Final report

1.1 Project details

Project title	EUDP 12-II, Kommercielle polymersolceller til selvforsynende produkter
Project identification (program abbrev. and file)	EUDP 12-II, J.nr. 64012-0202
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrations Program (EUDP). Området: Solenergi
Project managing company/institution (name and address)	Mekoprint A/S Hermesvej 4 9530 Støvring Project manager: Morten Christensen
Project partners	DTU – Technical University of Denmark Department of Energy Conversion and Storage
CVR (central business register)	10825598
Date for submission	31 March 2016

Content

1.2 Short description of project objective and results

The objective of the project is to commercialize polymer solar cells for small independent products. For the industry partner and project manager, Mekoprint, the objective was to get commercial inks and materials to work in an industrial environment and to direct this development towards customers large enough to reach competitive quantities. The market responded positively during the project, but the performance required for market introduction (efficiency, lifetime and cost) could not be achieved with the current technology and therefore it is decided to stop the project.

In support of the project objective the university partner, DTU, has developed methods for reliable testing and determination of the lifetime of polymer solar cells. Production of polymer solar cells has been carried out at both Mekoprint and DTU and lifetime tests at Mekoprint and DTU have been shown to yield corresponding results.

1.2.1 Dansk resumé

Formålet med projektet er at kommercialisere plastsolceller for små uafhængige produkter. For projektlederen og industrivirksomheden, Mekoprint, var målet at få kommerciel blæk og materialer til at fungere i industrielt miljø og rette denne udvikling mod kunder med potentiale til at aftage volumen, der kan gøre teknologien konkurrencedygtig. Markedets respons var positivt, men markedets krav til effektivitet, levetid og kostpris kan ikke opnås med den tilgængelige teknologi og derfor er det besluttet at stoppe projektet.

Til understøttelse af projektmålene har universitetspartneren DTU udviklet metoder for pålidelig test og bestemmelse af levetid for polymersolceller. Produktion af polymersolceller har foregået hos både Mekoprint og DTU og levetidstestresultater på Mekoprint og DTU har vist god overensstemmelse.

1.3 Executive summary

Commercial inks and other materials for polymer solar cells have been implemented in an industrial production at Mekoprint. Selected customers were involved and prototyping activities extended beyond the planned activities. The market introduction performance goals on efficiency, lifetime and cost have not been achieved in the industrial production, and thereby it is decided to stop the project.
DTU has developed an open-access computer tool for prediction of the lifetime of OPV device. The tool estimates the operational lifetime of a given OPV device based on inputs describing the device architecture, the processing method, the encapsulation, and data from accelerated stability tests when such is available. DTU has made their conceptual[1] active-layer inks available for the project and has shown that this ink gives access to modules with 5% efficiency when applied in Mekoprint's preferred device architecture but without losses due to encapsulation.

1.4 Project objectives

For the company partner Mekoprint, the technical objective was to get commercial inks and materials to work in industrial environment. The initial goal of the project was to find suppliers that could deliver all inks and materials, which were matched together to optimal performance. That would leave Mekoprint free to focus on encapsulation, lifetime, and cost engineering in their production environment. Work commenced with one supplier that could deliver a full ink stack (4 layers) and two suppliers that could deliver 2-3 layers in the stack. Early in the project, the full-stack supplier went out of business, and Mekoprint was facing the added complexity and work load of qualifying a full stack. Mekoprint tested and discarded all other inks except the photoactive layer from two suppliers and DTU.

The high workload for Mekoprint in integrating inks from various suppliers into one industrial stack required a strong focus on this task and lead to delays in the work on encapsulation and cost reductions. The corresponding milestones were postponed for later in the project. Resources at Mekoprint were reduced in order to wait for suppliers to evolve and this left the development of the ink integration slowly moving forward. This also resulted in M2, M4, M5, and KM3 not being fulfilled before the project was terminated.

Mekoprint has been working closely with selected customers that were ready to implement polymer solar cells in their products when the technology matured. From the beginning of the project, the commercial interest in the technology was promising. Demonstrators were

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[1] The project was planned to only encompass commercially available inks and testing of conceptual inks were thus not included in the original plan.

produced during the project for focus customers, the emerging technology conference (SXSW 2015) and printed electronics maker community (Printoo).
Mekoprint has established a setup for accelerated lifetime testing. As a part of the project, the setup was benchmarked against a corresponding setup at DTU via Round Robin tests and Mekoprint's measurements were found to be consistent with DTU's measurements. .

DTU has focused on developing a tool for prediction device lifetime for OPV devices based on information of the device architecture, processing methods, encapsulation, and possible also data from accelerated tests. The tool is based upon DTU extensive database holding stability data obtained from testing in DTU's laboratory and according to the ISOS[2] protocols stability testing. This data is supplemented with reliable data published in the open research literature. The database is available on www.plasticphotovoltaics.org/lifetime-predictor.html, DTU's open platform for OPV communication. DTU encourage the international OPV community to upload their own data to the database as this is an efficient means for improving the accuracy of the lifetime predictions.

1.5 Project results and dissemination of results

WP1: Commercial ink supply

IV tracer and solar simulator at Mekoprint

Mekoprint need the capability of in-house testing of manufactured OPV devices under standardized light conditions in order to test manufactured solar cells with ink from commercial suppliers. A realistic light source and a corresponding IV tracer was purchased and installed at Mekoprint. The equipment is shown in Figure 1.

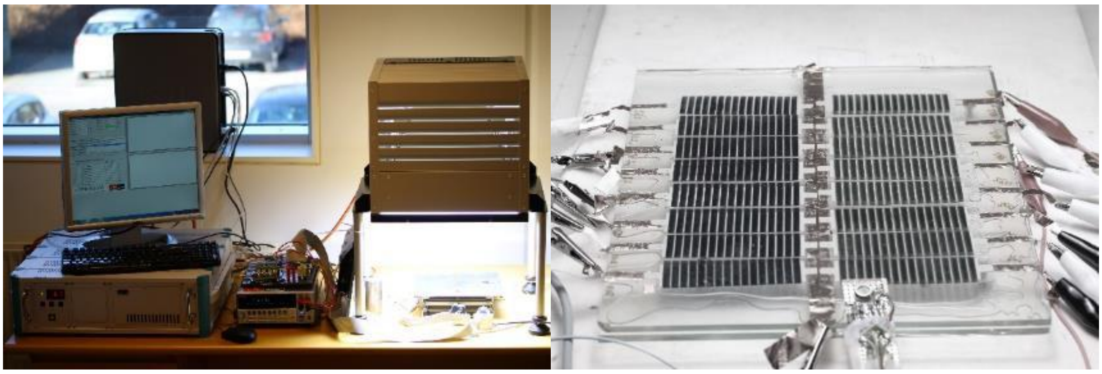

Figure 1: Left: Solar simulator with Keithley IV tracer setup at Mekoprint. Right: A setup of 16 glass-encapsulated modules for extended lifetime testing.

Mekoprint has written software to extensively test both single solar modules as well as lifetime test of up to 64 modules simultaneously, see Figure 2. The software and solar simulator have been testing in-house manufactured solar cells almost continuously since it was installed. *This fulfils M1: An IV tracer stand with same specifications as IV tracers at DTU installed at Mekoprint. This allows for comparison of specifications at both sites. The system currently on loan from DTU is returned.*

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[2] ISOS - International Summit on OPV Stability

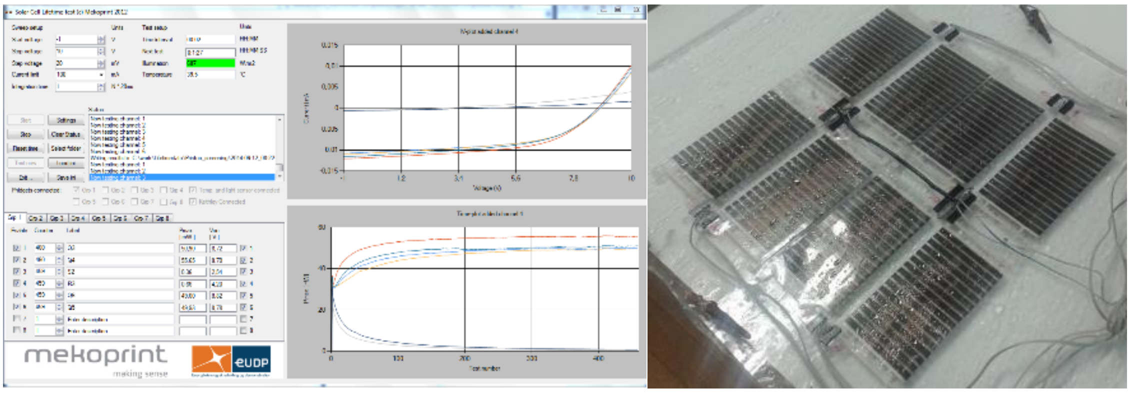

Figure 2: Left: In-house developed software at Mekoprint to run single IV-traces as well as extended lifetime testing of up to 64 OPV modules. Right: Modules from outdoor test being measured in the IV-tracer setup during life time test.

Commercial ink supply

In this project, one of the main objectives for Mekoprint was to move towards commercial suppliers of materials for the entire organic solar cell. The relevant materials of a Mekoprint polymer solar cell in order from the front of are listed below:

- Transparent front barrier
- Transparent adhesive
- Transparent plastic substrate
- Transparent conductor (TC)
- Transparent electron transport layer (ETL)
- Photoactive layer (PAL)
- Hole transport layer (HTL)
- Metallic back electrode
- Adhesive for back encapsulation
- Barrier for encapsulation

Mekoprint has investigated each of these materials and through cooperation with DTU and the industry chosen suitable suppliers that could both deliver a high performing solution, have the technical understanding of how to improve it in the future, and the ability to scale up the supply of the material. Due to confidentiality agreements with most of these suppliers, Mekoprint cannot mention the name of these suppliers in this report nor specific details of their performance and characteristics.

Within the scope of this project, it was chosen to have a single supplier of a *transparent plastic substrate* with sputtered Indium Tin Oxide (ITO) as a *transparent conductor*. Mekoprint has the unique in-house capability of patterning the ITO directly on the foil in a roll-to-roll (R2R) process. This process has been optimized considerably during this project and have resulted in a small spin-off business in the form of an ITO patterning service at Mekoprint. These activities will continue after this project ends.

Originally, the market was searched for commercial suppliers that could deliver an entire package/stack of inks that was thoroughly engineered to fit together. One supplier was found that was aiming to deliver four inks; ETL, PAL, HTL, and silver back electrode. After several extensive tests of this stack, the supplier went out of business and Mekoprint was forced to move forward with other suppliers that could not deliver a complete package of inks. This forced Mekoprint to handle a much larger development task where the individual inks in the

OPV stack were purchased from different suppliers and tested together at Mekoprint, as confidentiality concerns ruled out the possibility of screening at DTU. This task was given full priority and consequently led to delays in other project activities.

For the *ETL* three suppliers were tested and the doped nanoparticle ZnO dissolved in water from InfinityPV[3] was chosen as a clear winner independent of the other materials in the stack.

For the *photoactive layer* the market was searched for commercial suppliers that were able to supply a bulk heterojunction (BHJ) ink that needed no mixing and was ready for coating. In total Mekoprint have been in discussion with eight different suppliers during this project. Three suppliers were tested intensively in addition to DTU's active layer inks. The performance of the inks were largely identical even though many parameters during processing were different indicating that the performance was limited by something else than the photoactive layer.

For the HTL Mekoprint has chosen to solely work with PEDOT and have worked with two large suppliers of PEDOT. For the PEDOT, many different process parameters are possible and this has taken a considerable development share to optimize coating quality. Screen printing of PEDOT as well as two-layer PEDOT structures have been evaluated as well, but with mediocre results. The best performance was through single layer coating using the meniscus shaper described later in this report.

For the metallic back electrode Mekoprint have tested numerous silver pastes during several projects, but have chosen to move forward with a UV curable silver in order to remove solvents during printing which can be detrimental to the integrity of the PEDOT.

The description above completes the OPV layers (stack) of ink and Mekoprint was due to thorough preparations early in the project able to *fulfil D1.1: Different ink stacks are validated for ProcessOne. The main effort is in stretching the ProcessOne technology and inks are optimized for this. This is used as a reference for the developments in the following workpackages.*

Process control for drying of inks

In order to integrate the new commercial materials in the slot-die coating process, a need for fast and precise control of the initial part of the drying process was identified. The original industrial grade ovens on the coating line provides 8 meters with high drying capacity for the ZnO layer but for some materials, immediate drying is required, and the only way to obtain this is to integrate an oven with the coating section. Mekoprint designed and constructed an oven for conventional contact heat drying. The oven was constructed with glass sides in order to be able to visually monitor the drying process, which has proven very helpful. Pictures of the design and construction of the oven can be seen in Figure 3.

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[3] The patented ZnO ink was previously supplied by DTU but is now supplied by infinityPV, who has acquired the patent

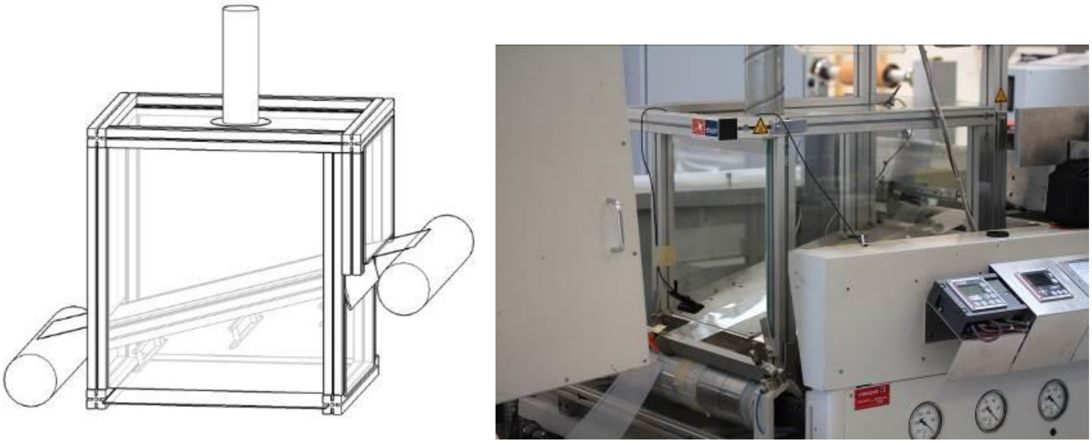


Figure 3: Left: A sketch of the initial oven design, where the foil passes over an aluminium plate, which is heated from the backside using IR lamps. The oven cavity allows for efficient removal of fumes from primarily volatile organic solvents. Right: The oven shown inline after the slot-die coating station.

The initial version featured 3 independent zones over the 800mm oven plate with individual temperature control and 3600 Watts heating power, but the design was refined and extended so also the temperature of the coating drum and a small oven section of 120mm between the coating drum and the glass oven could be controlled. The final oven section consists 6 zones with a total power of 8000 Watts and individual control and logging of temperature through 9 temperature sensors.

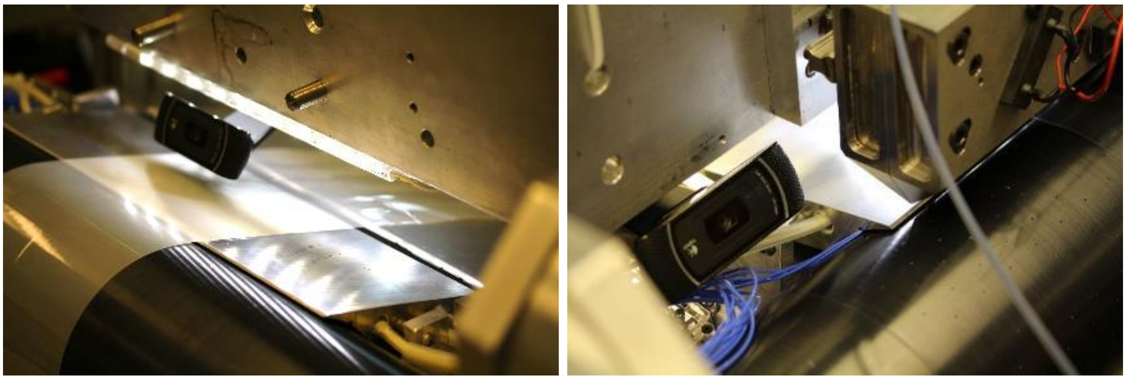
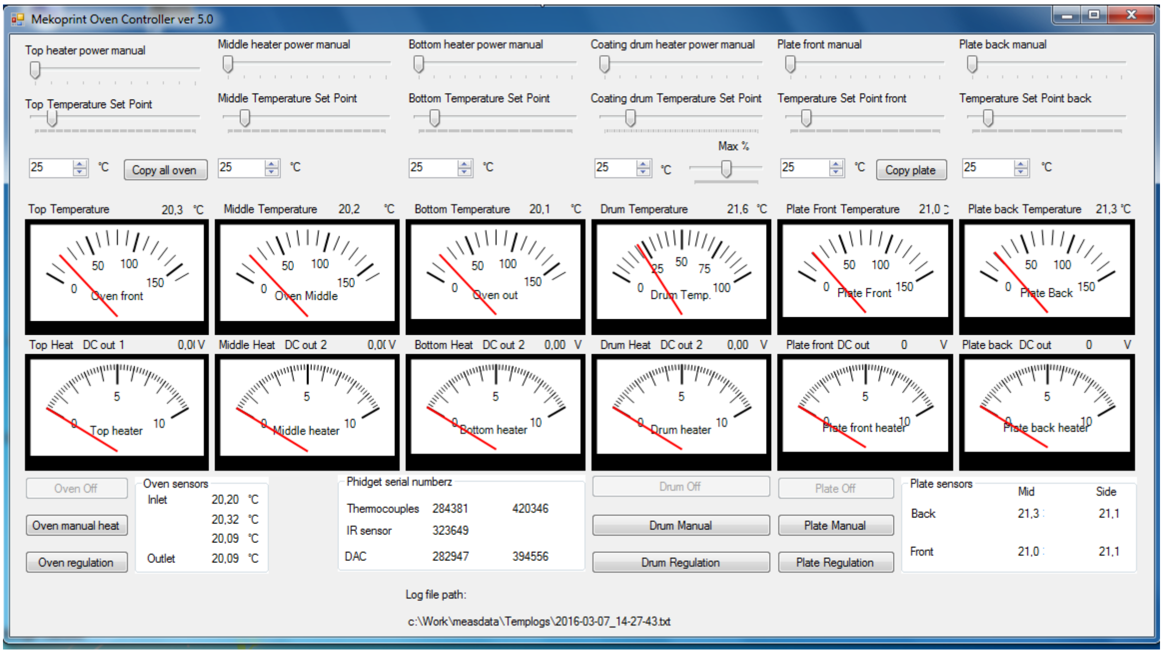


Figure 4: The latest addition to the oven is the small coating plate between the coating drum (black) and glass oven, where immediate drying was possible. Clear wires connects heating elements and blue wires are for temperature sensors. The surface is slightly curved to ensure full contact of the film and it is possible to move the coating head to coat on the first 5 mm of the coating plate. This eliminates any static electricity effects in the gap between the coating drum and the oven.

The controller software was developed inside the group to enable cross-referencing of temperatures with other process parameters. The heating capacity of the oven is sufficient for full 305mm coating at 5m/min of the thickest ink layers conceivable.


Mekoprint Oven Controller ver 5.0

Top Temperature Set Point 25 °C
Middle Temperature Set Point 25 °C
Bottom Temperature Set Point 25 °C
Coating drum Temperature Set Point 25 °C
Temperature Set Point front 25 °C
Temperature Set Point back 25 °C

Top Temperature 20,3 °C
Middle Temperature 20,2 °C
Bottom Temperature 20,1 °C
Drum Temperature 21,6 °C
Plate Front Temperature 21,0 ℃
Plate back Temperature 21,3 °C

Top Heat DC out 1 0,0l V
Middle Heat DC out 2 0,0(V
Bottom Heat DC out 2 0,00 V
Drum Heat DC out 2 0,00 V
Plate front DC out 0 V
Plate back DC out 0 V

Oven sensors
Inlet 20,20 °C
20,32 °C
20,09 °C
Outlet 20,09 °C

Phidget serial numberz

Thermocouples	284381	420346
IR sensor	323649	
DAC	282947	394556

Plate sensors

	Mid	Side
Back	21,3	21,1
Front	21,0	21,1

Log file path:
c:\Work\measdata\Templogs\2016-03-07_14-27-43.txt

Figure 5: Screenshot of the in-house developed software that controls the ovens.

The oven has proved its worth through a typical drying distance of 150mm from wet to dry ink for active layers and PEDOT at 1-2m/min and the response is fast enough for temperature sweeps, which enables process windows for the different inks to be established. In general, a temperature window of 20-40K was found with optimal coating uniformity. Heating of the coating drum in general did not improve coating, and in some cases made it impossible to maintain stripe definition, as heat increases the surface tension of the foil and the ink would smear into the gaps. Heating the drum also decreased coating precision due to thermal expansion of the drum. Optimal coating for the most demanding inks were obtained by coating on the edge of the coating plate with a room temperature coating drum, so the web was heated as the ink was deposited and the ink has the shortest possible wet time and static charge effects were eliminated.

The start-up waste has been significantly reduced through a new coating head design (see later in this report), which also enables full use of the 305mm ITO substrate. In addition, the thick PEDOT layer, which was cost driver of the 2012 Process One stack, has been replaced by a thinner layer of a different PEDOT, so ITO is now the cost driver. A different silver pattern has been implemented with same performance as the Process One busbar, but up to 80% reduced silver consumption. The back barrier, which was the same transparent type as the front barrier on the 2012 Proces One has been replaced by aluminium which – depending on contacting method – can reduce the barrier cost by more than 50%. *These initiatives together fulfils D1.2: New ink stack in combination with novel device design is introduced that presents a reduction in materials consumption by a factor of two relative to 2012 Process One devices.*

In order to establish process parameters quicker than possible with the production R2R equipment, a lab scale slot die coating prototype setup was made in the summer 2015. For highest flexibility, the setup was based on a commercial 3D-printer (see reference [2]), where the extrusion head was replaced by a slot die head. The feed system consists of a piston pump directly mounted into the coating head. The mini-coater proved its worth in establishing process windows for drying and for troubleshooting layer uniformity issues during its short operation period.

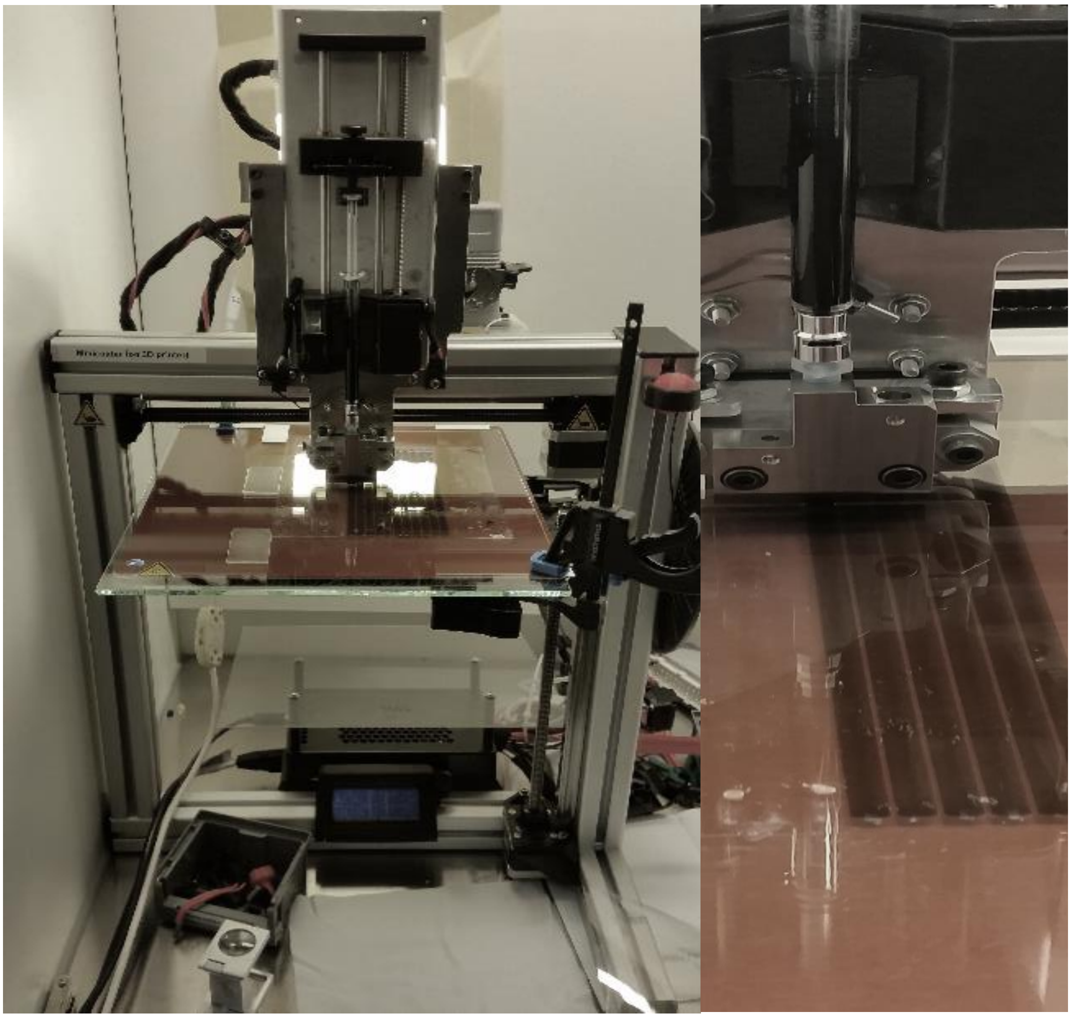


Figure 6: Left: The mini-coater mounted in the fume hood. Right: Printing stripes with functional ink.

The encapsulation is critical to lifetime of the polymer solar module. A good encapsulation material together with a clever encapsulation technique can ensure a long lifetime of the solar cell. For the front encapsulation a transparent barrier is needed, which makes this an expensive component in the device. Therefore, it is chosen not to use the same transparent barrier foil for the back encapsulation, but instead move forward with an aluminium foil, which is low-cost and readily available. The backside encapsulation is especially important since this is closest to the open layers of the printed module. Furthermore, the user needs access to the two printed terminals on the backside in order to draw power out of the module. Mekoprint has developed a device structure where a back encapsulation consisting of Alu/PEN/Alu/PET is used. The Alu between the PEN and PET foils is used as a full coverage barrier. The exposed Alu on the PEN side is patterned (wet chemically etched similar to the ITO patterning) in order to form a connection to the terminals of the solar module. An example of this is seen in Figure 7 and this technology of encapsulation can be used companywide at Mekoprint and for customers.

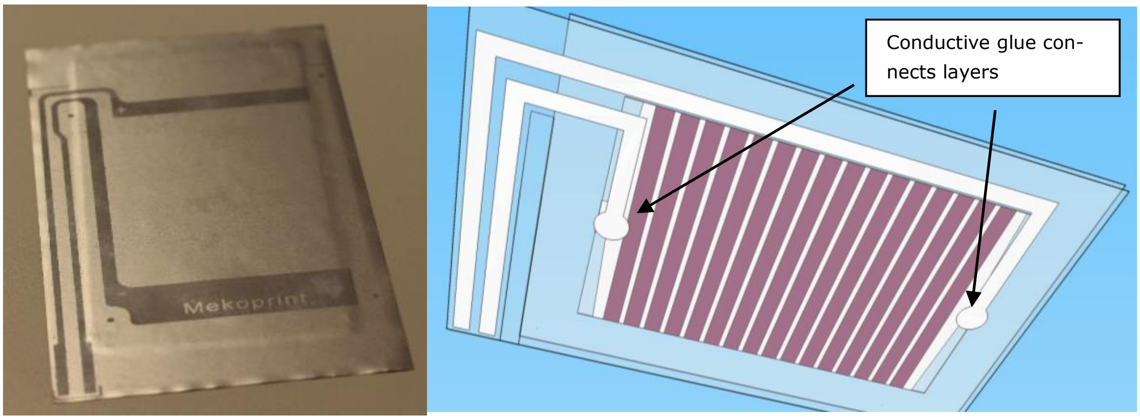


Figure 7: Left: The aluminium back encapsulation where an etched pattern is visible (with Mekoprint logo in one terminal). The solar cell is adhered in the middle with the terminals conductively glue to the large pads of aluminium. To the left the power is extracted. The matte substrate is PEN/Alu/PET that covers the entire surface. Right: sketch of the final assembly where the back aluminium barrier is shown transparent.

In general, Mekoprint have used this project to get all suppliers for all materials in the OPV stack tested. Due to the start-up of the DTU spinoff InfinityPV and the extensive knowledge about ink formulation and production at DTU, it was also late in the project chosen to include DTU as an ink supplier.

For adhering the solar cell foil to barriers, Mekoprint has used pressure sensitive adhesives (PSA) in earlier stages of the project. A general performance increase was observed when switching to hotmelt adhesive (HMA) and difference types were tested, where good performance was observed with 3M type 583, which is not clear and has an unappealing color. Same solar performance was obtained with Drytac type HMFC (Dry Mount), which is clear so it can be used on the front side and has better bonding at lower temperatures, and this adhesive was chosen for production scale up. This adhesive also showed good properties during lifetime testing and was readily integrated into test productions.

Testing of DTU’s conceptual active layer ink

High-efficient, commercially available inks for the solar cell’s active layer are generally developed and optimized for small-scaled laboratory experiments where the solar-cell stack is prepared on rigid glass substrates in a protective atmosphere by a combination of non-scalable spin-coating and energy-intensive vacuum evaporation. When applying such inks in industrial-scaled, roll-to-roll (R2R) processing where the processing conditions are vastly different, they seldom, or in practice never, hold what they promise with respect to processability and solar-cell efficiency.

Thorough scientific understanding of active-materials design and ink development has been generated at DTU through more than a decade of extensive research in large-scale processing of polymer solar cells. This has led to a unique understanding of the delicate interaction between the inks, the processing, and the machinery, and also of how the combination of these strongly influence the properties of the solar cells produced. Based on this scientific platform DTU has developed a series of promising active-layer inks and the PV-active materials comprised in the ink. These inks are optimized specifically for the processing techniques and technical requirements characteristic of large-scale R2R processing. The development of active-layer materials and inks are financed outside the EUDP project.

Identification and validation of commercial inks have been a key issue in the actual project, but identification of an adequate active-layer ink has presented difficulties. For this reason

DTU's conceptual, and so far not commercial, active-layer ink was made available for testing at Mekoprint as a part of the EUDP project, despite the fact that non-commercial inks was not originally planned to be a part of the project. The conceptual ink, named EB, was for the EUDP project adjusted and optimized for Mekoprint's production setup. Totally 5 versions of EB (named EB1-EB5) were developed at DTU and tested at Mekoprint by processing complete solar cells on Mekoprint's production line. The results were compared with what has been achieved by DTU with the same ink but in their production setup. All production trials at Mekoprint's line with the new inks were supervised by DTU. The results are summarized in table 1.

The first trial at Mekoprint (Figure 8) comprised two inks, EB1 and EB2, of which EB2 was the better performer and the effort was thus concentrated on this ink. The quality of the solar cells processed from EB2 was, however, inconsistent due to aggregation of the active material in the ink. All subsequent inks, i.e. EB3-5, were for this reason made from a version of the active material with improved solubility. This eliminated the agglomeration and gave consistent quality of the solar cells subsequently produced.

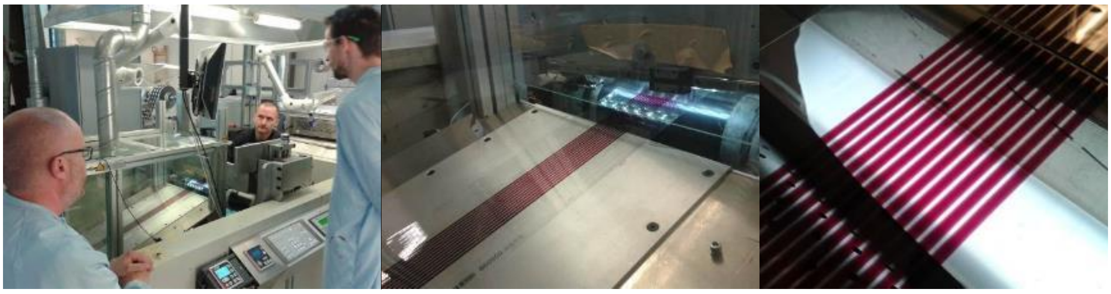


Figure 8: Pictures from the trial of EB1 and EB2 at Mekoprint.

Table 1: Testing of DTU's conceptual active-layer inks (EB1-EB5) at Mekoprint

Trial	Ink	Processed at				Comments
		Mekoprint		DTU		
		PCE	Electrode	PCE	Electrode	
1	EB1					- Not subjected to extended testing as EB2 was found to be superior
	EB2	~2.5%	ITO+ZnO	~4%	Flextrode	- Inconsistent ink quality caused inconsistent quality of the solar cells
2	EB3	3%	ITO+ZnO	7%	Flextrode	- Current restricted by the low conductivity of the ITO+ZnO electrode
	EB3			5%	ITO+ZnO	- Non-optimal drying conditions at Mekoprint
	EB4					- Not subjected to extended testing as EB3 was found to be superior
3	EB5	5.2%	ITO+ZnO	7%	Flextrode	- 5.2% is close to what is achievable with the low-conductivity ITO+ZnO electrode

The solar-cell modules produced at Mekoprint from EB2 showed a moderate performance (~2.5%) whereas up to 4% has been reached for modules prepared by DTU at DTU but with another configuration of the solar-cell stack. The difference between the two stacks lies in the electron-extracting front electrode. Mekoprint applies a front electrode of ITO+ZnO whereas DTU prefers their in-house-developed Flextrode as standard. The electrical conductivity of Flextrode is higher than the conductivity of the ITO+ZnO electrode, and Flextrode is thus associated with the lowest ohmic loss of the two - an aspect of increasingly importance as the efficiency and thus the current goes up.

For the next trial two inks were developed, EB3 and EB4, of which EB3 was preferred for the full-scale testing due to better properties. EB3 gave solar cells with up to 3% efficiency when produced at Mekoprint's line, i.e. higher that EB2 but far from the 7% achieved by DTU with EB3 and Flextrode. For elucidating this difference, EB3 was also processed at DTU on Mekoprint's ITO+ZnO electrode. This gave solar cells with up to 5% efficiency – a result illustrating how strongly the machine and processing conditions influence the cell's performance (Figure 9). Mekoprint's procedure implies coating at 60^{O}C followed by drying at 100^{O}C, whereas DTU, for their test, applied drying at 60^{O}C. Mekoprint's drying temperature was consequently reduced to 60°C for the final test with the EB5 ink.

EB5 is made from an active material stemming from an optimization of the active material comprised in EB3. Moreover, the solvent of EB5 was successfully adjusted for improved film-forming ability at Mekoprint's machine as compared to the previous trials. However, during the coating it was noticed that the coated layer appeared visually inhomogeneous to an unacceptable level. The inhomogeneity could be traced back to contamination of the surface, onto which the active layer was applied. The here and now problem was solved by cleaning the coating surface with iso-propylalcohol (IPA) immediately before the coating, and quality solar cells could successfully be produced. The cause of contamination was sought by subjecting the coating surface to careful TOF-SIMS analysis, see next section.

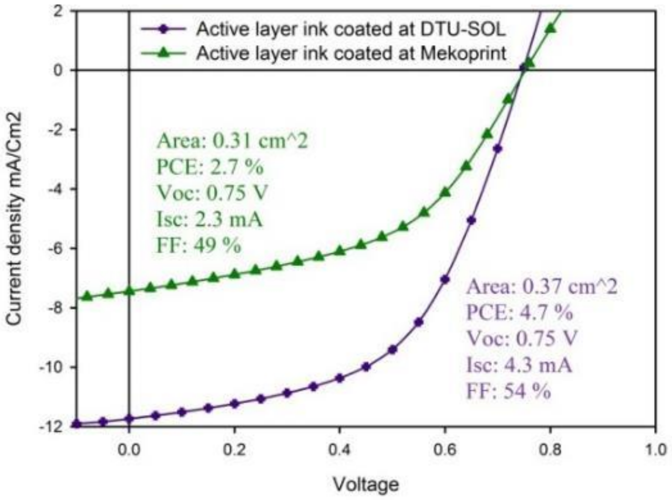


Figure 9: JV characteristics of devices where the active layer ink is coated at DTU and at Mekoprint applying identical ITO+ZnO substrate. The difference in IV characteristics illustrates the importance of optimizing the machinery and the drying cycle for the actual ink.

Comparing the IV characteristics of solar cells made from respectively ink EB3 and EB5 (Figure 10), shows that EB5 gives higher short circuit current (19.8 mA versus 10.9 mA), higher open circuit voltage (9.0 V versus 8.7 V), and higher maximum power P_{max} (53 mW versus 94 mW), resulting in significant higher efficiency (5.2% versus 3.0%) for the best cells. An efficiency larger than 5% is highly satisfactory and close to the limit for what is possible with the low-conductivity ITO+ZnO front electrode. In contrast, DTU has achieved up to 7% for cells made from EB5 on their Flextrode.

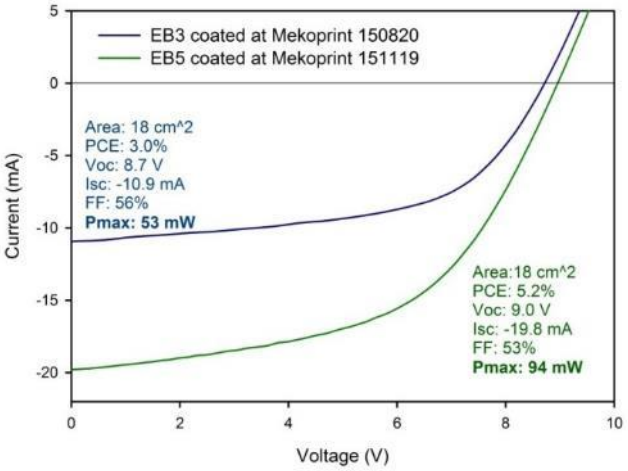


Figure 10: IV characteristics of the best performing modules prepared with the active layer inks EB3 and EB5 at Mekoprint the 08/20-2015 and 11/19-2015 respectively.

Contamination and TOF-SIMS analysis

In order to reveal what might have caused the contamination of the coating surface discussed in the previous sections, specimens were shipped to DTU for TOF-SIMS[4] analysis.

Figure 11 shows the contamination as seen after the active layer is applied. Islands of impurities are seen in the area not covered by the active layer, i.e. the gap between the stripes defining the individual solar cells (Figure 11, left), but are not seen in the area covered by the active layer or in the perpendicular band forming the separation between the modules (Figure 11, right).

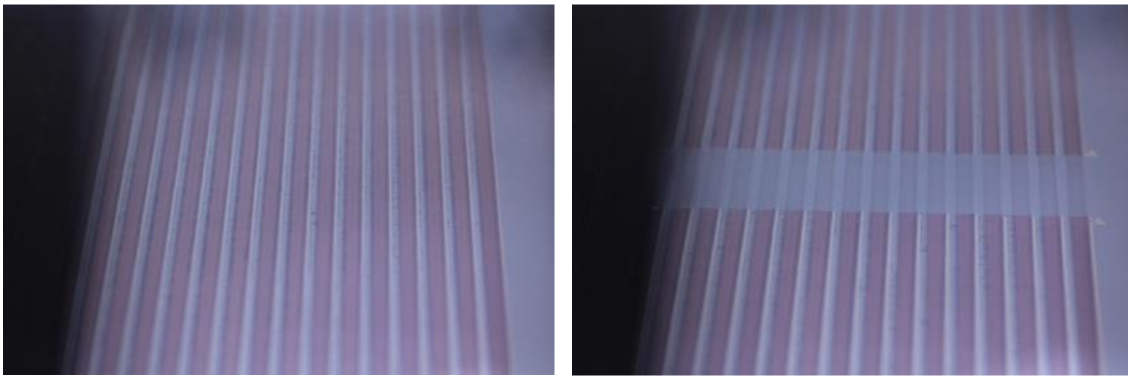


Figure 11: Contamination of the coated foils as it appears after the active layer is applied. The contamination reveals itself as islands in the gap separating the strip-shaped solar cells (left). Such islands are not observed in the area covered by the active layer or in the perpendicular band separating the individual modules (right).

As the contamination is predominantly seen in areas not covered by the active layer, the TOF-SIMS analyses were performed on the surface onto which the active layer is to be coated, i.e. the PET foil with the ITO+ZnO electrode. The analyses revealed that more silicone, Na, K, and Ca is present in the areas where islands of contamination are seen than in the areas where islands are not seen (Figure 12). These elements must have been either present in the sourced PET-ITO foil or added to this foil at Mekoprint.

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[4] Time-of-Flight Secondary Ion Mass Spectrometry

The sourced PET-ITO foil was investigated by collecting mass spectra from respectively the PET side and the ITO side of the foil (Figure 13). The mass spectra show that the two surfaces are exceptionally clean. The impurities must therefore have been added to the foil at Mekoprint and in one of the processing steps occurring before the active layer is added.

The visible contamination was sought removed in the processing by washing the foil with isopropylalcohol (IPA) before applying the ZnO layer and before applying the active layer (see previous section). The effect of the IPA washing was also analysed by TOF-SIMS (Figure 14). When collecting data from a region holding both ITO+ZnO stripes and the area between the stripes where the PET is exposed almost the same level of silicone can be detected in the washed and the unwashed specimen (Figure 14a). The same is true when data is collected solely from areas covered by ITO+ZnO (Figure 14b). This is as expected as the first sample area wise is dominated by the ITO+ZnO electrode. When analysing solely the area between stripe-shaped electrodes only half the amount of silicone is seen in the washed specimen as compared with the unwashed one (Figure 14c), i.e. the washing has a positive effect on the impurity level.

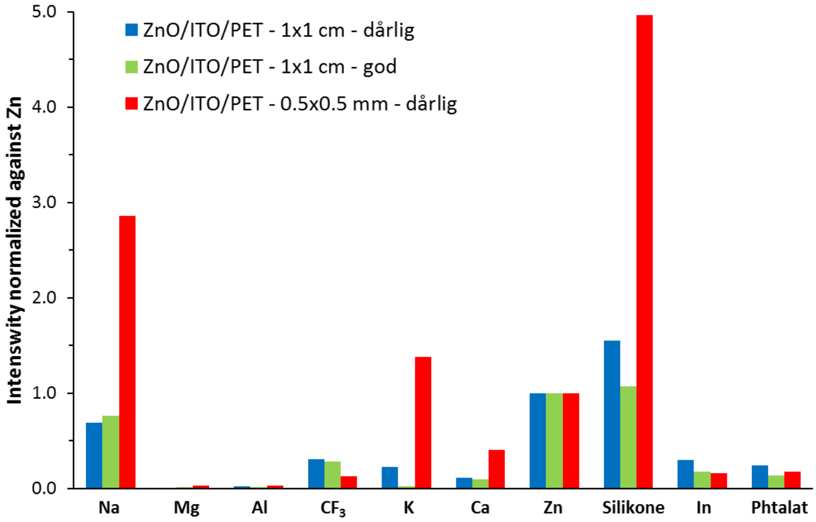

Figure 12: TOF-SIMS analysis of two areas with visible contamination (“dårlig”, labelled blue and red) and on area without visible contamination (“god”, labelled green). The blue and green pillars represent single measurements for which the signal is collected from a large area (1x1 cm2). These measurements should therefore be representative for the average composition in the analysed area. The red pillar represents the average of 9 measurements from smaller areas 0.5x0.5 mm2 (red), i.e. zooming in to areas where the contamination is seen. These measurements should therefore be more representative for the composition of the contamination than the measurements stemming from the larger areas.

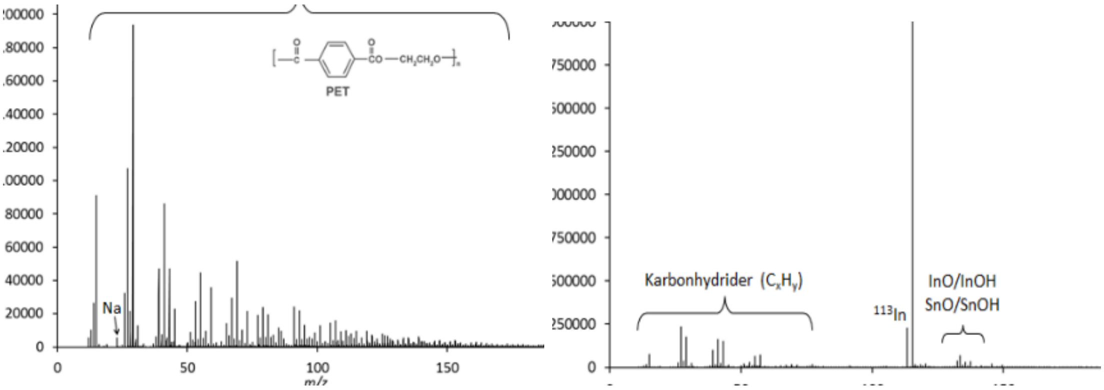

Figure 13: Mass spectra taken from the PET-ITO foil. The spectrum taken from the PET side of the foil (left) comprise peaks typical for PET and traces of Na, whereas the spectrum taken from the opposite side, i.e. the ITO side, is dominated by In and contains also traces of hydrocarbons as is expected on any surface exposed to the atmosphere.

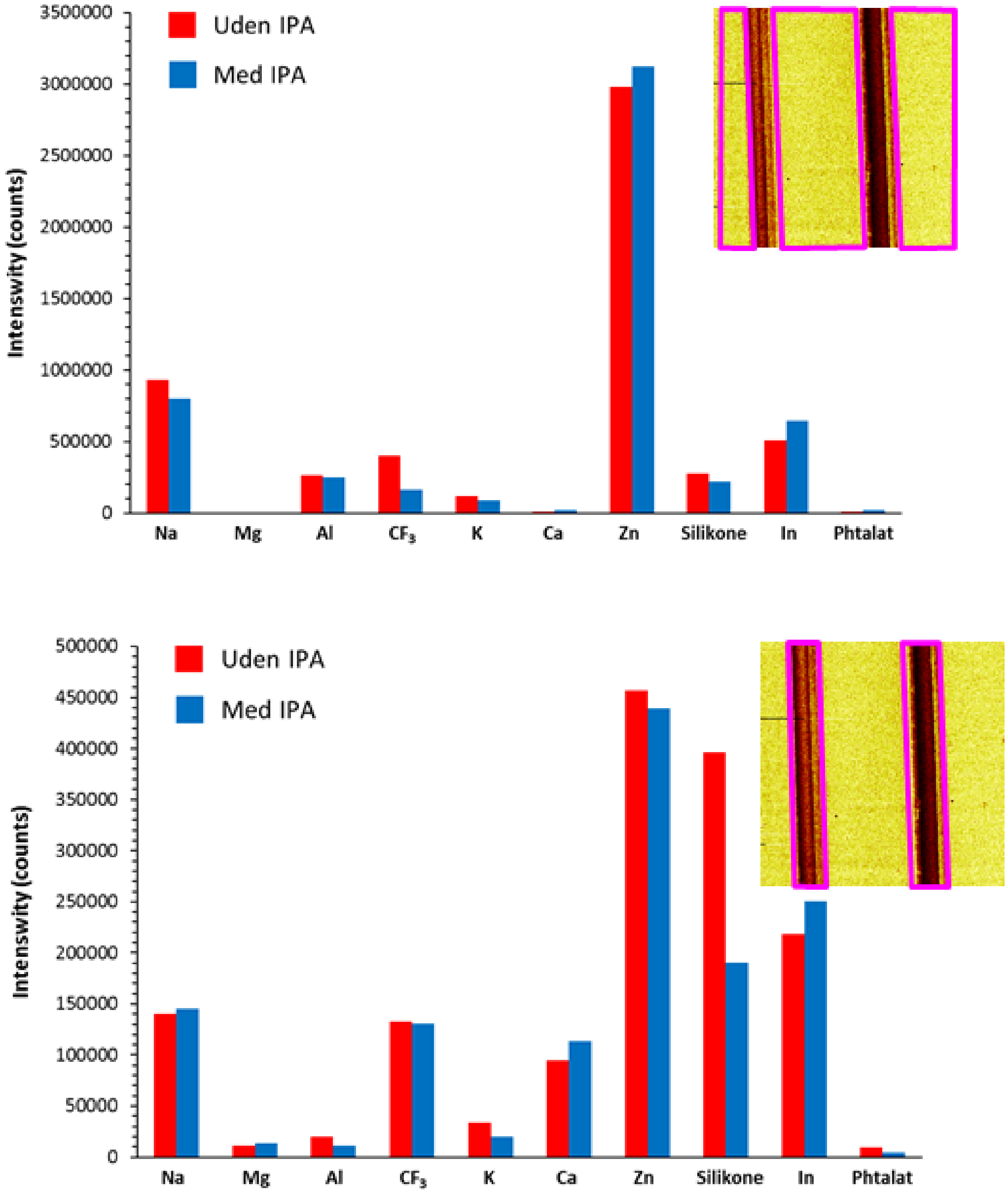

Figure 14: The effect of washing by IPA analyzed by TOF-SIMS. The purple frame marks the area analysed.

TOP: When analysing area containing both the ITO+ZnO electrode and the interspacing where the PET is naked only small differences in the occurrence of contaminations can be detected between samples washed with IPA and unwashed samples.

MIDDLE: When analyzing solely the areas covered by the ITO+ZnO electrode almost the same result as for a) is achieved. This is expected as the area analyzed under a) is dominated by the electrode.

BOTTOM: The difference in contamination between the washed and the unwashed specimens are small for all impurities except silicone. Washing roughly halves the amount of silicon

The TOF-SIMS signal stems from the uppermost 1-2 nm of the surface. Silicone that possibly is "buried" in the electrode, for example in the interface between the ZnO and the ITO layers, will therefore not be detected. For this reason and in order to obtain a clearer view on where in the surface silicone is concentrated, a map showing the spatial distribution of Zn, In, and silicone was constructed (Figure 15). In this map, silicone can be seen along the edges of the ITO+ZnO electrode, indicating that the silicone is buried in the electrode. However, as ITO layer already has been acquitted with respect to silicone contamination, it is reasonable to believe that the silicone stems from Mekoprint's handling of the PET-ITO foil taking place before application of the ZnO layer.

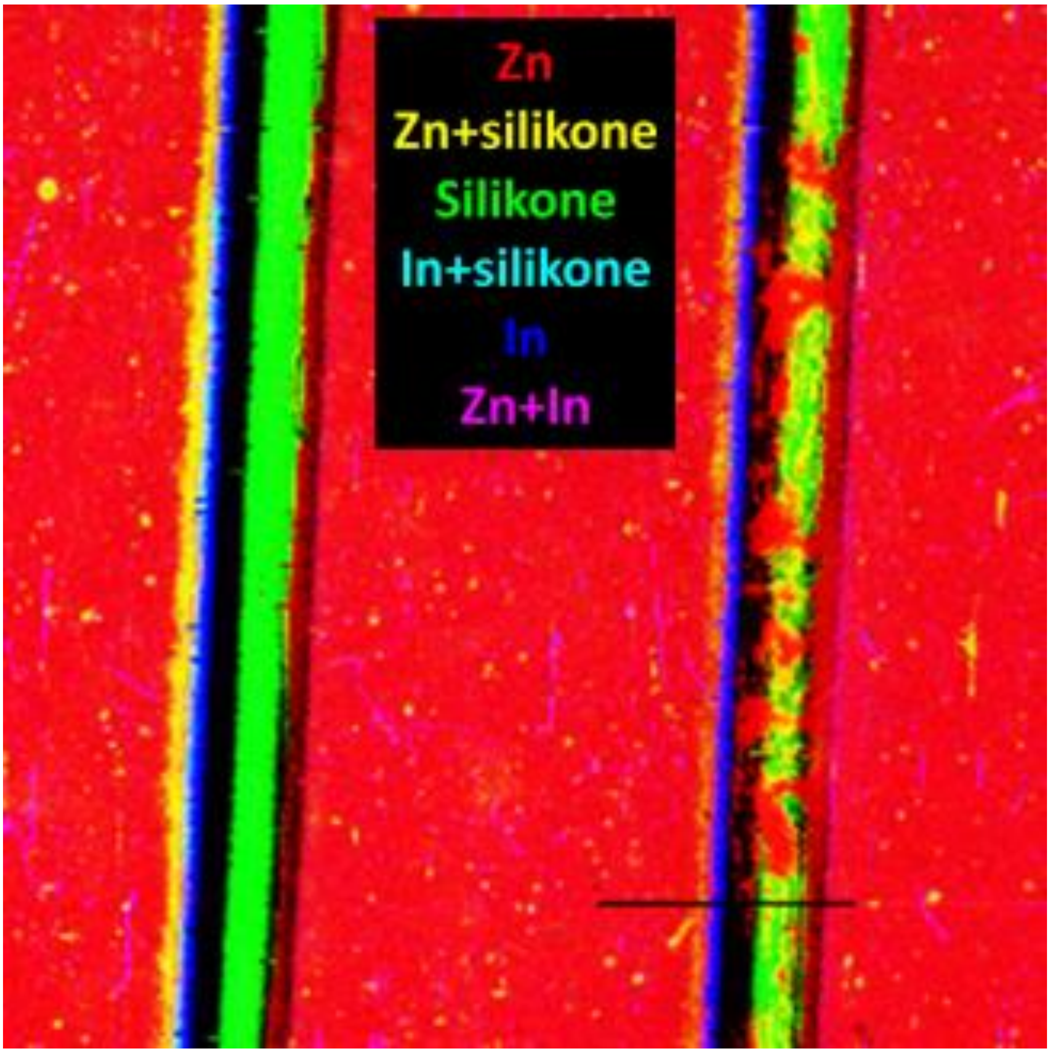

Figure 15: Maps showing the spatial distribution of Zn (red), Zn and silicon (yellow), silicon (green), In and silicon (light blue), In (blue), and Zn and In (purple).Silicone can be seen in stripes following the edged of the ITO+ZnO electrode.

This narrows the outcome space down to a handful processing operations. The most probable source is cross-contamination from other processes running on the same production line when slitting the foil. For this reason, sections cut out from one of the production rollers on the actual line were shipped to DTU for TOF-SIMS analysis. The signal detected was dominated by hydrocarbon with traces of Na, K and Si (Figure 16), and no correlation between the inhomogeneities observed optically and chemically could be found. The lack of correlation might be a consequence of the difference in probing depth, 1-2 nm for the chemical TOF-SIMS analysis and all the way through the specimens for the optical investigation.

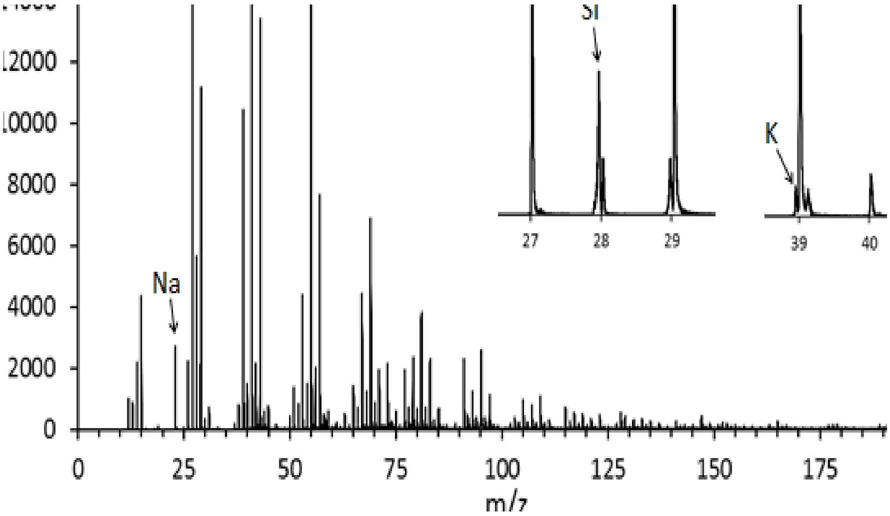

Figure 16: TOF-SIMS mass spectra taken from Mekoprint's production roller. The signal is dominated by hydrocarbon with traces of Na, K and Si.

The foil is slit in half after etching and before coating of ZnO. It is suspected that this slitting introduced silicone from both permanent rollers on the slitting machine and from other jobs that previously was processed on the machine. Therefore, actions have been taken to remove these rollers and change the machine setup to handle aluminum rollers instead.

The conclusions of the TOF-SIMS investigations are:

- The contamination observed on the coated foil is silicon
- The silicon is added before the active layer is processed and after etching of the ITO layer
- The silicone does not stem from the specifically tested production roller on the coating line
- Other suspected rollers have been changed to avoid contamination

WP2: Cost Optimization

Cost is an important parameter in the final commercialization of the polymer solar cell. Mekoprint has implemented an advanced cost calculation tool in an Excel sheet containing all relevant parameters:

- Material prices
- Material usage and thicknesses
- Process times and speeds
- Process properties

The extensive Excel sheet allows for tuning cost parameters to specific material suppliers prices and expectations. This allows for easy insight in the cost drivers of the complete polymer solar device as seen in Figure 17.

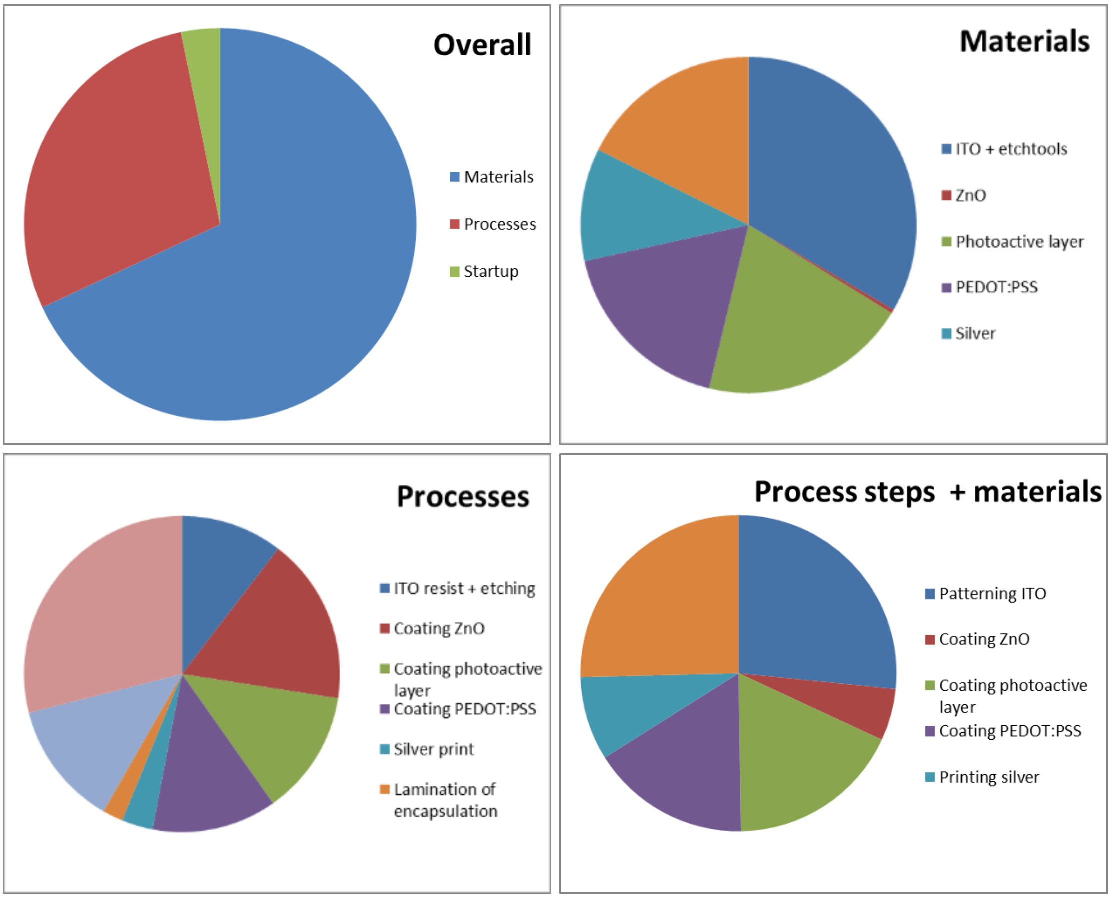

Figure 17: The resulting pie charts from the common cost calculation tool for a small module in high quantities.

This concludes *D2.1: Common cost calculation tool.*

One effective way for Mekoprint to reduce the overall price of the polymer solar cell device is to improve its own processes. To do this Mekoprint improved the coating speed for the coating line equipment to 5 m/min for the coating of ZnO and photoactive layer. The drying of the water based ZnO ink is still a limitation, so for effective scale up additional drying or another solvent will be necessary at this speed. For the last coated layer, PEDOT, adequate drying is an issue for the PEDOT used in the original Process One stack, so Mekoprint worked to change the PEDOT supplier in order to use a thinner PEDOT layer, which provides a cheaper product and easier drying. Most of the time during production, a coating speed of 1-2m/min were used, as this allowed more time for experiments to be carried out, but it was also proven that 5m/min does not pose a problem. For the screen printing of etch resist and silver the processes run on different machines. These machines run 5 m/min on a daily basis and Mekoprint has the option to continuously screen print up to 3 layers simultaneously in one machine at up to 25 m/min. *This fulfils M3: Coating speed 5 m/min at Mekoprint.*

Mekoprint introduced several cost optimizations:

- A new prototype coating head was designed and produced in-house (Mekoprint Mechanics). This reduced the start-up cost substantially as only a total of max. 15 ml ink is needed for the start of a coating in up to 300 mm width as opposed to 50ml with previous design. This is considered industry leading, and given the cost of small scale ink synthesis, the cost savings are significant. Furthermore, the assembly and cleaning times are drastically reduced with the new design. See more in the next section.
- New shims and meniscus guides for the coating head were designed and produced in-house (Mekoprint Chemigraphics). The traditional shims/guides were laser cut but this produced uneven edges at a macroscopic scale. Mekoprint developed a process to quickly etch shims/guides from sheet metal and get smooth edges, which results in more evenly coated layers.
- The reduction of web width (from 305 mm to 152.5 mm) introduced cost savings due to a more efficient usage of the ITO substrate during test productions.
- The printed silver back electrode is drastically reduced in coverage and in some cases completely eliminated in order to reduce cost, increase lifetime, and make the product more environmentally friendly. This is done using a highly conductive PEDOT layer (the layer immediately below the silver) that can itself extract and transport the current out of the cell.

Figure 18: Top picture of the in-house developed and produced prototype coating head. The inlet of ink is seen in the middle.

A special coating head for slot-die coating was developed by Mekoprint with the goals of reducing ink waste during coating start up, and to support the full ITO web width of 305mm. The design is scalable to wider webs as the coating line supports web widths up to 700mm and reduces assembly time as there are fewer parts in the construction. The coating head was milled at Mekoprint Mechanics using tool grade stainless steel.

A comparison of the specifications of the coating head used in phase 1 & 2 of the project and the Mekoprint developed head is shown below:

Coating head comparison	Coating width	Metal parts	Start-up ink waste	Bolts	Mask alignment	Coating direction
Phase 1 & 2	240mm	4	55ml	12	Manual	One way
Phase 3	300mm	2	15ml	9	Fixed	Both ways

Design details for the Mekoprint developed coating head are shown below in Figure 19 and Figure 20.

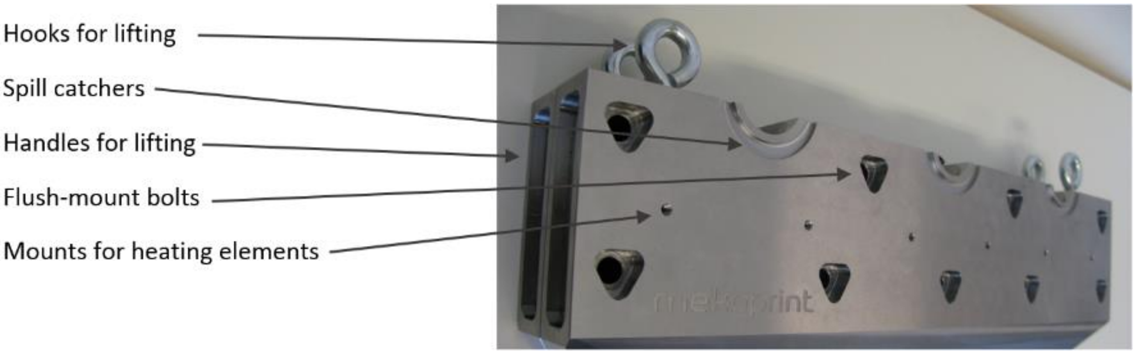

Figure 19: Front side of the prototype coating head.

The low ink waste is obtained by reducing the volume in the distribution chamber. To do this whilst maintaining coating uniformity, a *distribution tree* is introduced based on an idea from a student project in cooperation with Aarhus University in 2011 (reference). The shape of all joints in the distribution tree makes the fluid resistance equal to each of the eight distribution chamber entry points. A small section of the distribution tree is narrow to increase fluid resistance to ensure filling of all channels. Three inlets are used with the centre inlet being used for ink supply, while the outer two were used for ventilation during filling and for removing ink residuals after coating. The coating head was initially tested with a transparent counterpart to verify ink flow and has been used in all tests with commercial inks with better performance than the previous coating head.

Figure 20: Internal details of prototype coating head.

In order to accurately control the coating quality while reducing and optimizing the layer thickness of each layer during the coating and printing processes Mekoprint has used a Bruker Dektak XT 3D profiler. This enables fast feedback on the actual dry coating and printing thickness for both the overall thickness as well as the uniformity. A 3D map of a single stripe in a polymer solar cell before encapsulation is shown in Figure 21.

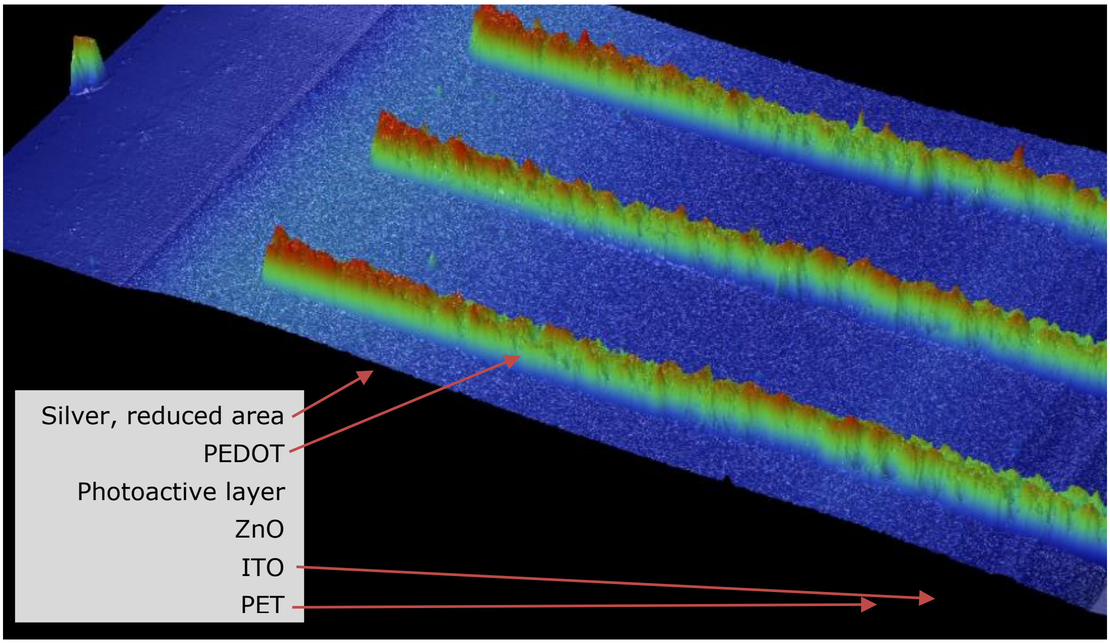

Figure 21: 3D profile scan of a completed polymer solar cell. The photoactive layer and the ZnO layer are coated below the PEDOT and are not easily seen in this image. The three thin stripes are silver electrodes oriented in the direction of the current unlike the previously used busbar arrangement which were perpendicular to the current direction.

Profiling with nm resolution has been a powerful tool to measure distances and thicknesses of individual layers, analysing coating edge quality and checking coating uniformity across a single stripe.

Meniscus shaper
In an attempt to coat thinner layers of ink- especially PEDOT - with uniform coverage, a new meniscus guide principle was developed: The Meniscus shaper.
In a conventional slot die coating head, two thin metal sheets are used to control the ink pattern on the foil: A shim is used to guide the ink unto a meniscus guide, which guides the ink unto the foil as seen below. The width of the stripe is normally much larger than the exposed length of it, so the ink tends to form a drop-like meniscus, which extends up in the edge of the slot die head. This leads to a greater ink volume at the center of the stripe and less on the edges, increasing the risk of edge thinning and wobbly edges.

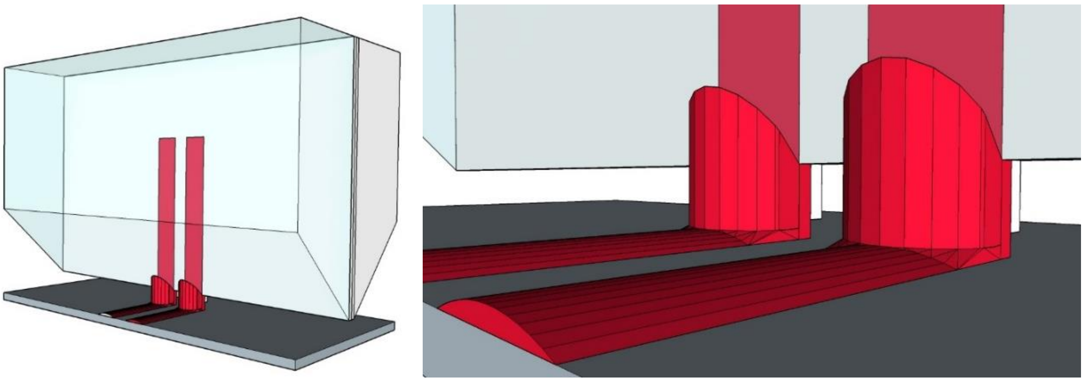

Figure 22: Slot die coating head with standard meniscus guide, where ink drop is formed and affects coating uniformity. Front part of coating head in transparent to show ink flow (red) inside coating head.

To counter this problem, Mekoprint has implemented a meniscus shaper, which is a third metal sheet of similar shape as the meniscus guide, which shapes the meniscus for more uniform coating as shown below:

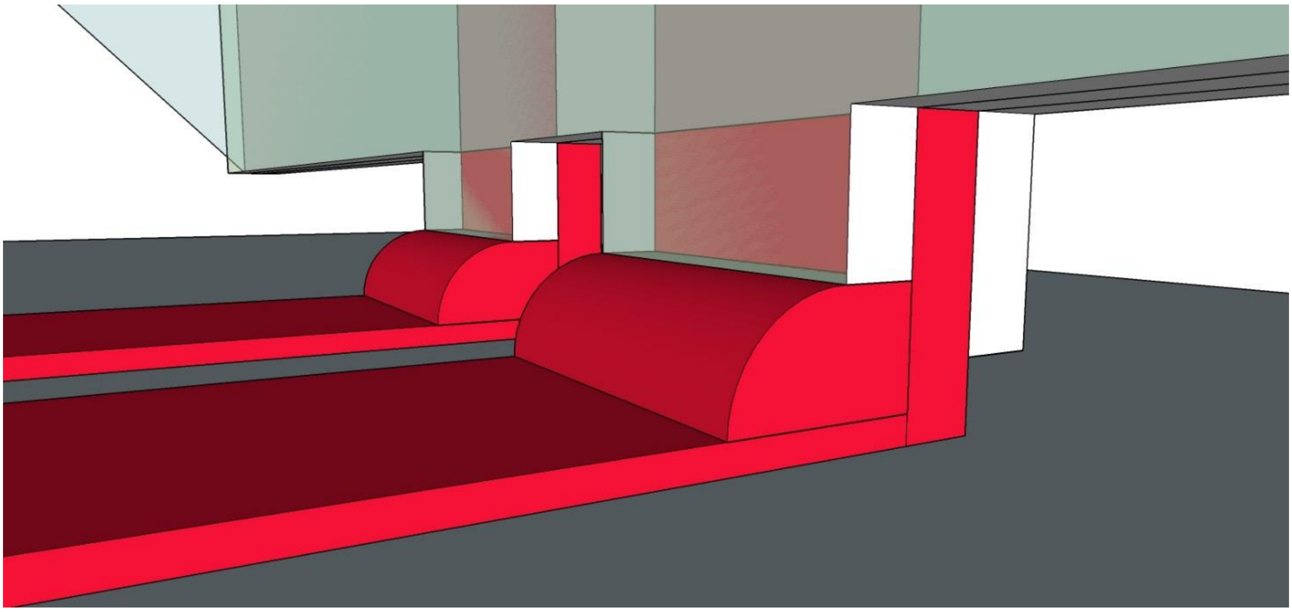

Figure 23: The meniscus shaper pins the meniscus by creating an anchor line for the ink, so the meniscus has more uniform size over the stripe width. The effect is exaggerated here for the purpose of illustration.

The improved slot die coating mask system has been tested with good results and has used for most coatings with commercial inks during 2015 and 2016.

For the total end price of a polymer solar cell device an ambitious milestone of 1 DKK (~13.4 €cent) for a device the size of a credit card was set up. Deliveries D2.2-6 was set up to follow the development, but during the project, the volume remained low and the material prices did not decrease as expected. Mekoprint was able to implement several cost reductions to *fulfil D2.2, D2.3, and D2.4: A cost of 6 Dkr pr creditcard module is achieved,* but *not able to fulfil M4: A cost of 1 Dkr pr creditcard module is achieved.* It is still believed that the technology has the potential to achieve this highly disruptive price point with substantial development, but not in the current state.

In order to increase the yield of the process (to reduce cost) Mekoprint has implemented extensive logging and traceability during the production. Through an in-house programmed control and logging program running on a Windows pc, the entire process is controlled as well as logged in order to have traceability of the solar cells produced. All relevant parameters can be displayed during the production or reviewed afterwards. As one of the last process steps the roll of printed solar cells are electrically tested with an IV sweep under full sun conditions and solar cell parameters such as efficiency, open-circuit voltage, short-circuit current, maximum power point and fill factor are calculated. Test engineers can then correlate solar cell characteristics with actual production parameters at specific devices on the foil. This is a powerful tool to optimize production and find optimal settings during an advanced multilayer production process.

Furthermore, a vision system was set up to analyse pictures taken of the individual coated layers during each production run. The tool was first used to post process the pictures for correlations to the solar cell characteristics and later in the project implemented in the production control/logging software for real-time analysis of the printed layers during production. This was deemed necessary since the tolerances were low and the demands for quality control exceeded the human vision capabilities. These improvements of control, logging, and vision has clearly improved the yield and understanding of the production of solar cells and thereby lowered the cost.

Electrically measuring the active area and current generation uniformity is important to evaluate coating quality. This has previously been possible at DTU through the specially developed Light-Beam Induced Current (LBIC) test equipment. Performing these measurements at DTU on modules with commercial active layers are not possible due to confidentiality. Mekoprint has therefore built a scaled down version, which gives one-dimensional LBIC results, which are actively used for process optimization. Below in Figure 24 is an example showing how 4 different process parameters during production (shown with different colours) influence uniformity of current generation and width of a coated stripe.

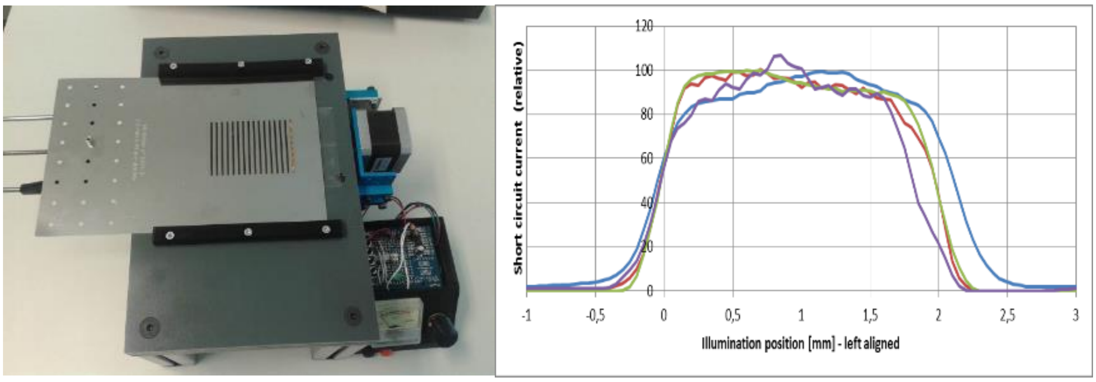

Figure 24: One-dimensional LBIC setup. Right: Example of results showing current generation (y-axis) across stripe width (x-axis) when masked with a 0.25mm width on all stripes simultaneously. The plot reveals a ±10% variation of stripe width for the modules, which directly reflects on the power of the module and therefore an important parameter for optimization.

WP3: Lifetime

A long and guaranteed lifetime is utterly important for the solar cells’ competitiveness. This is reflected in the project’s milestone of achieving a lifetime of 5 years (T80) for product integrated solar modules. The stability and thus the operational life of the polymer solar cell can be directly improved through the encapsulation methods and materials. Both aspects have been addressed in the project in the following tasks, which all lead towards the targeted 5 years lifetime:

- building and installation of a machine for encapsulation of the solar cells at Mekoprint
- benchmarking of Mekoprint’s setup for accelerated lifetime testing against DTU’s Characterization Laboratory for Organic Photovoltaics (CLOP), all testing are performed in accordance with the ISOS testing protocols, approved by the international OPV community
- extended testing of polymer solar modules produced by Mekoprint
- development of a computer tool for prediction of the operational lifetime of polymer solar modules produced by various methods and from various materials

Since the electrical performance of the manufactured polymer solar cells at Mekoprint were still under development late in the project it was chosen to postpone and finally stop the assembly of the encapsulation machine described in *M2: Automated encapsulation machine installed*. This also made it impossible to fully investigate the lifetime for product integrated OPV modules as it was not possible to fully encapsulate the OPV modules processed at Mekoprint in an automated manufacturing process. The initial investigations were made and the optimal design was found, but it was not possible to fulfil D3.3, D3.4 and M5.

To achieve optimal encapsulation conditions for the polymer solar cells produced, Mekoprint built a small nitrogen chamber within this project. This made it possible to test and encapsulate newly produced solar cells in an inert atmosphere without the presence of oxygen and water vapour. This chamber has been successfully used for testing newly prepared polymer solar cells without degradation caused by oxygen and moisture. Encapsulation in glass has also been achieved under nitrogen conditions.

Mekoprint has established a setup for accelerated lifetime testing. As a part of the project, the setup was benchmarked against a corresponding setup at DTU via Round Robins comprising the following standardized test procedures: ISOS-D-2, ISOS-D-3, ISOS-L-1 and ISOS-O-1, see Table 2. The extended testing of modules produced at Mekoprint revealed good agreement between Mekoprint's and DTU's testing (Figure 25), and allows a baseline for lifetime comparison to be set. *This fulfils deliverable D3.2: Lifetime testing of the new ink stacks and encapsulation procedures relevant to WP1, WP2 and WP3 are tested at both Mekoprint and DTU in the aim of finding consensus.*

Table 2: Accelerated testing conditions applied in the project

	ISOS-D-2 High temperature storage	ISOS-D-3 Damp heat	ISOS-L-1 Laboratory weathering testing	ISOS-O-1 Laboratory weathering testing
Light source	None	None	Simulator	Sunlight
Temperature (°C)	65/85	65/85	Ambient	Ambient
Relative humidity (%)	Ambient (i.e. low)	85	Ambient	Ambient
Environment	Oven	Environment chamber	Light only	Light only
Characterization light source	Solar simulator	Solar simulator	Solar simulator	Solar simulator
Load	Open circuit	Open circuit	MPP[5] or open circuit	MPP or open circuit

DTU has further focused on developing a tool for prediction device lifetime. The first step in this process was to build a database holding lifetime data. Such data was collected from DTU's database covering own experiments and from the literature. This involved, among others, identification of 2500 paper from the research literature holding lifetime data, and extraction of reliable data on lifetime, device structure and encapsulation from the papers. The database has proven to be highly useful for identifying the main stability bottlenecks among different organic solar cell architectures, and as a strong measure for the progress and current status of the lifetime of organic solar cells. The database is available online, and everybody is welcome to upload and compare experimental lifetime data obtained according to the ISOS guidelines.

From the database, a computer-based tool for predicting and optimizing the stability of OPV devices has been developed. The present tool offers the following services:

- Search for experimental lifetime data for specific OPV device structure and encapsulation
- Comparison of lifetimes for devices with different structures and encapsulations
- Comparison of lifetimes for devices produced by different techniques (R2R, spin coating, mini-roll coating)
- Comparison of lifetimes for devices tested under different conditions (including both indoor and outdoor ISOS tests)
- Using the comparative approach estimating the lifetimes of specified OPV devices in real operational conditions based on acceleration indoor tests

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[5] MPP – maximum power point tracker

The lifetime prediction tool is available on www.plasticphotovoltaics.org/lifetime-predictor.html, DTU's open platform for OPV communication. *This fulfils deliverable D3.1: Accelerated lifetime testing protocols are developed as a tool that based on a short accelerated lifetime dataset as input can project operational lifetime in an application. The tool is delivered as an executable*.

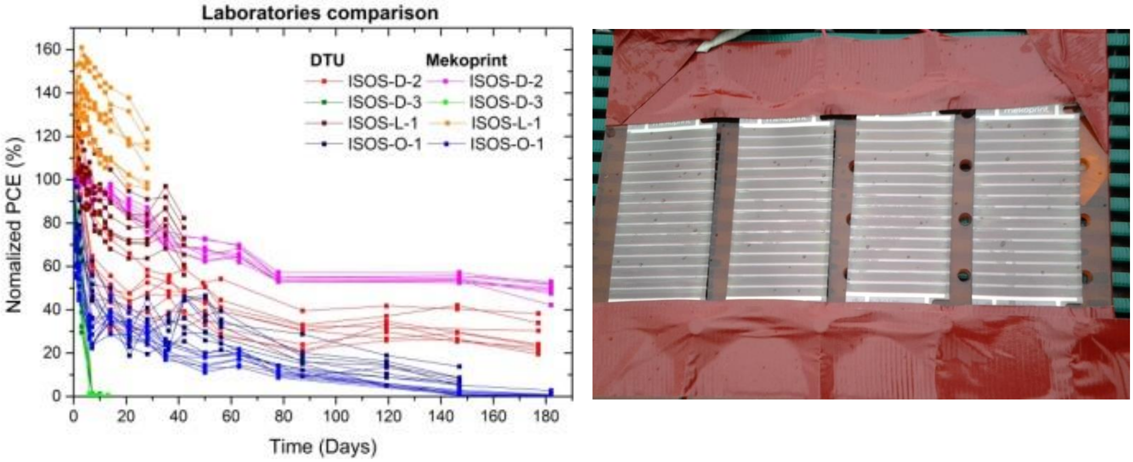

Figure 25: The stability curves of all the Mekoprint-produced modules tested by the two partners (left) and some of the modules as exposed to outdoor conditions (right).

In order to improve our ability to predict the lifetime of a given device, a range of various devices was tested at DTU under the ISOS conditions for durations up to one year. The devices were deliberately chosen to cover different geometric dimensions, stack configurations, production methods and encapsulations in order to give a spread in stability. The aging of each device was followed by the following test protocols: ISO-D-1, ISOS-D-2, ISOS-D-3, ISO-L-2, ISOS-L-3 and ISOS-O-1 or ISOS0-2 for the outdoor aging. The results were plotted in a so-called o-diagram that present the scatter of initial device performance as function of lifetime (Figure 26). The o-diagram expressed the time scale in the form of a logarithmic function with base 4, because this allows associating the time with commonly used time units (hours, days, week, months, seasons and years). From the plot it becomes obvious that the measured outdoor life time for the devices fall somewhat between what is measured in the accelerated indoor aging test (ISO-L/light soaking and ISO-D-3/damp heat) and the moderate dark tests (ISO-D-1 or ISOS-D-2). This is as expected.

The advantage of the o-diagram and its categorizing of data in time blocks is that it allows us to establish relations between the different ISOS tests and also to roughly determine accelerations factors. The o-diagram in Figure 26 shows that devices lasting only for days to weeks under accelerated indoor conditions have lifetimes of weeks to months under outdoor conditions and up to seasons and years in terms of shelf life. The diagram as presented is limited to the device types studied here and to Denmark as geographic location. The intention behind developing the o-diagram methodology is to demonstrate a simple method for comparing aging under different conditions and hereby to encourage other researchers to use the same method so that a large amount of comparable data can be made available for upgrading the present lifetime prediction tool for more precise predictions and increased validity range.

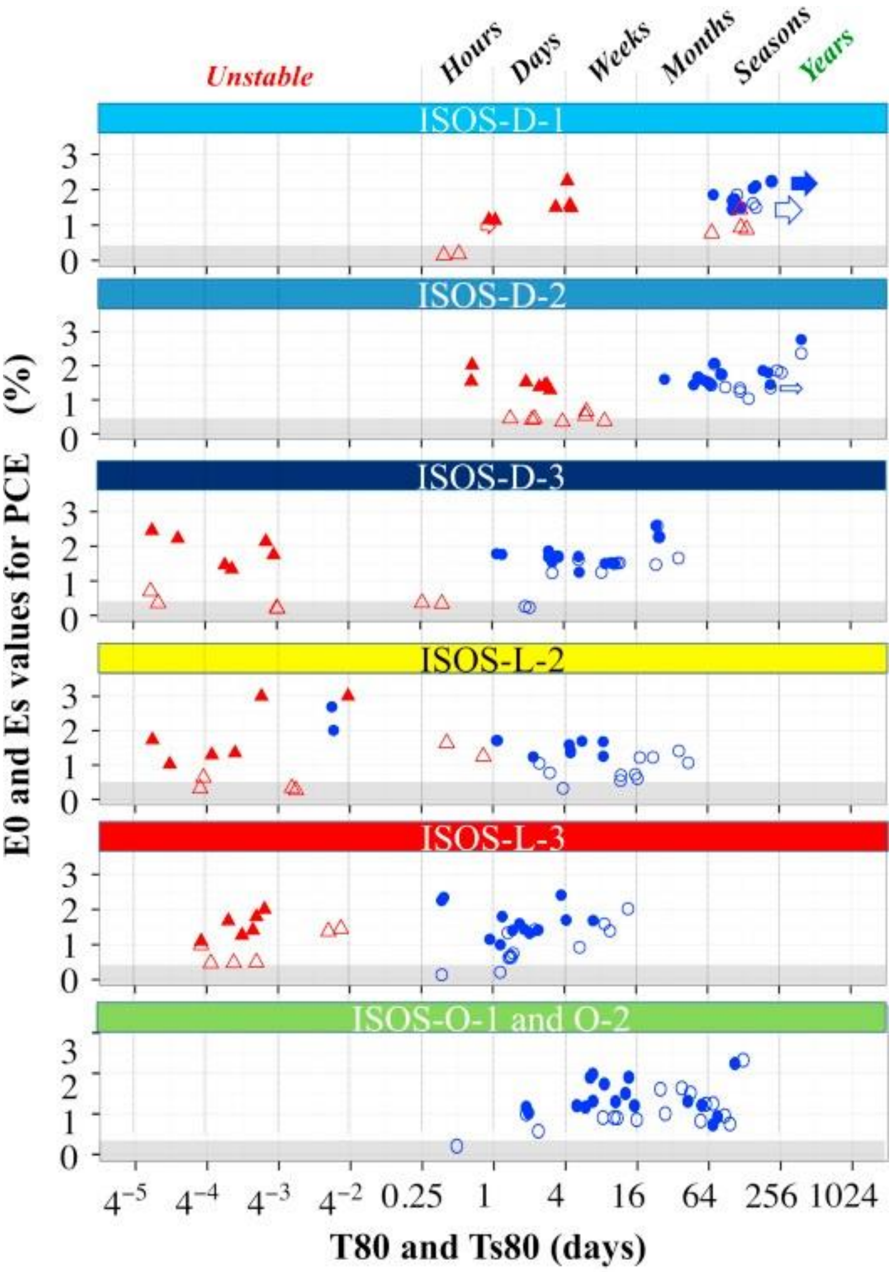

Figure 26: The o-diagram presents the T80 (solid markers) and Ts803 (open markers) values for all the tested samples under different ISOS testing conditions. The blue circles and the red triangles represent correspondingly devices with and without encapsulation. Arrows are used to indicate that the test was terminated before T80 was reached.

The o-diagram investigations based on devices produced by DTU was followed by a meta-analysis conducted on lifetime data reported in the literature. This has allowed for the compilation of an extensive OPV lifetime database based on a large number of articles, and subsequent analysis of the large body of data. The analysis revealed that the early reports of OPV lifetime were at the level of minutes, today stable performance up to years is reached (Figure 27). For the presentation of the progress of the OPV lifetimes the literature data was filtered for the best reports and plotted (Figure 28) similarly to the record cell efficiency diagram reported periodically by NREL[6].

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[6] www.nrel.gov/ncpv

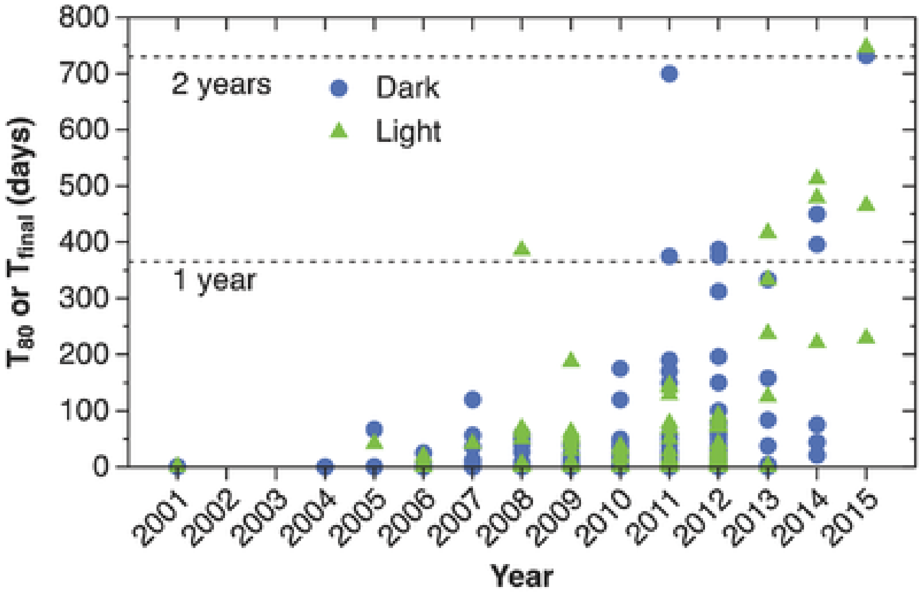


Figure 27: Scatter plot of reported lifetimes per year with the green triangles representing samples tested under light and the blue circles representing the tests in darkness. The dashed lines correspond to the one and two year threshold.

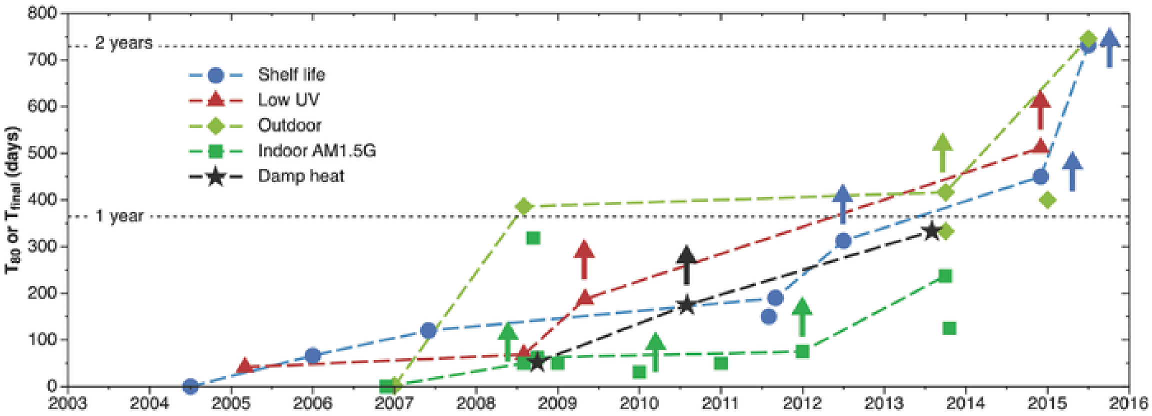


Figure 28: Diagram of the best OPV device lifetimes distributed according to the test conditions. The arrows highlight the samples that are limited by measurements duration rather than the sample lifetime.

**denotes damp heath testing conditions not compatible with ISOS-D-3.*

The plots demonstrate the rapid improvements that have been made in this area during the past few years. Such a fast development suggests that within a short period the technology will reach a durability opening for a range of new application and also the 5 years targeted in this project. The meta-analysis revealed also that the field is in great deficit of outdoor lifetime studies and accurately controlled indoor accelerated tests conducted in a consistent and reproducible manner. This challenges the further refinement of the present lifetime prediction tool. DTU's online platform for collection of lifetime data is seen as a vital tool for achieving this.

1.6 Utilization of project results

Commercialization is the most important part of this project, and therefore the commercial activities are placed in a separate work package: WP4.

WP4: Demonstration and commercialization

The first step of commercialization was to setup a collaboration with commercial ink and material suppliers in order to work with material volumes that could be scaled up compared to materials produced at a university. "*KM1: Signed contract with commercial ink supplier that can deliver ink with performance in accordance with project objectives and findings"* was successfully fulfilled early in the project. The relevant supplier's materials and solar modules produced herewith were tested as described under WP1. These tests also fulfil *D4.1: Modules specified and evaluated based on D1.1*.

The market for polymer solar cells has changed since the beginning of the project. Most of the hype around the technology has decayed and we now see fewer but more relevant requests for the technology. Where we used to have many requests from smaller companies with unrealistic expectations, we now see requests, which are more realistic about the energy output possible with OPV but also where the thinness, flexibility and low light performance all are desired features.

The project had from the beginning chosen 3 commercially interesting ”focus customers” in order to direct our attention to relevant subscribers to the OPV technology. They were chosen from a high potential for commercialisation and exposure and to make sure the development of the OPV technology was directly towards actual customer needs. From the beginning, one of the focus customers showed an increased interest and a close collaboration began with this customer on demonstrating the OPV modules in a prototype of their product. Through meetings with product designers and decision makers, a common understanding of the advantages of OPV was made clear and it was shown how this best could add value to the focus customer's product portfolio. Mekoprint was able to demonstrate how a polymer solar cell could drive a wireless- and an optical link only using indoor light. This is a clear advantage of the OPV technology along with the plastic nature and the easily changeable format when printing. From this customer dialogue, demonstrator OPV modules were specified and the focus customer invested resources in developing two prototypes. The details are covered by NDA, but it is possible to show the OPV module alone adapted for this product – see Figure 29 below. It is shown how printing technology can be used to shape a solar module in new ways despite the limitations of linear stripes. It this product, electronics were placed in a narrow central bay, so the solar cell was exposed on both sides of the bay.

Figure 29: Solar module adapted for customer product and used in customer's evaluation internally and in focus groups.

The solar module was first produced in 5 samples and the next version in 70 samples corresponding to approximately 150 credit card sized samples due to the size. This fulfils *D4.3:* Modules for demonstrator #1 is specified and prepared for production and *D4.6: Demonstrator #1 is manufactured (min. 100 credit card cells or similar area).*

Another customer bought 110 marketing products with integrated polymer solar cells from Mekoprint. This product were based on the laserpointer design of an earlier phase of the project but manufactured with commercially available materials only. See Figure 30 below.

Figure 30: Selection of laser pointer demonstrators produced with commercially available inks.

As a pure Mekoprint demonstrator in order to show the prospect of how the advanced OPV technology can be integrated in simple products Mekoprint has made a solar cell sticker. An example of how this implemented can be seen in Figure 31.

Figure 31: The polymer solar cell as a sticker. Left is a closeup of the adhesive on the backside with a stamped out hole for contacting the graphite electrode underneath the adhesive. To the right is an automated dispensing machine for polymer solar cell stickers.

Mekoprint has showcased this demonstrator at conferences (LOPE-C 2013 among others) with positive feedback. The simplicity of an adhesive on the backside is very compelling to potential customers, as it seems easy to integrate into products. It is, however, fairly complex to manufacture at high volume in a R2R production, due to the hole in the adhesive requiring registered lamination. Mekoprint has developed tools and machines for this process in another customer driven project and fully controls this technology in high volume. All this fulfils *D4.4: Modules for demonstrator #2 is specified and prepared for production* and *D4.7: Demonstrator #2 is manufactured (min. 500 credit card cells or similar area)*.

The Printoo project has taken a slightly different direction than other customer projects. The Printoo module was designed for a new platform for printed electronics, which is directed at the maker community. Funding for development of this platform has been successfully achieved through the online crowdfunding site Kickstarter. With Printoo enthusiasts around the world create new designs, which they share to the world through magazines and homepages. The Printoo packages are pre-ordered by the makers, and we know that a significant part of the 350 packages with the Printoo solar modules have been ordered by companies, who see an interest in experimenting with polymer solar cells.

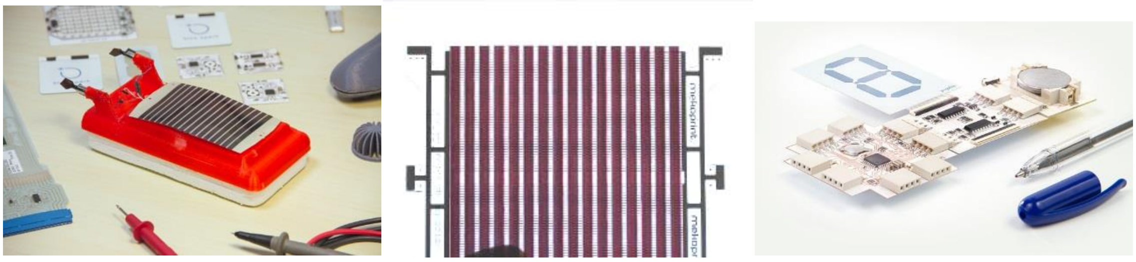


Figure 32: Left: Demonstrator by Ynvisible, Middle: The specially designed Printoo module and Right: Still from a Printoo video with the Arduino compatible board and a printed electrochromic display.

Since the Printoo solar module is a non-confidential design, it has been used also as a general demonstrator module for various customers. It is easy to interface to and self-explanatory through the video described below. We are looking forward to the response from the maker community and companies, when the platform is launched.
We have manufactured 750 "Printoo" solar modules which fulfils *D4.2: Modules specified and evaluated based on D1.3*, as well as *D4.5: Modules for demonstrator #3 is specified and prepared for production* and *D4.8: Demonstrator #3 is manufactured (min. 1000 credit card cells or similar area)*.

To further disseminate the Printoo module, an instructional video (Dissemination link 12) was produced, which passes on essential information on the usage of the module. The video is listed on the reference section of this report and has been shown 430 times.

Figure 33: Screenshots from the Printoo video

We have produced two versions of a marketing product demonstrator, which were presented at one of the biggest emerging technology conferences in the world, SXSW 2015 in USA. The product was based on the Printoo module with specially developed electronics according to the customer's specification.

Figure 34: Demonstrator for a marketing product. Left: Front side showing graphics and exposed part of solar module. Image has been manipulated to remove customer logo. Right: Solar module and electronics. This demonstrator was build using rigid PCB.

One customer request regarding a flexible solar module required higher output power than the above modules, and Mekoprint implemented a demonstrator module based on the newest encapsulation methods mentioned previously in the report. The back barrier is the 4-layer aluminium material with etched electrodes terminating in an FPC-connector ready flex circuit. There were made versions with different hot melt adhesives, where the image below (Figure 35) shows the 3M 583-type whose color is not adding to the appearance. This module is also the first where epoxy-based silver was used to connect the solar module with the electrodes on the back side barrier. A total of 18 modules were produced and a set of 11 samples were shipped to the customer.

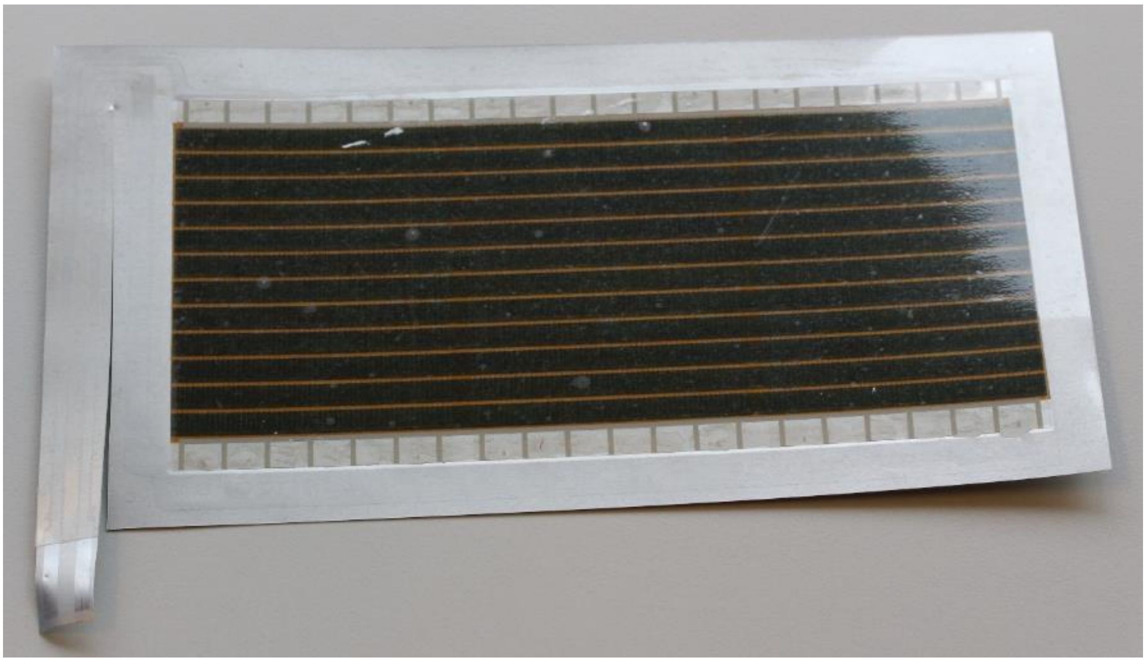
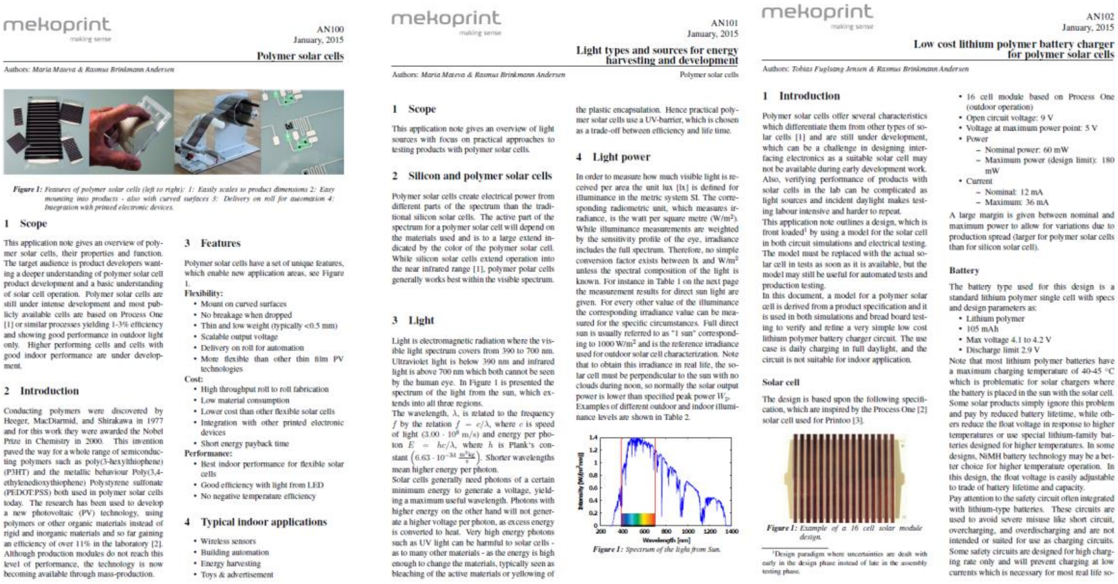


Figure 35: Solar module with aluminium back barrier, flex circuit terminals and hot melt back adhesive (Yellow.) The image has been modified to remove the name of the customer.

It is concluded that for the demonstration part of WP4, all planned demonstrators have been produced and evaluated together with the customers. This fulfils the milestone *KM2: Three demonstrators produced and evaluated*.

Alongside the engineering tasks of this project, the rest of the organization at Mekoprint such as sales, logistics, lean production and customer support have been informed on the development of the project and when appropriate also trained and involved in demonstration production and sale.

Due to the complexity of designing products with integrated polymer solar cells, it was chosen to publish three “Application notes” that describe how an electrical engineer should understand the technology and how to interface electrically with a polymer solar cell. Application notes are common in electrical engineering and are used not only in design work but also during evaluation of candidate solutions. The application notes also helps customers build realistic expectations to the technology and thus makes customer dialogues more efficient. The three application notes are published on the homepage of Mekoprint and a screenshot of the front pages are shown in Figure 36.



mekoprint
making sense

AN100
January, 2015

Polymer solar cells

Authors: *Maria Maeva & Rasmus Brinkmann Andersen*

Figure 1: Features of polymer solar cells (left to right): 1: Easily scales to product dimensions 2: Easy mounting into products - also with curved surfaces 3: Delivery on roll for automation 4: Integration with printed electronic devices.

1 Scope

This application note gives an overview of polymer solar cells, their properties and function. The target audience is product developers wanting a deeper understanding of polymer solar cell product development and a basic understanding of solar cell operation. Polymer solar cells are still under intense development and most publicly available cells are based on Process One [1] or similar processes yielding 1-3% efficiency and showing good performance in outdoor light only. Higher performing cells and cells with good indoor performance are under development.

2 Introduction

Conducting polymers were discovered by Heeger, MacDiarmid, and Shirakawa in 1977 and for this work they were awarded the Nobel Prize in Chemistry in 2000. This invention paved the way for a whole range of semiconducting polymers such as poly(3-hexylthiophene) (P3HT) and the metallic behaviour Poly(3,4-ethylenedioxythiophene) Polystyrene sulfonate (PEDOT:PSS) both used in polymer solar cells today. The research has been used to develop a new photovoltaic (PV) technology, using polymers or other organic materials instead of rigid and inorganic materials and so far gaining an efficiency of over 11% in the laboratory [2]. Although production modules do not reach this level of performance, the technology is now becoming available through mass-production.

3 Features

Polymer solar cells have a set of unique features, which enable new application areas, see Figure 1.

Flexibility:

- Mount on curved surfaces
- No breakage when dropped
- Thin and low weight (typically <0.5 mm)
- Scalable output voltage
- Delivery on roll for automation
- More flexible than other thin film PV technologies

Cost:

- High throughput roll to roll fabrication
- Low material consumption
- Lower cost than other flexible solar cells
- Integration with other printed electronic devices
- Short energy payback time

Performance:

- Best indoor performance for flexible solar cells
- Good efficiency with light from LED
- No negative temperature efficiency

4 Typical indoor applications

- Wireless sensors
- Building automation
- Energy harvesting
- Toys & advertisement

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AN101
January, 2015

Light types and sources for energy harvesting and development

Authors: *Maria Maeva & Rasmus Brinkmann Andersen*

Polymer solar cells

1 Scope

This application note gives an overview of light sources with focus on practical approaches to testing products with polymer solar cells.

2 Silicon and polymer solar cells

Polymer solar cells create electrical power from different parts of the spectrum than the traditional silicon solar cells. The active part of the spectrum for a polymer solar cell will depend on the materials used and is to a large extend indicated by the color of the polymer solar cell. While silicon solar cells extend operation into the near infrared range [1], polymer polar cells generally works best within the visible spectrum.

3 Light

Light is electromagnetic radiation where the visible light spectrum covers from 390 to 700 nm. Ultraviolet light is below 390 nm and infrared light is above 700 nm which both cannot be seen by the human eye. In Figure 1 is presented the spectrum of the light from the sun, which extends into all three regions.
The wavelength, λ, is related to the frequency f by the relation $f = c/\lambda$, where c is speed of light $(3.00 \cdot 10^8\ m/s)$ and energy per photon $E = hc/\lambda$, where h is Plank's constant $\left(6.63 \cdot 10^{-34}\ \frac{m^2 kg}{s}\right)$. Shorter wavelengths mean higher energy per photon.
Solar cells generally need photons of a certain minimum energy to generate a voltage, yielding a maximum useful wavelength. Photons with higher energy on the other hand will not generate a higher voltage per photon, as excess energy is converted to heat. Very high energy photons such as UV light can be harmful to solar cells - as to many other materials - as the energy is high enough to change the materials, typically seen as bleaching of the active materials or yellowing of the plastic encapsulation. Hence practical polymer solar cells use a UV-barrier, which is chosen as a trade-off between efficiency and life time.

4 Light power

In order to measure how much visible light is received per area the unit lux [lx] is defined for illuminance in the metric system SI. The corresponding radiometric unit, which measures irradiance, is the watt per square metre (W/m²). While illuminance measurements are weighted by the sensitivity profile of the eye, irradiance includes the full spectrum. Therefore, no simple conversion factor exists between lx and W/m² unless the spectral composition of the light is known. For instance in Table 1 on the next page the measurement results for direct sun light are given. For every other value of the illuminance the corresponding irradiance value can be measured for the specific circumstances. Full direct sun is usually referred to as "1 sun" corresponding to 1000 W/m² and is the reference irradiance used for outdoor solar cell characterization. Note that to obtain this irradiance in real life, the solar cell must be perpendicular to the sun with no clouds during noon, so normally the solar output power is lower than specified peak power W_p. Examples of different outdoor and indoor illuminance levels are shown in Table 2.

Figure 1: Spectrum of the light from Sun.

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AN102
January, 2015

Low cost lithium polymer battery charger for polymer solar cells

Authors: *Tobias Fuglsang Jensen & Rasmus Brinkmann Andersen*

1 Introduction

Polymer solar cells offer several characteristics which differentiate them from other types of solar cells [1] and are still under development, which can be a challenge in designing interfacing electronics as a suitable solar cell may not be available during early development work. Also, verifying performance of products with solar cells in the lab can be complicated as light sources and incident daylight makes testing labour intensive and harder to repeat.
This application note outlines a design, which is front loaded[1] by using a model for the solar cell in both circuit simulations and electrical testing. The model must be replaced with the actual solar cell in tests as soon as it is available, but the model may still be useful for automated tests and production testing.
In this document, a model for a polymer solar cell is derived from a product specification and it is used in both simulations and bread board testing to verify and refine a very simple low cost lithium polymer battery charger circuit. The use case is daily charging in full daylight, and the circuit is not suitable for indoor application.

Solar cell

The design is based upon the following specification, which are inspired by the Process One [2] solar cell used for Printoo [3].

Figure 1: Example of a 16 cell solar module design.

- 16 cell module based on Process One (outdoor operation)
- Open circuit voltage: 9 V
- Voltage at maximum power point: 5 V
- Power
  - Nominal power: 60 mW
  - Maximum power (design limit): 180 mW
- Current
  - Nominal: 12 mA
  - Maximum: 36 mA

A large margin is given between nominal and maximum power to allow for variations due to production spread (larger for polymer solar cells than for silicon solar cell).

Battery

The battery type used for this design is a standard lithium polymer single cell with specs and design parameters as:

- Lithium polymer
- 105 mAh
- Max voltage 4.1 to 4.2 V
- Discharge limit 2.9 V

Note that most lithium polymer batteries have a maximum charging temperature of 40-45 °C which is problematic for solar chargers where the battery is placed in the sun with the solar cell. Some solar products simply ignore this problem and pay by reduced battery lifetime, while others reduce the float voltage in response to higher temperatures or use special lithium-family batteries designed for higher temperatures. In some designs, NiMH battery technology may be a better choice for higher temperature operation. In this design, the float voltage is easily adjustable to trade of battery lifetime and capacity.
Pay attention to the safety circuit often integrated with lithium-type batteries. These circuits are used to avoid severe misuse like short circuit, overcharging, and overdischarging and are not intended or suited for use as charging circuits. Some safety circuits are designed for high charging rate only and will prevent charging at low currents which is necessary for most real life so-

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[1] Design paradigm where uncertainties are dealt with early in the design phase instead of late in the assembly testing phase.

Figure 36: 1’st page screenshots of the three application notes: Left: AN100 - Polymer solar cells. Middle: AN101 - Light types and sources for energy harvesting and development. Right: AN102 - Low cost lithium polymer battery charger for polymer solar cells.

AN100 describes basic features, advantages, and disadvantages for the technology in general and the produced polymer solar cells at Mekoprint in detail. It describes basic solar cell functionality and relates the polymer solar cell to the traditional solar cells.

AN101 describes light types for especially indoor energy harvesting with polymer solar cells. It describes which light source and testing conditions to use in order to get comparable results to the Mekoprint production qualification.

AN102 describes how to integrate the polymer solar cell with a low cost lithium-polymer battery charger and the electronics design used for this.

The application notes sum up the answers to many of the questions Mekoprint engineers were asked over the time by interested customers. It is comparable to the chip-industry’s use of datasheets and application notes for advanced chips/ICs and can be used, also as a guide to sales personnel for more in-depth information on the technology.
This fulfils *D4.9: Sales team appointed*, *D4.10: Sales team fully trained*, and *D4.11: Sales team actively selling products with integrated OPV*, but due to the issues mentioned in WP1-3 not *KM3: Revenue from sales enables sustained growth of the business unit (design, manufacture, integration and sales.)*.

During the project, DTU and Mekoprint have been at the forefront of the OPV development in each their field. This can be seen when competitors publish work on their progress of production of OPV modules for building integration (Annex [1]). Mekoprint can get the same performance and lifetime with all relevant materials used in this project. Cost is still not addressed in the published article but Mekoprint has made substantial cost reductions along with performance increases.
In the end however, the expected performance outcome and the generated interest as seen from the business side of Mekoprint have not been enough to continue with the development of the technology. Mekoprint will continue to offer some of the fully developed subparts for its customers, such as ITO patterning and silver printing.
It has not been found relevant to take out patents for the production processes involved.

Dissemination:

DTU:

1. S.A. Gevorgyan et al., Interlaboratory indoor ageing of roll-to-roll and spin coated organic photovoltaic devices: Testing the ISOS tests, Polymer Degradation and Stability 109 (2014) 162 – 170
2. M. Corazza et al., Predicting, categorizing and intercomparing the lifetime of OPVs for different ageing tests, Solar Energy Materials & Solar Cells 130 (2014) 99 – 106
3. M. Corazza et al., Lifetime of organic photovoltaics: Linking outdoor and indoor tests, Solar Energy Materials & Solar Cells 143 (2015) 467 - 472
4. S.A. Gevorgyan et al., Lifetime of organic photovoltaics: Status and predictions, Advanced Energy Materials (Submitted)
5. E. Bundgaard et al., Matrix Organization and Merit Factor Evaluation as a Method to Address the Challenge of Finding a Polymer Material for Roll Coated Polymer Solar Cells, Advanced Energy Materials 5 (2015)
6. M.V. Madsen et al., Worldwide outdoor round robin study of organic devices and modules, Solar Energy Materials & Solar Cells 130 (2014) 281 – 290
7. T.R. Andersen et al., A rational method for developing and testing stable flexible indium- and vacuum-free multilayer tandem polymer solar cells comprising up to twelve roll processed layers, Solar Energy Materials & Solar Cells 120 (2014) 735 – 743
8. F.C. Krebs and M. Jørgensen, Polymer and organic solar cells viewed as thin film technologies: What it will take for them to become a success outside academia, Solar Energy Materials & Solar Cells 119 (2013) 73-76

Mekoprint:

9. Application note: AN100 - Polymer solar cells, Maria Mateva & Rasmus Brinkmann Andersen, January 2015, kortlink.dk/kmny
10. Application note: AN101 - Light types and sources for energy harvesting and development, Maria Mateva & Rasmus Brinkmann Andersen, January 2015, kortlink.dk/kmnz
11. Application note: AN102 - Low cost lithium polymer battery charger for polymer solar cells, Tobias Fuglsang Jensen & Rasmus Brinkmann Andersen, January 2015, kortlink.dk/kmp2
12. Printoo Youtube video: https://youtu.be/m4xwWhoSghs
13. OPV Journal no. 6, 2014, Interview with Jakob Bork, Mekoprint: “A matter of compromise.”

Presentations at conferences:

- LOPE-C, München, 11.6.2013; Karsten Ries: ”Commercial breakthrough of OPV - within printed electronics”
- LOPE-C, München, 13.6.2013; Jakob Bork: ”Flexible OPV as a sticker”

- Kolding Fjord EUDP meeting, 30.1.2014; Morten Christensen: “Kommercielle polymersolceller til selvforsynende produkter”

1.7 Project conclusion and perspective

The conclusion is summarized in the following bullet points:

- Mekoprint has identified and tested commercial materials for all parts of polymer solar modules and worked closely with several key suppliers to optimize performance in real world production.
- The production of OPV modules at Mekoprint showed up to 4% efficiency with encapsulation thereby closing in on the targeted 5% efficiency in a R2R production but yet not enough to meet the goals for successful market introduction.
- The cost was reduced to 6 DKK for a credit card sized solar module, but did not reach the project target of less than 2 DKK.
- Lifetime goal was set to 5 years, current performance of the modules produced in this project is less than 1 year. Due to significant challenges on the selection and optimization of the ink package/stack, the activities related to lifetime optimization did not progress accordingly.
- Mekoprint has upgraded the manufacturing capability in order to produce the subcomponents for a polymer solar cell. This work created several spinoff technologies and learnings that have been implemented in the current business of Mekoprint.
- Mekoprint has upgraded test and prototyping capabilities and can measure lifetime of solar modules independent of DTU.
- Consensus between Mekoprint's and DTU's setups for stability testing according to the ISOS guidelines is achieved.
- Several high-volume customers have shown interest in the OPV technology and several prototypes and demonstrators were produced in close collaboration with these customers. The lack of performance has inhibited sales as customer requirements could not be fulfilled.
- DTU has developed and delivered an online tool for prediction of the lifetime of polymer solar cell devices of various designs and under different operating conditions.
- The developed o-diagram methodology where lifetime data is categorized in time blocks commonly used (hours, days, weeks, months, seasons, years) is a strong tool for establishing relations between the different ISOS testing protocols and to roughly determine acceleration factors for the various tests.
- A meta-analysis based on the open research literature reveals rapid improvements of OPV stability over the past ten years, from minutes to 1-2 years. Such a fast development suggests that within a short period, the technology will reach a durability opening for a range of new application and also the 5 years targeted in this project.
- The meta-analysis also revealed a great deficit of outdoor lifetime studies and accurately controlled indoor accelerated tests conducted in a consistent and reproducible manner. This challenges the refinement of the present lifetime prediction tool. DTU's online platform for collection of lifetime data is seen as a vital tool for the further refinement of the prediction tool.

Mekoprint and DTU have generated a large impact in the OPV community in each of their fields. DTU will continue to do so but Mekoprint has put the development of OPV technology on hold because the solar module performance achieved in the project does not fulfil the goals set up for successful market introduction.

Perspectives:

DTU will utilize the extended analyses of OPV stability performance performed in this project to build an even stronger platform in the field of stability testing and lifetime predictions. The online database for collection of stability data and the online lifetime prediction tool will serve

as corner stones for the future work in this field. The national and international OPV R&D community will benefit from these sources of open information.
Mekoprint will continue to serve the OPV community with patterned ITO on PET foil in a R2R process. Furthermore, Mekoprint is looking into stable R2R production of ITO-free transparent conductors for other applications such as touch devices or EMC shielding.

Annex
Relevant links:
www.plasticphotovoltaics.org/lifetime-predictor.html
www.mekoprint.dk/solceller.aspx and www.mekoprint.dk
www.printoo.pt

Other cited literature:

[1]. Berny, S., Blouin, N., Distler, A., Egelhaaf, H.-J., Krompiec, M., Lohr, A., Lozman, O. R., Morse, G. E., Nanson, L., Pron, A., Sauermann, T., Seidler, N., Tierney, S., Tiwana, P., Wagner, M. and Wilson, H. (2015), Solar Trees: First Large-Scale Demonstration of Fully Solution Coated, Semitransparent, Flexible Organic Photovoltaic Modules. Advanced Science. doi: 10.1002/advs.201500342

[2] Vak D., Hwang K., Faulks A., Jung Yen-Sook, Clark N., Kim Dong-Yu, Wilson G. J., Watkins S. E. (2015). 3D Printer Based Slot-Die Coater as a Lab-to-Fab Translation Tool for Solution-Processed Solar Cells. Adv. Energy Mater., 5: . doi: 10.1002/aenm.201401539

[3] Østerlund J., Jørgensen K., Olesen N., Andersen N., Hansen M. (2011) ”Hovedrapport Polymere solceller”, unpublished project report from AU ENGINEERING, Aarhus University,