HIGHLIGHTS FROM THE FP7 PROJECT ON PHOTOVOLTAICS CHEETAH: MORE POWER WITH LESS MATERIAL

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ABSTRACT. CHEETAH is an FP7 integrated research project on photovoltaics funded by the European Commission and was initiated by EERA PV. This project is structured into two type of activities: Coordinative and Support actions (CSA) and Joint Research activities (JRA). The CSA focuses on the creation of a long term collaborative platform by developing tools for knowledge sharing, e-learning platforms for training and education, mobility between researchers, efficient use of infrastructures and promoting best practices and standards. The JRA focuses on developing new concepts and technologies for wafer-based crystalline silicon PV (modules with thin cells < 100 micron), thin-film PV (advanced light management) and organic PV (very low-cost barriers), resulting in reduced cost of environmentally benign/abundant/non-toxic materials and increased module performance. This paper gives a summary of the main achievements of this project for the two categories of activities.

Keywords: Cost reduction, PV materials, Education and training

1 INTRODUCTION

CHEETAH (Acronym for *Cost-reduction through material optimisation and Higher EnErgy outpuT of solAr pHotovoltaic modules - joining Europe's Research and Development efforts in support of its PV industry*) [1] is a 4 year combined collaborative project and coordination and support action funded under the European Commission's 7th Framework programme and runs since January 2014. The project consortium consists of 34 partners from research institutes and universities.

CHEETAH's aim is to solve specific R&D issues in coherence with the EERA-PV Joint Program and SET plan, to overcome fragmentation of European PV R&D in Europe and intensify the collaboration between R&D providers and industry to accelerate the industrialization of innovations.

The main objectives in this project are threefold:

- **More power with less materials**: developing new concepts and technologies for wafer-based crystalline silicon PV (modules with thin cells < 100 micron), thin-film PV (advanced light management) and organic PV (very low-cost barriers), resulting in (strongly) reduced cost of environmentally benign/abundant/non-toxic materials and increased module performance.
- **Fostering long-term European cooperation in the PV R&D sector**, by sharing knowledge, organizing workshops, exchange and training researchers inside and outside Europe, efficient use of infrastructures, promoting best practices and standards
- **Accelerating the implementation of innovative technologies in the PV industry** by the involvement of Solar Power Europe and EIT InnoEnergy in this program.

This paper will describe the consortium (in section 2) and the main achievements of the project which are divided into two main categories: coordinative and supportive actions, and Joint Research activities (in section 3). Some concluding remarks and perspectives of the results of this integrated research project are given in Section 4.

2 DESCRIPTION OF THE CONSORTIUM

The CHEETAH project brings together a consortium of 34 partners spread around Europa, consisting of 31 research centers (universities and research institutes) of excellence in PV R&D, complemented by Solar Power Europe (formely known as EPIA) and Innoenergy (formerly known as KIC Innoenergy) as the associations with the aim to shape the regulatory environment and enhance business opportunities for solar power in Europe and consultancy company Ayming for project management support (see Figure 1 and appendix).

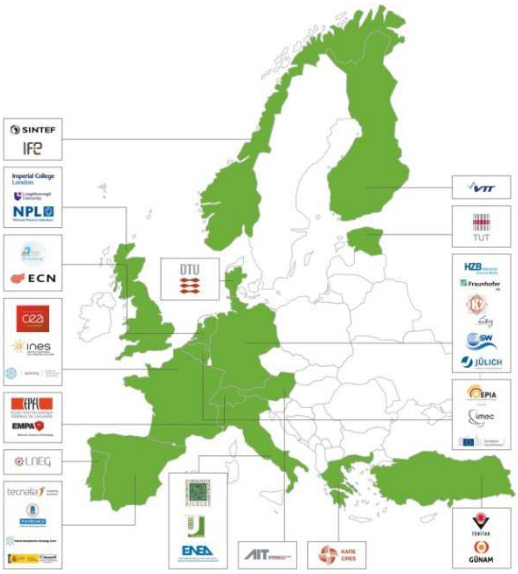


Figure 1. Geographical spreading of the 34 CHEETAH consortium members

3 DESCRIPTION OF THE PROJECT

The CHEETAH project is structured around two blocks of activities:

- **Coordination activities (CSA)**: developing the basis for long-term research and giving access to the knowledge to researchers and industry (WP2-5)
- **Joint research activities (JRA)**: improving the services provided and fill in the gaps: more power with less materials (WP6-10)

A Pert diagram of the project structure of CHEETAH is shown in Figure 2.

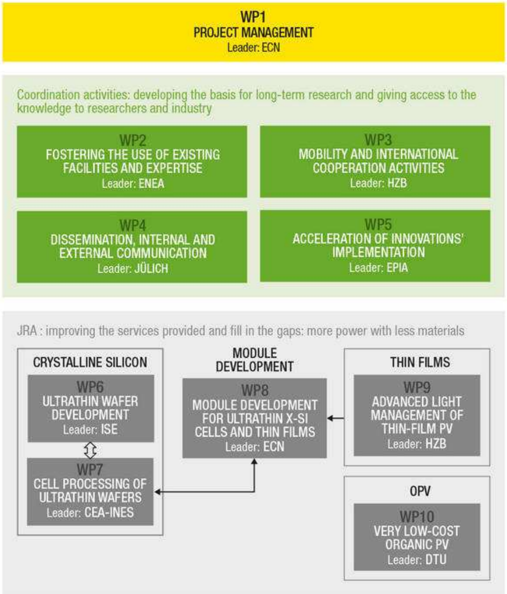


Figure 2. Pert diagram of the CHEETAH workpackage structure

In the following subsections 3.1 and 3.2 the main highlights of the achievement within the CSA and JRA activities will be presented.

3.1 Coordination (CSA) activities

The main aim of these cluster of coordination activities was to create a framework for cooperation by creating tools for knowledge exchange like a web-based knowledge exchange area portal, e-learning platform available for training courses, workshop lectures, as well to organize mobility actions by organizing research exchanges within the consortium for training and educational purposes of student and young researchers.

Some examples of important achievements within this coordinative cluster are listed in subsections 3.1.1 and 3.1.2.

3.1.1 Cheetah knowledge exchange web area portal

The CHEETAH Knowledge Exchange Web Area Portal (KEAP) is an online information source to promote knowledge exchange among experts and trainees on photovoltaic (PV) solar energy research in Europe. It is developed in the context of CHEETAH and open to non-CHEETAH partners and the wider photovoltaic community and is accessible via www.cheetahexchange.eu. KEAP supports cooperation among the CHEETAH partners and within the broader PV research community in Europe by facilitating knowledge and information sharing, identifying technical and scientific needs and making available a wide range of information on expertise, infrastructures, equipment and PV technologies.

This portal improves the state-of-the art of knowledge exchange thanks to a dynamic database, a powerful build-in search engine and a dedicated e-learning platform for on-line meetings with internal and external stakeholders, webinars, on-line tests and experiments. A lot has been done to improve the accessibility and impact of KEAP by advertising via all public channels (youTube. Linkedin, ResearchGate, Twitter, etc). KEAP counts 33 CHEETAH and 13 non CHEETAH corporate descriptions, 205 expert and 45 infrastructure profiles of both CHEETAH and non-CHEETAH organizations. 46 webinars have been organized since January 2014 by the platform with more than 1010 registered users, 930 “live” participants and hundreds accessing via streaming.

3.1.2 Joint support actions

As a continuation of the Round Robin trials, organized within the FP7 Sophia project, a number of Round Robin and inter comparison campaigns have been initiated in CHEETAH. They focused on characterization of thin film Silicon based tandem cells and perovskite cells with the aim to test and validate measurement protocols and research infrastructure. The outcomes of these campaigns are best practice documents that will be used as input for new pre-normative test protocols and standards. These documents will be shared and disseminated *via* peer reviewed papers and/or the KEAP.

3.2 Joint research (JRA) activities

In the current PV landscape, the PV market is dominated (>90 %) by crystalline Silicon (x-Si) PV and very strong cost driven inhibiting adoption of novel innovations. Thin film PV like CIGS has a much lower market share (< 10 %) but possesses a very low cost potential and able to compete with x-Si if module efficiencies are comparable. Emerging technologies like Perovskite/Organic PV could widen applicability of PV by introducing new assets like flexibility, free-form and colour.

For the three mentioned PV technologies, costs are highly dominated by the materials, i.e. for x-Si the wafer, for thin films the semiconductor like including indium, which is present in CIGS and some TCO’s (ITO) and for emerging technologies the encapsulation. These were selected as the drivers for the JRA carried out within CHEETAH. A few illustrations of the progress that has been made in CHEETAH are shown in the following subsections.

3.2.1 Cost reduction strategy in Wafer-based crystalline Si

The JRA activities were organized as follows:

1. Fabricate (ultra)thin wafers by
   - Epitaxial growth `kerf free` (EPI) foils ranging from 40-80 micron
   - Wire sawn wafers (high TRL) chemically thinned down to 80 micron
2. Development of a process for the fabrication of advanced solar cells and modules

Develop new technology bricks for ultra-thin wafers (40 µm)

- **front side textures** → optical light trapping, Jsc improvement
- **High surface passivation level** → Voc improvement
- **Advanced metallization** → low breakage rate, Jsc and FF improvement
- **Develop and/or redesign industrially compatible cell and module fabrication processes** for thin cells
    - Maximize yield, maintain performance

Fabrication of kerf free EPI foils from 40-80 micron

Processes were developed to prepare release layers, epitaxially thicken the Si foil and release layer resulting in thin epitaxially (EPI) grown Si wafers varying in thickness from 40 up to 80 µm featuring electronic and mechanical properties to allow for >20% solar cells. For the epitaxial thickening and layer release the standard foil size increased from 5 x 5 cm^2 to 12.5 x 12.5cm^2 and several batches of 40 µm foils were made for cell processing with good detachment yield and lifetimes up to 100 µs on average.

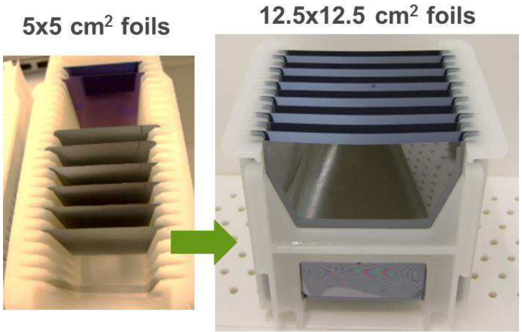
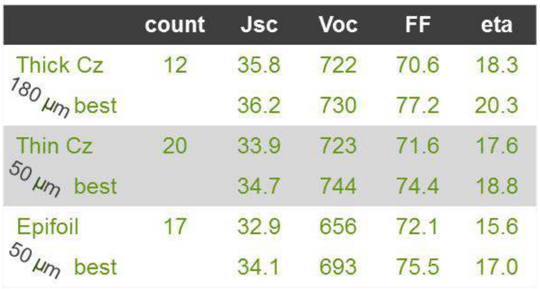


Figure 3. Change in foil size from 25 to 156.25 cm^2

Cell processing of ultra-thin EPI-wafers

Table I shows the I-V characteristics of a successful heterojunction (SHJ) cell process integration run performed on 50µm 125x125 mm^2 Epifoils (4x4 cm^2 cells) compared to Cz based 50 and 180µm SHJ cell processed in the same run. Optimized efficiencies up to 17 % were achieved, with further room for improvement for all the I-V parameters.

Table I. J-V characteristics for SHJ cells on thin, thick Cz wafers and thin EPI foils (*data courtesy imec*)



	count	Jsc	Voc	FF	eta
Thick Cz	12	35.8	722	70.6	18.3
180 µm best		36.2	730	77.2	20.3
Thin Cz	20	33.9	723	71.6	17.6
50 µm best		34.7	744	74.4	18.8
Epifoil	17	32.9	656	72.1	15.6
50 µm best		34.1	693	75.5	17.0

Cell processing of thin wire sawn wafers

Heterojunction (HJ) cells down to 80 µm were manufactured using the semi-industrial pilot line in automatic mode with minor process adjustments and low breakage rates compared to standard thickness. A maximum efficiency of **22 %** has been achieved to date for a ~90 µm four busbar bifacial SHJ cell. Wafers were all chemically thinned from 160-180µm commercially available sawn wafers. Complementary tests were also conducted on 120µm sawn wafers provided by CHEETAH partner SINTEF demonstrating further the compatibility of the industrialization line with such thin incoming wafers.

In addition, Interdigitated Back Contact (IBC) cells down to 80 µm were processed using a pre-pilot process flow starting from the same batch of 120 µm sawn wafers. Both cell types (SHJ and IBC) were used as input for module integration for which different interconnection technologies are used as is illustrated in the next paragraphs.

Cell integration into modules

Functional mini (4 cells) IBC and full sized (60 cells) HJ modules based on cells between 80 and 100 µm were successfully fabricated.

Figure 4 shows an IBC mini module (left) and an EL image (middle) revealing no cell breakage/cracks and FF > 74 %. The modules are manufactured in a mini-pilot line using foil based interconnection technology where cells are contacted to a conductive back sheet via electrically conductive adhesives [5]. The right picture demonstrates feasibility of cell handling down to 80 µm via pick an place using industrial module equipment.

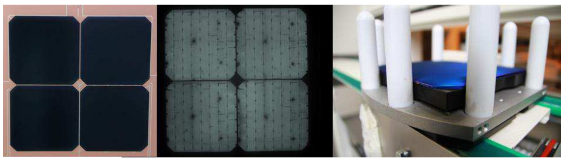


Figure 4. Left: an IBC mini module manufactured at ECN; centre: an EL image and right: industrial equipment showing feasibility of handling thin wafers

In addition, three 60 cells SHJ modules were fabricated, using standard glass, conductive glue, encapsulant and lamination process. A set of 93µm record SHJ cells were integrated in a 60-cell glass/backsheet and glass/glass module configuration, leading to very promising final module output power of 313Wp (cell to module power ratio – CTM - of 99% and 0.98Wp per g Si) and 297Wp (CTM of 96%) respectively, without specific breakage observed after PL inspection. This demonstrates the full compatibility of thin wafers with current module configuration.

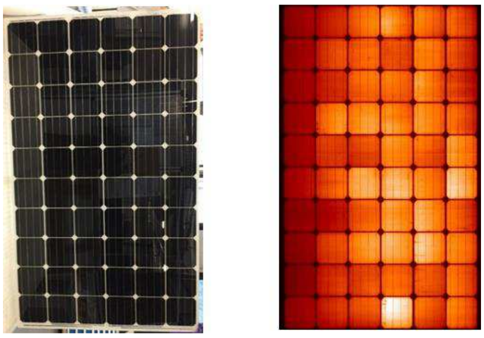


Figure 5. A first 60 cell HJ module + EL image, with HJ 4 bus bar cells (HJ) having an average thickness of 93µm (from 86 to 99µm), manufactured at CEA-INES.

3.2.2 Cost reduction strategy in thin film PV

The main driver for the JRA activities on thin film PV was to achieve higher efficiencies of thin-film solar cells (thin film Si, Cu(In,Ga)(S,Se)$_2$ and Kesterites) with less solar cell base materials by enhancing todays maximum efficiency using light management strategies and an envisaged cost reduction of 20 %. Moreover, the supply risks of In and Ga were simultaneously addressed for Cu(In,Ga)(S,Se)$_2$ cells. The consortium worked on two innovative approaches:

Light management strategies for thin film Silicon produced by liquid phase crystallization

Light management strategies like nano-patterning/-structuring of thin film silicon cells that are prepared via liquid phase crystallization or by introducing grating structures are applied to improve the optical absorption of the solar cell absorber without any electrical losses of the device. Work is in progress to reach efficiencies of ≥ 15% in the project with the ultimate goal to reach the potential of competitive efficiencies > 20%.

Micro concentrator approach

The approach is based on restriction of absorber material to a few ten to hundred microns diameter and use concentrated sunlight by a factor of 50 - 500 onto absorbers to compensate for the loss in light absorption.

In a top-down proof of concept study, close to 30% relative efficiency increase was achieved by light concentration onto planar CIGS solar cells of sub-mm^2 size patterned by lithography [3] and inkjet-printed CIGSSe.

Working CISe micro cells were made using a novel bottom-up approach for local chalcopyrite growth from indium islands. Corresponding millimeter-sized lenses are fabricated from PMMA by a casting process. Finally, an angular splitting concentrator exploiting both direct and diffuse light components by combining chalcopyrite and kesterite absorber material was proposed and are in the early stages of research. A more detailed description of the innovative approaches followed can be found in reference [4].

3.2.3 Cost reduction strategy in materials research for Organic PV

The main aim of the OPV JRA activities is to identify materials and develop device structures which are intrinsically stable towards water and oxygen so that barrier layer requirements can be significantly reduced. This will substantially reduce the costs of flexible OPV since the barrier is considered as one of the most important cost drivers for flexible OPV.

The consortium worked on the approach to establish a link between intrinsic and extrinsic stability of devices and effect of different barrier materials on device lifetime. Large intercomparison lifetime testing campaigns have been executed so far using various device designs and organic polymers. A wide range of active materials has been investigated in the cells with the purpose of improving the intrinsic lifetime of devices. The studies revealed that while the best device architectures could only improve the lifetime of an unprotected device by a factor of 2 to 3, application of a simple PET foil improved the device lifetime by two orders of magnitude. Although the use of ultrabarriers with UV filter could improve the lifetime by another order of magnitude compared to PET, the price for such barriers is too high. Thus, the conclusion of the study was that the best is to focus on developing cheap methods for improving barrier properties of cheap foil materials like PET and adhesives. Currently, deposition of barriers directly onto devices or PET via sputtering methods are investigated.

New organic materials (amongst others a non-fullerene acceptor) were additionally identified that both increased performance and thermal stability.

4 CONCLUDING REMARKS AND OUTLOOK

The technology developments within CHEETAH should lead to the realization of innovative and competitive PV concepts with a significant reduction in cost of materials and increase of the overall performance. These innovative developments should finally lead to a contribution to an accelerated implementation in the European PV industry, so that Europe can regain and build up own manufacturing capacity in all parts of the value chain in due time. In addition, the establishment of an effective collaborative platform for the PV R&D sector established via the CSA activities within CHEETAH will help Europe in realizing these goals.

The short term impact of the various technical achievements in terms of exploitability is not easy to judge in general. An important aim of many JRA in CHEETAH was to prove technical feasibility and bring it to TRL levels up to 7 so that will generate more interest from the industry. The production of thin cells down to 80 micrometer in an industrial environment as well as the technical capabilities to handle thin cells in a module line are examples of CHEETAH results that have the potential to be exploited by industry on a shorter timeframe as soon as silicon becomes more expensive. These are important achievements and demonstrate that we are far ahead of roadmap predictions by for instance ITRPV [6]. Silicon wafer production with Kerf free solutions as investigated in CHEETAH also attracts the attention of start-ups since this can ultimately result in significant cost savings for Silicon. For thin film PV and emerging technologies like Organic and Perovskite PV, the followed approaches within CHEETAH are still in its early infancy and more time is needed to bring these concepts up to higher TRLs(6-7) after which they can be scaled up and truly evaluated for their manufacturability and cost reduction potential.

Despite the fact that the PV industry is again in a consolidation phase and has other priorities at this moment to survive, there is certainly consensus that longer-term innovations like those investigated in CHEETAH are required to further reduce the costs to levels that will make PV a very low cost and competitive electricity source compared to others.

5 REFERENCES

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6 ACKNOWLEDGEMENT

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7 APPENDIX

List of beneficiaries

Nr.	**Short name**	**Country**
1	ECN	Netherlands
2	CEA/INES	France
3	Fraunhofer ISE	Germany
4	DTU	Denmark
5	HZB	Germany
6	FZ Julich	Germany
7	AIT	Austria
8	ENEA	Italy
9	EPFL	Switzerland
10	IFE	Norway
11	IKZ	Germany
12	IMEC	Belgium
13	NPL	United Kingdom
14	SINTEF	Norway
15	Tallinn University	Estonia
16	ZWS	Germany
17	LNEG	Portugal
18	Tor Vergata	Italy
19	METU	Turkey
20	TECNALIA	Spain
21	UPM	Spain
22	CIEMAT	Spain
23	KAPE-CRES	Greece
24	Loughbourough Univ	United Kingdom
25	EMPA	Switzerland
26	Imperial	United Kingdom
27	JRC-EC	Belgium
28	TUBITAK	Turkey
29	VTT	Finland
30	UPVLC	Spain
31	UNIMIB	Italy
32	Solar Power Europe	Belgium
33	Innoenergy	Netherlands
34	Ayming CG	France