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Outdoor Performance of a Reflective Type 3D LCPV System under Different Climatic Conditions

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Abstract. Concentrating sunlight and focusing on smaller solar cells increases the power output per unit solar cell area. In the present study, we highlight the design of a low concentrating photovoltaic (LCPV) system and its performance in different test conditions. The system essentially consists of a reflective type 3.6× cross compound parabolic concentrator (CCPC) designed for an acceptance angle of ± 30°, coupled with square shaped laser grooved buried contact (LGBC) silicon solar cells. A heat exchanger is also integrated with the PV system which extracts the thermal energy rejected by the solar cells whilst maintaining its temperature. Indoor characterization is carried out to evaluate the system performance under standard conditions. Results showed a power ratio of 3.12 and an optical efficiency of 73%. The system is placed under outdoor environment on a south facing roof at Penryn, UK with a fixed angular tilt of 50°. The high angular acceptance of the system allows collection of sunlight over a wider range. Results under different climatic conditions are presented and compared with a non-concentrating system under similar conditions. On an average, the LCPV system was found to collect an average of 2.54 times more solar energy than a system without the concentrator.

INTRODUCTION

This Concentrated Photovoltaics is an effective method of extracting large amounts of energy using smaller sized solar cells. A range of technologies has been developed using this concept using different optical concentrators. Typically, these technologies are classified based on the geometric concentration (×) that may be achieved using different optical configurations. Low concentrator photovoltaics (LCPV) can be classified as technologies having a concentration ratio of 1-10×. The key benefits of these systems include minimal or no seasonal tracking plus the use of standard silicon solar cell technology. A variety of these systems has been developed in the past few decades designed for building integration[1-5]. Both reflective and refractive type concentrators are utilised in LCPV devices. The most commonly used design is a Compound Parabolic Concentrator(CPC) as a concentrator optics in these systems. This may have a symmetric or asymmetric configurations [3, 6] and use reflective or dielectric optics. Three-dimensional designs using a CPC profile have been widely adopted in the LED industry to enhance the light output from the small sized lamps.

Similar approaches have been incorporated in CPV devices using a slightly modified approach using both reflective[7] and refractive[1] based three-dimensional Cross Compound Parabolic Collectors (3DCCPC). FIGURE 1 shows us the details of a typical CPC parabolic profile with an acceptance angle of 30°. The parabolic profile is swept around a square cross section for a geometric concentration of 4×. Truncation is carried out for an optimal performance[7], making the effective concentration of 3.6× which corresponds to a truncated height of 80mm. Results obtained from the indoor characterization of a single unit of this system where shown previously[8]. It was found that

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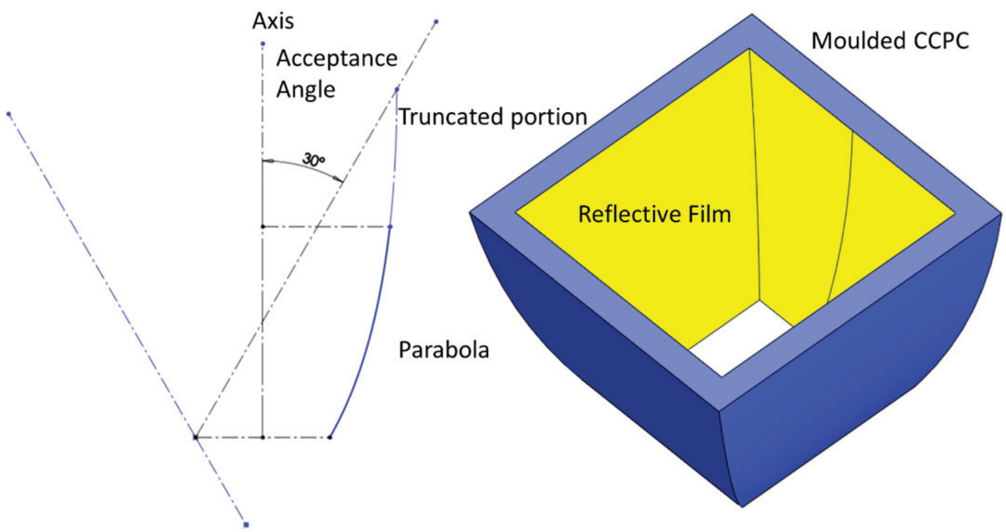
a maximum optical efficiency of 79 % was achieved against an expected optical efficiency of 93.8%. Only a portion of the incoming solar radiation is converted to electricity while the rest is rejected in the form of heat. The solar cell temperature without the concentrator was found to stabilise at around 56 °C while introducing the concentrator on top increased the solar cell temperature to a maximum of 78.9 °C.



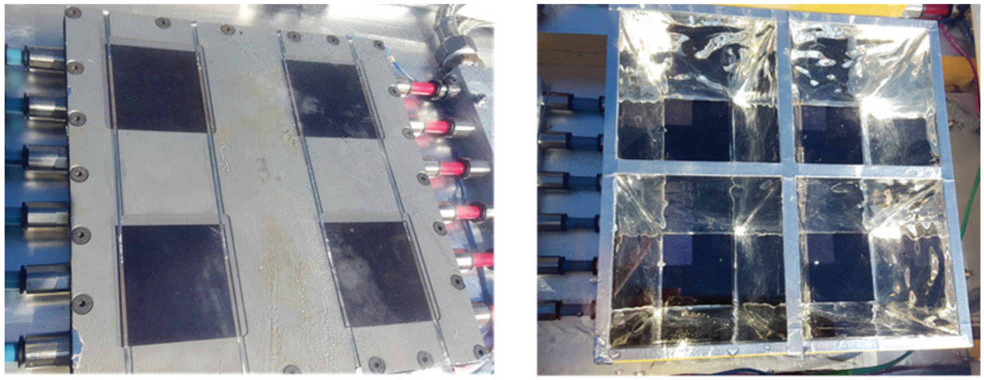
(a) (b)

FIGURE 1 (a) The parabolic profile of a CPC with a 30° acceptance angle (b) Schematic of a unit reflective 3DCCPC

In the present study, we couple a heat exchanger at the back of a 4x4 unit of such a system and carry out an indoor characterization followed by an outdoor performance evaluation. The addition of cooling system offers improved efficiency of the solar cell and increased lifetime.

SYSTEM DESIGN AND MANUFACTURE

Thermal forming of a thermoplastic polymer is carried out for the manufacture of the CCPC profile with four concentrators in an array. A reflective film is laser cut to match the profile of the system and glued along the surface. The concentrator is made of thermoplastic material and a reflective film is glued on the surface. The average reflectance[8] of this film is around 94% across the spectral range of 300-1200nm. The frontal window is made of a 3-mm-thick low iron glass. Laser Grooved Buried Contact (LGBC) Si solar cells having an active area of 50mm*50 mm are attached to an electrically insulated heat exchanger (using a thermally conductive adhesive) and the optical concentrators are coupled to the device as shown in Fig.2. Cold water flows into the heat exchanger, receives the heat rejected from the solar cell via conduction and maintains the solar cell at a desired lower temperature. The rate of heat exchange can be controlled by changing the flow rate the incoming cold water using an adjustment valve.



(a) (b)

FIGURE 2 (a) Solar cell module without the concentrator (b) LCPV system

EXPERIMENTAL SETUP

In an indoor controlled environment, an experimental setup was made to evaluate the performance of the LCPV unit. A solar simulator (Class A+A+A+, AM 1.5G irradiation spectrum) was used as the source of the light as shown in Fig.3. The I-V characteristics of the bare solar cell module were initially recorded. Later, the 3DCCPC LCPV module was placed over the solar cell to measure the electrical power output of the solar cell.

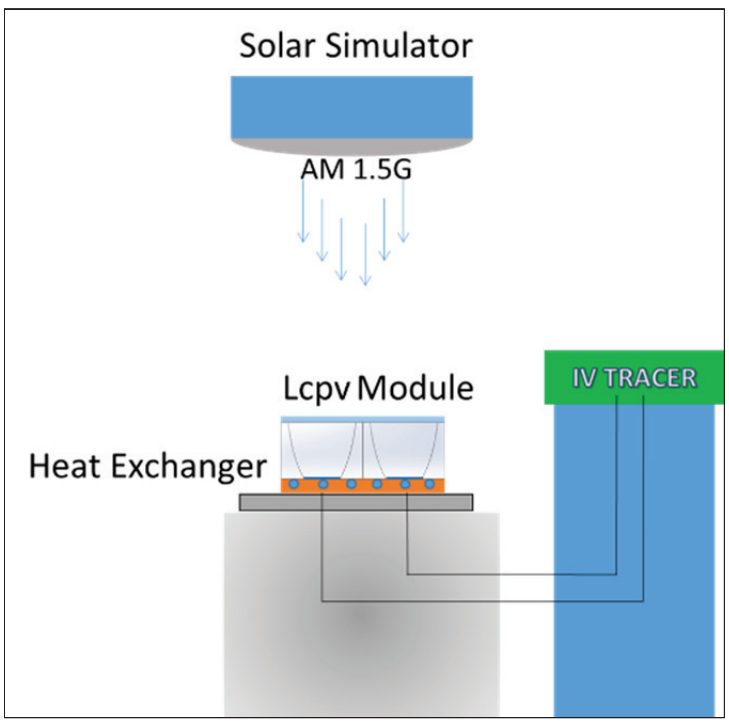


FIGURE 3 Indoor characterization of the LCPV module

For the outdoor characterization both the 4-cell modules were placed in a well-insulated enclosure with a glass top and placed at a fixed tilt of 50 ° at Penryn, UK. A water tank is connected to the system, cold water is pumped across the heat exchanger to maintain the solar cell temperature. K- type thermocouples were added at both the inlet and exit of the modules to monitor the temperature change across the system. An additional thermocouple was also placed to monitor the cover glass temperature of the system. A pump was used to drive the cold water through the heat exchangers at a fixed flow rate of 0.3lpm. The heat extracted was then dumped outside through a radiator while using a separate night time pump which would activate a sensor under dark conditions only. The electrical energy harvested is regularly collected through a battery and then dumped on an electrical load resistor as shown in Fig.4.

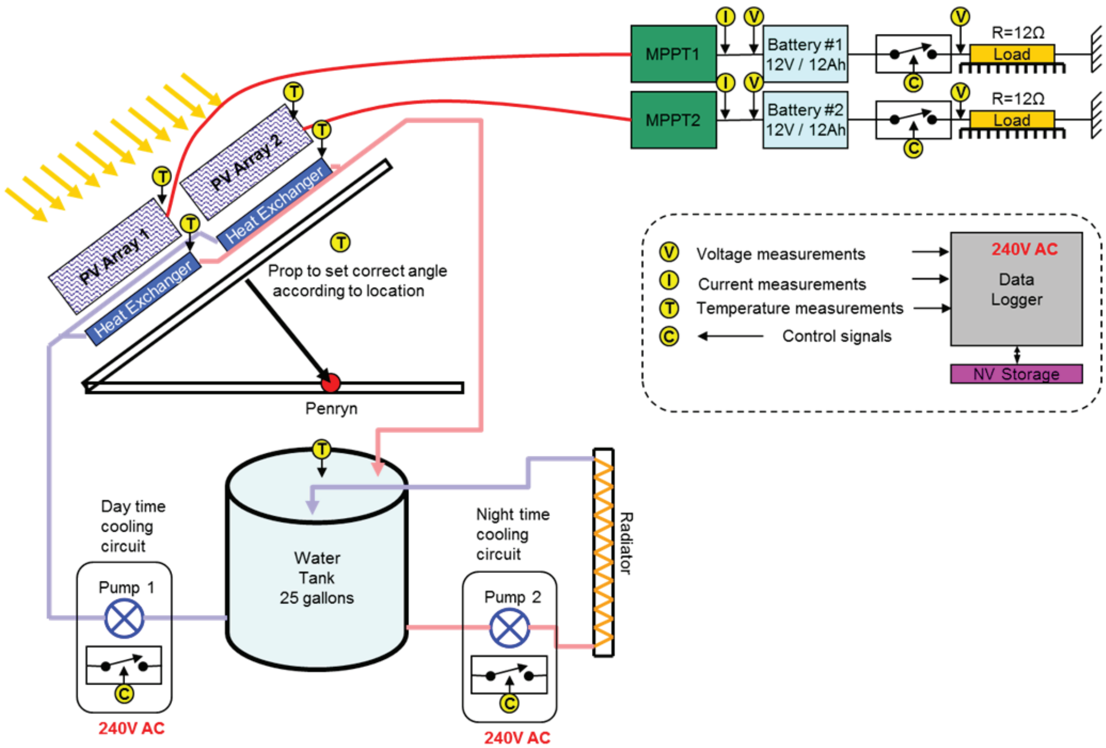


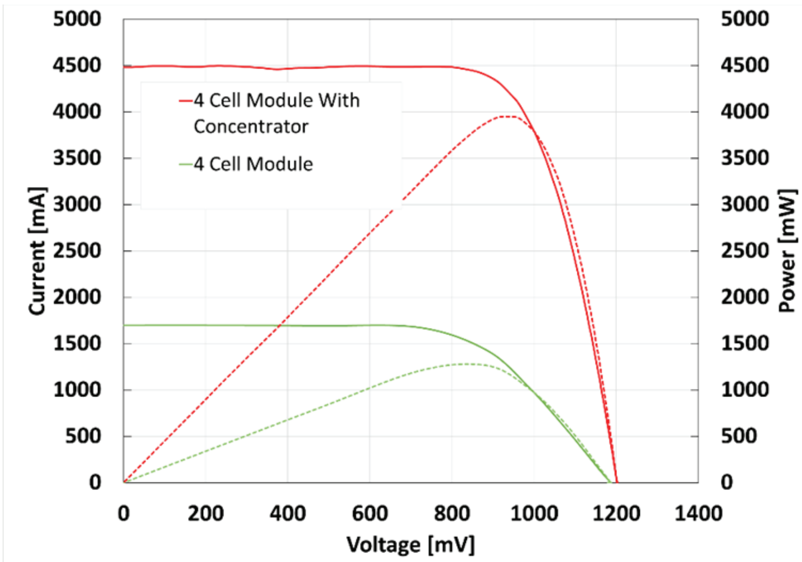
FIGURE 4 Outdoor characterization setup of the LCPV module

RESULTS

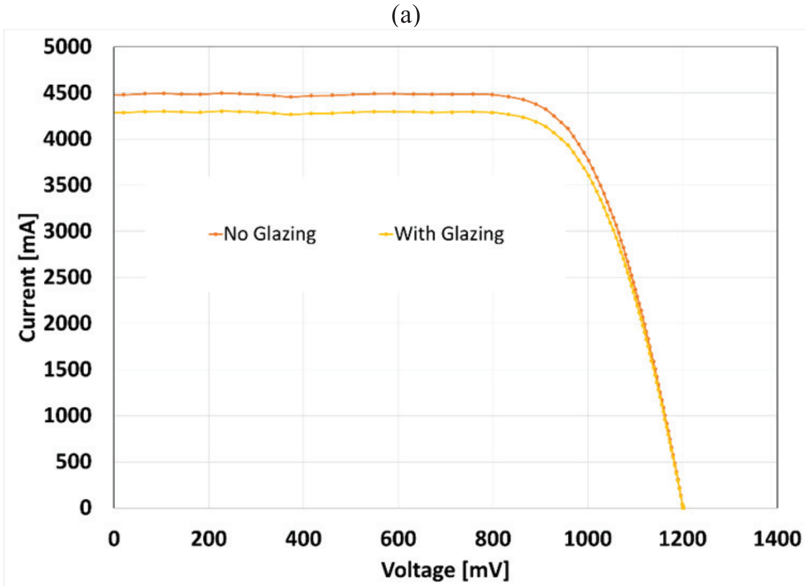
The optical properties (reflectance) of the material used to manufacture the concentrator, in addition to the geometrical profile, play significant roles in a photovoltaic concentrator. The performance of the LCPV system can be experimentally analysed by evaluating the performance of a module with the concentrator and comparing it with a non-concentrating counterpart. Both indoor and outdoor performance evaluations were performed for the system. I-V traces of both the systems were evaluated and the performances compared. Important parameters like the optical efficiency and the power ratio were evaluated.

Indoor Performance

The indoor characterization of the system is carried out under standard illumination conditions of the AM1.5G spectrum and 1000W/m^2 irradiance at 25° C. The I-V characteristics were recorded for the solar cell with and without the concentrator using the solar simulator setup shown in Fig.3. The photocurrent generated by the solar cell increases proportional to the incident light and is a good measure of estimating the amount of concentrated light reaching the solar cell. Results from this analysis are shown in Fig.5. The short circuit current increases from 1710 mA to 4510 mA, due to light concentration. This corresponds to an optical efficiency of 73 % which is lower than the theoretical optical efficiency of 94 % predicted using ray tracing. The key reasons for this drop include manufacturing errors and series resistive losses. The maximum power output obtained was found to be 3.94 W under these standard conditions. The addition of the glass cover glazing reduces the performance of the system to 3.77 W. The power ratio is defined as the ratio of the power output of the CPV module and the non-concentrating counterpart. The power ratio is not same as the optical concentration ratio of the system. Unlike the optical concentration ratio, power ratio has the effect of the change in fill factor and open circuit voltage in a CPV system compared to the non-concentrating counterpart while exposed to similar conditions. The fill factor of the system was found to be 0.72 in the LCPV module. The power ratio of the system was evaluated under both unglazed and glazed system. It was found that the power ratio increased from 3.12 to 3.3 for a glazed system. This is particularly due to the increased reflections within the enclosure. The open circuit voltage was also found to increase from 1144 mV to 1202 mV with and without the concentrator.



(a)



(b)

FIGURE 5 (a) I-V characteristics of the solar module with and without the concentrator (b) Impact of glazing

Outdoor Performance

The system is currently placed on an outdoor site at Environment & Sustainability Institute, University of Exeter, Penryn, UK. The electrical and thermal characteristics of the system are recorded for every five-minute interval. Figure 6 shows the maximum power output obtained under sunny, intermittent, and rainy weather conditions. It can be clearly seen that the maximum power output followed a linearized pattern along with the solar irradiation conditions.

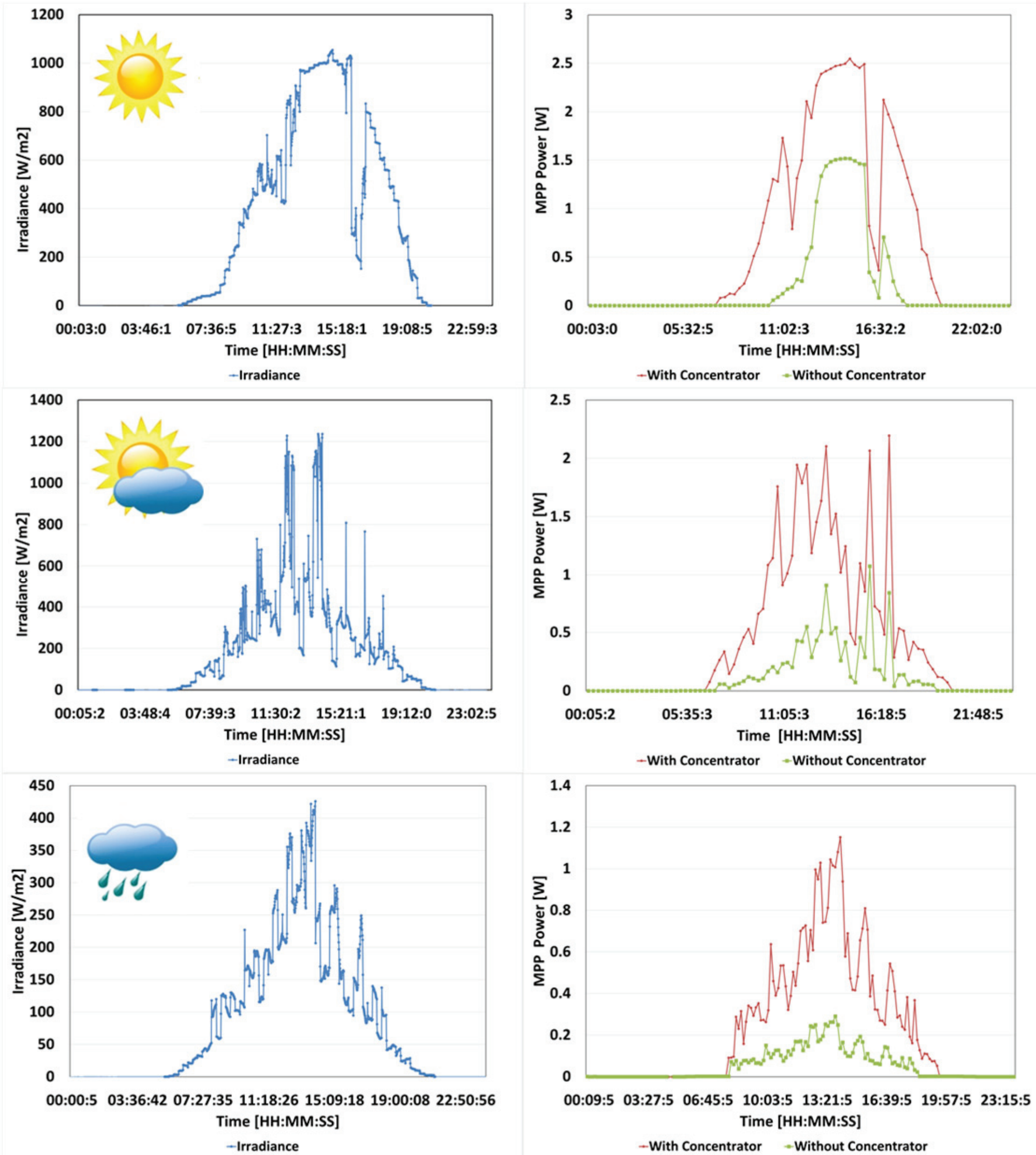


FIGURE 6 Performance of the system with and without concentrator under (a)Sunny, (b)Intermittent and (c)Rainy conditions

At a solar radiation intensity of about 1000 W/m^2, the power output of the system and the similar non-concentrating system was 2.6 W and 1.5 W respectively. This was found to be lower than the indoor characterization results by about 27 % under similar conditions. The key reasons for this drop were the ohmic losses between the interconnections, the loss due to Fresnel reflections occurring on the cover glass, the solar cell temperature and wiring losses. A fill factor of 0.66 and 0.61 was observed in both the systems at this condition against an indoor value of 0.726 obtained at indoor conditions. A maximum power ratio of 1.67 is observed at noon time under sunny conditions. Under rainy and cloudy conditions, the LCPV module was found to have a better power ratio compared to that under sunny conditions. It was found that the maximum power ratio reached a value of 2.3 and 3.6 respectively. The temperature of the water inlet and outlet through the heat exchanger were also measured under different climatic conditions as shown in Fig.7, however, a very small thermal gradient was observed at this flowrate.

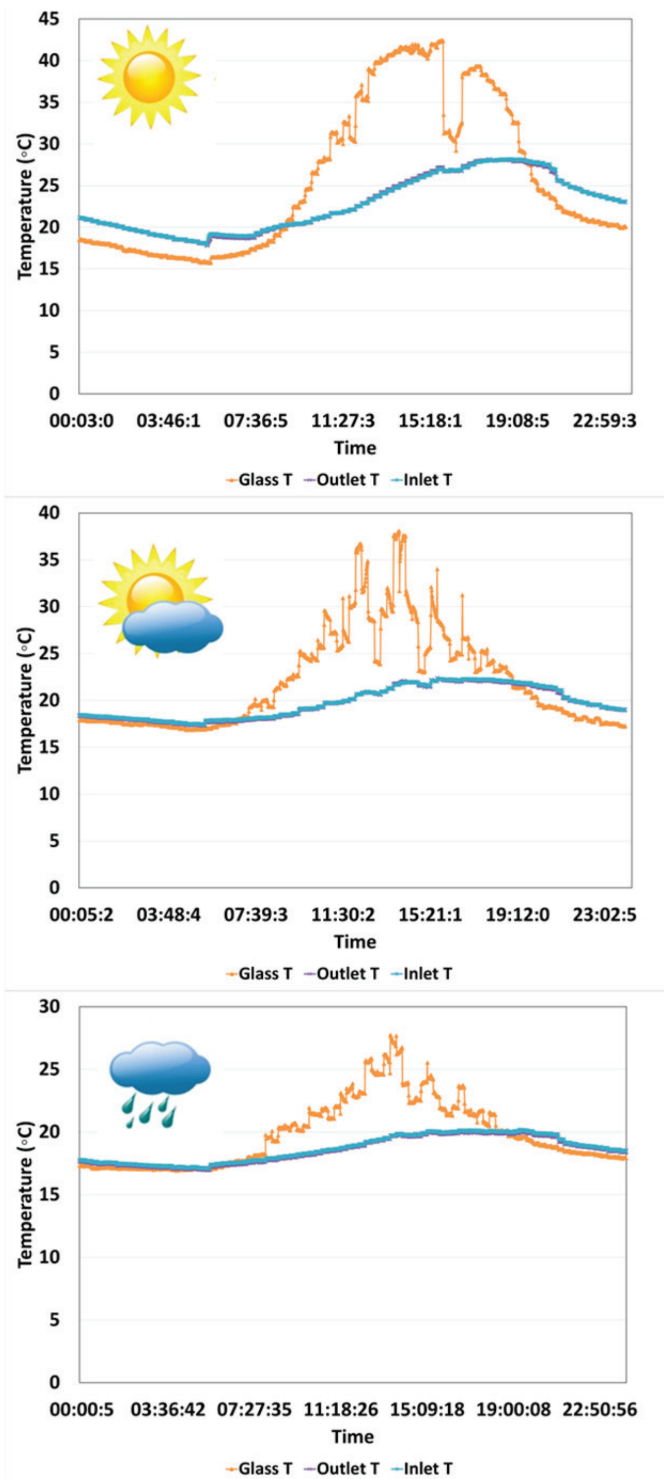


FIGURE 7 The glass temperature, inlet, and outlet water temperature under (a)Sunny, (b)Intermittent and (c)Rainy conditions

The glass temperature of the system was also monitored. A peak glass temperature of 43 C was observed in the sunny climatic conditions at 1000 W/m^2.

CONCLUSIONS

A water cooled 3DCCPC based LCPV module has been demonstrated in this study. The system was characterised under both indoor and outdoor conditions. A power ratio of 3.12 was observed in the indoor characterization and an optical efficiency of 73%. The module performance strongly depends on the solar cell efficiency and the solar cell temperature. The module was found to have a fill factor of 0.726 under indoor conditions. The system was analysed under different environmental conditions and compared with a non-concentrating counterpart in Penryn, UK at a fixed tilt of 50 °. Given the small size of the module, a small thermal gradient was observed in the cooling water passing through the heat exchanger. A fill factor of 0.66 was observed in the LCPV module under illumination levels of ~1000 W/m2 in outdoor conditions. The system can collect ~2.54 times more solar energy than a flat plate collector employing the same surface area of solar cells. A very small thermal gradient was observed given the small size of the module and high flow rates.

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