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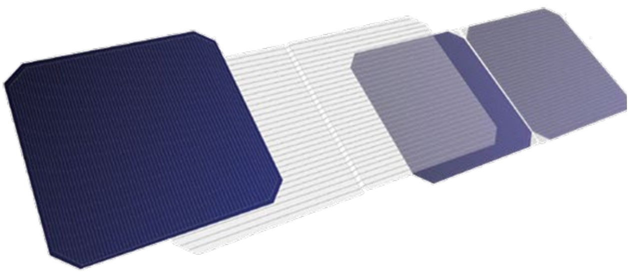
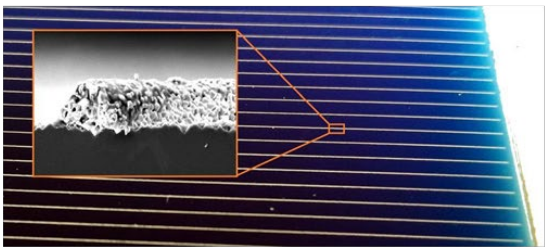
Final report

Refined PV

Reduction of Power Losses by Ultra-fine Metallization and Interconnection of Photovoltaic Solar Cells





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Zusammenfassung

In der Photovoltaik fand in den letzten Dekaden eine kontinuierliche Steigerung des Modul-Wirkungsgrades und eine Senkung der Herstellungskosten statt. Die ursprünglichen Ziele des Refined PV-Projekts waren die Steigerung der Modulleistung (>15 W_p) und die drastische Reduzierung des Silberverbrauchs (auf ≤30 mg; ca. 6 mg/W_p) für kristalline PERC Silicium-Solarzellen mittels einer neuen Zellmetallisierungstechnik und Feinliniendruck.

Die PTP-Zellmetallisierungstechnik (Pattern Transfer Printing) der israelischen Firma Utilight ermöglichte die Feinlinien-Metallisierung von Zellen, die dann ideal mit der Smart Wire Connection Technology (SWCT™) von Meyer Burger verbunden werden konnten. Das PTP ist eine ultrafeine Fingerlinien-Drucktechnik mit hohem Aspektverhältnis und SWCT™ verwendet dünne Drähte mit einer Elektrodenfolie als Träger, um Zellen miteinander zu verbinden. Dies ermöglicht eine bessere Optimierung des Metallisierungs-Musters als die Standard-Busbartechnik.

Erste Schritte im Projekt Refined PV waren die Installation, Prozessoptimierung und Hardwareverbesserung der PTP-Plattform von Utilight am ISC Konstanz. Zellseitig konnte der Verbrauch an Silberpaste für die Metallisierung für das M2-Zellenformat (156.75x156.75 cm^2) auf 28 mg (ca. 5 mg/W_p) gesenkt werden. Dieser Wert wurde mit einer Fingerbreite von 22 µm und mit einem Aspektverhältnis von 0.6 erreicht. Im Vergleich zu herkömmlichen Siebdrucktechniken liegen diese Werte weit voraus in der Technologie-Entwicklung. Fortschritte wurden auch bei Metallisierungspasten-Formulierungen erzielt, die die Kontaktqualität auf PTP-metallisierten Solarzellen verbesserten.

Modulseitig erzielte Meyer Burger Fortschritte bei SWCT™ mit Indium-freien-Drähten, die die Machbarkeit und Kostenreduzierung dieser Technologie mit PTP-metallisierten Zellen ermöglichten. Die Drähte wurden mit dieser neuen Legierung um rund die Hälfte kostengünstiger. Verschiedene Moduldesigns wurde getestet und weiterentwickelt (beispielsweise 72-Zellen- und Halbzellenmodule).

Maschinenseitig stand bei Meyer Burger 2018 eine neue Stringer-Entwicklung für die Zellverbindung im Mittelpunkt. Das Produkt wurde unter dem Namen IBEX-CCS550 vermarktet. Der Fokus bei dieser Maschine lag auf einem höheren Durchsatz und einem geringeren Platzbedarf sowie Halbzellenfähigkeit. Im Jahr 2019 wurde eine neue Roll-to-roll-Einheit (RRU) entwickelt. Die RRU produziert Folien-Draht-Komponenten (foil-wire-assembly, FWA) aus Polymerfilmen und Drähten. Die FWA wird für die Zellenverbindung im Stringer benötigt.

Aus den feinlinien-metallisierten Zellen wurden bei Meyer Burger 16- und 60-Zellen-Solarmodule mit SWCT™-Verbindung unter Verwendung von Indium-freien Drähten hergestellt. Dank der Fortschritte auf Zellebene konnte der Silberdruck von PTP auf 28 mg für optimale Zellen gesenkt werden, und sogar bis auf 17 mg für eine Fingerbreite von 18 µm, aber mit Einbussen in der Zellleistung. Mit diesen Ergebnissen wurde das erste Hauptziel des Projekts erreicht. Die mit diesen Zellen maximal erreichte Modulleistung betrug 310 W_p (Watt Peak) für 60-Zellen-Module. Die Zuverlässigkeit der Module wurde in Klimakammern getestet (PTC: Power Thermo Cycling, DH: Damp Heat, HF: Humidity Freeze). Ergebnisse: Die meisten Module bestanden 200 PTC-Zyklen (1 x IEC, <5 % Degradation) und 1000 h in DH (1 x IEC, <5 % Degradation). Die Ergebnisse zeigten, dass SWCT™ in der Lage ist, effektiv bis zu ≤ 20 mg Silber auf der Zellvorderseite zu verbinden. Dies wäre mit einem Busbar-Lötansatz nicht möglich. Mit den gebauten Modulen konnten wir den Benchmark des Projekts für kommerzielle 3-Busbar-Module (3BB) um mehr als 15 W_p übertreffen und damit das zweite Hauptprojektziel erreichen.

Am Ende des Projekts konnte Meyer Burger eine hohe Stabilität und Zuverlässigkeit von SWCT™-Modulen aus feinlinienförmigen metallisierten Zellen nachweisen. Dies war das dritte Hauptprojektziel.

Résumé

Lors des dernières décennies, on a assisté à une augmentation continue du rendement des cellules et panneaux solaires photovoltaïques, associée à une diminution des coûts de production. Dans cette optique, les buts initiaux du projet « Refined PV » sont une augmentation de la puissance du panneau photovoltaïque (>15 W) et une réduction de l'utilisation d'argent (jusqu'à ≤30 mg; env. 6 mg/W_p) pour des cellules solaires PERC à silicium cristallin, grâce à de nouvelles techniques de métallisation visant à obtenir des structures métalliques très fines sur les cellules.

La technique de métallisation dite « PTP » (Pattern Transfer Printing) de l'entreprise israélienne Utilight permet de réaliser de telles structures très fines, qui se combinent idéalement avec la technique d'interconnexion SWCTTM (Smartwire Connection Technology) de Meyer Burger. Cette technique PTP permet l'impression de doigts métalliques ultrafins avec un grand ratio d'aspect sur la cellule solaire. La technologie SWCTTM utilise des fils d'interconnexions très fins implémentés dans une structure porteuse en feuille de polymère, qui permettent de relier les cellules solaires en série. La combinaison de ces deux technologies permet d'optimiser en détail l'interconnexion avec la métallisation de la cellule solaire (en comparaison avec un technique « busbar » standard).

Une première étape du projet consiste à installer et optimiser la plateforme PTP de Utilight à ISC Konstanz. Sur la cellule solaire, l'utilisation de la pâte de metallisation pour l' impression métallique ultrafine est réduite à 28 mg (env. 5 mg/W_p) par cellule M2 (156.75x156.75 cm^2). Ceci a été réalisé avec des doigts de métallisation d'une largeur de 22 µm et avec un ratio d'aspect de 0.6. En comparaison avec des structures conventionnelles réalisées par sérigraphie, ces valeurs sont très en avance sur le développement technologique. En parallèle, des progrès sont réalisés sur les formulations des pâtes de métallisation, pour améliorer la qualité du contact des fils sur les structures ultrafines.

Meyer Burger a récemment obtenu des résultats probants avec la technologie SWCTTM, en utilisant des fils d'interconnexions ne contenant pas d'indium. Ces fils sont utilisés sur des cellules métallisées avec la technique PTP, permettant de diminuer les coûts d'interconnexion de moitié environ. Différentes configuration et designs de module PV sont implémentables et testées (par exemple demi-cellules, modules à 72 cellules).

Côté équipement, Meyer Burger a développé une nouvelle machine d'interconnexion („stringer") révolutionnaire en 2018, et qui a été lancée sur le marché sous le nom IBEX-CCS550. Cet équipement permet de réaliser une interconnexion à haut débit avec une empreinte de surface au sol minimale, et est modulable au niveau des cellules à interconnecter (cellule complètes ou demi-cellules). En 2019, une nouvelle unité « roll-to-roll » est également lancée (RRU). La RRU réalise l'implémentation des fils d'interconnexion dans la feuille polymère (FWA ou Foil-Wire Assembly), prérequise pour le stringer IBEX-CCS550.

Dans le cadre du projet, Meyer Burger a réalisé des modules PV à 16 et 60 cellules combinant SWCTTM et des cellules à doigts métalliques ultrafins. Grâce aux progrès obtenus sur ces cellules PTP, l'utilisation d'argent est réduite à 28 mg pour des cellules optimisées, et à environ 17 mg pour des cellules tests avec des doigts de métallisation d'une largeur de 18 µm. Ces résultats correspondent au premier objectif initial du projet. Les modules PV 60-cellules fabriqués avec de telles cellules atteignent une puissance crête de 310 W et sont ensuite testés en chambre climatique. La plupart des modules obtenus passent les tests standard IEC (PTC : powered thermo-cycling 200 cycles, DH : damp heat 1000 heures, HF : humidity freeze) avec moins de 5 % de dégradation. Ces résultats démontrent que SWCTTM permet l'interconnexion de cellules solaires contenant <20 mg d'argent sur la face frontale de la cellule, ce qui est impossible avec une approche busbar classique. Les modules obtenus sont comparés avec des modules traditionnels à 3 busbars, avec une puissance de crête améliorée de 15 W, ce qui constitue le 2ème objectif du projet.

A la fin du projet, Meyer Burger démontre également une haute stabilité et fiabilité de modules SWCTTM et métallisation très fine, ce qui réalise le 3ème objectif du projet.

Summary

Photovoltaics has seen a continuous increase in module efficiency and a decrease in production costs in the last decades. The initial goals of the Refined PV project were to increase module power (>15 W_p) and drastically reduce silver consumption (to ≤30 mg; ca. 6 mg/W_p) for crystalline PERC silicon solar cells thanks to fine-line printing.

The Pattern Transfer Printing (PTP) cell metallization technique of the Israeli company Utilight enabled fine-line metallization on cells, which could then be ideally interconnected with the Smart Wire Connection Technology (SWCTTM) of Meyer Burger. The PTP is a high aspect ratio ultra-fine finger lines printing technique, and SWCTTM uses thin wires, with an electrode foil as support, to interconnect cells. This enables better optimization of the printing pattern than standard ribbon technique.

First achievements in the Refined PV project were the installation, process optimization, and hardware improvement of the PTP platform from Utilight at ISC Konstanz. On cell side, silver paste consumption for metallization could be lowered to 28 mg (ca. 5 mg/W_p) for the M2 cell format (156.75x156.75 cm^2). This was achieved with metallization fingers of width 22 µm, and an aspect ratio of 0.6. Compared to conventional screen printing techniques, this is far ahead in the photovoltaic technology roadmap. Progress was also made in metallization paste formulations that improved contact quality on PTP metallized solar cells.

On Meyer Burger's module side, advancements in SWCTTM with In-free wires were made, which enabled the feasibility and cost reduction of this technology with PTP metallized cells. Wires became 50 % cheaper with this new alloy. Various module designs was tested and advanced (e.g., 72-cell and half-cell modules).

On Meyer Burger's machine side, a new stringer development for cell interconnection was the main focus in 2018. The product was commercialized under the name IBEX-CCS550. Focus on this machine was higher throughput and lower footprint, as well as half-cell capability. In 2019, a new roll-to-roll unit (RRU) was developed. The RRU produces foil-wire assembly (FWA) from polymer films and wires. The FWA is then used for cell interconnection in the stringer.

At Meyer Burger, 16-cell and 60-cell modules were fabricated from the fine-line printed cells, with SWCTTM interconnection using In-free wires. Thanks to the advances on cell level, the silver print laydown of PTP was decreased to ca. 28 mg for optimum cells, and even down to 17 mg for 18 µm finger width, but with cell power losses. The first main objective of the project was reached with these results. The maximum reached module power with these cells was 310 W_p (Watt peak) for a 60-cell module. The reliability of the modules was tested in climatic chambers (PTC: power thermo cycling, DH: damp heat, HF: humidity freeze). Results: Most modules passed 200 PTC cycles (1 x IEC, <5 % degradation), and 1000 h in DH (1 x IEC, <5 % degradation). The results show that SWCTTM is able to connect effectively down to ≤20 mg of silver on the cell front side. This would not be possible with a busbar soldering approach. With the modules built in 2019, we were able to exceed the project's benchmark of commercial 3 busbar (3BB) modules by more than 15 W_p, thus reaching the second main project objective.

At the end of the project, Meyer Burger was able to show fine climatic chamber reliability of SWCTTM modules made from fine-line metallized cells. This was the third main project objective.

Main findings

- The project team was able to reach the main goals of the Refined PV project: Combine fine-line metallization of solar cells with SWCT^{TM} module technology, and show the feasibility, cost decrease, and reliability of this technology.
- In the course of Refined PV, important improvements were made in Meyer Burger's SWCT^{TM} technology, both on production equipment, and on module level.
- Photovoltaics is an essential component of Switzerland's energy policy. Development and progress of solar module technology and its key production equipment is the core competence of Meyer Burger (Switzerland) AG. It is an essential part of Meyer Burger as a photovoltaics company.

Contents

Abbreviations

Ag	Silver (main component of solar cell metallization paste)
BoM	Bill-of-Material (Dt. Stückliste)
FWA	Foil-wire assembly. Cell connecting component of SWCT^{TM} modules. The FWA is produced on the Roll-to-roll unit (RRU).
IBEX-CCS550	Commercial stringer from Meyer Burger. The solar cells are merged with the FWA and linked together on the stringer.
IEC 61215	International standard with test procedures for climatic chamber tests
ISC Konstanz	International Solar Energy Research Center Konstanz e.V.
IV analysis	Current-voltage characteristic curve analysis of solar cells
LCOE	Levelized cost of energy
PERC, PERT, HJT	Solar cell types
PTP	Pattern Transfer Printing (cell metallization procedure)
RRU540	Meyer Burger’s Roll-to-roll unit for FWA production
SP	Screen printing (cell metallization procedure)
SWCT^{TM}	SmartWire Connection Technology
Utilight	Utilight Ltd, Israel

1 Introduction

Photovoltaics has seen a continuous increase in module efficiency and a decrease in production costs in the last decades [Ref. 1].

The highest leverage for reducing costs of solar applications is achieved by increasing the efficiency of the solar module and by reducing the materials cost of the expensive ingredients (i.e. silicon, silver and module materials). A higher efficiency reduces costs all along the value chain. The project Refined PV aimed at providing an efficiency increase of at least 5 % (relative) by shrinking the fraction of front side metallization drastically. A further target was to reduce the silver paste consumption by up to 30 %. The interconnection based on SWCT™ allowed for additional reduction of resistive losses and optical losses in the modules at competitive costs.

The second leverage to a competitive product is the reduction of material costs. Current solar cells (of the PERC type) use about 80 mg silver (ca. 15 mg/W_p), according to the ITRPV roadmap [Ref. 1]. At project start, this value was even higher, ca. 100 mg for standard 156x156 cm^2 cells (>20 mg/W_p). The silver is, besides the wafer, the most costly material in cell processing. The project Refined PV aimed at reducing the consumption to 30 mg (ca. 6 mg/W_p) per cell, a value which is many years ahead of market trends according to the ITRPV roadmap. Moreover, as SWCT™ used indium-based solder at project start, which is a costly material, this project aimed to reduce the costs of the contacting scheme by qualifying new solder materials and reducing the amount of solder.

Third, module reliability is a key to achieve low levelized cost of energy (LCOE). Within the project we demonstrated that for the developed module prototypes with ultra-fine Ag-metallization lines a superior reliability and efficiency can be achieved.

The novel ultra-fine line Pattern Transfer Printing (PTP) [Ref. 2] metallization equipment and process was developed at Utilight Ltd. (WP3, WP4). ISC Konstanz implemented and optimized the ultra-fine line cell metallization on high-efficient mono crystalline (Czochralski) PERC solar cells (WP2, WP5). ISC Konstanz also took the coordination part of the project (WP1). Hanwha QCells as associated partner provided high quality precursors and performed process variations. Meyer Burger (Switzerland) as module specialist made the interconnection based on SmartWire Connection Technology [Ref. 3] (WP6). The main focus of this project report is on Meyer Burger's contribution (WP6).

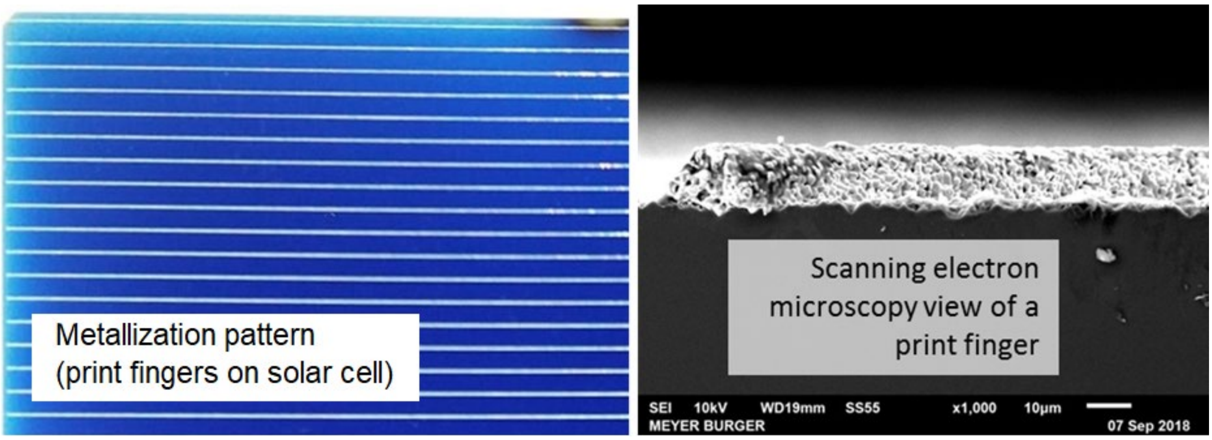


Figure 1: Solar cell surface with PTP-printed silver paste metallization (print fingers), and scanning electron micrograph of a print finger.

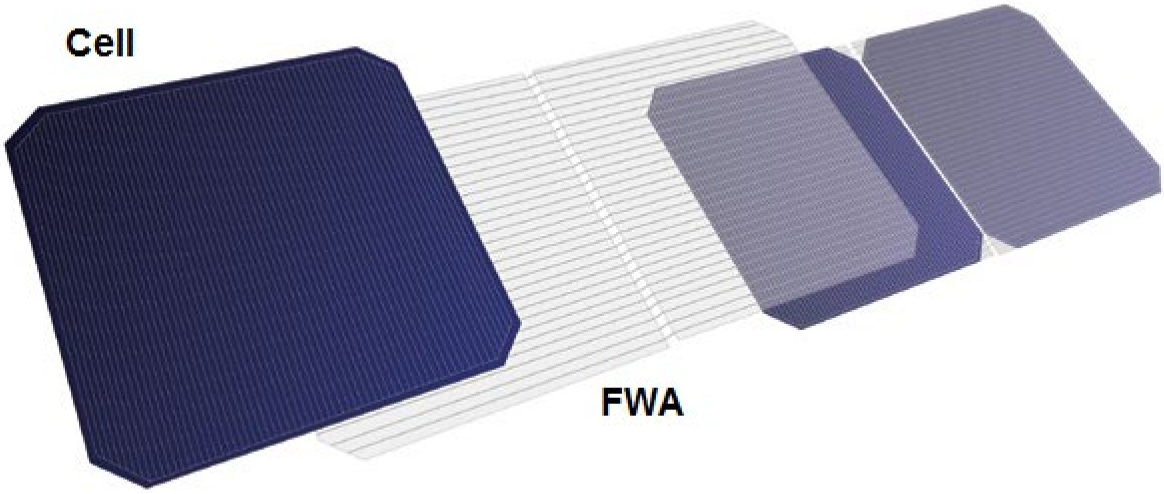


Figure 2: Schematic view of cell interconnection in SWCT™ modules.

2 Work packages overview

2.1 WP1: Coordination (ISC)

ISC Konstanz coordinated the project. It kept track of timely performance of the tasks, ensured a good communication within the project, invited for project meetings and teleconferences, reviewed the progress and mastered changes in management. Figure 3 shows the Gantt chart of the project. In deviation from the original project plan, the three partners started on different dates. Utilight as provider of the Pattern Transfer Printing (PTP) equipment for fine-line cell metallization had to deliver the first milestone.

A change in the Refined PV project at a late stage was the announcement of financial insolvency and shutdown of activities by Utilight in Q4/2019. Because screen-printing (SP) had moved towards finer metallization lines in the course of the Refined PV project, a decision was taken to replace the unique PTP platform from Utilight by fine-line SP. A transition from PTP-SWCT^{TM} to fine-line SP-SWCT^{TM} was made by the remaining project partners (ISC Konstanz and Meyer Burger).

With this change to a well-established platform, the project objectives remained in line or could be matched even more with the current market situation.

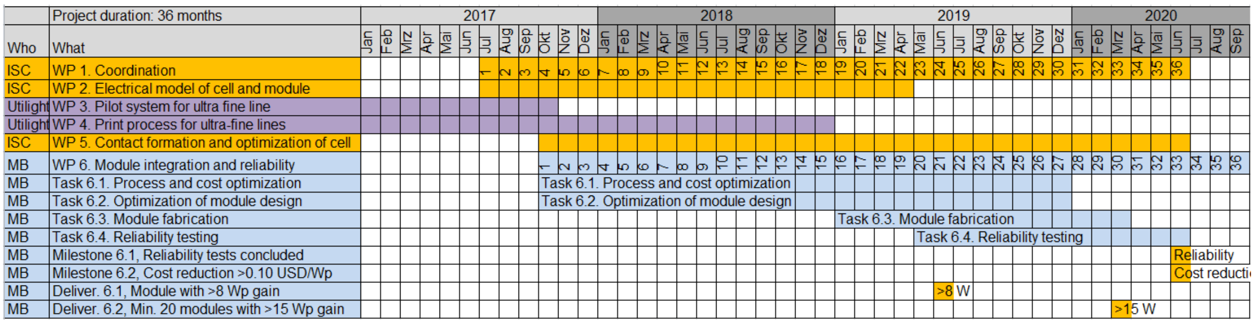


Figure 3: Gantt chart of Refined PV work packages.

2.2 WP2: Electrical model of cell and module (ISC)

This work package was under the lead of ISC Konstanz with participations of Meyer Burger and Hanwha QCells to understand and minimize the losses at cell and module level. This work included establishing & correcting the basic model with input parameters and definition of non-ideal conditions.

2.3 WP3: Pilot system for ultra-fine line (Utilight)

This work package concerned the installation and process establishment of PTP 1800i printing system at ISC Konstanz. In 2017, the Utilight printing system was successfully installed at ISC Konstanz. In October 2018, it was upgraded and retested by Utilight.

2.4 WP4: Print process for ultra-fine lines (Utilight)

At project start, Pattern Transfer Printing (PTP) was able to print reliably in pilot production with a line width of 30 µm. The scope of this work package was a process development for reaching the best printing quality, at first, for fingers of 20 µm width, and then, for fingers of 15 µm width. This required, on the one hand, a detailed study and optimization of the printing parameters. On the other hand, the printing paste characteristics had to be investigated and optimized. Whereas the 20 µm width scope was successfuly reached for PTP, the 15 µm finger width scope was not reached due to the shutdown of activities by Utilight.

2.5 WP5: Contact formation and optimization of cell (ISC)

The cell metallization process was optimized at ISC Konstanz, with cell precursors from Hanwha QCells. Different pastes, sheet resistances, processing sequences and firing processes were tested to define best contact properties.

2.6 WP6: Module integration and reliability (MB)

This work package included the following tasks:

- Task 6.1: Process and cost optimization
- Task 6.2: Optimization of module design
- Task 6.3: Module fabrication
- Task 6.4: Module reliability testing

Process and cost optimization, and optimization of module design: Meyer Burger started work on Tasks 6.1 and 6.2 earlier than indicated on project plan, as the customer requests urged us to move forward faster. Wires with In-free coating were qualified in glass-glass modules with bifacial PERC cells and certified at external institute in 2017. In 2018, two new MB SWCT™ customers could be gained thanks to this technological advancement of SWCT™ development. Machine deliveries, process development and ramping up of these production lines were our main commercial tasks in 2019. A new stringer was developed and commercialized in 2018. A new Roll-to-roll unit (RRU, which produces the FWA) was developed in 2019, and released to market in 2020.

Module fabrication and reliability testing (Tasks 6.3 and 6.4) of modules made from PTP cells from ISC Konstanz had started with first mini-modules in middle of 2018 and tests in HF (humidity freeze) chamber. In 2019, PTC (power thermo cycling) and DH (damp heat) chamber tests were carried out to identify the best cell and module process parameters, and to fabricate reliable 60 cell modules fulfilling the power requirements of our project deliverables. In 2020, the focus was on module reliability.

3 Milestones, deliverables and results by work package

Project results are given by work package in the following sections. The highest focus in this report is on work package 6, because this is the work package that was in the full responsibility of the Swiss project partner Meyer Burger and was therefore sponsored by the Swiss Federal Office of Energy (SFOE). Further, all the achievements from work packages 1-5 were harvested in work package 6 and contributed to the outcome and success of this work package.

Table 1 lists the project milestones as defined in the project proposal, and Table 2 lists the deliverables, along with the status at the end of the project.

Table 1: Milestones table.

Milestone	Month	Owner	Title	Status at end of project
1.1	36	ISC	Project management and reports	Achieved
2.1	12	ISC	Verified model of cell and module	Achieved (basic level)
3.1	7	Utilight	Pilot system for cell metallization operational	Achieved
5.1	20	ISC	Identification of main cell factors	Achieved
6.1	36	MB	Module reliability tests concluded	Achieved 1xIEC on the modules. Achieved 3xIEC on best PERC module. Achieved 4xIEC on PERT modules.
6.2	36	MB	Module cost reduction >0.10 USD/W_p	Ca. 0.05 USD/W_p achieved. See section 8 for more details.

Table 2: Deliverables table.

Deliverable	Month	Owner	Title	Status at end of project
4.1	15	Utilight	Printing process for 20 µm lines	Achieved
4.2	24	Utilight	Printing process for 15 µm lines	Not achieved, mainly due to Utilight insolvency.
5.1	22	ISC	First mc-cell optimization	Achieved, but on c-Si cell
5.2	30	ISC	Second mc-cell optimization	Achieved, but on c-Si cell
5.3	36	ISC	High eta cell optimization	Achieved
6.1	24	MB	Module with >8 W_p power gain (compared to 3BB)	Achieved: 30 W_p gain (310 W_p vs. 280 W_p, see section 8)
6.2	33	MB	Module with >15 W_p power gain. Pilot run of min. 20 modules with 15 W_p power gain.	Power requirement achieved. Pilot run was cancelled in agreement with the project sponsor. As a consequence from changing from PTP to SP (due to Utilight insolvency), ISC was not able to supply enough cells to build the modules.

4 WP2: Electrical model of cell and module

The purpose of solar cell metallization and interconnection with smart wires (or any ribbon technique) is to harvest the photoinduced charge carriers in the cells as thoroughly as possible. This means optimization of both the print finger metallization grid, and the smart wire grid, and adjusting the two for optimum electrical charge transport. Theoretical modeling is an aid to achieve this goal. Such calculations have been done on a basic level at ISC Konstanz for single cells, with geometrical and electrical (line and contact resistances) input parameters for PTP metallization. Figure 4 shows the result of such a calculation (on a 6BB PERC cell). For 18 wires connection, and standard cell size (M0 = 156 mm or M2 = 156.75 mm), the optimum is at 110-120 print fingers (ca. 20 µm finger width).

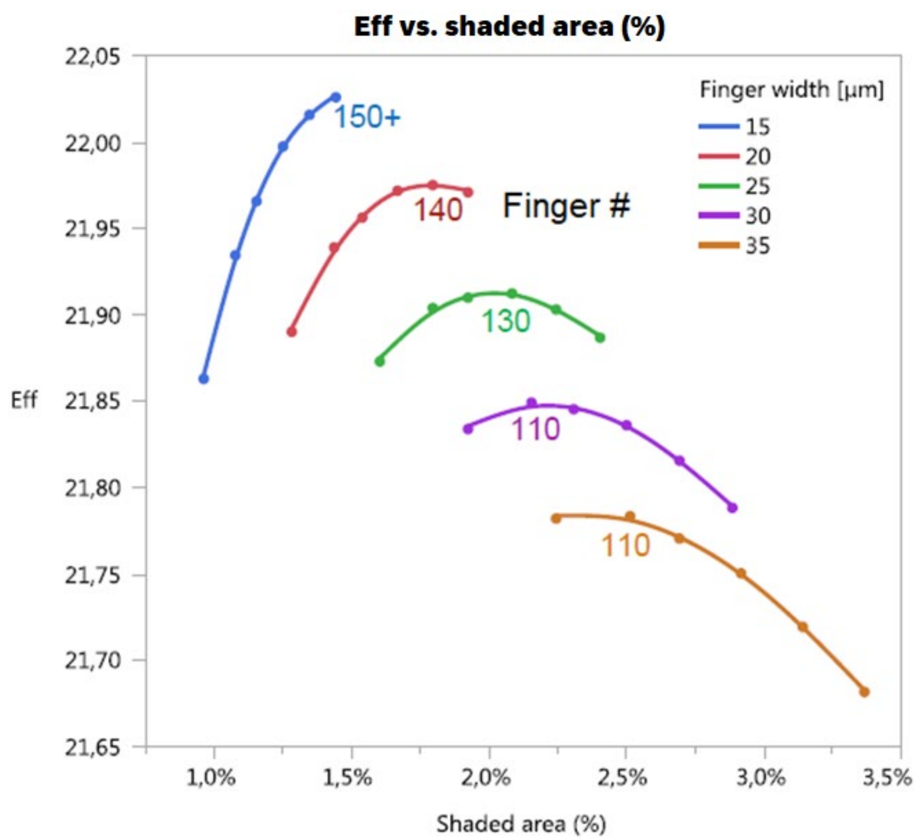


Figure 4: Cell efficiency simulation for variations in metallization finger width (15…30 µm) and number of fingers (100…150). [Ref. 4]

5 WP3: Pilot system for ultra-fine lines

The principles of Pattern Transfer Printing for solar cell metallization are explained in Figure 5. Utilight provided PTP pilot equipment and upgrade kits to ISC Konstanz. Various challenges were solved in the course of the Refined PV project, to improve the print finger uniformity, and the process speed. With the efforts of Heraeus to modify silver pastes, the paste properties were optimized for PTP.

A high technology readiness level of the PTP print system was attained. Utilight evaluated the PTP system in three major PV manufacturing sites in China, and in all of them the PTP process was qualified for production.

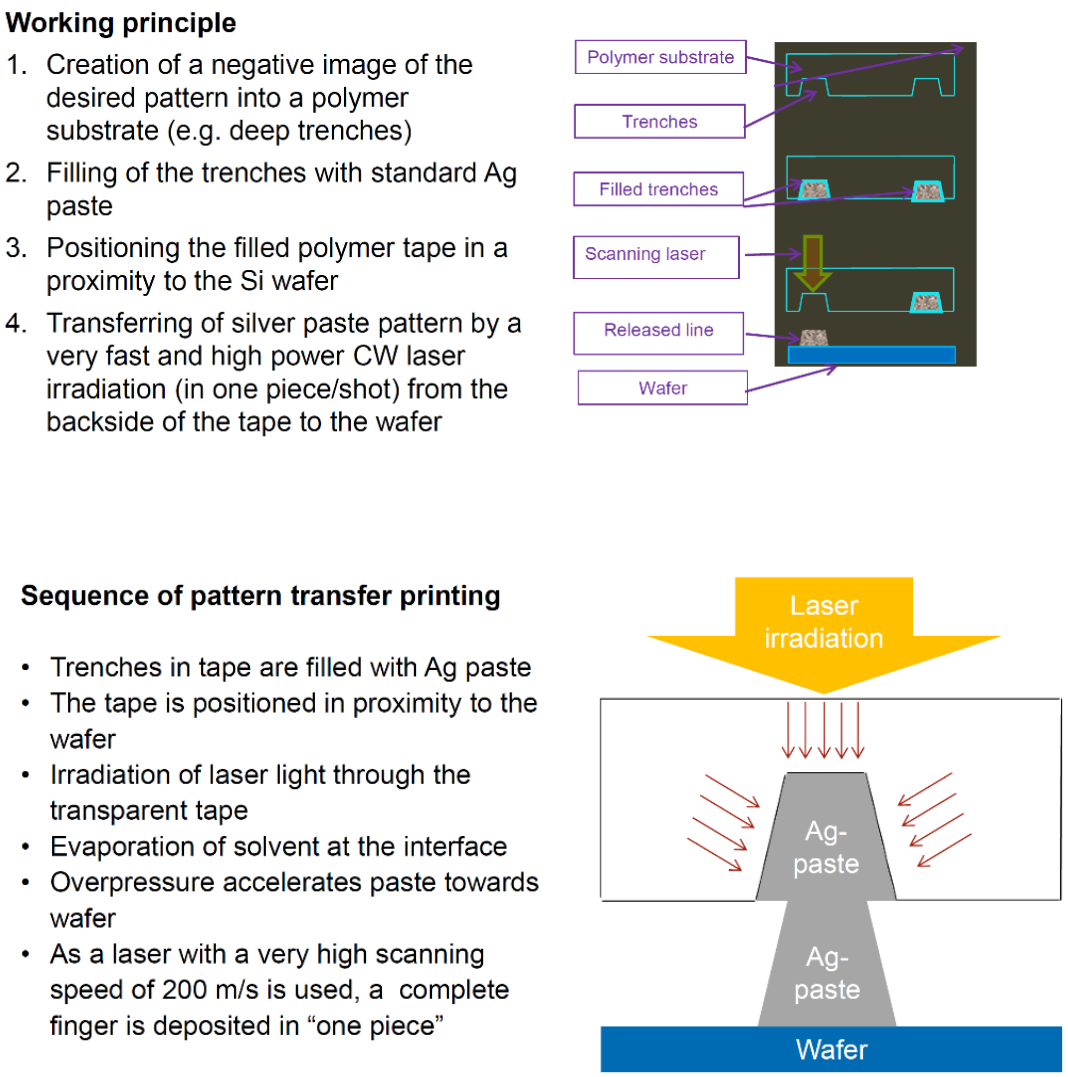


Figure 5: Principles of Pattern Transfer Printing. [Ref. 4]

6 WP4: Print process for ultra-fine lines

At project start, Pattern Transfer Printing (PTP) was able to print reliably in pilot production with a line width of 30 µm. The scope for Refined PV was a process development for reaching lower finger widths. Printing lines with width of ca. 18 µm were achieved in the course of the project. The target of 15 µm finger width was not achieved due to a shutdown of Utilight activities. Figure 6 shows a scanning electron micrograph of a typical PTP metallization finger. Table 3 shows the achieved PTP finger profiles and paste consumption in comparison with a SP reference. The trench width in Table 3 refers to the trench dimension of the tapes that were used in the PTP process [Ref. 2]. The aspect ratio (finger height/finger width) of PTP fingers is significantly higher than of SP fingers. Overall, PTP was able to reduce strongly the paste consumption on cell level.

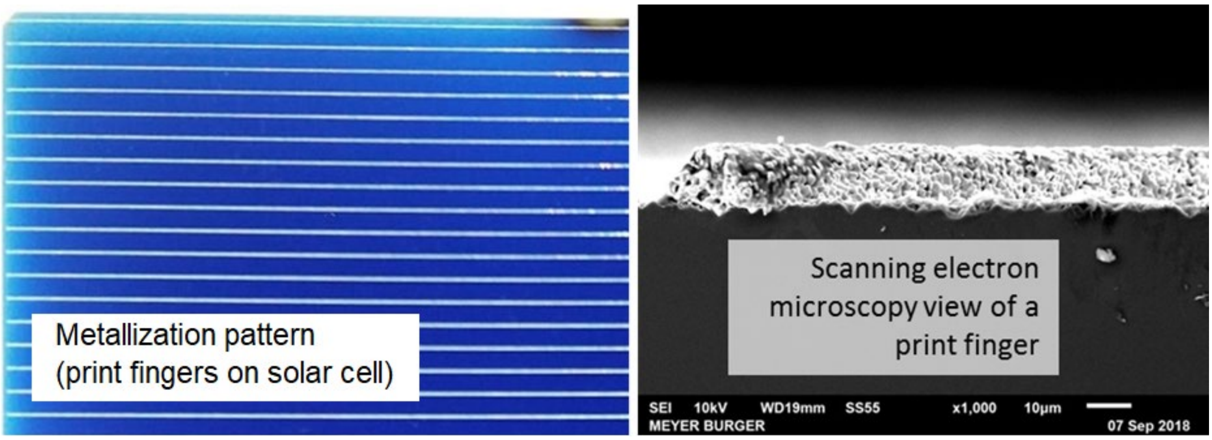


Figure 6: Solar cell surface with PTP-printed silver paste metallization (print fingers), and scanning electron micrograph of a print finger, trench width 30 µm.

Table 3: Typical finger profiles and paste consumption.

Trench width [µm]	Print method	Finger height [µm]	Finger width [µm]	Finger cross section [µm²]	Finger aspect ratio	Paste consump-tion [mg]
20	PTP	8.0	18.7	139	0.43	17
30	PTP	12.0	21.5	219	0.56	27
28	SP	14.5	37.9	418	0.38	68

7 WP5: Contact formation and optimization of cell

In collaboration with Utilight as a PTP provider, QCells as a cell precursor (non-metallized solar cell) supplier, and Heraeus as a silver paste supplier, ISC made a thorough screening to find the optimum cell metallization, yielding the best cell parameters (high fill factor, high cell efficiency). It was decided in the project to put the focus on mono-crystalline PERC cells, since multi-crystalline are decreasing in market share.

In a typical investigation (test run), cell precursors were metallized with PTP fingers of a defined profile. The resulting metallization finger profiles were characterized microscopically. Then, the electrical properties of the metallization fingers were measured (line resistance, contact resistivity). Finally, the cells were characterized by current-voltage (IV) analysis.

Conclusions from these tests:

- With fineline PTP printing, the silver print laydown was decreased to ca. 28 mg for optimum cells. Actual solar cells (of the PERC type) use about 80 mg silver, which is, besides the wafer, the most costly material in cell processing.
- Fineline PTP printing allows for aspect ratios >0.6 (finger height/finger width), increasing the cross section for narrow fingers. PTP leads to a gain on Jsc (short circuit current) of the cell due to narrow fingers with low shading of the active cell surface.
- There is a trade-off between low cell shading (high Jsc) and electrical conductivity of the metallization grid. I.e., higher line resistance of the silver fingers leads to a decrease of the cell FF (fill factor), which means lower cell efficiency.
- As a result, the highest cell efficiency is found at a finger width in the range 25 µm…30 µm. Because of the silver savings of the 25 µm finger cells, these were the favoured cells for the most promising module tests (see work package 6).
- The mono-crystalline cells produced in the Refined PV framework and built into modules had an efficiency in the range 21.1…22.4 %.

Overall, the gains of PTP over SP were lower than expected. Line resistances of PTP fingers were higher than the screen printing reference, because of lower finger cross section. Nevertheless, 25 and 30 µm PTP fingers exceeded the results of the SP reference, due to gains in Jsc and Voc.

8 WP6: Module integration and reliability

8.1 Components, process and cost optimization (Task 6.1)

SWCT™ technology, in comparison with conventional busbar technology, offers the advantage of lower silver consumption for cell metallization. This is because SWCT™ technology consists of a dense mesh of contact points between wires and metallization fingers on the cell surface. To benefit fully from this cost advantage, both the wires and the electrode foil (polymer film) used in SWCT™ technology have to be optimized with respect to cost.

For the wire, we use indium-free wires now. This has enabled a decrease of 50 % of the wire price for the same power and reliability (in comparison with the first SWCT™ generation, containing indium). On the electrode foil side, film improvement has gone on in close cooperation with foil suppliers. For the type of cells used in the Refined PV project (PERC), a foil was developed with high reliability in the module, but also good processability on the SWCT™ tools.

Further savings in module production costs arise from the reduced CAPEX (capital expenditure). This was achieved during Refined PV by advancing our machines (stringer and RRU) to a higher throughput, at a lower cost.

Finally, increasing the cell and module power at a given BoM (bill-of-materials), and given production line costs, means another cost reduction per Watt peak (W_p) of energy. A higher cell and module efficiency reduces costs all along the value chain.

An estimate for overall cost savings in Refined PV modules, including materials, production cost, and power gain, is given in Figure 7 and Figure 8. Power gain is included by reporting costs in USDcts/Wp. A module manufacturer's cost of ca. 30 USDcts/W_p was assumed here (status 2018, middle of Refined PV project). However, this cost has dropped in the past years at a rate of roughly 20 % per year.

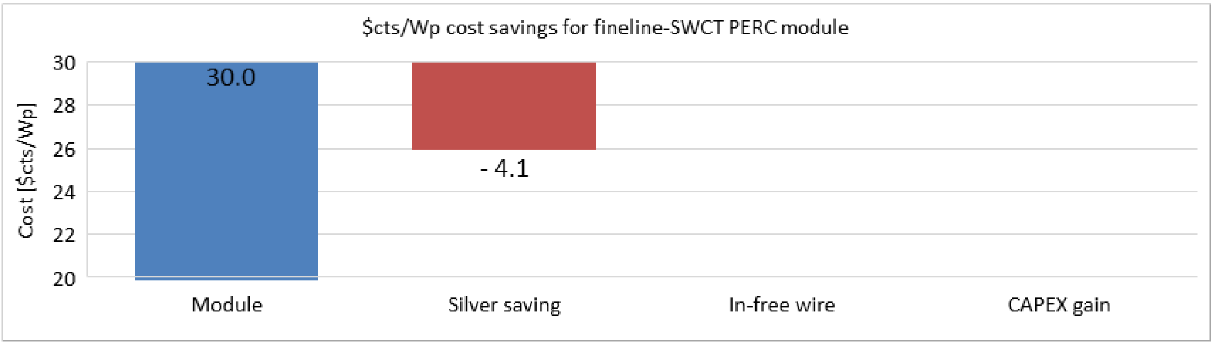


Figure 7: Cost savings in Refined PV modules, in comparison with a conventional busbar module.

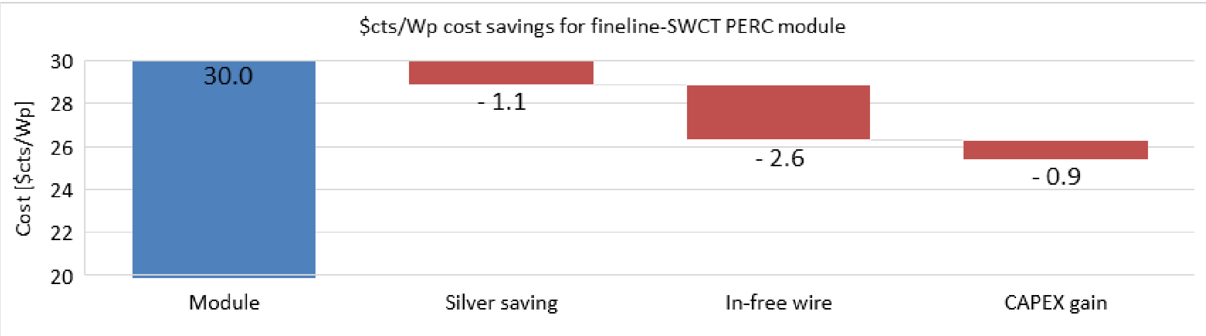


Figure 8: Cost savings in Refined PV modules, in comparison with a SWCT™ module of the first generation.

Figure 7 is a comparison with a conventional busbar module (at start of Refined PV project), and Figure 8 is a comparison with a SWCT™ module of the first generation (status when initiating Refined PV project). For lack of data, Figure 7 considers only the silver savings. Silver savings is higher in Figure 7 than in Figure 8, because SWCT™ was a silver savings technology from the very beginning. Overall, cost savings is ca. 4–5 USDcts/W_p in both comparisons.

A module cost reduction >0.10 USD/W_p was strived for in milestone 6.2 for Refined PV (see Table 1). This was not achieved, if considered under this approach. However, the general cost drop in PV manufacturing affects all module technologies. Under this aspect, overall module price has decreased by more than 0.10 USD/W_p even without the specific gains from Refined PV [Ref. 1].

8.1.1 Machines

Two machines are establishing the core production equipment of SWCT™ technology: the roll-to-roll unit (RRU) for the production of foil-wire assembly (FWA), and the stringer for the production of cell strings. Both machines were subject to complete redesign as well as process and cost optimization in the course of the Refined PV project.

- The roll-to-roll unit (RRU) produces foil-wire assembly (FWA) from polymer films and wires. The FWA is then used for cell interconnection in the stringer. A new RRU was released to market in 2020 under the name RRU540. In comparison to the previous version, it decreased the footprint by a factor of 2. Further, it offered an important increase in throughput as well as a better optimization and control of the process.
- The stringer produces cell strings from FWA and cells. The new stringer was released to market at the end of 2018 under the name IBEX-CCS550.

Both machines have involved big efforts in hardware design, software control, and process development. They have to meet the requirements for various polymer films, wires, and cell types and formats, according to the customer needs.

8.2 Optimization of module design (Task 6.2)

8.2.1 Half-cell modules

For module power optimization, a half-cell module design was established and tested. It is shown in Figure 9. It consists of having 2 submodules in parallel and having 10 (or 12) half-cells in series per string for a 120 (or 144) half-cell module. The division of the module into 2 sub-modules required a new design of string interconnection, in comparison with a conventional 60-cell module. A new design was established in compliance with automatic interconnector soldering. Figure 9 shows a picture of the first half-cell module produced at MB with the new design.

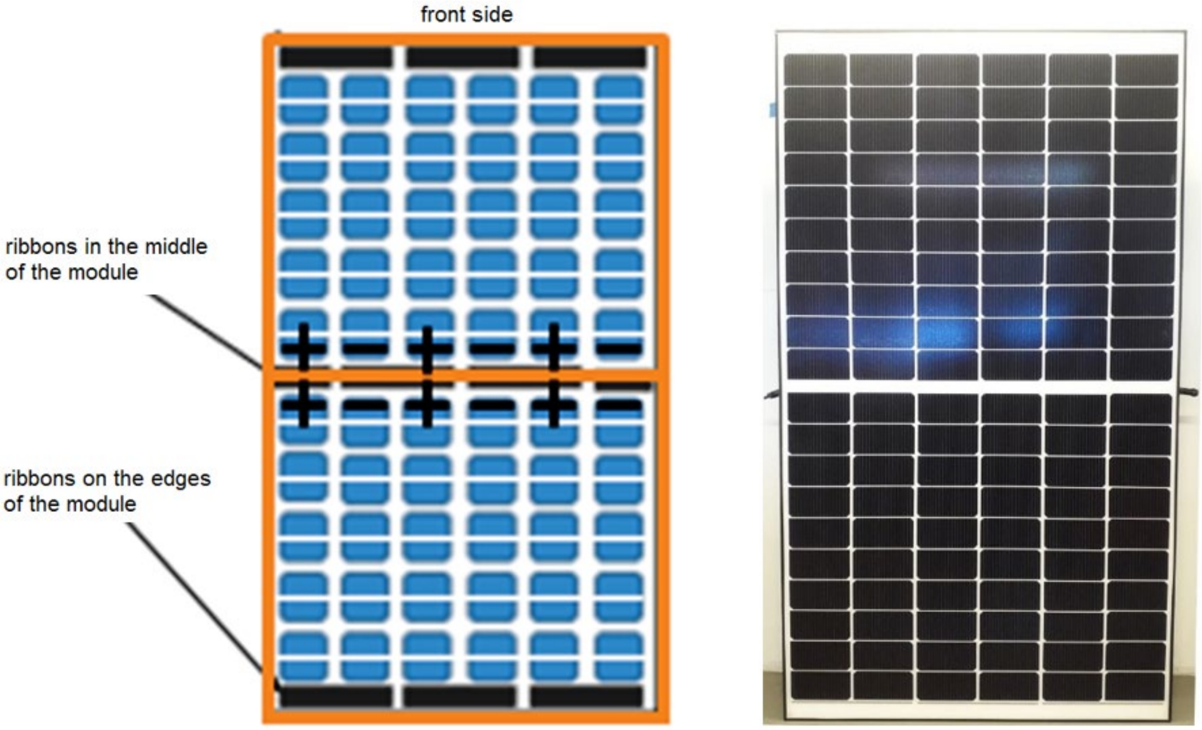


Figure 9: Half-cell module design.

8.3 Module fabrication and reliability testing (Tasks 6.3, 6.4)

8.3.1 Solar module fabrication, materials, and testing methods

SWCT^{TM}-interconnected glass-backsheet modules were built at Meyer Burger from cells strings produced on a CCS550 stringer (or its precursor) as described earlier in this report. The matrix layup (assembly of module components, and soldering of interconnectors) was done manually, and the modules were laminated on a JT (or NG) laminator from Meyer Burger.

Bill-of-material (BoM): The FWA (polymer films and wires) and all other module components (front glass, encapsulant, backsheet, interconnector ribbons, junction boxes) were chosen according to our best practice, for best fit with the PERC cells used in most of the Refined PV tests.

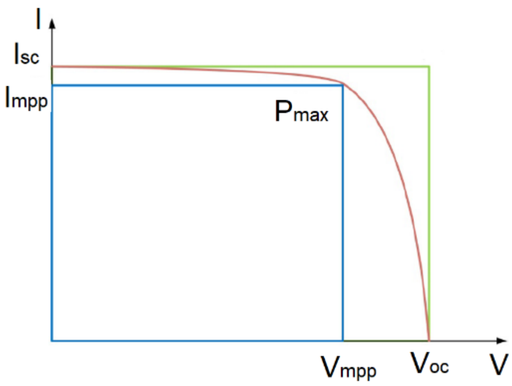


Figure 10: Current-voltage (IV) curve of a solar cell or module. Characteristic parameters: open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power ($P_{max} = V_{mpp}*I_{mpp}$) at the maximum power point (mpp), fill factor (FF). FF = $P_{max}/(V_{oc}*I_{sc})$.

The modules were characterized by current-voltage (IV) analysis, at 1000 W/m^2 AM 1.5 standard light spectrum, with a Pasan module inspection system (MIS), by electroluminescence (EL) imaging with a MBJ EL inspection system, and by visual inspection. Cells were characterized by IV analysis with a Pasan SpotLight cell tester before module building.

Module reliability was tested in climatic chambers (Figure 11). After each climatic chamber test run, the modules were characterized by V analysis, EL, and visual inspection.

Climatic chambers were available for power thermal cycling (PTC), damp heat (DH), and humidity freeze (HF) testing. Tests were done according to the norm IEC 61'215. This means a test pass criterion of P_{max} degradation <5 %.

- "Pass 1 x IEC" = pass PTC 200 cycles (33 days), or DH 1000 h (42 days), or HF 10 cycles (10 days), with P_{max} degradation <5 %.
- "Pass 2 x IEC" = pass PTC 400 cycles, or DH 2000 h, or HF 20 cycles, with P_{max} degradation <5 % vs. initial measurement.
- etc.

Power thermal cycling test: To determine the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperature.

Damp heat test: To determine the ability of the module to withstand the effects of long-term penetration of humidity.

Humidity freeze test: To determine the ability of the module to withstand the effects of high temperature and humidity followed by sub-zero temperatures.

Figure 11: Left: Climatic chamber (PTC, DH). Middle/right: Examples of 60-cells, and 16-cells modules.

8.3.2 Fine-line metallized cell performance in SWCT^{TM} modules

In collaboration with Utilight as a PTP equipment supplier, and Heraeus as a paste supplier, ISC improved and tested different PTP patterns (metallization geometries) and silver pastes, to find the optimum with respect to cell efficiency and silver consumption. Meyer Burger supported this activity by building these cells into modules, to confirm the compatibility with SWCT^{TM}. Figure 12 shows the IV analysis result of two test series (Runs 2707 and 2900), as an example. The current-voltage behavior of the modules vs. cells shows losses in short-circuit current and fill factor from cell to module. The losses may be explained to some extent by a bias in the cell measurement (too high nominal current of the reference cell). One of the two test series (Run 2900) shows unexpected losses in open-circuit voltage, as well as higher FF losses than the other test series; however, those cells had not been regenerated after contact firing prior to module building. Overall, the IV curves, characteristic parameters, and the transition from cell to module, were in the same range as for cells with conventional silver metallization.

The IV curve characteristic parameters showed the same trends for PTP and the SP reference (included in both test series). With regard to PTP finger width, 25-30 µm gave the best performance. Lower finger width (20 µm) showed a decrease in fill factor because of higher metallization finger line resistance. However, this becomes apparent on cell level already (before module building); the SWCT^{TM} modules just reflect what is happening on cell performance level.

The cell-to-module power loss (CTM) values shown in Figure 12 (bottom right graph) are impaired by the bias in the cell measurement mentioned above. Further, the modules fabricated in this test were not optimized with respect to cell-to-module power loss (CTM).

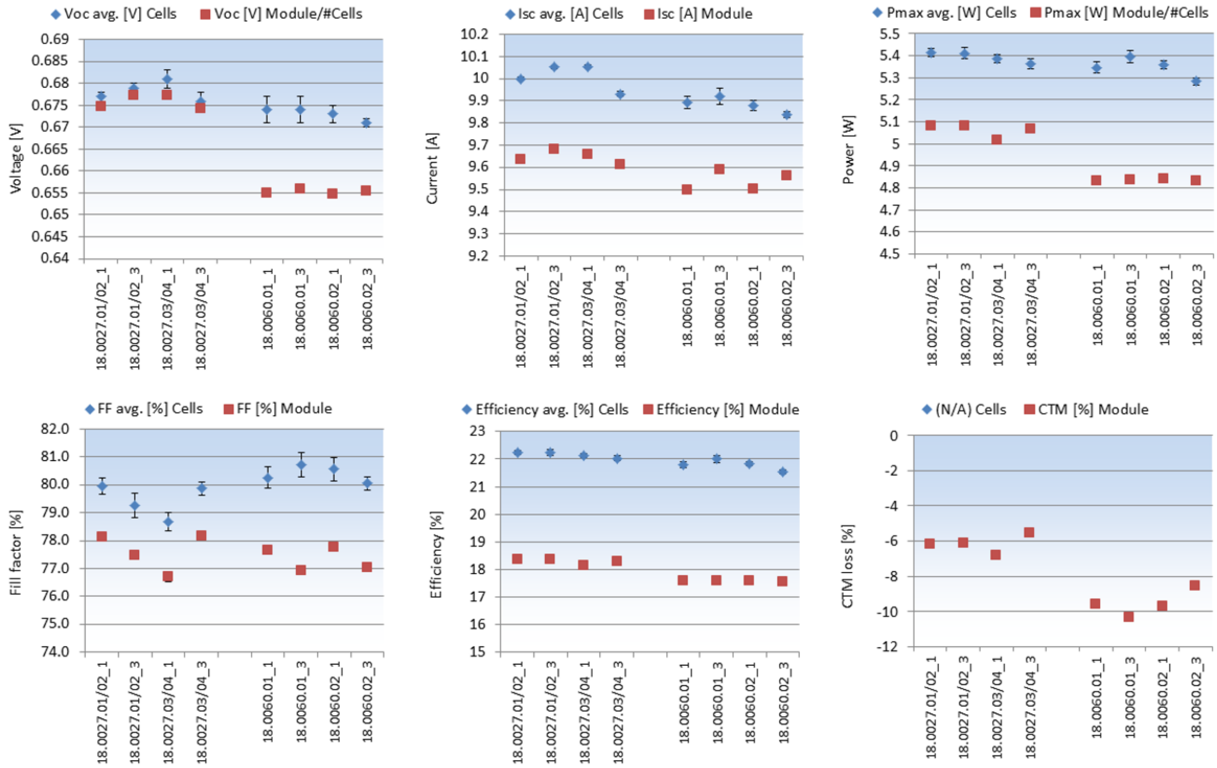


Figure 12: Current-voltage (IV) analysis of cells and modules from cell metallization tests. Each cell modification was built into 20-cell strings, assembled into 60-cell modules. Various metallizations (silver paste and finger width) were compared with each other. Module efficiency was calculated based on a 60-cells module size of 166.4 x 99.6 cm (not to be confused with cell efficiency in module). See Table 4 for module designations (Runs 2707, 2900).

Table 4 is a list of the modules described in this and the following sections. Note that the reliability tests were done in different climatic chambers (PTC, DH, HF) for different test series; the chamber type is written in the table header for each test series.

Two module sizes were built: 16-cells and 60-cells. As a means to save materials and cells, three 20-cell strings with different cell types were assembled into 60-cell modules in many cases, and measured separately. 60-cell modules with only one cell type were built as well. In Table 4, all P_{max} values from these modules are scaled (normalized) to 60 cells for easier comparison.

Table 4: Modules and cell descriptions for section 8.

Module	BoM type	Cell metallization (and additional information) Run 2505 (22103-22106) Run 2603 (22113-22114)	P_{max} [W] for 16 cell module	CTM [%]	HF10 P_{max} Degr. [%]	HF20 P_{max} Degr. [%]	HF30 P_{max} Degr. [%]	HF40 P_{max} Degr. [%]
22103	1	PTP, paste 1330, trench 30 µm, 112 fingers (cell format FSQ M0)	77.7	-6.7	-2.8	-2.8	-2.8	--
22104	1	PTP, paste 1330, trench 20 µm, 112 fingers (cell format FSQ M0)	77.5	-7.3	-4.9	-4.9	-4.9	--
22105	1	PTP, paste 1349, trench 30 µm, 112 fingers (cell format FSQ M0)	77.2	-7.2	-1.1	-1.1	-1.1	--
22106	1	PTP, paste 1349, trench 20 µm, 112 fingers (cell format FSQ M0)	77.5	-7.3	-4.3	-4.3	-4.3	--
22113	1a	PTP, paste 1349, trench 30 µm, 112 fingers (cell format FSQ M0)	78.0	-7.9	-0.3	-0.3	-0.3	--
22114a	1	PTP, paste 1349, trench 30 µm, 112 fingers (multicrystalline cell, cell format FSQ M0)	75.1	-2.8	-2.3	-2.3	-2.3	--
22114b	1	PTP, paste 1349, trench 30 µm, 112 fingers (cell format FSQ M0 with 6 busbars)	78.3	-7.0	-1.2	-1.2	-1.2	--
Module	**BoM type**	**Cell metallization (and additional information)** Run 2707 (18.0027.xx)	**P_{max} [W] for 60 cell module**	**CTM [%]**	**PTC200 P_{max} Degr. [%]**	**PTC400 P_{max} Degr. [%]**	**PTC600 P_{max} Degr. [%]**	**PTC800 P_{max} Degr. [%]**
18.0027.01_1	1	PTP, paste 1489, trench 30 µm, 112 fingers	304	-6.3	-3.2	-9.7 (note 1)	--	--
18.0027.01_3	1	PTP, paste 1490, trench 30 µm, 112 fingers	305	-6.2	-3.3	-10.4 (note 1)	--	--
18.0027.03_1	1	PTP, paste 1490, trench 20 µm, 112 fingers	301	-6.9	-2.9	-5.3	--	--
18.0027.03_3	1	SP, paste 9641B, trench 28 µm, 112 fingers	303	-5.7	-4.6	-5.5	--	--
Module	**BoM type**	**Cell metallization (and additional information)** Run 2707 (18.0027.xx)	**P_{max} [W] for 60 cell module**	**CTM [%]**	**DH1000 P_{max} Degr. [%]**	**DH2000 P_{max} Degr. [%]**	**DH3000 P_{max} Degr. [%]**	**DH4000 P_{max} Degr. [%]**
18.0027.02_1	1	Same as 18.0027.01_1	305	-6.0	-4.1	-5.3	--	--
18.0027.02_3	1	Same as 18.0027.01_3	305	-6.1	-3.6	-5.2	--	--
18.0027.04_1	1	Same as 18.0027.03_1	301	-6.8	-3.6	-5.6	--	--
18.0027.04_3	1	Same as 18.0027.03_3	304	-5.4	-3.2	-5.1	--	--
Module	**BoM type**	**Cell metallization (and additional information)** Run 2768 (18.0049.xx)	**P_{max} [W] for 16 cell module**	**CTM [%]**	**PTC200 P_{max} Degr. [%]**	**PTC400 P_{max} Degr. [%]**	**PTC600 P_{max} Degr. [%]**	**PTC800 P_{max} Degr. [%]**
18.0049.01	1	PTP (front; PTP/SP rear side), paste 9620c, trench 30 µm, 126 fingers (p-PERT cell, bifacial)	75.8	-9.1	1.5	2.0	1.5	2.3
18.0049.02	1	PTP (front; SP/SP rear side), paste 9620c, trench 30 µm, 126 fingers (p-PERT cell, bifacial)	76.0	-7.4	0.3	0.5	-0.1	1.1
Module	**BoM type**	**Cell metallization (and additional information)** Run 2768 (18.0049.xx)	**P_{max} [W] for 16 cell module**	**CTM [%]**	**DH1000 P_{max} Degr. [%]**	**DH2000 P_{max} Degr. [%]**	**DH3000 P_{max} Degr. [%]**	**DH4000 P_{max} Degr. [%]**
18.0049.01	1	(DH chamber test after PTC test)	77.5	-7.0	0.9	0.0	-0.3	-3.2
18.0049.02	1	(DH chamber test after PTC test)	76.8	-6.4	0.4	-0.4	-0.8	-6.1

Module	BoM type	Cell metallization (and additional information) Run 2900 (18.0060.xx) Run 2991 (18.0071.xx)	P_{max} [W] for 60 cell module	CTM [%]	PTC200 P_{max} Degr. [%]	PTC400 P_{max} Degr. [%]	PTC600 P_{max} Degr. [%]	PTC800 P_{max} Degr. [%]
18.0060.01_1	2	PTP, paste 1349, trench 30 µm, 112 fingers	290	-9.6	-5.9	-4.9	-4.9	--
18.0060.01_3	2	PTP, paste 1349, trench 25 µm, 126 fingers	290	-10.3	-3.0	-5.1	-8.3	--
18.0060.02_1	2	PTP, paste 1491, trench 25 µm, 126 fingers	290	-9.7	-6.2	-2.5	-2.2	-5.0
18.0060.02_3	2	SP, paste 9641B, trench 28 µm, 112 fingers	290	-8.5	-6.2	-2.9	-2.8	-5.9
18.0071.01	2	PTP, paste 1349, trench 25 µm, 126 fingers	310	-5.1	-4.0	-6.9	--	--
18.0071.02	2a	PTP, paste 1349, trench 25 µm, 126 fingers	311	-4.9	-4.1	-8.1	--	--
Module	**BoM type**	**Cell metallization (and additional information)** Run 3106 (18.0083.xx)	**P_{max} [W] for 16 cell module**	**CTM [%]**	**PTC200 P_{max} Degr. [%]**	**PTC400 P_{max} Degr. [%]**	**PTC600 P_{max} Degr. [%]**	**PTC800 P_{max} Degr. [%]**
18.0083.01	2	SP, paste SOL9641B, 39 µm, 112 fingers (rear side without Ag pads)	81.4	-5.7	-3.2	-2.9	--	--
18.0083.02	2	SP, paste SOL9641B, 39 µm, 112 fingers (rear side with Ag pads)	81.4	-5.5	-2.4	-1.5	--	--
Module	**BoM type**	**Cell metallization (and additional information)** Run 3178 (18.0089.01)	**P_{max} [W] for 16 cell module**	**CTM [%]**	**PTC200 P_{max} Degr. [%]**	**PTC400 P_{max} Degr. [%]**	**PTC600 P_{max} Degr. [%]**	**PTC800 P_{max} Degr. [%]**
18.0089.01	2	SP, paste SOL9651B, screen opening 22 µm, 120 fingers	81.8	-5.0	-6.1	--	--	--

- Note 1: A chamber operation failure may have caused increased degradation of module 18.0027.01.
- BoM type refers to the type of FWA film used in the module.
- PTP = pattern transfer printing, SP = screen printing.
- Cell type is monocrystalline PERC, format M2 or “M2+” (156.75 cm or 158 cm), monofacial (full aluminium rear side), print finger metallization without busbars, unless otherwise stated. FSQ M0 = full square M0 (156 cm).
- CTM = cell-to-module power loss.

8.3.3 PTC chamber tests

A key module reliability indicator is given by the power thermal cycling (PTC) chamber test. In this test, the module is subject to temperature cycles in the range -40…+85 °C, while a current profile (0/8 A) is applied to the modules as an additional fatigue stress.

Figure 13 shows the IV analysis results for two PTC module test series. 20-cell strings with different cell types were assembled into 60-cell modules for this test. Table 4 lists the investigated cell types and module parameters.

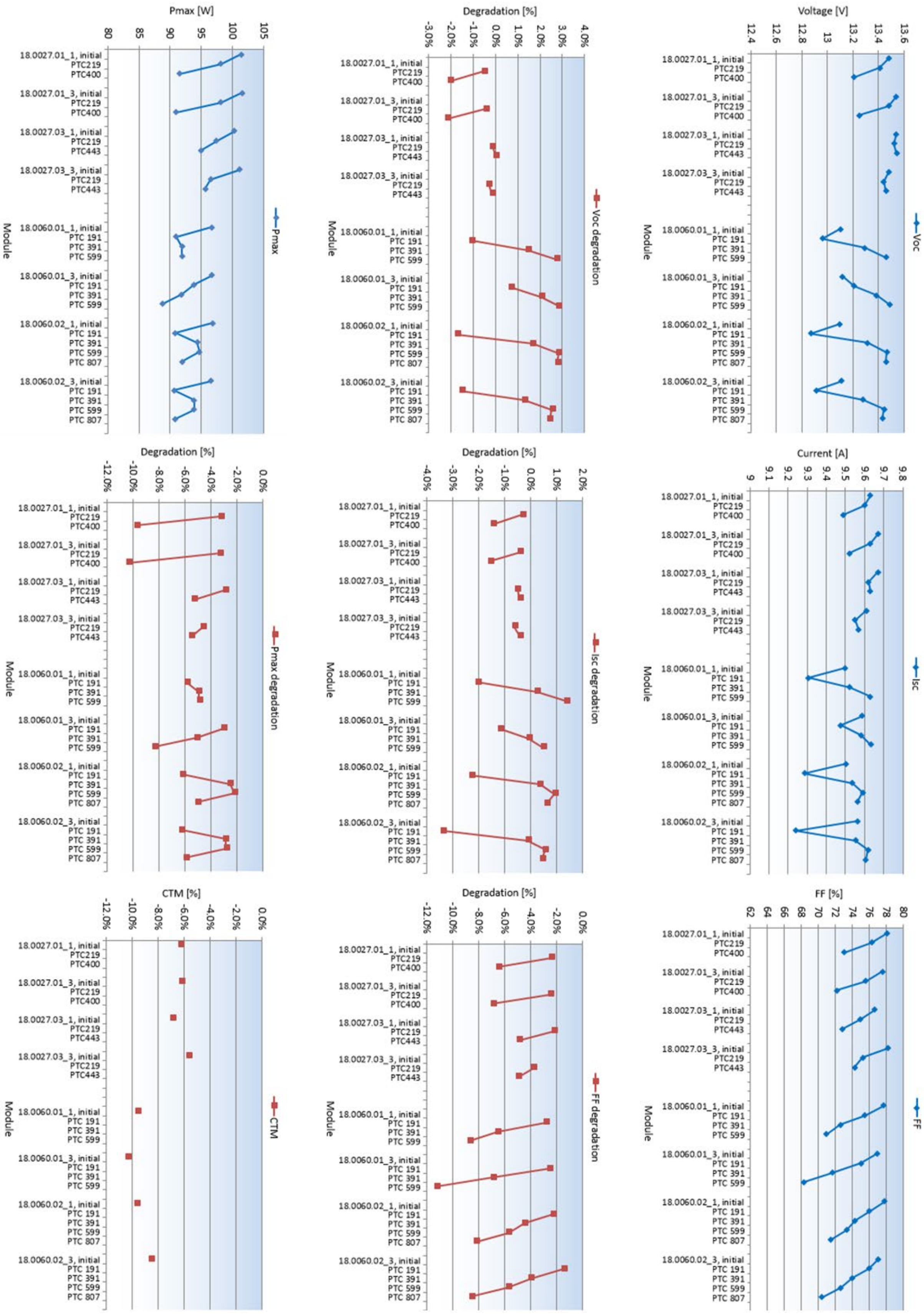
Test results:

- Most modules passed 1 x IEC in PTC (<5 % degradation after 200 PTC cycles)
- Part of the modules passed 2 x IEC in PTC (<5 % degradation after 400 PTC cycles).
- One module (with 25 µm finger width) passed 3 x IEC in PTC (<5 % degradation after 600 PTC cycles) [but failed at 1 x IEC].

Conclusions:

- The modules show good reliability. Albeit, an industrialization of this module type requires further optimization. Passing 1 x IEC is sufficient for module certification (at TÜV). However, according to our internal benchmark at Meyer Burger, for launching a new commercial module type, modules have to pass 3 x IEC at least (i.e., <5 % P_{max} degradation after 600 PTP cycles, or 3000 h in DH chamber, or 30 HF cycles).
- An analysis of possible degradation mechanisms will be given in section 8.3.6.
- No systematic trends could be identified concerning the different metallization patterns. This statement is also valid for the DH and HF chamber tests shown in the following sections. This means that the combination of fine-line PTP cell metallization with SWCTTM module interconnection technology establishes a robust module in a stable process window.
- IV analysis results showed differences between modules, which we attribute to non-systematical (i.e., statistical/random) errors. Possible sources of random errors: differences in cell precursors, ageing and variations of consumables for cell metallization and module building, irregularities and technical failures in chambers cycling, calibration errors in module IV measurement, and others.

Figure 13 (on page 28): PTC chamber reliability testing. Current-voltage (IV) analysis of different cell metallization types built into 20-cell strings, assembled into 60-cell modules. Initial measurement is shown along with IV analysis results after 200/400/600/800 cycles in PTC chamber. See Table 4 for module designations. (Runs 2707, 2900).


Pmax [W]
Module
Pmax
Degradation [%]
Voc degradation
Voltage [V]
Voc
Degradation [%]
Pmax degradation
Degradation [%]
Isc degradation
Current [A]
Isc
CTM [%]
CTM
Degradation [%]
FF degradation
FF [%]
FF
18.0027.01_1, initial
PTC219
PTC400
18.0027.01_3, initial
18.0027.03_1, initial
PTC443
18.0027.03_3, initial
18.0060.01_1, initial
PTC 191
PTC 391
PTC 599
18.0060.01_3, initial
18.0060.02_1, initial
PTC 807
18.0060.02_3, initial

8.3.4 DH chamber tests

In the damp heat (DH) test, the module is subject to high temperature and humidity for an extended time period (+85 °C, 85 %, 1000 h).

Figure 14 shows the IV analysis results for a DH module test series. 20-cell strings with different cell types were assembled into 60-cell modules for this test. Table 4 lists the investigated cell types and module parameters.

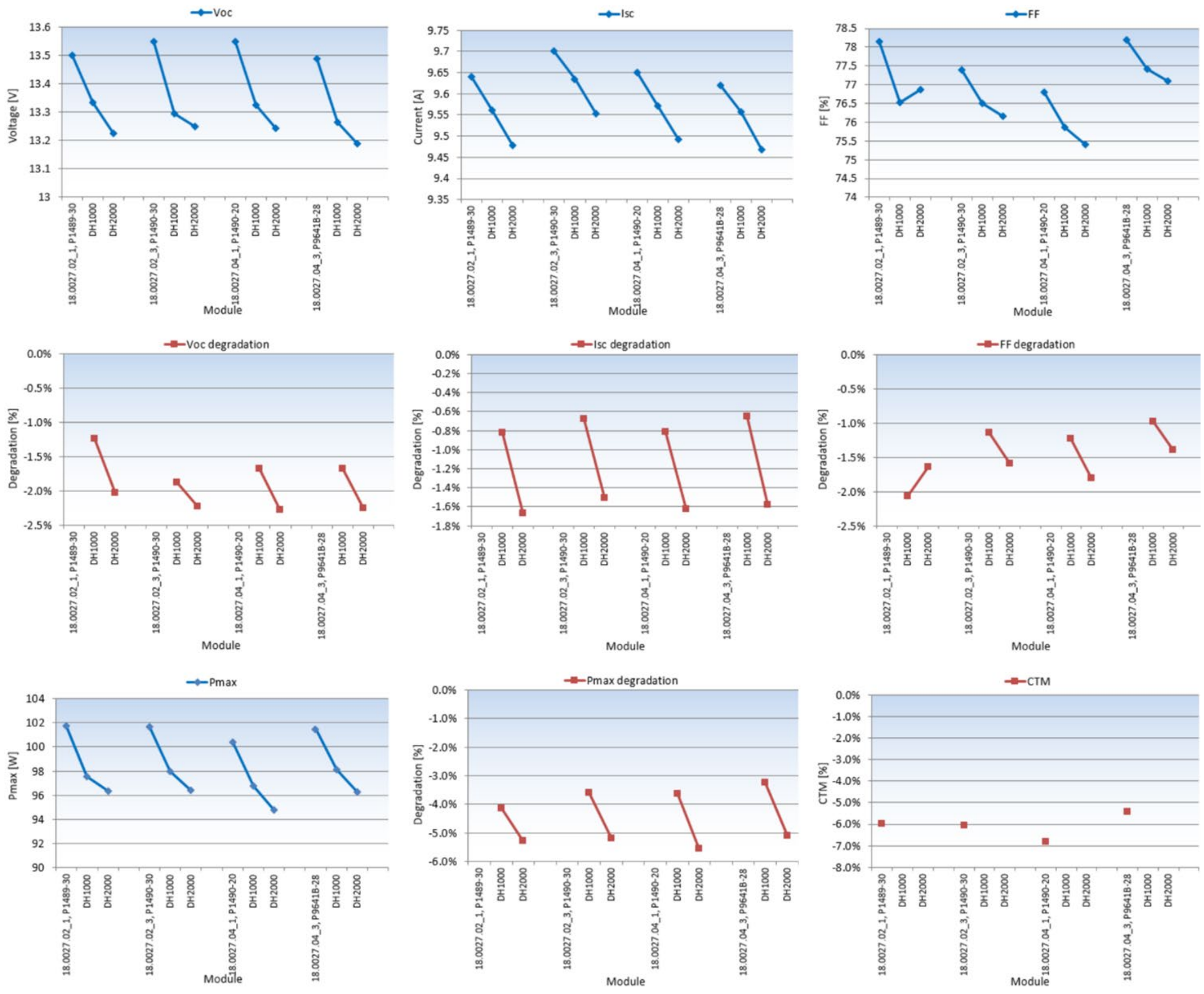


Figure 14: DH chamber reliability testing. Current-voltage (IV) analysis of different cell metallization types built into 20-cell strings, assembled into 60-cell modules. Initial measurement is shown along with IV analysis results after 1000/2000 h in DH chamber. See Table 4 for module designations. (Run 2707).

Test results:

- All modules passed 1 x IEC in DH (<5 % degradation after 1000 h in DH chamber).
- All modules failed 2 x IEC in DH (>5 % degradation after 2000 h in DH chamber).
- Conclusions: See under PTC chamber tests.

8.3.5 HF chamber tests

In the humidity freeze (HF) test, the module is subject to temperature cycles in the range -40…+85 °C in a highly humid atmosphere.

Figure 15 shows the IV analysis results for a HF module test series. For HF chamber tests, 16-cell modules were built and tested (the HF chamber does not support larger module formats). Table 4 lists the investigated cell types and module parameters.

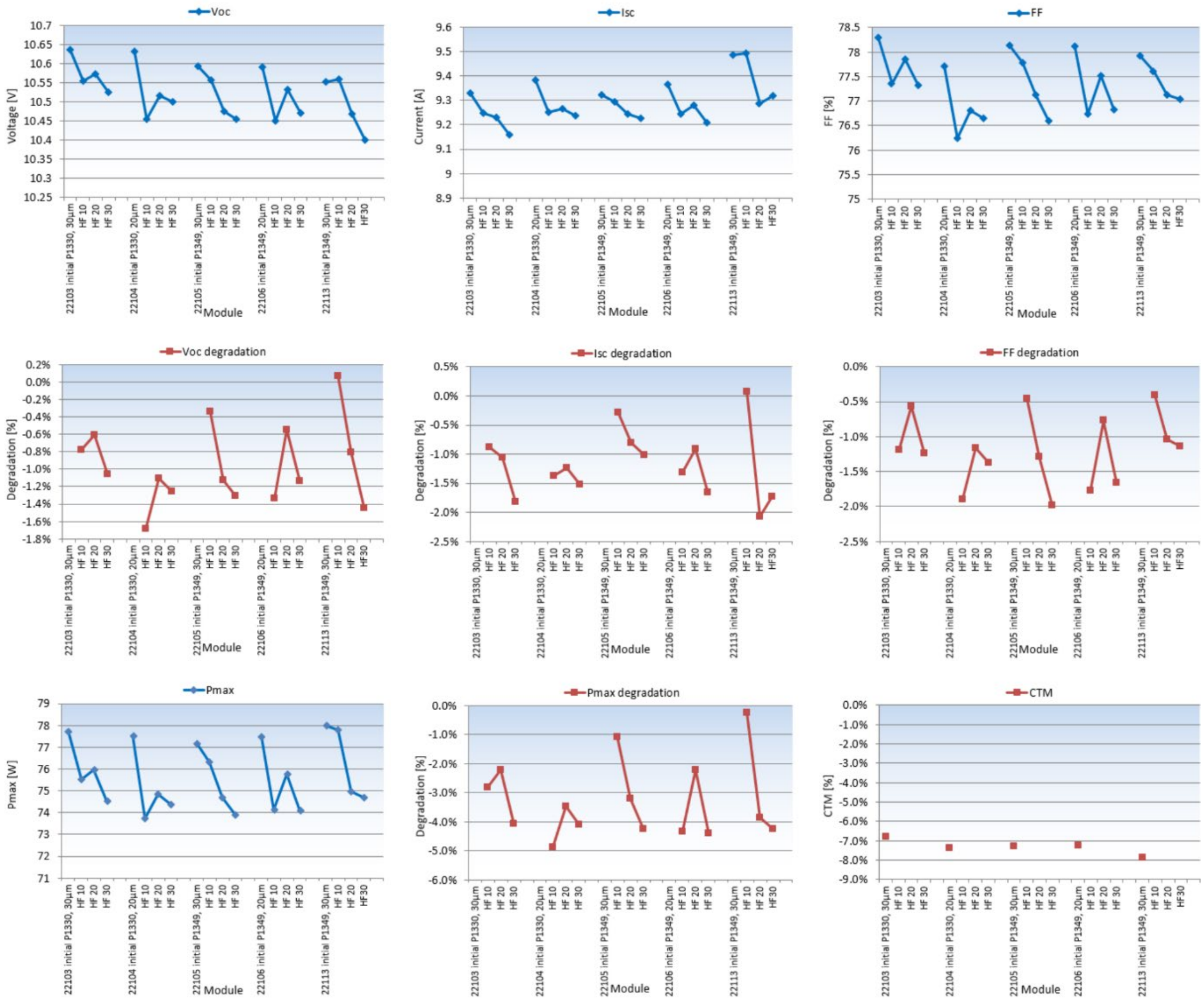


Figure 15: HF chamber reliability testing. Current-voltage (IV) analysis of different cell metallization types built into 16 cell modules. Initial measurement is shown along with IV analysis results after 10/20/30 cycles in HF chamber. See Table 4 for module designations. (Runs 2505, 2603)

Test results:

- All modules passed 3 x IEC in HF (<5 % degradation after 30 HF cycles).
- Conclusions: See under PTC chamber tests.

8.3.6 Analysis of possible degradation mechanisms

Electroluminescence images are a diagnostic tool for understanding IV analysis results, module failures and degradations.

Figure 16 shows EL images for module 18.0027.01 (as an example) at initial status (left image), and after 400 PTC cycles (right image). The vertical shadow lines must be neglected, they are due to technical restrictions of the instrumentation. Transversal lines on all cells occur both on the initial status, and after 400 PTC cycles. The most probable explanation for these lines is that they arise from cell processing, but since they did not increase in the course of the chamber test, they do not explain the degradation that occurred during the chamber test. On the other hand, a difference in cells brightness occurs on the right image (after 400 PTC cycles). We attribute this to electrical contact loss on the rear side of the cells.

In section 8.3.8, modules from a bifacial cell of the p-PERT type will be discussed. They have been investigated for comparison.

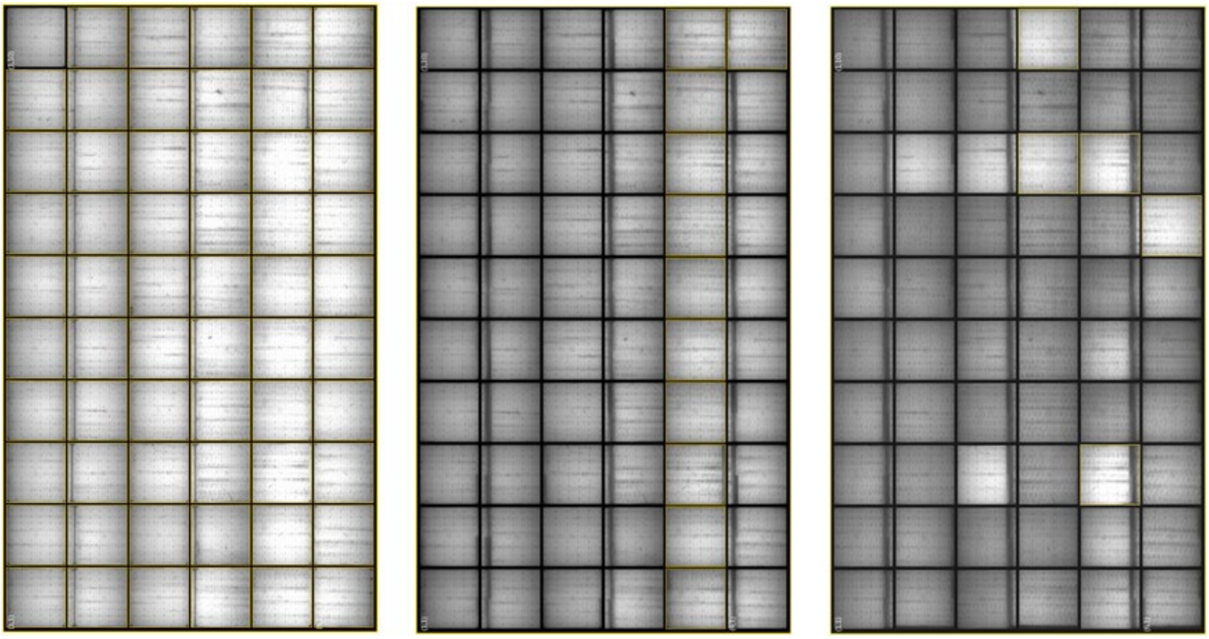


Figure 16: EL images for module 18.0027.01 at initial status (left), and after 200/400 PTC cycles (middle/right).

8.3.7 Reliability improvement through cell rear side modification

To overcome the module reliability issues described above, silver metallization pads (Ag pads) were added to the rear side metallization of the monofacial PERC cells. The Ag pads were placed such that the smart wires for cell interconnection were positioned exactly on the pads. A 16-cell module was built from these cells, and the reliability was tested in PTC climatic chamber in comparison with a 16-cell module made from cells without pads. Figure 17 shows the cells, and Figure 18 shows the module performance and reliability.

After chamber testing, the module made from cells with Ag pads showed lower degradation than the module made from cells without pads, due to lower fill factor (FF) loss.

Figure 17: Monofacial PERC cells. Left: front side; middle: full aluminium rear side; right: rear side with Ag pads. (Run 3106)

To make full advantage of this module reliability improvement, an optimization of the Ag pad size on the cell rear side would be needed, to diminish the amount of Ag needed on the rear side of the cells (currently 67 mg/cell). The layout shown in Figure 17 was designed for a proof of the concept.

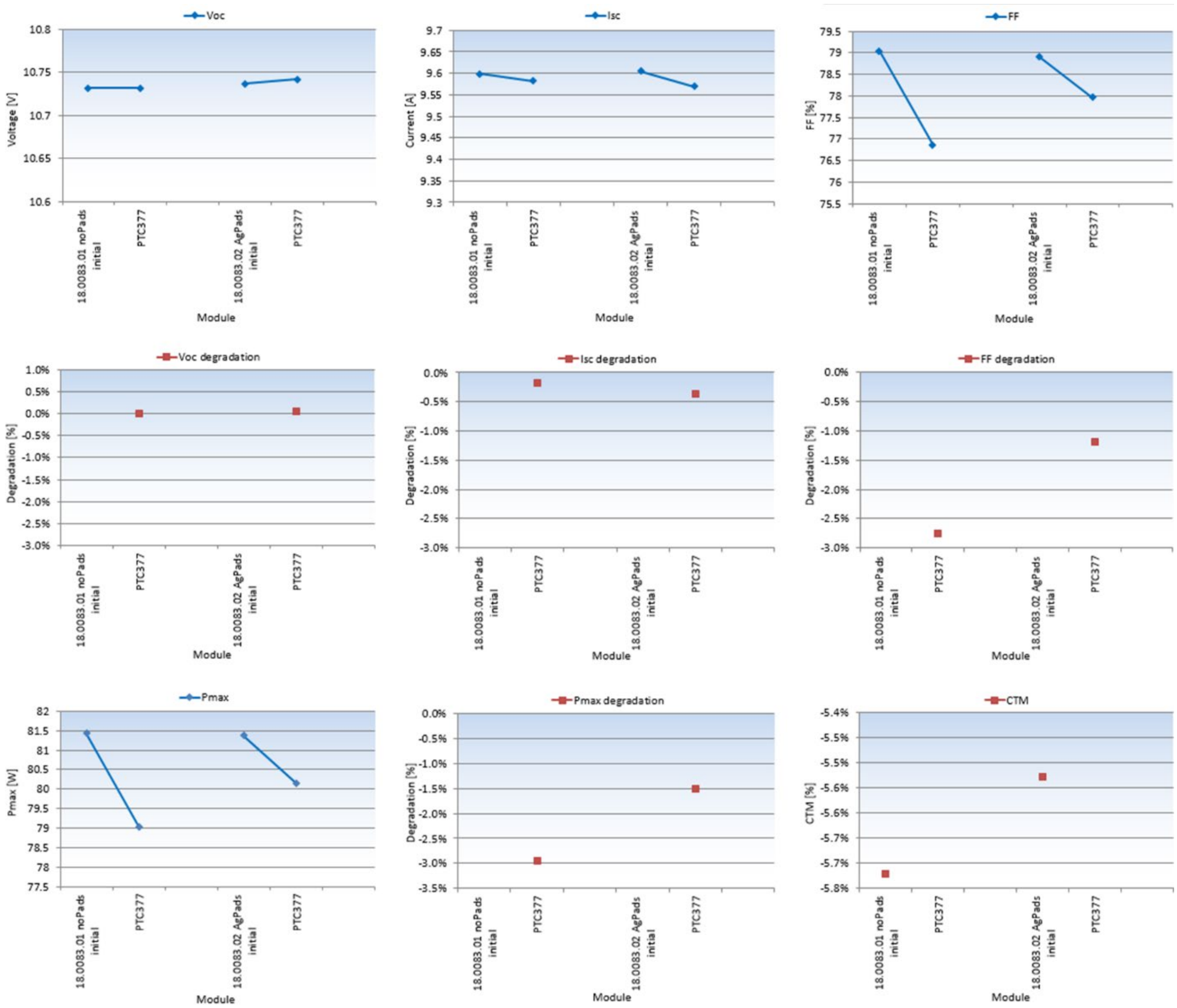


Figure 18: PTC chamber reliability testing. Current-voltage (IV) analysis of PERC cells built into 16-cell modules. Module 18.0083.01 (left of each graph): without pads. Module 18.0083.02 (right): with Ag pads on the cell rear side. Initial measurement is shown along with IV analysis results after 377 cycles in PTC chamber (2 x IEC). See Table 4 for module designations. (Run 3106)

8.3.8 Reliability of fine-line PTP-SWCT^{TM} modules from bifacial p-PERT cells

Cells used in most of the Refined PV project were of the monofacial PERC type. They have a full area aluminum rear side. Another cell type that was temporarily available for this project, is a bifacial cell of the p-PERT type (www.sol-around.com). ISC metallized cell precursors of this type with PTP fingers (trench 30 µm) on the front side. The cell rear side was metallized with PTP/SP (module 18.0049.01) or SP/SP (module 18.0049.02) silver fingers in checkered arrangement.

16-cell, glass-backsheet modules have been built and reliability tested from the p-PERTcells. This is shown in Figure 19.

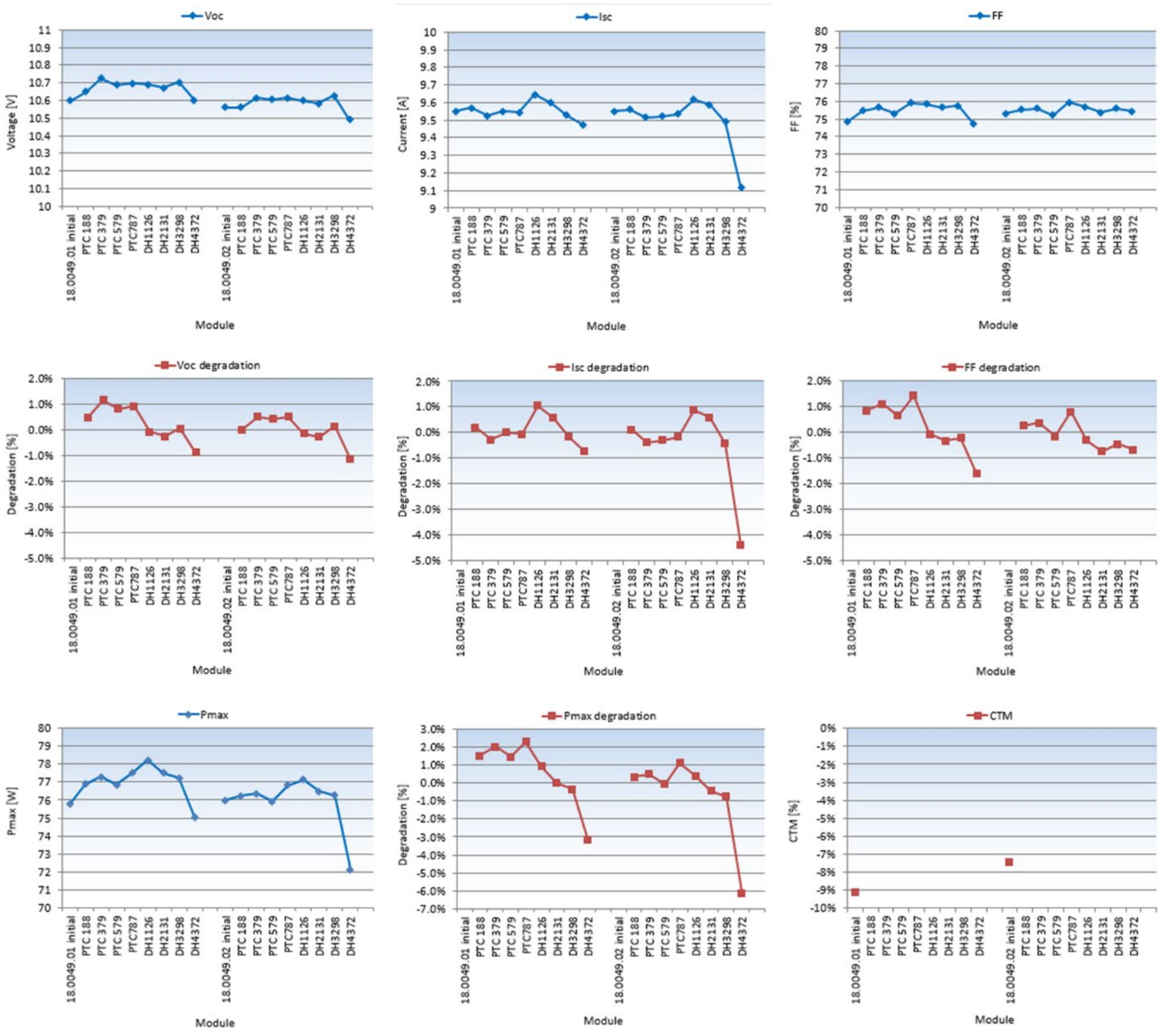


Figure 19: PTC and DH chamber reliability testing. Current-voltage (IV) analysis of bifacial p-PERT cells built into 16 cell modules. Initial measurement is shown along with IV analysis results after 200/400/600/800 cycles in PTC chamber, followed by 1000/2000/3000 hours in DH chamber. See Table 4 for module designations. (Runs 2768)

These modules show excellent PTC, and DH, climatic chamber stability. DH chamber test was done after PTC test on the same modules. Even after 800 PTC cycles = 4 x IEC, they showed no sign of degradation. Very high stability was observed also for the DH test. Only little degradation occurred after 3000 DH hours = 3 x IEC. Just after 4000 DH hours, one of the modules failed with higher than 5 % P_{max} degradation.

This is an excellent proof of the outstanding module reliability that can be reached with fine-line metallization fingers in combination with SWCTTM.

8.4 Deliverables 6.1, 6.2: modules with >8 W_p, >15 W_p power gain

According to the Refined PV project proposal, deliverables 6.1, 6.2 are 60 cell modules, made from PTP cells with SWCT™ module technology, with >8 W_p, >15 W_p power gain compared to a soldered 3BB module (made from screen-printed cells).

With the modules built in the Refined PV project, we exceed these benchmarks. This is shown in Figure 20. Our PTP-SWCT™ modules reached a module power P_{max} in the range 290...311 W (modules from Runs 2707, 2900, 2991, see Table 4). This is well above the P_{max} of commercial 3BB modules (265...280 W).

However, today, 3BB modules are no longer state-of-the-art. There has been a commercial shift to 4BB, and 5BB modules. Our PTP-SWCT™ modules compete well with these modules, but are not yet able to exceed them.

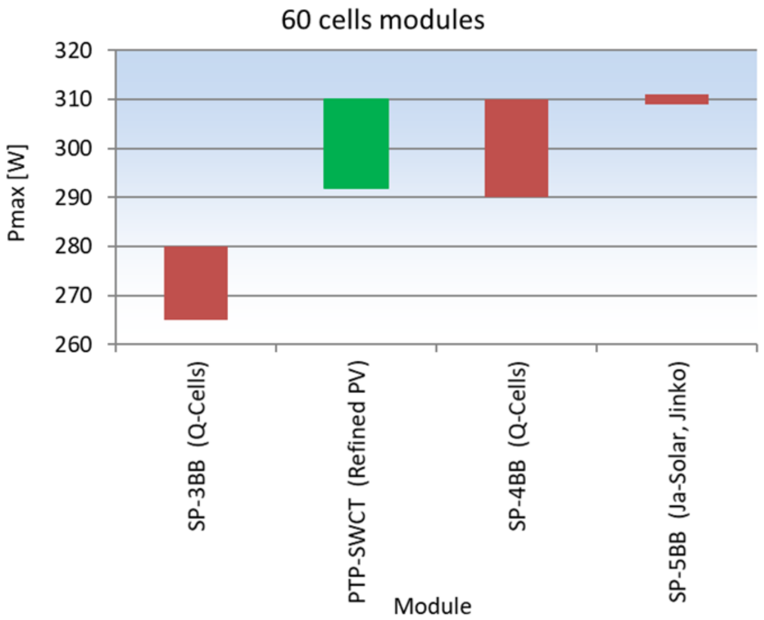


Figure 20: 60 cells PERC modules comparison of PTP-SWCT™ modules (green bar) with 3BB, 4BB, and 5BB module technology.

8.5 From PTP-SWCT™ to fine-line SP-SWCT™

For the last phase of the Refined PV project, there was a move from PTP-SWCT™ to fine-line SP-SWCT™. This step became necessary because of the shutdown of Utilight activities. ISC Konstanz started cell metallization by fine-line SP, and Meyer Burger followed by encapsulating these cells into SWCT™ modules. Results are shown in Figure 21 for 16-cell modules made from these cells. Overall P_{max} of the module made from fine-line screen-printed (SP) metallized cells is on the same level with the modules made from conventional SP metallized cells. Silver paste laydown on cell front side is 48 mg/cell in the fine-line SP case, whereas it is 73 mg/cell for the conventional SP case. Further reduction of silver paste laydown would require further development.

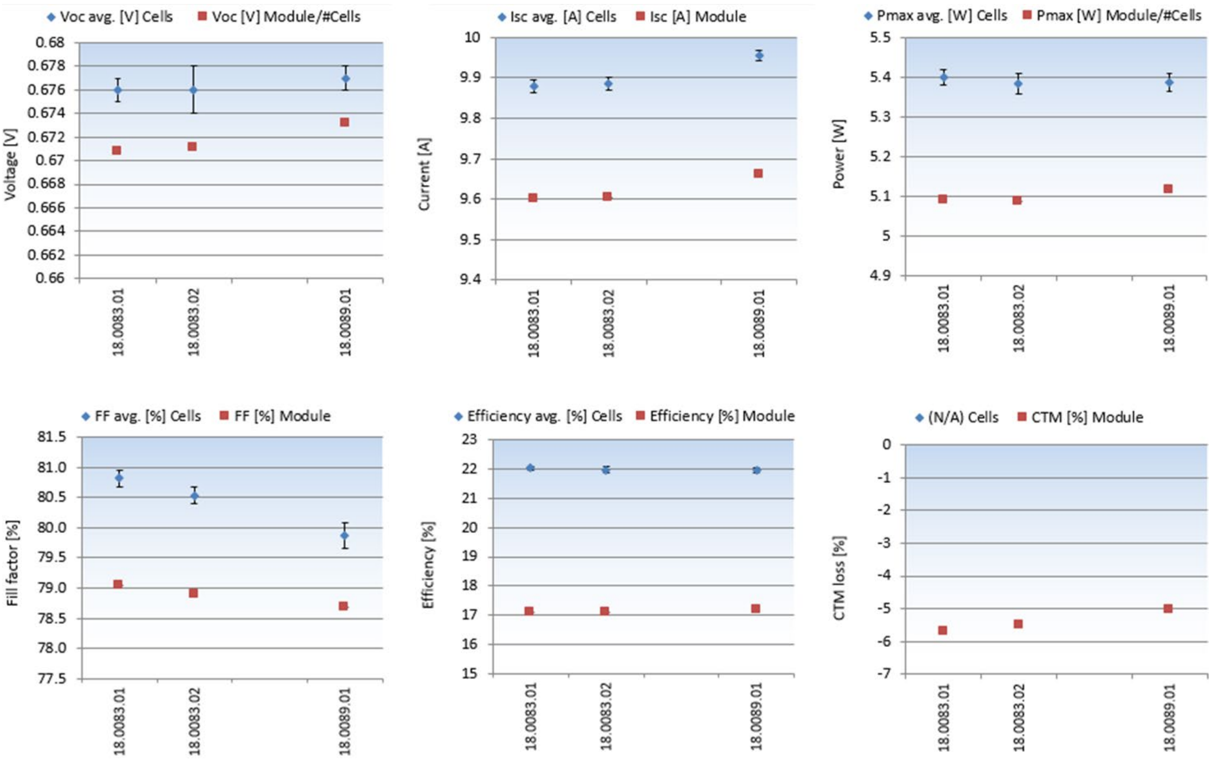


Figure 21: Current-voltage (IV) analysis of cells and 16-cell modules from cell metallization tests. Modules 18.0083.01 and 18.0083.02 have a conventional screen-printed (SP) front side, whereas module 18.0089.01 has a fine-line SP metallized front side. Module efficiency was calculated based on a 16-cells module size of 67 x 71 cm (not to be confused with cell efficiency in module). See Table 4 for module designations. (Runs 3106, 3178)

The conclusion from these results is that fine-line SP metallization is a viable route for essential silver savings over conventional SP metallization. Fine-line SP-SWCT^{TM} cell and module technology proves to be on the same performance level with PTP-SWCT^{TM} that has been thoroughly investigated in the previous phases of the Refined PV project.

9 Evaluation of the project outcomes and outlook

The project team was able to reach the main goals of the Refined PV project: Combine fine-line metallization with SWCT^{TM} module technology, and show the feasibility, cost decrease, and reliability of this technology.

On the other hand, the PV market has seen an increase in module power and a strong cost reduction during the running time of the Refined PV project. Hence, part of the important progress that took place in the Refined PV project was worked on simultaneously by different market participants and was rapidly transferred into the market.

On Meyer Burger's module side, advancements in SWCT^{TM} with In-free wires were made, which enabled the feasibility and cost reduction of this technology with fine-line metallized cells. On Meyer Burger's machine side, important progress was made with the new stringer and RRU developments and their market releases. This happened in parallel with the Refined PV project, promoting each other.

For Meyer Burger, the specific value of the partnership lies in the additional know-how that was gained in the field of PERC cell interconnection with SWCT^{TM}. Refined PV gave us a chance for testing and improving SWCT^{TM} with In-free wires on fine-line metallized PERC cells, but it also showed us where the current limitations of this technology are. The expected benefit of a close collaboration with Utilight and the targeted market expansion did not take place due to Utilight's insolvency.

Module reliability remains an ongoing task especially when it comes to PERC cell technology. Improving polymer films and wire coating alloys at competitive cost for SWCT^{TM} involves collaboration with suppliers and institutes. This would be the next steps for a follow-up project.

10 National collaboration

Within Refined PV project, there is no other Swiss partner than Meyer Burger to collaborate nationally.

11 International collaboration

The project had international collaborators located in Germany and Israel. Main activities on cell processing took place in Germany, with the PTP system from Israel company Utilight installed in the facility of ISC Konstanz. At ISC Konstanz, cell precursors came from their own lab as well as the cell producer Hanwha QCells to make sure that baseline processes were mass production compatible. Pastes were supplied by Hereaus and developed according to feedback of ISC & MB. Cell backend processes, such as drying and firing, also took place at ISC Konstanz, followed by process and/or device characterization. The integration of such cells with very low paste consumption into modules took place at Meyer Burger (Switzerland) AG, Switzerland, where not only module performance was evaluated, but also reliability and module costs.

Joint efforts and expertise from international collaborators were put in place to ensure the success of this project, not only from the point of view of achieving project targets, but also for the equipment producers and cell producers to implement a readily transferrable process to mass production.

On 2nd October 2019, Utilight chairman Giora Dishon gave an announcement of financial insolvency to ISC Konstanz. For the Refined PV project, this announcement meant that the development of the PTP system had stopped, and the consumables needed for operation of the PTP pilot plant at ISC Konstanz were no longer available. Work packages under the leadership of Utilight (WP3 and WP4) were not affected, because they were already closed.

ISC Konstanz as project leader took immediate steps to guarantee the continuation of the Refined PV project. PTP was replaced by fine-line screen-printing (SP). SP is the alternative to PTP. SP has wide commercial spread. The ability of SP to go down to narrower finger width had advanced since the beginning of the Refined PV project. ISC Konstanz was able to change from PTP to fine-line SP on cell level (however, on smaller volumes of cell production). Meyer Burger built and tested SWCT™ modules from these cells and continued WP6.

The main goal for Meyer Burger was maintained: combine fine-line metallization with SWCT™ module technology, and show the feasibility, cost decrease, and reliability of this technology.

12 Acknowledgement

We (Meyer Burger) acknowledge financial support by the Swiss Federal Office of Energy.

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