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Status and perspective of Concentrating Photovoltaic Systems: the results of the BioCPV project and opportunities for a sustainable energy supply to rural areas

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Abstract

The present paper reports the results of the BioCPV project, a venture of six universities conceived to develop a novel integrated renewable energy system for an autonomous electrical power generation for rural electrification. Concentrating Photovoltaics (CPV) is coupled to an Anaerobic Digestion Biogas system through a smart control mechanism to maximize the efficiency and to supply electricity uninterruptedly. The excess electricity generated during the day time is used to generate hydrogen, stored using metal hydride technologies and released during evening hours as input of an electricity generator. The waste heat of the CPV is recovered and used to accelerate the biogas production. The outcomes of the research on concentrating photovoltaic technologies are resumed: two high-concentrating systems have been developed, different thermal and electrical models have been proposed and the results of innovative researches on optics, building-integration and cooling have been presented.

Keywords: *Concentrating photovoltaics, rural electrification, integrated renewable energy system*

1. Introduction

Global energy consumption is constantly increasing, driven by the emerging economies. In 2013, renewable

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energies contributed to the 5.3% of global power generation, and accounted for more than half of the yearly global power capacity installed (Renewable Energy Policy Network for the 21st Century, 2014). Despite the grid requirement for a balanced and continuous power supply, the electricity generated by renewable sources is generally fluctuating both on short-term (seconds to hours) and long-term scales (months to years) (Weitemeyer et al., 2014). Hybrid power plants with different renewable technologies have already been identified as efficient, cheap and sustainable options for rural electrification (Bajpai and Dash, 2012). In this light, the BioCPV project aims to contribute to the optimization of hybrid renewable power generation systems and to the electrification of a rural village in the eastern part of India. The system under development integrates concentrating photovoltaic (CPV), anaerobic digestion (AD) and hydrogen storage systems. The present paper reports the latest progresses made in terms of scientific achievements on the development of innovative concentrating photovoltaic systems.

2. Concept and system's configuration

The BioCPV system is installed in the village of Kaligunj – Pearon Pally, adjacent to Visva-Bharati, Santiniketan, West Bengal, India, and supplies renewable energy to 14 household, one school, one community building and 50 street lights. In the early stage of the project, a survey has been carried out to estimate the energy need of the village (Mallick et al., 2013). During summer the peak load was found to be 5.8kW, whereas during winter it dropped to 5.5kW. Therefore, the system configuration has been designed in order to meet the necessities of the villagers. Taking into account the load profile, the peak energy demands and the weather conditions of the locality, a 10kW high concentrating photovoltaic (HCPV) system has been designed. The energy produced by the HCPV is mainly used to supply electricity to the village, whereas, during the low-load times, part of it is used by an electrolyzer to produced hydrogen. The hydrogen is stored and used through a generator during the peak-consumption times. The same generator uses the biogas produced by an anaerobic digestion system: the food waste and the local biomass are used to generate the biogas. In order to maximize the performance of the system, the waste heat generated by the HCPV system is recovered and used to support the anaerobic digestion.

The HCPV is expected to supply the electrical energy needed: the energy surplus is stored by producing hydrogen and used during the low-irradiance hours. It consists of four HCPV units with two axis tracking: each unit is made of two primary concentrators and two receivers. The electrolyzer requires 1kW in input from the HCPV and is designed to work for 7 hours a day. It has an efficiency of 60 % and it is expected to produce about 3 liters of hydrogen per minute. The hydrogen is stored in a metal hydride system, which has an efficiency of 90-95 % and can release about 300 liters of hydrogen for 4 hours. The digester for the AD system has been dimensioned to produce daily an adequate amount of biogas. A maximum of 15kW of thermal energy can be recovered by the HCPV (K. S. Reddy et al., 2014) and used to support the anaerobic digestion.

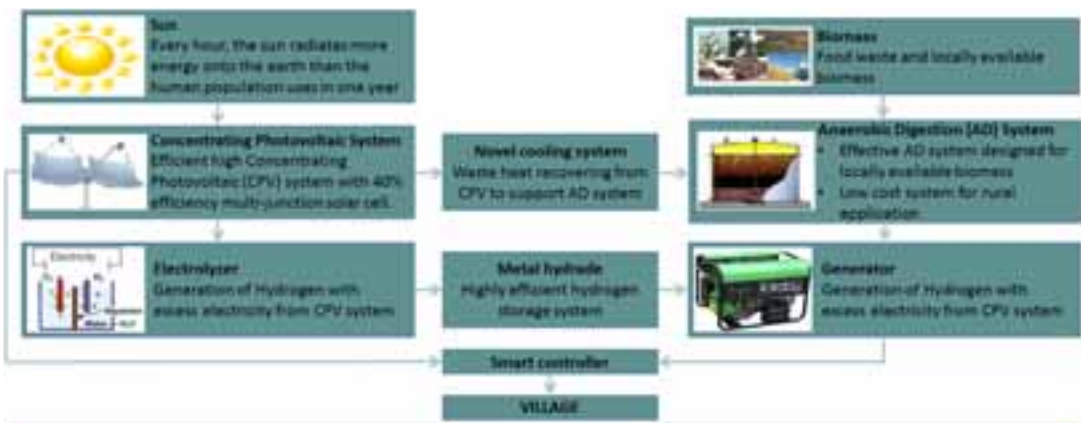

Fig. 1: Schematic of the BioCPV system.

The integrated renewable energy system designed for the BioCPV project has been demonstrated to be more beneficial than a single source system (Castellanos et al., 2015). A cost of \$ 0.289 per kWh^{-1} was estimated and is lower than that predicted for other technologies and scenarios ($ 0.335–1.332 per kWh^{-1}). According to the authors, the main reasons for this achievement are due to the synergy between the various production and storage elements at meeting the demanding load profile with a very high quality of supply.

2.1. Expected social and health benefits

The tribal communities residing in the villages of Kaligunj – Pearon Pally do not have access to the grid. These people are mostly dependent on leaf litters, forest wood, cow dung cakes for cooking and use kerosene lantern in the night time for education and other household activities, which is responsible for the indoor pollution as well. This lack of proper electrical/power facilities is deterrent for their development in terms of education, sanitation, health and entertainment. Electrification drive through renewable energy recourses like solar and biomass in the form of BioCPV system is conceived to face the problem of poverty, illiteracy, and lack of healthiness and also to ensure a clean and sustainable environment by reducing greenhouse gas emission thereby curbing indoor and outdoor pollution. Once implemented, the renewable energy harvesting system through AD/PV will generate employment opportunities among the tribals, make them self-sufficient and inculcate better competitiveness to take on the challenges of the rest of the world.

2.2. In-loco components installation

In the project site of Santiniketan, where the BioCPV system is being implemented, a control room has been built for housing different components of the system, such as the genset, the biogas engine or the inverter. Electrification works have been done for providing electricity to the designated households, school building, primary health center in the village. The Anaerobic Digester (Fig. 2) has been set up which will produce biogas (methane) with locally available aquatic weeds (such as water hyacinth and salvinia), kitchen waste, and cow dung as the source of inoculums. The biogas can be used for cooking purpose as well by the villagers and also used to generate electricity in the rainy season when the radiation is not enough to run the solar technologies at their highest capacity.

Fig. 2: Components of the AD system: gas chamber (a), main digester (b), predigester (c), chopper/grinder (d).

3. The concentrating photovoltaic systems

Concentrating Photovoltaic (CPV) systems make use of optical components which concentrate the incoming sunlight and focus it on solar cells. The concentrated light reaching the solar cell magnifies the production of energy several times. These optical components often referred to as concentrators, make use of reflective/ refractive principles of optics, individually or in combination for concentrating the sunlight.

3.1. 144-cell HCPV systems

A novel densely-packed HCPV system has been developed. The optics consists of a 125× primary and a 4× secondary optics that focus the sunlight onto a 144-cell receiver. The CPV system is equipped with two reflective geometries a square parabolic reflector as primary concentrator and 12 x 12 array of three-dimensional compound parabolic concentrators (CPCs) with optical homogenizer as secondary concentrator.

The geometrical concentration ratio for primary concentrator is 125× primary and secondary concentrator is 4×. The secondary concentrator integrated with CPV cell assembly and an active cooling system forms the complete CPV receiver. The incoming rays falling on the aperture of the parabolic dish will be reflected to CPCs. The CPCs will concentrate and redirects the rays towards the cell. The light rays which are parallel to the CPC's optical axis will not lose energy because it falls directly on the cell surface without any reflection, whereas the light rays entering the CPC within the acceptance angle will go multiple reflections in both CPC and homogenizer before reaching the cells. The homogenizer mounted on the exit aperture of the CPC will homogenize the flux distribution on the cell surface by multiple reflections. The irradiation distribution on one-fourth (6 x 6) of the 12x 12 CPV receiver is shown in Fig. 3 (S. Lokeswaran et al., 2015). The characteristics of the concentrators are resumed in Tab 1.

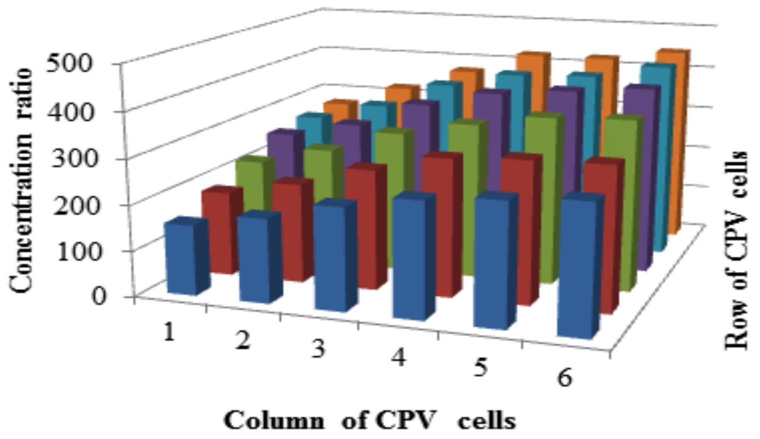

Fig. 3: Flux distribution for one-fourth of the array

Tab 1: Specifications of the concentrator optics.

Primary concentrator		Secondary concentrator	
Geometric concentration ratio	125×	Geometric concentration ratio	4×
Aperture area	3m×3m	Cell side aperture area	10mm 10mm
Rim angle	20°	Acceptance angle	30°
Focal lenght	3.37m	Length of CPC	25mm
f/d ratio	0.794	Length of the homogenizer	10mm

The design of the receiver has been conceived to lower the costs and reduce the electrical losses (Micheli et al., 2015e). The receiver is built on an insulated metal substrate (IMS) that gives mechanical support to the receiver, collects the electrical energy produced by the cell and facilitates the removal of the waste heat. It was already known that IMS had a similar resistance to fatigue to that of the direct bonded copper (DBC) boards (Mabille et al., 2013), dominantly used to produce the HCPV receivers. Within the BioCPV project, IMS have been demonstrated to have a thermal behavior similar to that of DBC and more advantageous in terms of fabricability and costs (Micheli, 2015).

Each board allocates 144 1cm^2-sized 3C40 cells, supplied by Azurspace. The geometry of all the components has been designed to fit the requirements of the standards and to grant acceptable thermal management and electrical performance to the assembly. The shape of the electrically conductive layer has been conceived to minimize the electrical resistance. One Schottky diode per cell has been employed in the receiver to avoid damages to shaded cells and to reduce the power losses in case of current mismatch among different series-connected cells. Aluminum wires have been bonded to interconnect the cells and the conductive layers: they have been sized to safely work even in presence of overcurrents.

Fig. 4: A prototype of the HCPV system developed for the BioCPV project.

The HCPV systems are required to work for 20+ years in outdoor conditions, with minimum degradation. For this reason, the developed receiver has been mechanically and electrically tested (Micheli, 2015). At 500x, each cell is expected to work at a maximum power point power of 14.7W, achieving, under 1000W/m^2 DNI, an efficiency of 29.4%. A full scale prototype of the HCPV system has been installed (Fig. 4) and is being tested on the roof of the Institute of Technology Madras, in Chennai (India).

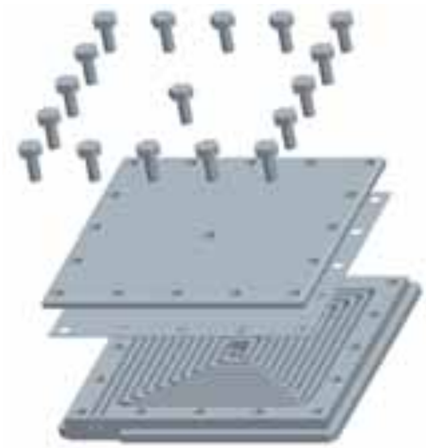

Fig. 5: Spiral Heat sink for CPV Cooling

The HCPV receiver is mounted on an active spiral mini channel heat sink, made of aluminum (S Lokeswaran et al., 2015). It consists of spiral flow mini channel heat sink with rectangular cross section channels where separate inflow and outflow paths with inlet and outlet ports were grooved as shown in Fig. 6 (K. Reddy et al., 2014). The base of the mini channel receives heat flux from the cells and the heat is transferred directly to the coolant by convection from the bottom surface and indirectly through the dividing wall. The large surface area of mini channel enables the coolant to take away large amounts of heat per unit time per unit area while maintaining a considerably low device temperature. Water is used as cooling fluid. The coolant enters the inlet port at ambient temperature and takes up the heat all the way through the flow path grooved in heat sink flowing clockwise towards the center. From the center the fluid flows anticlockwise towards outlet port through outflow channels located adjacent to the inflow channel. So, high heat fluxes can be dissipated at relatively low surface temperatures. The dimensions of the heat sink have been optimized to keep the HCPV module at a temperature of 80°C, with an overall pressure drop of 8.0 kPa. The solar radiation is concentrated on secondary reflector (CPC) which in turn concentrates onto the bottom surface of the mini-channel spiral cooled receiver holding the 12 x 12 dense array of efficient triple junction PV cells.

3.2. Cassegrain Concentrator Photovoltaic System

Along with the large HCPV system, a cassegrain 500x HCPV module has been developed. The system consists of two reflective optics and a homogenizer, which concentrate the sunlight on a 1 cm^2-sized multijunction cell. The two-stage reflector configuration has been chosen to enhance the compactness of the module. The optics geometries (Tab 2) have been optimized to achieve an efficiency as high as 84.82% at normal incidence and limiting the losses in case of a ±1° tacking error (Shanks et al., 2014).

Tab 2: Specifications of the cassegrain concentrator optics.

Primary concentrator		Secondary concentrator		Homogeniser	
Geometric concentration ratio	125×	Geometric concentration ratio	3×	Geometric concentration ratio	9×
Aperture area	23cm×23cm	Aperture Area	5cm × 5cm	Aperture Area in	3cm × 3cm
Focal Length	27cm	Focal Length	7cm	Aperture Area out (Cell)	1cm 1 cm
Height of dish	2.8cm	Separation Distance from Primary	15.6cm	Length	7.5cm
Width of dish	23cm	Full system Height	20cm	f/d ratio	1.2

The surface roughness of the homogenizer can significantly affect the overall optical efficiency and to compensate for this inherent loss due to manufacturing processes, a new conjugate refractive reflective homogenizer (CRRH) was developed and proven capable of increasing the optical efficiency of the system by 6% (Shanks et al., 2015a). The new homogenizer was found to improve the optical efficiency by 3% at normal incidence (Fig. 6).

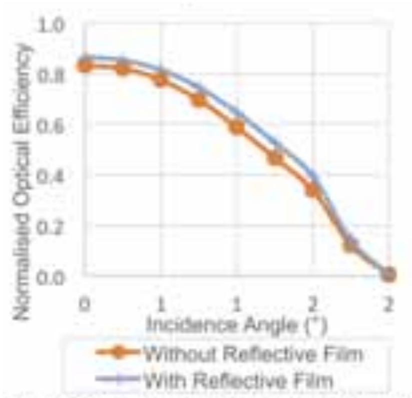

Fig. 6: Enhanced optical efficiency of the homogenizer due to the use of the reflective film (Shanks et al., 2015a)**.**

The Cassegrain Concentrator Photovoltaic modules have been arranged in 3x3 arrays (Fig. 6) and are currently being outdoor tested in Spain and India.

Fig. 7: The 3x3 Cassegrain Concentrator Photovoltaic System a) top and b) side view.

3.3. Electrical and thermal modelling

Electrical and thermal modelling of HCPV is a fundamental research aim to optimize the design of the systems and the prediction of energy production. In this light, different studies on the electrical and thermal behavior of the HCPV systems have been presented and made available in literature (Almonacid et al., 2015; Fernández et al., 2015). A comparative studies demonstrated that the available models could predict the maximum power output of different HCPV systems with discrepancies lower than 5% (Soria-Moya et al., 2015). An integrated thermal-electrical model has been developed: it has been found that a $1cm^2$-sized cell can be adequately cooled by an heat sink with a thermal resistance of 1.63 K/W or less (Theristis and Donovan, 2015).

3.4. Data logging and system integration

The data acquisition system produced for the BioCPV project differs from standard systems at it collects data from the off-grid system and stores them remotely, making them available through a real time interface (Calabria, 2015). Generally, the data recorded in a stand-alone system are stored in a "black box" that needs to be directly accessed in order for the data to be retrieved. On the other hand, biosciences data logging systems transmit the GPS coordinates to track the animal movements but the data is stored on the microprocessor directly and retrieved by following the GPS signal.

The system used in BioCPV has been programmed using LabVIEW, a software package developed by National Instruments (NI). The system, shown in Fig. 8, is composed of 5 independent units connected through a NI chassis. The NI controller is the cRIO-9024, a real time controller used for deterministic control, data logging and analysis. Three standard modules have been used for the acquisition of currents, voltages and temperatures. A communication module developed by the Science & Engineering Applications Datentechnik GmbH, based in Germany, has been configured to transfer the data through a M2M platform and has been connected to a GPS and a GSM positioning antennas

(b)

(c)

(a)

(d) (e) (f) (g) (h)

(i)

Fig. 8: The data logging system (Calabria, 2015): (a) GPS Antenna, (b) GSM Antenna, (c) NI 8-slot Chassis, (d)SEA 9721 3G Module, (e) Current Sensor (NI 9227), (f) Voltage Sensor (NI 9225), (g) Temperature Sensor (NI 9213), (h) CompactRIO 9024 microcontroller, (i) Power Supply

4. Scientific impacts on the future of HCPV

4.1. Future scenarios for HCPV optics

Shanks et al. (Shanks et al., 2015c) listed the main features of an ideal solar concentrating optical system which should be aimed for when designing a solar concentrator: 100% optical efficiency, uniform irradiance distribution, maximum acceptance angle, high optical tolerance, reliability and durability. Along with these characteristics, the optics should be cheap, easy to manufacture and to install as well as light in weight. In this light, the results of a multi-disciplinary work have been recently presented (Shanks et al., 2015b): the wings of white *Pieris* butterflies have been investigated to understand their applicability in HCPV. The white *Pieris* butterflies use their highly reflective white wings to increase their thorax (and hence flight muscles) temperature. To do this, they hold their wings in a v-shape, similar to a V-trough concentrator. It was found that, using the butterfly wings instead of a standard reflective film to concentrate the light on a 1cm multi-crystalline cell (Fig. 4), the electrical power output to weight ratio was enhanced by 17 times. Although the wings had a very high reflectance of >80%, this is not as high as reflective films available at present (>90%), however the wings have the advantage of being extremely lightweight. This lower weight and enhanced power to weight ratio would be a great benefit to CPV systems. HCPV systems in particular are often heavy and bulky due to the large optics used but developing a lighter reflective material could greatly expand their applications. In the research by Shanks et al., 2015b a single mono-layer of scale cells removed from the wings was able to perform as a high-reflective coating as well, enhancing its potential applicability in HPCV system as a new reflective coating or film material. The unique nanostructure of these wings is at present being investigated and replicated for a new reflective and lightweight material for CPV systems.

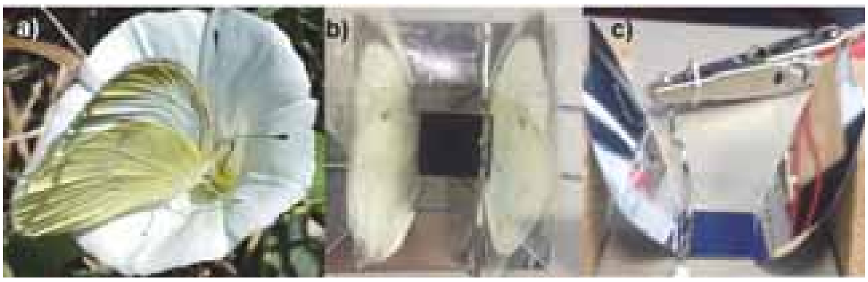

Fig. 9: (a) The cabbage white butterfly (photographed by Tina Pilipović, permission for use granted). (b) Top view of wings positioned in V shape with 1cm x 1cm solar cell at base of wings. (c) Side view of reflective film in shape of wings also positioned in V shape.

4.2. Building Integrated Concentrating Photovoltaics

The general principle of Building Integrated Photovoltaics (BIPV) is that PV modules are integrated into the building envelope, substituting standard glass and other cladding materials with glass/glass laminates encapsulating PV cells within. Incorporating the concentrating photovoltaics into any part of the building architecture is referred to as Building Integrated Concentrating Photovoltaics (BICPV). These systems can be classified based on the type of concentrator used for achieving solar concentration. The systems may be classified primarily two type's (a) linear concentrators, (b) three-dimensional concentrators

An asymmetric design was applied to refractive based optics and a new generation of concentrator was developed for building integration. This system consisted of linear dielectric non-imaging concentrators with an asymmetric CPC and a geometric concentration ratio of 2.82. Three different systems were designed to have half acceptance angles of 0° and 55°, 0° and 66° and 0° and 77°. The optical analysis of these systems showed that the DiACPC-55 outperformed the other two designs. A prototype of the same was later reported (Sarmah et al., 2014). The indoor characterization of the system showed as maximum power ratio of 2.27 when compared to a similar non-concentrating counterpart. A detailed optical-thermal-electrical modelling procedure for such type of system was shown recently (Baig et al., 2013). Use of ray trace methods was made to carry out the optical analysis of the system. Based on the illumination profile found from the optical simulation, a coupled electrical and thermal simulation was carried out on the system. The impact of non-uniform illumination was also studied. A prototype was developed and tested for its electrical performance under $1000W/m^2$. About 0.5% absolute drop in solar cell efficiency was observed due to non-uniformity at 5° incident angle.

The 3D concentrator principally concentrated the light from all the directions unlike the linear concentrators. One of the first designs proposed for building integration is the reflective 3D crossed compound parabolic concentrator (3DCCPC) for building integration (Mammo et al., 2012). The system consisted of an array of 3DCCPC placed over 1cm2 sized LGBC solar cells. The developed system was found to perform with optical efficiencies of 75 % experimentally for a 60° acceptance angle. An improved optical efficiency of 81% was achieved experimentally in the second prototype of the system. Based on the similar design a refractive based 3DCCPC was modeled and experimentally evaluated (Baig et al., 2014b). The refractive based system has higher acceptance angle as compared to the reflective type system. A detailed optical, electrical and thermal modelling of the system was carried out with experimental validation. A maximum power ratio of 2.67 and an acceptance angle of 80° were found when comparing the electrical output of the concentrator unit with the bare cell. The temperature was found to have a parasitic effect on the overall performance of the system bringing about 14.6% drop in the overall power production. A further enhancement to the above system was recently reported recently (Baig et al., 2014a), where light trapping was performed by applying a reflective film along the edges of the 3DCCPC concentrator. A maximum power ratio of 2.73 was observed at an incidence angle of 10°. The system optical efficiency improved, however this reduced the acceptance angle slightly. In another study, a 3D concentrator reported for the building integration is the Square Elliptical Hyperboloid (SEH) concentrator (Sellami and Mallick, 2013). Four different concentration ratios were investigated: 4×, 6×, 8× and 10×. Results showed that the 4× system gives higher optical efficiency compared to the other systems. A complete optical-electrical and thermal analysis of a 6×SEH based concentrator was studied under AM1.5G spectrum (Baig et al., 2015). A detailed analysis highlighting the illumination non-uniformity and its effect on the system performance has been presented (Baig et al., 2012).

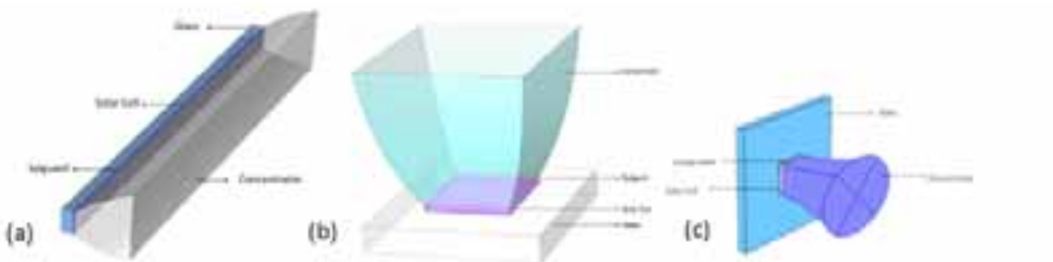

Fig. 10: (a) Linear Dielectric based concentrator (b) 3d CCPC concentrator (c) SHE concentrator

4.3. Passive micro-cooling for HCPV systems

Heat removal is a non-negligible concern in HCPV: any photovoltaic cell is negatively affected by the increase in temperature. The HCPV cells are therefore particularly sensitive to this issue because of the high amount of heat produced. The heat sinks used in HCPV are generally made of Al and can contribute to more than 60% of the module's weight of the system (Timò, 2014). A reduction in the heat sink weight is beneficial for both the system's efficiency and the emissions' drop. In this light, micro- and nano-technologies offer new perspectives for HCPV cooling. Among the several solutions reviewed, the micro-fins under natural convective conditions have been found to be one of the most suitable for HCPV applications, due to their intrinsic simplicity and high potentials (Micheli et al., 2013). In order to find out the best geometry for HCPV applications, the thermal behaviour of micro-fins have been experimentally investigated. In this light, the correlations among the performance and the fin geometry have been determined (Micheli et al., 2015c). Moreover, the micro-fins have been found to have higher heat dissipation per unit of mass than convectional heat sinks or flat plates (Micheli et al., 2015d). For the first time, the applicability of micro-fins for an effective passive cooling of CPV has been proved: the reduction of temperature obtained by using micro-fins compared to a flat heat sink can lead to an enhancement in cell electrical efficiency up to 1% (Micheli et al., 2015f).

4.4. Ultra-High CPV

In recent years, the interest in for systems working at concentrations higher than 1000 suns, generally called Ultra-High concentrating Photovoltaic (UHCPV), is increased (Algora and Rey-Stolle, 2012), because of the potential in cost and material usage reduction as well as in efficiency enhancement (Vossier et al., 2012). Handling the large amount of heat produced by a cell under ultra-high concentration is one of the main challenges for the development of this solution. For this reason, the use of optimized least-material heat sinks has been investigated (Micheli et al., 2015a, 2015b): they were found able to passively cool a UHCPV systems, with a normalized cost ranging between 0.10 and 0.18$/$W_p$ for concentrations from 1000x to 8000x.

5. Conclusions

The BioCPV project addresses the rural electrification of an off-grid village in the west of India, by using an innovative renewable energy power system. Concentrating photovoltaic, anaerobic digestion and hydrogen technologies are integrated to produce continuous and reliable electricity. The present paper focuses on the latest outcomes of the researches conducted on concentrating photovoltaics. A large 2.5kW$_p$ receiver and a cassegrain concentrator system have been designed and are currently being tested: the novel designs and the fabrication processes have been made available in literature to contribute to the development of more-efficient and reliable HCPV systems. Moreover, new thermal and electrical models have been presented. The BioCPV project team has investigated new scenarios that can in future benefit the development of HCPV. The butterfly wings can represent an innovative, light-weight solution for HCPV concentrators, whereas micro-fins can be used for the cooling of cells under natural convection.

Acknowledgments

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