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Combined Heat and Power Generation with a HCPV System at 2000 Suns

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Abstract. This work shows the development of an innovative solar CHP system for the combined production of heat and power based upon HCPV modules working at the high concentration level of 2000 suns. The solar radiation is concentrated on commercial InGaP/InGaAs/Ge triple-junction solar cells designed for intensive work. The primary optics is a rectangular off-axis parabolic mirror while a secondary optic at the focus of the parabolic mirror is glued in optical contact with the cell. Each module consist of 2 axis tracker (Alt-Alt type) with 20 multijunction cells each one integrated with an active heat sink. The cell is connected to an active heat transfer system that allows to keep the cell at a high level of electrical efficiency ($\eta el > 30\%$), bringing the heat transfer fluid (water and glycol) up to an output temperature of 90°C. Accordingly with the experimental data collected from the first 1 kWe prototype, the total amount of extracted thermal energy is above the 50% of the harvested solar radiation. That, in addition the electrical efficiency of the system contributes to reach an overall CHP efficiency of more than the 80%.

INTRODUCTION

CPV systems represent an efficient technology to convert solar radiation into useful energy. As the multijunction cells that are applied in HCPV modules must be cooled, the overall efficiency could be raised by recovering the thermal energy that must be dissipated from the receiver.

In the framework of the FAE "Fotovoltaico ad Alta Efficienza" ("High Efficiency Photovoltaic") Research Project funded by the Sicilian Region under the program PO FESR Sicilia 2007/2013 4.1.1.1, we have developed an innovative solar CHP system for the combined production of heat and power based upon HCPV modules working at the high concentration level of 2000 suns [1] [2].

In the present work we report some of the fundamental steps that have brought to the finalization of the first prototype and some of the results about its performance in different operational conditions. Some specific details about the systems have to be omitted from this report as those are under an intellectual property agreement among the parties and are going to be patented.

DESCRIPTION OF THE SYSTEM

The primary optics of FAE HCPV system is a rectangular off-axis parabolic mirror, providing a nominal concentration that exceeds 2000 suns per cell. As secondary optics at the focus of the parabolic mirror we use a frustum made of BK7 glass glued in optical contact with a TaiCrystal cell (108 mm^2 total). The field of view on sky of the cell is a square with a full width at half maximum (FWHM) side of 2.6 degrees. The 1 kWe module prototypes consist of 20 multijunction cells, each one is integrated with the secondary optic and the active heat sink. Primary reflective optics and integrated receivers are mounted on a 2 axis tracker (Alt-Alt type) composed by a N-S primary axis supporting 10 E-W secondary rotation supports, each one is moving a couple of mirrors and receivers.

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The secondary axes are driven by a single linear actuator. The system is highly scalable and it can be installed on roofs, urban areas or industrial spaces. The tracking algorithms are managed by a double control loop: an “open loop” algorithm (providing an accuracy of a fraction of a degree, limited by installation inaccuracies and by mechanical tolerances) and a “closed loop” system (based on a four quadrant sun sensor) providing a high tracking accuracy. The cell is connected to an active heat transfer system properly designed in order to reduce the thermal resistance of each substrate of connection material.

Optical Design

The optical simulation optimized the sizes both the mirrors and light pipes according to the scheme reported in Figure 1.

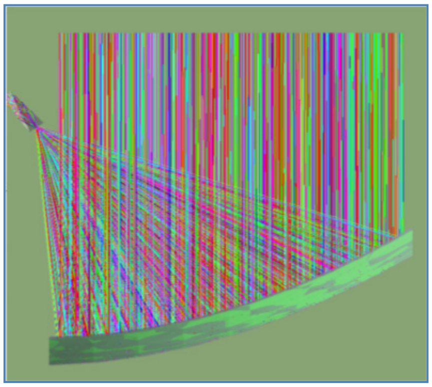


FIGURE 1. Section of primary mirror with light pipe incident angles

The simulation shows how the sunlight (vertical beams) invests a segment of an off-axis parabolic mirror in a projection normal to the sun that forms an image of the sun on the front face of a frustum with a square base.

A square shape of the mirrors has been chosen in order to reduce the overall costs and to simplify the structural supports. They’ve been designed through a parametric simulation to reach a level of concentration above 2000 suns with a focal length that optimizes the size of the sun image and the incident angle of the concentrated light beam on the surface of the multijunction cell.

Mirrors have been manufactured in float extraclear glass by hot slamping, adding a silver coating on the back side. The silver coating brings the reflectivity up to the 95% without significant scattering losses. The glass surface has a good resistance to atmospheric agents and it is easy to clean.

The incident radiation is focalized within a spot with a diameter of 7 mm on the lower face of the frustum as shown in Figure 2.

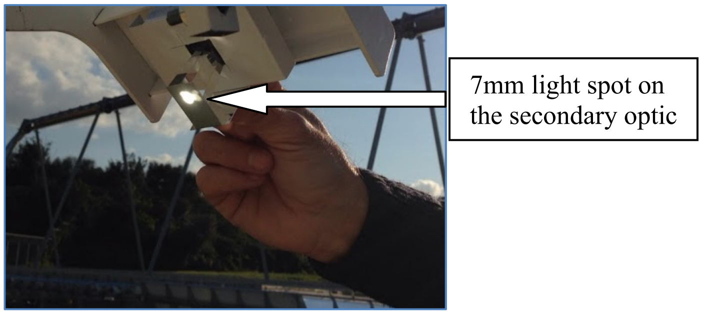


FIGURE 2. Section of primary mirror with light pipe incident angles

Some specific improvements have been introduced in the manufacturing process of the mirror to reduce the incidence angle of the reflected rays on the frustum.

Among the possible manufacturing solution for frusta, some have been chosen for a deeper analysis [3]. In particular, frusta made in BK-7 and BALF5 glass and Savosil^{TM} sol-gel have been investigated to verify their resistance to UV exposure and optical transmission.

The final optical system is composed by a couple of mirrors integrated in a metal frame each concentrating into a BK-7 light pipe. The mounting solution was able to relax most of the tolerances on the opto-mechanical subsystems and to collect most of the circumsolar radiation.

The optimization of the whole opto-electrical system has been performed thanks to a testing facility that has been developed to characterize under the real solar radiation both refractive and reflective concentrators, multi-junction cells, as well as different materials and components (frusta, encapsulants, etc...) for HCPV applications. The facility consists primarily of a heliostat that reflects the actual solar light in a dedicated laboratory that has been optimized to operate efficiently mainly in the a.m. hours with a beam flux up to 90% of the direct sunlight [4].

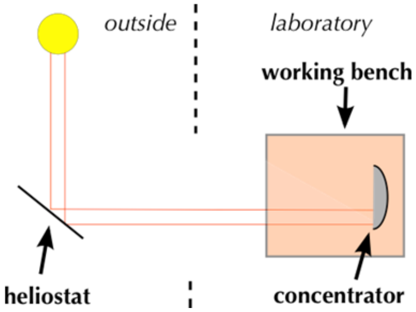


FIGURE 3. Sketch of the reflection apparatus to bring the solar light in HCPV-FAE dedicated laboratory.

Beside the heliostat, the set-up testing facility is equipped with: an optical bench for mounting and aligning the HCPV module components and an electronic equipment to characterize the I-V curves of high efficiency multi-junction cells operated at high sunlight concentration up to 2000 suns. An I-V curve can be acquired using a 300 W programmable DC electronic load, that acquires automatically an I-V curve scanning about 1000 data points with an acquisition time lower than 10 ms, with a maximum measured current of 60 A.

The optical performance of each component has been experimentally estimated. Optical losses of POE are around 5% while SOE is generating a total loss of about 10% both by reflection and absorption. Accordingly to these results an overall performance of about 85% should be reached by the integrated systems. These feature could be slightly deteriorated by the optical mismatch at frustum/cell interface, but it could be still improved applying an anti-reflection coating on the parabolic mirror and on front face of frustum.

Tracking System

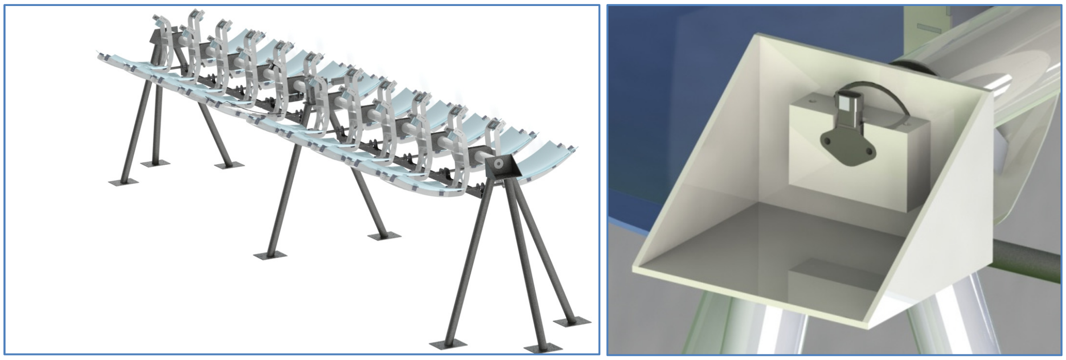
Accordingly to the final design, each tracking module is made by 10 couples of mirrors fixed on 2 separated axis (5 couples for axis), each one connected on the motor unit for the East West rotation. Two linear motors installed on axis allow the Nord-South tilting of 5 couple of mirrors each. The ground supports of the tracker are designed in order to connect more modules in the same line. At the end of each module an angular sensor measures the East-West position in respect to the set point position calculated by an astronomic algorithm according to time and geographical position. The control board uses this information to drive the elongation of the linear actuator, accordingly to an experimentally extrapolated characteristic curve, at the South-North setpoint.

The accuracy of both the angular transducer and the linear encoder of the actuator are such as to ensure a good precision; the optimal positioning is then achieved by a 4-quadrant sensor which supports the control system to make a further fine adjustment.

In a composed optical system, the simultaneous movement of each mirror as well as the perfect alignment of all the mirrors is of fundamental importance. This constraint has driven the design of the components of the tracker to minimize angular errors due to tolerances on mechanical machining of components and assembly tolerances that can not be entirely eliminated.

The optimal solution was obtained by a "cradle" built on very accurate elements which allow the accommodation and installation of all the optical parts in the correct mutual position.

The figures below shows a general picture of the present prototype design and the particular of the insertion of the angular sensor.



(a) (b)

FIGURE 4. General view of HCPV-FAE tracker design (a) and particular of the insertion of angular sensor (b).

Active Heat Sink

An active heat sink has been designed both to keep the multi-junction cells at a reasonable working temperature and to extract useful thermal energy by means of a thermal carrier fluid.

The thermofluid dynamic constraints to be considered for the design of the heat exchanger were the water temperature at the inlet, the maximum temperature that could be reached by the cell and the inflow rate to the heat sink. The goals were the best cooling effect on the cell due to a large thermal exchange with the HTF and the lowest pressure drop between input and output to the heat sink.

The project started with the CFD evaluations of different geometries and their effect on the heat exchange between the multi-junction cell, and the carrier fluid. Both pin fin and planar exchangers have been simulated and promising models have been manufactured and tested in order to verify and improve the multiphysics calculation.

In order to have an accurate evaluation of the performance of the system as a function of sun concentration, inlet fluid temperature, flow-rate, and pressure drop, a specific testing facility has been developed. Cells are operated under concentrated solar radiation (up to 2000 suns) with a circulating fluid (water) at controlled temperature and flow-rate. The cells can be tested using a constant fluid temperature in the range between 20÷90°C and flow rate in the range 0.2÷2.0 l/min. The chiller is equipped with an on/off thermostat while the heater regulates the temperature of the water with a closed-loop algorithm.

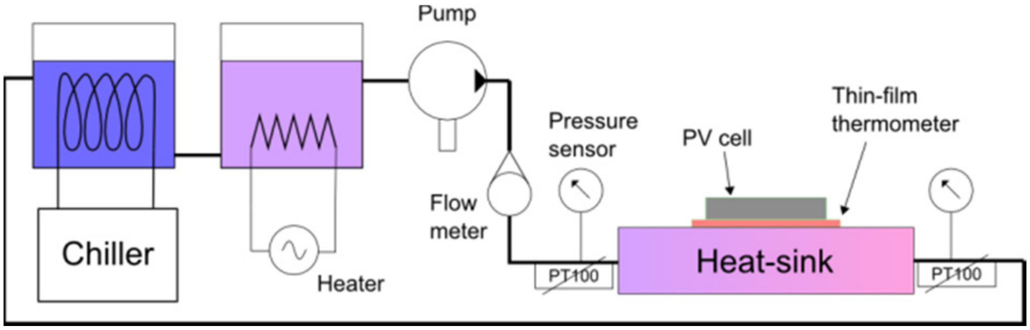


FIGURE 5. Sketch of the device set-up to control temperature and flow rate of the cooling liquid in heat-sink.

In order to perform an accurate monitoring of the PV cell temperature [5] [6] we have developed a metal thin-film thermometer with a very low thermal resistance on Cu/Be substrates as shown in Figure 6. The temperature sensor is placed between the cell and the heat sink, overcoming the limitations of commercial bulk sensors, that would produce a significant disturbance in the heat flow. We are currently developing the processes to deposit the temperature sensor directly on the back of the photovoltaic cell.

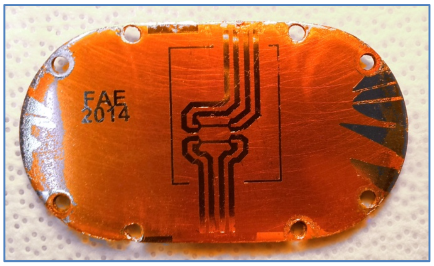
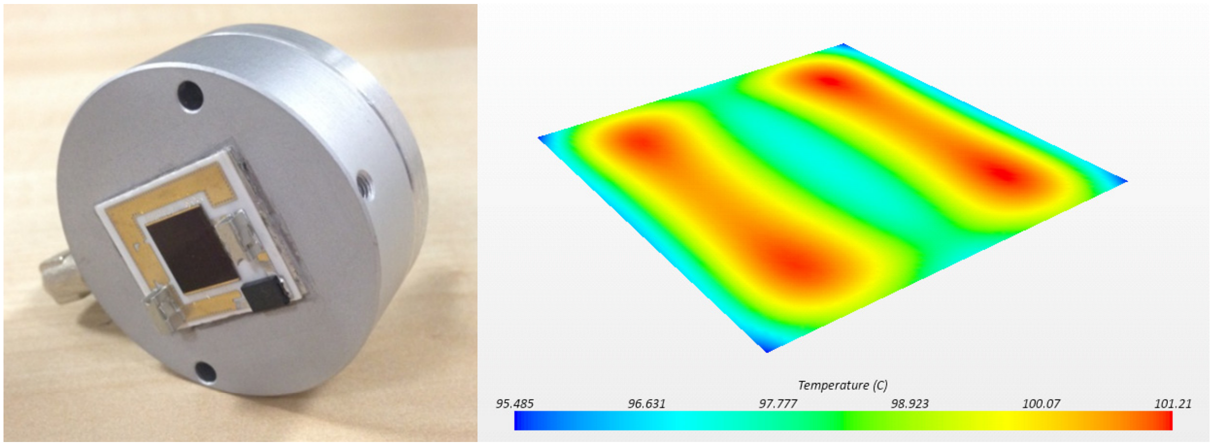


FIGURE 6. Cu/Be thin-film sensor specifically developed to characterize the heat exchange in HCPV-FAE active heat sinks.

After some iterative improvements a final aluminum prototype has been consolidated as it is able to combine good working conditions for the cell with significant output of heat, low pressure drop and low flow rate.

Figure 7 shows the final prototype mounting the cell on a DBC board and a typical temperature profile on the back of the cell obtained by a CFD simulation of the system.



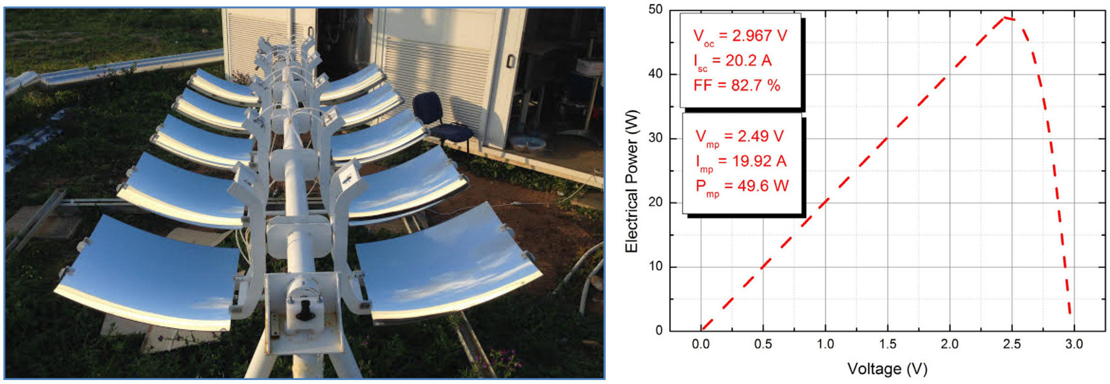
(a) (b)

FIGURE 7. Active heat sink with the cell DBC board (a) and temperature profile (b) on the cell accordingly with a CFD simulation of the heat exchanger.

RESULTS

The final prototype of the module has been fabricated and installed in a specific area that the University of Palermo has dedicated to the open-air test of solar systems, that is managed by Consorzio ARCA, a public-private partnership with the aim to boost the rate of technology transfer and spin-off generation form the RTD activities in the Sicily region. It is shown in Figure 8 together with a power performance curve derivated form experimental data collection.

The on-field tests of the 1kWe prototype confirmed the performance forecasts. An electric power of 50 W and a thermal output of 100 W per cell at a DNI of 900 W/m^2 have been recorded at a cooling fluid output temperature of 80°C.



(a) (b)

FIGURE 8. HCPV-FAE 1kWe prototype installed in the open air solar laboratory at Consorzio ARCA in the campus of the University of Palermo (a) and the characteristic curve (b) of one cell in real operation conditions @DNI=900W/m^2.

Accordingly with the experimental data the overall electrical efficiency is above the 30% while the total amount of extracted thermal energy is more than 50% of the harvested solar radiation. By a variation of the flow rate of the cooling fluid from 0.2 l/min to 1.0 l/min it seems possible to modulate both the thermal response and the electric efficiency of the system.

Accordingly to this preliminary results, HCPV-FAE can have an total CHP efficiency that goes above the 80%, being a good candidate technology both for building integrated polygeneration and energy district application in civil and industrial environments.

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