of using daylight effectively, higher optical efficiency is anticipated to reduce the cost of the unit power output from the system. In a very recent study mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC) design is found attractive for building application (Muhammad-Sukki et al., 2014). Performance analysis with different design configuration shows that while designed for an acceptance angle of ±15°, this kind of design can achieve optical concentration ratio up to 13.54 (Muhammad-Sukki et al., 2014). However to achieve a wider range of acceptance angles (±30°), the optical concentration ratio needs to be reduced to 4.43. The performance of stationary low concentrating systems largely depends on the position of the sun (or sun angles), the solar cell used, system temperature, and the ability to collect direct and diffuse radiation. The advantage of the low concentrating devices is the wide range of acceptance angles, which enables the concentrator to collect a large portion of diffuse radiation along with direct radiation. However the amount of diffuse radiation collected is different than the direct radiation, so they need to be treated differently (Sarmah et al., 2011).

In this paper, the performance of a CPV module with a dielectric concentrator in an outdoor environment has been reported. The performance in different weather conditions has been carried out in order to evaluate the influence of difference weather parameters. Three days consisting of one day with sunny intervals, one cloudy day and one rainy day has been considered in this study. The temperature of the module has also been monitored to realise the effect on the power output. The performance of the CPV module is compared with a similar non-concentrating counterpart to evaluate the performance of the designed dielectric concentrator during different times of the day in different weather conditions.