Final publishable Project Report

HERCULES – GA N°608498

High **E**fficiency **R**ear **C**ontact solar cells and **U**ltra powerful modu**LES**
THEME [ENERGY.2013.2.1.1 – High efficiency c-Si photovoltaics modules]

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1. Executive summary

The HERCULES project is articulated around two main n-type solar cell technologies regarding the second generation of high efficiency crystalline silicon solar cells and modules: heterojunction bifacial (SHJ) and Interdigitated Back contact (IBC). Moreover, it also deals with the combination of both in the so called Interdigitated Back contact Heterojunction (IBC-SHJ) concept for new ultra-high efficiency solar cells. The aim of the project is to:

1. Improve efficiency/ lower fabrication cost at the solar cell and module level
2. Move up to TRL6 and evaluate them in a production environment (SHJ & IBC)
3. Analyse the performance, cost, sustainability and reliability of all HERCULES technologies

With the ultimate goal of creating a premium European PV Technology, this development will allow differentiating from the mainstream with a cost effective, reliable and sustainable solution. Such ambitious objectives can only be achieved in a collaborative project as HERCULES, combining partners from Industry, Institutes and Universities with different strengths and competences. The main results of the HERCULES project can be summarized as follows:

a) Concerning SHJ technology:

Development of high efficiency and low cost processes for SHJ technology improving open circuit values over 735mV thanks to very high passivation layers and improved n-type material; Large area solar cells with industrial-compatible processes reaching almost 23% efficiency in the lab scale with improved metallization with copper; Development of innovative module interconnection based on the so-called *Smartwire* approach. Improving encapsulation, bifaciality and module fabrication to reach more than 325W in a 60-cells module passing all reliability tests and with a>350W equivalent if considering the bifacial behaviour of such technology; Production of more than 100000 SHJ cells in a production environment with mean efficiencies over 22% and 22.9% for the best cell in busbar less configuration.

b) Concerning IBC technology:

Development of high efficiency/low cost approaches for IBC devices obtaining record J0e values lower than 10fA/cm^2/Rsh~450Ω/sq for implantation emitters, reducing silver consumption and simplifying process steps solving main bottlenecks transferring to large area; Cells over 24% efficiency were fabricated on small area and IBC configuration; New approaches based on passivated contacts appeared to be very promising with small area cells over 25% efficiency; Development of simple and innovative IBC module solutions surpassing 310W and fulfilling at reliability tests; Production of 1200 IBC cells in industrial equipment with mean efficiencies of 21.4% and 21.9% best cell.

Concerning the IBC-SHJ technology, high efficiency devices over 22.5% were fabricated with innovative patterning designs and first solution for module encapsulation/interconnection were proposed with positive and reliable results.

CoO below 0.4$/Wp for both technologies IBC and SHJ taking into account 500MW production in Europe have been demonstrated. Advantageous LCOE for Bifacial SHJ cells was also shown at the system level with values as low as 25€/MWp in high irradiation conditions. LCA showed Energy Payback Time lower than 1.5years in medium irradiation for all HERCULES technologies.

Thanks to the above mentioned outcomes, HERCULES brings interesting benefit and development perspectives for the EU PV research and industry stakeholders. Continuing projects both at research and demonstration levels have already been jointly launched by the core partners to take HERCULES key results closer to the concrete application and market uptake.

2. Summary description of project context and objectives

2.1. Project concept

The concept proposed by the HERCULES project is to develop innovative n-type monocrystalline c-Si device structures based on back-contact solar cells with alternative junction formation, as well as related structures including hybrid concepts (homo-heterojunction). These concepts are the most promising technologies to reach ultra-high efficiencies with industrially relevant processes. The HERCULES strategy is to transfer the developed processes to the industrial scale by considering all major cost drivers of the entire manufacturing process chain of modules. Only success in developing both high-efficiency structures and adequately simple process sequences requiring high expertise and equipment mastering will lead to a successful technology for the European PV industry. To this end, the HERCULES consortium takes advantage of the leading European expertise in both research and production.

2.2. Summary description of the project objectives

The key objectives of the HERCULES project objectives are to:

1) Develop ultra-high-efficiency ($\eta > 21\%$) modules at the pilot line scale;
2) Reduce production and investment complexity and demonstrate costs of 0.4 €/Wp at a 500 MW/year commercial plant level;
3) Increase the lifetime of modules up to 35 years;
4) Demonstrate ultra-high-efficiency solar cells with $\eta > 25\%$.

3. Description of the main S&T results/foregrounds

3.1. WP1 - Silicon wafers for ultra-high efficient solar cells & modules

Aiming at increasing the conversion efficiency of silicon solar cells by innovations in the solar cell process is likely to induce stricter quality requirements for wafers. The purpose of this WP has been to ensure a close connection between cell processing and wafer production developments and to investigate routes for potential wafer production cost reductions.

An important activity has been dedicated to material quality, addressing quantification and improvement in relation with oxygen (O_i) content, material resistivity, thermal donors and bulk lifetime. A detailed study on thermal donor (TD) and their recombination activity has been performed, stressing the requirement of maintaining TD concentration below 10^{15} cm^{-3} to minimize negative impact on Silicon hetero-junction performances. NorSun has produced in the scope of the project several n-type 8" ingots for cell processing developments and material tests. By improving the puller hardware and the growing recipe, the oxygen and TD concentrations have been reduced with beneficial impact on wafer minority carrier lifetime. Typical material characteristics observed on NorSun's wafers, taken at different height of ingots, after the aforementioned improvements are summarized in Figure 1.

The wafering and solar cell processing of thinner wafers down to 120um thin has been investigated. Comparison of slurry and diamond wire based processed has been performed as well as a study of possible sawing wire core diameter reduction. The advantages of the diamond wire based approach has led to a rapid implementation of this technique for the wafering, core wire diameter has been reduced from 100 to 80µm and 145um wafer thickness has become the new standard. Wafer breakage study has highlighted the role of micro-cracks located in the sub-surface damage region, the impact of relative direction of the load and the sawing striation and finally the benefit of the etching process for the wafer mechanical resistance.

To gain insights on the role of material lifetime and resistivity on IBC performances, 2D simulation has been run. It results in the requirement for bulk resistivity higher than 2.5 Ohm·cm and in lifetime of 3 ms, respectively 10ms, for the wafer bulk in order to achieve 21%, respectively 25%, IBC cell efficiency. At cell level, the influence on BSC-HET performances of resistivity, oxygen (Oi), TD in n-type Cz Silicon wafers and also the potential benefit of performing thermal donor killing (TDK) on this material has been tested. To this end, NorSun wafers selected form 4 different heights of a single ingot, leading to a variation in the aforementioned parameters, have been used. The remarkably low concentrations in O_i, TD and generally excellent Si wafer quality achieved have reduced the generally observed TD impact on device below the sensitivity to other process parameters. TDK process produces mixed results as function of the TDK and cell fabrication processes stressing again that the low amount of oxygen and TD present in these NorSun Cz wafers are very much in line with wafer quality requirements for high efficiency BSC-HET increasing the device sensitivity to processing conditions. A parallel investigation using the very same groups of wafers has been performed to test the impact of high temperature and low temperature processes in function of different substrate quality. For this purpose, IBC and BSC-HET cells have been produced. Interestingly, both technologies show very stable efficiencies as a function ingot height (wafer property).

The relative efficiency variation along the ingot height is plotted in Figure 2 for both, high and low temperature cell technologies. It can be observed that an efficiency variation of max. 0.6%$_{rel}$ for IBC technology and of max. 1.8%$_{rel}$ for SHJ technology was demonstrated here along the entire n-type Cz ingot.

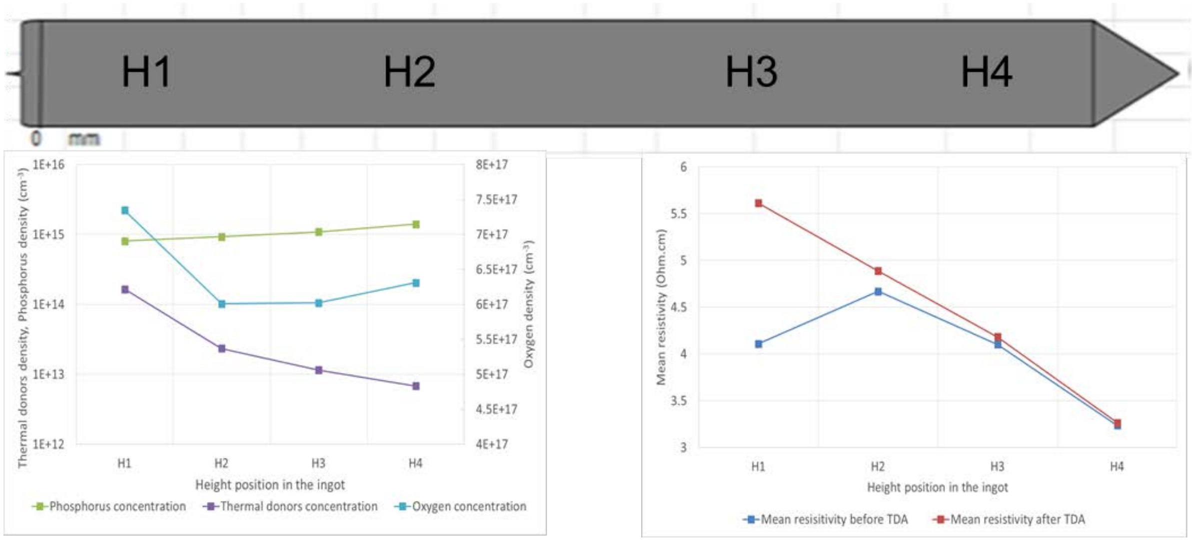


Figure 1: (left) Thermal donor, oxygen and phosphorous density along the ingot. (right) Bulk resistivity along the ingot before and after thermal donor killing treatment.

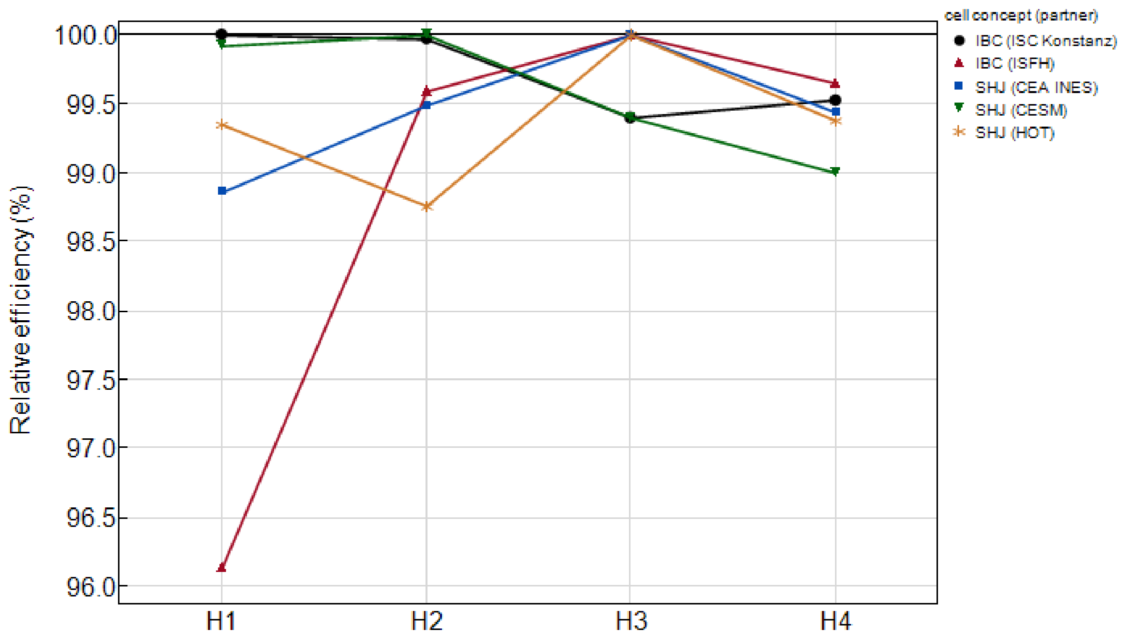


Figure 2: Relative efficiency variation as a function of ingot height for different cell concepts

3.2. WP2 - Emitter and back surface field formation

In this work package the formation processes for emitters, back surface fields (BSF) and front surface fields (FSF) are investigated with respect to the requirements of high efficiency silicon solar cells. Different technologies for the formation are investigated:

i) Ion-implantation (Emitter, BSF, FSF)
ii) Hetero (Emitter, BSF, FSF)
iii) Laser doping (selective Emitter, local BSF)

The processes targeted cell structures are i) ion implantation for interdigitated back contact (IBC) solar cells and bifacial solar cells, ii) heterojunction (HET) emitter and BSF for bifacial and IBC HET solar cells and iii) laser doping for IBC and bifacial solar cells. It is also possible that the solar cells are fabricated as hybrid structures by combining homo- and heterojunctions. For all technologies the focus lies on the realization of high-quality emitter and BSF regions (low recombination), the structuring of these regions as well as the integration of these emitter and BSF formation technologies into a scalable process (temperature stability, contacting, etc.).

The progress that was achieved in this work package from the members of the HERCULES consortium is manifold and the most important and notable developments are highlighted below.

In the framework of the project, ion implantation processes for crystalline silicon (c-Si) were further optimized with respect to different annealing technologies (single- and co-anneal) to activate the implanted species and to fully remove the implantation induced damage. On the one hand, it was presented that ion implanted phosphorus (P) and boron (B) dopants can be full activated by a tube furnace anneal in a single- or co-anneal process allowing saturation current (J0) values on planar surfaces as low as ~7 fA/cm2 for a sheet resistance (Rsh) of ~447 Ω/sq. when passivated with aluminum oxide (AlOx) and ~9 fA/cm^2 for a Rsh of ~147 Ω/sq. when passivated with silicon nitride (SiNx), respectively. Applying a silicon oxide (SiOx) passivation, low J0 values of ~39 fA/cm^2 were provided for Rsh of ~61 Ω/sq. and ~29 fA/cm^2 were obtained for Rsh of ~134Ω/sq., respectively. Beside a tube furnace anneal, also rapid thermal or laser processes were investigated as an alternative annealing technology. On the other hand, ion implantation into amorphous silicon (a-Si) was also investigated to form the so-called tunnel oxide passivated contacts (TOPCon). Here, implied open-circuit voltage (iVoc) of the P-doped and B-doped TOPCon layers after high-tempearure annealing and hydrogen passivation were above 720 mV and at 694 mV, respectively. Furthermore, carrier-selective junctions based on poly-Si/c-Si junctions, the so-called poly-silicon on oxide (POLO) junctions, were applied and locally doped by in-situ masked ion implantation. Here a very high passivation quality with low J0 values of ~2 fA/cm^2 for n+ poly-Si and +7 fA/cm^2 for p+ poly-Si were enabled with low contact resistance (ρcont) values of ~2 mΩcm^2.

Laser doping was studied in terms of realizing locally p- and n-doped regions by using different dielectric films such as i) aluminum oxide (AlOx) and intrinsic silicon carbide (SiCx), ii) AlOx combined with a boron-doped SiCx:B and iii) AlOx and a boron-doped silicon oxide (SiOx:B) or phosphorus-doped SiCx:P and a phosphorus-doped silicon nitride (SiNx:P), respectively. In combination with different laser sources based on infrared (IR) laser with a pulse duration in the nano- and picosecond regime and an ultra-violet (UV) laser with pulse duration of in the picosecond regime a wide range of parameters were investigated.

From the investigations, it was conclude that the best choice to create a locally p-doped regions with low laser damage, is the combination of an UV laser with AlOx/SiCx:B films, resulting in J0 values of ~4000 fA/cm^2 while maintaining Rsh of ~55 Ω/sq. Lower J0 values of ~2000 fA/cm2 were achieved by laser processing AlOx/SiCx films, but a Rsh values of 480 Ω/sq indicate a poorly p-doped region that is likely to face contact problems in finished solar cells. For creating locally n-doped regions, the surface passivation of SiCx:P and SiNx:P yielded starting values of 1 cm/s and 5 cm/s, respectively. After laser processing, the generated n-doped regions were characterized by contact surface recombination velocities (Scont) of 5500 cm/s and 3500 cm/s, respectively, with Rsh values well below 100 Ω/sq. Based on these results, the best choice for the creation of n-doped regions is the SiNx:P layer with Scont= 3500 cm/s and Rsh of 31 Ω/sq. when applying an UV laser.

For the heterojunction technology, several approaches were investigated within the project such as i) amorphous and nano-/microcrystalline silicon (a-Si or nc-/µc-Si), ii) alternative a-Si layers (incorporating oxygen or carbon), iii) new doping method for a-Si by ion implantation and iv) novel carrier-selective contacts based on metal oxides such as molybdenum oxide (MoOx). Different partners were working on the development of passivating layers with low optical absorption and ideal band alignment for HET BSC solar cells. In this respect, intrinsic a-Si layers were replaced by intrinsic a-SiOx to assess its potential as a buffer and window layer at the front. No significant differences in passivation were observed and comparable implied Voc values of ~725 mV were obtained. These layers have been applied to HJ solar cells and short-circuit current density (Jsc) was increased by up to 0.43 mA/cm2 when a stack of intrinsic a-SiOx and doped a-Si was used. Improved properties such as higher transparency, band gap and temperature stability in SHJ solar cells was also achieved by using trimethylboron (TMB) instead of B2H6 as a dopant source for p-doped a-Si emitters or by applying additionally p-doped nc-SiOx emitters in combination with the aforementioned intrinsic a-SiOx buffer layers. The nc-SiOx emitters were deposited using CO_2 as oxygen precursor and TMB for p-type doping. In cell-equivalent “lifetime test” structures, i.e. emitter/wafer/BSF, effective carrier lifetimes of > 2.5 ms, corresponding to an implied Voc of ~720 mV, were measured, confirming the suitability of such films for high efficiency SHJ solar cells. The optimization of boron-doped amorphous silicon carbide (a-SiCx) alloys as alternative materials for the front-side emitter enabled the tuning of the band-gap to ~2.3 eV by the addition of methane (CH4) in the gas phase and lead to iVoc values of ~725 mV while keeping absorption losses in the layer to a minimum. iVoc of ~ 730 mV and 40.4 mA/cm^2 were obtained for doped µc-Si. Plasma immersion ion implantation (PIII) was used as a new way to dope a-Si layers, evaluating different energies, doses and post-implantation annealing treatments. On the one hand, after B_2H_6 implantation, both the doping and the passivation reached a good level after a 300°C annealing. However, there was a compromise controlled by the PIII energy: the higher the energy, the higher the doping and the lower the passivation. The investigations resulted in a dark conductivity of ~ 2×10-5 $\Omega^{-1}cm^{-1}$ and an implied V_{OC} of ~710 for 25 nm thick a-Si layers. On the other hand, after PH3 implantation, passivation recovery upon annealing had a similar behavior, but due to damages in a-Si after implantation, the doping remained very low after the annealing. Besides, the work on carrier selective contacts was pursued by replacing the doped a-Si layer with novel dopant-free metal oxides such as MoOx with the aim to reduce absorption losses. It was shown that by inserting an intrinsic a-Si passivation layer between the metal oxide contact and the silicon absorber, MoOx/a-Si/c-Si, an efficiency of 18.8% was obtained.

With a band gap of 3.3 eV, MoOx contacts enabled an impressive current gain of 1.9 mA/cm^2 while maintaining the same Voc as compared to standard silicon heterojunction solar cells. A technology platform for the production of full-area 6'' BSC-HET solar cells was established, going from the wet-chemical preparation of as-cut wafers to the metallization of solar cells, using industry-compatible fabrication processes. Excellent process uniformity and passivation level were obtained with the developed a-Si:H layers: lifetime values above 6 ms was reached on actual precursors (textured CZ n-type wafers, 160 µm thick, 3 Ω·cm, passivated with ~20 nm thick in/ip a-Si:H layers), yielding implied Voc values above 740 mV.

3.3. WP3 - Metallization and contact development

The main objectives regarding the metallization of the solar cells in the HERCULES project were to: Develop low and high temperature metallization processes based on screen/stencil printed with reduced material utilization and related costs for the silicon heterojunction (SHJ) as well as for the interdigitated back contact (IBC) cell concepts. Investigate plating as an alternative for screen printed contacts. Develop and integrate, on one hand, low cost indium-free and, on the other hand, very high efficiency TCOs. Understand the contact formation and functionality on microscopic scale. Develop new concepts and processes for module integration of IBC cells and adapt them to industrial processing.

Based on the above ambitions, the HERCULES consortium achieved significant progress compared with the state-of-the-art at the time. The most notable results are highlighted in this report.

For high temperature metallization (i.e., IBC cells), we demonstrated simultaneous contacting of phosphorus doped and boron doped surfaces by a single screen print and firing through of a silver paste, with specific contact resistivity ρ_C < 1 mΩcm^2 (for R_{sh} = 45-140 Ω/sq). We demonstrated that double printing or stencil printing is a feasible option to increase the contact finger aspect ratio, further improve cell efficiency by 0.2-0.3%$_{abs.}$, and to reduce silver lay-down at the same time. Very low silver lay-down of less than 47 mg (front and back) was achieved for 6-inch SHJ cells using SmartWire® interconnection, while maintaining a conversion efficiency of 22.7%. This resulted in a cost of silver below 0.35c/Wp, which is below state-of-the-art for today's screen printed metallization.

The development of novel/alternative TCOs had the goals to a) provide high quality TCOs which are essential to achieve high conversion efficiencies and, b) to find low-cost alternatives to In-based TCOs. High performance TCOs based on hydrogen doped In_2O_3:H (IOH), such as IOH or IOH/ITO stacks, have been successfully developed and integrated as front and/or back electrode for SHJ cells. Two metallization approaches were used: screen-printing of silver paste and Cu electro-plating. In both cases, replacing ITO by IOH (front and back) led to a strong increase in the photocurrent (up to +0.8 mA/cm^2) while FF was maintained at a high level. This resulted in a 0.3%$_{abs.}$ efficiency improvement as compared to the ITO reference, with a record efficiency of 22.8% demonstrated using Cu-plating. Alternatively, Al-doped ZnO (AZO) was successfully integrated as back electrode, thus substituting ITO, without any efficiency loss. The electrial properties of the most succesful TCOs investigated in the project are summarized in Table 1**.**

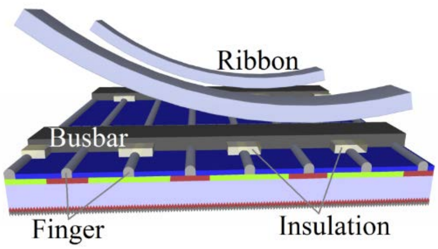
Moreover, EPFL demonstrated that the doped amorphous silicon layers can be replaced with highly transparent transition metal oxides such as molybdenum oxide, resulting in cell efficiencies as high as 22.5%.

Table 1: Electrical properties of ITO, AZO and IOH, as obtained from Hall measurements.

	Ne [cm^{-3}]	µ [cm^2/Vs]	ρ [µOhm*cm]
ITO (annealed 5min@200°C in air)	2.43E+20	54.5	472
AZO (deposited @ 180 °C)	2.62E+20	32.7	728
IOH (annealed 1h@180°C in vacuum)	1.70E+20	126.6	290

Various plating processes on different seed layers and cell architectures have been investigated for IBC as well as SHJ cell concepts within the project. Plating on large area IBC cells showed that using printed seed layers and copper plating gives a considerable cost saving potential. For bifacial SHJ cells, CSEM PV-Center developed a vertical process with which both sides of the cell can be plated in parallel. The process works with copper evaporated seed layer on both sides and patterning of the seed layer with resist or ink-jet. Plated modules passed 2 times IEC standard climatic tests with relative absolute degradation smaller than 5%, meaning that no copper diffusion into the cell occurs in these configurations and that the adhesion of plating and interconnection is stable and reliable.

Two interconnection methods for the IBC cell technology have been evaluated and optimized during the project: a low temperature multi-layer (3D) interconnection, and a co-planar (2D) interconnection. The two concepts are shown schematically in Figure 3. The multi-layer metallization was successfully adopted and tested in pilot line production of large area IBC (ZEBRA) cells and modules during the project. Average cell efficiency in pilot line of 21.4% (best cell of 22%) and full size module with 311 Wp were realized. Moreover, thermal cycling and damp-heat tests on modules demonstrated the reliability and compatibility of this interconnection method with module materials.



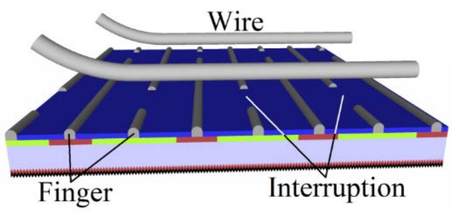


Figure 3: Schematic of the multi-layer (left) and co-planar (right) metallization concepts utilized to interconnect metal fingers and to provide an interface between solar cell and ribbon or conducting back-sheet used for module integration

3.4. WP4 - Module integration

Work Package 4 addressed the interconnection of cells and module integration, integrating processes based on WP 1, 2 and 3. It was tackled by focusing on 4 topics: (1) encapsulation (2) reliability, durability and cell-to-module losses, (3) efficiency measurement and energy yield, and eventually (4) high efficiency large area module. Here we highlight the main results stemming from each of these topics. The best results for each technology are then summarized.

First, each solar cell has its specificity and therefore requires different encapsulant properties to prevent outdoor module degradation. Combining research on encapsulation, reliability and durability, we identified that for heterojunction (HJT) solar the highest reliability is achieved when a polyolefin-based material is used as encapsulant. For IBC Zebra technology, the highest reliability was achieved using EVA based encapsulation. Latest tests with polyolefin-based material show promising preliminary results. These results were based on damp heat, thermal cycling, humidity freeze, UV and peel test adhesion tests as well as lamination processes optimization. The results of some tests are summarized in the table below.

Second, the electrical and optical cell-to module losses (CTM) were modeled and quantified. Direct comparison of each technology is not easy as these technologies have their specificities and norms for bifacial modules are not yet available. We, however, show that the BOM of ISC using IBC Zebra cell interconnected with 4BB, of ISE using IBC cell interconnected with 3BB and of MB using HJT with smart wire interconnection technology (SWCT) and a low cost BOM, all have CTMs in a similar range. INES achieved lower CTM losses thanks to light harvesting ribbons, which admittedly presents challenges for production environments but enables low CTMs.

Third, the energy yield of several modules was monitored. For both IBC and HJT, it was shown a strong yield increase of using bifacial modules, varying from 10% to 21% depending on mounting systems and conditions. Power bifaciality factors of 75% and 92% were achieved for, respectively the IBC concept from ISC and HJT/SWCT from MB. Moreover, the HJT technology is measured to be less temperature sensitive compared to a standard p-type technology due to its low temperature coefficients and the IBC Zebra technology shows the second best performance for illumination levels lower 400 W/m² after the p-type reference.

Eventually, each partner combined the improvements stemming from the Hercules projects to provide high-efficiency modules, which are summarized in the table below and highlighted in the Figure below. In the Table 2, several measurements are given for the bifacial glass-glass (GG) HJT-SWCT, as no norm yet exists. Value are given for (1) a albedo of 14%, based on outdoor monitoring data from Hercules, (2) with a very low reflective background to have no rear contribution and (3) with a white back-sheet taped to rear side of the module. The latter measurement is a certified measurement.

Table 2: Summary table of module technologies developed within Hercules

	HJT-SWCT (production)	HJT-BB	HJT IBC	IBC	MWT (FhgISE)
Best Power of the module 60 cells [W]	362Wp_eq_bif14, 318Wp_stc for GG 329Wp_stc for GBS	308	**	311	276
Best power of the module 4 cells and {1-cell, 199 x 100 mm2} [W]	(21.9)	(20.5)	(16.2)	20.4	(17.1)
Best area efficiency as defined in project [%] – 60-cell **Best area efficiency as defined in project [%] – 4-cell**	21.6	20.4	**	20.4 20.5	17.4
Best Total area efficiency [%] – 60-cell	20.0	18.5		19.2	
Best CTM as defined in the project [%]	2.9	5.9	2.1	4.6	3.1

	HJT-SWCT (production)	HJT-BB	HJT IBC	IBC	MWT (FhgISE)
DH [0 not achieved, 1 = 1000h passed, 2= 2000h passed, 4= 4000 h passed]	4	2	2	2	0
TC [0 not achieved, 2= 200 TC passed, 4= 400 TC passed]	12	4	**	10	0
HF [0 not achieved, 1= 10 HF passed, 2= 20 HF passed]	2	0			
Maturity of the technology [0-10]	8	7	2	7	5

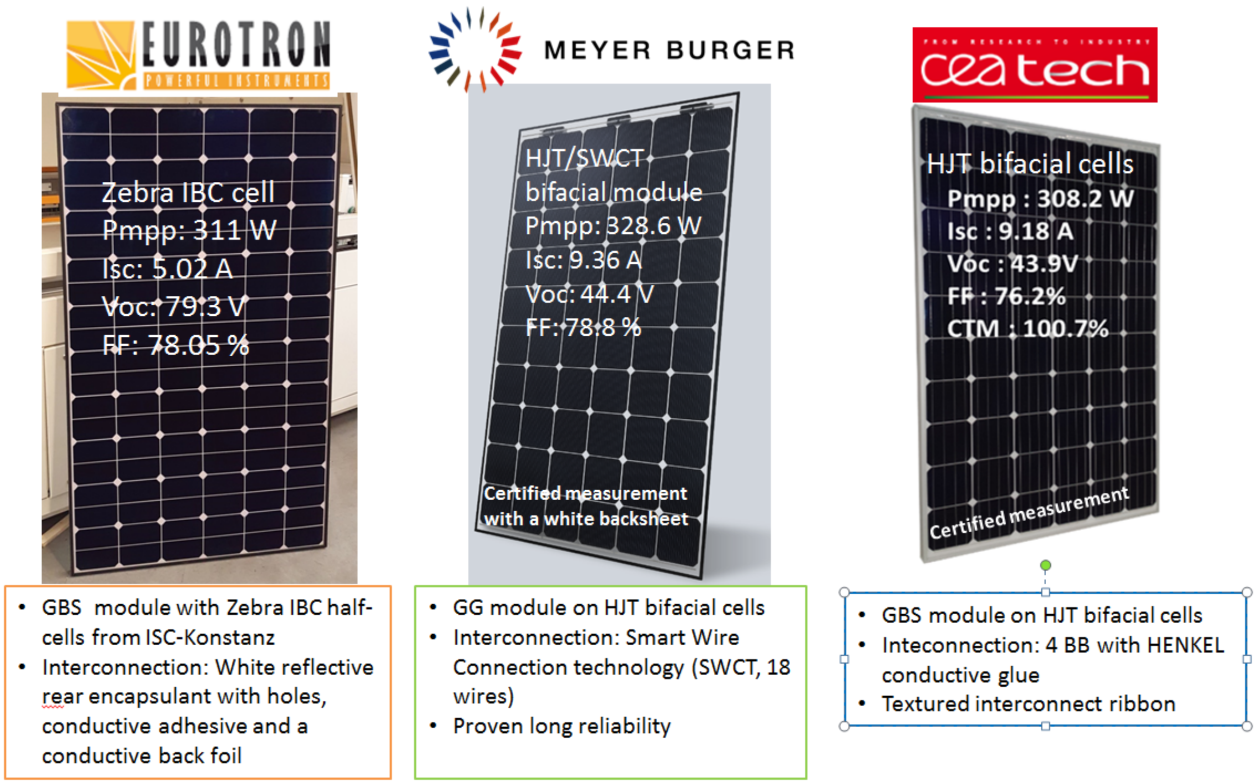


Figure 4: Record modules for several technologies developed within Hercules

3.5. WP5 - High efficiency prototype solar cells

WP5 deals with high-efficiency prototype solar cells and it requires the integration and the upscaling of the best results obtained in WP1 (development of high-quality silicon wafers), WP2 (emitter and back-surface field formation) and WP3 (metallization and contact development). Different solar cell technologies are available within the strong consortium HERCULES is composed of.

During the duration of the project, WP5 has been fruitful in terms of patterning solutions to increase efficiencies of IBC solar cells, the design of new simplified processes for the fabrication of this kind of devices, the solution of efficiency-limiting issues in HET solar cells as well as the upscaling towards large-area devices.

Major developments on IBC cells featuring tunnel oxide passivated contacts (TOPCon)[1] layers formed by ion implantation into amorphous silicon have been done. The development of a completely new process flow for the fabrication of IBC cells with poly-silicon on oxide (POLO) junctions[2] for both polarities, emitter and BSF, has also been implemented. A champion efficiency of 24.25% with this approach has been obtained which corresponds to the highest value reported so far for fully ion-implanted IBC cells.

Improvements in metallization and diffusion process allowed for the fabrication of a 22% efficient ZEBRA cell on large-area substrate (6-inch, n-type, Cz)[3]. To our knowledge this result represents a record efficiency for a large area IBC cell architecture that is fabricated using only industrial techniques for mass production.

Concerning the low temperature developments, a continuous optimization of all process steps (wet-chemistry, PECVD, TCO, metallization) for standard 6-inch both side contacted heterojunction (BSC-HET) cells has been pursued. An improved intrinsic a-Si:H buffer layer, more transparent front layers, improved edge isolation or copper plating on 6-inch cells amongst others have allowed for increased performances, in a mass-production environment and with cost-effective processes.

A record efficiency of 22.8% on a Cz *n*-type 239 cm^2 cell has been obtained at CSEM, with a busbar-less front grid design compatible with the SmartWire® technology[4]. Best V_{oc}s were measured above 735 mV on 160 µm thick CZ wafers, with the potential of reaching higher values by using thinner substrates. On a 100 cm^2 area, efficiencies as high as 22.9% have been obtained using a 3-busbar screen-print metallization. Besides, MBR measured 23% on 6'' busbar-less BSC-HET cells, whereas CEA-INES obtained an average efficiency of 22.7% on a 56-cell batch, in which a record efficiency of 23.15% was measured (all SmartWire® configuration).

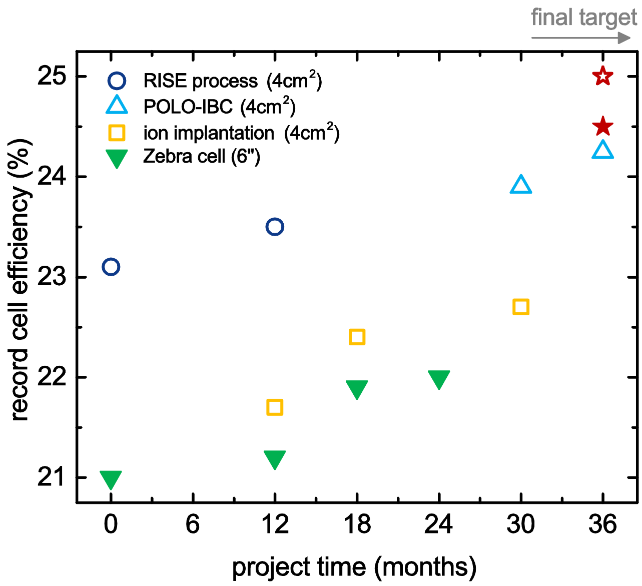
[1] C. Reichel *et al.*, 29th EUPVSEC, Amsterdam, The Netherlands, 487 – 491 (2014)
[2] M. Rienäcker *et al.*, DOI: 10.1109/JPV,2016.2614123
[3] R. Kopecek *et al.*, PV International 32 (2016)
[4] A. Descoeudres *et al.*, Energy Procedia 2015

On small-area BSC-HET devices, alternatives to doped amorphous silicon have been developed with the aim of reducing absorption losses. Doped nanocrystalline layers deposited by PECVD have been developed and successfully implemented in cells featuring a reduced absorption in blue part of the solar spectrum[5] as well as increased FF[6]. Another significant progress has been made on the development of molybdenum oxide (MoOx) as hole transport layer. By substituting the (p)a-Si:H by this MoOx layer in BSC-HET[7], cells with conversion efficiencies of 22.5% were fabricated. With the "standard" BSC-HET device architecture using doped a-Si:H layers CSEM demonstrated a record efficiency of 23.5%.

With a combined effort of EPFL, CSEM and MBR, intermediate sized IBC-HET devices were fabricated. These devices were made without any photolithographic step, but rather relied on shadow masking of PECVD film deposition, combined with inkjet printing of hotmelt inks and chemical etching.[8,9] Following further process sophistication, an efficiency of 22.9% was reached for these 9-cm^2-active-area devices. Similar efficiencies have been also obtained on 25-cm^2-area cells. Other approaches based on laser patterning have also been proved by HZB[10] and CEA-INES[11].

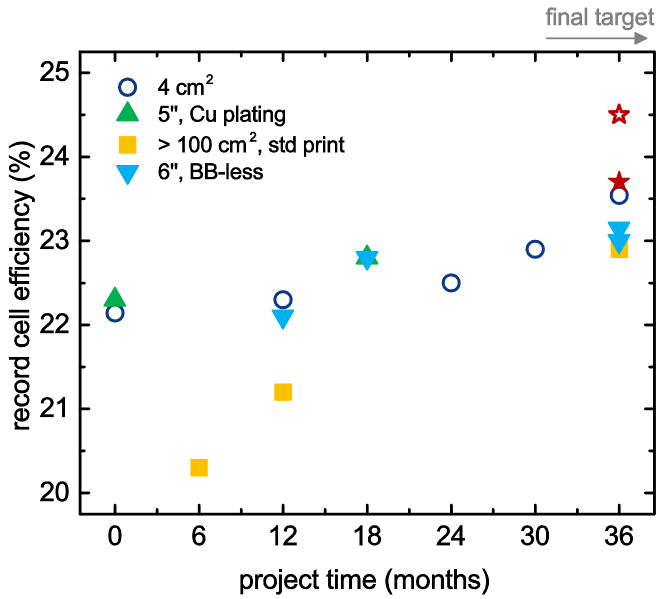
Figure 5 presents the evolution of the efficiencies of high- and low-temperature devices obtained throughout the project execution, both for small- and large-area cells. As it can be seen, a steady increase of efficiencies has been possible, undoubtedly demonstrating the strong position in the PV sector of all partners in the HERCULES consortium.

(a)



[5] L. Mazzarella *et al.*, APL 106, 023902 (2015)
[6] J. P. Seif *et al.*, IEEE JPV 6, 1132 (2016)
[7] J. Geissbühler *et al.*, APL 107, 81601 (2015)
[8] A. Tomasi *et al.*, IEEE JPV 4, 1046 (2014)
[9] B. Paviet-Salomon *et al.*, IEEE JPV 5, 1293 (2015)
[10] S. Ring *et al.*, IEEE JPV 6, 894 (2016)
[11] S. Harrison *et al.*, Energy Procedia pp. 730-737 (2016)

(b)



(c)

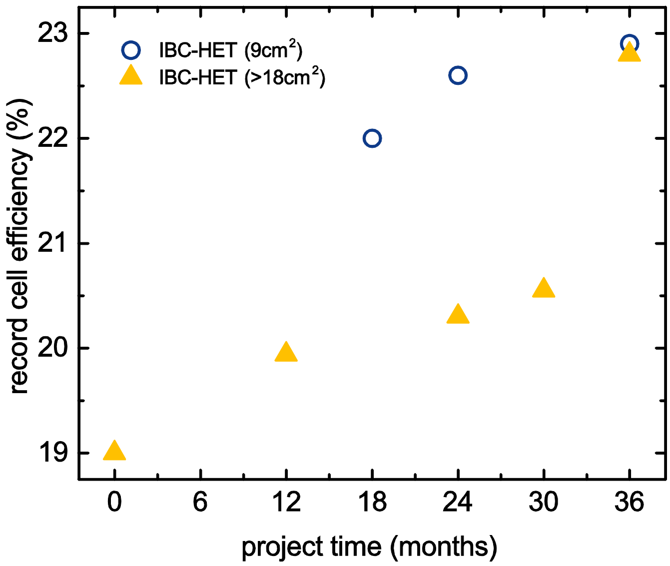


Figure 5: Efficiency evolution of (a) IBC, (b) BSC-HET and (c) IBC-HET small- and large-area solar cells during the project

3.6. WP6 - Pilot cells and modules integration

The objective of this work package was to transfer of the developed processes in the project from the lab to industries and to demonstrate the process capability of ZEBRA IBC and HJT bifacial technology in a new ramped up pilot line with an industrially relevant amount of high efficient cells. Moreover, the production of high efficient modules for both cell technologies has to be demonstrated. Both technologies have the biggest potential for a cost competitive and high efficient solar cell production. At first, the ZEBRA IBC cell, developed from ISC, was combined with the new developed backcontact module technology from Eurotron. On the other hand, the bifacial and busbarless heterojunction cell technology from Meyer Burger using Smart Wire interconnection technology for the module production.

ISC-Konstanz fabricated approximately 1200 ZEBRA IBC cells as a pilot production run. The cells were fabricated in the ISC research laboratory on industrial equipment. The median efficiency was 21.4% and 21.9% for the best cell. Based on these cells, 6 IBC modules were fabricated from ISC and Eurotron by using an automated industrial assembly line with conductive backsheet technology. The best 120 half-cell module was measured with 311W_p and demonstrated the potential of the development by further improvements in the cell process.

The process capability of the heterojunction cell technology was demonstrated by Meyer Burger with a new ramped-up pilot line and the by the amount of more than 100000 bifacial cells with a median efficiency >22% and 22.9% for the best cell, independent certified from ISE Callab. These cells are used for a pilot production run with SWCT line equipment. More than 100 bifacial HJT-SWCT modules were manufactured with >350W_{eq_bif14}, taking into account a 13% power increase for 14% albedo due to module bifaciality. Furthermore, the used bill-of-material in pilot production shows excellent reliability under damp heat, thermal cycling and UV exposure. Eventually the module design was improved to lower the cell-to-modules losses and to increase the biaficiality factor >92% by using a decentralized jbox. However, the lighthouse module in production, measured monofacial with a white backsheet, achieved 328.6 W_{P_STC}, certified by Supsi and presented in work package 4.

CEA-INES and CSEM has worked on the development of industry-compatible process-flow for HJT-IBC technology. However, the demonstrated process sequence needs further improvements for current industrial requirements.

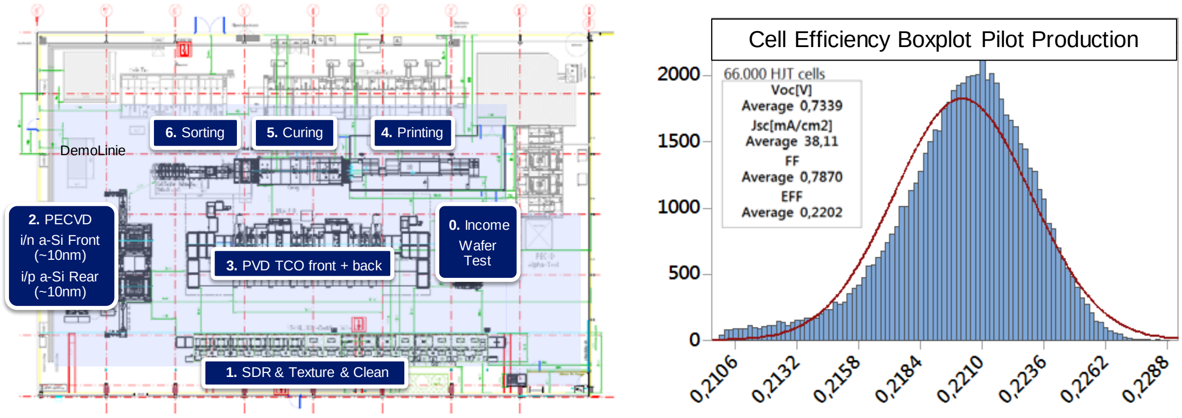


Figure 6: Schematic configuration and process flow of HJT cell pilot line (left) and the result for the median cell efficiency of a pilot production run (right).

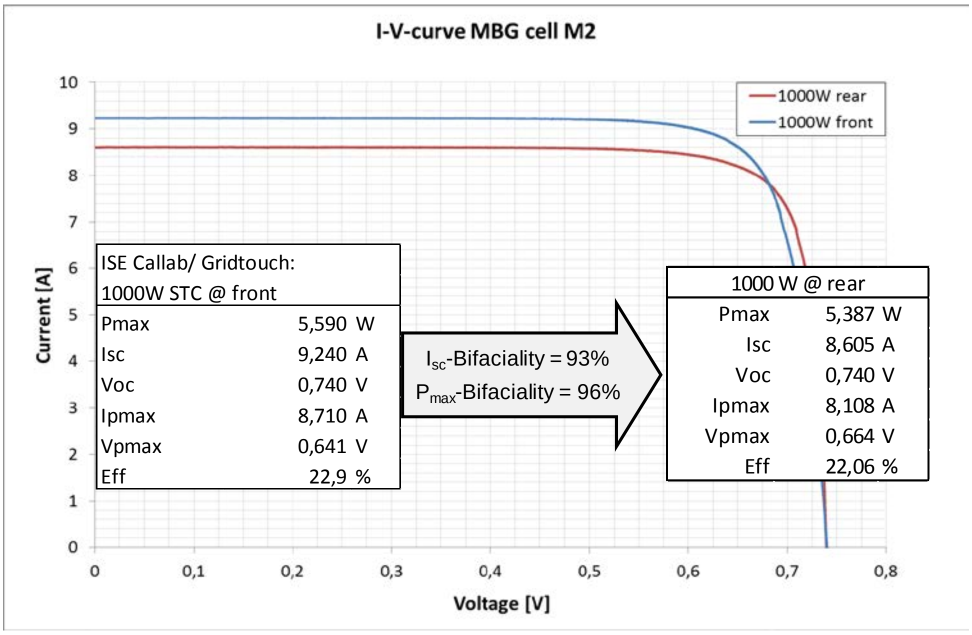


Figure 7: IV- cure of the best bifacial cell from pilot production, measured from front- and backside for the calculation of the bifaciality ratio on cell level

Figure 8: HJT SWCT Module produced in the MB cell and module lines

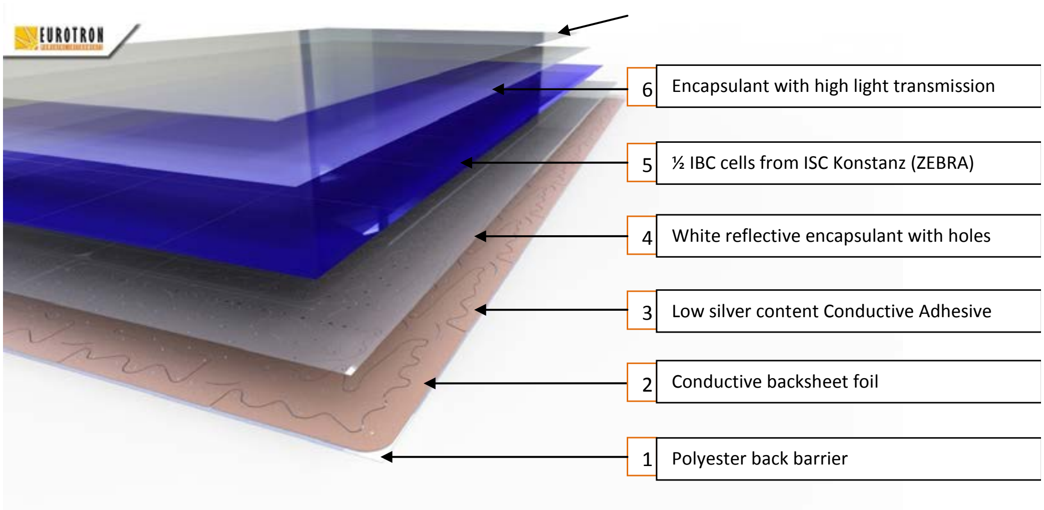


Figure 9: Build-up of the foil-based IBC modules (source Eurotron)

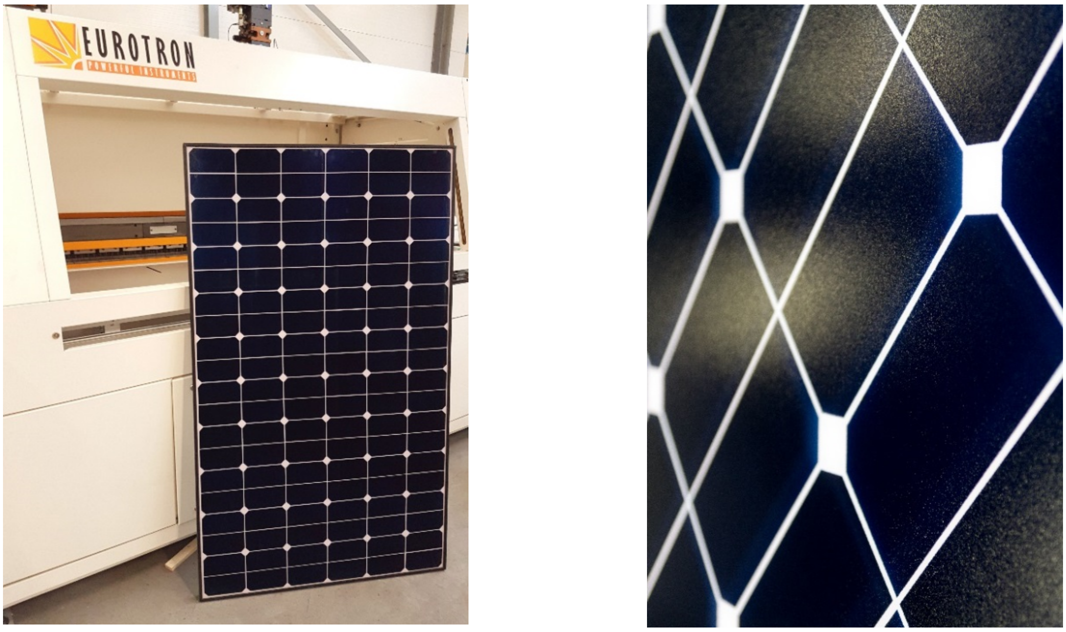


Figure 10: IBC module produced on Eurotron's module pilot line (Source: Eurotron)

3.7. WP7 - Simulations and characterizations

The WP7 focuses on standard and advanced characterizations tools and simulations that were applied to provide feedbacks to the WPs devoted to the device and module fabrication. The characterizations were performed at different levels of the cell development, ranging from individual layers, hetero-interfaces to test structures. Module characterization including outdoor monitoring was also a specific task undertaken in the WP7. In a parallel way, the simulation task was used to provide design guidelines for all IBC cell designs and propose a roadmap to reach high efficiency (27%).

Several round-robin tests focused on the thickness optimization of the intrinsic (i) a-Si:H layer for bifacial hetero-emitters were performed. µ-PCD and MPL measurements showed, in a reproducible manner, lifetimes greater than 1 ms and implied VOC higher than 700 mV for a threshold intrinsic thickness of 6 nm. Mapping measurements applied to some n-type Cz-Si wafers with poor surface passivation also evidenced the presence of grown-in defects noticeable by concentric striation patterns. (Partners involved: CEA-INES, ISFH, EPFL, CNRS-LGEP, HZB, SEMILAB)

Advanced rear-side contact schemes based on locally highly doped PCs were investigated and studied by way of round-robins. Highly p-doped PCs were formed with different multilayer dielectric stacks on c-Si wafers that were fired with different pulsed lasers. The lowest sheet resistance values were in the range 10-50 Ω/sq and were found for Al_2O_3/SiCx:B and Al_2O_3/SiOx:B stacks. A combination of micro-Raman and PL measurements confirmed the incorporation of high amount of boron as high as 1020 cm^3. (Partners involved: UPC, CEA-INES, Fraunhofer ISE, CNRS-LGEP, SEMILAB)

New TCOs were developed with the purpose to optimize the optical absorption and to decrease the serial resistance. Structural and optoelectronic characterizations were applied on several TCOs, including IO:H, a IZO, ITO:Zr and ZnO-SiOx. IO:H and a-IZO films demonstrated after optimization high mobility values 110 cm^2/Vs and 60 cm^2/Vs, and carrier densities of 1.5×1020 cm^{-3} and 2.5×1020 cm^{-3}, respectively. DH tests (85°C, 85% relative humidity) performed on IO:H capped with ITO and IZO showed high stability with 9% and 13% sheet resistance degradation after 1000 h. WOx layers as a possible hole contact layer for c-Si HET solar cells were also investigated. PS analysis confirmed the high work function (6.3 eV) and the existence of a significant density of oxygen vacancies that impacts the Fermi level position in WOx, and reduces unfortunately the band bending across the junction. (Partners involved: EPFL, HZB, CEA-INES)

Several technologies and structures involving IBC were simulated. Notably, n-type c-Si IBC cells involving homojunctions (IBC-HOMO), heterojunctions (IBC-HET) and structures combining the previous two technologies called “Hybrid” IBC. 2D-modelling of the following structures demonstrated that efficiencies over 26.5% (VOC>750 mV, JSC>41.6 mA/cm^2, FF>84%) could be achieved for a wafer thickness of 150 µm. The best performances for IBC-HOMO and IBC-HET structures were found when minimizing the BSF width compared to the pitch of the interdigitated structure, for highly doped homojunctions (>1020 cm^{-3}) and surface defects concentration at the a-Si:H/c-Si interface below 1011 cm^{-2}. IBC-HOMO cells based on PC structures were specifically simulated in function of the EMC and for different emitter vertical pitches.

This study pointed out the importance of decreasing the pitch instead of increasing the EMC, and showed that new designs based on different vertical pitch for the emitter with respect to the base are more robust to a poor passivated base contact. (Partners involved: HZB, UPC, Fraunhofer ISE, CNRS-LGEP)

From the module point of view, PVB and EVA low cut-off encapsulants in module demonstrated the best performances in terms of EQE and CTM losses. Optical and electrical losses were also modeled showing that the CTM losses can be reduced down to 0.3-0.4% if the perfect material combination is being used (no bifaciality was taken into account). The outdoor monitoring of the modules rated under STC revealed that all the modules efficiencies were pretty stable and reliable over a one year period (Partners involved: CEA-INES, ISC, EPFL).

3.8. WP8 - Tech-eco & environmental assessments

In this work package, the techno-economic and environmental assessments were done on both main industrial technologies developed by industrial partners from the HERCULES project. The work includes technological bricks and costs improvements linked with the project.

3.8.1. CoO Calculations

The main achievements in WP8 are related to the elaboration of a full cost of ownership for both hetero-junction (HET) and interdigitated back contact cells (IBC) and modules technologies. Data from the project and from the market were used.

Cost obtained in the case of a 500 MWp factory implanted in East of Europe can be as low as <0.36€/Wp for the HET technologies and <0.40 €/Wp for the IBC. These achieved values validate the cost objectives aim at the beginning of the project (0.40€/Wp) and are in accordance with today best module prices based on n-type cells.

HET and IBC are showing promising performance, cost results and future promising process improvement. One of the remaining challenge will be for these technologies to be adopted by the market in real mass production in order to get further significant cost reduction.

3.8.2. Environmental assessment

PV systems powered by high-efficiency solar modules are promising in terms of reducing energy payback times and greenhouse gas emission mitigation of PV electricity generation. This appears to be enabled by cutting-edge wafer, cell and module production processes and facilities supplied by electricity with low greenhouse gas emissions. A prospective life-cycle assessment of the HERCULES technologies was executed. More specific, the cumulated primary energy demand (CED), the energy payback time (EPBT) and the greenhouse gas emissions (GHG) are used to assess a 500 kWp PV system located in Eastern Europe. Results are given on ingot, wafer, cell, module and system level as well as related to annual PV electricity generation.

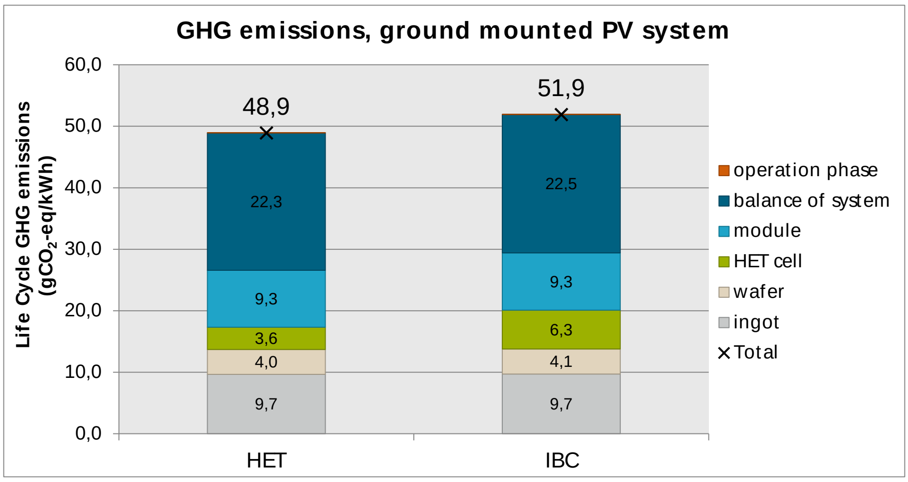


Figure 11: Greenhouse gas (GHG) emissions from the life-cycle of ground mounted 500 kWp PV systems. The assessment is based on Eastern Europe module plane irradiation of 1.392 kWh/m2*a, a performance ratio of 0,77 (HET) and 0,75 (IBC), life-time of 30 years. The system includes frames, mounting, cabling, inverter and excludes recycling. This is a prospective LCA based on Norwegian n-type Si crystallisation and wafering and Eastern Europe cell and module production with a capacity of 500 MWp/a.

PV systems based on HET and IBC cells can realized a EPBT of 1,2 and 1,4 years, respectively, at a location with medium irradiation of 1245 kWh/(m²*a). In Figure 11 the results for the GHG emissions of HET and IBC for each device level are shown.

PV systems powered by high-efficiency solar modules are promising in terms of reducing energy payback times and greenhouse gas emission mitigation of PV electricity generation. This appears to be enabled by cutting-edge wafer, cell and module production processes and facilities supplied by electricity with low greenhouse gas emissions.

3.8.3. LCOE calculation

The last task of this work package was dedicated to a techno-economic assessment of the whole production system (which is the module itself integrated into its environment). This evaluation was performed regarding the site localization, the irradiation level, the size of the installation, its kind (industrial one), the type of technology used among those studied within this project, and any other condition which can differentiate the systems. The principal key parameter will be the Levelized Cost Of Energy (LCOE) which could lead to comparison with other electricity sources.

The techno-economical assessment of the whole production system was evaluated for a 50MWp ground mount PV system and on side-by-side-side comparison of utility-scale monofacial and bifacial installations for:

- A standard fixed tilt structure orientated south in the northern hemisphere (respectively north in the southern hemisphere) and tilt at 20°.
- An Horizontal Single Axis Tracking (HSAT) having its rotation axis along the North-South axis running along the North-South direction.

For this task, both HET and IBC modules from the project was used to obtained real efficiency and temperature coefficient data. There costs were taken following the final CoO studies from this work package. All these data were then used in a modelling software to optimise for the two different systems (fixed tilt and HSAT).

The implantation is investigated in three regions with in high level of Direct Normal Irradiance (DNI) and of albedos (ground reflectance): Spain, India and Chile.

LCOE [€/MWp] HET bifacial				LCOE [€/MWp] IBC monofacial			
Fixed tilt	**1-Spain**	**2-India**	**3-Chile**	**Fixed tilt**	**1-Spain**	**2-India**	**3-Chile**
min	32,2	29,1	25,1	min	35,9	32,5	28,6
max	48,2	44,3	38,2	max	53,4	49,2	43,3
HSAT	**1-Spain**	**2-India**	**3-Chile**	**HSAT**	**1-Spain**	**2-India**	**3-Chile**
min	34,4	30,0	24,6	min	38,8	35,7	29,0
max	49,6	43,9	36,1	max	55,7	51,9	42,3

Table 3: LCOE results for IBC/ HET modules – fixed tilt vs HSAT for 3 locations

The Table 3 show that LCOE between 24 and 39 €/MWp are achievable on condition of high solar irradiation and attractive economic environment. These results are in the best range of state of the art of LCOE.

HSAT may be an interesting option but only in Chili for heterojunction modules. The module cost entails a higher relative difference in LCOE due to BoS impact. Then, the production gain observed is absorbed by BoS cost difference between HSAT and fixed tilt.

To conclude, as well as each PV utility-scale project is unique because of its localization (meteorological conditions, techno-economical choices…) each LCOE calculation will be specific.

4. Potential impact

4.1. Socio-economic impact and the wider societal implications of the project

4.1.1. Boosting this EU stakeholders leadership

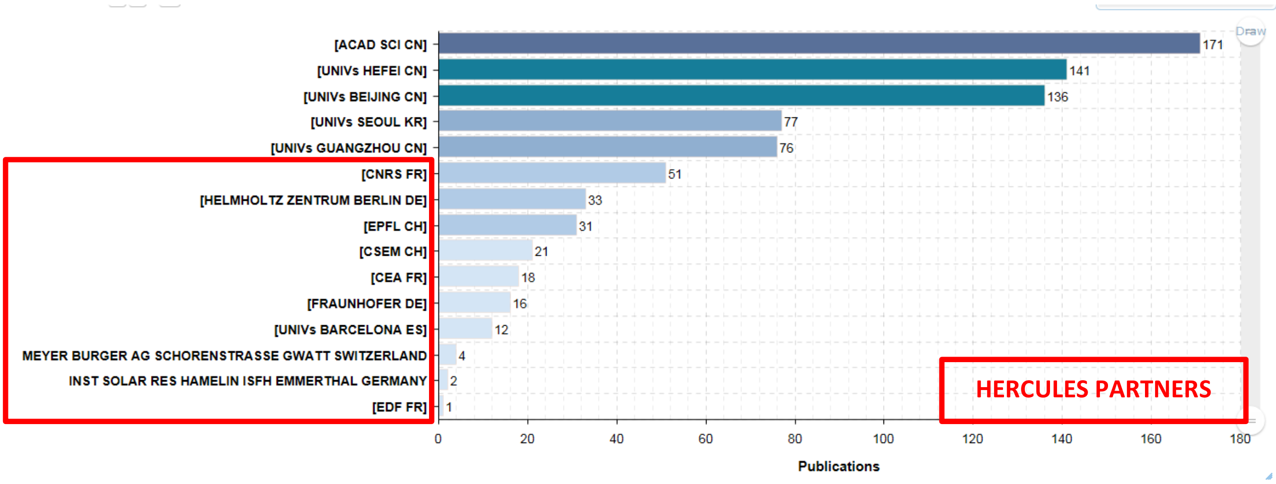
The HERCULES project developments were based on three core technologies:

- Heterojunction PV cells
- IBC cells
- Hybrid IBC-HET cells

In order to evaluate the impact of the HERCULES project, Ayming/ALMA performed a specific study in order to benchmark the project partners against their competitors in terms of innovative developments in the three above mentioned PV technological fields. This study was conducted by screening worldwide patents and publications databases for each one of the technologies.

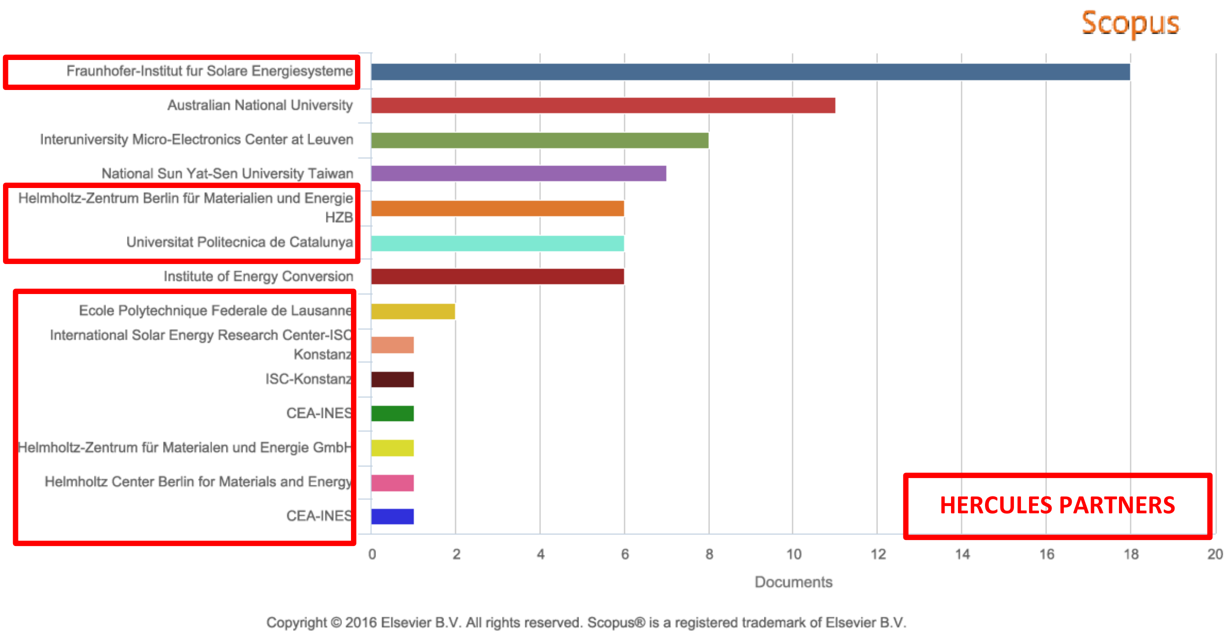
Heterojunction PV cells

Unsurprisingly the top 5 leading organisations in terms of publications are all based in Asia (China and Korea). However, one can notice that the HERCULES group including both R&D and industrial stakeholders is also quite powerful in this highly competitive research and development domain.



IBC cells

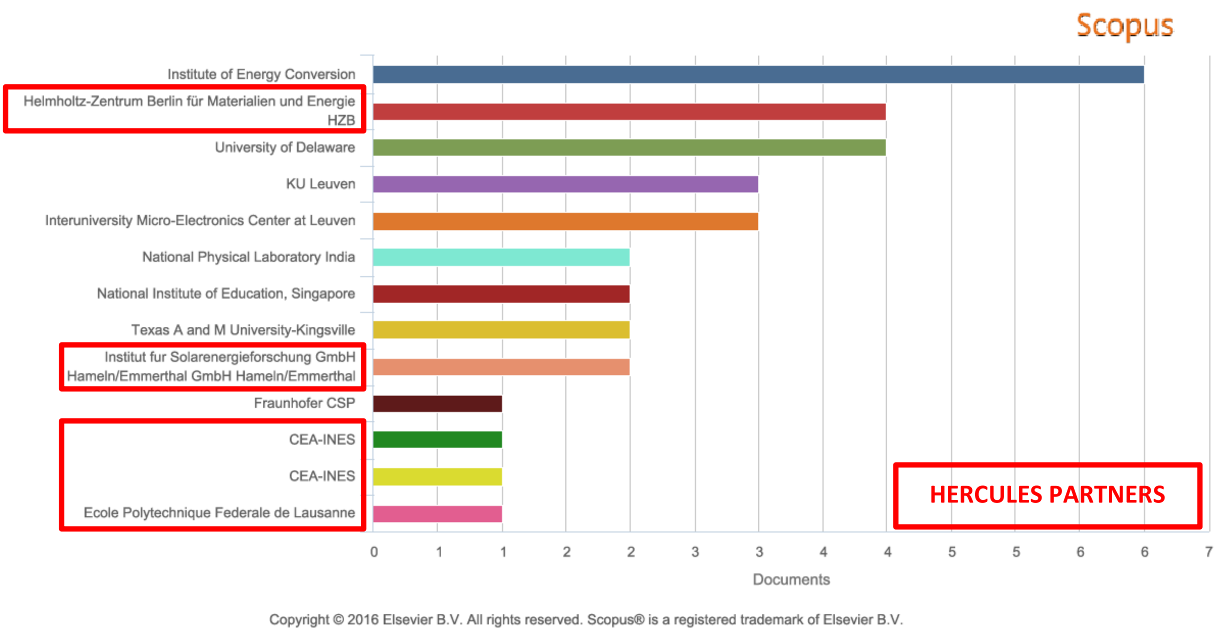
In this field the HERCULES partners have a strong position in the worldwide ranking. The encouraging results obtained at industrial pilot line scale by Eurotron for example demonstrate also that some EU industry representatives could in a short to medium term benefit from a commercial exploitation of such IBC technology.



Hybrid IBC-HET cells

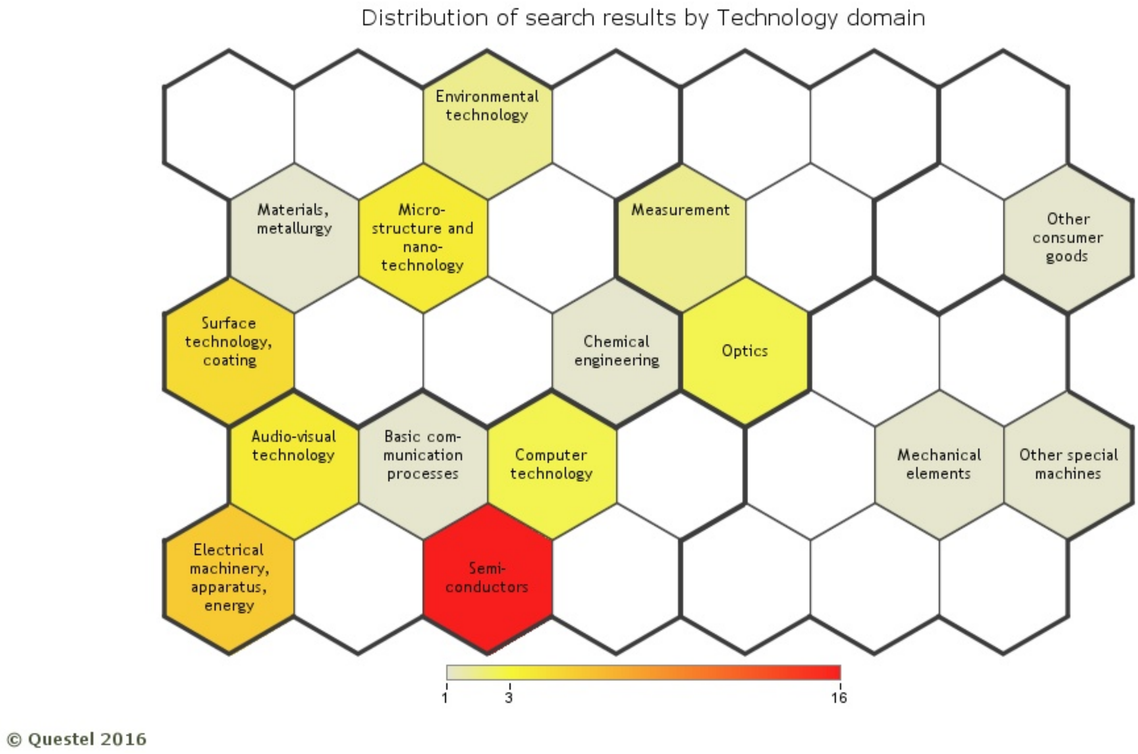
The volume of scientific papers published in this field since the HERCULES project start (i.e. 2013) is far much less important than for the two other technologies studied in the project.

Indeed, the hybrid IBC-HET technology is still considered as being at an emerging stage. HERCULES then helped a lot the partners concerned to stay at the forefront of this technology as shown in the graph below on which the top 13 organisations active in this field are displayed.



4.1.2. Developing new technologies for various industrial sectors

In more general terms, the HERCULES project results can find exploitation ways in various technological domains. These latter are presented here below for specific developments done in the project framework such as ion implantation of a:Si layers, anti-reflective coating and transparent conductive oxides. The colour code provides a priority scale.



4.2. Main dissemination activities and exploitation of results

4.2.1. Logo and project identity set

A project identity set consisting of a logo, public website and project brochure as well as a PowerPoint template to be used for internal and external presentations has been created.

URL of the public HERCULES website: http://www.helmholtz-berlin.de/projects/hercules/. During the course of the project, this website was updated e.g. with information on conferences & workshops relevant contact details or list in the scope of HERCULES.

The logo composed of a pictogram associated with the HERCULES name, which figures on the heading of this document, tends to represent the sunlight caught by a solar cell.

HERCULES

Four internal newsletters have been redacted by the coordinator and the dissemination manager up to now with the main achievements of the partners and updates on state-of-the-art.

4.2.2. Activities from WP10 – Dissemination and exploitation of project's results

4.2.2.1. Dissemination

In this work package, the dissemination of the project results was coordinated, the exploitation of the project results was promoted, and IPR issues were managed.

The main achievements in WP10 are related a) to the presentation of project results to scientific and industrial audiences as well as to the general public through conference presentations, press releases etc., and b) to an assessment of the potential for integration of the HERCULES technologies in high performance PV, which are summarized in a Technology Implementation Plan (TIP).

Most HERCULES partners have published and presented results achieved within the project in peer-reviewed journals, at international workshops and international conferences such as the SiliconPV conferences, European Photovoltaic and Solar Energy Conference, the IEEE PVSC and the PVSEC. In total, 76 project-related peer-reviewed papers and 26 proceedings contributions have been published, and 159 dissemination activities (mostly oral & visual presentations at conferences and workshops) have been carried out. Furthermore two HERCULES workshops were held in March 2015 in Konstanz, Germany, and in October 2016 at the Helmholtz-Zentrum Berlin, Germany. Presentations given by various project partners about the topics and achievements within the HERCULES project as well as presentations from external speakers from industry and R&D provided the basis for lively discussions of the project and its context. The two workshops had more than 100 and 60 participants, respectively, from research and industry. The workshop presentations have been made freely available to the public on the HERCULES project website, www.helmholtz-berlin.de/projects/hercules/ (PDFs are linked to the workshop presentation titles).

Figure 12: Participants of the 2nd HERCULES workshop (10-11 Oct 2016, Helmholtz-Zentrum Berlin, Germany)

4.2.2.2. Exploitation

Regarding the commercial exploitation of HERCULES results, MEYER BURGER Germany, Hohenstein-Ernstthal, has set up a SHJ cell pilot line, where the heterojunction process sequence has been demonstrated and optimized on full industrial equipment with more than 100 000 manufactured high-efficient cells during the last 10 months.

Based on the cells produced in MB Germany, a module pilot line from Meyer Burger, located in Thun/ Switzerland, has been producing bifacial SWCT modules. First, about 600 commercial modules were produced end of 2015 using the SWCT line. Then, over 1000 glass-glass HJT SWCT commercial modules with a high bifaciality factor were produced from September to October 2016. Different PV power plants are now installed in the Swiss market and provide important field experiences about the new developed SHJ-SWC technology.

The process of the cell pilot line will be transferred to the first integrated European customer Ecosolifer with a first SHJ cell capacity of 95MW/year. The move-in and ramp up phase will start by the beginning of 2017. Furthermore, Meyer Burger reported a growing customer interest on SHJ cell and module production equipment for cell supplier and Institutes in Asia, North America and Europe.

Eurotron's fully automated production line is ready to produce IBC modules with a throughput of at least 90 modules per hour. First all necessary adaptations were done followed by optimizations. The complete process is demonstrated in Eurotron's Test Center, located in Bleskensgraaf [NL].

Discussions with interested customers are ongoing to ramp up this technology from lab to fab. In this stage also recommendations for the Bill of Materials can be given based on accumulated experience and reliability testing done in the Hercules project.

5. Public website and illustrations

5.1. Public website

URL of the public HERCULES website: http://www.helmholtz-berlin.de/projects/hercules/.

5.2. Contact details

Main contact for dissemination and communication activities:

- Lars KORTE (HZB), korte@helmholtz-berlin.de
- Delfina Muñoz (CEA INES), delfina.munoz@cea.fr
- Etienne MACRON (AYMING), emacron@ayming.com

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