Concentrated photovoltaics: the path to high efficiency

Francisca Rubio & **Pedro Banda**, ISFOC, Puertollano, Spain

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ABSTRACT

The costs of a photovoltaic installation are driving the market and the need for subsidized schemes, such as feed-in tariffs. Concentrated photovoltaics (CPV) is leading the development of future lowcost renewable energy sources in two ways: on one hand offering high efficiency systems, and on the other, being most capable of reducing manufacturing costs. The idea to decrease the cost of the photovoltaic system using optical elements to focus the radiation into the cell to reduce the size of the cells has been in the mind of the scientists since the 1970s [1]. But, apart from a reduced market, there were several issues that did not allow CPV success at that time. This paper puts forth the proposition that the key is to replace the area of active material, which is the most expensive, with optic elements, which are well known and cheaper.

Introduction

In order to optimize the performance under concentrated light, the cells should be very efficient – more efficient than the 20% record lab efficiency reached in the initial days of research [2]. Cell technology did not permit very high concentration levels; the maximum concentration ratio was 40% and therefore the optical elements were very simple. Cell technology based on Si and its low efficiency did not allow a large reduction of the cell size and therefore, the temperature budget was low, creating degradation problems in the system. For example, in the SOLERAS project in Saudi Arabia, installed by Sandia Labs in the 1980s, the systems degraded by up to 20% in six years, mainly due to delamination issues at high temperature. A further issue resulted from the use of outdated tracker technology, creating problems with the algorithms and control systems. Despite these hurdles, this project continued in operation for 18 years [3].

CPV technology relies particularly on these three areas: high efficiency cells, optics and sun tracking. In each of these areas there have been significant developments in the last five years, leading to current commercial systems already competitive in the current market.

Cells

Cell technology has been greatly improved and the efficiency consequently increased. Si-based solar cells with back point contact [4] reached an efficiency record of 27.6% and some manufacturers like Amonix or Guascor Foton use this type of cell under more than 400X concentration [5]. However, the best improvement in cell technology lies in the use of compound III-V semiconductors. Ternary alloys of III-V elements like GaAs together with In, Al and P allow a better temperature behaviour of the cell. GaAs' thermal coefficient is $1.76 * 10^{-3}$ °C^{-1}, compared to $3.21 * 10^{-3}$ °C^{-1} for Si. Also, III-V technology allowed the development of multijunction solar cells. Two or more p-n junctions are monolithically integrated into a single device. The use of these cells allows a better use of the solar spectrum as each of the junctions is optimized to capture the radiation of a different part of the spectrum. Based on the spectral response, the theoretical limit efficiency of silicon cells is 40%, whereas multijunction cells could potentially reach 86% [6]. Current records for laboratory multijunction cell are Spectrolab's 40.7% record [7] and 40.8% from NREL [8]. These very high efficiencies would allow the reduction of the cell size down to 1cm^2 or even 1mm^2, like in Isofotón or Concentrix systems [9]. This decreasing area also allows the improvement of the thermal behavior and the reduction of the serial resistance [10]. Currently, almost all systems using multijunction cells have concentration ratios of more than 350X, while the majority feature more than 450X (Concentrix, Solfocus, Arima...), with some using ratios of up to even 1000X (Isofotón). The way is paved to proceed to higher concentrations.

Thermal management

Thermal management continues to be a challenge for CPV systems. Most of them use some type of heatsink or thermal dissipater as passive cooling. In most of the designs an alumina plate is used to mount the cell die as it is a good electrical insulator and a good thermal conductor. In order to improve the thermal behavior, there are designs which use a very simple and small Cu or Al plate [11]; others link directly to the metal housing of the module, whereas others use intermediate thermal systems. In large parabolic mirror dish systems, such as those from Solar Systems (Australia) [12], an active cooling system is needed due to the fact that all the cells are together and the thermal dissipation area is lower.

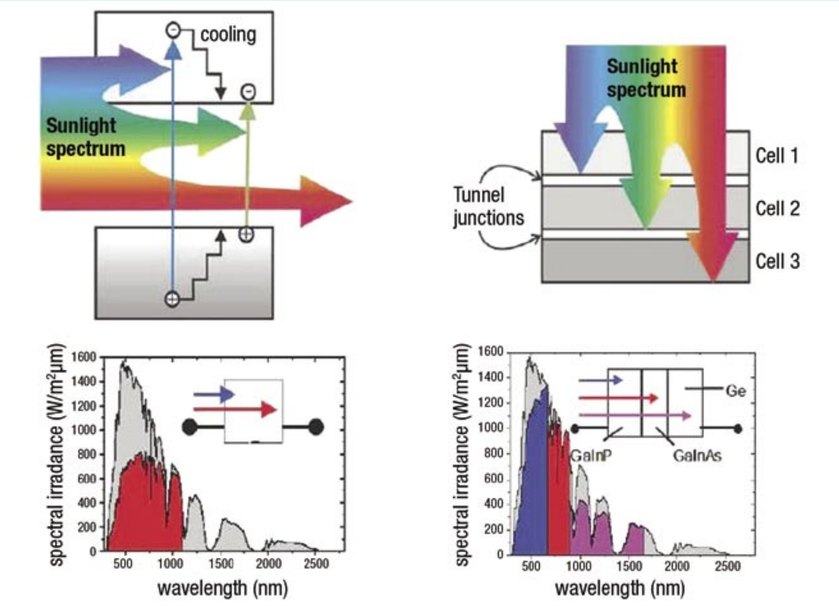


Figure 1. Solar spectrum in Si and multijunction cells.

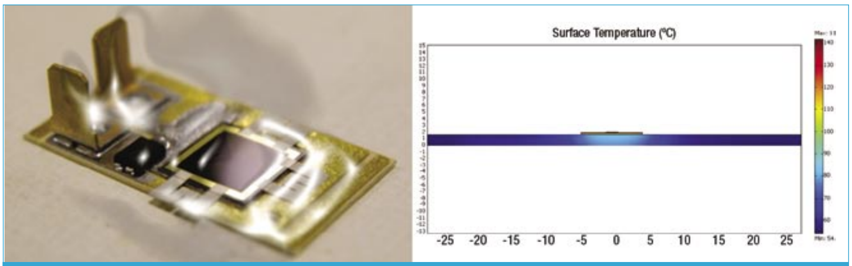
Courtesy of A. Luque, CONSOLIDER project.

Optics

Optical designs that meet the strict criteria for high concentration systems are key to new CPV concepts. Traditionally, flat Fresnel lenses or mirrors have been used, such as those in Sandia, Ramon Areces, and Euclides systems [13]. In current systems, the Fresnel lens is still the optical element of choice for companies such as Concentrix, Amonix, Guascor, Emcore, Arima ECO, Renovalia CPV, Sol 3G and Entech, among others. Ease of design and simulation, as well as reduced cost, are the contributing factors for this being considered a lead component. Nevertheless, its manufacture meets a number of challenges under the requirements for high concentration CPV. There are various technological approaches to the manufacture of Fresnel lenses, from injection or compression molding, with very difficult tuning, to silicone films, which do not always allow good prices. In order to improve the acceptance angle of the system, a secondary element can be used. This element is normally made of a solid glass or hollow metal prism, both of which allow a better light distribution on the cell and improve the collection of the light [14]; optical systems without a secondary element can also provide very high efficiencies [15].

Reflective optics are an alternative method, capable of being used in several ways, such as in a large parabolic mirror dish, using a parquet of cells, like Solar Systems' technology [16], or as compact mirror systems, with one parabolic mirror per cell, which can incorporate additional reflection steps like Solfocus' system [17].

Additionally, other non-imaging optical concepts like the Total Internal Reflexion (TIR) system [18] are used by companies such as Isofotón. In recent years, new optical concepts such as XR [19] or RXI [20,21] have been developed, concepts that combine reflection and refraction and have the potential to achieve very high concentration with a wide acceptance angle.



Courtesy of Renovalia CPV.

Figure 2. Cell featuring alumina and thermal simulation.

Tracking systems

Depending of the acceptance angle of the optics, tracking systems should be more or less accurate and should be adapted for every module technology. Up to a concentration ratio of 2.5X, there is no need for sun tracking. For mid concentration (up to 40X), the tracker can be lineal, like the Euclides system, with elevation movement in a polar axis or east-west movement in a north-south axis. However, for high concentration systems, two-axis sun tracking with a very high accuracy is mandatory [22].

The control of the tracking system can be carried out in open loops (sun movement equations) or closed loops (light sensor). Use of a single control method can pinpoint tracking errors, while tracking accuracy can be reduced by using an open loop control on a system that has not been precisely installed and positioned. A closed loop system will not work properly if there are clouds shadowing the light sensor. Current systems use hybrid control, which include both sun movement algorithms and radiation or power output sensors [23].

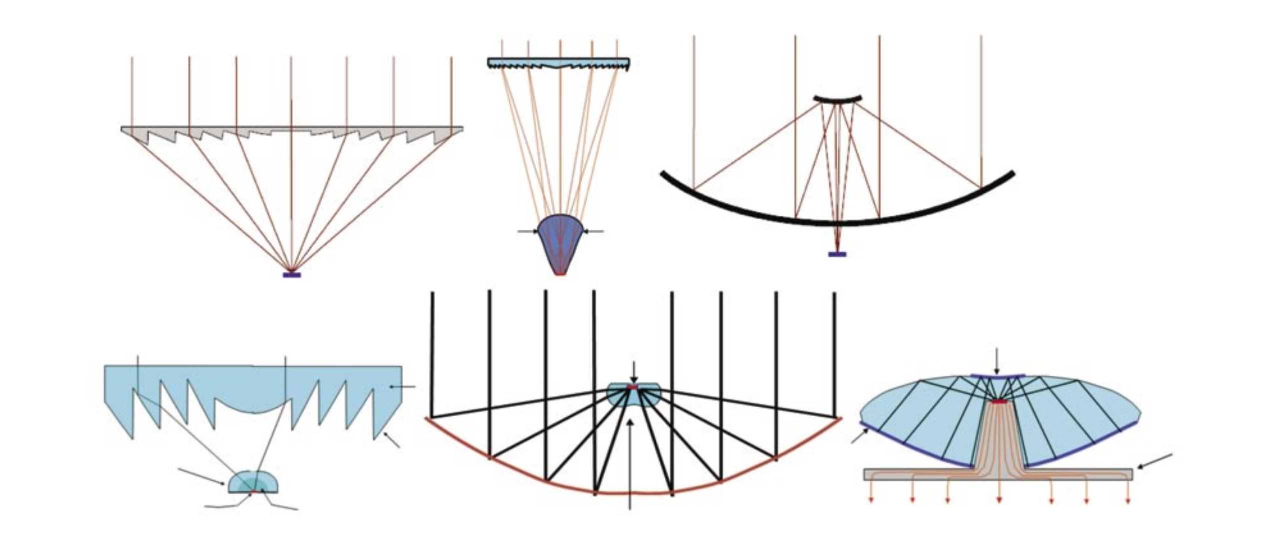


Figure 3. Different optics layouts: Fresnel without secondary, Fresnel with secondary, mirror, TIR, XR optic and RXI optic.

Institute for Concentration Photovoltaics Systems – ISFOC

Technology developments and a buoyant PV market have made it possible for CPV to be deployed. High efficiency cell technology is already available for terrestrial applications; new optical concepts or processes have also been developed and, finally, tracker systems and controls are being developed and validated. With proven technology and manufacturing processes available, manufacturing lines and utility-sized CPV power plants are ready for deployment.

Armed with the objective of making this a reality, ISFOC, formed in September 2006, is the result of the R&D plan promoted by the Spanish Department of Education and Science from the Castilla La Mancha Government and the IES-UPM (Institute of Solar Energy from the Universidad Politécnica de Madrid). The project is financed by the Spanish Ministry of Education and Science [24].

In order to generate key knowledge on this technology, ISFOC is executing a number of power plants (up to 3MW in total) incorporating different concentrator technologies. Companies featuring in the first phase include Isofotón (ES), Solfocus (US) and Concentrix (DE). The second phase includes Emcore (US), Sol 3G (ES), Arima Eco (TW) and Renovalia CPV (ES).

Currently, there are 1.1MW already installed and connected to the grid from the first phase. The objective of these pilot plants is to assist the industries in the setting up of pilot fabrication lines. There will also be valuable information obtained from the process such as reliability, suitability and production from each technology [25].

Figure 4. Euclides system.

Figure 5. Two-axis tracker.

Standards

In December 2007, the first standard for CPV (IEC 62108) was approved. This standard establishes the reliability tests for the CPV modules. The tests to be carried out are:

- Electrical tests: electrical performance measurement, ground path continuity test, electrical insulation test, wet insulation test, bypass/blocking diode thermal test and hot-spot endurance tests).
- Climatical tests: thermal cycling test, damp heat test and humidity freeze test.
- Mechanical tests: hail impact test, robustness of terminations test and mechanical load test.
- Ambient conditions: water spray test, off-axis beam damage test, ultraviolet conditioning and outdoor exposure test.

There are a number of laboratories that are now in the process gaining of

Courtesy of Denis Lenardic, www.pvresources.com.

Figure 6. ISFOC HCPV power plants in Puertollano.

Manufacturers	Company	Today on sun (MW)	Plant location	Manufacturing capacity (MW/year)
Abengoa Solar	Spain	1.2	Spain	
Guascor foton	Spain	10.275	Spain	15
Isofotón	Spain	0.4	Spain	5
Renovalia CPV CS La Mancha	Spain	0	Spain	11
Sol 3G	Spain	1.4	Spain	12
Concentrix	Germany	0.3	Spain	25
Solfocus	USA	0.5	Spain	50
EMCORE	USA	0.35	Spain	10
AMONIX	USA	0.61	USA	
Arima ECO	Taiwan	0.05	Spain	7.5
Solar Systems	Australia	1.2	Australia	5
Total		**16,285**		**140.5**

Table 1. Main CPV manufacturers showing total installed power versus actual manufacturing capacity.

accreditation for performing these tests. All companies under ISFOC's project must pass the most important tests of this standard before installation. During performance of the standard procedures, designs were improved and modifications were added to comply with the IEC tests. The isolation test and the damp heat test are among the most difficult trials, as the modules need to show they are watertight while maintaining electrical isolation.

Other standards under development include CPV modules power rating, CPV system energy rating (with ISFOC participation) as well as tracker requirements and safety.

At ISFOC, power and energy rating of CPV systems and concentrator characterization is being carried out using the methodology described in [26]. ISFOC's experience is aiding in the improvement of the procedures outlined in this publication.

The standard conditions for concentrator characterisation are defined at 850W/m^2 and a cell temperature of 60ºC. The possibility and potential benefits of changing this temperature value to 25ºC is currently being researched in order to be comparable with flat panel conditions and indoor characterisation.

The measurement conditions are established as:

- Clear sky conditions.
- The direct radiation should be higher than 700 W/m^2.
- The wind speed should be lower than 3.33m/s.

In order to determine the DC Power of the concentrator, the following variables are monitored during the measurements:

- The I/V curve of the system is measured with a capacitive charge. This equipment incorporates a discharged capacitor, which is charged during the measurement until the system reaches the open circuit condition. This tracer is capable of carrying out very fast measurements over long periods of time automatically, for a range of different concentrator systems.
- Direct radiation is measured in real time by two pyrheliometers.
- Cell temperature is measured with several thermal sensors on the back part of the module behind the cell. The V_{oc} value of either the complete system or an independent and calibrated cell in open circuit could also be used for temperature measurement.
- Wind conditions (speed and direction) are also measured in order to determine their effect on the final rating in the cooling mechanisms.
- Additionally, the spectrum of the sun could also be measured in order to determine its deviations from the spectrum to which cells are characterised.
- The ambient temperature is also measured in order to study the relation between all the parameters and conditions.

Current and voltage values are then translated to as-defined standard conditions following the equations, deduced from the Shockley equation model:

$$I_2 = I_1 \cdot \frac{B_{oper}}{B_{mea}} \qquad (1)$$

Other Companies	Company location
Boeing	USA
Concentrating Technologies	USA
Cool earth	USA
Energy Innovations	USA
Enfocus Engineering	USA
Entech	USA
GreenVolts	USA
JX Crystal	USA
Opel International	USA
Pyron Solar	USA
Semprius	USA
Skyline	USA
SolarTech	USA
Soliant Energy	USA
Menova	Canada
Morgan Solar	Canada
ENEA	Italy
Magpower	Portugal
Solar Tec AG	Germany
Whitfield Solar	UK
Daido Steel	Japan
Sharp Solar	Japan
Everphoton Energy	Taiwan
Green and Gold Energy	Australia

Table 2. Other CPV manufacturers.

where I_2 is the current under standard conditions; I_1 is the measured current; B_{mea} is the measured direct beam radiation and B_{oper} is the direct beam radiation under standard conditions;

$$\Delta V_i = N\frac{0.0257\times(T_{oper}-T_{cel})}{297}\left[\ln\left(\frac{(I_{Lmea1}-I_i)(I_{Lmea2}-I_i)(I_{Lmea3}-I_i)}{I_{Lmea1}I_{Lmea2}I_{Lmea3}}\right)\right]+\left[N(E_{g1}+E_{g2}+E_{g3})-V_{ocmed}\right]\left(1-\frac{T_{oper}}{T_{cel}}\right) \quad (2)$$

and

$$T_{cell} = T_{h-s} + B_{mea}\cdot R_{th,sys} \quad (3)$$

where N is the number of cells in series connection; I_{Lmeaj} is the photocurrent of each junction; E_{gj} is the band gap of each junction; V_{oc} is the system open circuit voltage; T_{oper} is the standard temperature; T_{cell} is the cell temperature; V_{oc} is the system open-circuit voltage and $R_{th,sys}$ is the thermal resistance of the system.

This method allows the calculation of DC power of the concentrator using only a few representative measurements. ISFOC has already validated this procedure using data from the first installation, the results of which are publicly available [27].

Conclusion

With the available technology, approved standards, installation of the first demonstration plants and the availability of their results, the CPV industry is experiencing extraordinary progress. The number of CPV and cell manufacturers has increased in the last two years and the number of CPV installations has become considerable.

CPV is in the early developmental stages of deployment, and holds great potential for rapid growth. With a global PV market driven by government subsidies, CPV will rely on special measures that will allow its growth, independent of other renewable energy sources. We expect that early deployment will be sufficient to show the capabilities of this technology in fulfilling the needs of cost and productivity to reach grid parity in the short term.

References

[1] Burgess, E.L. & Pritchard, D.A. 1978, *Proc. 13th Photovoltaic Specialists Conference*, (IEEE New York), p. 1121.

[2] Nasby, R., Gardner, C.M., Weaber, H.T., Sexton, F.W. & Rodriguez, J.L. 1981, *Proc. 15th IEEE Photovoltaic Specialist Conference*, (IEEE New York), p. 132.

[3] Sala, G. & Luque, A. 2007, 'Past Experiences and New Challenges of PV Concentrators,' *Concentrator Photovoltaics*, Eds. Luque, A. & Andreev, V. (Springer Series).

[4] Swanson et al 1984, 'Point-Contact silicon solar cells,' *IEEE Transactions on electron devices*, 31, p. 661.

[5] Slade, A. & Garboushian, V. 2005, '27.6% efficient silicon concentrator cell for mass production,' *Technical Digest*, 15th International Photovoltaic Science and Engineering Conference, Shanghai, October 2005, p. 701.

[6] Castro, M. & Creixell, J. 2007, 'Guascor Foton: Contributions to the manufacturing of Concentrator PV Systems,' *Proc. 4th International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen*, El Escorial, March 2007.

[7] Emery, K., Meusel, M., Beckert, R., Dimroth, F., Bett, A.W. & Warta, W. 2000, 'Procedures for evaluating multijunction concentrators,' *Proc. 28th IEEE Photovoltaic Specialists Conference*, Anchorage, Alaska 2000, pp. 1126-1130.

[8] King, R.R., Law, D.C., Edmondson, K. M., Fetzer, D.M., Kinsey, G.S., Yoon, H., Sherif, R.A. & Karam, N.H. 2007, '40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells,' *Applied Physics Letters 90*, [note 183516].

[9] Geisz, J.F., Friedman, D.J., Ward, J.S., Duda, A., Olavarria, W.J., Moriarty, T.E., Kiehl, J.T., Romero, M.J., Norman, A.G. & Jones, K.M. '40.8% efficient inverted triple-junction solar cell with two independently metamorphic junctions,' submitted to APL.

[10] Bett, A.W., Siefer, G., Baur, C., van Riesen, S., Peharz, G., Lerchenmüller, H. & Dimroth, F. 2005, 'FLATCON® concentrator PV-technology ready for the market,' *Proceedings of the 20th European Photovoltaic Solar Energy Conference*, Barcelona.

[11] Algora, C. & Díaz, V. 2000, 'The influence of series resistance on the guidelines for the manufacture of concentrator p-on-n GaAs solar cells,' *Prog. Photovoltaics 8*, PP. 211-225.

[12] Jaus, J., Fleischfresser, U., Peharz, G., Dimroth, F., Lerchenmüller, H. & Bett, A. 2006, 'Heat Sink Substrates for Automated Assembly of Concentrator Modules,' *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden, 2006.

[13] Verlinden, P.J., Lewandowski, A., Bingham, C., Kinsey, G.S., Sherif, R.A. & Lasich, J.B. 2006, 'Performance and reliability of multijunction III-V modules for concentrator dish and central receiver applications,' *Proceedings of 4th World Conference on Photovoltaic energy Conversion*, Hawaii, pp. 592-597.

[14] Jaus, J., Nitz, P., Peharz, G., Siefer, G., Schult, T., Wolf, O., Passig, M., Gandy, T. & Bett, A.W. 2008, 'Second stage reflective and refractive optics for Concentrator photovoltaics,' *33rd IEEE Photovoltaic Specialists Conference*, San Diego.

[15] Bett, A.W. & Lerchenmüller, H. 2007, 'The FLATCON System from Concentrix Solar,' In *Concentrator Photovoltaics*, Eds. Luque, A. & Andreev, V. (Springer Series).

[16] Verlinden, P.J., Lewandowski, A. & Lasich, J.B. 2006, 'Performance and reliability of a 30-kW triple-junction photovoltaic receiver for 500X concentrator dish or central receiver applications,' *Proc. SPIE High and Low Concentrations for Solar Electric Applications*, San Diego, Vol. 6339, 633907.

[17] Gordon, J.M. 2007, 'Concentrator Optics,' In *Concentrator Photovoltaics*, Eds. Luque, A. & Andreev, V. (Springer Series).

[18] Alvarez, J.L., Hernández, M., Benítez, P. & Miñano, J.C. 2001, 'TIR-R Concentrator: a new compact high-gain SMS design,' *Nonimaging optics: maximum efficiency light transfer VI*, Ed. Winston, R., Vol. 4446, pp. 32-42.

[19] Benítez, P., Miñano, J.C., Hernández, M., Cvetkovic, A., Dross, O. &

Jones, R. 2007, 'A high-performance photovoltaic concentrator.' *4th International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen* (proceedings CD and multimedia DVD - ISBN 978-84-690-6463-4) El Escorial, Spain.

[20] Miñano, J.C., González, J.C. & Benítez, P. 1995, 'RXI: a high-gain, compact, nonimaging concentrator,' *Applied Optics* 34, pp. 7850-7856.

[21] Álvarez, J.L., González, J.C., Benítez, P. & Miñano, J.C. 1998, 'Experimental measurements of RXI concentrator for photovoltaic applications,' *Proc. 2nd World Conference and Exhibition on Photovoltaic Solar Energy Congress*, Vienna, Austria, pp. 2233-36.

[22] Luque-Heredia, I. et al 2003, 'A subdegree precision sun tracker for 1000X microsoncentrator modules,' *Proc. 3rd World Conference on Photovoltaic Energy Conversion*, Osaka, Japan.

[23] Luque-Heredia, I., Gordillo, F. & Rodríguez, F. 2004, 'A PI based hybrid sun tracking algorithm for photovoltaic concentration,' *Proc. 19th European Photovoltaic Solar Energy Conference*, Paris, France.

[24] Rubio, F., Banda, P., Pachón, J.L. & Hofmann, O. 2007, 'Establishment of the Institute of Concentration Photovoltaics Systems – ISFOC,' *Proc. 22nd EU PVSEC*, Milan, Italy.

[25] Rubio, F., Martinez, M., Coronado, R., Pachón, J.L., Banda, P., Sala, G. & Luque, A. 2008, 'Deploying CPV Power Plants - ISFOC Experiences,' *33rd IEEE Photovoltaic Specialist Conference*, San Diego, USA.

[26] ISFOC 2007, 'Specifications of general conditions for the call for tenders for concentration photovoltaic solar plants for the Institute of Concentration Photovoltaic Systems (ISFOC).'

[27] Martínez, M., de la Rubia, O., Sánchez, D., García, M.L., Coronado, R., Rubio, F., Pachón, J.L. & Banda, P. 2008, 'Concentrator Photovoltaics connected to the grid and systems rating,' *Proc. 23rd EU PVSEC*, Valencia, Spain.

About the Authors

Francisca Rubio graduated as an electronic engineer from Granada University in Spain. She worked for ten years in the fields of electronics and LEDs and was responsible for the Electronic Area in the R&D Department of Valeo Lighting in Martos, where she developed LED-based headlamps for the automotive industry. She joined ISFOC in September 2006 as head of the R&D Department.

Pedro Banda has a Ph.D. in electronic engineering from RMIT in Australia and graduated as a telecommunications engineer from UPM in Spain. His background is in the semiconductor industry, where he held various technology, development and management positions at Lucent Technologies, BPSolar (Spain) and IMEC (Belgium). He currently holds the role of ISFOC Director General.

Enquiries

ISFOC
Juan Bravo 22
13500 – Puertollano
Spain

Tel: +34 926 441 673
Fax: +34 926 429 142
Email: isfoc@isfoc.com