CPVMATCH - CONCENTRATING PHOTOVOLTAIC MODULES USING ADVANCED TECHNOLOGIES AND CELLS FOR HIGHEST EFFICIENCIES

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ABSTRACT: This paper presents the project *Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies* (CPVMatch), which has received funding from the European Union's Horizon 2020 research and innovation program. The aim of CPVMatch is to bring practical performance of HCPV closer to its theoretical limits with research and development in the field of III-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. 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 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 solar cells and HCPV modules complete the work plan of CPVMatch.

1 INTRODUCTION

The EU-funded project *Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies* (CPVMatch) is presented here. The collaborative project started in May 2015 with a duration of three and a half years and an EC contribution of 4.95 M€. The consortium consists of four research institutions (Fraunhofer ISE, RSE, CEA, Tecnalia), one University (UPM), two industry partners (AZUR Space Solar Power, AIXTRON) and two SMEs (ASSE, Cycleco) and is coordinated by Fraunhofer ISE. The consortium addresses in their research all topics required to manufacture highly-efficient CPV modules. This includes material issues, manufacturing and equipment aspect and production challenges. University and research institutes are working in close co-operation with industry partners in order to ensure fast industrial exploitation of all results within the whole value chain (see Fig. 1).

The overall aim of this project 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 above 800x with an efficiency of 48% and 40%, respectively, with a low environmental impact.

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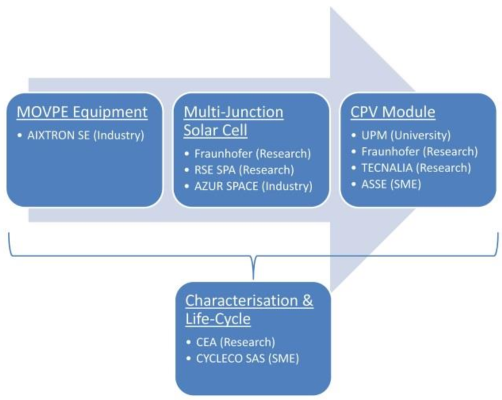


(b)

Figure 1: Partners of CPVMatch (a). Alignment of the CPVMatch partners along the value chain (b)

2 CONCEPT AND OBJECTIVES OF THE PROJECT

The aim of CPVMatch is to bring practical performance of HCPV closer to its theoretical limits. 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 following gives a short overview on the approach of the scientific work of the project. Note that the description is not necessarily comprehensive and does not present all details.

2.1 Solar cell development

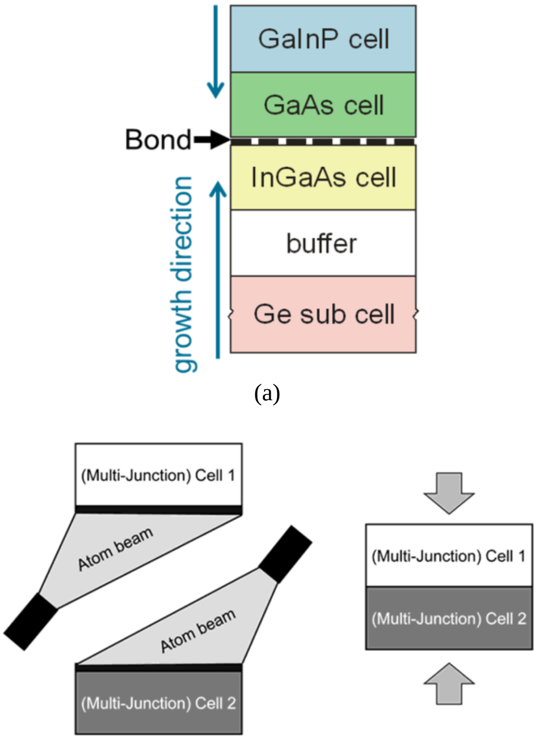
The current landmark for III-V multi-junction solar cells is the $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell, which only contains lattice-matched layers. Hence all materials have the same lattice constant. This “standard” triple-junction on a Ge substrate suffers from poor current matching under the solar spectrum, leading to a limited efficiency potential. A record efficiency of 41.6% (364xAM1.5d) was achieved in 2009 [1] and currently this device is commercially available with efficiencies around 40% under concentrated sunlight. 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. Recently, a four-junction solar cell with an efficiency of 46.0% at a concentration of 508 suns has been achieved [2]. In CPVMatch two different bandgap engineering approaches for four-junction solar cells are followed:

- the first one concerns cutting edge multi-junction solar cell technologies, namely a combination of the metamorphic growth and wafer bonding to create multi-junction solar cells, which can be considered the latest, most advanced stage of development related to multi-junction solar cells
- the second one concerns frontier multi-junction solar cell technologies, 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.

2.1.1 Cutting edge multi-junction technologies: metamorphic growth combined with wafer bonding

Lattice-matching strongly restricts the range of materials which can be used and thus limits possible bandgap combinations. Therefore, the concept of metamorphic growth has been developed. Here, materials with different lattice constants are grown on top of each other, widening the range of available bandgaps. However, metamorphic growth is challenging since the change in the lattice constant introduces defects and strain. Therefore, very specially designed buffer structures are necessary. Fraunhofer demonstrated the successful application of the metamorphic approach in 2009 by achieving a world record efficiency of 40.7% (454xAM1.5d) [3]. A similar structure is now available on the market, provided by AZUR SPACE.

In CPVMatch, the metamorphic approach is further implemented and used for the first time to realize the optimal four-junction solar cell with the combination GaInP/GaAs//GaInAs/Ge (Fig. 2 (a)). This structure requires metamorphic growth technology as a buffer between the Ge and the GaInAs subcell for increasing the lattice constant is required. A major challenge of this structure is that the lattice-constant of GaInAs is significantly larger compared to GaInP and GaAs. Realizing this structure in a monolithic metamorphic approach is extremely challenging and would require a second buffer between the GaInAs and the GaAs subcell to decrease the lattice constant.



(a)

(b)

Figure 2: (a) Concept of a four-junction GaInP/GaAs//GaInAs/Ge solar cell using wafer bonding to combine two independently grown dual-junction solar cells. The upper two subcells are grown in inverse direction. (b) Schematic illustration of Fast Atom Beam Activated Wafer Bonding. Before the actual bonding of the two (dual-junction) solar cells their surfaces are cleaned with atom beams in order to allow for a bond interface with low resistance and high mechanical stability.

Therefore another option, which is investigated in CPVMatch, is to use the advanced post-growth technology, wafer bonding (Fig. 2 (b)), to combine an inversely grown, lattice-matched GaInP/GaAs dual-junction solar cell with an upright, metamorphic GaInAs/Ge dual-junction solar cell. During the bonding process the cell stacks are pressed together without the requirement of monolithical growth of the complete structure. Using this technology, a four-junction solar cell with a record efficiency of 46.0% under 508xAM1.5d has recently been achieved by a partner of the consortium (Fraunhofer) [2]. With respect to the cited record device, the proposed multi-junction structure to be developed in CPVMatch has the obvious advantage of using cheaper substrates and materials, which are more abundantly available in nature. This new four-junction solar cell can be industrialised much faster since it is based on material compositions which are more equal to the current industrial standard. One of the key issues will be to develop a reliable wafer bonding process.

2.1.2 Frontier multi-junction solar cell technologies with lattice-matched approach

Conversely to the presented cutting edge multi-junction solar cells technologies, in which metamorphic materials are exploited to increase the solar cell efficiency value, the frontier multi-junction solar cell technologies proposed in CPVMatch are based on the lattice-matched approach by adopting new materials in order to enlarge the band gap engineering possibilities and then increase the solar device performances. Theoretical calculations show that a 1.0 eV subcell placed in between the $Ga_{0.99}In_{0.01}As$ middle cell and the Ge bottom cell of the standard lattice-matched triple-junction solar cell would lead to a nearly optimal four-junction device. Yet, the realization of such a 1.0 eV material in a lattice-matched configuration is challenging. The promising and thoroughly investigated candidate GaInNAs, e.g. with 7% In and 2% N, suffers from a low minority carrier diffusion length if the material is grown in MOVPE reactors [4]. A promising and novel material alternative to dilute nitrides is the pseudo binary $Ge_{1-x}(Si_{0.8}Sn_{0.2})_x$. A unique feature of these ternary alloys is the possibility of changing compositions while keeping the lattice parameter at a constant value. In particular by increasing the share of Si and Sn – with constant 4:1 ratio – in the Ge matrix, the bandgap of the alloy can be tuned between 0.8 eV and 1.4 eV [5], while maintaining lattice-match to Ge (Fig. 3).

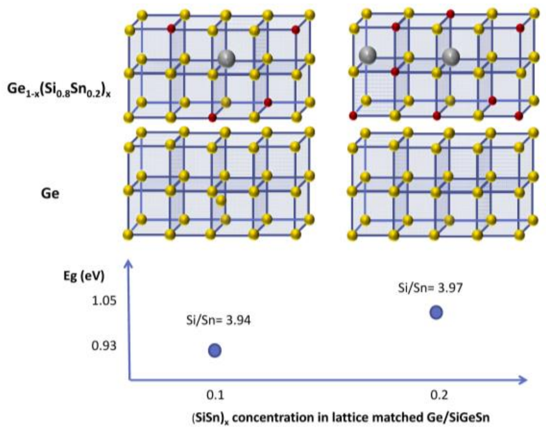


Figure 3: Simplified representation of the crystalline structure of Ge and SiGeSn and of the compositional tuning concept for Ge-rich SiGeSn alloys latticed matched to Ge (yellow circles), in which a ratio of Si (red spheres) to Sn (large grey spheres) of 4 is almost maintained. The plots below illustrate the corresponding increase in bandgap associated with the addition of Si and Sn, while almost preserving the 4:1 ratio.

The central technical challenge for realizing multi-junction solar cells at low cost with this advanced material lies in the growth of III-V with IV elements in the same MOVPE growth chamber. The proof-of-concept has already been demonstrated in the MOVPE growth chamber installed at RSE SPA by growing SiGe and III-V elements [6]. This result brought the partners of the consortium in an outstanding position in the roadmap toward the realization of four-junction GaInP/Ga(In)As/ SiGeSn/Ge solar cells, with an ideal energy gap combination of 1.9 eV/1.4 eV/1 eV/0.7 eV. Therefore, starting from the proof of concept demonstrated on SiGe, a novel design of the MOVPE growth chamber is being developed in CPVMatch in order to widen the utilization of IV elements (including Sn) and to reduce the cross over effects between group IV and III-V elements. The target structure for high efficiencies is a GaInP/GaInAs/SiGeSn/Ge four-junction solar cell. After the successful investigation of the advanced material SiGeSn, single and dual-junction SiGeSn/Ge and GaAs/SiGeSn solar cells will be developed. These devices will be overgrown by GaInP/(GaInAs) to form triple and four-junction solar cells with high efficiency potential.

2.1.3 Nanostructured coatings

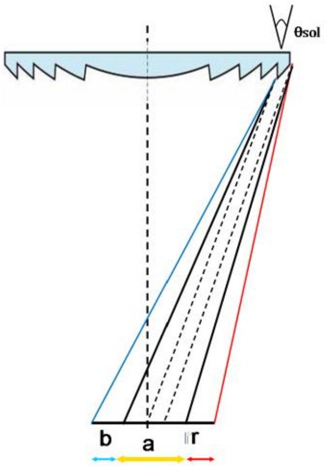
Incomplete light trapping is another challenge to be faced in order to increase solar cell efficiency and bring practical performance close to the theoretical limit. In CPVMatch, new nanostructured coatings are being developed in order to reduce the light reflection from the surface of the solar cell and then increase the light trapping performance in the multi-junction device. Nanostructured coatings have been already demonstrated for different applications [7], and also on III-V-based solar cells [8, 9]. In these last cases, however, the proposed solutions were not applicable for concentrating solar cells. Based on lessons learned thus far, RSE SPA will apply proper deposition techniques, select different materials and planarization processes, in order to develop broadband and omnidirectional nanostructured coating able to work over a wide spectral range and highly performing at different light incident angles, as needed for high concentration multi-junction solar cells. The more challenging solution will be to realize a nanostructure coating composed of a suitable material (stable and transparent), with a refractive index value near to the value presented by the window layer of the multi-junction solar cells, deposited, after a planarization process, on the multi-junction solar cell. In this case, in fact, the nanostructured coating will allow a gradual change of the refractive index from the value of the air to the value of the semiconductor, strongly minimizing the light reflection. If this first challenging solution does not give rise to the expected improvement, a hybrid nanostructured coating-multilayer film solution will be investigated, in which the nanostructured coating will be deposited over a proper planarization layer and a subsequent multilayer film.

2.2 HCPV module development

The efficiency of III-V multi-junction solar cells is about twice as high as conventional Silicon or thin-film solar cells. However, multi-junction solar cells are currently too expensive for the use in flat-plate modules on Earth. Hence, the development of high concentrating photovoltaic (HCPV) systems with concentration factors above 300 was essential to introduce III-V multi-junction solar cells to the terrestrial market. The use of cost-efficient concentrating optics reduces the need for expensive cell area, which allows competitive levelised cost of energy (LCOE). However, it is a big challenge to realize low cost optics with high optical efficiency and at concentration levels above 800x. Based on the long-standing experience provided by the partners of this project, two promising approaches will be followed: one is based on Fresnel optics and the other one on mirror optics.

2.2.1 The Fresnel optics concept

The CPV industry mainly uses Fresnel lens-based optics, primarily because they greatly simplify the internal architecture of CPV modules, and additionally because they can be manufactured in "parquets" composed of many lenses. However, the standard Fresnel lenses exhibit chromatic aberration due to the variation of the refractive index with the wavelength of light (Fig. 4 (a)). This aberration spreads out the rays, leading to an extended "spot" at the focus, which limits the maximum attainable concentration factor of any given lens. The result is that these lenses can only achieve concentrations of between 100x (with absolutely no chromatic losses) and 350x (with limited losses).



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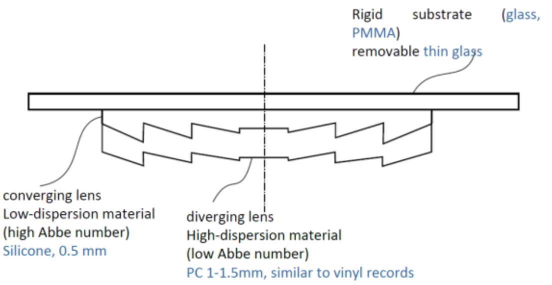


(b)

Figure 4: (a) The sketch illustrates how chromatic aberration (CA) requests larger receivers (b+a+r) for capturing all rays. Avoiding CA the cell receiver could be significantly smaller ("a"). Thus the product "Concentration X Acceptance Angle" increases by a factor between 3 and 4. (b) Proposed achromatic Fresnel lens structure and processing, which could directly replace conventional Fresnel lenses in CPV modules.

In this project a novel low-cost solution for an achromatic Fresnel lens working at high concentration (800x) (patent pending) will be developed. These achromatic lenses (Fig. 4 (b)), which could directly replace conventional Fresnel lenses, have a hybrid configuration that corrects, in large part, the ray deviation caused by chromatic aberration and thereby increases the achievable concentration to around 800x. Achromatic lenses have been used in photographic cameras and other "expensive" optics for decades. The significant novel aspect in this project is the development of a viable method to produce achromatic Fresnel lenses that meets the requirements of solar energy: large area, small f-number, high concentration and most importantly, low cost. In order to reduce the reflection losses caused by the difference in refractive indexes between air and lens materials, Anti-reflective (AR) coatings are being developed and applied to the Fresnel lenses. Anti-reflective (AR) coatings provide not only a way to reduce losses but also can ensure long-term durability against atmospheric conditions and cleaning processes.

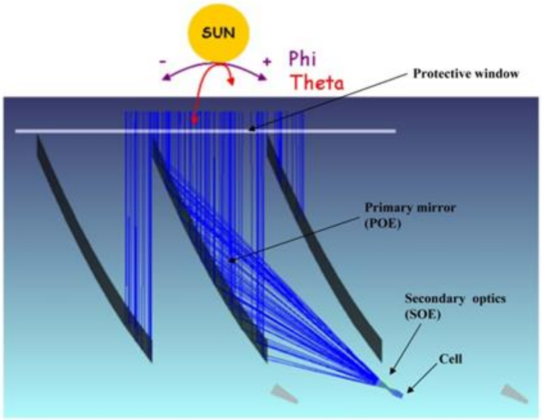
The specific objective of this development within the project is to perform detailed designs and analysis, as well as to identify the best materials and techniques for obtaining and validating various prototypes of achromatic Fresnel lenses. The new lenses will be integrated into FLATCON®-type modules, a module technology developed at Fraunhofer [10]. It must be emphasized that the absence of a secondary optical elements (SOE) in the module not only reduces costs but promises increased reliability, less degradation and failure rate. The achromatic improvement is a step in the way of these developments that tries to improve the most proven technologies beyond the already demonstrated performance.

2.2.2 The mirror-based optics concept

Another solution to circumvent the issue of chromatic aberration is to use mirror-based optics. Fig. 5 shows one possible concept for such optics as well as a prototype, which was developed in the EU-project APOLLON (involving four partners of CPVMatch: RSE SPA, AIXTRON SE, TECNALIA and ASSE) [11]. The experimental proof-of-concept of the off-axis mirror-based concentrator has been demonstrated. Such a solution allows working at higher concentration levels around 850x. The major benefits of the proposed mirror-based configuration are the following:

- no central obstruction is present at the input aperture of the concentrator, so better optical and collection efficiency can be achieved, in comparison with other mirror based design;
- the light impinges on the mirrors with high incident angles thus improving the reflection (optical) efficiency;
- the PV cell is located in the cooler position of the concentrator which is not illuminated by the sun; this position also allows a possible replacement of the photovoltaic cell, which will make O&M tasks easier in case receiver replacement is needed, and could also be used for a product update, e.g. in case the PV cell efficiency is improving significantly along the whole lifetime.

Within CPVMatch the lessons learned from the first proof-of-concept must be materialized and validated in the lab and in the relevant environment. In particular the mirror-based smart module design will be innovated with the main goal to improve performances in standard and operative conditions at a competitive cost. This includes new solutions for the thermal management, mirror design and manufacturing. The thermal path is being optimized by using new receiver technologies. In particular the feasibility of the Chip-on-Flex and the Chip-on-Metal technology is being investigated. Moreover, electrical contacts with low resistance and high maintainability are being developed. As the optical efficiency of the mirror is strictly related to the mirror form error, adequate material and appropriate mirror dimension are being assessed.



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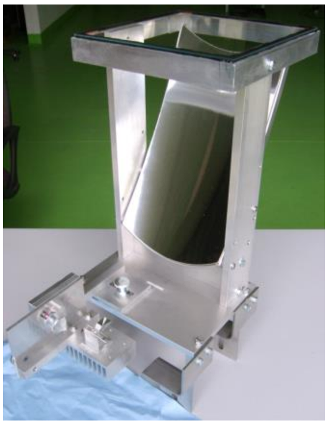

(b)

Figure 5: (a) Concept of a mirror-based concentrator using off-axis primary optical elements (POE) and secondary optical elements (SOE). (b) Prototype of such an off-axis module developed in the EU-funded APOLLON project.

From the optical point of view, the downscaling of the optic can be performed because the optical components work far from their diffraction limits. Possible limitations related to the manufacturing and mounting precision of the optical components are being defined and considered. The low-cost aim is being pursued throughout several research activities comprising: the selection of cheaper and reliable material, the assessment of the downscaling of the module and the implementation of the smart module design with low cost module integrated point sensitive detectors (PSD) and DC/DC converters. The two main targets for the latter are a cost level of 0.2 €/W_p and a 98% peak efficiency. The smart module mirror-based design also supplies an innovative answer for operating at higher conversion efficiency, since better and reliable tracking accuracies are reached (by the innovative module integrated PSD unit) and power mismatches losses are reduced (by the module integrated DC/DC devices). The module low cost objective is intended not only for the prototype stage, but also towards a future industrial stage, meaning that the laboratory prototype will be designed in such a way that future industrialization aspects are already analyzed and included (advanced manufacturing).

2.3 Characterisation and Testing

The development of novel solar cells and CPV modules needs to be supported by in depth testing and characterization. The main objective is to assess the developments realized throughout the project by means of adapted characterization methods with a special focus on: the analysis of advanced materials developed in the project, the development of adapted tools for the characterization of the multi-junction solar cells and subcells, the development of adapted tools for the characterization of the different optics, the indoor and outdoor testing of the CPV modules.

The different partners are working to adapt their equipment and then compare the results and methods in order to give a relevant feedback on how these future generations of solar cells need to be characterized. In particular the use of four-junction solar cells requires adoption of the measurement tools with respect to the particularities of each subcell material and the higher number of junctions in the device.

Part of this project is focused on the development of HCPV optics and modules. New characterization equipment is being developed for them. In particular, an imaging system is being set-up which is able to quantify the uniformity of the spot light at the cell plane for different ranges of wavelength. This information will help to quantify the losses at the module level implied by the optics and then to give some hint for the redesign of it in order to achieve the maximum module efficiency. Second, equipment is being developed to measure the exact spectra at both the cell and optical plane. The spectral transmission of the lens must be quantified to validate the lens design. This will give information about the matching of the optical transmission spectra to the cell absorption spectra, providing information to better adapt them to each other (i.e. tune design to maximize the overall performance at the module level).

Finally, CEA adopts a prototyping tool able to measure samples of single optics and cells at difference irradiances and geometrical configurations. This tool is being improved in order to measure the performances of single lens / cell coupling at different temperatures, irradiances and spectra in order to optimize the geometrical configuration and to understand what module optical designs will provide the best results at concentrator standard testing conditions (CSTC) conditions. This tool will also give some hint on how to improve the lens/cell coupling and will be used recursively during the project. Finally, the developed module will be measured indoors and outdoors at different partner's sites in order to share the results and ensure a more reliable performance analysis.

2.4 Life-Cycle Assessment

Life Cycle Assessment (LCA) has proven to be a useful tool for environmental impacts assessment in the energy sector [12]. LCA is more and more largely used due to the availability of consensual standards and guidelines such as the ISO 14040-44 (ISO, 2006) and now ILCD handbook (ILCD, 2010). The method is divided into two steps: the environmental screening and a detailed life cycle assessment. The environmental screening is used to identify hotspots and prioritize ecodesign routes. The detailed LCA is used to validate the overall findings and share the results with all stakeholders.

Within CPVMatch a profound LCA study is being carried out to evaluate the environmental impact of the developed multi-junction solar cells and CPV modules. The Life Cycle Assessment is being used to optimize the entirety of the product environmental characteristics and servers as a decision-making tool at the product (re)conception step. The study takes into account raw materials extraction and transformation, production processes, transport, distribution, end product use and reuse, recycling and eventually disposal steps. Currently, inputs and outputs linked to the life cycle are being identified and quantified and their potential environmental impacts are being evaluated. The LCA is an iterative process and the hypothesis will be constantly rethought during CPVMatch depending on new developments and information.

3 CONCLUSION

CPVMatch is an ambitious project, which brings together leading European partners in the field of CPV. All project partners have a high motivation to collaborate and to achieve high-level scientific results, in particular against the background of the current industrial crisis of CPV, which makes technical innovation even more important. 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.

4 ACKNOWLEDGMENTS

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