CPVMatch - Concentrating Photovoltaic Modules Using Advanced Technologies and Cells for Highest Efficiencies

Simon P. Philipps[1, a)], Mathieu Baudrit[2], Karla Hillerich[3], Valentine Moreau[4], Rolando Parmesani[5], Eduardo Román[6], Gabriel Sala[7], Bernd Schineller[8], Gianluca Timò[9] and Andreas W. Bett[1, b)]

[1]*Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany*
[2]*CEA-LITEN, LCPV, INES, 50 avenue du Lac Léman, F-73375 Le Bourget-du-Lac, France*
[3]*AZUR SPACE Solar Power, Theresienstraße 2, 74072 Heilbronn, Germany*
[4]*CYCLECO, 18 Avenue Roger Salengro, 01500 Ambérieu-en-Bugey, France*
[5]*ASSE, Via Milano 5, 34132 Trieste, Italy*
[6]*TECNALIA Research & Innovation, Parque Tecnológico de Bizkaia c/ Geldo, Edificio 700, 48160 Derio, Spain*
[7]*Instituto de Energia Solar-Universidad Politécnica de Madrid, Av. Complutense 30, 28040 Madrid, Spain*
[8]*AIXTRON AG, Kaiserstraße 98, 52134 Herzogenrath, Germany*
[9]*RSE SPA, Strada torre della razza, 29122 Piacenza, Italy*

[a)]Corresponding author: simon.philipps@ise.fraunhofer.de
[b)]andreas.bett@ise.fraunhofer.de

Abstract. This paper presents the project *Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies* (CPVMatch), which is funded from the European Union's Horizon 2020 research and innovation programme. V multi-junction solar cells and CPV modules. Concerning cells, novel wafer bonded four-junction solar cells made of GaInP/GaAs//GaInAs/Ge are optimized with the target of reaching 48% efficiency under concentration at the end of the project. Moreover, multi-junction solar cell technologies with advanced materials - like ternary IV element mixtures (i.e. SiGeSn) and nanostructured anti-reflective coatings - are investigated. Concerning CPV modules the project focuses on both Fresnel-based and mirror-based technologies with a target efficiency of 40% under high concentrations beyond 800x. Achromatic Fresnel lenses for improved light management without secondary optics are investigated. In addition, smart, mirror-based HCPV modules are developed, which include a new mirror-based design, the integration of high efficiency, low cost DC/DC converters and an intelligent tracking sensor (PSD sensor) at module level. A profound life-cycle and environmental assessment and the development of adapted characterization methods of new multi-junction cells and HCPV modules complete the work plan of CPVMatch.

INTRODUCTION

The recent status of the EU-funded project *Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies* (CPVMatch) is presented here. Table 1 indicates some statistical facts about the project. The consortium is aligned along the value chain for CPV modules (see Fig. 1). Accordingly the project addresses all topics required to manufacture high-efficient CPV modules. This includes material issues, manufacturing and equipment aspects and production challenges. University and research institutes are working in close co-operation with industry partners to ensure fast industrial exploitation of all results.

The overall aim of CPVMatch is to increase the practical performance of High Concentrating Photovoltaics (HCPV) modules and to close the gap to the theoretical limits. This should be achieved through:

- novel multi-junction solar cell architectures using advanced materials and processes for better spectral matching
- innovative HCPV module concepts with improved optical and interconnection designs, thus including novel light management approaches.

The central objective of CPVMatch is to realize HCPV solar cells and modules working at a concentration level ≥800x with an efficiency of 48% and 40%, respectively, with a low environmental impact. In order to develop such high performing CPV solar cells and modules, two strategies are adhered to (both for the multi-junction solar cell and module technology). The work on cells and module technologies is accompanied by a profound life-cycle and environmental assessment and the development of adapted characterization methods of new multi-junction cells and HCPV modules.

TABLE 1. Facts about CPVMatch

Acronym	CPVMatch
Coordinator	Fraunhofer ISE
Participants	9 partners (4 Research Institutions, 2 SMEs 1 University, and 2 Industry Partners)
Project duration	42 months (3 and a half years)
Dates	May 2015 - October 2018
Type	Collaborative project
Project Funding	4.95 M€
Effort	536 person/months

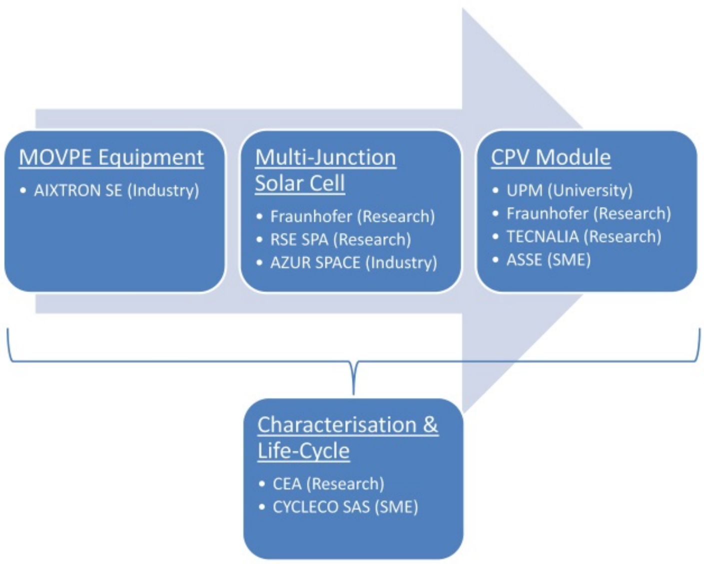


FIGURE 1. Alignment of the CPVMatch partners along the value chain

The project is structured into six scientific work packages. The following gives a short overview on the results achieved in the different work packages after the first project year. Note that the description is not necessarily comprehensive and does not present all details.

SOLAR CELL DEVELOPMENT

Multi-junction solar cells made of III-V semiconductor material achieve the highest efficiencies of any photovoltaic technology. This is achieved by stacking subcells with different bandgaps on top of each other. The standard technology for the production of such devices is metal-organic vapor phase epitaxy (MOVPE), in which the III-V layers are epitaxially grown sequentially. For a long time triple-junction solar cells have been standard and several architectures achieved efficiencies above 40%, e.g. [1-5]. In order to increase the efficiencies further, hence to bring practical performance of photovoltaics closer to theoretical limits, the number of junctions has to be increased. The two most recent efficiency records have been achieved with four-junction solar cells [6, 7]. Recently, a four-junction solar cell with an efficiency of 46.0% at a concentration of 508 suns has been achieved [8]. In CPVMatch two different bandgap engineering approaches for novel four-junction solar cells are followed:

- the first one targets an (Al)GaInP/(Al)GaAs/GaInAs/Ge solar cell, which requires a combination of metamorphic growth and wafer bonding. As this approach is fairly advanced the related work package (WP1) is called cutting edge multi-junction solar cell technologies.
- the second one concerns frontier multi-junction solar cell technologies (WP 2), in which new advanced materials, like new alloys of IV elements and nanostructured coatings, are employed in combination with the adoption of novel advanced MOVPE deposition techniques.

WP 1: Cutting-Edge Multi-Junction Solar Cells

The objective of this work package is the development of a novel wafer bonded four-junction solar cell for better spectral matching with an efficiency of 48% using advanced materials and processes. Fraunhofer ISE and AZUR SPACE carry out the main part of the scientific work with consulting by RSE SPA, UPM and ASSE. The first step in this work package was to analyse existing similar solar cell structures from previous projects and to identify possible routes for improvement based on theoretical modelling. Simulations using a transfer matrix method (TM) and realistic material parameters were carried out to optimize the GaInP/(Al)GaAs/GaInAs/Ge four-junction solar cell structure. A theoretical potential of 50.2% efficiency was identified. The optimized External Quantum Efficiency is shown in Fig. 2.

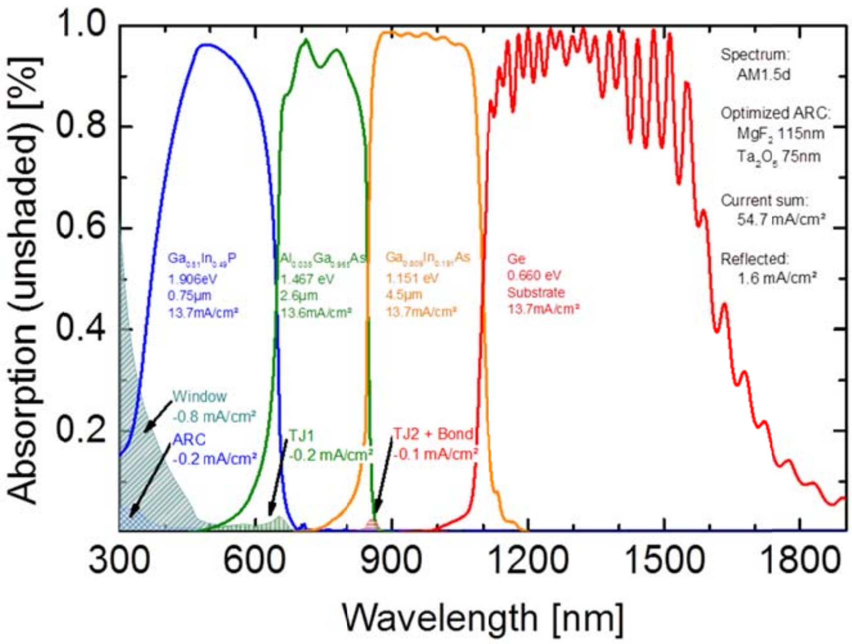


FIGURE 2. Result of the TM simulation showing the optimized four-junction solar cell structure for CPVMatch. Apart from the External Quantum Efficiency (EQE) of the individual junctions, the parasitic absorption in the Anti-Reflective Coating (ARC), the window layer of the top cell, the tunnel junctions (TJ1 and TJ2) and the bonding layers are displayed as hatched areas.

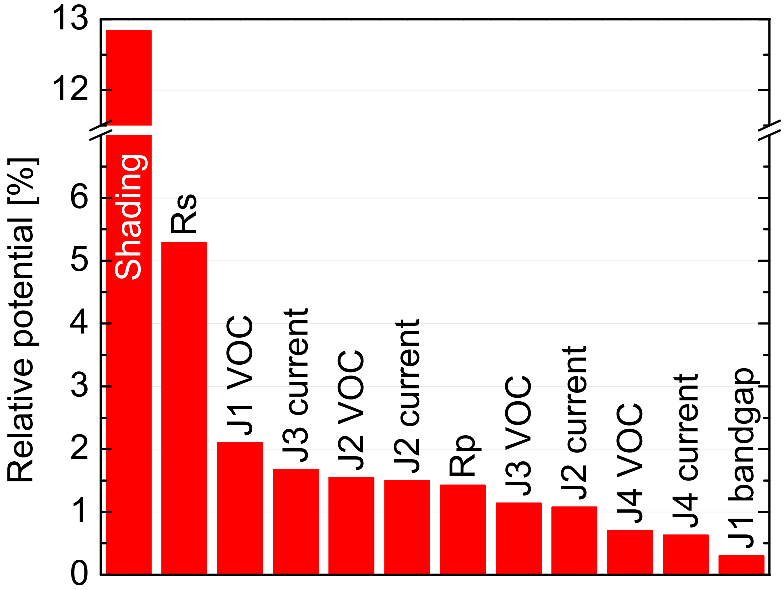


FIGURE 3. Efficiency improvement potential in realized structure with respect to target structure (b).

A comparison of simulation results with experimental cells from previous projects was carried out. The main loss mechanisms in previous cells were identified and quantified (Fig. 3). To this means previous cells have been analyzed very thoroughly. Parts of this analysis were published in Ref. [9]. The origins of the main loss mechanisms were investigated to improve the cell performance. In addition, another batch of four-junction solar cells has been fabricated at Fraunhofer ISE and is currently in the measurement process. The cell structures already include first changes resulting from the investigations of the main loss mechanisms. Intensive collaboration between AZUR SPACE and Fraunhofer has taken place throughout the first project year to manufacture four-junction wafer bonded solar cells. An experimental analysis identified the most critical parameters during epitaxy and the bonding process. First four-junction structures grown at AZUR and bonded at Fraunhofer are currently being analyzed.

WP2: Frontier Multi-Junction Solar Cells

The objective of WP2 is the development of a frontier lattice multi-junction solar cell, comprising nanostructured coatings and innovative lattice-matched materials, obtained by combing III-V and IV elements. The solar cell development is carried out by RSE with consulting by Fraunhofer ISE. The main task of AIXTRON is to develop an adjusted MOVPE reactor for the growth of group IV and III-V elements in the same reaction chamber.

As a first task in this WP RSE has carried out a literature review study and experimental tests that allowed selecting suitable gas sources to start performing the MOVPE growth of the SiGeSn ternary material. Based on this analysis the following candidates were selected: Si_2H_6 diluted in hydrogen, Ge_2H_6 diluted in hydrogen, GeH_4, $SnCl_4$, IBuGe. The experimental tests performed by RSE in particular allowed coming to the following preliminary conclusions:

- nitrogen has to be preferred as a carrier gas with respect to hydrogen
- IBuGe, can be used as a gas source for supplying the Ge element, for n-type SiGSn thin layer; Ge2H6 diluted in hydrogen and GeH4 can be a more suitable precursor to avoid carbon incorporation
- disilane has been confirmed as a suitable source for supplying the Si atoms in the ternary SiGeSn material
- nowadays SnCl4 is supplied with low purity (99,99%), further purification will be necessary to get the desirable background impurities level in the epitaxial layers
- a modification of the MOVPE reactor chamber as far as the ceiling cooling is required.

Based on this input AIXTRON has carried out extensive CFD computations to optimize the MOVPE reactor configuration and is currently constructing the optimized hardware to be implemented at RSE.

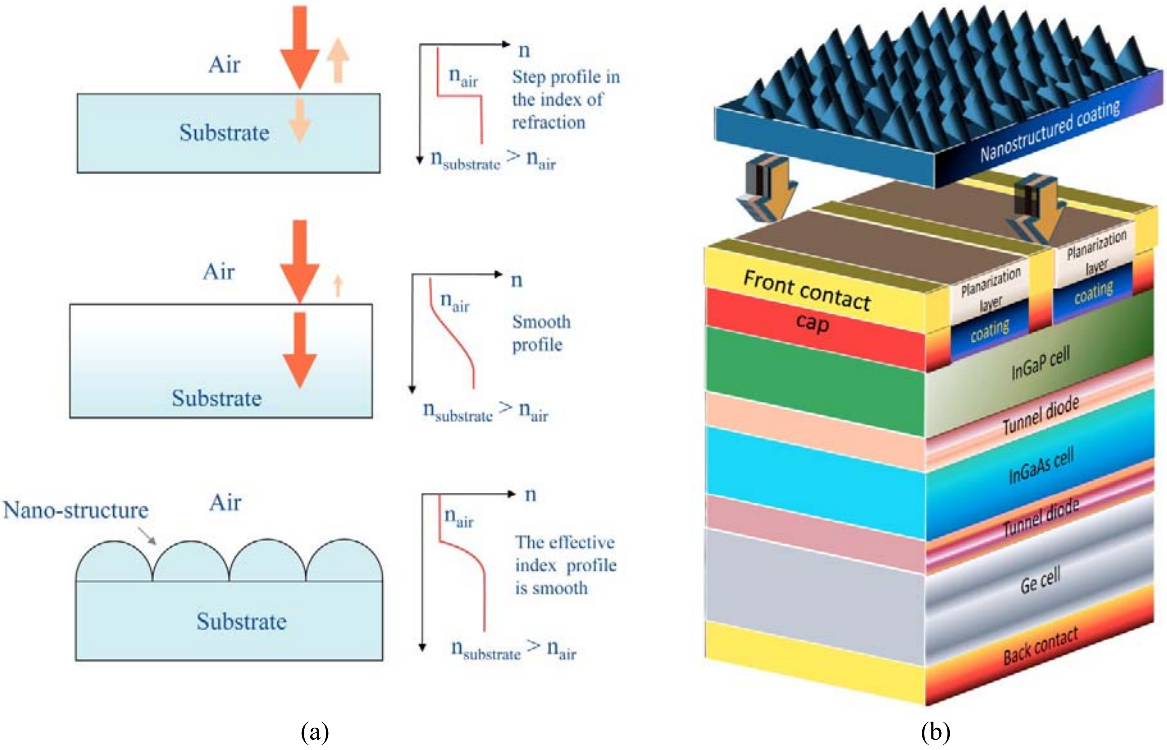


FIGURE 4. Concept related to the utilization of nanostructured coatings for decreasing the light reflection from the solar cell front (a). Sketch of a multi-junction solar cell including nano-structured coatings (b).

Moreover, nanostructured coatings for anti-reflection are being developed in this WP. The principle is shown in Fig. 4. First, available techniques and materials to be used for the nano-coatings were evaluated by RSE in terms of their optical properties, toxicity and usability. Then, a new apparatus for the deposition of nanostructured coatings, consisting of a rotating and tilting platform was assembled and mounted inside the evaporation chamber available at RSE. It will be used for different types of nanostructures by using the evaporation technique. Some preliminary tests have been performed to check the rotation speed adjustment and the motion uniformity.

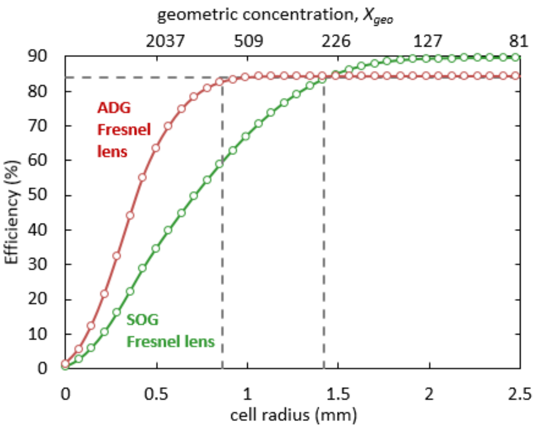
CPV MODULE DEVELOPMENT

Due to their higher manufacturing costs multi-junction solar cells are too expensive for the use in flat-plate modules on Earth. To achieve cost competitiveness in terrestrial applications the cells are implemented into high concentrating photovoltaic (HCPV) systems with concentration factors above 300. Cost-efficient concentrating optics reduce the required cell area, which can allow competitive levelised cost of energy (LCOE). Higher concentration factors can reduce costs further. However, realizing low cost optics with high optical efficiency and at concentration levels above 800x is challenging. Within CPVMatch two promising approaches will be followed: one is based on Fresnel optics and the other one on mirror optics. The innovative, Fresnel lens-based HCPV modules are based on achromatic Fresnel lenses for improved light management and possible concentration ratios of 800x without secondary optics. In addition, smart, mirror-based HCPV modules are developed, which include a new mirror-based design for modules with a high concentration ratio, i.e. > 850x, the integration of high efficiency and low cost DC/DC converters and an intelligent tracking sensor (PSD sensor) at module level.

WP3: Innovative, Fresnel-Lens-Based HCPV Modules

The objective of this work package is to develop achromatic Fresnel lens-based HCPV modules. The work package is coordinated by UPM and involves Fraunhofer ISE, CEA and TECNALIA. In standard Fresnel-lenses chromatic aberration limits the concentration factor. Achromatic lenses can be an option to circumvent this limitation. A method for the design of achromatic lenses has been developed at IES-UPM. Making use of this method a new achromatic lens was designed. Ray-tracing simulations have been used to estimate the performance of the lens compared to a classic Silicone-on-Glass (SoG) Fresnel lens (Fig. 5 (a)). A significantly sharper irradiance spot cast and hence a higher concentration is achieved by the achromatic lens (diameter of 0.84 mm vs. 1.77 mm and a concentration of 694x vs. 254x). To produce these lenses, a laminator has been built at IES-UPM for CPVMatch. The lamination procedures (temperatures, times, degasification step…) have been optimized for the different pairs of materials that compose the achromatic doublet. First experimental measurements based on photographing the irradiance spot using a CCD camera showed the achromaticity of the lens. A 'biFresnel' lens has been designed and manufactured (Fig. 5 (b)) after discussions with several optics manufacturers. Based on these meetings a preliminary cost estimation and a detailed analysis of the main manufacturing errors and their effects on the lens performance was carried out.

Anti-reflective (AR) coatings are essential for high performance CPV modules. Within CPVMatch TECNALIA will develop a new kind of AR coating. In a first step TECNALIA has synthesized different AR coatings based on porous SiO_2 by sol-gel and Evaporation-Induced Self-Assembly (EISA) method by dip-coating. Prior to coating synthesis different coatings structures were simulated in order to select the most adequate system layer. First deposition trials on small and bigger samples have been performed and the reflectance spectra were analyzed.



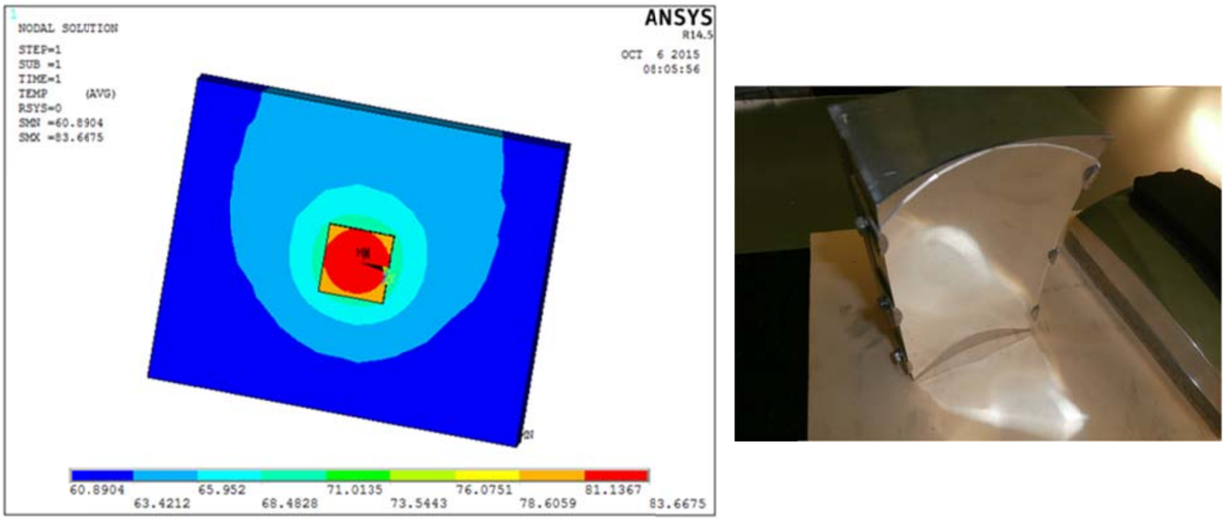
(a)

(b)

FIGURE 5. Simulated optical efficiency of the lens vs. radius of the receiver. Both lenses have the same optical aperture (40x40 mm^2) and focal distance. Operating at the same efficiency, the ray-tracing predicts that the concentration attained by the Achromatic Doublet on Glass (ADG) Fresnel lens is 694X while that achieved by the SoG is 254X (a). Right: Achromalens prototype (b).

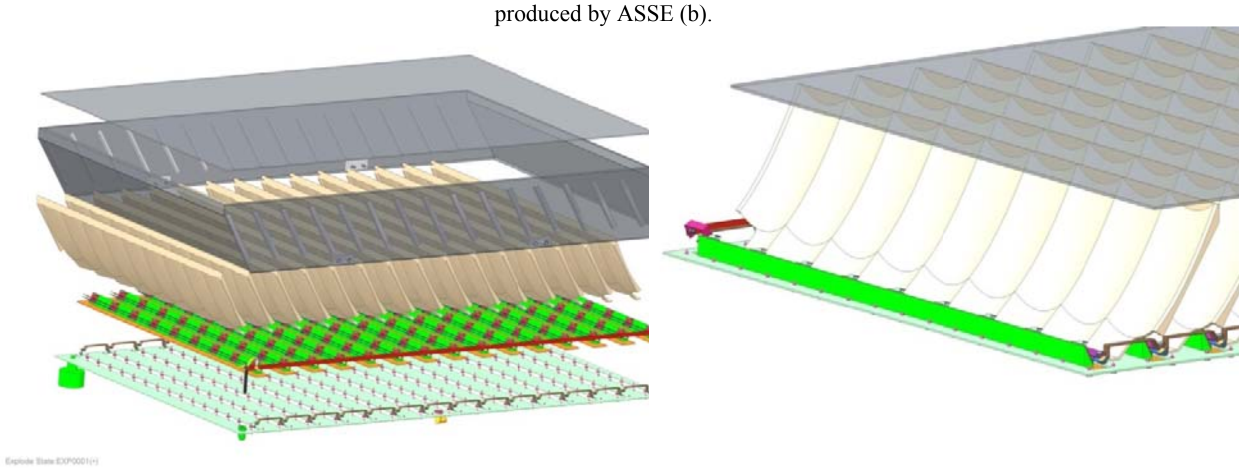
WP4: Smart, Mirror-Based HCPV Modules

The objective of work package 4 is the development of smart, mirror-based HCPV modules. ASSE coordinates this work package, which involves Fraunhofer ISE, RSE, and TECNALIA. First experiences with a new kind of mirror-based HCPV module were gained in the EU-funded project APOLLON [10]. The first task in CPVMatch was the update of the cost estimate for the industrial production of an optimized mirror-based module. The largest cost reduction potential is seen in the cell substrate and the heat exchanger. The receiver assembly was hence analyzed and optimized by FEM (Finite Elements Method), in particular with respect to the thermal resistance (Fig. 6 (a)). In addition, the primary mirror was studied for downscaling and improving its performance. First mirror prototypes were manufactured by ASSE (Fig. 6 (b)) and production methods were optimized. A 5x5 laser matrix device was constructed at ASSE to verify the mirror shape. Moreover, RSE upgraded its optical simulation software (Zemax) to allow for a precise simulation and optimization of the optical performance of a mirror-based concentrator. Based on this, RSE designed a new mirror based concentrator, whose performance has been optimized including the angular acceptance of the multi-junction solar cell and the effective spectral reflectivity of the mirrors measured by RSE at different incidence angles. A sensitivity analysis of the optical components to mechanical misalignments and shaping errors was also performed. A new simulation technique was developed in order to evaluate the photocurrents generated in each of the subcells of the multi-junction device. This provided useful information on the current mismatch produced by the optical transfer function of the concentrator. A new CPVMatch mirror-based module has been developed by ASSE (Fig. 7), implementing the optical design suggestions by RSE and the findings of ASSE in the first semester activities to increase the receiver performances. Manufacturing tests on both mirror and secondary optical element (SOE) have already begun, including iron float glass plates covered with anti-reflective layers provided by TECNALIA.



(a) (b)

FIGURE 6. Finite Elements Method (FEM) thermal analysis results for cell substrate assembly (a). Prototype mirror-optics produced by ASSE (b).



(a) (b)

FIGURE 7. Left: Mirror Based Module exploded view. Right: Mirror Based Module Internal view (a). Optical design provided by RSE, mechanical design & manufacturing provided by ASSE. (b)

The mirror-based modules in CPVMatch should include a DC-DC converter and a positioning sensor (PSD) on module level. With respect to the development of such smart modules, TECNALIA has identified a buck synchronous converter as most suitable power optimizer for the CPVMatch system. For this selection, CPVMatch system operation has been simulated under different working conditions. Concerning the MPPT method a modified

P&O (Perturbation & Observation) algorithm was identified to be most suitable. The functional characteristics of the DC-DC converter as well as of the communication system have been pre-specified by TECNALIA.

Moreover, RSE has started with the design and cost optimization of the PSD sensor starting from the prototypal sensor realized in the APOLLON project. This work already lead to a new PSD unit, which incorporates a 3D-printed water proof box, a new electronic processing board realized with Surface-Mount Technology (SMT), new firmware and a new CCD sensor. These developments have led to a significant size reduction of the PSD sensor unit, which enables cost reduction. Moreover, possible automated production was incorporated as an essential design requirement.

WP5: Characterisation and Testing

The objective of this work package is to assess the developments realized on solar cells and modules by means of adapted characterization methods. The work is coordinated by CEA with participation of Fraunhofer, RSE SPA, UPM and ASSE. Concerning characterization the main challenges within CPVMatch lie in the analysis of four-junction solar cells as well as of new mirror-type optics. To enable the characterization of four-junction solar cells, CEA adapted a measurement process and evaluation algorithm in its measurement lab with the support of Fraunhofer. For the characterization of new CPV optics a test method that measures the spectrally resolved irradiance distribution for a concentrator photovoltaic (CPV) optical system has been developed (Fig. 8). The indoor characterization test bench, METHOD (**M**easurement of **E**lectrical, **TH**ermal and **O**ptical **D**evices), decouples the temperatures of the primary optical element (POE) and of the cell allowing to analyse their respective effects on optical and electrical performance. A calibration procedure has been performed to accurately image the spectral irradiance distribution of a CPV system. After calibration the bench was used to characterize Fresnel optics in a first stage and then mirror-type optics in the second stage. More details on this tool can be found in Ref. [11].

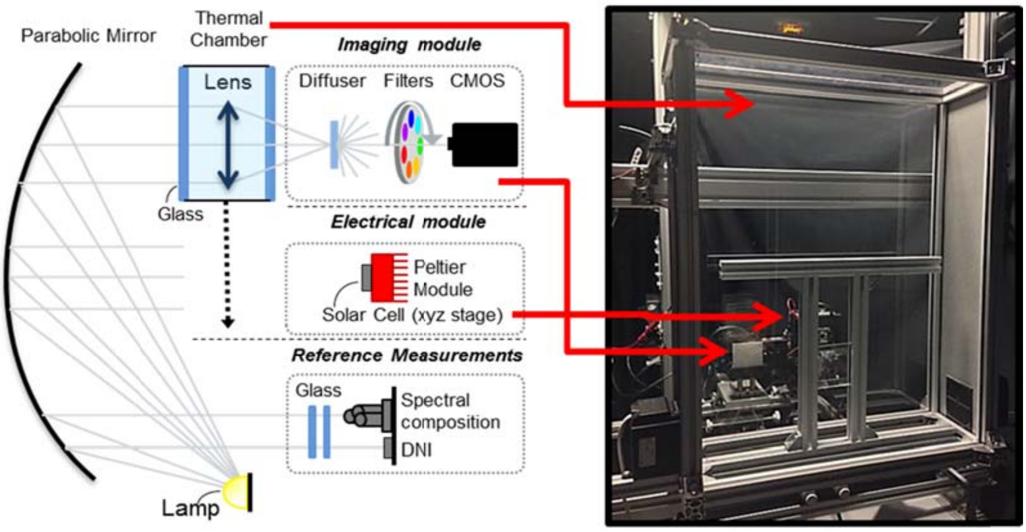


FIGURE 8. Schematic of the instrumentation used in the METHOD test bench.

Further characterization work was carried out by RSE, who performed a deep characterization of the mirrors developed by ASSE in terms of mirror thickness, curvature and incidence angles of the impinging radiation. It was demonstrated that the moulding process (pressure effect on the mirror surface) does not affect the mirror performances. However, it was noticed that for the curved mirrors the reflectivity of the mirrors tends to increase with the surface curvature.

Moreover, the IEC TC82 WG7 was continuously supported in respect to power rating of CPV modules by several partners of the consortium. The power rating draft IEC 62670-2 is expected to become a full standard until the end of the year. Rating procedures under discussion for the draft standard were tested on data of three CPV round robin activities performed in the past years [12].

WP6: Life-Cycle Assessment

The objective of this work package is to carry out a life-cycle and environmental assessment of new multi-junction cells and HCPV modules. This work package is coordinated by CYCLECO and includes Fraunhofer ISE, AZUR SPACE, ASSE and AIXTRON.

The Life-Cycle Assessment started by describing the system under study for the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) that will be used in CPVMatch. The objective is to have a common vision of the system to realize a complete environmental study with the aim to reduce the environmental impacts, the energy consumption and the related costs. This resulted in a general process flow chart (Fig. 9). Based on this system description, a questionnaire to collect qualitative data about the system has been developed to obtain data from the partners. This initial screening will employ the methodology for the specific material and process developed in CPVMatch and will be continuously refined during the project.

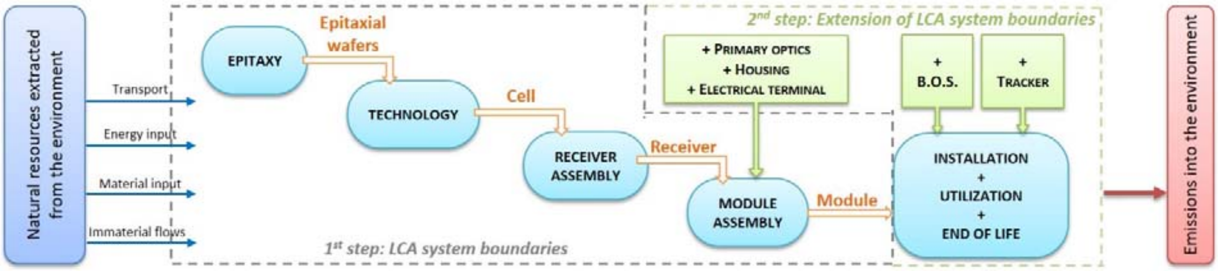


FIGURE 9. Schematic of the LCA system boundaries (2 approaches will be realized during the project).

CONCLUSION

CPVMatch brings together leading European partners in the field of CPV. Following two parallel, but strongly interlinked routes in the development of multi-junction solar cells and CPV modules it is expected that the project will bring practical efficiencies closer to theoretical limits by reaching 48% at the cell level and 40% at the module level under high concentrations beyond 800x. The first project year has been successful. All project partners have a high motivation to collaborate and to achieve high-level scientific results. Scientific results have already been achieved, which is also underlined by two journal papers and nine conference papers submitted in the first project year.

ACKNOWLEDGMENTS

This work has received funding from the European Union's Horizon 2020 research and innovation programme within the project CPVMatch under grant agreement No 640873. The authors are solely responsible for the content of this work and it only reflects the author's view. The European Commission or any of their agencies are not responsible for any use that may be made of the information it contains.

REFERENCES

1. R. King, A. Boca, W. Hong, et al., Band-gap-engineered architectures for high-efficiency multijunction concentrator solar cells, Proceedings of 24th European Photovoltaic Solar Energy Conference and Exhibition, 2009, Hamburg, Germany, pp. 55-61.
2. W. Guter, J. Schöne, S.P. Philipps, et al., Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight **94**, 223504-6 (2009).
3. K. Sasaki, T. Agui, K. Nakaido, et al., Development of InGaP/GaAs/InGaAs inverted triple junction concentrator solar cells, Proceedings of 9th International Conference on Concentrator Photovoltaic Systems, 2013, Miyazaki, Japan, pp. 22-5.

4. V. Sabnis, H. Yuen and M. Wiemer, High-efficiency multijunction solar cells employing dilute nitrides, Proceedings of 8th International Conference on Concentrating Photovoltaic Systems, 2012, Toledo, Spain, pp. 14-9.
5. J.F. Geisz, A. Duda, R.M. France, et al., Optimization of 3-junction inverted metamorphic solar cells for high-temperature and high-concentration operation, Proceedings of 8th International Conference on Concentrating Photovoltaic Systems, 2012, Toledo, Spain, pp. 44-8.
6. F. Dimroth, M. Grave, P. Beutel, et al., Wafer bonded four-junction GaInP/GaAs//GaInAsP/GaInAs concentrator solar cells with 44.7% efficiency **22**, 277-82 (2014).
7. R.M. France, J.F. Geisz, I. Garcıa, et al., Quadruple-Junction Inverted Metamorphic Concentrator Devices **5**, 432-437 (2015).
8. M.A. Green, K. Emery, Y. Hishikawa, et al., Solar cell efficiency tables (version 47) **24**, 3-11 (2016).
9. F. Dimroth, T.N.D. Tibbits, M. Niemeyer, et al., Four-Junction Wafer-Bonded Concentrator Solar Cells **6**, 343-349 (2016).
10. RSE SpA. *APOLLON (Multi-APprOach for high efficiency integrated and inteLLigent cONcentrating PV modules (Systems))*. Available from: http://cordis.europa.eu/result/rcn/55852_en.html (2014).
11. P. Besson, P.M. White, C. Dominguez, et al., Spectrally-resolved measurement of concentrated light distributions for Fresnel lens concentrators **24**, A397-A407 (2016).
12. M. Steiner, G. Siefer, M. Baudrit, et al., Rating of CPV Modules: Results of Module Round Robins, Proceedings of 12th International Conference on Concentrator Photovoltaics, 2016, Freiburg, Germany, pp. to be published.