DEVELOPMENT AND CHARACTERISATION OF A LOW CONCENTRATING DIELECTRIC PHOTOVOLTAIC CONCENTRATOR

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Abstract

A prototype concentrating photovoltaic module is designed and constructed with dielectric asymmetric compound parabolic concentrator (DiACPC) for building integration in higher latitudes (>55°). The 5.5 W_p module is characterised in an outdoor environment in Edinburgh, UK (55°N, 3°W). The dielectric concentrator of geometrical concentration ratio 2.8 is manufactured from clear polyurethane material with a maximum transmission of 89.5% within the visible range. The stationary concentrator is designed to collect radiation within the range of incidence angles 0° to 55°, to correspond with the seasonal variation of altitude angle at higher latitudes. A maximum electrical power output of 4.3W from the CPV system is measured for solar irradiance 865 Wm^{-2}. Compared to the similar non-concentrating counterpart, a maximum of 2.3 times increase in power is observed. The optical losses within the concentrating system have limited the maximum power ratio to the 84% of the designed concentration ratio 2.8. The optical losses and manufacturing defect has been investigated for detail analysis of the variation of power output for different sun position and change in intensities over a day.

1. Introduction

Building integrated photovoltaic (BIPV) systems have enormous potential for power generation as an alternative to use of land for PV installations [Strong, 1996]. Roofs are still a popular choice for BIPV as it offers, less shading, cost is partially reduced by roof materials and optimum inclination can be used [Norton et al, 2010]. Now a days, building façades are increasingly attractive for PV installation, with designs such as PV glass curtain walls and rainscreen overcladding [Norton et al, 2010]. However, the concentrating photovoltaic (CPV) system is expected to reduce the cost of the unit energy output; replacing solar cells by less expensive materials. While many concentrators with different profile and receiver designs have been reported so far for photovoltaics applications [Winston, 1974; Rabl, 1976; Luetz et al, 1999; Koltz, 1995], for building integration, a stationary concentrator with low a concentration ratio is reported as suitable option [Zacharopoulos et al, 2000, Mallick and Eames, 2007].

A 1kW flat plate roof tile concentrating system with 16% efficiency has been reported for building roof integration [Bowden et al, 1993]. The concentrating tiles have been designed for bifacial solar cells to achieve a concentration ratio of 2 on the bottom surface and 1.5 on the top surface. Another flat plate static concentrator (FPSC) for both monofacial and bifacial solar cells has been reported with concentration ratios of 1.5 and 2 respectively [Uematsu et al, 2001]. The concentrator is a sub-millimetre V-groove reflector placed inbetween the solar cells. Outdoor testing of the FPSC module results in 1.23 times higher short circuit current density compared to the conventional module. In other studies, static asymmetric concentrators have been designed to achieve a concentration ratio from 2.96 to 4.65 depending on the inclination of the module and the optical axis of the concentrator [Gajbert et al, 2007]. Simulation results with the data of solar irradiation in Stockholm, Sweden, shows that the system having 2.96 concentration ratio with 25° module inclination and 20° concentrator inclination can achieve 72% higher electrical power than that of a vertical reference module. For higher latitudes special design of the static concentrator is required for BIPV to collect solar energy over a year considering the seasonal variation of solar altitude angle. The Asymmetric Compound Parabolic Concentrator (ACPC) is found to be suitable for building integration because of design flexibility and the ability to collect 40% of solar radiation even outside the angular acceptance range [Zacharopoulos et al, 2000]. A 62% increase in maximum power was observed with reflecting type ACPC concentrators of concentration ratio 2 and acceptance half angles (0^o and 50^o) [Mallick et al, 2004]. Dielectric ACPC is found more effective over the reflective type in achieving higher concentration ratios with a wide range of acceptance angle [Mallick and Eames, 2007].

The present study investigates the performance of the optimum dielectric ACPC designed for higher latitudes ($>55^o$) in terms of power output from concentrating photovoltaic (CPV) module. The study has been carried out with a prototype module with the designed concentrator and the results have been compared with a similar non-concentrating counterpart.

2. Material and Method

In designing a geometric photovoltaic concentrator for building integration, the following factors have been taken into account: The concentrating photovoltaic module is to be mounted vertically on the building facades; the concentrator is able to collect solar energy over a day and year with diurnal and annual variation of sun position; the concentration ratio is to be kept low (>10) to an avoid active cooling requirement in the CPV module; light-weight and less-expensive material to be considered to reduce the weight and cost of the system.

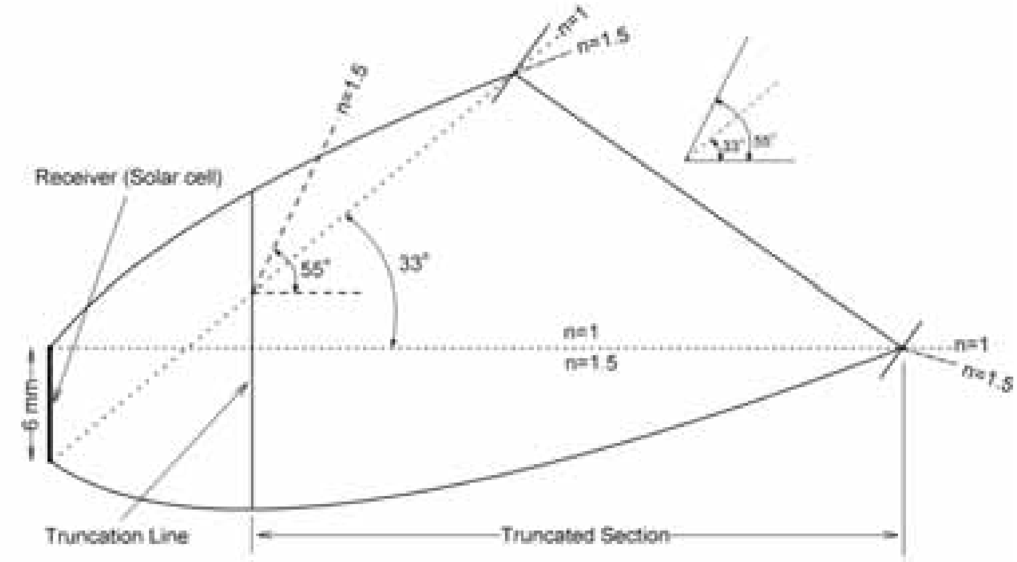


Figure.1. Schematic diagram of the designed concentrator showing truncation and acceptance half angle

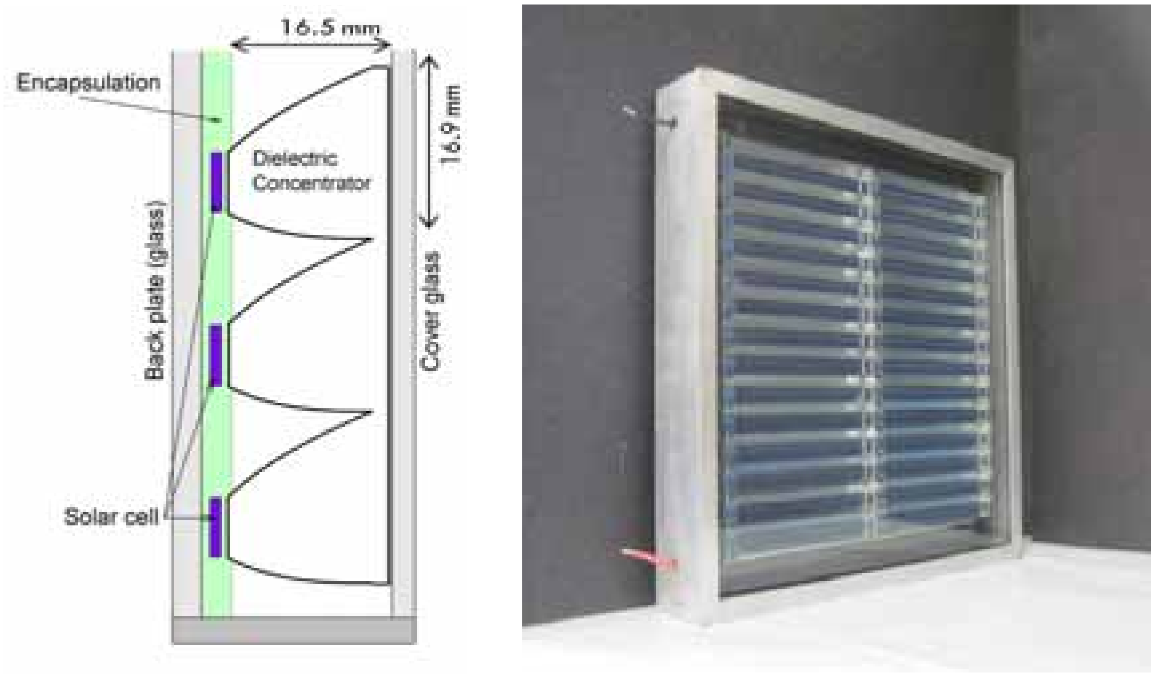
The reported concentrator is an ACPC (as shown in figure.1) which is achieved after truncation of 68% of the complete profile. The dielectric concentrator is designed for 2.8 geometrical concentration ratio, with acceptance half angles 0^o and 55^o. The theoretical study shows that this concentrator has better optical performance compared to its counterpart of similar concentration ratio and acceptance angle, while having smaller depth. Dielectric CPC concentrators can collect over a wider range of incidence angles than reflecting CPCs for a given concentration ratios. The radiation incident on the aperture of the concentrator is concentrated to the receiver from the parabolic sides of the concentrator due to the total internal reflection, which is expected to reduce the reflection losses compared to the reflecting type concentrators. Considering all the reflections to be specular, the optical efficiency of this dielectric concentrator is found to be maximum of 83% within the range of the acceptance half angles [Sarmah et al, 2011]. The majority of the losses occur due to the partial reflection at air-dielectric interface on the aperture and absorption in the material. The cover glass in the CPV system, which is not optically coupled with the concentrator aperture, results in higher air-dielectric interface reflection loss. This partial reflection loss increases with increase in incidence angle. The designed concentrator is to be used with 6 mm wide and 116 mm long crystalline solar cells.

3. Fabrication of the concentrator

The designed concentrator is fabricated with clear polyurethane plastic having good transmission properties. Polyurethane is being used in various industries because of its good resistance to degradation by water, oil and solvents [Saunders and Frisch, 1964]. The clear polyurethane from Smooth-on^{TM} is also expected to have high durability with good resistance to weather and UV degradation for PV applications. The dielectric concentrator is manufactured by casting process to give better transmission properties than would be obtained by injection moulding or extrusion. The chosen polyurethane has an easy and cost effective curing process, unlike PMMA. It shrinks negligibly to maintain the designed concentrator profile during the curing process. The material cures at room temperature and pressure with excellent transmission properties within the visible range, without post curing treatment. The aluminium mould for the casting process is manufactured by machining an aluminium block with a cutter fabricated to the concentrator profile. The mould is designed to manufacture 8 concentrator troughs as one unit. The number of troughs in one concentrator unit is restricted to avoid any mechanical structural defect that may arise with ageing, such as bending problems which can cause delimitation of the solar cell and the concentrator [Mallick and Eames, 2008]. The urethane monomer is supplied as part-A and part-B, which are mixed in a 10:9 ratio. The mixture is placed in a vacuum chamber for 10 minutes to eliminate air-bubbles before pouring into the pre-constructed mould. The complete set is then kept at room temperature and pressure for 24 hours to cure. The cured plastic with the designed concentrator profile is then used to construct a CPV module.

4. Design and construction of CPV module

A prototype CPV module of 5.5 W_p has been designed and constructed for outdoor testing. The CPV module is constructed with two parallel strings of 14 solar cells in series. The interconnection of the solar cells is carried out in a pre-designed jig to achieve correct alignment of the receiver and solar cell in the module. 1.8 mm wide and 0.1 mm thick PV ribbon is used for inter-connection. The schematic diagram of the designed module and the image of the CPV module used in the characterisation is shown in figure. 2(a)&(b). To compare with the commercial building integrated PV set-up, 4 mm window glass is used as back substrate. A silicon elastomer (Sylgard-184) from Dow-Corning is used to encapsulate the solar cell. This encapsulation material also works as binding material to fix the solar cells to the back substrate and the concentrator units on top of the solar cells. Sylgard-184 has excellent transmission properties within the UV-visible spectral range with refractive index 1.5. This provides an excellent optical coupling between the concentrator receiver, encapsulation material and solar cell. Unlike the conventional encapsulation material, EVA, Sylgard-184 has a simple curing process. The elastomer is prepared by mixing the base and curing agent (as supplied) in a 10:1 ratio by weight followed by 10 minutes in a vacuum chamber to eliminate air bubbles. The mixture is poured on top of the glass where the inter-connected solar cells have been placed. Once the solar cell and encapsulation material are in place, the concentrator units are placed on top of the solar cell taking care to align the receiver and solar cell. A layer of Dow-Corning primer 92-023 is used to enhance the bonding of the glass, solar cell and concentrator. The elastomer in the system is then allowed to cure for 48 hours to ensure good binding between the glass and concentrator units. To evaluate the performance of the CPV system and the designed concentrator, a similar non-concentrator system is constructed using the same procedure and the same materials. The set-up is then framed in an aluminium structure with low iron content cover glass. The cover glass prevents scratching of the concentrator aperture and protects the concentrating system from degradation due to weather.



(a) (b)

Figure.2. (a) Schematic diagrams of the CPV module design. (b) Image of the constructed CPV module

5. Experimental procedure

The experimental performance of the constructed CPV module is carried out by characterising the electrical power output over a day compared to the similar non-concentrating counterpart. The experiment was carried out on the roof of Heriot Watt University building in Edinburgh, Scotland (55°N, 3°W), placing the modules vertically and facing south. A high speed data acquisition and I-V curve tracing set-up from EKO was used to obtain I-V reading from both concentrating and non-concentrating modules. Both the modules are connected to the IV curve tracer through a switching device called module selector. A Kipp and Zonen MP11 pyranometer is connected to the IV tracer, for continuous measurement of solar radiation in 1 minute intervals.

6. Results and Discussion

6.1. Spectroscopic characterisation

The spectroscopic analysis of the manufactured concentrator is carried out in terms of transmittance for the ray’s incidence normal to the aperture. The transmittance of the different components used in the CPV module is shown in figure.3. For a 14.5 mm thick concentrator trough, the transmittance is found to be 79-89.5% within the wavelength range 420-1100 nm. The transmittance starts dropping below 420nm and becomes zero at 396 nm. This is because of the uv-stabiliser within the material, added to prevent UV degradation of the polymer. As the crystalline solar cell responds from 300nm to 1100 nm, the absorption losses below 420 nm will result in reduction of the designed CPV system’s performance. The transmittance of the 2.75 mm thick BF glass used as cover glass is found to be 60-92% within 300nm to 1100 nm. The transmittance of the 0.5mm thick sylgard-184 is found to be 71-93.1% within the range of 300-1100 nm. The spectral response of the solar cell in the CPV module is affected by the absorption losses of the dielectric concentrator compared to the bare solar cell (figure.3).

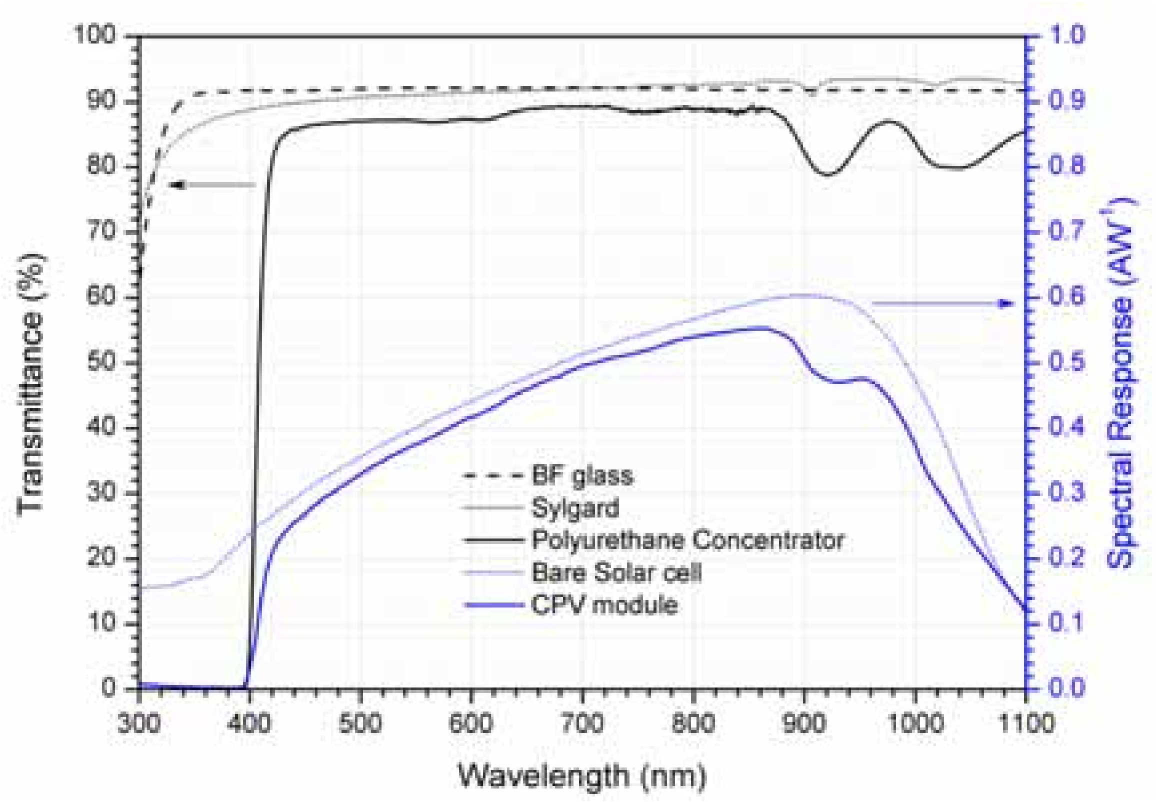


Figure.3. Transmission results of different components used in the designed CPV module and spectral response of the bare solar cell and CPV module

6.2. Electrical performance analysis

The experimental results from outdoor characterisation of the designed CPV module on 9th of June are reported. The outdoor characterisation of the CPV module was undertaken on a typical Scottish day with sun shine, rain and clouds, which helps in understanding the performance of the system in real environment for both direct and diffuse radiations. The diurnal variation of the solar radiation on the vertical plane facing south and the power output of the CPV system are shown in figure.4. The maximum power output of the system is found to be 4.3 Watt, corresponding to maximum solar radiation of 886 W/m^2 at 10:42 am. The fill factor is recorded as 79% for the CPV system and 73% for the non-concentrating system during the maximum power output. The maximum open circuit voltage is found to be 8.5V during this time of maximum solar radiation. The systematic study on the effect of the increase in temperature couldn't be carried out because of the rapid change in solar radiation. However, when the solar irradiation more than 800 W/m^2 remain steady for 2-3 minutes, the open circuit voltage in CPV module tends to decrease, which is because of increase in temperature. The maximum solar cell temperature of the CPV module is found to be 27^{o}C, while the ambient temperature was 15^{o}C. The diurnal variation of short circuit current follows a similar pattern to diurnal variation of solar radiation as shown in figure.5.

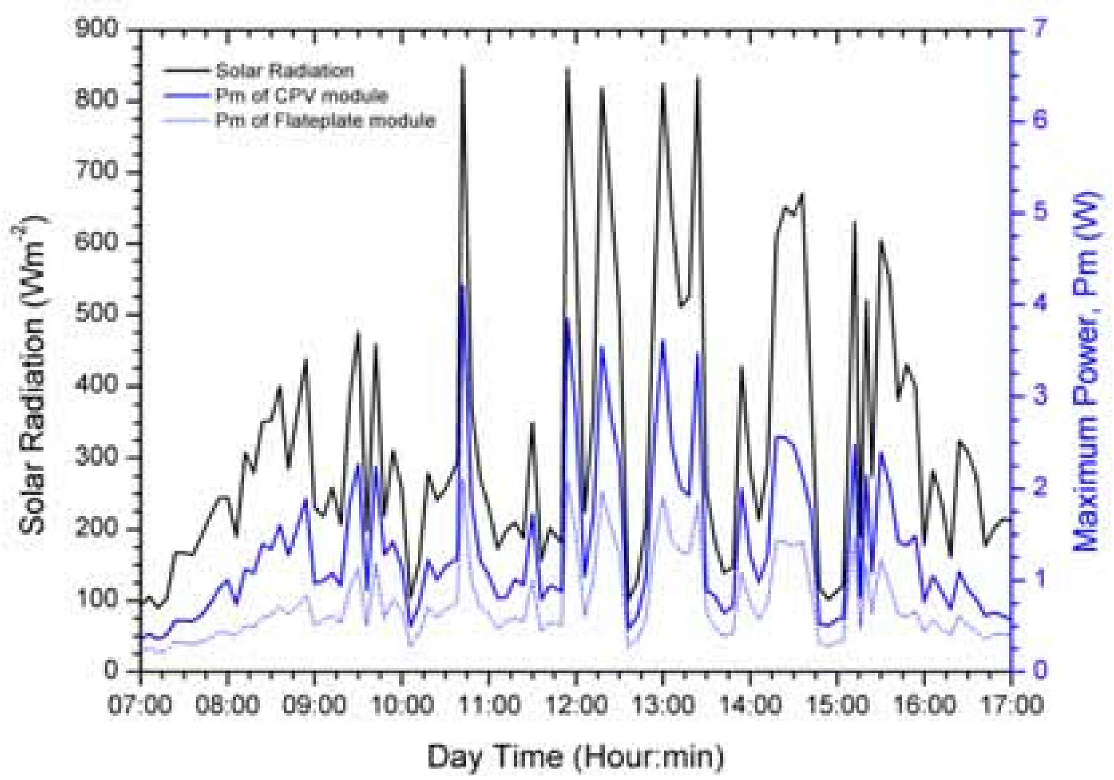


Figure.4. Diurnal variation of solar radiation and maximum power of the designed CPV and flat-plate modules

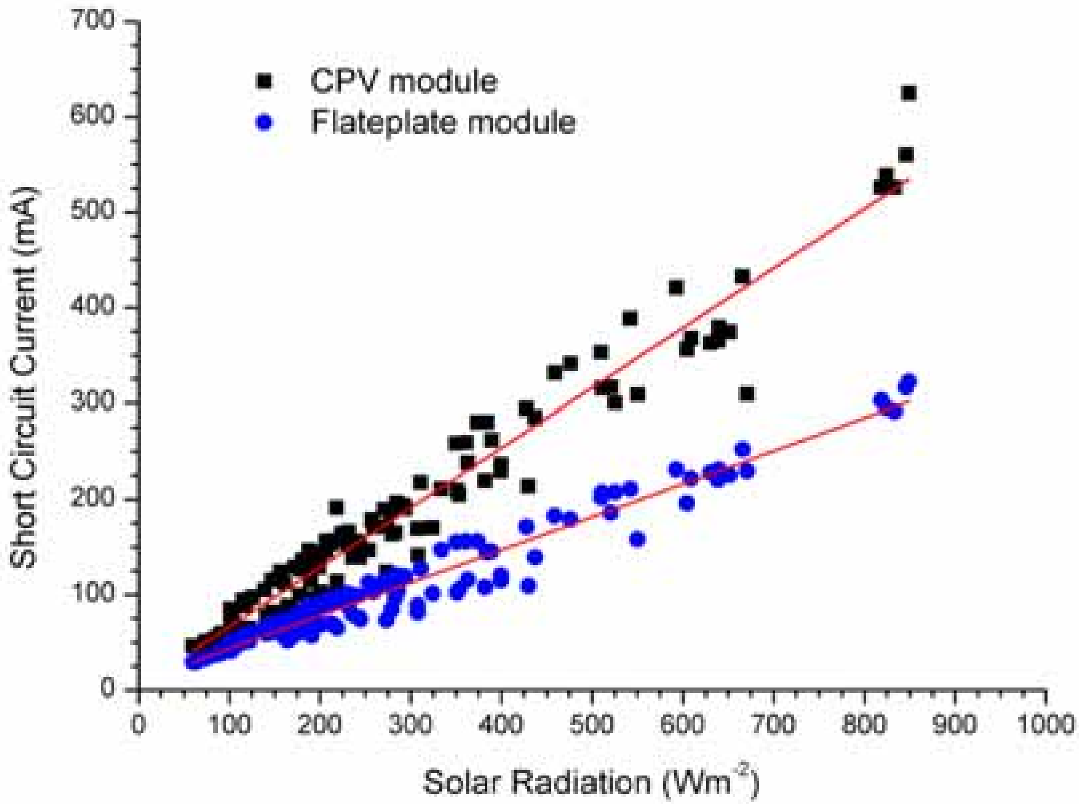


Figure.5. Variation of short circuit current of the designed CPV and flat-plate modules over a day, with variation of solar irradiation

Because of the rapid change in solar radiation and electrical output of the system; the results are given as 15 minute averages of data collected in 1 minute intervals. For the maximum solar radiation 886 W/m^2 at 10:42 am, the maximum short circuit current of the CPV system is found to be 641 mA, while the non-concentrating system results to be 329 mA. The minimum short circuit current recorded was 80.4 mA at 12:36 pm for solar radiations of 104 W/m^2. The variation of power ratio of the CPV system, over the non-concentrating counterpart for different solar radiation intensities is shown in figure.6. For higher solar radiation intensities, the major part of the radiation is due to direct radiation and for lower intensities the major contribution is diffuse radiation. It is observed that the power ratio for lower intensities is 1.6 at 91 W/m^2, while for higher intensities it is found to be a maximum of 2.3 at 530 W/m^2. Study shows that the designed dielectric concentrator performance for both direct and diffuse irradiation correlates very well with the theoretical analysis [sarmah et al, 2011].

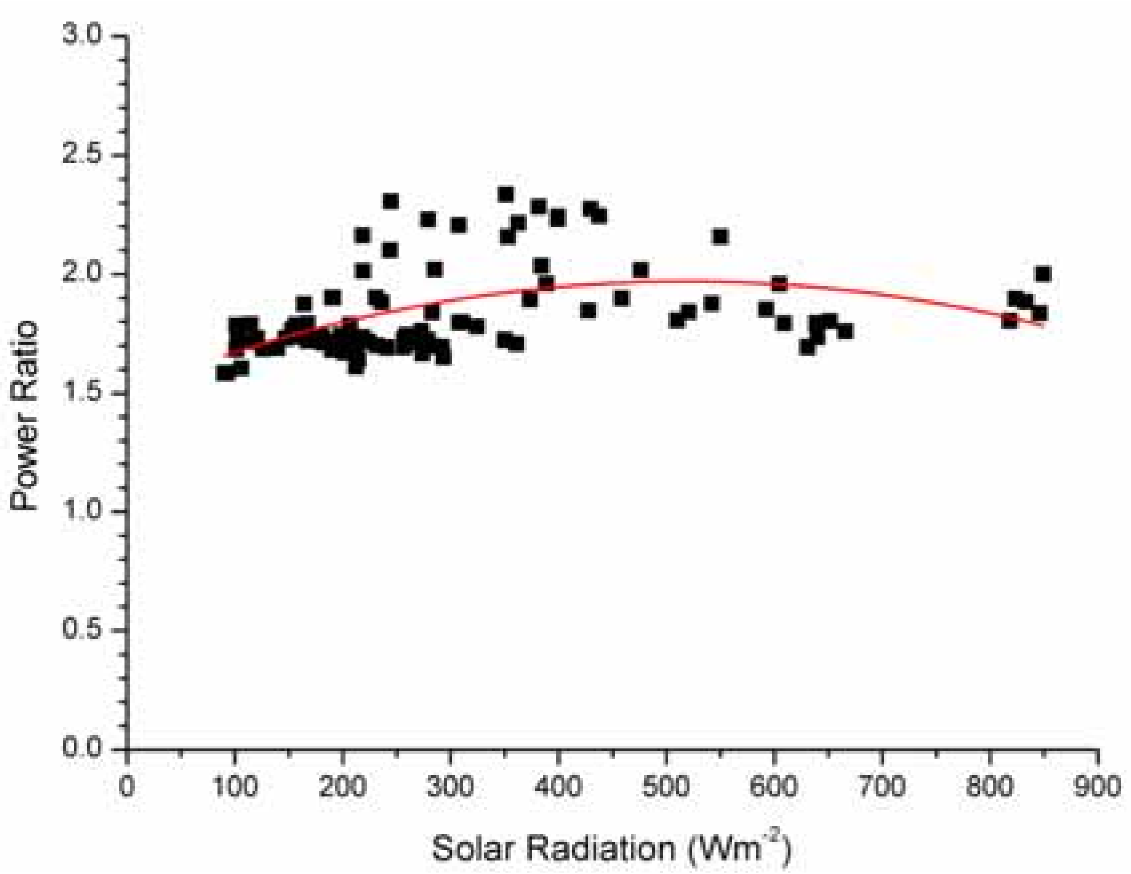


Figure.6. Power ratio of the concentrating system over the non-concentrating with diurnal variation of solar irradiation

The system efficiency of the designed CPV module and the non-concentrating system for different solar radiation intensities over the day is shown in figure.7. The system efficiency of the CPV module is calculated considering the effective aperture area of the concentrators, while the total area of the solar cells in use are considered in the case of the non-concentrating system. The maximum system efficiency of the CPV module is found to be 9.2% at 500 W/m^2 irradiation compared with 14.2% for the non-concentrating system. The system efficiency of both CPV and non-concentrating system increase with increasing solar radiation intensities up to 500 W/m^2; falling with further increases in intensity. The increase in temperature of the system with increase in radiation intensity may have lead to the decreases in system efficiency. To reduce significant errors due to change in solar radiation intensities, the system efficiencies are calculated based on an instantaneous measurement of power at a particular time.

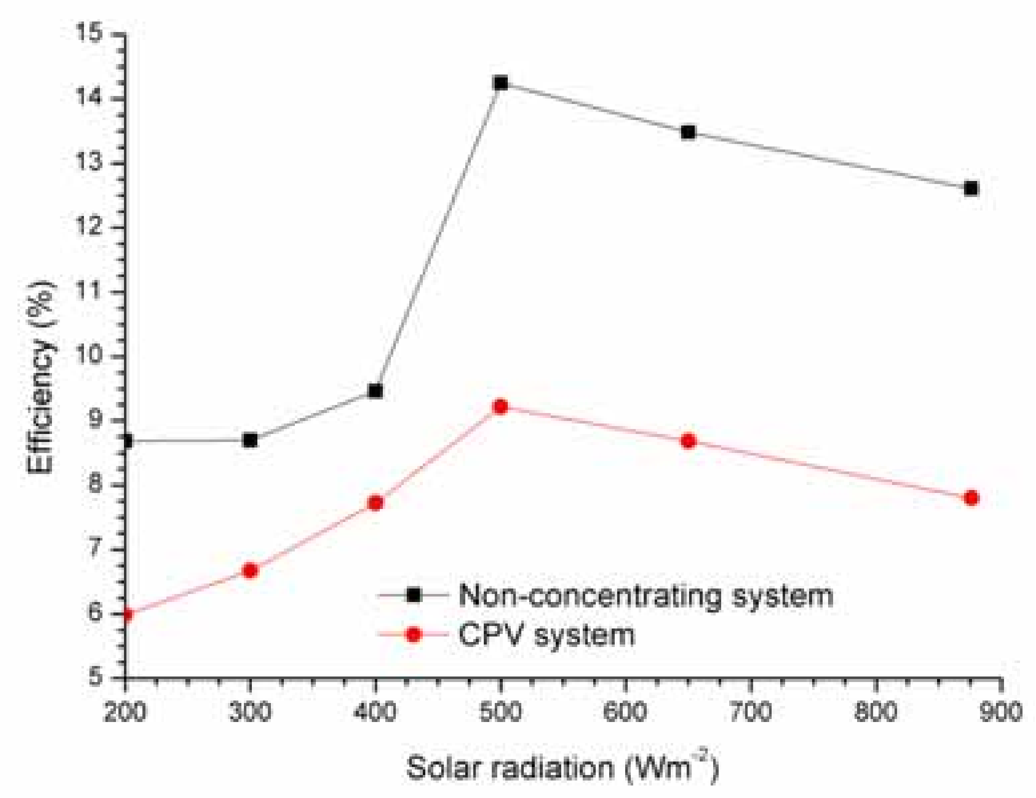


Figure.7. Variation of system efficiency of the Concentrating and non concentrating system for different solar radiation intensities over a day

The study shows that that the concentrating system increases the output power by a maximum of 2.3 times over the non-concentrating counterpart in contrast to the designed concentration ratio of 2.8. The power ratio is found to be inconsistent over the range of acceptance half angle of the designed concentrator (0° & 55°). Manufacturing errors such as slight misalignment of the receiver of the concentrator and solar cell may be one of the reasons for this inconsistency. For extreme acceptance half angles concentrated rays may escape from the concentrator-encapsulation-cell interface, which lead to the lower short circuit current and system efficiency of the system.

7. Conclusion

A prototype CPV module with designed dielectric concentrator is constructed and characterised in an outdoor environment. The manufactured concentrator is based on the optimum CPC design with 2.8 concentration ratio and acceptance half angle 0° and 55° for building integrated photovoltaic systems in northern latitudes (>55°). The prototype module of 300mm×300mm is constructed with 28 solar cells of 116mm long and 6mm wide. Electrical characterisation of the CPV module results in a maximum power output of 4.3 Watt for the maximum solar irradiation of 886 W/m^2 on the day of experiment. Compared to the similar non-concentrating counterpart, a maximum power ratio of 2.3 is observed. However inconsistency of power ratio for different solar radiation intensities and for different time of the day is observed, due to losses occurring due to manufacturing defects such as misalignment and light escaping from the concentrator-encapsulation-cell interface. Continuous monitoring of the system for a few months has been undertaken and will be reported in future with detailed performance analysis of the designed dielectric CPV system in different weather conditions.

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