Industrialisation of polymer solar cells
Phase 2: Consolidation

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Content

Summary & Conclusion

The present report refers to the project "Industrialization of polymer solar cells – phase 2". Both the project and this report build directly upon the prior phase 1 where the basic OPV technology, ProcessOne, was transferred to Mekoprint. This second phase focuses on an anchoring of the transferred technology in Mekoprint's industrial environment and an anchoring of the technology as an attractive solution for low-demanding PV applications. This second phase is also concerned with DTU's further development of the OPV technology towards DTU's ultimate goal of qualifying OPV for large-scale power production. The project represents thus a crossroad, where Mekoprint and DTU gradually differentiate themselves with respect to applications and therefore also their R&D priorities.

The key targets of phase 2 relate to production cost, stabilization of the production and operational lifetime of the OPV devices – targets that are import both for niche applications and bulk power production. Besides the work dedicated to solving these three key targets, two more activities have been included in the project; a pre-study on OPV solar parks and an evaluation of the business opportunities arising not only from this project but from the entire Danish OPV effort.

Production cost

The road map from phase 1 defines three main tools for reaching the cost target of 1 €/W_p: increasing the efficiency to 4.5 %, replacement of the costly ITO front electrode and removal of as much materials as possible. The project confirms that all this plus a foreseen decrease in material's cost coming with economy of scale are required for driving the production cost below 1 €/$W_{p.}$ Calculating also with the economy-of-scale effect is found reasonable as the present cost is heavily dominated by materials not yet available in bulk.

Silver has appeared as a critical cost issue due to a steep rise in the silver prices. For this reason the cost of identical ProcessOne cells has more than double from 5 €/W_p to 11 €/W_p over the project period. A considerable effort has thus been given to silver-free processes, even though this was not a topic in the original project.

Power conversion efficiencies > 11 % has now been reported for small OPV devices. It has, however been proven exceptionally hard to achieve such high efficiencies at the scale required in this project. 4.5 % has been achieved, but with a proprietary material that is so expensive that it conflicts with the 1 €/W_p target. This leaves us with the standard P3HT:PCBM material as the most efficient active material available so far when considering the combined effect of cost, stability and processing.

The ITO front electrode has successfully been replaced by printed electrodes, and this introduces savings on more accounts; fewer processing step, less expensive materials and removal of materials. The previously used lithographic patterning of the ITO electrode, the subsequent washing of the electrode and the substrate that comes with the ITO are saved, as the new electrode is printed directly onto the barrier foil in the right pattern. More printed electrodes are developed; silver-based and carbon-based.

The cost figures at the onset of the project are: 11 €/W_p for ProcessOne, 6 €/W_p for the present technology with silver, and 4 €/W_p without silver. If the economy of scale for the materials is taken into account the cost will be 0.4 €/W_p.

Industrial production

Mekoprint has taken a series of initiatives in order to stabilize their production and further to prepare for full scale production. Actions have been taken to control process tolerances, to R2R test the quality of the devices produced, to document the process and to train the operators. The planned and performed actions have been summarized in a SIPOC chart.

A new solar-powered laser-pointer has been developed and 2000 items have been produced. The laser pointer is used actively to promote polymer solar cells. A commercial project for third world lighting products has been launched which uses silicon solar cells to build a market for polymer solar cells and switch technology when a competitive level is reached.

Mekoprint has evaluated the commercialization potential for Process One at its current level. This shows that the cost, lifetime and performance of the current Process One device need to be improved to reach a competitive product. A roadmap for this has been made, and it forms the basis for the next phase of this project.

Encapsulation and operation life time

Investigating and reporting operational life-time for immature technologies an OPV is not trivial, as standard accelerated testing protocols are missing. To establish such tests, the behavior of the devices in real-time tests must be well studied and compared with the acceleration tests. DTU's Characterization Laboratory for Organic Photovoltaics, CLOP, is built for performing real-time and accelerated testing of OPV devices both in indoor and outdoor, and from this to establish a reliable technique for predicting the lifetime from accelerated studies. All testing done by CLOP is according to what is recommended by ISOS[1].

Based on the CLOP methodology a lifetime close to 2 years have been proven for OPV devices encapsulated in a single layer of a high-quality food packaging. Preliminary accelerated test results for a corresponding device but encapsulated in a double layer of the same barrier shows a 5-fold improvement in stability. From this it is judged that an operational life of 5 years is within reach.

Solar parks

Gaia Solar has in a pre-study investigated various scenarios for large OPV solar installations. The analysis emphasizes three potential sites for the installation: on uncultivated land, along highways and as environmental cover for landfills, moreover is an installation procedure where the OPV devices are rolled out directly onto the pre-treated ground recommended. The rolling out installation is attractive for cost reasons; cost-effective mounting structures and labor-effective mounting process. The cost of a roll-out OPV installation is estimated to 1.25 €/W_p at an module cost of 0.85 €/W_p.

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[1]) The International Summit on Organic Photovoltaic Stability

The economy of a 400 kW_p OPV installation is investigated under different scenarios covering variations in the degradation rate, the operational periods and the ownerships. The economics are calculated in accordance with the Danish PV regulations of December 2012. The analysis shows that the investment is attractive provide that the module degradation is limited.

Business opportunities

The present and near-future business opportunities for the OPV technology relates to the PV market for niche applications, i.e. low-demanding applications and low volumes as compared to the PV mass market. The Danish OPV companies; Mekoprint, Grafisk Maskinfabrik and FOMTechnologies, contributes to the commercialization of the present technology within their specific business areas; OPV devices for niche applications, OPV processing machinery and OPV axillaries for R&D purposes. These initiatives are judged to be adequate and sufficient for bringing ProcessOne and the near-future technology to the market. Addressing, on contrary, the high-volume PV mass market by a more advanced OPV technology targeted at large-scale power production, requires far stronger financial – and R&D commitment than what is the case for the implementation of the technology in the niche market. International strategic partnerships and venture capital might be required for bringing the next generation of DTU’s technology to the market.

1. Introduction

The objective of the project “Industrialization of polymer solar cells” is to bring DTU’s strategic research effort (> 10 years) to an industrial level with ensuring commercialisation in a Danish context. The project is, according to the original plan, divided into three phases. The present report refers to the project’s second phase, where the polymer solar cell technology and the industrial production facilities investigated in the project’s first phase are consolidated and further developed. Phase 1 was in contrast concerned with technology transfer and development of low-demanding applications.

In phase 1, the basic production technology for polymer solar cells, ProcessOne [1-1], was transferred from DTU to Mekoprint. The deliverable comprised assistance in establishing a production line, running this line in, training the operators and delivery of process-specific materials. Another important activity in phase 1 was investigation, development and demonstration of possible applications for this new technology. The applications in focus were the ones matching the polymer solar cell’s actual maturity level, i.e. low-demanding application as for example charging of small batteries for powering of LED lightening. Team members in phase one were Mekoprint A/S, Gaia Solar A/S, Faktor 3 ApS and DTU.

In the present phase, DTU has focused on a consolidation of the polymer solar technology. This means to go back to the research labs in order to develop and implement the technology improvements needed for bringing polymer solar cells to a higher quality level where they can compete with other thin-film technologies in applications such as the ones investigated in phase 1. The ultimate future goal for DTU is to develop the technology to a level where on-grid power production is feasible, and it is expected that Mekoprint’s process of technology ripening will generate the necessary improvements for its use in low-power and integrated products. DTU’s work is, in phase 2, consequently focused on lowering the module’s production cost, miniaturisation and technical yield, and moreover on increasing the module’s energy-conversion efficiency and stability. The progress with respect to the first two issues namely cost and efficiency are described in the report’s chapter 2, whereas the progress on stability is reported in chapter 4.

Consolidation of the production of polymer solar cells means for Mekoprint to stabilize the production so that the product’s quality is predictable, constant and at a level corresponding to comparable modules produced at DTU. Stabilization has obtained in a joint effort with DTU, and Mekoprint has subsequently analyzed the requirements for competition and started to implement the automations and process improvements needed to enter commercial production in 2015. The current ProcessOne has been used for a new laser-pointer demonstrator and a number of customer interactions have been handled, of which three have potential for not only market introduction but also world-wide exposure of the Danish polymer solar cell technology. The third world solar lamp activities in phase 1 has uncovered a potential path to building a market for polymer solar cells and has spawned a separate project as it has the potential to run on commercial conditions. The report’s chapter 3 describes this work in details.

At the time of planning and applying for funds for the project’s phase 2, i.e. summer 2010, rigid encapsulation was seen as necessary for achieving an operational life consistent with energy production in bulk. For this reason Gaia Solar and their expertise on rigid encapsulations for conventional solar panels was regarded as essential for the project. Concurrent investigations have, however, revealed that rigid encapsulations do not support the bulk-power target, as such encapsulations drives up the system's embedded energy and thereby the energy pay-back time. All activities related to rigid encapsulations have thus been replaced by activities in direct support of the bulk-power target: cost- and energy-effective flexible encapsulations and PV parks with flexible OPV modules. The first task relates to the module stability and forms an integrated part of DTU's work in this field, see chapter 4, whereas the later activity is an independent investigation performed by Gaia Solar and reported in chapter 5.

DTU has, upon request from EUDP, explored various strategies for commercialization of the OPV technology, and the analysis is reported in chapter 6.

This report focuses entirely on the achievements made in phase 2. For a general description of the polymer solar cell, its production and its quality profile please refer to the report for phase 1, [1-2]. DTU's main channel for reporting their R&D progress is by publications in internationally prestigious scientific journals. The majority of DTU's work refereed in this report has thus been published in such journals, and all details about the already published work can be found in the referred papers.

References

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1-2 H. Lauritzen et al: "Industrialization of Polymer Solar Cells, EUDP project 64009-0050", project report, Department of Energy Conversion and Storage, DTU, issued Marts 2012.

2. Production cost

A key achievement in the previous phase 1 of this project was a more than halving of the processing cost for ProcessOne solar cells down to 5 €/W_p, and a roadmap leading the way further down to 1 €/W_p. The roadmap defines three main tools for reaching the 1 €/W_p target: increasing the solar cell's efficiency to 4.5%, replacement of cost-driving materials and removal of as much materials as possible. This overall plan has been followed in phase 2. Scarcely available materials have also been a topic in phase 2, as such materials represents a crucial bottleneck for scale the OPV technology to the levels required for serving as a persistent energy conversion technology.

The main learning with respect to the power conversion efficiency achieved in this project is that the high efficiencies reported internationally for small cells, > 10 %, is extremely hard to reconstruct at large scale and in a full roll-to-roll setting. An efficiency of 4.5 % has been reached in this project but for a proprietary material that is so expensive that it will never meet the project objective of 1 €/W_p. This leaves us with the standard P3HT:PCBM material as the most efficient active material available so far when considering the combined effect of cost, stability and processing.

Replacement of major cost-driving materials is a matter of; first of all, replacing the indium tin oxide (ITO) used in the solar cell's front electrode, see Figure 2-1. ITO is purchased externally and is delivered as a uniform film that needs to be patterned into the stripe motif of the module. The ProcessOne patterning process contaminates the foils, which requires thus a cleaning before further processing. Replacing ITO by a roll-to-roll printed electrode allows, on contrary, the electrode to be printed directly in the requested motif and directly onto the solar cell's barrier foil. Hereby are, not only, the patterning and washing steps surpassed, but the substrate that comes with the ITO electrode is also saved. Print processing and a corresponding upgrade of DTU's R2R machinery have been essential for reaching the cost targets in phase 2.

During the course of the project silver has appeared as a critical cost issues due to a steep rise in the silver price over the project period. For this reason the cost of identical standard ProcessOne cells has more than double over the project period from 5 €/W_p to 11 €/W_p. A considerable effort has thus also been given to replacement of silver, even though this was not a topic in the original project plan. The achievements here are also hinges on the new printing machinery available in the laboratory.

As both silver and indium are scarcely available materials they should also be phased out in order to ensure full scalability of the OPV technology.

Upgrade of R2R processing facilities

DTU's roll-to-roll processing equipment have been upgraded with units for washing, corona treatment, ink-jet printing, UV curing and water cooling. This fulfils deliverable 1.1 "Coating line is upgraded", deliverable 1.2 "Ink-jet printer is installed" and deliverable 1.3 "R2R washer is installed".

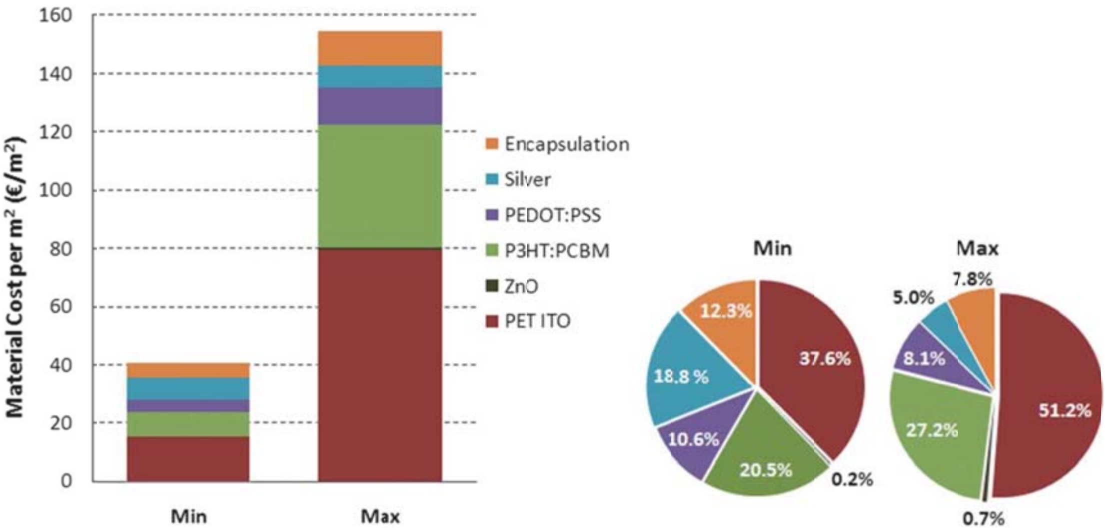

Figure 2-1: Total materials cost for manufacture of 1 m^2 OPV module by ProcessOne; absolute cost (top) and fractional cost (bottom) [2-1]. Market prices for the materials were taken from up to three different sources, and based on this a minimum and maximum cost per area was determined.

Ink-jet printer

Already early in the project it was realised that it was too complex to install the ink-jet printer on the existing roll-to-roll machine, as there are exceptional requirements on the angular precision of the print heads with respect to the web. A small new machine was thus co-financed and the ink-jet printer was installed on this new machine. The system employs 3 printing heads with a resolution of 600x1200 DPI, and the machine can print in the full web width of 305 mm at speeds up to ~70 m min^{-1}.

The installation of the new machine and its running in has been resource - and time consuming, because the process itself is complicated and because of incorrect deliveries. The first prints were made in November 2011, but it turned out that the wrong washing liquids were supplied. This destroyed all three printing heads, representing a cost of 36.000 €. Massive negotiations with the supplier were settled with an agreement saying that each part should cover half the expenses for a new set of heads. The new heads were not realised until spring 2012.

After spring 2012 the system has been running well, see Figure 2-2. It should, however, be stressed that the inks are still very expensive, ~ 5.000 €/litre, and the system is not robust in use. The conclusion so far is that ink-jet printing is unsuited for cost-efficient mass production of OPV even if it does offer advantages as a research and development tool.

Washing machine

The cleanliness of the patterned ITO electrodes has been a concern in phase 1. All ITO coated substrates used in the previous project phase, was provided from external suppliers. The ITO substrate was then lithographically printed and selectively etched into the solar modules' stripe pattern by Mekoprint. This processing leaves behind impurities on the electrode. Such impurities might not be critical for other Mekoprint products, but they are critical for OPV. A roll-to-roll washing system was therefore installed to solve this problem, see Figure 2-3.

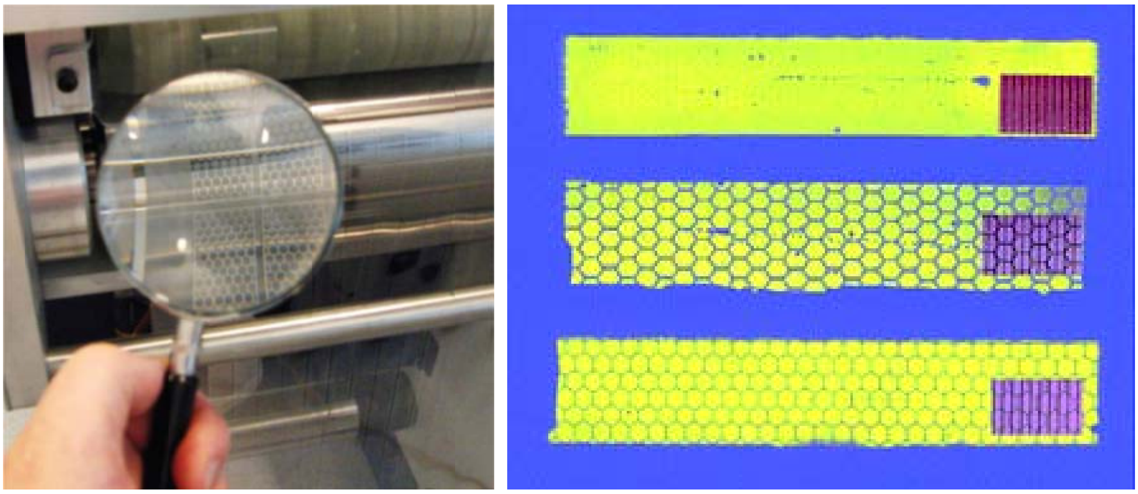

Figure 2-2: Printed grid electrode (left) and LBIC images of devices with printed grid electrodes (right): thermally imprinted (top), an ink-jet printed (middle) and a flexographic printed (bottom). The small insets show photos of the particular cell with strong backlighting [2-2].

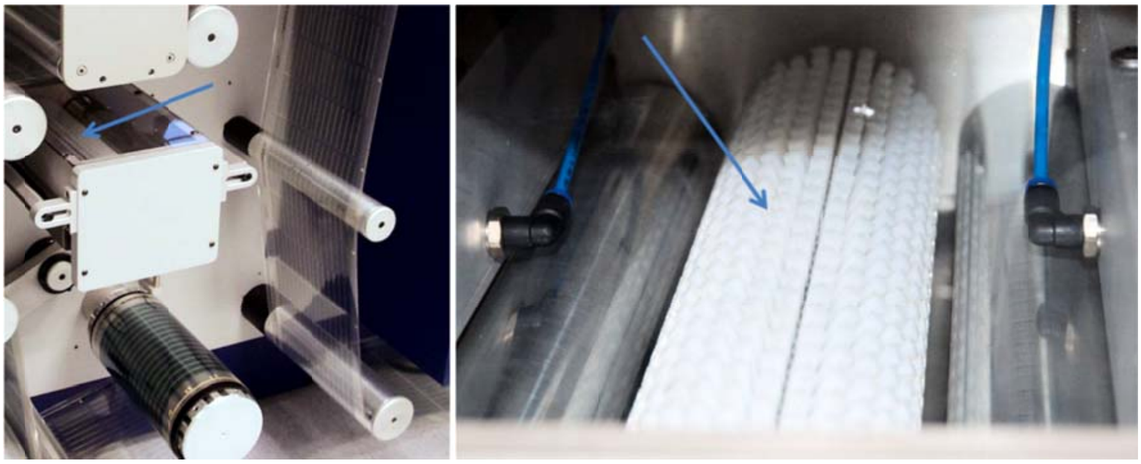

Figure 2-3: Roll-to-roll washing machine. The blue arrows mark the washer roll.

The R2R washer has been tested and is found both functional and operational as it solves the problem. Its future use is, however, uncertain as it is likely to become obsolete through development of more efficient processes. The strategy is to simply avoid washing by not using the lithographic procedures, but to surpass this by printing electrode in the desired motif.

Power-conversion efficiency

One obvious way to decrease the cost in €/W_p is to increase the power conversion efficiency. During the course of the project the global OPV research has progressed significantly, and efficiencies >10 % have been reported, see Figure 2-4. It has proven exceptionally hard to scale the high reported efficiencies to the large scale required in this project. We have achieved more than 4.5% power-conversion efficiency for a proprietary low band-gap polymer. This result has been corroborated by many European research groups [2-3]. The proprietary material is, however, so expensive that it will never meet the project target of 1 €/W_p for cost reasons, even if it does meet the > 4.5% PCE target of the project, (deliverable 1-5, milestone M1).

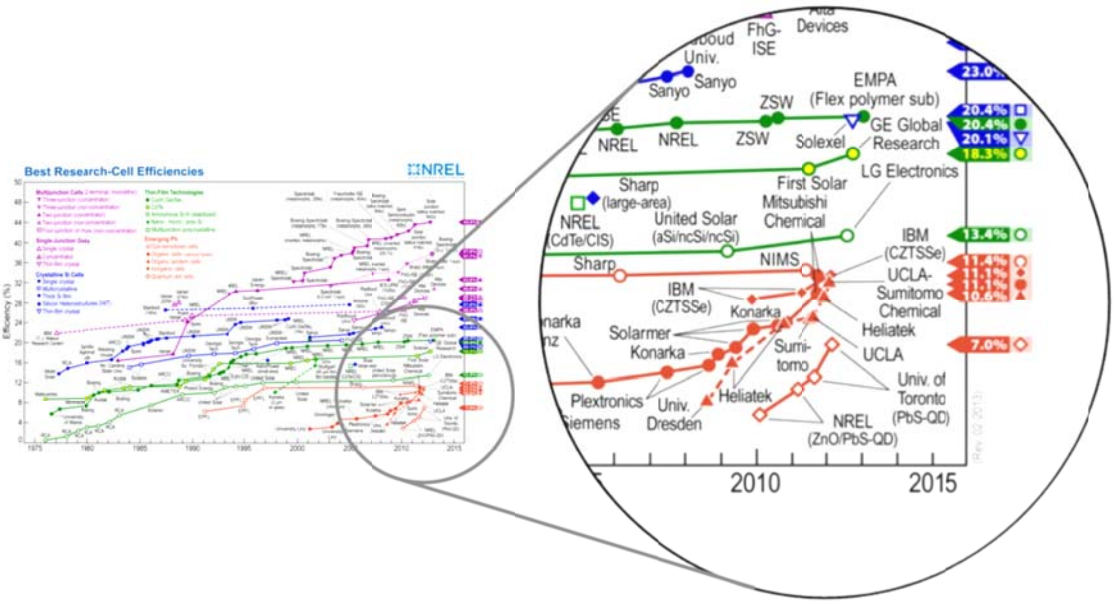

Figure 2-4: Research Cell Efficiencies by NREL [2-4]. The insert zooms in on organic solar cells (red line and red filled dots) from 2005 to date.

Materials cost

The major cost drivers identified at the beginning of this project was the ITO-based substrate, the active materials and the packaging materials, Figure 2-1. The first action taken was to replace the ITO electrode by a printed electrode. More versions of the printed electrode have been investigated; silver-based [2-2] and a version using only abundant carbon-based materials [2-5].

The reduction in cost through process and materials optimisation for the most cost efficient active layer was then sought. Currently P3HT:PCBM is the most efficient active material available when considering the combined effect of cost, stability and processing. The cost of 1 g of this active-layer material is now 65 € when purchased in kg scale. Further cost reduction is only to be expected when volumes increase to ton scale, and 10 € per g for the active layer is considered as the absolute lowest achievable cost at multi-ton industrial scale. The current usage of active layer is ~ 250 mg per square meter of active layer, which yields in best cases practical power levels of 18-20 W m^{-2}. From this point the cost of electrical power from the active layer alone is 0.0125 – 0.8125 €/W_p.

Then packaging, electrodes etc. are also needed which add to the cost. In this project we worked from a scenario saying that the most efficient way to save on the materials account is to remove as much material as possible. This had as a basic requirement that the expensive ITO was removed and also the substrate that comes with it.

The removal of the ITO and its substrate allowed the solar cell to be processed directly on barrier foil [2-5]. The current cost of the barrier foil is 6.6 € m^{-2}, when purchased in quantities > 10.000 m^2. Two layers of barrier foil is required for packaging the cell leaving us at a cost of minimally 0.66 €/W_p. It is estimated that the ultimate cost of polymer solar cells will be ruled by the cost of the barrier material. Based on these facts the starting point of the project was besides removal of ITO, to develop methods to process solar cells directly on barrier foil and thereby lower the cost.

It should also be noted that efforts to remove scarce materials such as indium are not only mandatory, but the replacement materials must also not be scarce. Silver does not satisfy this criterion, see Figure 2-. Silver has approximately the same abundance as indium and is thus also unlikely to be justified as a material in a future organic solar cell. We actually experienced this during the project through the enormously steep rise in the silver cost during the project. At the start of the project silver flake for ink had a cost of 345 €/kg and in late 2012 the cost was 850 €/kg. It is clear that it is impossible to efficiently develop cost reduction for a complex technology that employs a material that is subject to such large fluctuations in cost. We therefore sought also replacement of silver which was not an objective of the original project but deemed necessary for the success of this project.

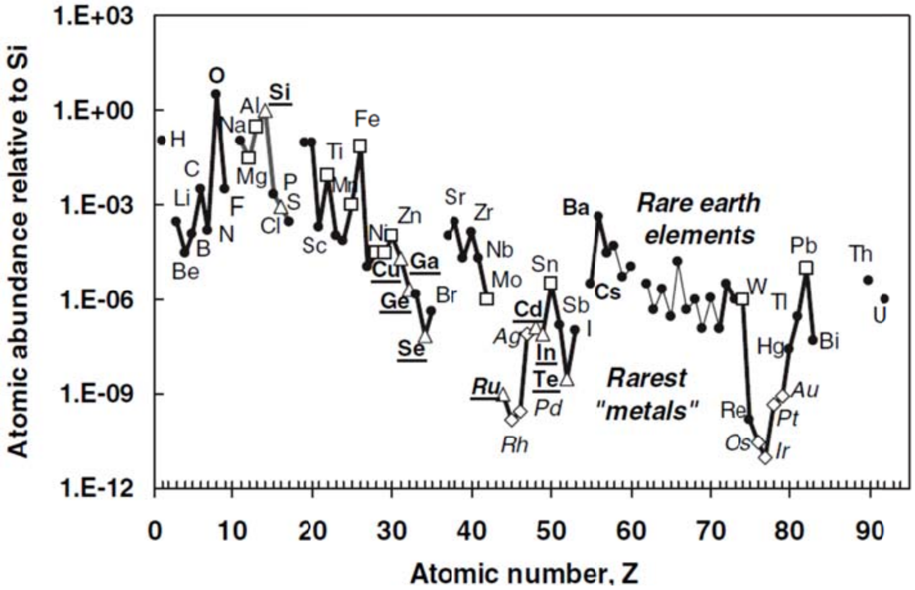

Figure 2-6: Atomic abundance relative to Si of elements in Earth's upper continental crust [2-5].

Cost structure

Table 2-1 summarized the cost structure at the outset of this project, as a result of this project and with the anticipated economy of scale for materials. We find this a reasonable way to present the project achievements, as the cost of the polymer solar cell, that is a result of this project, is heavily dominated by materials not yet available in bulk. In spite of the fact that we have significantly increased the manufacturing efficiency, reduced the manufacturing cost, reduced the materials use and bill-of-materials, see Table 2-1, the cost for ProcessOne has increased from 5 €/W_p to 11 €/W_p in the project period due to excessive rise in the cost of silver flake. A decrease in the cost of materials with the economy-of-scale was not anticipated to enable reaching the project objectives, but as concluded in the table: it will be necessary. Finally, higher efficiencies were also anticipated to be required to drive the cost towards the 1 €/W_p objective, and this was found to be correct.

The discussion above justifies that the deliverable 1.4 “2 €/Wp for standard ProcessOne” has been reached when neglecting the rise in silver cost and by using the cost of silver at the start of the project, and the deliverable 1.6/milestone M2 “1 €/Wp achieved for modified ProcessOne” has been reached under the “economy-of-scale” condition.

Table 2-1: The cost structure in €/m^2 of processed active area and €/W$_p$ for polymer solar cells at the start of this project (ProcessOne), as a result of this project (EUDP-II) and with estimated materials cost for fully scaled materials production (Economy-of-scale). The cost is given per active area as this eliminates the effect of the actual application on cost. The processed area is assumed to be 1 m^2.

	Cost (€)			
Component	**ProcessOne[1]**	**EUDP-II**	**EUDP-II no silver[2]**	**Economy-of-scale**
Barrier	6,6	6,6	6,6	3
Adhesive	2,53	2,53	0	0
Substrate	0	6	0	0
Electrode-1	39	10	10	1,24
Electron transporting layer	50	11	0,1	0,1
Active	16,25	16,25	16,25	2,5
Hole transporting layer	16	16	16	0,6
Electrode-2	24	24	4	4
Adhesive	2,53	2,53	2,53	2,53
Barrier	6,6	6,6	6,6	3
Processing cost	40	4	2,66	0,43
Total cost (€)	203,5	105,5	64,7	17,4
Process time per m^2 (min)	30	3	2	0,3
Typical efficiency (%)	1,8	1,8	1,8	4,9
Cost (€/W$_p$)	**11,3**	**5,9**	**3,6**	**0,4**

[1] The cost of silver has increased during the project’s running period and therefore the cost of ProcessOne is higher than the 5 €/W$_p$ reported in in the previous project 64009-0050 “Industrialization of Polymer Solar Cell”, Phase 1.
[2] The carbon based solar cells are only efficient for small areas such as the credit card sized modules. Currently reached conductivities of printed carbon pastes do not allow for transport of high current

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2-3 T.T. Larsen-Olsen et al, *Adv. Energy Mater.*, 2012, 1091.
2-4 National Renewable Energy Laboratory (NREL), USA, 7 February 2013
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3. Industrial production

The overall goal for Mekoprint was to obtain stable production for DTU's ProcessOne polymer solar cell technology, which has been fully achieved (Milestone M3). To obtain stable production, a series of initiatives has been carried in cooperation with DTU, which effectively transferred the production technology for Process One to Mekoprint. At the same time, the commercialization potential for Process One in the current form was evaluated, and it was found that the cost, lifetime and performance need to be improved to reach a competitive product. The roadmap for this can be found in Mekoprint's 2012 business plan for polymer solar cells, which is available upon request. The focus for the remainder of this project has therefore been to get the production streamlined and ready for commercial production in phase 3a. Work on the commercial side has paved the way for market introduction once the polymer solar cells are competitive.

Stabilized production

One of the first project objectives for Mekoprint was to obtain stabilized production for Process One solar cells, which not only requires understanding of materials and processes but also good craftsmanship.

The production processes has been stabilized through a joint effort involving several coating trials at Mekoprint, first under supervision by Professor Frederik Krebs and later without supervision from DTU. This task was supported by analysis work at DTU including microscopy, IV-characterization, LBIC imaging, TOF-SIMS elemental analysis, and spectrometry to eliminate defects and optimize coating uniformity. The production was stabilized according to schedule, completing deliverable 2.2/milestone M3: "Mekoprint's production is stabilized".

This work was extended by testing 3 alternatives of the ITO PET foil, which is the substrate for solar cell production. A Chinese origin ITO PET foil was rejected for low uniformity of the resistivity, while an American product, OC50 from Solutia proved far superior. A low resistivity alternative was compared to the standard material and highlighted the importance of a very tight match of the materials in the solar cell, since it introduced non-reversible failure modes to the solar cell.

Process improvements

Following successful stabilization, a number of improvements to the production lines have been implemented to prepare for full scale production.

ITO patterning

The ITO patterning process has been optimized to remove sources of scratches, which impair performance and visual quality. The main work carried out is removal of an inspection station, surface treatment of static web guides, lowering of web tension and tests to verify the quality improvements. The result is that the ITO foil now only has small scratches, which do not affect performance.

Barcode printer

An inkjet printer has been installed for writing bar codes and serial numbers during early stages of production, which allows for full traceability of solar cells through production and logging of process parameters and test results, see Figure 3-1. The coating section and the R2R tester have been equipped with bar code readers and software updated for storing bar codes. Data analysis scripts have been written for analysis of data with reference to bar codes. This makes it easy to map the performance of solar cells to specific process parameters like layer thickness.

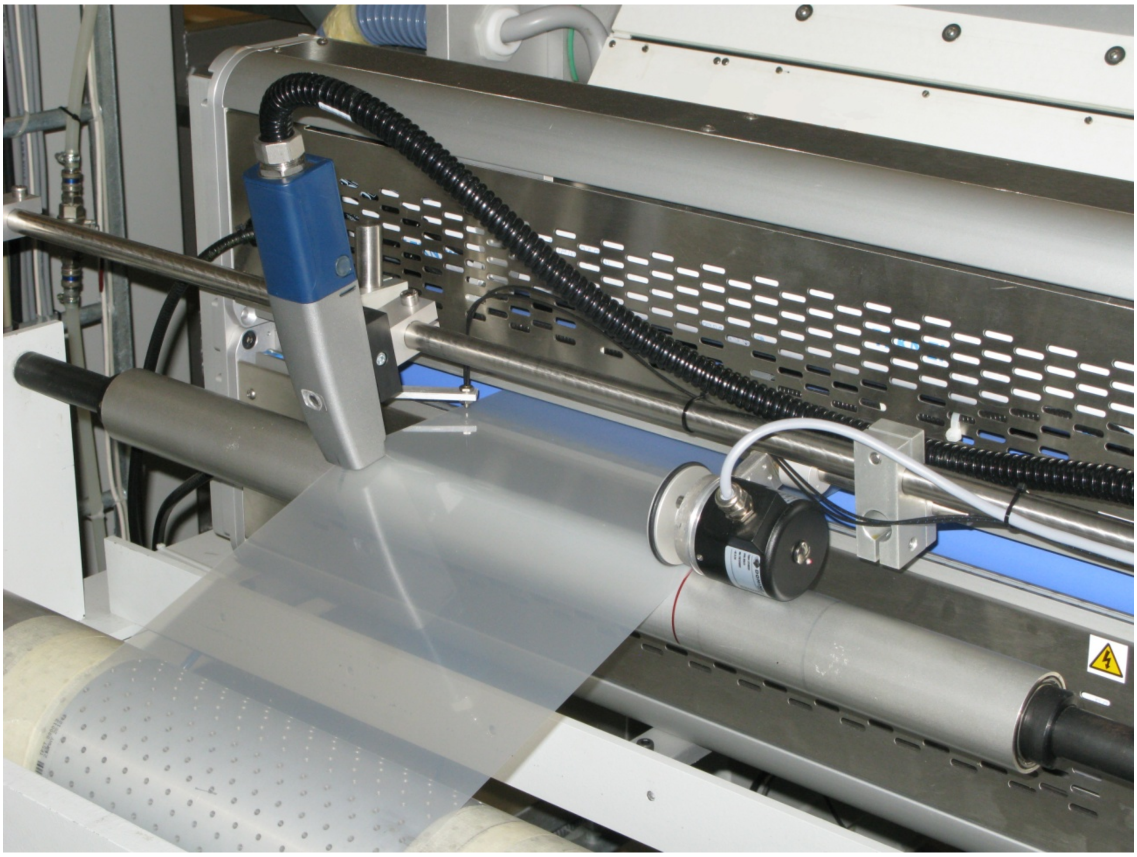


Figure 3-1: Ink-jet printer writing barcodes for tracking of process parameters and performance

Dedicated pumps

Dedication of pumps for specific solvents was achieved by the purchase of a new Knauer pump, which is now dedicated to isopropanol-based inks, while the original Knauer pump is dedicated to chloro-benzene-based inks. This reduces contamination problems and allows for quicker set-up when coating multiple layers.

Automatic cleaning

An automated in-line wetting and cleaning process for improved coatability has been implemented. Wetting makes the solar cells more receptive to new layers of materials increasing yield and performance. The main work is design of a setup for cleaning and wetting as well as installation of a dedicated pump for this purpose and embedding it into the production control- and log system. The result is that the line can be operated without paying attention to the cleaning or wetting process.

Web guide

The web guide system on the coating line, which keeps the web in the correct position during coating, has been found insufficient and replaced by a new camera based system capable of detecting the low contrast lines of ITO, which now serves as reference for all coating steps. This increases the registration precision of the coated layers, which eventually raises the yield.

Logging and traceability

The logging system for recording of process parameters, which was initiated in phase 1 is now updated with data processing and is actively used for production feedback. The main work is in developing Matlab software, which analyses production log files and test data. Further, the logging system is open and extendable for new sensors and imaging during phase 3a.

Masks for coating

A crucial part of setting up the coating line is alignment of the mask and shim used for guiding the ink. This task is time consuming and requires great caution as 45 fragile metal strips must be positioned within roughly 100µm for the solar cells to work. Extensive development efforts has been put into testing adaptable and quickly deployable replacements for this system, as it is important for production cost and user adaption of the solar cell form factor. Experiments include laser cutting, contour etching and partial etching of three different mask/shim materials. It has proven impossible to combine the mask and shim into a single unit, see Figure 3-2, due to tolerances, even though this would have been the optimum solution. Instead, a material has been found, which allows for precise contour etching replacing laser cutting for both mask and shim, which reduces tooling cost and tool production time. The resulting masks no longer need to be reused, have less internal tension, have less edge roughness and give full freedom for designing custom solar cells for customers.

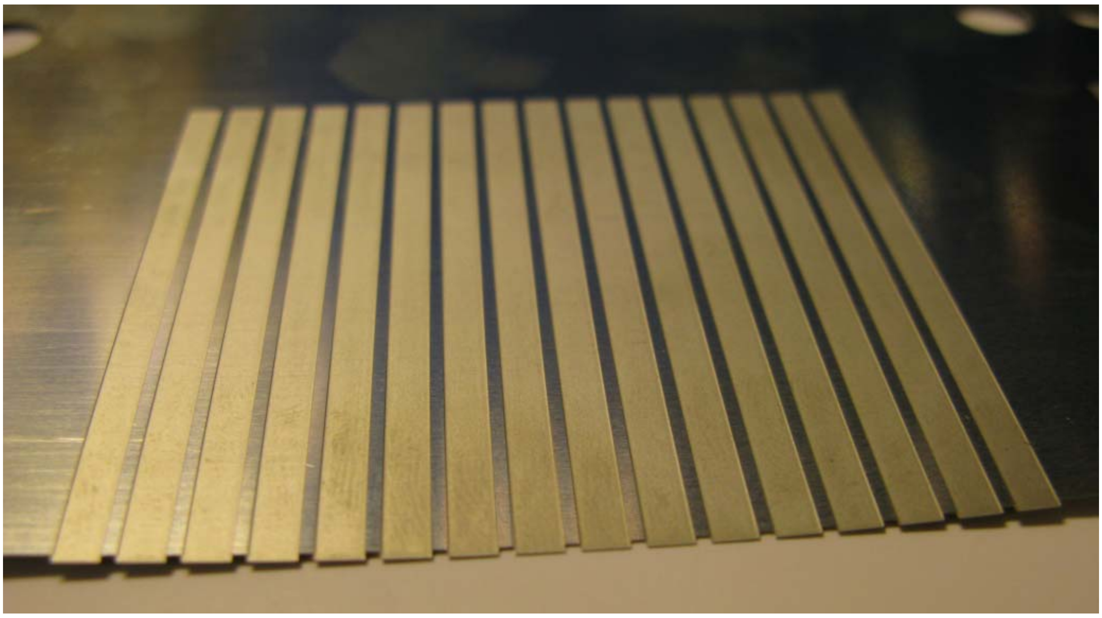


Figure 3-2: Combined mask and shim for fast assembly of the coating head produced at Mekoprint. This solution was investigated and finally rejected due to the tolerances on the etched ink channels. A simpler etched solution was implemented instead.

Training of operators

Operators have been trained through both production of solar cells and coating trials with much cheaper non-functional inks, which are prepared from IPA and dyes for visual evaluation. The operator, who was trained first in coating of functional inks resigned his position late 2011 and a new operator has been trained in addition to the process engineer. To become less vulnerable to a similar situation, a formal process description has been prepared.

All product types at Mekoprint has a formal description called PKS; process- and quality specification, which defines all process steps and special considerations for materials and machine settings. A PKS for polymer solar cells has been developed and tested during coating and solar cell productions and is now in effect. The result is that a trained machine operator can now produce DTU's Process One solar cells as any other product at Mekoprint concluding *deliverable 2.5: "Production team is trained"*.

Test and automation

A sun simulator lamp, SolarTest1200 from Atlas, was loaned by DTU to Mekoprint for this project, which together with a Keithley 2400 Source meter, a CM4 bolometer and custom software from DTU forms an IV-test system, which has been used extensively to test solar cells. Mekoprint has extended the test system to a multi-channel life time tester, see Figure 3-3, which has been used to test life time of solar cells produced. The test system was programmed in C# and built on a similar data format as used by DTU for easy transfer of test results.

In addition to providing important data during the current project, the life time test facility will be central to future life time improvement activities. The life time test system is compatible with ISOS-L-1 and through use of a climate chamber also for ISOS-D-3 lifetime measurement protocols [3-1]. This concludes deliverable 2.1: "IV-test system is installed".

Figure 3-3: IV-test stand with multichannel 4-point IV-trace and life time measurement.

R2R testing

An automatic R2R tester for fully assembled solar cells on roll has been built to provide full production data on solar cells produced for development work and the same machine can perform production pass/fail-testing, see Figure 3-4. The work was primarily devellopment of a new fixture for a production standard inspection machine, and incorporates retractable electrical contacts and a 575W metal-halide lamp for illumination.

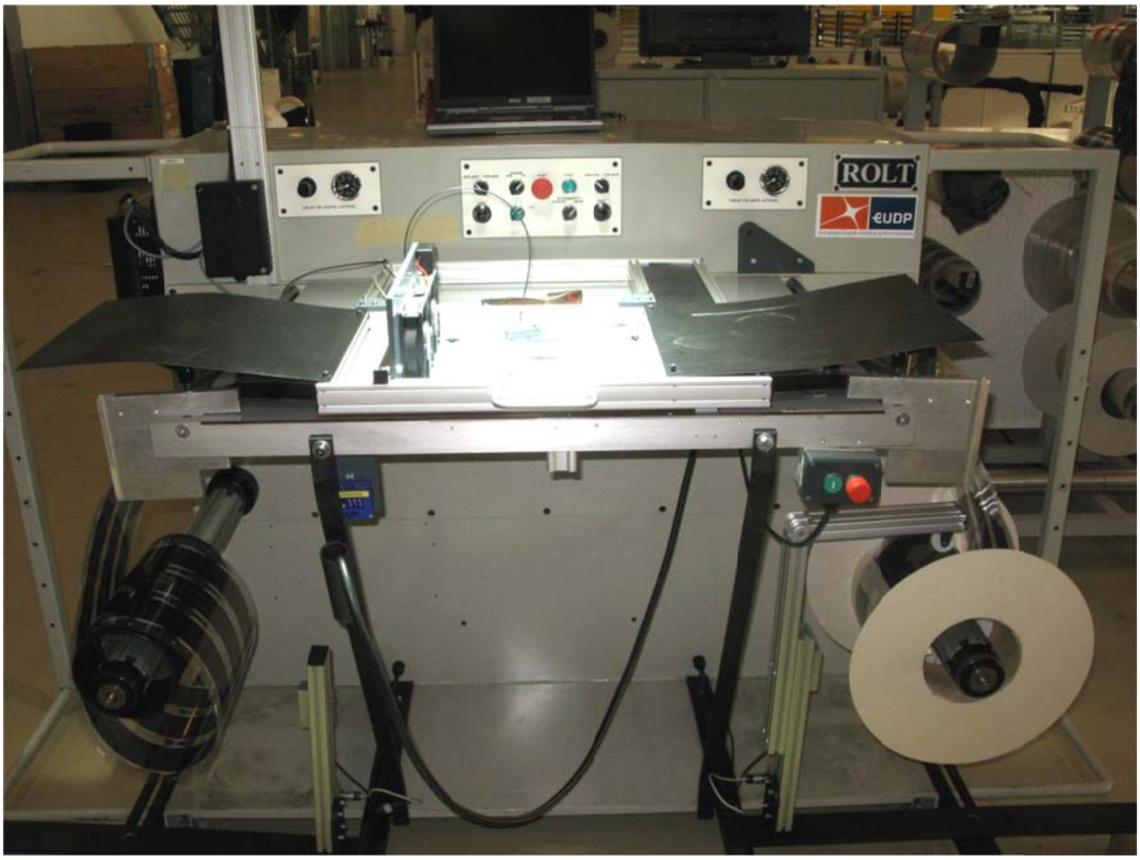


Figure 3-4: Automatic R2R-tester for full characterization of solar cells produced.

The R2R tester was originally implemented using a Keithley 2400 source meter, but for test speed purposes, it was replaced by an Agilent U2722A source meter, capable of characterising three solar cells in parallel. A stepper motor based positioning system was implemented and is controlled by an optical fibre sensor for positioning of the solar cells in the illumination mask. A complete control system was developed in C# and deployed on a PC, which control all parts of the R2R tester. The measured electrical characteristics of solar cells from the R2R-tester can be cross-correlated with the process parameters from the logging system and forms a powerful platform for process optimization.

Vision support

One focus area is inline vision control, which can monitor and aid in optimizing the margins in the production. There are commercial systems available, but these are focussed on classification and documentation of defects rather than providing real time process feedback, so alternatives have been investigated.

To support this activity, a project has been carried out with Aalborg University, where two master students in signal processing has assessed different algorithms and computational complexity for finding the edges of the stripes on the solar cells [3-2]. The main conclusion is that reliable edge tracking for coating processes is computational intensive and not straightforward to make robust. The search for a suitable vision system for solar cell production is on-going.

Encapsulation

Analysis work has been carried out to specify an automatic R2R encapsulation machine, which can provide state of the art encapsulation for polymer solar cells. In this project, different layouts have been outlined (see Figure 3-5) and an excellent back side barrier material has been purchased for test with polymer solar cells. This material uses a 20µm aluminium foil as barrier for the solar cell, which gives a water-vapour transmission rate below the measurement limit of the manufacturer of 0.005g/m2/24hours, which is more than 20 times better than the current barrier while at the same price. It is likely that more than one encapsulation type will be offered to the customers as there is a tough trade-off between cost and lifetime.

Printed adhesives

Printed adhesives have been investigated as a part of the initial planning for automated encapsulation. Seven UV-cured adhesives from four vendors have been tested in Mekoprint's production setup, and results so far has shown adhesion properties similar to the currently used 3M 467-series pressure sensitive adhesive for the two best types. The result is that printed adhesive is now a candidate for the encapsulations work scheduled for phase 3a.

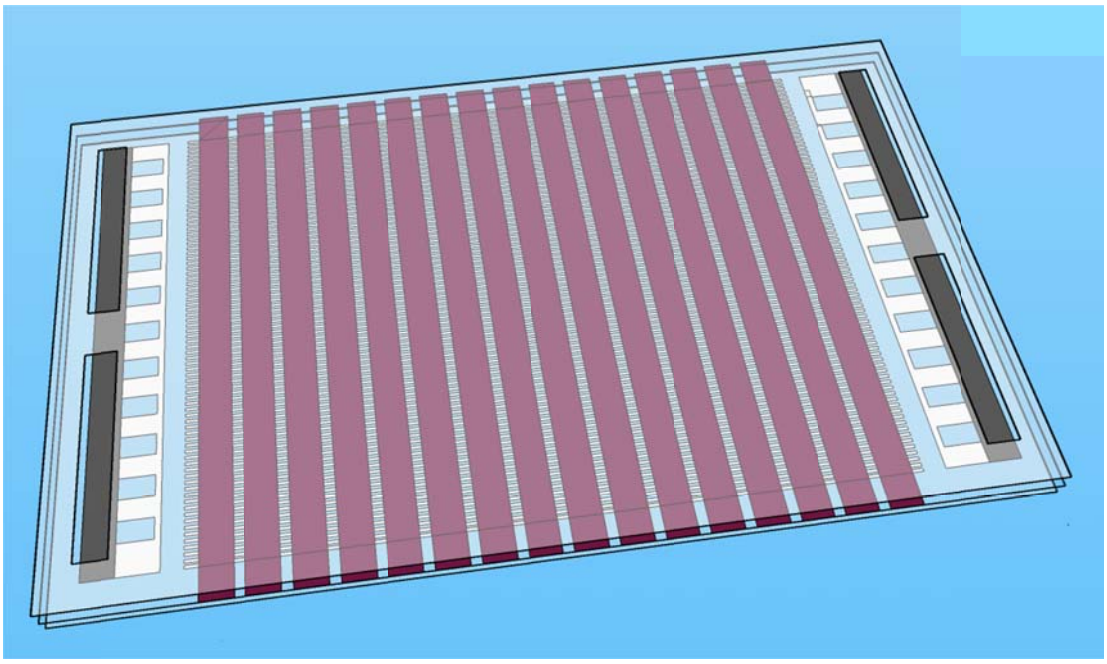


Figure 3-5: Concept study for production friendly R2R encapsulation. Here shown a refined version of currently produced encapsulation with more stable output voltage.

SIPOC

To sum up the work on the production process, a SIPOC[2] chart, see Table 3-1, is included below for overview of the progress in this and the first project stage as well as activities planned for the next stage.

Table 3-1: SIPOC chart summarizing the planned and performed actions taken to improve the production of polymer solar cells

	Phase 1 Carried out	**Phase 2** Carried out	**Phase 3a** Projected
Suppliers / Materials			
ITO	Initiated	Partnership	No further work
Functional inks	DTU	DTU	Commercial company
Silver contacts	Mekoprint standard	Candidates identified	Best types found
Adhesives	Mekoprint standard	Test printed types	New types implement.
Barrier materials	DTU standard	New back barrier	Test and implement
Inputs / IP / tools			
Cell design drawings	DTU design	DTU design	Customer designs
Process Parameters	Copy DTU setup	Copy DTU setup	Ink suppliers & DTU
Operator instructions	Guidance from DTU	PKS implemented	Adapt to new inks
Screen printing masks	Mekoprint standard	Mekoprint standard	No further work
Coater head	DTU design	DTU design	DTU/Mekoprint
Coater masks/shims	DTU design	Mekoprint produced	Refinements
Pumps	DTU setup	Extended	No further work
Web guide	Web side aligned	Print aligned	No further work
Log system	Implemented	Extended	Vision feedback
Process			
Pattern ITO	Adapt etching to ITO	Remove scratches	No further work
Wetting/cleaning	Manual	Automated	No further work
Coat functional inks	DTU supervision	Independent of DTU	Adapt to new inks
Print contacts	Standard process	Standard process	Standard process
Encapsulate	Standard process	Standard process	More advanced
Bar code printing	None	Implemented	No further work
Test solar cells	Done by DTU	R2R tester built	Adapt to custom cells
Outputs			
Solar cells	Working solar cells	Performance as DTU	Competitive cells
Process data	Collected	Analysed	Automated learning
Customers			
Orders	None	Laser pointers	Solar cells

[2]) SIPOC is short for Suppliers, Inputs, Process, Outputs and Customers. SIPOC is a standard chart used in Six Sigma and Lean Manufacturing to give an overview of a process.

Commercialization

During the project there has been numerous customer contacts; most through e-mail and phone, but also face to face meetings. Potential customers have visited Mekoprint 17 times during the project period and Mekoprint has visited potential customers 6 times at their premises. Demonstrator solar cells, flashlights and laser pointers have been widely distributed, and for 5 customers, early demonstration activities have been carried out. For 7 of the customers, we see a potential for future commercial activities. 3 customers have been selected with particular high impact potential not only for sale but also for world-wide exposure of the technology, once certain target specifications are met.

Competitiveness

Evaluations with customers of polymer solar cells in 16 applications where polymer solar cells have a realistic potential, reveal a picture of the currently prohibiting factors for commercialization, see Table 3-2. In this table, all requests for third world lighting products have been treated as one, as specifications are similar. We see that there is an even distribution of the prohibiting factors between the 16 applications. Unfortunately, customers who can accept current state of technology for one or two of the three factors have high demands in others. Therefore we have seen no commercial activities on polymer solar cells except for small demonstration projects. The conclusion is that the efficiency, the lifetime and the cost must be improved, which is part of the next phase of this project.

Example customer project

One customer enquired about a solar cell lamp for temporary installation on a flexible roof. The area could be as large as needed, and the life time should only be 12 months dark storage followed by 2 months usage. This project could have been realised with the current ProcessOne provided a cost match with other flexible solar cells, which is currently not possible. This example shows that niches exist for polymer solar cells, but the level of competitiveness has not yet been reached.

Table 3-2: Customer feedback on the current technology. The number refers to the number of customers giving one of the two statements with respect to three performance parameters; cost, efficiency and lifetime.

↓Statement	Performance→	Cost	Efficiency	Lifetime
The most prohibiting factor is		5	6	5
The current state is acceptable		2	3	2

Laser pointer demonstrator

The flash light demonstrator reported in phase 1 has been further developed to target business executives, who need a laser pointer more than a flash light, see Figure 3-6. The aim is to have this laser pointer laying around at meeting rooms and used during presentations with references to DTU and Mekoprint. The work involved new electric and mechanic design, where the adaptability of the polymer solar cell was proven: The design required a cut-out in the solar cell and moving the contacts to a new position, which was easily implemented and would have been cumbersome if not impossible on other types of solar cells. Close to 2000 laser pointers have been produced so far concluding delivery 2.3: “Credit card modules produce” and deliverable 2.4: “Upscaled production with product integration”.

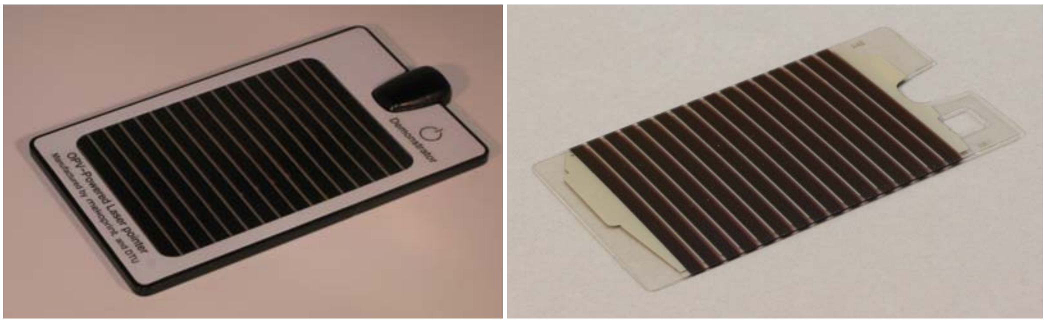


Figure 3-6: New demonstrator for phase II: A solar powered laser pointer (left) and the specially adapted solar cells (right), where terminals have been shifted sideways and contour cut to fit the product design.

Other publicity

In addition to the presentations listed in Appendix A. Two events have been hosted by Mekoprint for groups of people with special interest in sustainable energy and inventions, see Figure 3-7, where the Danish Inventors Association is introduced to slot die coating. At both events the audience was initially expecting a new technology for roof mounted energy production, but after the presentations a great interest in the many other fields of applications was created. A third event has been planned for February 2013.

Figure 3-7: Introduction to polymer solar cells for the Danish Inventors Association. Here at the coater equipment.

Installation: Bio Cult

Installation artist Louise Toft needed special solar cells for an art project called BioCult, which explores the interaction between nature, technology and human beings. The installation, which is shown in Figure 3-8, contains soil, grass and worms, and spectators can interact by sending an electrical current through the soil, which drives out the worms. To further emphasis the interaction between nature and technology, the power for the installation should be supplemented by solar cells, and from an artist's perspective, the design freedom of polymer solar cells and the fact that electricity is produced from organic materials was a perfect fit for the installation. The solar installation was made from 25 credit card solar cells grouped in five sets of five series connected solar cells with separate reverse diode per set. This way, the solar cell sets could charge the battery individually according to their orientation towards the sun The installation was first exhibited may 18'th 2012 and has been shown at 8 musical festival events called "Chill i Parken" in 5 Danish cities.

Figure 3-8: Art project BioCult on display before (left) and during (right) mounting of solar cells.

Lighting Africa

Following the third world lighting activities reported in phase 1, 10 different businesses and organizations have inquired about further activities in this field with the aim of buying solar cell powered lamps for sale or distribution in the third world. This is seen as a great opportunity for polymer solar cells to build a market before they are mature, as silicon solar cells can be used to power the first lamps and later switching to polymer solar cells, which are the much preferred solution due to their inherent ruggedness and low weight, which is important for logistics in primarily Africa. A similar strategy is followed by the British competitor Eight19.

In this project, a design sketch, see Figure 3-9 and cost calculation has been carried out which underlines that full production in Denmark is not feasible. Assembly in China, which is the normal alternative has been ruled out, as China products are widespread already in Africa and are increasingly picking up bad reputation due to quality issues. The innovative approach is to design and manufacture the electronics and other quality critical parts in Denmark and perform final assembly in Africa close to the end user. This approach paired with a few previously unseen distinguishing factors has made this project interesting to not only investors in Africa but also foundations in Denmark, which are willing to sponsor development and business setup in Africa.

Even though further development of a new Africa lamp is relevant to this project, the Lighting Africa project has been separated out to run on commercial basis with the aid of investors and development foundations, and the coordination and product ownership has been transferred to an external company, SMD Holding, which allows Mekoprint to focus on polymer solar cell development. The external product owner, Mads Mølgaard, who lives part time in Tanzania and runs business there, has increased the activity level by the end of this project period. Mekoprint has received a visit from one major investor from Kenya, who has the infrastructure and experience to establish manufacturing facilities in Africa.

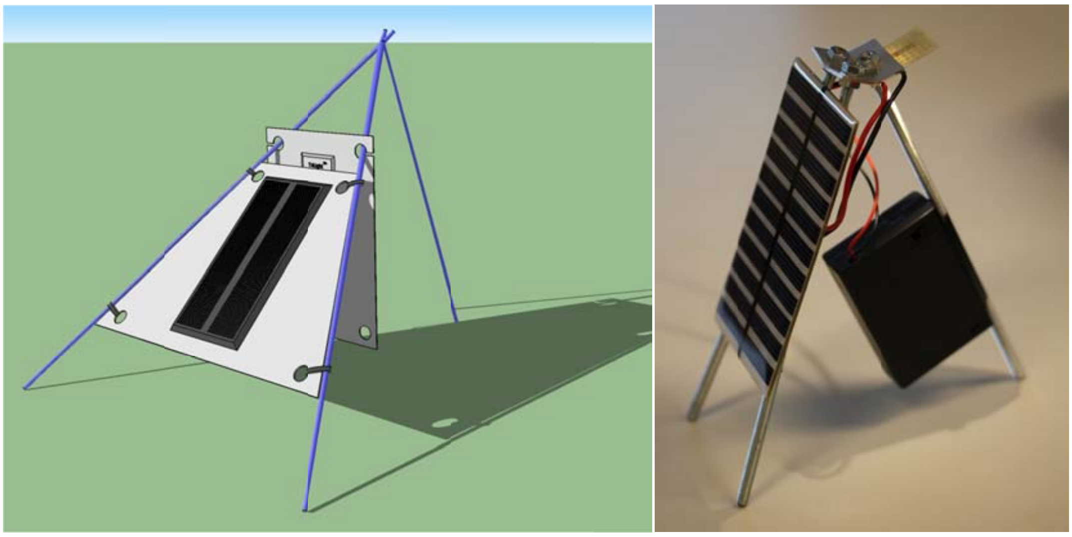


Figure 3-9: Early stage concept studies for a new Africa Lamp for building a marked for polymer solar cells.

Continued commercialization

The lack of competitiveness of the current process has led to investigations of ways to surpass competitors on cost, performance and lifetime. The main effort is to find inks with higher efficiency and lower cost, which can be supplied on commercial terms. In this connection, Mekoprint has established contact to world-leading ink suppliers, who are interested in supplying inks and enter deeper cooperation for the next phase of the project.

To obtain the required life time, the cooperation with DTU has been continued, with focus on test methods and materials for new encapsulations. With these initiatives, it will be possible to produce polymer solar cells on commercial terms in 2015.

References

3-1 M. O. Reese, et al., Consensus stability testing protocols for organic photovoltaic materials and devices, *Solar Energy Materials & Solar Cells*, 95, 2011, 1253.

3-2 Jonas Kuipers Haastrup and Christian Birk Sørensen: "Edge Tracking for Organic Solar Cell Production", Master Thesis, Aalborg University, May 2012

4. Encapsulation and operational lifetime

In order to be able to report and compete for the most reliable and long living technology in the field, there must be performed a standard qualification testing of the technology according to standard testing protocols. Stability testing standards for inorganic photovoltaic devices/modules/panels, such as for example Si based devices, have been long established and published by American Society for Testing and Materials (ASTM) and International Electrotechnical Commission (IEC). Unfortunately, this is not the case for the new field of organic photovoltaics (OPVs), as OPVs are still in a phase of progressive developments with continuous upgrades in the device architecture and structure and the materials used in the device.

Establishing standard testing protocols for such an erratic technology is not trivial. This is especially the case for the accelerated testing, where excessive amounts of stresses are applied onto the device to accelerate the ageing process and then using the accelerations factor to estimate the device lifetime in a real time. In order to define the acceleration factor of a particular stress, the effect of the stress on the device in real time must be well established. In other words, in order to be able to establish a reliable standard for acceleration testing, the behavior of the technology in real-time tests must be well studied and compared with the acceleration tests [4-1].

The OPV field currently benefits from the recently published ISOS testing recommendations [4-2], which address the issue of reliable stability testing of the OPV devices and offer general guidelines, which can improve the reproducibility of the OPV stability testing, but which do not offer standard qualification tests for reporting device lifetimes.

Thus, in order to achieve the target of 5 year lifetime of an OPV device a Characterization Laboratory for Organic Photovoltaics (CLOP) was built at DTU. The prime objective of the laboratory was to continuously perform real-time and accelerated testing of OPV devices and modules both in indoor and outdoor conditions according to the ISOS testing recommendations [4-2] and to establish a reliable technique for predicting the device lifetime based on accelerated studies.

As a next step devices and modules with various encapsulations were tested to establish the most stable devices that would survive the accelerated tests and predictably present the required lifetime of 5 years. Special focus has been given to devices encapsulated in ultra-thin barriers as this is in line with the strategy of removing as much material as possible, see section 2. I order to explore such ultra-thin encapsulations a R2R UV laminator has been installed, deliverable 3.2.

CLOP - Characterization Laboratory for Organic Photovoltaics
The following equipment was purchased for the CLOP in order to fulfill the aforementioned targets:

- Solar testing setup based on a sulfur plasma lamp (SPL) with class A spectrum, which was customized for accurate testing of device/module photovoltaic properties in indoor conditions. This also involved a reference Si photodiode with KG5 filter calibrated at Fraunhofer Institute, used for performing accurate calibration of the solar testing setup.

- An instrument for measuring Quantum Efficiency (QE) of the photovoltaic devices according to ASTM standards.
- A weathering chamber for performing indoor ageing experiments according to ISOS-L-3 recommendations with a full control of parameters, such as temperature, relative humidity and irradiance with AM1.5G spectrum.
- A thermal cycling chamber for simulations of outdoor temperature and humidity cycles in an accelerated mode according to ISOS-T-3 recommendations.
- Solar testing setups based on Metal Halide Lamps (MHL) with class B spectrum for performing accelerate ageing experiments with intensive light soaking in indoor conditions according to ISOS-L-1 recommendations.
- Apart from the purchased equipment a number of units have been utilized within DTU for reaching the target of this project, such as:
- An oven with a wide range of temperature control for performing ageing tests involving high temperature dark storage according to ISOS-D-2 recommendations.
- An outdoor solar tracking platform with an integrated light concentrating unit. The platform allows for performing both real-time outdoor ageing of devices according to ISOS-O-3 recommendations and accelerated ageing using concentrated light with intensities up to 200 times higher than the normal sunlight.
- Low light testing setups based on halogen and sulfur plasma lamps, commonly used for indoor lighting in rooms and offices, for performing low light ageing tests according to ISOS-LL recommendations.

This fulfills deliverable 3.1 "IV-test system is installed", deliverable 3.4 "Weather/thermal chambers are installed", deliverable 3.5 "Outdoor tracker is installed".

Procedure for lifetime testing

The diagram in figure 4.1 outlines the plan of device testing procedures that were developed at CLOP and employed for evaluating device lifetimes. The detailed steps are as follows:

1. *Accurate characterization of the initial performance of all the samples, which involves:*
   - Quantum Efficiency (QE) measurements of the sample
   - Mismatch Factor (MF) calculations for the sample using the QE data
   - Calibration of the SPL solar simulator using MF data of the sample and Fraunhofer reference photodiode
   - Accurate masking and IV testing of the sample under the calibrated light source

2. *Distribution of the samples among the different ageing tests, such as:*
   - ISOS-O-3 (outdoor ageing using solar tracking platform)
   - ISOS-L-2 (indoor light soaking under irradiance of 1 sun and temp. of 70^{o}C using B class MHL simulators)
   - ISOS-L-3 (indoor weathering under irradiance of 0.7 sun, temp. of 65^{o}C and relative humidity of 50 %)
   - ISOS-D-1 (reference storage in a shelf)
   - ISOS-D-2 (Storage in the oven in dark at 85^{o}C, low humidity)
   - ISOS-D-3 (Storage in weathering chamber in dark at temp. of 50^{o}C and relative humidity of 85 %)

- ISOS-TC-3 (Dark storage in thermal cycling chamber with periodic cycling of temp. -40 to 85°C; Relative humidity 50 %, ca. 6 cycles daily)
- ISOS-LL (Light soaking under Halogen or Sulfur Plasma lights at low irradiance of 0.1-0.2 suns).

3. *Comparison of T_{80} for accelerated and real-time aging tests and estimation of accelerated factors.*

During the storage the samples were periodically IV-characterized to establish the degradation pattern of the performance. Typical ageing experiment was performed until T_{80} is reached or until total destruction of the sample takes place.

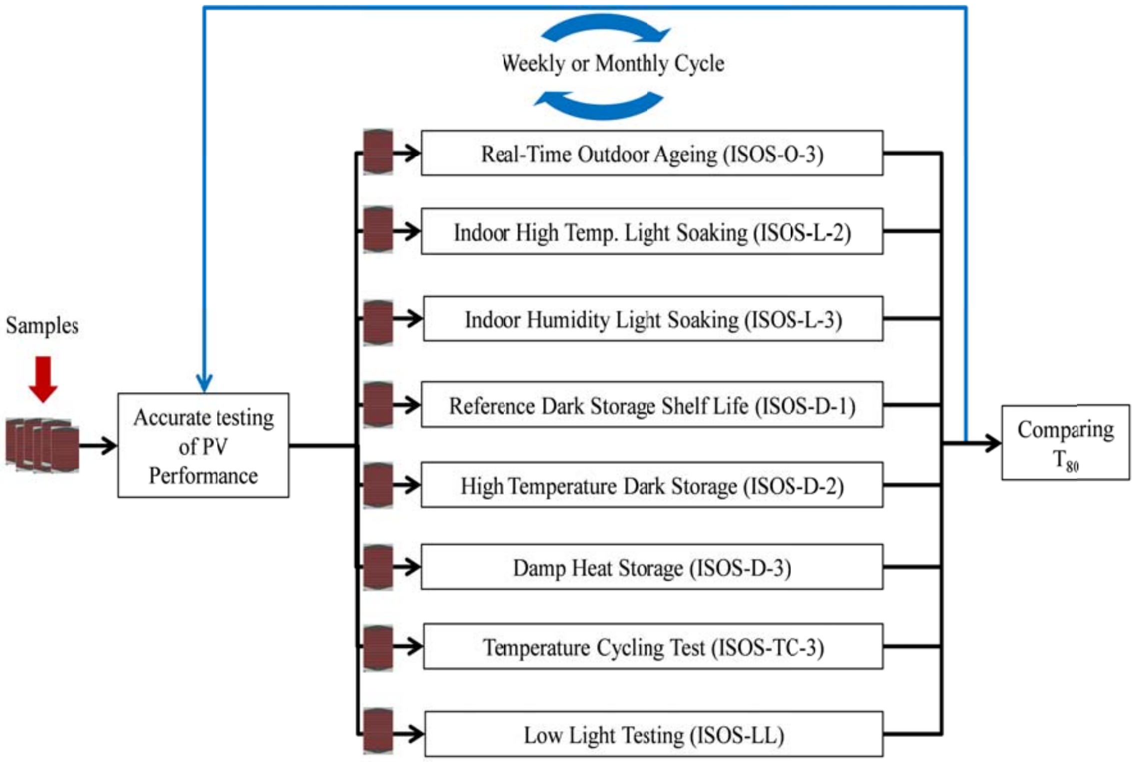


Figure 4.1: The schematics of the lifetime testing at CLOP.

Lifetime testing

The initial experiments of more than one year showed that the roll-to-roll coated flexible modules encapsulated with a single layer of UV filter/barrier (Amcor) with a pressure sensitive adhesive (467 MPF, 3M) had a lifetime over 10.000 hours after outdoor real-time testing in Denmark and up to 17 months lifetime for single cells measured in a number of countries, such as Germany, Australia, Israel and Denmark. Figure 4.2 shows the maximum power generation for the module measured in Denmark for over 10.000 hours. The module performance decreased in the winter season due to the low altitude of the sun resulting in shading of the module by the surrounding trees. This followed by almost total recovery of the performance in the summer season again. The T_{80} (a point in time when the sample reaches to the 80 % of its initial performance) of this module was estimated to be in the range of 18 to 24 months. Most of the indoor accelerated ageing tests revealed lifetimes close to 1000 hours for the same type of modules and single cells except the very harsh conditions with 85 % relative humidity. For the latter the typical T_{80} was a few hundred hours. Thus, a correlation was made between the accelerated and real-time studies, such as 1000 hours of accelerated ageing with moderate conditions and a few hundred hours of accelerated ageing under harsh (85 % relative humidity) conditions would correspond to about 1-2 years real-time outdoor measurements.

Further, the preliminary accelerated ageing tests of modules encapsulated using single or double layers of the same barrier material demonstrate ca. 5-fold improvement in the lifetime under harsh conditions (ISOS-D-3) suggesting that with such an encapsulation the target of 5 years can easily be achieved. Figure 4.3 shows the comparison of the single and double encapsulated modules after the damp heat test ISOS-D-3. The T_{80} for single encapsulation was ca. 270 hours, while for the double encapsulation ca. 1500 hours.

To summarize, lifetime of up to almost 2 years have been reached with single layer encapsulation using Amcor barrier with a pressure sensitive adhesive, and the preliminary results of the accelerated testing show that the double encapsulation has an effect of up to 5-fold improvement in the module stability. Based on these results we consider that the deliverable 3.6/ milestone M4 "5 years lifetime is achieved" is fulfilled.

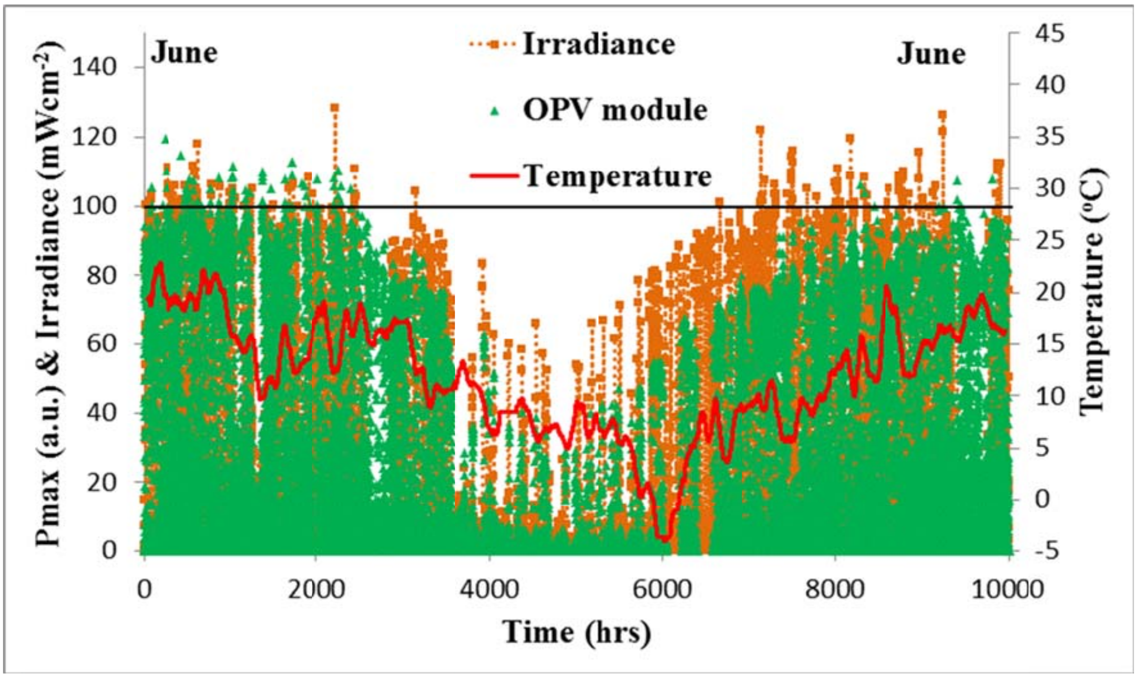


Figure 4.2: Maximum power generated by the OPV module measured for 10.000 hours in Denmark. The irradiance and daily average of the temperature are shown as well.

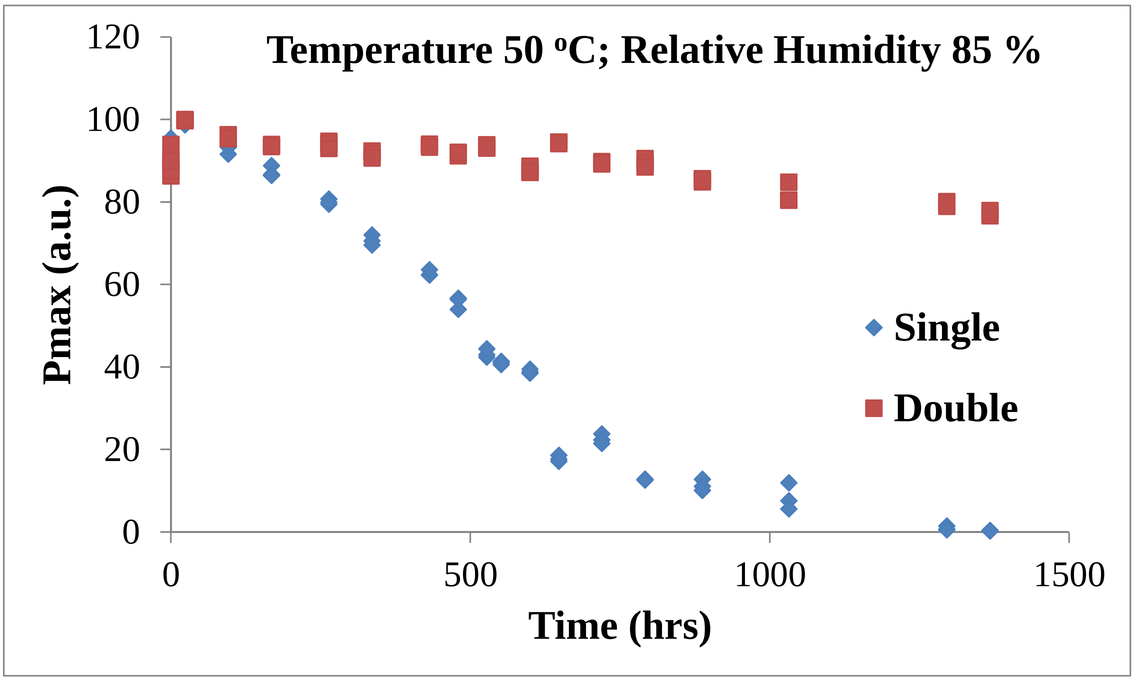


Figure 4.3: Comparison of module performance with single of double encapsulation tested according to ISOS-D-3.

References

4-1 O. Haillant, Accelerated weathering testing principles to estimate the service life of organic PV modules, *Solar Energy Materials & Solar Cells*, 95**,** 2011, 1284.

4-2 M. O. Reese, et al., Consensus stability testing protocols for organic photovoltaic materials and devices, *Solar Energy Materials & Solar Cells*, 95, 2011, 1253.

5. Polymer solar parks

The chapter describes an extensive development plan for bulk energy production by means of polymer solar modules. Three potential installation types have been identified; on uncultivated land, along highways, as environmental cover for landfills. A corresponding SWOT analysis concludes that the main technological opportunities are linked to new deployment, the installation process and the module encapsulation. With these applications in mind, different installations scenarios have been identified and considered with respect to advantages and disadvantages of each scenario (ground mounted, tracking, and deployment of solar cell rolls). In extension of this analysis, the cost structures for installation of selected scenarios have been calculated on per W_p basis The cost ranges from 1.25-3.36 €/W_p.

The conclusion of the analysis is that the installation approach of rolling out polymer solar modules directly from the roll and onto the pretreated ground has the lowest cost and utilizes the inherent advantages of the technology. Ration installation can for be done by a modified timer harvester.

On the basis on the current technology development, the preferred module design and module specifications for bulk energy production are determined. The module needs a considerable amount of strips connected in series to generate a sufficient voltage and power for commercial inverters.

Lastly in the sensitivity analysis, the return on investment (ROI) is analyzed as a function of the annual degradation in module power output (5-20%), the interval between replacement of the polymer solar modules (5-10 years), the type of investor (industrial enterprises, small/medium businesses, municipalities), and the module cost (0.25-0.85 €/W_p). The annual degradation is the one factor affecting ROI most strongly. Crystalline PV parks with 0.5% annual degradation take 8 year+ to payback. While polymer solar installations may have a lower costs structure limited by the balance of system cost, the annual degradation strongly needs to be reduced in order to even reach the financial pay back times of silicon solar parks.

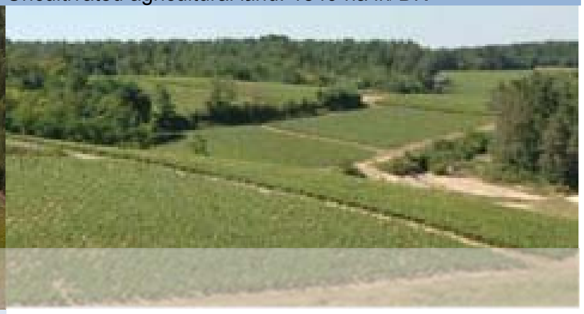
The site, the mounting and the encapsulation

Three potential installations sites are identified as attractive for polymer solar plants; on uncultivated land, along highways and as environmental cover for landfills where the installation serve a double purpose, see Figure 5-1. These are chosen because of an attractive cost for purchasing or leasing the require land.

Table 5-1 shows a SWOT analysis for the polymer solar technology. The technology's main opportunities are identified as the polymer technologies suitability for fast and automated installation, the opening for circumventing the costly step of converting the roll-to-roll process modules into individual panels and the technology's fast learning rate and its suitability for mass production. In the design, the installation and the operation of polymer solar parks one should seek to take full advantage of these opportunities.

Along highways	**Slope, mounds, uncultivated land**
Road network: 1130 km highway in DK/ ~170 ha	Uncultivated agricultural land: 1849 ha in DK

Photo: Between Silkeborg og Herning



Closed recycling plants

Closed and current recycling plants: 2000 ha in DK

Photo: Hine Møllevej

Figure 5-1: Attractive sites for large polymer solar installations

The polymer solar modules can be encapsulated and mounted in various manners. The encapsulation options are; in flexible protections as plastic, steel or textiles or as framed rigid panels similar to the ones frequently seen in conventional PV pants. Textiles are not considered further, because cost-effective and reliable textile encapsulations are not immediately feasible. The mounting options are; tilted on ground-mounted racks, on trackers and on the ground after a suitable priming/pretreatment of the ground. The latter one allows for cost-effective installation directly from the roll. Table 5-2 illustrates the installation possibilities, and Table 5-3 lists their advantages and disadvantages.

Table 5-1: Swot analysis for polymer solar parks

SWOT	
Strengths	**Weaknesses**
Efficient roll-2-roll process	Efficiency
Flexible, robust, adaptable technology	Stability
Light weight, and easy transport	High BOS costs per W_p
Integration of processes: circuit printing, printable electrodes, encapsulation.	Variations in cell performance
	Large land area usage
Opportunities	**Threats**
Ideal for automatized installation and disassembly	Competing low-cost CSi and thin film technologies
Circumventing typical module costs	Competitive technological breakthroughs
Circumventing typical installation costs	~ 10 years stability cannot be reached
Fast learning rate	
Primed for mass production	

Table 5-2: Various encapsulation and mounting methods for polymer solar cells

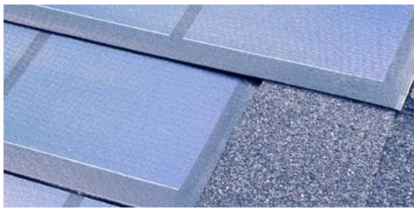
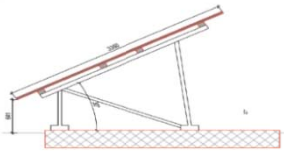
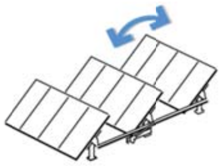
MOUNTING	**On tilted racks** The polymer cells are inclined on a ground mounted structure		
	On trackers The polymer cells are attached on a solar tracker.		
	On the ground The polymer solar cells are rolled out on a primed area		
ENCAPSULATION	**Flexible** Plastic/steel		
	Solid Frame Aluminium frame		
	Textile		

Table 5-3: Advantages and disadvantages for viable installation options

	On tilted racks	On trackers	On the ground
			
Flexible	**+ 15% irradiance*** **+ Draining** - Row shadowing - Low coverage ratio		**+ No wind loads** **+ Roll-able / Low cost** **+ High coverage ratio** - Water/snow/dirt draining - Lower energy yield per W_p
Al frame	**+ 15% irradiance*** **+ Draining** - Row shadowing - Expensive mounting and panels	**+ 26% irradiance*** - Expensive mounting and panels - Very low coverage ratio - Mechanical complexity	

*increase in irradiance compared to horizontal installation

For polymer solar parks to become cost competitive, competitive installation, competitive operation and competitive end-of-life management are required. Table 5-4 lists the installation cost per W_p for the considered installations options. Construction, mounting and BOS costs are based on 2011 figures for Gaia Solar PV park installations. For the rolled-out installation directly on the primed ground, cost of labor and mounting structures are estimated to be respectively 1/2 and 1/6 of the corresponding costs for installation on tilted racks. Table 5-5 ranks viable installation options with respect to usage of land. The system performance ratio is based on a rule of thumb for the respective systems. The analysis shows that rolling out of the flexible solar modules directly on the ground is the most attractive option with respect to both cost and usage of land.

Table 5-4: Cost per W_p for the viable installation options

	On tilted racks		On trackers	On the ground	Compare
Costs	**Al Frame**	**Flexible**	**Al Frame**	**Flexible**	**C:Si park**
Site Development costs [€]	0,00	0,00	0,00	0,02	0,00
Construction (labour) [€/Wp]	0,22	0,22	0,45	0,07	0,15
Mounting structures [€/Wp]	0,20	0,20	0,50	0,05	0,30
BOS components [€/Wp]	0,11	0,11	*	0,11	0,11
Cost of inverter replacement * [€/Wp]	0,13	0,13	*	0,13	0,13
Transformer & grid connect [€/Wp]	0,02	0,02	0,02	0,02	0,02
Modules [€/Wp]	2,39	0,85	2,39	0,85	0,65
Total [€/Wp]	**3,07**	**1,53**	**3,36**	**1,25**	**1,36**

* Inverter to be replaced after 15 years, cost of initial inverter is included in cost of BOS components

Table 5-5: Area required for the viable installation options

System design	On tilted racks Al Frame	flexible	On trackers Al Frame2	On the ground Flexible	Compare C:Si park
Annual horiz.global irradia. [kWh/m^2/yr^2]	1000	1000	1000	1000	1000
Increase due to tilt angle [%]	0,15	0,15	0,26	0,00	0,15
Ground Coverage Ratio* [%]	0,55	0,55	0,35	0,90	0,55
Module efficiency [%]	4.5	4.5	4.5	4.5	17
System Performance Ratio	0,75	0,75	0,80	0,75	0,80
Area required for 1 MW plant [ha]	**4,68**	**4,68**	**6,31**	**3,29**	**1,16**

* The fraction of the total area of the installation that is covered by solar modules

The installation process

A step-to-step guide for installation of large areas of flexible rolled-up polymer solar modules directly on the ground is shown in Table 5-6. The suggested procedure comprises methods used for rolling out flexible thin film solar cells on abolished landfills in Italy, among others.

The process of rolling out the band containing the solar modules is not complex, but the installation machinery has to be designed for the task. An example of how this can be done by means of a modified timber harvester is shown in Figure 5-2. The timber harvester is equipped with a rolling-out device attached at the rear of the harvester. The rolls can be stored on the vehicle and are from here easily accessible during the installation. A timber harvester running at 1-2 km per hour allows installation of 1.6-3.2 hectares 2 meters wide modules in one working day (8 hours). This corresponds to ~ 0.5-1 MW per day for solar modules with an efficiency of 4.5 %.

Figure 5-2: Deployment by a modified timer harvester

Initiation of rolling out process **Deployment of several solar strings**

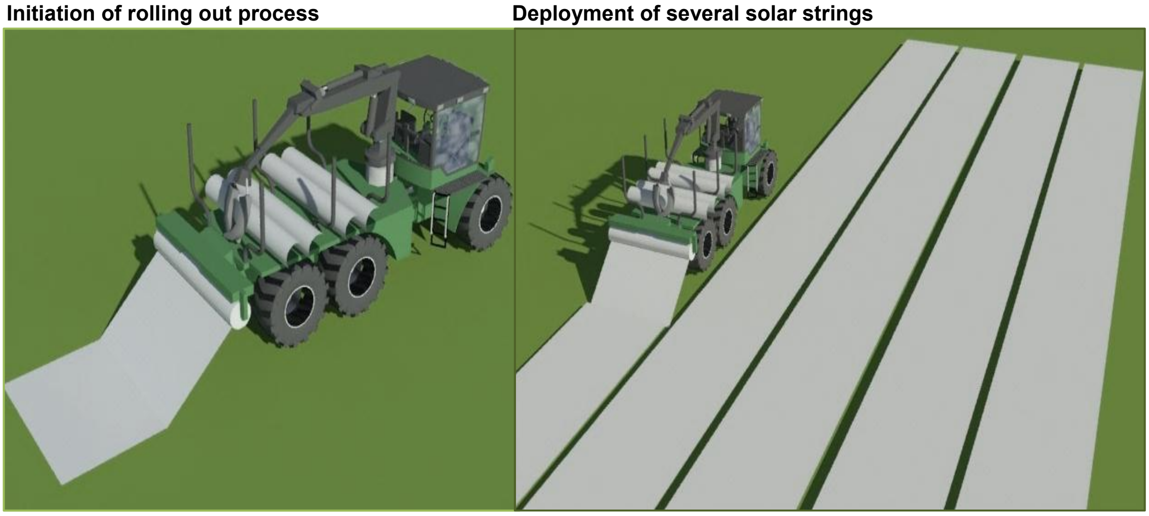


Table 5-6: Step-by-step guide for the installation of roll-out modules

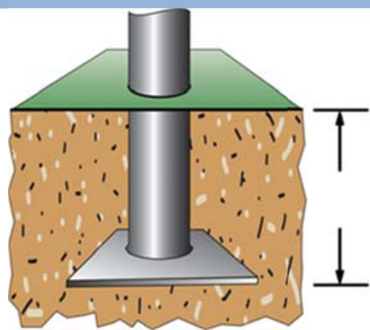
Site selection: mound	**Site development**
	
Rolling out PV roll Placing solar cells on top of ground cover	**Alignment of OPV strings**
	
Merging OPV strings Glue-sealing or otherwise merging string covers	**Ground fixing**
	
Project design of electrical system	**Finished OPV park**
PV system components are described in the following section	

Table 5-7: Installation by means of a modified timber harvester

Equipment	Modified timber harvester	
Installation speed	1-2 km/hour 1.6-3.2 hectare/day ~ 0.5-1 MW/day	
Leasing cost	~ 50.000 DKK per day	

The module design

The module design must be an optimum between manufacturing capability, manufacturing costs and solar park system performance. The module specification is furthermore important for the configuration of inverters and strings. Figure 5-3 illustrates the effect of the module design and electrical connection scheme on the energy output. Long strip panel design (say 5-30 m) with a width of say 2 m is ideal. Each module is preferably connected with a string inverter, or in parallel with blocking diodes. Table 5-8 is an example of a detailed specification for a module suited for a polymer solar park. The power output and voltage should be sufficiently high for commercial inverters, and therefore multiple stripes in series are necessary. The performance figures are worked out for modules consisting of stripe-shaped 13 mm wide cells connected in series.

Modules connected in strings must have similar performance characteristics; otherwise the weakest module limits the string's performance. Module sorting is thus important for improving PV park system performance. A spread in module performance has been reported for Process-One of 10% [5-1]. The spread should be reduced in order to improve the system performance[3].

The polymer solar modules should preferably reach similar field performance as crystalline modules, and for this the following critical issues should be addressed:

- Robustness against breakage of electrical connection and contacts
- Mechanical stability of screen-printed silver contacts
- Delamination along the module-rigid PCB board interface, if PCBs are used and are mounted on the flexible modules
- Robustness against mechanical stresses in general, and against repetitive bending and buckling
- Stability in output power, especially the light-induced stability
- Spread in module performance
- Increased geometric fill factor.

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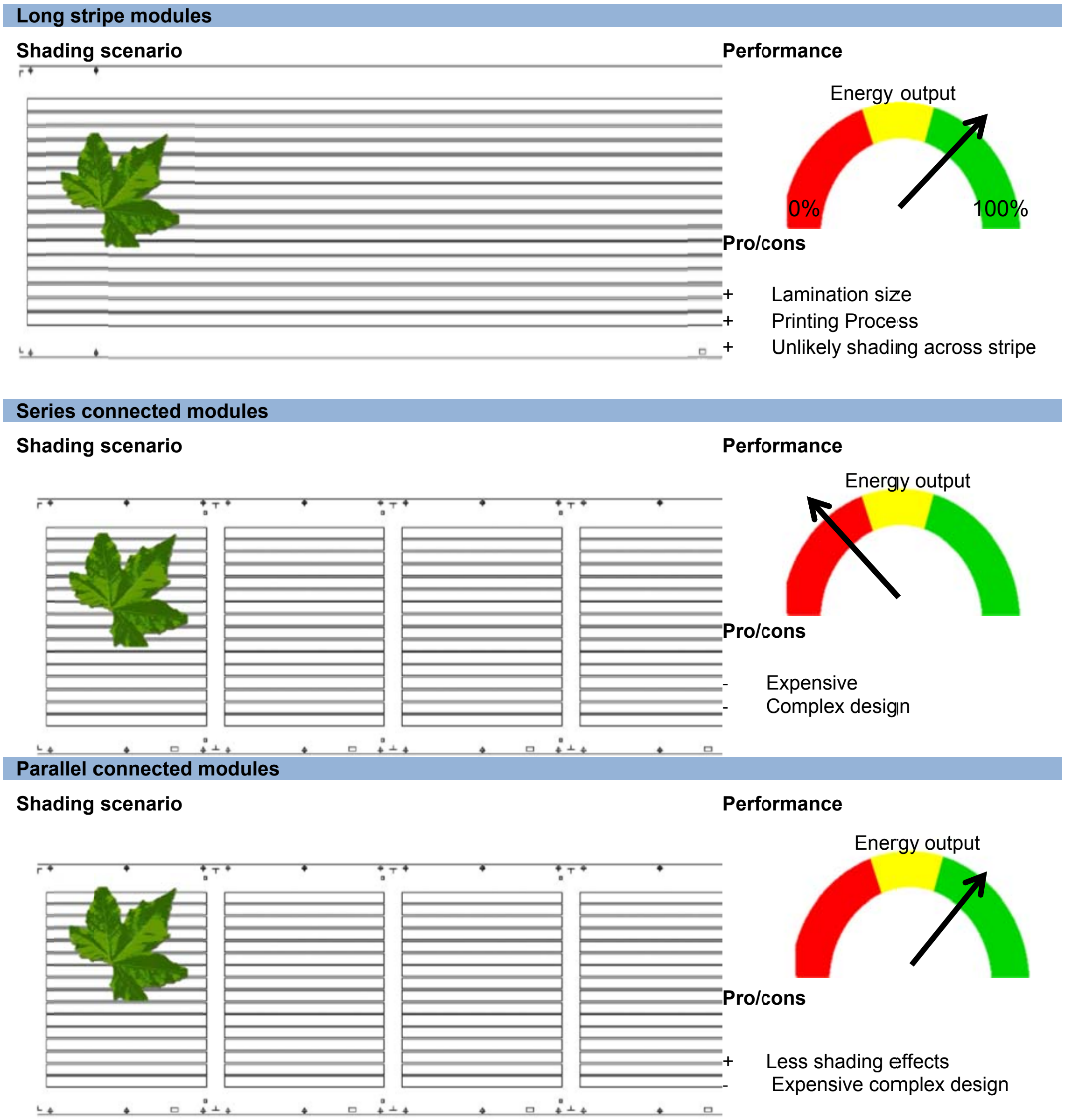
[3] The spread is significantly reduced in DTU's more advanced processes. Published data on spread is p.t. not available.

Figure 5-3: System performance for various connection schemes and module designs

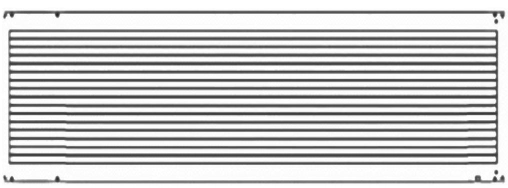
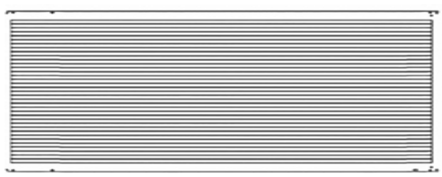


The economy

The economy of a polymer solar park is investigated for the concept found most attractive in the previous analysis, i.e. an installation where the solar modules are rolled out directly on the pre-treated ground.

The annual internal rate of return averaged over the operational period (IRR) is used as a criterion for sound economic operation, and a sensitivity analysis is performed in order to identify the parameters having the strongest influence on IRR. As more parameters act simultaneously, the effect of each parameter should be weighted in order to draw a realistic scenario, and from this a market strategy can be worked out.

Table 5-8: Examples of module specifications suited for large installations

	Prototype	Future design
Tech	Polymer solar cell (OPV)	Polymer solar cell (OPV)
Stripes	Composed of 41 stripes	Composed of 136 stripes
Width	13 mm	13 mm
Gap	gap of 2 mm	gap of 1 mm
Length	5 m	5 m
Sealing	Degradation requirements: Impermeable to water and oxygen	IP 65 certificate: protection against low pressure jets of water from all directions
P_{mpp}	46 W	377 W
Efficiency	1,83%	4,5%
Power tolerance	+/- 5 %	+/- 5 %
Weight	3,5 kg	11,5 kg
Size		
Width	610 mm	2000 mm
Length	5 m	5 (or longer)
Height	1-2 mm	1-2 mm
Junction box	Weatherproof MC4 connector	IP 65 certificate Incl. microinverter MC4 connector
Circuit	Long strips in series Circuit printing	Long strips in series Circuit printing
Contacts	Printed metal electrodes (silver ink)	Printed metal electrodes (silver ink)
Setup (illustrative)		

The basic assumptions used in the sensitivity analysis are listed in Table 5-9. The strength of the following parameters is considered: the system degradation, the operational period and the character of the ownership. These parameters are investigated under various modules costs and various degrees of own consumption, i.e. the fraction of the energy produced that is consumed by the owner.

The four different ownerships investigated are; owned by respectively a municipality, an industrial enterprise, a supplier of professional service, and a community[4]. Owners within these categories will, due to the Danish solar regulation[5] and due to their VAT and tax obligations, experi-

[4]) In Danish: fællesanlæg i boligforeninger etc.

[5]) of December 2012

ence different economics, see Table 5-10. Operating the installation under business regulations allows for depreciating the asset with maximum 25 % per year. It should be noted that this limit does not apply for community-owned installations. The size of the installation investigated is 400 kW_p as this is the upper limit set by the present regulations.

Private household ownership is not considered, because the Danish regulations do not allow private households to depreciate the assets, and because a private household is unlikely to own sufficient land and have a sufficient large own consumption for making a 400 kW_p installation realistic.

Table 5-9: Assumptions used in the sensitivity analysis

Assumptions	
size	400 kW_p
BOS cost	0.40 €/kW_p
depreciation rate	25%
annual land lease	843 €/ha
annual inflation, general	2.1%
annual inflation, electricity	4%
investment	100% debt
loan period	10 years
interest	4% per anno
disassembly cost	equal to scrap value
orientation of panels	30% inclination, south facing
output ratio	960 kWh/kWp
allocation for replacement of inverter	3429 € per year
operation and maintenance cost (excl. inverter)	0.5% of investment + land lease
year of installation	2014

Table 5-10: The categories of ownerships considered in the sensitivity analysis

Owner category	Examples	Electricity price (€/kWh)		Tax	VAT
		Buying*	Selling**		
Municipality		0.27	0.16	0%	yes
Industry		0.11	0.16	25%	no
Professional services	layers, dentists, real estate brokers	0.27	0.16	25%	yes
Community	housing associations (boligforeninger)	0.27	0.18	25%	yes

*cost of buying electricity from the grid

**income from selling excess production to the grid

The percentage of the energy produced by and consumed by the owner has become important due the revision of the Danish solar regulations of December 2012. In this investigation the fraction own consumption is defined as the fraction that yields for the initial, non-degraded installation. It is assumed that the numeric value of the own consumption is constant over the operational period whereas the fraction that is consumed by the owner will increase it the energy output goes down.

The system energy output will decrease over time due to degradation of the modules. The annual decrease in output power is assumed to follow a course where the annual output in a given year, X(n), is a fix percentage, Y, lower than the output the previous year, X(n-1):

$$X(n) = X(n-1) \cdot (100\%-Y) \qquad n=1, 2, 3, 4, \ldots\ldots$$

The normalized energy output from an installation following this relationship is shown in Figure 5-4. Y is in the following denoted the year-to-year degradation.

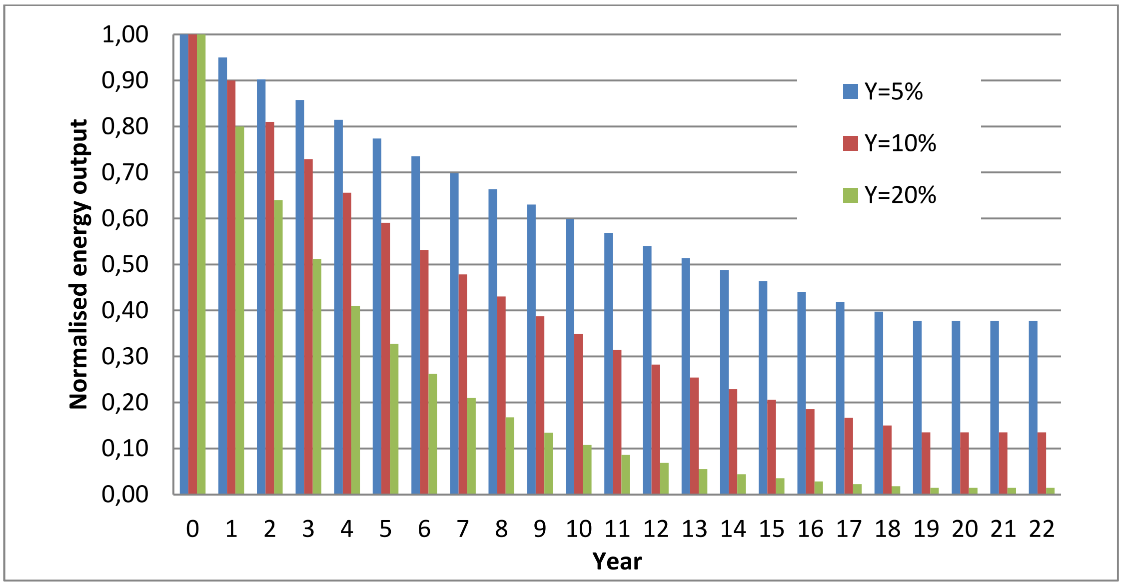


Figure 5-4: Normalised energy output for installations with three different degradation courses following the X(n)=X(n-1)·(100-Y) where Y is respectively 5%, 10 % and 20 %.

Operating the solar installation under the present Danish business regulations allows for depreciating the asset with maximum 25% per year. As the rate of degradation is higher for the polymer solar technology than for conventional PV technologies, a shorter depreciation period and a correspondingly higher annual depreciation might be argued, but will require a revision of the present practice, and it thus not considered here.

The operational period is the period the installation is operated before disassembly or replacement of the degraded modules.

The optimum operational period

The optimal operational period for the installation is defined at the operational period giving the highest return on investment (IRR). Figure 5-5 shows how the optimal operational period varies with the module cost. The effect of ownership and degradation are included in the vertical bars (range of results). The ownerships included are the four categories listed in Table 5-10, and the degradation is according to Figure 5-4, with Y equal 5%, 10% and 20%. The ideal period for operation the PV plant ranges from 13 years to 24 years depending on the degradation rate, the ownership and the modules cost.

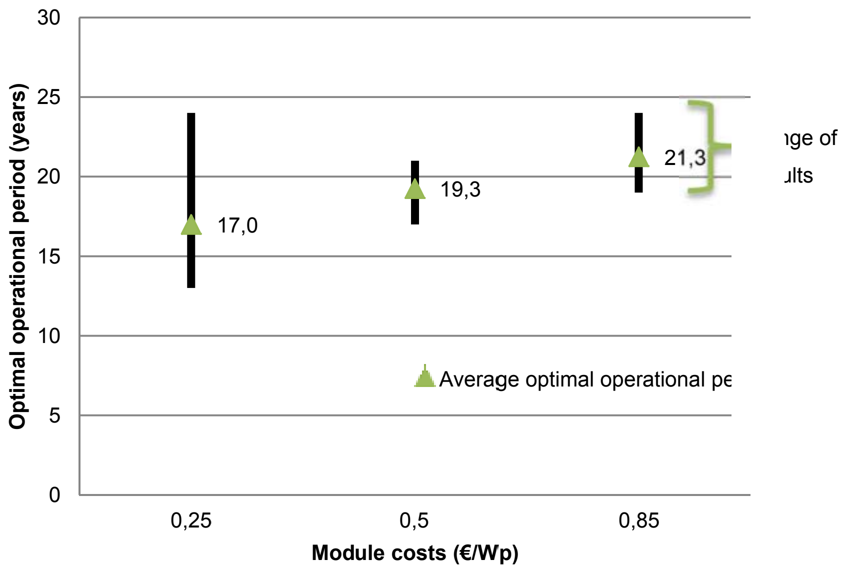


Figure 5-5: Optimal operational period for an installation with modules of three different costs. The vertical bars show the spread in results caused by a variation in the year-to-year degradation (5%, 10% and 20%) and by the four categories of ownerships listed Table 5-10. The optimal operational period is an averaged over the three degradations rates and the four categories of ownership.

Effect of degradation: example plant owned by a municipality

The average annual return of investment for a municipal installation operated is analyzed under various conditions covering variations in the year-to-year degradation, the module cost, and the fraction own consumption, see Figure 5-6. The operational period is set to what is optimum for the specific degradation rate. For a year-to-year degradation of 20% only a module costs of about 0.25 €/W will provide a positive IRR, whereas module costs of 0.5 € and above are not economically feasible with such a high degradation rate. For a year-to-year degradation $\leq$ 10%, the installation becomes profitable even for a module cost of 0.85 €/W. Reduced degradation is seen as an important key to economic attractiveness.

Effect of ownership: example 10% year-to-year degradation

The average annual return on investment is investigated for a plant with 10 % year-to-year degradation under various ownerships; industry, professional service and community, see Figure 5-7. The operational period is set to what is optimum for the ownership and the module cost in question. The most profitable installations are the ones owned by suppliers of professional services (dentists, layers, consultancy etc.). This is due to the high cost of electricity from the grid that the production from the installation replaces. The municipal ownership is also attractive and so is also the community-owned installations, as they their income from selling surplus energy to the grid is high (0.18 €/kWh) as compared to the other owner categories (0.16 €/kWh), see Table 5-10.

References

5-1 F. C. Krebs, Upscaling of polymer solar cell fabrication using full roll-to-roll processing, *Nanoscale*, 2, 2010, 873.

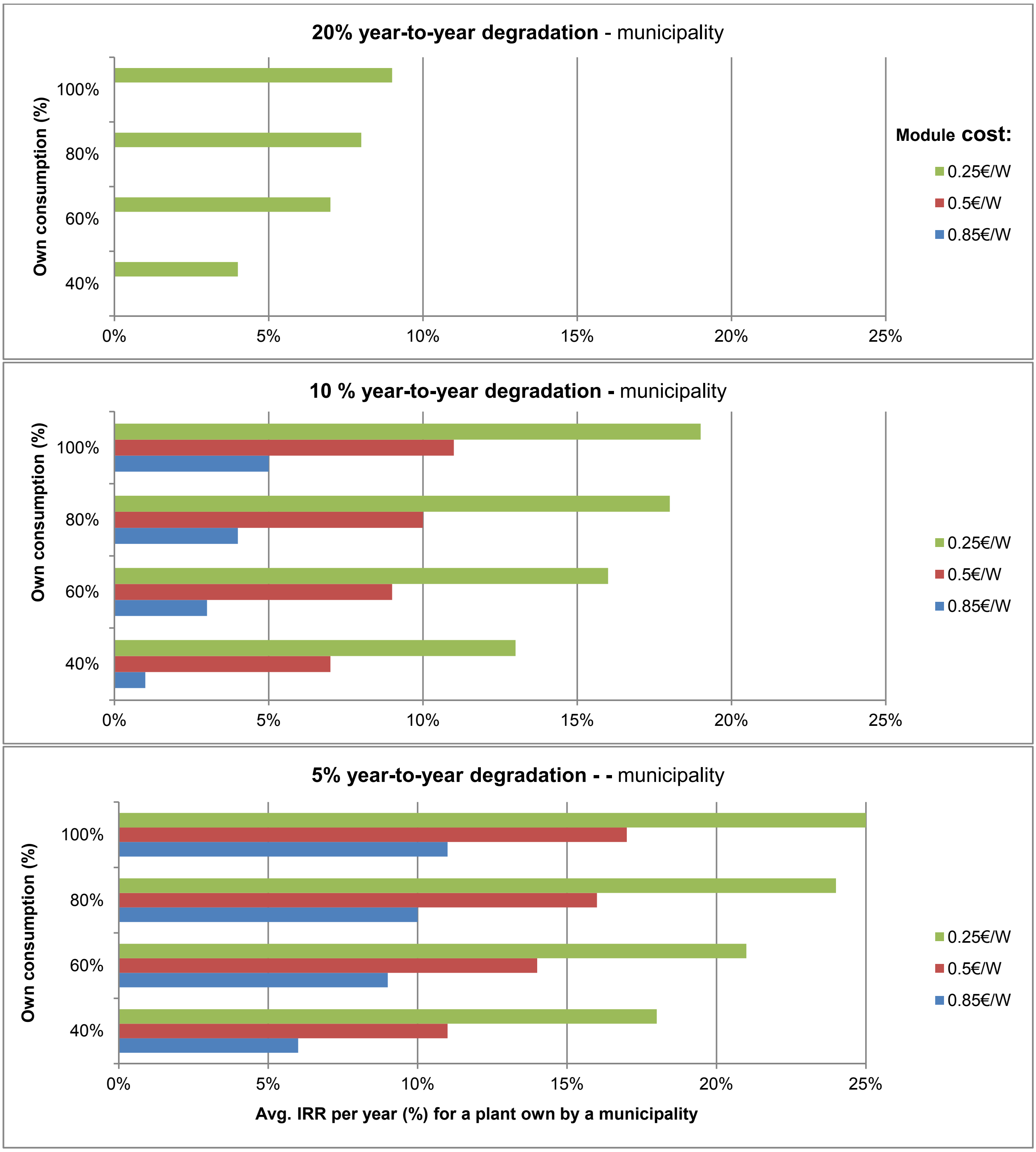


Figure 5-6: Average internal rate of return (IRR) for a polymer solar plant owned by a municipality and operated for 7 years. The diagram illustrates the effect of degradation rate, module cost and own consumption.

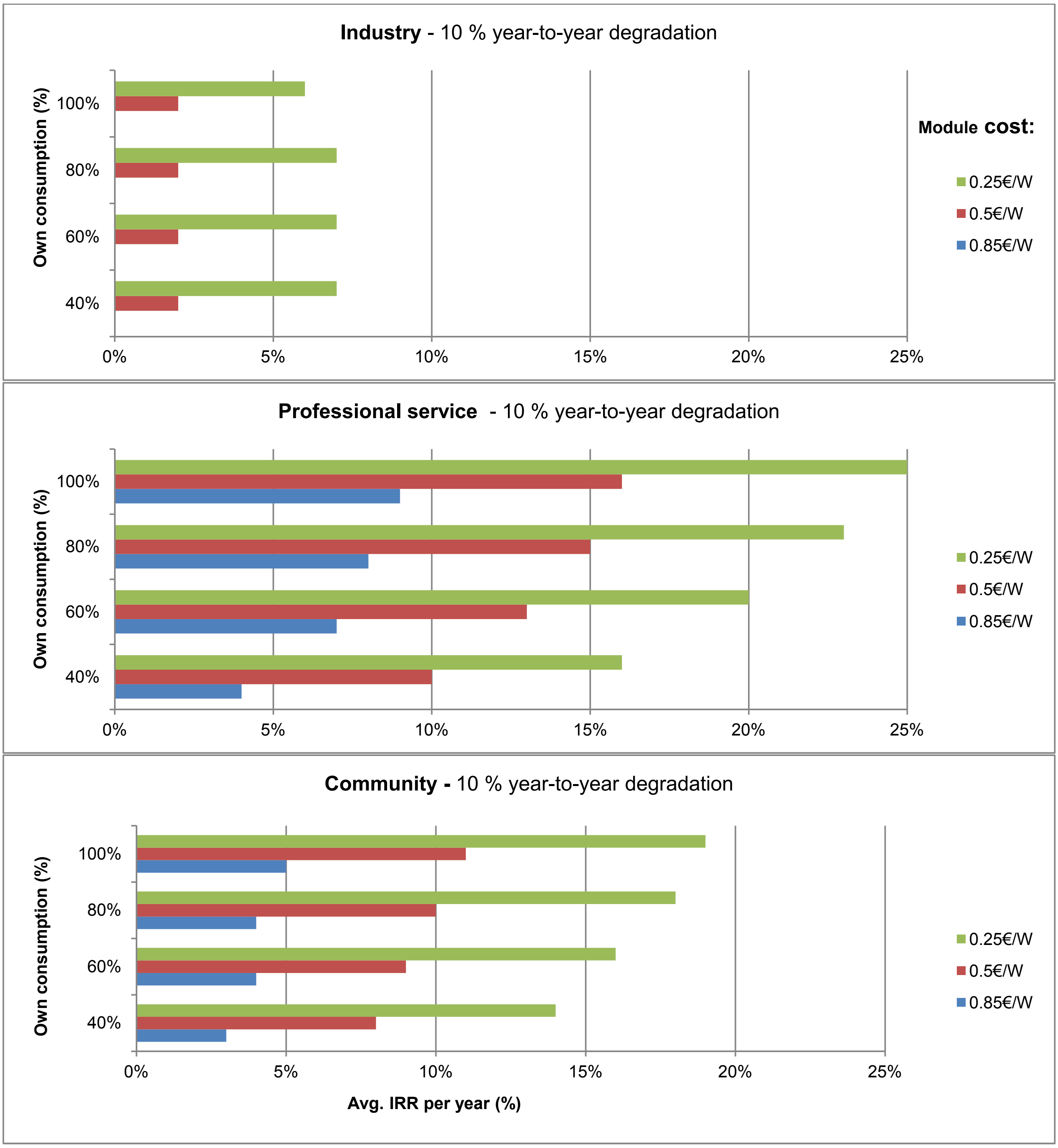


Figure 5-7: Average internal rate of return (IRR) for a polymer solar plant under various ownerships, own consumptions and module costs. 10 % year-to-year degradation is assumed, the operational period is set what is optimum for the actual ownership and module cost.

6. Business Opportunities

DTU has in a concentrated effort spring 2011 explored various strategies for commercialization of the OPV technology, and more precisely analysed the prospects for a spin-out company rooted in DTU's technology.

DTU's polymer solar technology represents business opportunities in more segments:

- The business of producing and selling solar cells in a more or less refined versions; as "raw" polymer solar cells, as solutions where the solar cell is adapted to a specific application and as solar-powered end products.
- The auxiliary business covering process-specific materials, production machinery, instrumentation for quality control and/or R&D investigations
- The business of selling knowledge; contracted R&D, training programs, IPR etc.

Present and near-future business opportunities

At present three Danish companies are commercially involved in OPV, see Figure 6-1. Mekoprint A/S who is marketing roll-to-roll produced polymer solar cells and customized polymer solar-cell solutions. Grafisk Maskinfabrik A/S who is building and selling roll-to-roll machinery for production of polymer solar cells, and the recently founded FOMTechnologies who is selling R&D equipment for coating and testing of functional organic materials and special materials here for. FOMTechnologies is founded by a previous DTU employee together with a partner from the printing industry. DTU is not co-founder of the company but has licensed the sale of their solar cell tester and a mini roll coater both to FOMTechnologies.

Besides these three, two companies are in the "pipe line" as they are following the technology closely with the purpose of being there when their share of the polymer solar cell market takes off; Faktor 3 ApS, with the business idea of designing and developing solar-powered products, and Gaia Solar A/S whose mission is to supply alternative energy with electricity producing solar technology.

These five companies contribute to the commercialization of the OPV technology, or will do so at the time when their specific market evolves. Their initiatives are judged to be adequate and sufficient for bringing OPV to the markets presently available, namely the market for low demanding niche applications and machinery/instrumentation/materials for R&D purposes plus the dawning business of producing polymer solar cells.

None of these companies has, however, sufficient technological – or financial strength for taking the position as DTU's strategic partner in the long-sighted R&D effort needed for entering the solar-cell market in its full width. This means more advanced OPV devices and more demanding applications.

The route to advanced products and demanding markets

Entering the solar-cell market in its full width means developing the OPV technology to the point where grid-tied OPV installations are competitive with alternative PV technologies; competitive with respect to installation cost and levelized cost of energy, but also competitiveness with respect to energy pay-pack time and energy return factor. At the time these targets are met, the solar-cell mass market will be gradually opened for OPV. The PV mass market is characterized by significant higher volumes but also stronger price pressure price than the presently available niche markets. The large business potential is, according to our best believes and despite the high price pressure, on this solar cell mass market. OPV is born for mass production, and high production volumes are therefore important for generating profit.

Figure 6-1: Example of commercially available OPV product: a roll-to-roll coating/ printing machine from Grafisk Maskinfabrik (top), a mini roll coater for OPV R&D purposes developed by DTU and sold by FOMTechnologies (middle) and an OPV flash light sold by Mekoprint (bottom).

The technological keys to the high-volume mass market are more advance processes than ProcessOne and derived from here competitive power production. This means improved solar cell performance and cost-effectiveness at all levels from materials via installation and operation to decommissioning, and also energy-effectiveness at these levels. Bringing the OPV technology to this point should preferably be done in a strong strategic partnership where the partner should provide venture capital and business knowledge

DTU's qualified strategic partners should be sought in environments familiar not only within the target marked, namely the PV mass market, but also familiar with the key technologies required in the R&D phase and in the subsequent commercial phase. The role of the strategic partner will be to lift the R&D tasks that are heavy in technology and development out of DTU's R&D labs and into a setting where the commercial anchoring is ensured. The role will furthermore be to mirror major R&D considerations commercially. The characteristics of the qualified strategic partner are:

Technology wise:	Must identify with the R&D intensive segments of the OPV value chain, namely process-specific materials and the processing itself. This requires general knowledge in materials science and PV technology, matched with core competences in organic chemistry and solution processing.
Business wise:	Must identify with a technology-push strategy and long-sighted R&D, and must be comfortable with "high technological risk & high expected return" investments.

The medium- to long-sighted business opportunities are more; OPV modules, OPV process-specific materials (inks and substrates), OPV processing machinery, installation and operation of OPV plants, and eventually also businesses of various auxiliaries. Except for the OPV plants are these opportunities identical to the present – and near future business opportunities, but the effort required is markedly different and so are also the market volumes. Entering the high volume markets requires a considerably stronger financial – and R&D commitment than what is seen in the present phase. International partners/investors might therefor be required.

A preliminary ranking of the business opportunities according to investor profile and DTU's strengths are given in **Error! Reference source not found.**. The very first bid of the investment needed for entering the solar cell mass market via a start-up producing OPV modules but not installing them, is DKK 10 mill.x10 years. Raising this amount of capital requires a strong streamlined patent portfolio and a recognized potential for above-average returns. DTU has pt. a strong knowhow in this field, but further actions await a strengthening and streamlining of the patent portfolio for the purpose and a comprehensive valuation of commercial risks and potentials.

Establishment of a company developing and selling R2R machinery for OPV production is less capital intensive and involves less risk. The main manufacturing equipment; roll-to-roll lines with relevant coating and printing stations, adequate process control, and pre- and post-treatment stages, can to a large extent be built from industrially proven building blocks. A start-up company will, consequently experience a strong competition with existing well-established Danish and international companies in this field, and the start-up company will have a disadvantage with respect to credible long-sighted guarantees. The best strategy here might therefore be to explore this business in collaboration with established players in this field.

Production of OPV-specific materials hinges on general knowledge in chemistry and wet-chemical processing equipment, which can be reached as a ramp-up of laboratory setups at low volumes, whereas the setup suited for high volumes equals what is found among commercial actors with speciality materials and chemicals.

Further actions

DTU will maintain a strong focus on their key target: to develop of the OPV technology towards the PV mass market and large-scale power production. Essential for addressing the PV mass market will be to continue the on-going effort on strengthening the patent portfolio, on discussing with potential investors and strategic partners, on benchmarking OPV as a large-scale energy conversion technology, and on generating the R&D results required for achieving this.

Appendix A Dissemination

Presentations at conferences, seminars etc.

Mekoprint

- J. Bork: "R2R printing and coating of functional materials at Mekoprint", Nanolab seminar, Aalborg University, Aalborg, 12. December 2012
- J. Bork: "Mekoprint Printing Services", Prinse'12 - Printed Intelligence Industrial Seminar, Oulu, Finland, 14. March 2012
- K. Ries: "Innovation - Printed Electronics - Polymer Solar Cells @ Mekoprint", Støving Gymnasium, Støvring, 29. February 2012
- K. Ries: "Industrialization of polymer solar cells", EnergiForsk 2011, Copenhagen, 22. June 2011
- S. Kowalski: "Mekoprint OPV progress", SMT hybrid packaging 2011, Nürnberg, Germany, 1. March 2011
- J. Bork: "Roll-to-roll mass production of polymer-based solar cells", OE-A Workgroup meeting, Stuttgart, Germany, 1. March 2011.
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DTU

- H. Lauritzen: "Status and perspectives for R&D in PV", WEC Denmark members meeting, Lyngby, 27. November 2012.
- H. Lauritzen: "Seneste udvikling inden for plastsolceller", Roskilde Håndværkerforening, Roskilde, 7. November 2012.
- H. Lauritzen: "Fremtidens solceller", Debatmøde om solceller og bygningskultur - Bygningskulturens plads i solen/ Landsforeningen for bygnings- og landskabskultur, Fredericia, 25. October 2012.
- H. Lauritzen: "Er fremtidens solcelle lavet af plast?" Har solceller en fremtid i Danmark?/ IDA Energi, Copenhagen, 3. October 2012.
- H. Lauritzen: "Polymer solar cells and their perspective in our future fossil-free energy supply", NextNano – Next generation of nanotechnology for solar energy and lighting", Malmø, Sweden, 19-20 September 2012.
- H. Lauritzen: "Seneste udvikling indenfor plastsolceller – plastsolceller og fremtidens energiforsyning", IDA region Sjælland, Roskilde, 18. September 2012.
- H. Lauritzen: "Nye solceller på markedet – plastsolceller", Temadag om solceller/Dansk Energi, Kolding, 19. April 2012.
- Hanne Lauritzen: "Product Integration of Polymer Solar Cells - from Circuitry to Functional Units", Printed Electronics Europe 2011, Düsseldorf, Germany, 5-6 April 2011.
- Hanne Lauritzen: "Plastsolceller – fra kemi laboratorium til industriel produktion", Temadag om plast i solcellemoduler, Toftlund, Danmark, 16 March 2011.

Events

- Inventors Association DK visits Mekoprint with focus on polymer solar cells. Presented by Morten Chistensen and Rasmus B. Andersen (Mekoprint), 23. October 2012
- Biocult installation with polymer solar cells, first exhibit by Louise Toft (Platform 4) and Rasmus B. Andersen (Mekoprint) in Hjørring followed by 7 other exhibitions in 5 Danish cities, 18. May – 18. August 2012.
- Networking group of companies within sustainable energy from Thy, Denmark visits Mekoprint with focus on polymer solar cells. Presented by Rasmus B. Andersen, 23. August 2011.

Papers in peer reviewed journals

1. **Title:** "Edge sealing for low cost stability enhancement of roll-to-roll processed flexible polymer solar cell modules
   Authors: D. M. Tanenbaum,* H. F. Dam, R. Rösch, M. Jørgensen, H. Hoppe and F. C. Krebs
   Journal: *Sol. Energy Mater. Sol. Cells* (**2012**), *97*, 157-170.
   http://dx.doi.org/10.1016/j.solmat.2011.09.064

2. **Title:** “Interlayer adhesion in roll-to-roll processed flexible inverted polymer solar cells
Authors: S. R. Dupont , M. Oliver , F. C. Krebs and R. H. Dauskardt*
Journal: *Sol. Energy Mater. Sol. Cells* (**2012**), *97*, 171-175.
http://dx.doi.org/10.1016/j.solmat.2011.10.012

3. **Title:** “Application of optical coherence tomography (OCT) as a 3-dimensional imaging technique for roll-to-roll coated polymer solar cells”
Authors: L. Thrane, M. Jørgensen, M. Jørgensen and F. C. Krebs*
Journal: *Sol. Energy Mater. Sol. Cells* (**2012**), *97*, 181-190.
http://dx.doi.org/10.1016/j.solmat.2011.10.004

4. **Title**: **“**Solar cells with 1-day energy pay back for the factories of the future**”**
Authors: Nieves Espinosa, Markus Hösel, Dechan Angmo and Frederik C. Krebs*
Journal: *Energy & Environmental Science* (**2012**), *5*, 5117-5132.
http://dx.doi.org/10.1039/c1ee02728j

5. **Title:** “The ISOS-3 inter-laboratory collaboration focused on the stability of a variety of organic photovoltaic devices”
Authors: David M. Tanenbaum, Martin Hermenau, Eszter Voroshazi, Matthew T. Lloyd, Yulia Galagan, Birger Zimmermann, Markus Hösel, Henrik F. Dam, Mikkel Jørgensen, Suren A. Gevorgyan, Suleyman Kudret, Wouter Maes, Laurence Lutsen, Dirk Vanderzande, Uli Würfel, Ronn Andriessen, Roland Rösch, Harald Hoppe, Gerardo Teran-Escobar, Monica Lira-Cantu, Agnès Rivaton, Gülşah Y. Uzunoğlu, David Germack, Birgitta Andreasen, Morten V. Madsen, Kion Norrman and Frederik C. Krebs*
Journal: *RSC Advances* (**2012**), *2*, 882-893. http://dx.doi.org/10.1039/C1RA00686J

6. **Title:** “Stability of polymer solar cells”
Authors: Mikkel Jørgensen, Kion Norrman, Suren A. Gevorgyan, Thomas Tromholt, Birgitta Andreasen, Frederik C. Krebs*
Journal: *Adv. Mater.* (**2012**), *24*, 580-612. http://dx.doi.org/10.1002/adma.201104187

7. **Title:** “Roll-to-roll fabrication of polymer cell cells”
Authors: Roar Søndergaard, Markus Hösel, Dechan Angmo, Thue T. Larsen-Olsen, Frederik C. Krebs*
Journal: *Mater. Today* (**2012**), *15*, 36-49.
http://www.sciencedirect.com/science/article/pii/S1369702112700196

8. **Title:** “Investigation of the degradation mechanisms of a variety of organic photovoltaic devices by combination of imaging techniques—the ISOS-3 inter-laboratory collaboration”
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