Presented at the 27th European PV Solar Energy Conference and Exhibition, 24-28 September 2012, Frankfurt, Germany

ADVANCED CONCEPTS IN CONCENTRATING PHOTOVOLTAICS (CPV)

Maike Wiesenfarth, Henning Helmers, Simon P. Philipps, Marc Steiner and Andreas W. Bett
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
phone: +49 761 4588 5470, fax: +49 761 4588 9250, maike.wiesenfarth@ise.fraunhofer.de

ABSTRACT: In this paper an overview on the history and actual status of the CPV market is given. Since the introduction of multi-junction solar cells to terrestrial concentrator systems, the installed capacity of high concentration systems has strongly increased. Today, commercial CPV power plants produce electricity cost competitive compared to other solar technologies. To verify the system design and prove reliability, the certification IEC 62108 was introduced and today several modules have successfully completed the test sequence and received the certificate. Beside the widely used point focus systems there are different system approaches with the potential to increase the efficiency and solar concentration. At Fraunhofer ISE the CPV tower and the CPV and thermal (CPVT) system approaches are investigated. Using the thermal energy in addition to the electrical energy, test receivers showed that 75 % of the solar energy can be utilized.

Keywords: CPV market, concentrator cells, system, reliability, performance, co-generation.

1 INTRODUCTION

Currently high concentration concentrator photovoltaic (CPV) systems are entering the market. They are reliable and cost competitive. Typically these systems have concentration factors between 400 and 700 suns and the system efficiencies are up to 29 % AC. However, in the future, the efficiency will increase and the costs will be reduced further. This will be achieved by advanced designs and concepts which needed to be developed. This includes the development of new processing schemes as well as new designs and applications. In this work the actual status of the CPV technology is reviewed and advanced concepts which are under R&D at Fraunhofer ISE are presented.

2 HISTORY AND ACTUAL STATUS OF THE CPV MARKET

CPV systems are divided into low concentrating systems (LCPV) and high concentrating systems (HCPV) depending on their concentration factor. According to reference [2] for LCPV systems the concentration factor is below 100x and for HCPV from 300x up to 1000x.

Figure 1 presents for LCPV systems the installed system capacity during the recent years. One major plant was finished already in 2006 by Abengoa with a capacity of 1.2 MW in Seville [3]. Solaria announced on their webpage a total installed capacity of 3.7 MW during the last years. Other companies like Cogenra Solar, CPower Entech Solar, JX Crystals or Skyline Solar, WS Energia realized prototype installations and demo systems ranging from few kilowatts up to 300 kW. In total the installed capacity of LCPV today is about 6 MW.

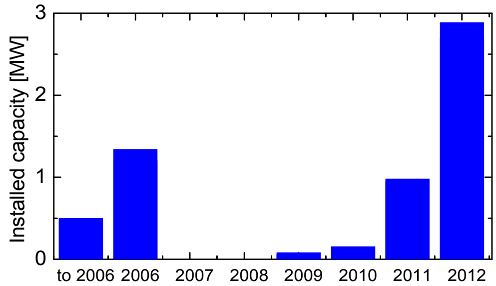

Figure 1: Yearly installed capacity in Megawatt (MW) for low concentration photovoltaic (LCPV).

For HCPV systems the yearly installed capacity is shown in Figure 2. Until 2008, mostly silicon solar cells were used. However, since the introduction of multi-junction solar cells to terrestrial solar concentrator applications, the growth of HCPV is rapid. After several prototype installations, in 2008 the first large demo systems were installed. For example at ISFOC, in Puertollano I, a total capacity of 800 kW was grid connected [1]. From then on, the yearly installed capacity increased significantly.

It should be noted, that the data presented in Figure 1 and Figure 2 are taken from publications and press releases, unpublished installations are not included or publications not revealed.

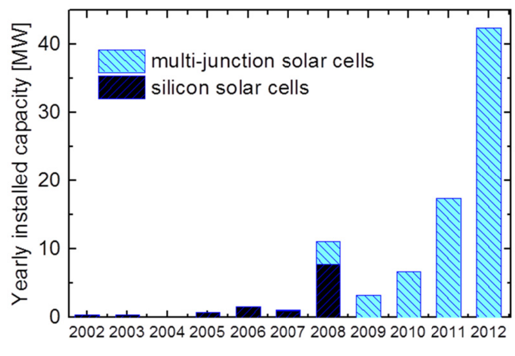

Figure 2: Yearly installed capacity in MW for high concentration photovoltaic (HCPV) systems with a distinction which type of solar cell material was used (silicon or multi-junction).

Today, a total capacity of 86 MW is installed. Most of the installed systems are point focus systems and in particular lens based systems. As Figure 3 shows, Amonix has the largest installed capacity with almost 40 MW. Guascor Foton, Soitec, SolFocus and Suncore have installations of more than 5 MW and Arima, Greenvolts, Solar Systems and Suntrix each published installations that add up to more than 1 MW. Currently many installations are under construction, for example in Goldmund China (Suncore), in Hami China (Focusic), Italy (Soitec, Suntrix), Portugal (Magpower), Mexico (SolFocus), Saudi-Arabia (SolFocus, Solar Systems) with a total capacity of more than 60 MW. Moreover, considering already finalized power purchase agreements (PPAs), the accumulated CPV projects reach the three digit volume per year.

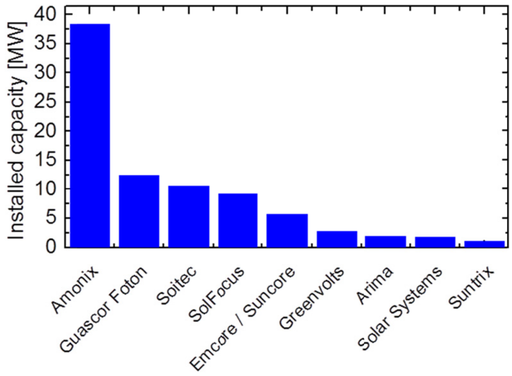

Figure 3: Total installed capacity in MW for HCPV systems of different companies according to published data. It represents the status of 09/2012, numbers change very quickly.

Production capacities above 30 MW were announced by Amonix, SolFocus (50 MW expandable to 100 MW), Soitec (80 MW, under development 200 MW), and Suncore (200 MW). In addition many companies are active in the market with smaller production capacities or do not publish their capacity. Hence, the increasing demand for CPV products can be satisfied by the industry.

3 TECHNICAL STATUS OF CPV

The efficiency of the solar cells is the key driver for the HCPV technology. In Figure 4 record efficiencies for solar cells as published in reference [4] are displayed. Since 2002 the efficiency has increased by 0.9 % absolute per year. Solar cells made by Solar Junction [4] and Sharp [6] achieved the today´s champion efficiency of 43.5 %. As can be seen in Figure 4, commercial cell efficiencies follow R&D results very quickly, showing that R&D results were introduced into the production immediately. According to product data sheets of the companies, today multi-junction solar cells are commercially available with efficiencies between 37 and 40 %. Companies are for example AZUR SPACE Solar Power, CESI, Cyrium, Emcore, JDSU, M-Com, Microlink Devices, Spectrolab and Solar Junction.

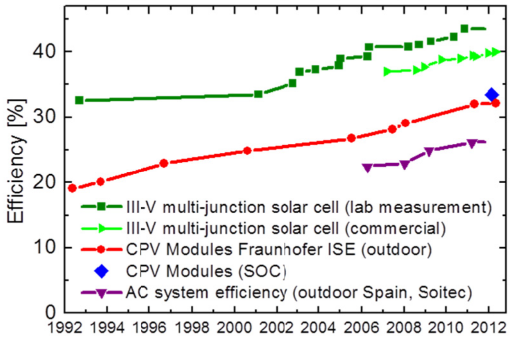

Figure 4: The graph shows the best solar cell and module efficiencies as published in [4], commercial cell efficiencies according to product data sheets, measured efficiencies for Fraunhofer ISE CPV test modules and commercial installations from Soitec [5].

Also, the module development has been successful. In Figure 4 the development of the ISE test module efficiencies are shown. The improvements are obvious. The IV curve of the most recent module ISE-044 is shown in Figure 5. This module uses triple-junction solar cells from AZUR SPACE Solar Power. The aperture area is 832 cm² and the measuring conditions are very close to standard operating conditions with a DNI of 830 W/m² and temperature of 23.7 °C. A spectral parameter Z [7] of -0.008 close to zero indicates that the spectrum is similar to AM1.5d low AOD. The wind speed during the measurement was only 1 m/s. The measured efficiency under these operating conditions was 32.1 %.

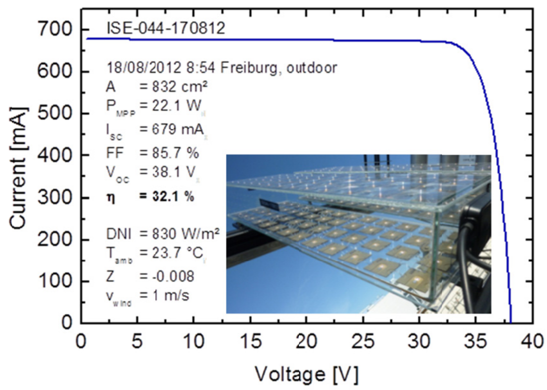

Figure 5: Outdoor measurement of a FLATCON® module in Freiburg with conditions close to SOC (standard operating conditions).

Recently, a module efficiency of 33.9 % [8] was published by the company Semprius. They claim that this is the highest reported efficiency value for a CPV module. The measurement of the module efficiency was performed indoors by the Instituto de Energía Solar at the Universidad Politécnica de Madrid (IES-UPM) at an illumination intensity of 850 W/m², a cell temperature of 25°C and a spectrum matched to AM1.5d. In reference [4] a calibrated module efficiency of 33.5±0.5 % has been reported. The module was manufactured by the company Amonix and was measured by NREL.

Figure 4 presents also the efficiencies of commercial CPV systems. The shown efficiencies are on the basis of in reference [5] published data from Concentrix/Soitec.

However, also other companies like Abengoa, Amonix, Emcore, SolFocus or Suntrix claim on their webpage that they achieve DC or AC system efficiencies between 25 and 29 %.

As any other PV system, CPV installations are designed for at least 25 year, thus they have to be reliable. The standard IEC 62108 called "Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval" issued by the International Electrotechnical Commission (IEC) in 2007 is a mandatory step to demonstrate this reliability. Today many companies have certified their products according to this standard. Table 1 lists companies that received the certification according to their own websites or to announcements by the certification labs. Please not that additional UL and IEC standards (e.g. for power and energy rating, module safety) are under preparation and drafts are already available.

Table 1: Companies that received the certification IEC 62108:

Company	Product	Certification institution	
AEST	Oculis-A-24B	TÜV Rheinland	[9]
Amonix	Not specified	Not specified	[10]
Cogenra	200-0992	TUV SUD America	[11]
CPower	R4120	Albarubens Srl.	[12]
Emcore/ Suncore	G3-1090X	Intertek	[13]
Entech Solar	SolarVolt™	TÜV Rheinland Photovoltaic	[9]
Greenvolts	GV-MOD001	TUV SUD America	[11]
Isofoton	GEN 2	TÜV Nord Cert GmbH	[14]
Skyline	X14	TUV SUD America	[11]
Soitec	CX-75-200 CX-75-III CX-M400 CX-M500	CENER (Centro Nacional de Energías Renovables) Certified by AENOR (Asociación Española de Normalización y Certificación) TÜV Rheinland	[15] [9] [11]
SolFocus	SF-1000P SF-1100P	Six 9's Reliable, L.L.C. certified TÜV Rheinland PTL	[9]
Suntrix	SCPV-500	CGC (China General Certification.) CNAS (China National Accreditation Service	[16]

3 ADVANCED CONCEPTS IN CPV

Several promising CPV concepts are under development at Fraunhofer ISE. In general, the R&D focus is on the increase of concentration and efficiency in order to lower the cost on kWh basis.
To increase the concentration factor towards 1000x and beyond, module concepts with mirror optics are of interest. The mirror optics has no chromatic aberration and can easily be scaled to large units.
The solar tower concept, which is well-known in CSP technology [17], is an interesting path for CPV technology. The sunlight is focused by a heliostat field onto a centralized area in a tower [18]. This means PV receivers with a size of several square meters, actively cooled and suitable for light intensities of 1 MW/m² are needed. Obviously this approach is technically very challenging. However, first pilot installations, but with lower concentration ratios, have been already realized by Solar Systems [19].
Another interesting approach is to use a dish system with diameters of several meters. This requires also an actively cooled CPV receiver. However, if properly designed the generated thermal energy can be utilized. These systems are called CPVT (CPV and thermal) systems. An example for a commercial CPVT installation is in Yavne (Israel) from Zenith Solar [20].

The potential of the CPVT approach has been investigated theoretically in reference [21]. In order to investigate it experimentally, a test dense array module was developed at Fraunhofer ISE. The receiver consists of four single-junction monolithically interconnected modules (MIMs) [22] with a size of 4.41 cm² each, mounted to a water cooled heat sink and electrically interconnected. The module was assembled to a secondary optics to homogenize the flux distribution on the solar cells (Figure 6). The receiver was tested in the outdoor test set-up at Fraunhofer ISE [24] as shown in Figure 7.

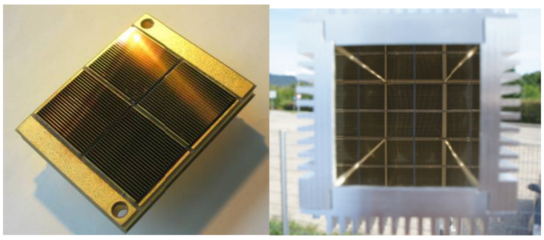

Figure 6: CPVT receiver with 4 single-junction MIMs (left) and receiver assembled to the homogenizer (right).

Figure 7: CPVT receiver and homogenizer assembled to the outdoor test setup at Fraunhofer ISE.

In Figure 8 the efficiency curves of the CPVT receiver ISE 023-CO23 are shown. The total system efficiency at T_m-T_{amb} is 63 % with an electrical efficiency of 14 % and a thermal efficiency of 50 %. The electrical efficiency is nearly constant over the temperature range whereas the thermal efficiency decreases due to losses by thermal convection.

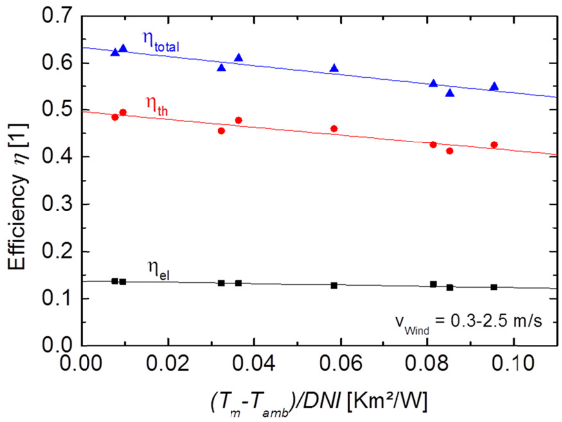

Figure 8: Efficiency curve of a CPVT receiver measured at Fraunhofer ISE. T_m is the medium fluid temperature and T_{amb} the ambient temperature. In black squares the electrical efficiency, in red dots the thermal efficiency and in blue triangles the total efficiency are given. During the measurement the wind velocity fluctuated between 0.3 and 2.5 m/s causing fluctuation especially in the thermal performance.

It should be emphasized that there is a large potential for optimization of this prototype receiver. Firstly, this is using multi-junction solar cell structure for increased electrical efficiency and reducing the shading of the metallization on the solar cells as described in [23]. Secondly, the area and reflection losses due to gaps around and between the cells can be reduced.
To evaluate the potential of the CPVT a thermal-only receiver was tested. The cooler was coated with black solar absorber paint and assembled to the homogenizer. This means the reflection losses were reduced but still the optical losses of the homogenizers are included. A thermal efficiency of 75 % was measured.

For the electrical performance a second test receiver ISE_017-C020 was recently assembled using lattice matched triple-junction solar cells with a size of 1 cm². So far, the module was characterized only indoors at Fraunhofer ISE at the flash simulator under homogeneous illumination with an intensity of 52 W/cm². The IV-curves for the receiver is shown in Figure 9. The efficiency is 30.1 %, where the full area (441 cm²) of the illuminated area is taken into account. I.e. in addition to the solar cell area the gap between the solar cells of 0.5 mm and a small gap around the solar cells with a thickness of 0.25 mm (half gap thickness) is included. Hence, the large part of the edge area is neglected. It is in proportion higher for this small test unit than for larger receivers and in the system it is covered by the secondary optics.

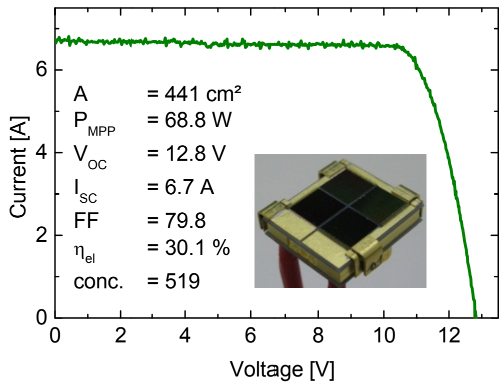

Figure 9: IV curve prototype module measured under concentrated illumination (519x, 1000 W/m², 25 °C) at the flash simulator at Fraunhofer ISE.

4 CONCLUSION

The major part of CPV installations in the market today are high concentration systems. This is due to the high efficiencies of multi-junction solar cells which are used in these systems. Commercially available solar cells achieve efficiencies up of up to 40 %. So far more than 86 MW of HCPV systems are installed and in operation and several MW projects are under construction.
Regarding module efficiencies values as high as 33.9 % have been reported. In this paper we presented an outdoor measurement of a FLATCON®-module with an efficiency of 32.1 %.
Moreover, briefly advanced concepts which are under development Fraunhofer ISE are discussed, i.e. CPV tower systems with centralized power generation and CPVT systems. Using the thermal energy additionally, it was shown that the efficiency can be increased to 75 %.

5 ACKNOWLEDGEMENT

The authors would like to thank all colleagues of the "III-V Epitaxy and Solar Cells" department at ISE for their contributions, with special thanks to Alexander Dilger, Andreas Nübling, Armin Bösch, Eduard Oliva, Fabian Eltermann, Jan Feldges, Gerald Siefer, Sebastian Gamisch, Thomas Schmidt, Tobias Dörsam and Wei Yi Thor. H. Helmers gratefully acknowledges the scholarship support of the German Federal Environmental Foundation (DBU). This work has been partly supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under the KoMGen project, contract number 0327567A. The authors are responsible for the content of this paper.

6 REFERENCES

[1] M. Martínez, F. Rubio, G. Sala, D. Pachón, A.W. Bett, G. Siefer, M. Vetter, A. Schies, J. Wachtel, A. Gombert, J. Wüllner, V. Díaz, M. A. Vázquez, F. Abulfotuh, K. Fetyan, A. el Moussaoui, S. Mansouri, K. Loudiyi, H. Darhmaoui, T. Mrabti, "CPV Plants Data Analysis. ISFOC And NACIR Projects Results", 8th International Conference on

Concentrating Photovoltaic Systems, 16-18 April 2012, Toledo, Spain.
[2] N. Pearsall, "A Strategic Research Agenda for Photovoltaic Solar Energy Technology, EDITION 2", Publications Office of the European Union (2011).
[3] V. Salas, E. Olias, "Overview of the photovoltaictechnologystatus and perspective in Spain", Renewable and Sustainable Energy Reviews, Volume 13, Issue 5, June 2009, Pages 1049–1057 (2009).
[4] M. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, "Solar cell efficiency tables (version 40)", Progress in Prog. Photovolt: Res. Appl. 20, 606–614 (2012).
[5] A. Gombert, "Low Cost Reliable Highly Concentrating Photovoltaics – a Reality" in Proceedings of the 38th IEEE photovoltaic specialists conference (PVSC), 3-8 June 2012, Austin, USA.
[6] Sharp press release 20/05/2012, accessed online 19/09/2012: http://sharp-world.com/corporate/news/120531.html
[7] G. Peharz, G. Siefer, A.W. Bett, "A simple method for quantifying spectral impacts on multi-junction solar cells", in Solar Energy 83, pp. 1588–1598 (2009).
[8] Semprius Press announcement from 21/01/2012, accessed online 18/09/2012: http://www.semprius.com/pdf/press_releases/press_release_19.pdf.
[9] TÜV Rheinland database, http://www.tuvdotcom.com/.
[10] Amonix webpage, press release 25/01/2012 accessed online 19/09/2012: http://amonix.com/pt-pt/node/1190.
[11] TÜV Süd America database, https://www.tuev-sued.de/industry_and_consumer_products/certificates
[12] CPower webpage, accessed online 19/09/2012: http://www.cpower.it/index.php?option=com_content&task=view&id=44&Itemid=2&lang=en
[13] Emcore webpage, press release 25/01/2012 accessed online 12/07/2011: http://investor.emcore.com/releasedetail.cfm?ReleaseID=627366.
[14] Isofoton product data sheet "HCPV Solar technology high concentration" accessed online 19/09/2012: http://www.isofoton.com/de/hcpv-de.
[15] Soitec webpage, press release 28/01/2010 accessed online 19/09/2012: http://www.soitec.com/en/news/press-releases/article-438/
[16] Suntrix webpage, accessed online 19/09/2012: http://www.suntrix.cn/home-en/about/about-suntrix.aspx
[17] S. Alexopoulos and B. Hoffschmidt, "Solar tower power plant in Germany and future perspectives of the development of the technology in Greece and Cyprus", Renewable Energy 35, pp. 1352-1356 (2010).
[18] D. Frohberger, J. Jaus, M. Wiesenfarth, P. Schramek, A.W. Bett, „Feasibility Study on High Concentrating Photovoltaic Power Towers" in AIP Conference Proceedings 1277, American Institute of Physics, Melville, N, 2010, pp.194-198 (2006).
[19] P.J. Verlinden, A. Lewandowski, D. Edwards, H. Kendall, S. Carter, I. Thomas, P. Wakeman, M. Wright, W. Hertaeg, R. Metzke, M. Daly, M. Santin, A. Neumann, A. Wilson, A. Caprihan, M. Stedwell, "World's first demonstration of a 140kWp Heliostat Concentrator PV (HCPV) system", in Proceedings of the 34th IEEE Photovoltaic Specialists Conference (PVSC), Phildelphia, USA, pp. 2275 – 2280 (2009).
[20] H. Chayet, O. Kost, R. Moran, I. Lozovsky, "Efficient, Low Cost Dish Concentrator for a CPV Based Cogeneration System", in AIP Conference Proceedings 1407, American Institute of Physics, Meville, pp. 249-252 (2011).
[21] H. Helmers, A.W. Bett, J. Parisi, C. Agert, "Modeling of Concentrating Photovoltaic and Thermal Systems", in Progress in Photovoltaics: Research and Applications, published online (2012).
[22] R. Loeckenhoff, F. Dimroth, E. Oliva, A. Ohm, J. Wilde, D. Faiman, S. Biryukov, V Melnichak, S. Kabalo, D. Bokobza, A.W. Bett, "Development, characterisation and 1000 Suns outdoor tests of GaAs monolithic interconnected module (MIM) receivers", in Progress in Photovoltaics: Research and Applications, Volume 16, Issue 2, pages 101–112 (2008)
[23] H. Helmers, E. Oliva, W. Bronner, F. Dimroth, A.W. Bett, "Processing Techniques for Monolithic Interconnection of Solar Cells at Wafer Level", in IEEE Transactions on Electron Devices Vol. 57, Issue: 12, pp. 3355 – 3360 (2010).
[24] H. Helmers, A. Boos, F. Jetter, A. Heimsath, M. Wiesenfarth, A. W. Bett, "Outdoor Test Setup for Concentrating Photovoltaic and Thermal (CPVT) Systems", in AIP Conference Proceedings 1407, American Institute of Physics, Melville, N, 2011, pp. 175-179 (2011).