PROJECT FINAL REPORT

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4.1 Final publishable summary report

Basic summary for the general public

Hiflex – New Organic Photovoltaic technology promises flexible, cheaper, on-the-go charging for mobile electronics

A light-weight, flexible organic photovoltaic (OPV) module, which can be used as a standalone charger or integrated with small electronic products such as mobile phones or electronic packaging and labels to give them their own solar energy supply, has been developed by the Hiflex research project. As the OPV module has been developed for mobile and remote applications, it is lightweight, pliable and performs well under different light conditions.
The project - a collaboration between Energy research Centre of the Netherlands (ECN), Fraunhofer Institute for Solar Energy Systems (ISE), TNO / Holst Centre, Technical University of Denmark (DTU), Pera Technology / The UK Materials Technology Research Institute (UK-MatRI), Dr. Schenk and Agfa Gevaert – was supported by the European Commission as part of the FP7 Information and Communication Technologies (ICT) Programme.
The project has overcome a number of the key challenges towards the commercialisation of this technology as the modules are fully roll to roll (R2R) processed, indium free, and demonstrate good outdoor stability.

Jan Kroon from ECN, project coordinator for Hiflex says:
"Our consortium has developed a relatively low cost module which will significantly accelerate the take up of OPV technology in the mobile electronics market and will also find future applications with other products such as leisure and building industries to name but a few."

A key feature of the Hiflex project is the removal of indium tin oxide (ITO) which is used as a transparent conductive layer in other OPVs. ITO is very expensive and there are concerns about future supplies of Indium, so removing ITO has been key to the cost effectiveness and long term viability of the Hiflex technology. In addition, silver has also been removed from the production process of small credit card sized modules, further reducing costs and potential resource supply issues. Overall, the approach also demonstrates significantly lower embedded energy than competing technologies.

To ensure increased process efficiency and performance and to keep costs under control, testing tools have been built into the production process, which analyse the material for any faults. In particular Hiflex partner Dr. Schenk has installed their SolarInspect RollToRoll Metrology System within DTU's (Technical University of Denmark) inline printing and coating system.

Kroon continues: "We've made some technological breakthroughs in OPV development here, without losing sight of the user requirements, both in terms of the film's performance and quality but also regarding production costs, which could limit applications if too high."

The Hiflex consortium held a final dissemination event in Eindhoven in December 2012 to demonstrate the modules and discuss issues around OPV development and commercialisation. As well as attracting other research and technology organisations, the event also attracted a good number of potential end users such as building products and solar canopy manufacturers in addition to mobile electronics producers.

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Executive technical summary

The main aim of HIFLEX was to develop a cost-effective Highly Flexible Printed ITO-free Organic Photovoltaics (OPV) module technology matching the particular requirements of mobile and remote ICT applications, simultaneously delivering the required efficiency under different light conditions, sufficient lifetime, acceptable cost structure, appropriate power-to-weight ratio and fit-to-purpose mechanical flexibility. An application-driven research approach was followed by developing large area, solution processable ITO-free OPV using scalable, reproducible and commercially viable printing and coating techniques enabling the low-cost production of highly flexible and lightweight OPV products.

The work that has been performed in HIFLEX varied from designing and fabricating various ITO-free device architectures using optimized electrodes based on printed current collecting metal grids and highly conductive PEDOTs, development of fabrication technologies for optimal S2S and R2R processing of OPV, electrical modelling to design optimal cell and module structures for ITO-free device concepts and experimental validation, evaluation of large area characterization methods for process control, stability testing, life cycle and cost assessment and market evaluation studies

The consortium consisted of two companies and five research organizations. The companies were: Dr Schenk GmbH, an SME with valuable expertise in the inline process and quality control of Roll-to-Roll processed thin film PV and Agfa-Gevaert with market-tested experience on photographic development of silver grid lines, polymeric antistatic coatings and large scale coating as well as on developing innovative coating solutions. The five research organizations comprise: Energy research Centre of the Netherlands (ECN), Fraunhofer Institute for Solar Energy Systems (ISE), Risø National Laboratory for Sustainable Energy (Risø DTU), TNO/Holst Centre, and UK Materials Technology Research Institute (MaTRI). They all have a technology development and market implementation focus with complementary expertise in the field of device and module engineering, up-scaling and large area printing, and long-term lifetime testing.

The combined efforts of the consortium have led to a number of important achievements that will form an essential basis for creating an economically accessible and widely applicable OPV technology for a range of future applications:

- An extensive performance evaluation of five different ITO free device concepts has been performed in terms of efficiency and lifetime. Power conversion efficiencies measured at STC, range between 1 and 2.5 % for the different ITO free device concepts using P3HT:C60-PCBM as the photoactive layer. Continuous light soaking tests were carried out at different illumination intensities (0.1-1 sun) and at various temperatures (From 25 to 85^{o}C). These lifetime tests reveal some ITO free device concepts are more stable compared to ITO based polymer solar cells aged under identical conditions.This evaluation formed the basis of a selection of most promising concepts to be investigated on a S2S and R2R processing platform
- Alternative ITO free inverted S2S processed modules with evaporated electrodes achieved 2.2% aperture area efficiency using P3HT:PCBM as the absorber material, implying > 70% of small cell efficiency.
- OPV Modules down to 12 µm substrate thickness can be manufactured both on S2S and R2R scale without considerable loss in performance
- Very good efficiencies up to 6 % under low, fluorescent light conditions have been achieved for selected ITO free OPV based designs based on P3HT:PCBM.
- A successful translation of an ITO free device architecture to a R2R platform has lead to the first flexible, all solution processed ITO free OPV modules produced by full R2R coating and printing processes with sizes more than 100 cm^2 and aperture area efficiencies > 1% using P3HT:PCBM as the photoactive system.
- Excellent stabilities of encapsulated modules under various indoor accelerated and outdoor lifetime testing conditions have been demonstrated.
- First successful demonstration of an optical inspection tool integrated in a R2R OPV processing line for process and quality control
- Product oriented LCA and CoO assessment showing the cost potential and promising environmental profile of ITO free OPV
- An extensive report has been produced which describes the work performed to investigate product integration requirements and the market readiness of the HIFLEX technology for certain ICT applications.

- A successful final dissemination event was organized in conjunction with the ISOS series. Over 70 people attended the event from universities, research technology organizations, OPV product developers and manufacturers, materials suppliers, manufacturing and test equipment suppliers and prospective end users.
- 250 CE labeled functional credit card sized laser pointers have been manufactured using ITO free OPV modules as the final demonstrator of the project

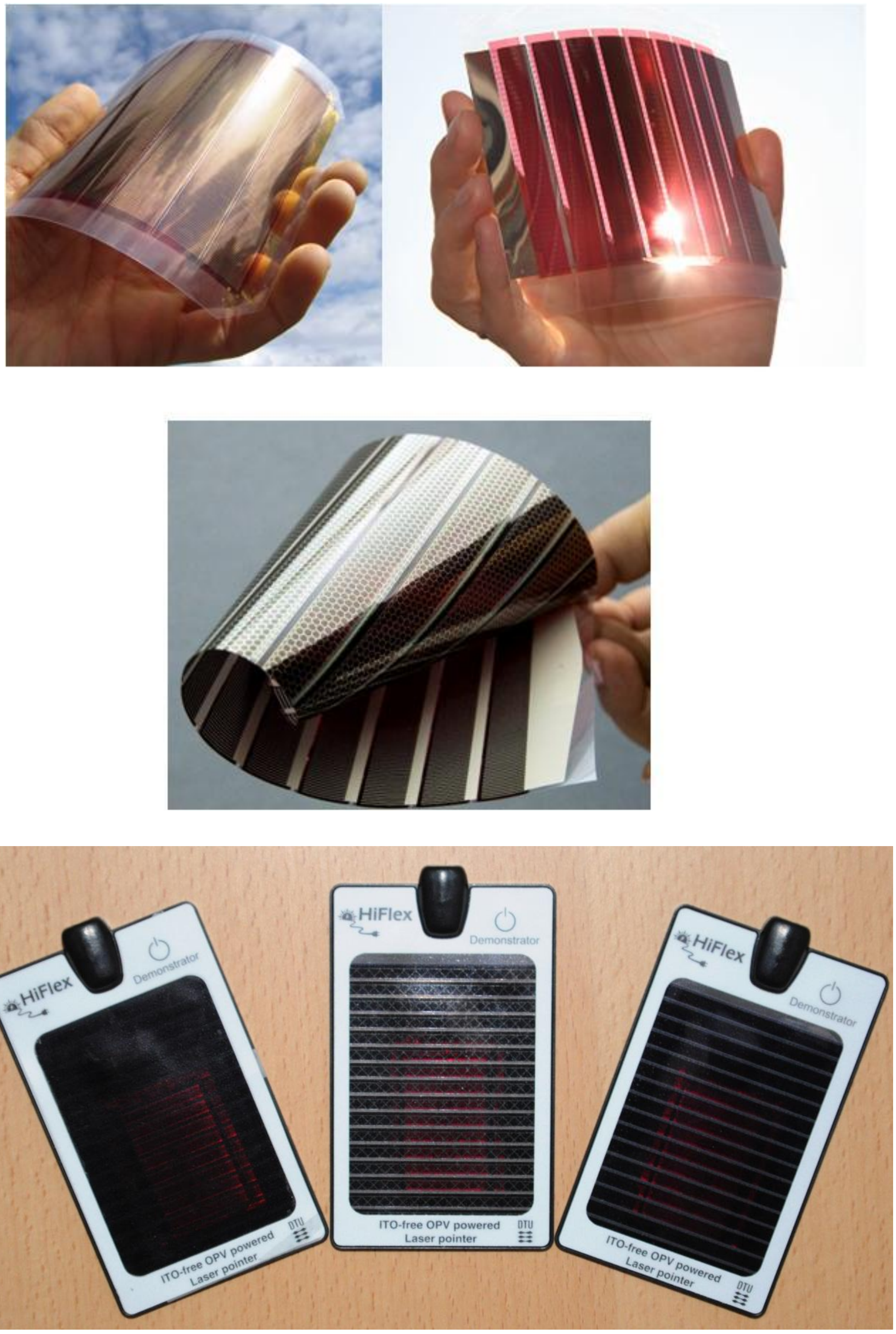


Figure 1 *Pictures of S2S processed (Top) and R2R processed ITO free modules (middle) and three variants of ITO free powered laserpointer demonstrators*

A summary description of project context and objectives

The main aim of HIFLEX was to develop an Organic Photovoltaic (OPV) module technology that matches the particular requirements of mobile and remote ICT applications. Existing "grid-dependent" and future energy autonomous ICT applications cover a broad range of products. These are "classical" applications such as: PDAs, laptops and mobile phones, but also future applications like wireless sensor networks, e-labels, e-packaging, e-posters, smart blisters and smart bandages. Most of these applications will have low power consumption and may be based on printed electronics in the future. Their usage would be more versatile and have a high degree of comfort if they could be self-supporting in their energy supply and thus the benefits gained through integration of OPV modules would be obvious.

In order to construct an energy autonomous system powered by light energy, the implemented solar cell technology has to fulfil certain requirements. The primary but not the sole requirements that a solar cell technology has to fulfil in order to contribute to an added value of the product are:

- **Power-to-weight ratio and power conversion efficiency:** A high power-to-weight ratio is in particular required for mobile ICT applications with a reasonable power demand. Because of the extremely thin photoactive layers (100-300 nm thickness), OPV has a high potential to outperform their inorganic counterparts in this characteristic even with state-of-the-art power conversion efficiencies. Nevertheless, high power conversion efficiency is of significant importance because only small surface areas are available for powering mobile ICT products or short loading times are required. Also for large scale power generation this is particularly addressed within research projects aiming at on-grid applications. According to present roadmaps, it is recognized that for on-grid applications for residential use, module efficiencies of over 10 % are required.

- **Lifetime:** The lifetime of mobile ICT products generally range from ~1-5 years and this also has to be covered by the OPV module if it is integrated in such a product. The stability of the performance for an OPV module is based on interplay between intrinsic properties of the materials used, i.e. stability (chemical and physical) of photoactive layers and interfaces, contacts between electrode and the nanophases, and finally the protection against ingress of water and oxygen. Light, storage at elevated temperatures, temperature cycling, fast temperature change (indoor/outdoor) and also bending are the most typical stress factors that will influence the final lifetime of a flexible PV product. One of the important challenges in this research field is to define a test protocol that leads to a justified extrapolation towards the typical lifetimes of an ICT product by taking the specific aforementioned stress conditions into account.

- **Costs:** The cost criteria are very demanding when the focus is to replace power stations with less than 1 Euro per Watt peak (Wp) for "energy parity". However with energy harvesting for small consumer electronics devices, figures of up to ten times as much are very acceptable because one is willing to pay for avoiding inconvenient wiring from battery chargers or the burden of visiting millions of installed batteries to replace them. Also the convenience of being mobile with the specific ICT application is of great value to users who consequently are prepared to pay significantly for this convenience.

Next to the key requirements mentioned above that basically address the feeling of satisfaction of consumers of mobile ICT applications there are additional but mandatory requirements of a more technical nature that are very important for successful integration of OPV modules in mobile ICT applications:

- **Mechanical flexibility**: A high mechanical flexibility is required that allows the implementation of tightly rollable PV modules or modules that can be integrated in mobile ICT applications with curved exterior design (rollable powerfoils for ease of storage). From a technical point of view a serious limitation for current flexible or bendable inorganic PV modules is the brittle transparent conducting oxide, e.g. ITO which only allows large curvatures or has a low resistance against fatigue (repeated bending and unbending).

- **Ambient light efficiency:** Mobile ICT applications are often operated indoors under artificial light conditions or indirect sunlight. Efficient energy harvesting is required under these conditions to extend the operational time of the mobile device that is powered. Fortunately in contrary to most crystalline silicon solar cells, OPV devices exhibit excellent characteristics for low light illumination conditions.

- **Module design**: It is very likely that the large number of different types of mobile ICT applications requires a specific module design with respect to the required output voltage and current, but has also to be integrated in the ICT device under consideration of ergonomic and design aspects. This means that module concepts must be very versatile, design tools must be available to easily make fit-to-purpose module design and manufacturing technologies very flexible in producing different kinds of modules.

- **Technological compatibility:** The vision of energy autonomous all-organic electronic systems appears very attractive. Therefore the use of a single printing and coating technology for the circuitry, as well as for the photovoltaic module will enable the low-cost production of flexible energy autonomous mobile ICT systems.

The OPV technology that was developed within HIFLEX aimed at covering all the above mentioned requirements at the same time by achieving "Highly Flexible Printed ITO-free OPV Modules" HIFLEX – OPV Module.

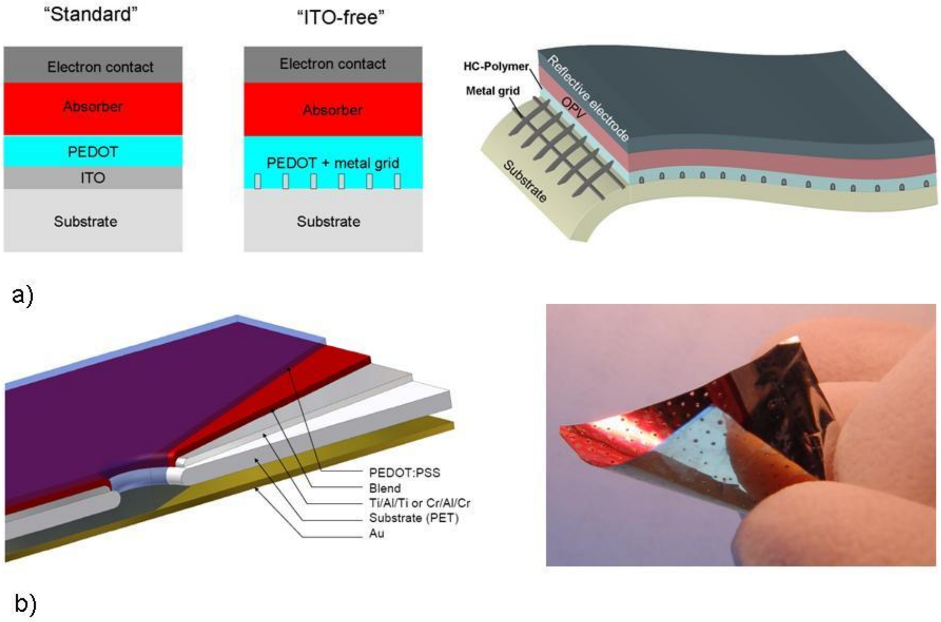
The unique thin film thicknesses employed in OPV devices (in the order of a few tens or hundreds of nanometres) are one prerequisite to achieve the high flexibility and high power-to-weight ratio. However highly mechanically stable electrodes and barrier layers, as well as higher power conversion efficiencies need to be reached to make OPV modules fit to mobile ICT applications and thus solutions and improvements for this determined the science and technology focus within this project.

The aspired roll-to-roll production of OPV modules by printing and coating techniques is one requirement to enable **low-cost** production of **flexible** and **lightweight** photovoltaic modules. At the same time it guarantees the technological compatibility with other printed electronic components and systems. The high flexibility and lower costs will be addressed by the **solar cell module design**. In "standard" OPV device configurations, the photoactive layer or absorber is sandwiched between two electrodes of which one is usually a transparent indium tin oxide (ITO) ITO, especaily on plastic foils, is known to be a significant cost determining factor in current OPV devices and at the same time too brittle to allow tight rolling of PV-modules or integration in strongly curved products.

In HIFLEX, <u>an application-driven research</u> approach was followed by investigating two key technologies as a starting point enabling the manufacturing of ITO-free solar cell modules by roll-to-roll production:

1) A solar cell structure containing a transparent polymer anode PEDOT:PSS, supported by a printed metal grid instead of ITO

2) A wrap through solar cell device architecture with an inverted layer sequence compared to a regular cell structure. This enables a module geometry where both contacts are at the same surface side of the module



1. *Schematic picture of a "standard" ITO based OPV device configuration (left) and an ITO-free OPV device containing a transparent polymer hole contact supported by metal grid (middle and right). PEDOT acts as a transparent polymer hole contact*
2. *Left: Cross-section of an ITO free wrap through solar cell. Right: Demonstration sample of a wrap through solar cell containing 200 perforated holes (courtesy of ISE).*

The partnership consisted of four well known research institutes in the field of PV and Organic Electronics (ECN, ISE, DTU, Holst) with a technology development and market implementation focus and with complementary expertise in the fields of device engineering, module fabrication, up-scaling and large area printing and long-term testing of OPV. The fifth research institute, MatRI, brought significant materials development expertise in barrier layers and polymer processing as well as extensive experience of technical delivery and management in collaborative research projects on a national and European level, enabling effective dissemination of project outputs and, through industrial support, effective and suitable protection of technology and ensuring commercialisation of products and processes. The industrial participants are one SME (Dr Schenk) and one large enterprise (Agfa). Dr. Schenk has invaluable expertise in the inline process and quality control of R2R processed PV. AGFA contributed to HIFLEX with a "large industry" perspective, with market tested experience on photographic development of Ag grid lines, PEDOT antistatic coatings and large scale coating as well as developing innovative coating solutions.

The general objective of HIFLEX was to develop cost-effective **Highly Flexible Printed ITO-free OPV modules that match the requirements of mobile and remote ICT applications** in terms of good efficiency under different light conditions, sufficient lifetime, acceptable cost structure, appropriate power-to-weight ratio and fit-to-purpose mechanical flexibility.

In order to reach these targets, an effective experimental platform was established from lab-scale device fabrication to Sheet-to-Sheet (S2S) as an intermediate step towards Roll-to-Roll (R2R) processing of OPV modules. The HIFLEX consortium performed their activities according to the following workpackage structure:

WP1: Cell development (**R**<u>esearch line</u>)
WP2: Module Engineering and prototypes (**R&D** line)
WP3: Envelope (substrate/encapsulation) development
WP4: Upscaling and Large Area printing (**D**<u>evelopment</u> line)
WP5: Implementation
WP6: Dissemination and exploitation
WP7: Consortium management

The R&D activities in the **WP 1, 2** and **4** were strongly interrelated and followed a logical approach to bring the ITO free device concepts from Lab to Fab. A separate work package (**WP3**) was dedicated to the development of highly conductive ITO free substrates and encapsulation methods to serve as input for the activities in the aforementioned WPs. In order to prove the robustness of the developed OPV technology accelerated indoor testing as well as field testing under realistic test conditions were done in **WP3**.

The technical activities were supported by activities related to future introduction of OPV in the market place such as standardization, life cycle analysis including the environmental impact and an identification of the cost structure with an analysis of the raw material costs (**WP5**). **WP6** ensured the successful dissemination and exploitation of the project results by developing and implementing an agreed dissemination and exploitation plan. **WP7** ensured effective management and coordination of all the consortium, legal aspects and other issues in the project as well as effective communication with the EU commission.

A graphical presentation of the work packages showing their interdependencies is shown in the Figure below.

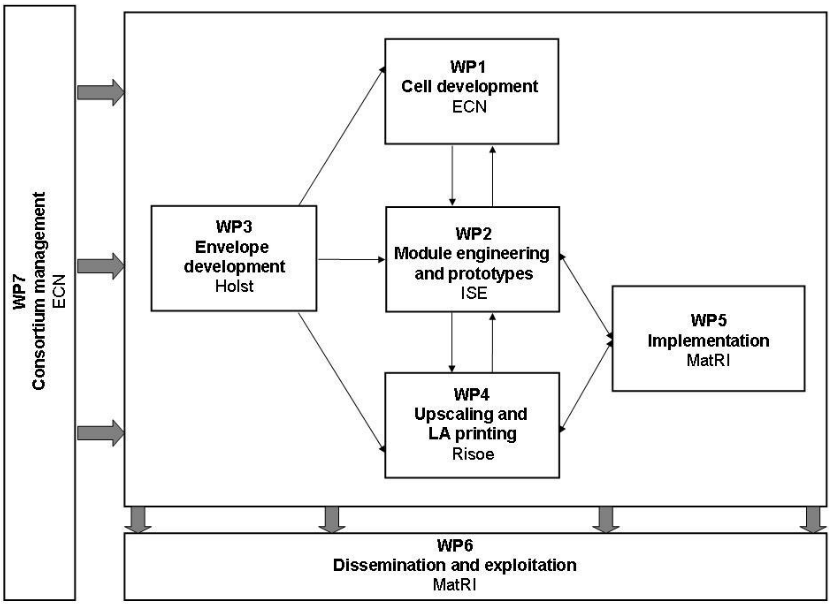


Figure 2 *Project structure showing the interdependencies between the work packages*

A description of the main S&T results/foregrounds

In this part the main achievements of HIFLEX are summarized per Workpackage. A lot of these achievement have been disseminated via scientific publications which can be found in Section A1 of this report.

WP1: Cell development (Research line)

Objectives

- Assess ITO-free, R2R compatible cell concepts; transfer these concepts to the R&D (WP2) and D-line (WP4).
- Determine the photovoltaic performance and intrinsic stability of 'standard' polymer solar cells (as defined in figure 1a) as benchmark for polymer solar cells based on:
  - novel, state-of-the art, commercially available material combinations (from Plextronics and other relevant material providers)
  - ink formulations and deposition methods used in WP2 and WP4,
  - ITO-free device concepts developed in WP1.
- Characterize devices under standard test conditions as well as conditions relevant for mobile ICT applications (determined in WP5).

Solar cells often consist of a light absorbing layer sandwiched between two electrodes. At least one of these electrodes should be semi-transparent to transmit the light to the light absorbing layer. In polymer solar cells one often uses indium-tin-oxide (ITO) as semitransparent electrode. Figure 3 shows two device structures which are commonly used for polymer solar cells. For historical reasons, one device structure is called the standard device configuration (figure 3, left), the other the inverted device configuration (figure 3, right).

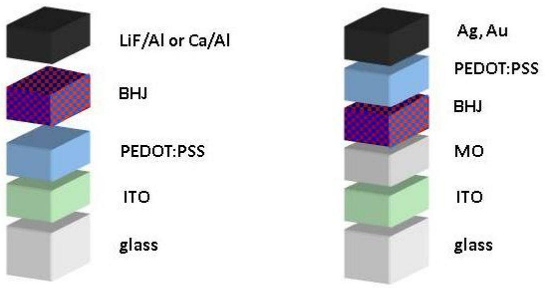


Figure 3 *Schematic representations of typical device structure used for polymer solar cells. The structure on the left gives a device architecture which is often referred to as the standard device configuration; the layer sequence shown on the right represents the inverted device structure for polymer solar cells. See text for further details.*

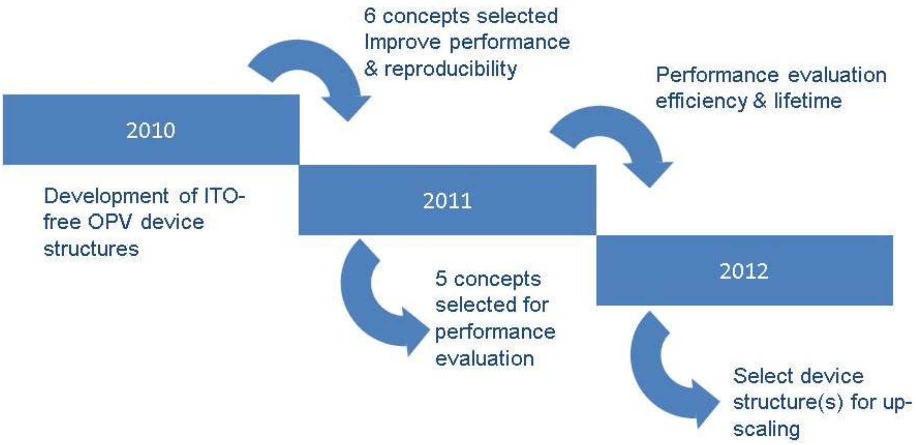
For research purposes, the substrate is typically a glass plate. The glass plate is (partially) covered with the transparent electrode, here ITO. Next, the ITO is either coated with a conductive polymer (PEDOT:PSS) or by a metaloxide (MO) such as ZnO or TiO_2. In the standard device configuration PEDOT:PSS is used. This layer is then covered by the bulk heterojunction (BHJ); followed by a counter electrode formed by for instance LiF (~1 nm) and Al (~100 nm).

The BHJ layer acts as the light absorbing and charge generating layer. In polymer solar cells, the bulk heterojunction is formed by donor and acceptor components. For the results reported here, poly(3-hexylthiophene) (P3HT) was used as donor and [6,6]-Phenyl-C_{61}-butyricacid-methyl-ester ([C60]PCBM) as acceptor unless otherwise stated. The components are mixed on the nanometer scale to form a network of donor-acceptor heterojunctions: light is absorbed throughout the BHJ, which leads to excited states called excitons. The excitons dissociate efficiently in holes and electrons at the donor-acceptor heterojunction. After this charge separation process, the generated charges travel to the electrodes: holes through the donor material to the PEDOT:PSS/ITO electrode and electrons through the acceptor component to the LiF/Al electrode. Here PEDOT:PSS makes a good electrical contact to the donor to collect the holes from the BHJ and, at the same time, it blocks electrons. The counter electrode (i.e. LiF/Al, Ca/Al) forms a good contact to the BHJ to (only) collect the electrons from the acceptor component of the blend. As a result, upon illumination, the ITO electrode becomes positively charged and the Al electrode negatively charged.

In an inverted device structure, the polarity is reversed. Between the BHJ and the ITO layer there is a metaloxide layer such as ZnO or TiO_2. These metaloxides form a good contact to collect electrons from the acceptor component while blocking holes from the donor material. In this device structure, the ITO because negatively charged and the metal counter electrode (Ag, Au) positively charged. In other words, compared to the standard device structure, the polarity is inverted which explains the name of this device configuration.

As explained and motivated in the introduction of this public report, one of the main objectives of HIFLEX is to demonstrate scalable, low cost, solution processed polymer solar cells. In order to reach these objectives, it is important to replace the ITO layer. Therefore, the task for work package one (WP1) is to develop scalable, low-cost and ITO-free device concepts. These concepts were further developed to enable an evaluation for use in mobile ICT applications. Based on the evaluation, device structures were selected for further up scaling in work packages two and four. Scheme 1 gives a schematic representation of the activities to develop and evaluate the developed device structures.

Originally, one of the objectives in WP1 was to achieve a high efficiency (>7%) ITO benchmark lab device. Despite the fact that 6.5 % was already obtained, it was decided to abandon this specific task, since this was not the main scope of HIFLEX and it was considered to be more important to focus the efforts to the upscaling of the ITO-free device concepts towards Sheet-to-sheet and Roll-to-roll scale.



Scheme 1 *Schematic representations of activities to develop and select scalable, low-cost and ITO-free device concepts for further up scaling in work packages two and four.*

At the end of 2010 six concepts were developed in the **R**esearch line. From these concepts, five device structures were sufficiently reproducible, efficient and stable to be part of the performance evaluation. These device structures are presented in figure 4.

Roughly two routes towards ITO-free devices are followed. In the first device concept, ITO is replaced by a high conductive PEDOT:PSS layer, combined with a metal grid, typically Ag (ALCR, AGNP, NORM and ASP). The second route makes use of the so-called wrap through device structure. In this device structure, both electrodes of the device are contacted at the back of the device. To make this possible, holes are made through the device. The hole is electrically insulated from the back contact. The top electrode (high conductive PEDOT:PSS) is electrically connected to the backside of the device through the hole, also called 'via'. Since the holes can be placed close together (roughly at a similar distance as the finger spacing in a grid based device), the need for a metal grid is alleviated (WT).

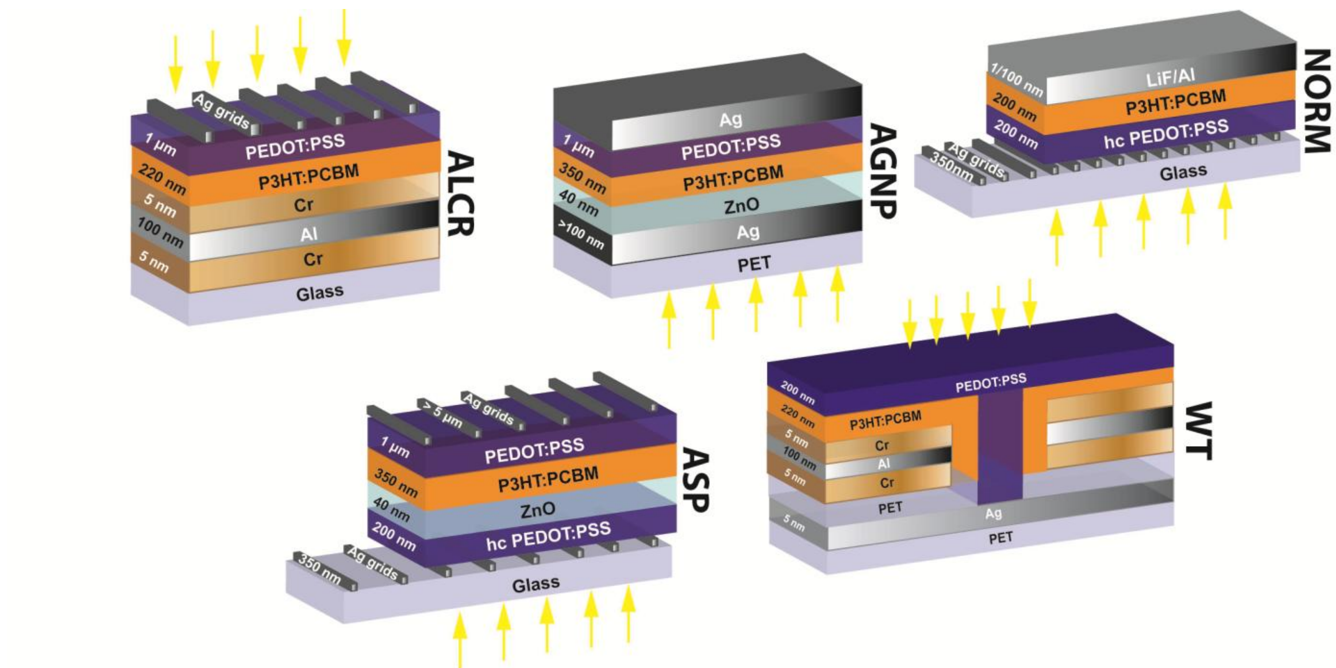
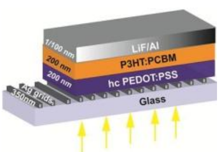
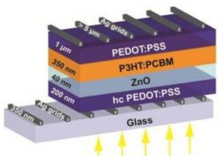
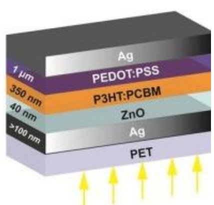
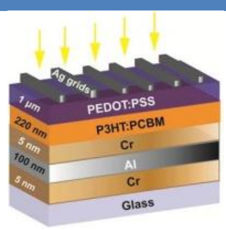
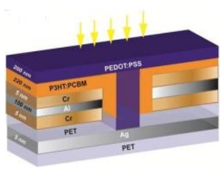


Figure 4 *Schematic representations of the five device concepts which were selected for the performance evaluation. The yellow arrows indicate from which side the devices are illuminated.*

For the performance evaluation, the power conversion efficiency (PCE) was determined both under standard test conditions (STC: AM1.5, 100 mW/cm^2, at 25 ^{o}C) denoted in table 1 as 'outdoor'. Under indoor conditions, the illumination conditions may differ substantially from the standard test conditions as both the intensity of the light and the spectrum over the light differs. For the evaluation, the indoor power conversion was determined using fluorescent light tubes. When the polymer solar cells were illuminated, the short circuit current-density was roughly 1/10 of the value measured under STC.

The lifetime of the different device concepts was assessed by aging the devices under various conditions. The results are summarized in table 1. Outdoor lifetime refers here to illuminating the device continuously with 0.7 sun at 65 ^{o}C. It is noted that the lamp spectrum of the lamp used for the stability test ranged from the IR to the UV part. For indoor conditions, the samples were illuminated under 0.1 sun at room temperature. The results were compared to inverted, ITO based reference devices. A minus sign in table 1 indicates the ITO free cell concept performs not as good as the ITO based reference device; a + sign indicates the stability is similar as the ITO based reference and ++ is used when the lifetime was significantly improved. It is noted that no degradation was detected under indoor conditions during the 1000 hours of the experiment. All samples for lifetime testing were encapsulated in the same way using a glue and glass plate. Finally, additional criteria were added in the evaluation and added to table 1 such as the possibility to process the device using printing and coating techniques (printability); whether vacuum steps are required during sample preparation (vacuum free); whether the substrate was flexible or rigid.

Device description	NORM	ASP	AGNP	ALCR	WT
Schematic representation					
Active area of cell (cm^2)	1	1	1	1	2.1

PCE (outdoor) [%]	**2.0**	**1.6**	**1.0**	**2.5**	**1**
PCE (indoor) [%]	**2.0**	**2.0**	**1.1**	**2.5**	**1**
Lifetime (outdoor)	**--**	**-**	**++**	**+**	**n.a.**
Lifetime (indoor)	**+**	**+**	**+**	**+**	**n.a.**
Printability	**-**	**+**	**+**	**-**	**-**
Vacuum free	**-**	**y**	**y**	**n**	**n**
Flex. substrate	**n**	**n**	**y**	**n**	**y**

Table 1. *Overview of the performance evaluation on ITO free device concepts. PCE outdoor: 1 sun AM1.5 STC; PCE indoor: fluorescent light tubes measured currents were approximately 1/10 of the currents measured under outdoor conditions; lifetime outdoor: (65 ^oC, 0.65 sun); lifetime indoor: 25 ^oC, 0.1 sun)*

Based on the data described in table 1, there is no clear winner that shows high performance and high stability. The ALCR device type shows good performance. In fact, the average performance of a large number of ALCR devices is very similar (93 %) to the average performance of similarly processed ITO based reference devices. The AGNP device shows the best stability results but the lowest PCE score. The ASP architecture is intermediate in performance and shows somewhat lower lifetime compared to the AGNP device type. The NORM device concept lacks stability which is attributed to the easily oxidized electrode LiF/Al. The WT device was not part of the lifetime evaluation due to processing difficulties. Therefore the choice for up scaling is among ALCR, AGNP and ASP. The choice among these three concepts to up-scaling also depends on material and processing advantages and disadvantages for each of the architectures from the point of view of up scaling via facile and fast low cost R2R processing as well as a good match with ICT applications. For example, the ALCR device requires several vacuum processing steps in processing. On the other hand, the ASP and AGNP architectures in principle do not require vacuum processing and can both be all printed/coated. Concerning indoor ICT applications, the ALCR concept reveals excellent performance under low light levels as reported in work package 2. Finally it was decided to select the ASP and ALCR device architectures for further up scaling in work packages two and four.

In conclusion, it has been demonstrated that:

- 5 ITO-free OPV device concepts have been developed and evaluated
- The performance of these concepts may be up to 93 % (ALCR, on average) of the average performance of ITO based reference devices)
- The stability of the 5 ITO-free device concepts under indoor conditions is good: no significant performance changes were observed in 1000 hrs.
- The stability of 2 of ITO-free device concepts (AGNP and ALCR) under more stringent conditions here referred to as outdoor can be as good or better compared to the stability of ITO based reference devices

WP2: Module Engineering and prototypes (R&D line)

Objectives

- Design and S2S development of OPV modules that match the electrical and design requirements of specific ICT applications
- To minimize the loss in power conversion efficiency from laboratory single cells to larger area OPV modules
- To achieve high efficiencies under all light conditions
- Evaluation of large area characterization methods
- Transfer results to Development line (WP4)

Within the R&D line, coating and printing technologies were used which are compatible with a Roll-to-Roll process to assure the transferability to the Development line of the different ITO-free module concepts. The organic semiconductors and electrodes were applied by inkjet printing and slot-die coating while metal fingers were printed with inkjet-, screen and aerosol printing. In several module concepts for full area metallization vacuum evaporation was used as this is an established and extremely fast and cheap process in packaging industry.

In total, four different concepts have been evaluated in this WP during the whole project (See Figure 1 for the schematic device layouts):

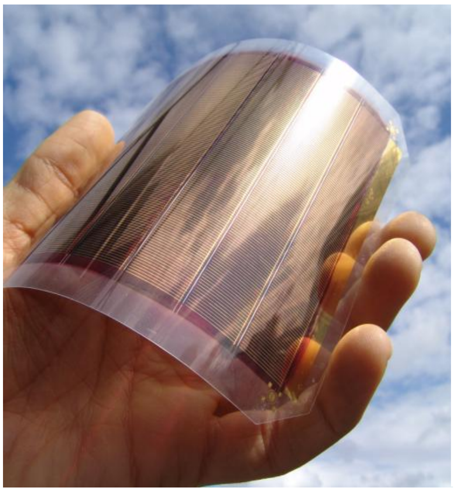
ALCR: this concept is based on a metalized foil to which the organic layers are applied. The ITO-replacement is formed by a transparent conductive organic electrode combined with a metal grid on top (top illumination). This concept was finally selected as the main workhorse to achieve the key deliverables of the project

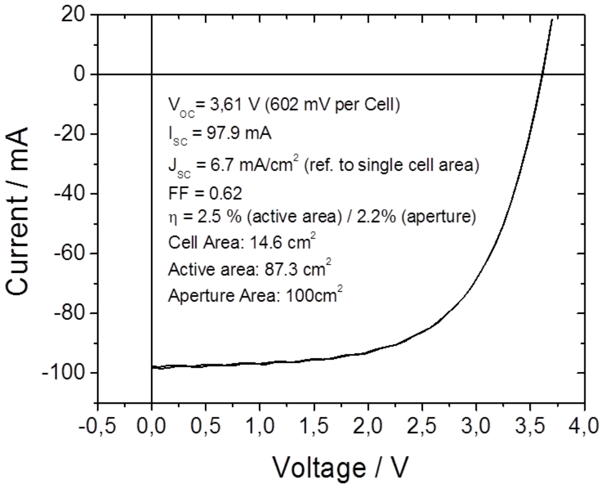
NORM: uses the same ITO replacement but as bottom electrode, while the top contact is formed by metal evaporation (bottom illumination).

ASP without metal grids. It makes use of two organic transparent electrodes (PEDOT and Zn)) and an additional metal oxide layer as electron transport layer. In principle these devices can be built without additional metal grids but for outdoor use these grids are needed for efficient charge carrier collection.

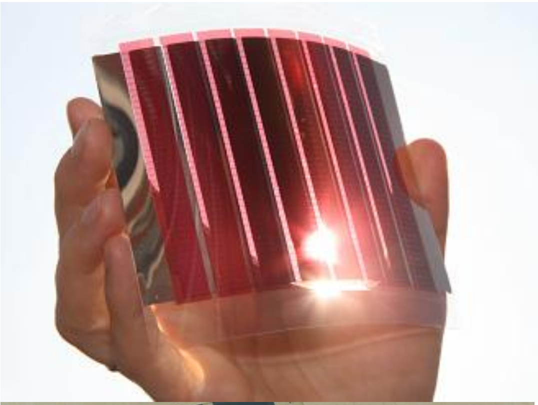
WT is based on **ALCR** with the difference that the grid is replaced by a pattern of vias which guide the current from the top transparent organic electrode to a metallized backsheet. This concept has the advantage of decreased area loss due to point contacts instead of grid lines and could furthermore be realized using only very cheap metalized foils and no printed silver.

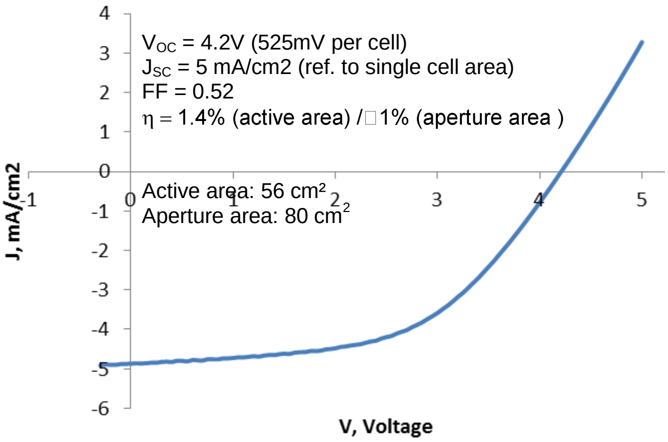
In Figure 5, pictures and Current-Voltage (I-V) characteristics are shown for representative S2S modules made in the project.



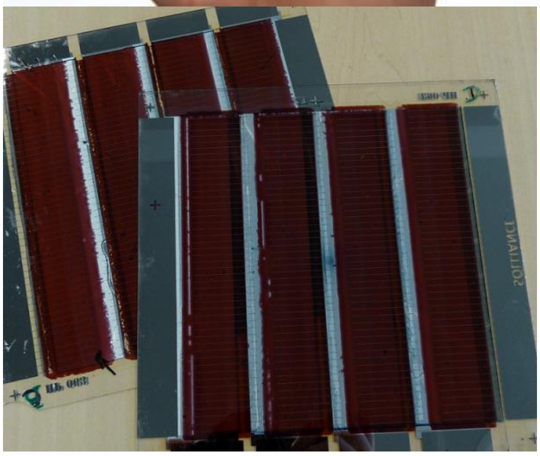


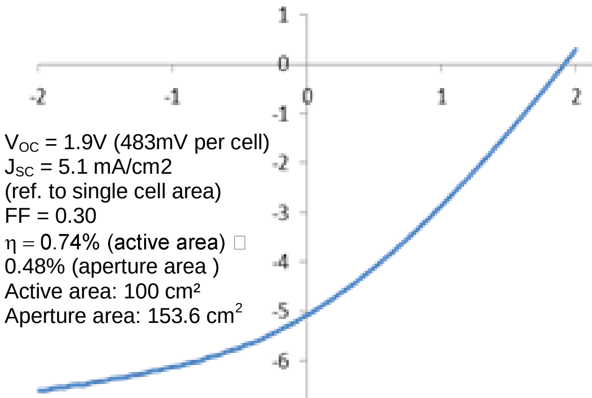
V_{oc} = 3,61 V (602 mV per Cell)
I_{sc} = 97.9 mA
J_{sc} = 6.7 mA/cm^2 (ref. to single cell area)
FF = 0.62
η = 2.5 % (active area) / 2.2% (aperture)
Cell Area: 14.6 cm^2
Active area: 87.3 cm^2
Aperture Area: 100cm^2
Current / mA
Voltage / V
20 0 -20 -40 -60 -80 -100
-0,5 0,0 0,5 1,0 1,5 2,0 2,5 3,0 3,5 4,0



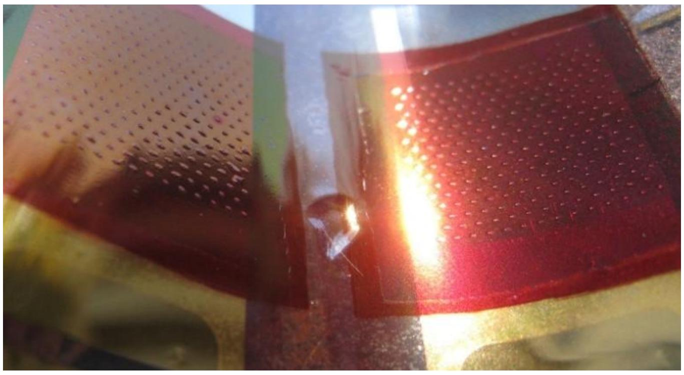


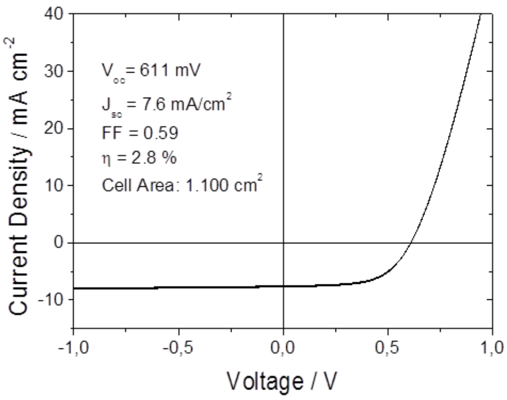
V_{OC} = 4.2V (525mV per cell)
J_{SC} = 5 mA/cm2 (ref. to single cell area)
FF = 0.52
η = 1.4% (active area) /□1% (aperture area)
Active area: 56 cm²
Aperture area: 80 cm^2
J, mA/cm2
V, Voltage
4 3 2 1 0 -1 -2 -3 -4 -5 -6
-1 0 1 2 3 4 5





V_{OC} = 1.9V (483mV per cell)
J_{SC} = 5.1 mA/cm2
(ref. to single cell area)
FF = 0.30
η = 0.74% (active area) □
0.48% (aperture area)
Active area: 100 cm²
Aperture area: 153.6 cm^2
1 0 -1 -2 -3 -4 -5 -6
-2 -1 0 1 2





V_{oc} = 611 mV
J_{sc} = 7.6 mA/cm^2
FF = 0.59
η = 2.8 %
Cell Area: 1.100 cm^2
Current Density / mA cm^{-2}
Voltage / V
40 30 20 10 0 -10
-1,0 -0,5 0,0 0,5 1,0

Figure 5 Photos (left) and JV-curves (right) of the different Sheet-to-Sheet processed modules. ALCR has given the best efficiencies while ASP has a high potential for cost reduction and low environmental impact. Both were transferred to the Roll-to-Roll Development line. The WT concept has reached a very high efficiency on cell level (S2S process) after extensive optimization but was not up-scaled within the project due to reproducibility issues.

The layout of the modules was based on numerical optimization of the tradeoff between area loss due to metal grid fingers and serial interconnections. A model was developed which accounts for the tradeoff between conductivity and transparency of the transparent electrode to find the global optimum for a given module concept. As one outcome for specific ICT applications where only or mainly low intensity indoor light is expected, the use of a single polymeric transparent electrode without metal grid offers a simple and low cost option for the module. If sunlight shall be harvested efficiently, the use of a metal grid to support the conductivity of the organic electrode is mandatory.

For an optimized design an efficiency of the module of 2.2% was achieved using the standard workhorse materials P3HT:PCBM as the photoactive blend which corresponds to more than 73% of the efficiency of a small single cell with the same device architecture (3%). With this result the self-set goal of 60% was overachieved considerably and the gap from small cell efficiency to module efficiency was closed significantly. As 87% of the module area was photoactive in this case, there is still potential for higher efficiencies if the processing of the layers is further optimized.

As the modules were designed for the use in mobile ICT applications, where devices are used in- and outdoors, the efficiency was not only determined for sunlight illumination but also under fluorescent indoor-lighting conditions with low intensity. Under these conditions the efficiency is higher by a factor of more than two, because the sensitivity of the organic semiconductors used here (P3HT:PCBM) matches exactly with the human eye sensitivity to which modern artificial light sources are optimized. For ITO-free devices, efficiencies of about 6% were obtained and the module retains more than 80% of the small cell open circuit voltage. The indoor efficiency of the module is limited by local defects (shunts) to about 3%. With new organic semiconductors ca. 10% efficiency could be obtained under indoor light.

One major challenge for the fabrication of large area modules is the local variation of coating quality and defects due to contamination e.g. with dust particles. Furthermore the preparation of a module involves structured features where different layers end or overlap, potentially introducing defects at edges. To analyze such defects imaging methods were evaluated. Light Beam Induced Current (LBIC) gives insight into the homogeneity of current generation, Dark Lock-In Thermography (DLIT) helps to localize shunts and Electro-Luminescence Imaging (ELI) gives insight into local voltage and excess recombination.

Two architectures were finally transferred to the Development line (see WP4), the **ALCR** and **ASP** with additional Ag grids on the bottom and top. While the efficiency of the Roll-to-Roll processed **ALCR** modules lags significantly behind the R&D results up to now, the ASP devices were successfully upscaled to the Roll-to-Roll Development line with even higher efficiency than in the R&D line (see WP4).

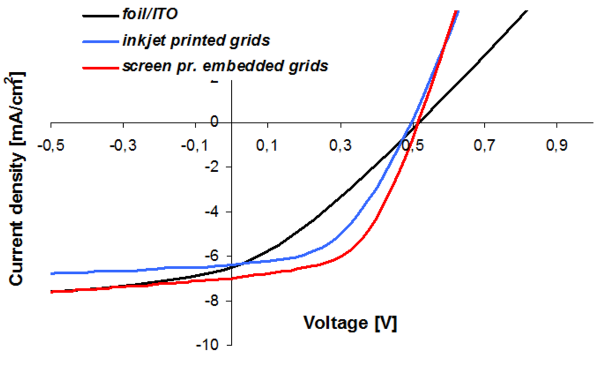
WP3 Envelope (substrate/encapsulation) development

Objectives

- To develop low cost, printable, highly conductive transparent patterned electrodes based on a metal grid in combination with a polymer anode with low sheet resistance and high transparency
- Evaluation of existing and exploration of novel barrier technologies suitable for OPV
- Long term stability (in-and outdoor) testing of encapsulated modules of different designs. Understanding of stability determining factors for cells and modules

Development of low cost, low resistance ITO-free substrates

Indium tin oxide (ITO) is commonly used as transparent conducting electrode in OPV. However, the high price of indium in combination with the relatively low conductivity of ITO on flexible substrates (60 Ω/□) creates a need for finding an alternative transparent electrode. The alternative electrode investigated in HIFLEX contains semiconducting material poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT:PSS) in combination with printed current collecting metal grids. Current collecting grids are either inkjet printed or screen printed. Inkjet printed current collecting grids have an average height of 300 nm and provide sheet resistance in the range of 5-15 Ohm/sq (depends on the cross section of the grids and sintering condition of the Ag). A further improvement of the performance of the electrode is possible by further increasing of the amount of metal in the current collecting grids. However, an increasing amount of metal in ink-jet printed current collecting grids will automatically increase the height of the grids. Furthermore, the processing yield of OPV devices with printed current collecting grids with a height of > 600 nm decreases rapidly. The only way to overcome this problem is to embed the grid lines into the substrate. This approach was demonstrated where 2 µm high screen printed gridlines with a sheet resistance of 1 Ohm/sq were embedded into the substrate. Applying this method here to ITO-free devices with screen printed embedded current collecting grids leads to an improvement of the efficiency compared to that of ITO-free cell. Typical Current-Voltage characteristics of similar sized (2 x 2 cm^2) flexible ITO and ITO-free devices with inkjet and screen printed current collecting grids are shown in Figure 1 and clearly shows the higher Fill Factor obtained for the ITO free devices compared to the highly resistive ITO based cells.



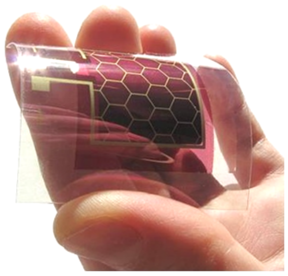


Figure 6 *JV-curves of flexible 2x2 cm^2 devices with ITO and ITO-free electrodes.*

The effect of grid line density was explored for a large series of devices and present a careful modeling study enabling the identification of the most rational grid structure. The spacing between the grids lines were varied between 1 and 20 mm. Both experimental and theoretical results of the relationship between grid spacing and efficiency of polymer solar cells with different grid structures are shown in Figure 7.

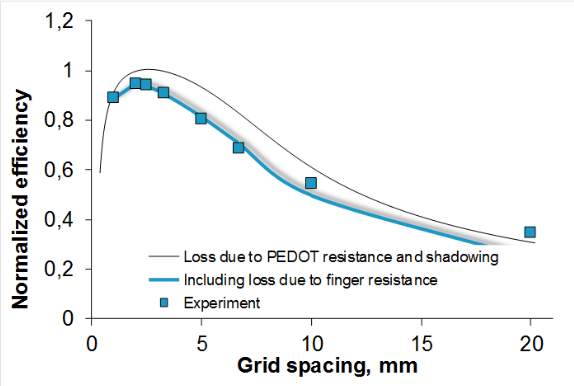


Figure 7 *Experimental and calculated efficiencies for grid based devices with. The grey lines account for the Ohmic loss in the PEDOT layer and the optical loss due to shadowing by the gridlines, but not for the Ohmic loss in the grid lines.*

The theoretical modelling accounts for resistive losses due to PEDOT:PSS, grid series resistance and shadow losses. Experimental results illustrate very good match with theoretical calculations. The optimal grid spacing for the different types of the grids was in a range of 2-2.5 mm.

The next question which comes out from the use of composite (current collecting metal grids / PEDOT) electrode is: "what is the maximum cell dimension?". Increasing the active area of the solar cell devices typically leads to efficiency losses. The magnitude of the losses strongly depends on the sheet resistance of the electrodes. The efficiency of ITO-free OPV devices with different cell lengths (width) has been modelled and the result is shown in Figure 8a. As can be observed from the picture, for a module with an ITO-free electrode with sheet resistance of 1 Ohm/sq, the width of single cell can be increased up to 6 cm, with efficiency drop of only 10%. The theoretical calculations were verified by experimental results. Up-scaling of the solar cell from 1 to 6 cm in length and the effect of grid line resistance is explored for a large series of devices. Figure 8b illustrates very good match between experiment and theoretical estimation.

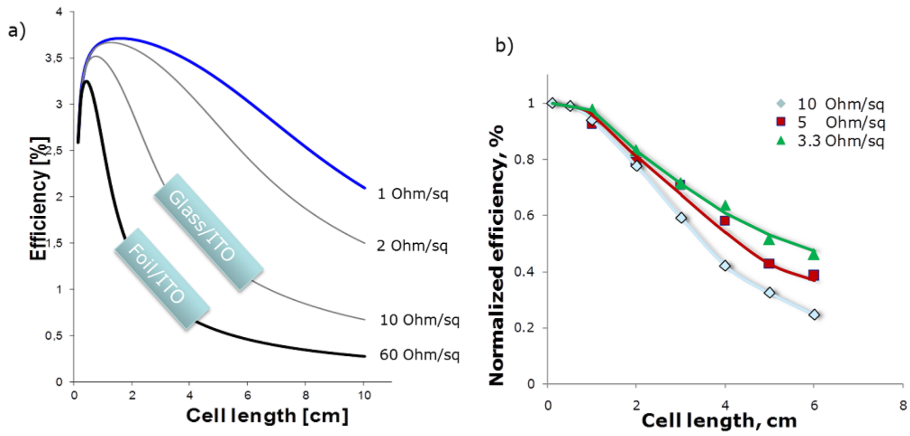


Figure 8. *(a) – theoretically calculated efficiency of the OPV modules, for the electrodes with different resistances; (b) – comparison of experimental and theoretical results for single ITO-free cells with different dimensions.*

A detailed analysis was performed on the formulation of water based PEDOT:PSS coating inks by optimizing the composition and determining the optimal drying conditions to get an optimum between transparency and conductivity. Figure 9 shows for the optimal formulation the dependency of drying conditions and shows the existence of optimal windows. Further optimization of the PEDOT:PSS formulations was done to increase the transparency while maintaining the conductivity. Transmission spectra of PEDOT:PSS layers with different thicknesses are shown in Figure 9. A Generation "6" PEDOT:PSS formulation was developed which showed a sheet resistance of 200 Ohm/sq and 98% of transparency after coating a layer of 200 nm thickness . Such a layer of PEDOT:PSS can be combined with screen printed embedded grids, with 6.4% surface coverage providing ITO-free electrode with a sheet resistance below 1 Ohm/sq and total transparency of 92 % without the substrate, to be related to comparable transparent ITO electrodes on glass (>10 Ohm/square) and PET (~60 Ohm/square).

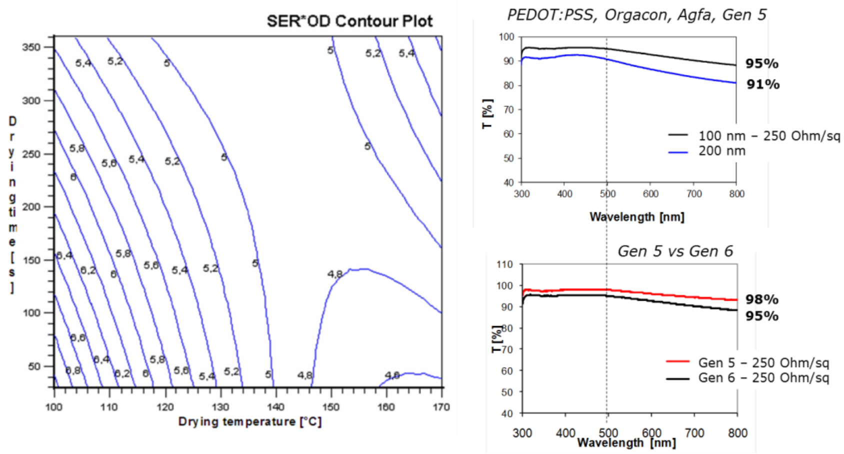


Figure 9. *Left: Relationship between drying conditions (temperature, time) and transparent conductivity (SER*OD) and* ***Right:*** *Transmission spectra of PEDOT:PSS layers: PEDOT:PSS generation "5" with the layer thicknesses of 100 nm and 200 nm; generation "5" versus generation "6", with the thickness of 100 nm.*

Barrier technology for substrates and superstrates

Within WP3, some barrier foils and technologies for substrates and superstrates have been used and tested. Four barrier types were used for a Ca-test, to determine the water vapor transition rate (WVTR) as a basic property of the foil . The following results were obtained:

Type of barrier	WVTR (gr/m^{2}day)
Amcor (commercial)	10^{-3}
Fuji (experimental)	10^{-4}
PEN/SiN (explorative)	$10^{-5}/10^{-6}$
Holst barrier (explorative)	10^{-6}

The series of OPV modules were encapsulated lamination using the above mentioned barriers. The commercial and experimental barrier foils from Alcan and Fuji, as well as the PEN foil with inorganic SiN layer, are good for the encapsulation of the solar cells for short periods (0.5-1 year). Evaluation of the barriers for the long term is only possible if the problem of side leakage will be solved and a full analysis of the degradations mechanism of of the solar cell devices used will be done A separation of intrinsic and extrinsic degradation will help to find the main requirements of the barrier, for long term use of encapsulated devices. Additionally, among the main characteristics of the barrier, such as WVTR, OTR, and transparency, the flexibility and bending radius are also playing a very important role, and should be added to the specification.

For the long term tests of the modules as described in the following section and under WP4, commercial packaging solutions have been used because of their unlimited availability and have demonstrated encouraging lifetime results when exposed to relatively low humidity conditions.

Work was performed towards developing exploratory solution processable barrier technologies. A solution processable approach to mimic the high barrier performance of inorganic/organic multilayer vacuum deposited coatings was developed. Therefore organic and inorganic solution processable coatings were developed that could later be applied as multilayers. POSS (polyhedral oligomeric silsesquioxane nano cages) was chosen as an inorganic dispersant as POSS has an ability to form an active glassy layer if exposed to appropriate conditions (for example by using corona, plasma or other oxidative environment) and as a nanoparticle could also help form a tortuous path to molecular transport across the coating. The approach has fallen considerably short of the WVTR and OTR performance objectives despite considerable effort during

“Year 2” therefore the decision was made to halt any further work on this particular task and make use of alternative suppliers of (commercial) barriers as mentioned above.

Accelerated lifetime testing of encapsulated cells/modules and outdoor long term performance testing at various locations

Different ITO and ITO-free OPV cells were fabricated by the partners of HIFLEX consortium. The ageing behaviour of the cells were investigated under three distinct illumination conditions [9]. Accelerated lifetime testing of encapsulated cells helps us to identify critical stress factors, such as UV and visible light soaking, temperature, humidity. The devices were analyzed and characterized at different points of their lifetimes by a large number of non-destructive and destructive techniques in order to identify specific degradation mechanisms responsible for the deterioration of the photovoltaic response. Imaging methods employed within this study are laser beam induced current (LBIC), dark lock-in thermography (DLIT), electroluminescence (ELI) and photoluminescence (PLI) imaging. The Incident Photon-to-Electron Conversion Efficiency (IPCE) and the in situ IPCE techniques were applied to determine the relation between solar cell performance and solar cell stability. Time-of-flight secondary ion mass spectrometry (TOF-SIMS) was used in order to study chemical degradation in-plane as well as in-depth in the organic solar cells [12].

As a final verification of the stability of R2R processed free modules, three different stability tests were conducted according to the ISOS consensus protocols on DTU ITO-free ASP modules using simple food packaging barrier foils (as described in WP4) at the same time at two partner locations (ECN and DTU). Additional ISOS tests have been performed at the DTU site itself and are shown in Figure 13 under WP4.

ISOS-D-2: Modules are placed in a in a drawer or cupboard that is not frequently opened at ambient conditions

ISOS-L-2: Modules are placed under constant illumination (1sun equivalent) under a solar simulator at a temperature between 40 and 50 ^{o}C.

ISOS-O: Modules are placed on a solar tracker or roof top on a stationary inclined surface facing south. Measurement are done at regular intervals offline under standard test conditions

A summary of the results with the performances measured at the beginning of the test (t=0) and after 1000 hours (t=1000) is given in Table 2, showing T80 values over 1000 hours for these test conditions

Table 2. *Result of stability study conducted on DTU R2R ITO-free modules*

ECN	Module nr.	Isc/mA	Voc	PCE/%	FF	Isc/mA	Voc	PCE/%	FF	PCE 1000/ PCE 0
ISOS-O-2	11	31,25	5,8	1,01	0,558	30,82	5,8	0,98	0,548	0,97
ISOS-O-2	12	31,78	5,8	1,01	0,55	32,28	5,8	1,04	0,557	1,03
ISOS-D-2	5	30,67	5,8	0,97	0,548	29,34	5,8	0,91	0,532	0,93
ISOS-D-2	9	31,06	5,8	1,02	0,566	31,13	5,8	1,00	0,554	0,98
ISOS-L-2	13	32,11	5,7	1,02	0,555	27,50	5,7	0,80	0,509	0,79
ISOS-L-2	14	32,90	5,8	1,01	0,531	26,74	5,8	0,82	0,526	0,81
DTU										
ISOS-O-2	N04	30,29	5,51	0,91	0,545	29,38	5,49	0,90	0,557	0,99
ISOS-D-2	N02	29,88	5,45	0,87	0,536	29,25	5,45	0,85	0,532	0,97
ISOS-L-2	13	29,47	5,53	0,90	0,553	25,56	5,51	0,78	0,554	0,87

Outdoor tests were continued after 1000 hours. At the moment of writing, the modules at the ECN location are still very stable as shown in figure 10. During the period of testing ambient temperatures were always below 18 ^{o}C down to levels below 0 ^{o}C during freezing nights in December. Temperatures on the sample were not measured. The Irradiance dose on the modules during the first 1000 hours period of testing (from Oct. 8 until December 17, 2012) was about 90 kWh/m^2 as recorded by continuous irradiance measurement via a pyranometer placed in the plane of the tested modules.

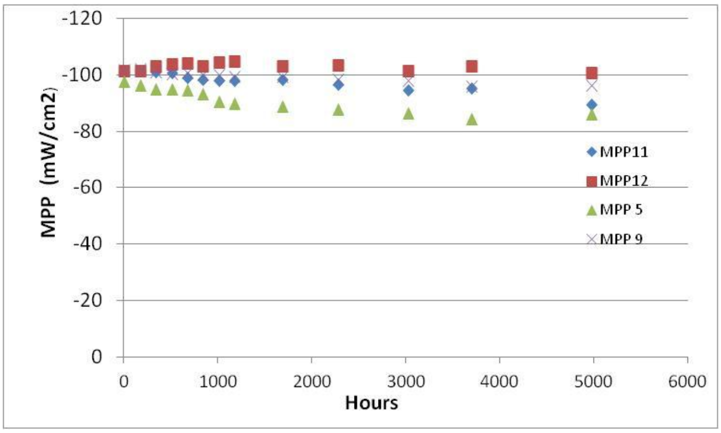


Figure 10.
The Maximum Power Point (MPP) recorded over time for DTU R2R ASP modules exposed to Outdoor conditions at ECN Petten. The modules are aged at open circuit conditions. Modules 11 and 12 have been exposed to outdoor testing conditions (ISOS-O-2). Modules 5 and 9 are reference modules stored in a drawer during the period of testing (ISOS-D-2)

WP4. Upscaling and Large Area printing (Development line)

Objectives

- The solar module architectures and prototypes developed in WP1 and WP2 are transferred to a full solution based industrial scale R2R process with minimum compromise in performance.
- The scalability of the prototypes is evaluated and processes are derived that enable production of OPV modules with a cost <10 €/Wp on a scale of <100 m^2.
- Encapsulation and characterization by R2R methods using encapsulation materials identified in WP3 with subsequent contacting are developed.
- Processes defined through suitable combination of printing and coating techniques will be explored in the context of minimizing process and module cost.
- Integration of OPV into complete flexible electronic products will be demonstrated through specific ICT applications.

DTU's main task under work-package WP4 was to adopt ITO-free polymer solar cell (PSC) prototypes developed within the consortium in roll-to-roll (R2R) processing of large-area ITO-free modules. The target for WP4 was to develop a robust R2R process in the fabrication of ITO-free PSC modules that in turn would display these properties: high efficiency (>60% of PCE of prototypes) on large area (>100cm^2); high operational and storage stability; and low-cost of production. Realizing these requirements in one prototype was not an easy task as some prototypes would propel in one category but not in the others. Many of the processing steps adopted in the prototype development were not low-cost and upscaling friendly. For example, vacuum-based processing such as evaporation and sputtering were used in the prototype development which cannot be accommodated in low-cost large scale processing. When low-cost ambient processing methods were substituted for vacuum-based methods whenever possible, the devices would not display similar photovoltaic and stability properties as the suggested prototypes. In all, five prototypes were put forth within the consortium as were described in WP1; however none was a winner architecture that stood-out in all three categories of efficiency, stability, and low-cost processing. Nevertheless, three were found arguably worthy of upscaling investigation primarily based on the efficiency and/or stability displayed by the prototypes. The three selected architectures are shown in Figure 11. Table 3 lists the key photovoltaic parameters of PSCs based on each prototypes as investigated in a round-robin study.

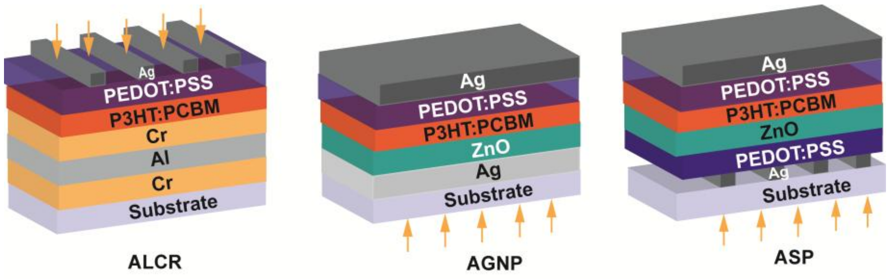


Figure 11: *Three prototype architectures found suitable for upscaling.*

Table 3 *Key photovoltaic parameters of prototypes and R2R processed modules based on the architectures shown in Figure 11.*

	ALCR		AGNP		ASP		
	Prototype	**R2R**	**Prototype**	**R2R**	**Prototype**	**R2R single cell**	**R2R module**
J_{sc} (mA cm²)	7.06	0.21	3.68	3.9	5.79	7.02	*5.45*
V_{oc} (V)	0.59	5.9	0.54	6.8	0.52	0.51	4.76
FF (%)	61.80	0.41	56.80	40.30	52.40	51.2	55.60
PCE(%)	2.56	0.53	1.12	0.44	1.58	1.82	1.62
Device active area	1	160	1	35.50	1	6	121

The **ALCR** and **AGNP** prototypes are developed using either or both vacuum deposition and glove box conditions. When the processing of these devices is adapted to the ambient R2R processing, the modules demonstrate far lower performance than shown by the prototypes (Table 3). Only ASP prototypes were based on an all solution processing route that required no vacuum steps. As such, the up-scaled modules based on ASP structure (now known as IOne process) demonstrates similar performance to the prototypes. The key photovoltaic properties of R2R processed modules based on the upscaling of three architectures listed in Figure 11 are also shown in Table 3 alongside the performance of prototypes. Figure 12 shows the processing of *IOne* modules which is based on ambient processing of all layers by coating or printing in a R2R line and at web-speeds reaching 20 m min^{-1}.

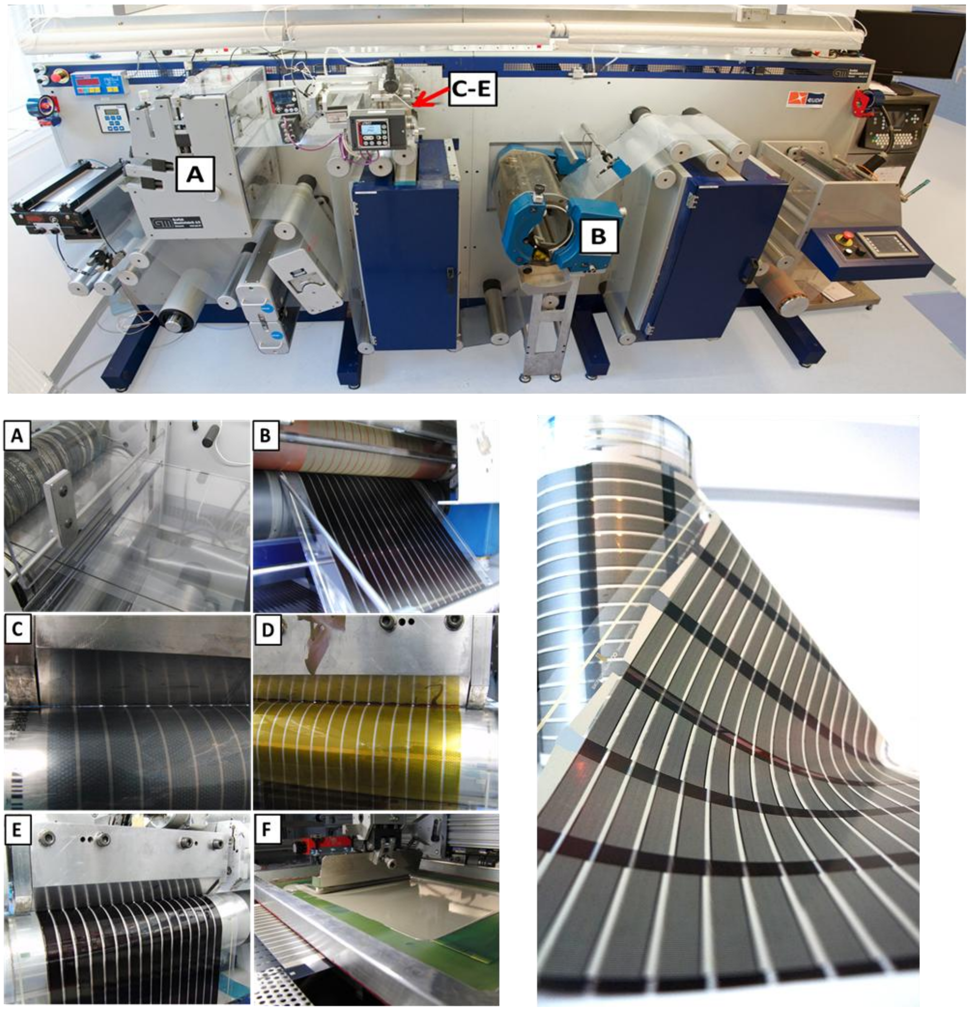


Figure 12. ***Top**: Panoramic view of a roll-to-roll machine equipped with 3 inline printing/coating stations: flexographic, slot-die and rotary screen printing. Bottom left: R2R processing of ITO-free PSCs: (A) Flexographic printing of Ag grid; (B) Rotary screen printing of highly conductive PEDOT: PSS; (C-E) Slot-die coating of ZnO, photoactive layer, and PEDOT:PSS, consecutively; (F) Flat-bed screen Printing of Ag. **Bottom right**: A roll with R2R processed PSCs on flexible substrate.*

In the IOne modules, the R2R processed ITO-free front electrode (Ag grid/hcPEDOT:PSS) on flexible substrate demonstrates an optical transmission of 70 % (at 550 nm) and a sheet resistance of ~10 $\Omega\square^{-1}$. In contrast, ITO on flexible substrates demonstrates an optical transmission of 80% (at 550nm) and a sheet resistance of 60 $\Omega\square^{-1}$. Consequently, IOne modules are highly scalable and results in similar FF (>55%) irrespective of module area. On the other hand, scalability is a big challenge with ITO electrodes because of its higher sheet resistance that leads to diminishing FF (<40%) upon upscaling. *IOne* modules based on Ag grid/hcPEDOT:PSS front electrode results in an average PCE of 1.5% on active area (120 cm^2) and 1.1% on a total module area (186 cm^2). The performance on *IOne* modules is slightly higher than ITO-based modules that display an average PCE of 1.2% on active area (160 cm^2).

Finally, *IOne* modules are found to be highly stable under various operational and storage conditions when encapsulated with a simple food packaging barrier foil (from Amcor) having an oxygen permeability of 0.01 cm^3 m^{-2} bar^{-1} day^{-1} and water vapor permeability of 0.04 g m^{-2} day^{-1}. Based on the accelerated stability tests, operational lifetime of >1 year is predicted [3]. Figure 13 demonstrates scalability and stability of *IOne* modules. Only under very high humidity conditions do the modules demonstrate poor stability; however under such conditions, improvement in barrier properties will lead to higher stability. This is evident when a double encapsulation is used which leads to an improvement in stability when stored under high humidity conditions (85% RH) by a factor of 3.

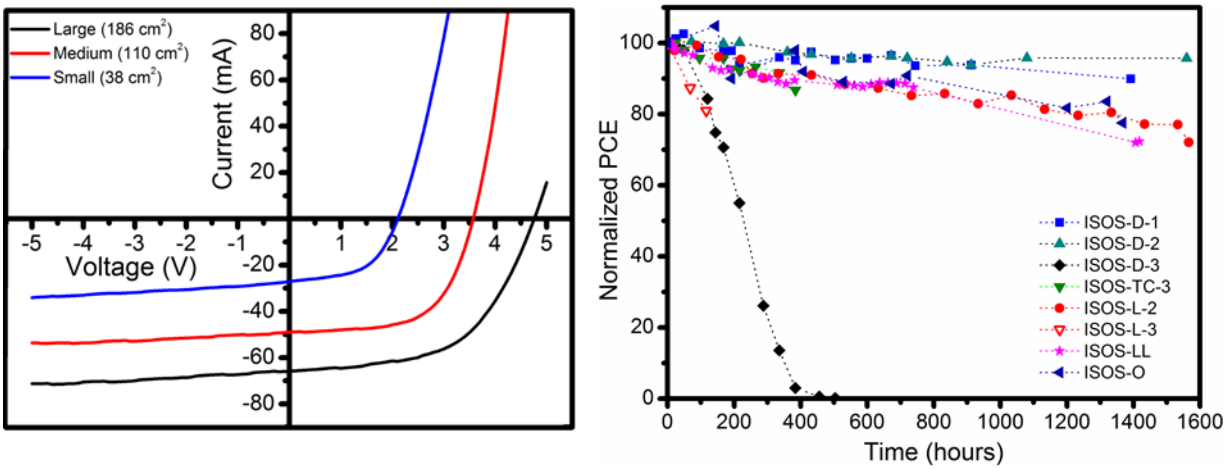


Figure 13. *Scalability is demonstrated in the IV curves of IOne modules of different sizes (left). Stability of IOne modules tested under various ISOS protocols [5]: ISOS-D-1 is shelf life; ISOS-D-2 is dark storage at elevated temperature of 65 °C; ISOS-D-3 is dark storage at 65 °C/85% RH; ISOS-TC-3 is temperature and humidity cycle and temperature ranging from -40 °C to 85 °C and RH ranging from 0 to 55%; ISOS-L-2 is operational conditions under constant 1 sun (1000 W m^{-2}) illumination at 70 °C; ISOS-L-3 is operational conditions under constant 0.7 sun (700 W m^{-2}) illumination at 65 °C and 50% RH; ISOS-LL is constant exposure to low light (0.1 sun, AM 1.5 G); and ISOS-O is constant outdoor exposure in Denmark (June-Sep, 2012).*

DTU is currently equipped with a R2R inspection system contributed by Dr. Schenk GmbH in HIFLEX as shown in Figure 14 that allows DTU to visually monitor layer quality and defects during processing of each layer. The optical inspection tool can operate in three modes: bright field, dark field, and transmission. The early detection of layer quality and defects aids in processing optimizations allowing high production yield. We are now able to identify areas with non-functional devices due to misalignment during the printing and coating steps which can subsequently be extracted from further handling, for example, in lamination, device characterization, and integration. This of course has improved our production yield in addition to saving costs.

Figure 14. *Optical inspection tool assembly in the DTU R2R line.*

A variant of IOne modules was further integrated in a credit-card size laser pointer based on an all printed circuitry (Figure 15). The integrated modules displayed an average PCE of >1.5%. Cost analysis suggests that the OPV part cost is 0.30 € per unit which is significantly lower than the HIFLEX target of 1€ per unit.

Figure 15. *Picture of a credit card size demonstrator laser pointer taken alongside a credit card.*

In all, under HIFLEX in corporation with other inline projects, DTU has successfully developed a robust low-cost R2R process for ITO-free modules that results in superior properties in comparison to ITO-based modules in terms of photovoltaic properties, stability, scalability, cost, and flexibility.

WP5 Implementation

Objectives

- Specification of relevant measurement and lifetime testing protocol for the performance determination of OBPV cells and modules in mobile ICT applications that simulate both indoor and outdoor circumstances
- Specification of requirements for product integration
- Conduct life cycle analysis and in-depth cost assessment (materials and environmental impact)
- To assure that the results of the project will be disseminated to the scientific community

Standardization of performance measurements (efficiency and lifetime)

A standard protocol for OPV performance determination has been generated in a collaborative manner by the consortium. The protocols are based upon test procedures developed and optimized during the HIFLEX project and from studies of the academic and standardisation literature and through active participation (and organisation) of the ISOS summits with the wider OPV community.

The protocols included focus on 'Technology Specific Testing'. So the standard is designed to qualify a technology not to qualify a product. So the standard will help the OPV (and wider thin film PV) community to develop the technology using a common measurement approach. Evaluation of a particular technology using these standard protocols should then give an answer to the question "Will this technology work well enough to be used in the market?"

It is also worth noting that a Standardisation document 'Nano-enabled photovoltaic devices – Stability test' is currently being evaluated by IEC committee TC113 (Nanotechnology standardization for electrical and electronic products and systems). The document specifically covers bulk-heterojunction photovoltaic devices made from organic polymers or small molecules, dye sensitized solar cells, organic/inorganic hybrid solar cells and devices made from inorganic nanoparticles. The submission and drafting of this document is being led by Jens Hauch (EnCN), the content has been discussed, developed and tested during the ISOS summits and in particular during the last HIFLEX/ ISOS-5 event which was held in Eindhoven on 6-7 December, 2013.

Product Integration and requirements

A report has been produced which describes the work performed to investigate product integration requirements and the market readiness of the HIFLEX technology for certain applications. Four mobile ICT applications with good commercial potential were chosen for more detailed evaluation:

- Laser pointer
- Flexible charging panel
- Helmet
- Shop price displays

Product Integration requirements for these 'target products' are included; these were developed with consideration of the required product features and the steps necessary for commercialization. Emphasis is given to the products and features which customers will actually buy and for realistic current and near future (up to 2015) performance.

Assessment of the relative merits of PV technologies which are competing against OPV has been performed. This includes evaluation of large scale processing of modules in relation to other thin film production techniques.

The conclusion of the PV technologies competition analysis is that, at present and up to 2015, OPV is outcompeted on both cost and most performance metrics, although, as is demonstrated with the flexible charging panel, this need not mean an uncompetitive price if a lower profit margin is accepted. The main case for OPV is that its lower efficiency will be outweighed by its significantly lower cost compared to other thin film technologies.

Roll-to-roll solution-based production processes should have an advantage against others, but it is a matter of realising these and avoiding compromise through higher materials or energy costs. Increasing line speed is a less important route to lower production costs. Improving cell efficiency in the field (without any significant associated rise in production costs) is however an automatic way to reduce OPV production costs when using the critical measure, by cell production capacity and should be prioritised. It will give a greater cost per Watt advantage to OPV in due course.

In addition to the comparison of PV technologies in quantitative and manufacturing issues terms, the technologies were also compared on more qualitative basis, identifying a number of product features of potential attraction to customers.

The commercial dimensions of the HIFLEX technology were also developed, including product cost and price points, the cost of existing charging products, comparative operating costs, non-price factors in the marketplace, profit & loss and cash flow modelling and estimating revenue streams from manufacturing and IP sale/licensing. Possible returns on investment (ROI) are part of the analysis.

Overview of potential OPV products were discussed and reasons for selection of 4 specific products for further investigation were highlighted. The benefits of the Hiflex results to the products are also discussed as were the suitability of OPV for the product power demands.

Cost and Life Cycle Assessment

Cost and life cycle assessments of selected devices and processes investigated within HIFLEX have been performed and compared with ITO based devices.

In terms of cost, a key project goal was to determine if a reduction of 50 % can be achieved by using ITO free electrodes instead of ITO. In addition, a specific cost target of less than 1 Euro was set for the OPV components of the OPV powered laser pointer selected as the final demonstrator of the HIFLEX project.

A comprehensive and realistic Life Cycle and Cost assessment performed by DTU has been undertaken on the targeted ITO free OPV powered laser pointer demonstrator based on real production and material parameters from the DTU R2R production line. Three ITO free variants of the ASP type (see Figure 1) have been assessed and the extensive analyses are compiled in a full manuscript which is published in Journal of Materials Chemistry A[2].

Costs

In Figure 16, the materials costs and anticipated module costs of the ITO based and ITO free devices are shown. The non-material related costs have been taken from *Azzopardi B. et al. , Energy &environmental Science, 2011, 4, 3741*). For ITO, a minimum and maximum cost scenario is taken because of the price uncertainty of ITO/PET on the present market.
Three variants of ITO free OPV were assessed: An inkjet printed silver grid (front) and a silver back electrode = SSE (left), only a Pedot front and a silver back electrode= PSE (middle) and a module based on silver free electrodes = SFE, utilizing all carbon modules (right). The core of the OPV module consisted of a Front PEDOT/ZnO/OPV layer/Back PEDOT.

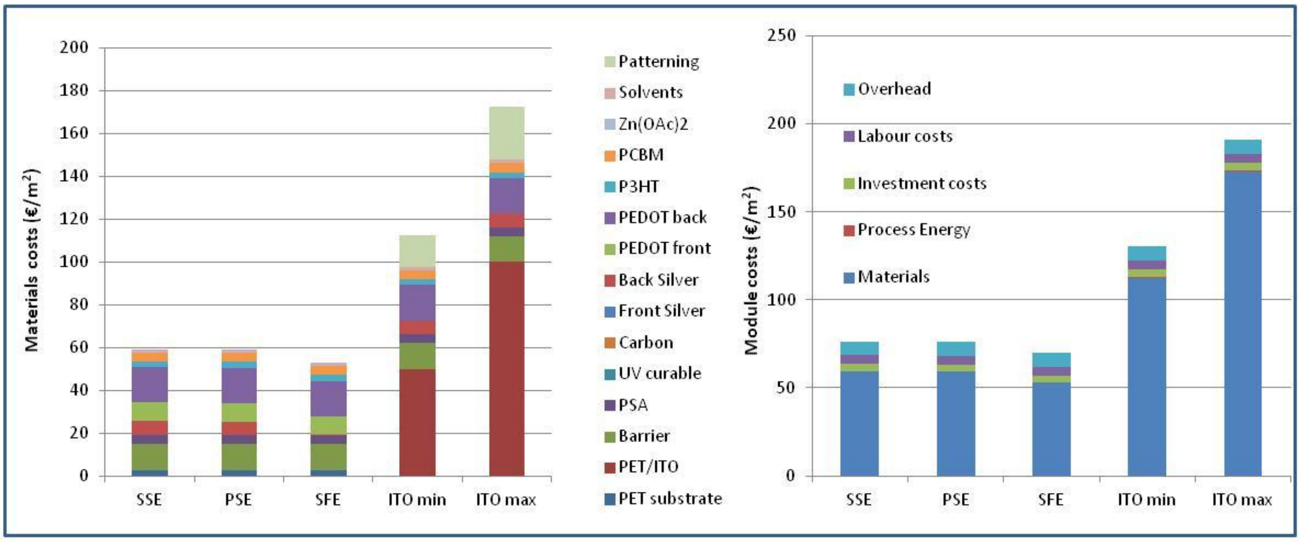


Figure 16. Material and module costs in €/m^2 of the various processed substrates (ITO free and ITO based)

Based on the lowest module costs as shown in Figure 16, module efficiencies have to increase to ~15 %, to reach values of 0.5 Euro/Wp, which are the current cheapest selling prices for x-Si. It should be mentioned that in the calculation for the OPV modules no heavy encapsulation schemes like glass or ETFE foils that withstand long term outdoor conditions have been considered.

In addition, cost assessment of ITO based and the selected ITO free device concepts within HIFLEX has been performed. The cost model developed was based on a virtual 250 MWp R2R production line. This tool is very useful to identify the cost driving elements for OPV manufacturing and provide important guidelines for further technological development. The different ITO-free designs ASP, ALCR and WT developed at Holst/ECN and Fraunhofer ISE were subjected to cost of ownership calculations in a tool

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[2]. Espinosa E, Lenzmann FO, Ryley S, Angmo D, Hösel M, Søndergaard R, Huss D, Dafinger S, Gritsch S, Kroon J. M, Jørgensen M, and Krebs, FC. OPV for mobile applications: An evaluation of roll-to-roll processed indium and silver free polymer solar cells through analysis of life cycle, cost and layer quality using inline optical and functional inspection tools OPV for mobile applications: An evaluation of roll-to-roll processed indium and silver free polymer solar cells through analysis of life cycle, cost and layer quality using inline optical and functional inspection tools, accepted for publication in Journal of Materials Chemistry A, 2013, 1, 7037-7048

developed by Holst and compared to an ITO based design. The WT design on a metal foil carrier obtains the **lowest cost per Wp (€ 0.34/Wp) for a cell efficiency of 12%.** The main drivers for the cost reduction from the Ag grid design to the wrap through design on Al foil are the replacement of PET foil with the barrier to a metal foil (-23%) and the replacement of Ag by cheaper metal electrodes (-19% for 4% cell efficiency to -33% for 12% cell efficiency).

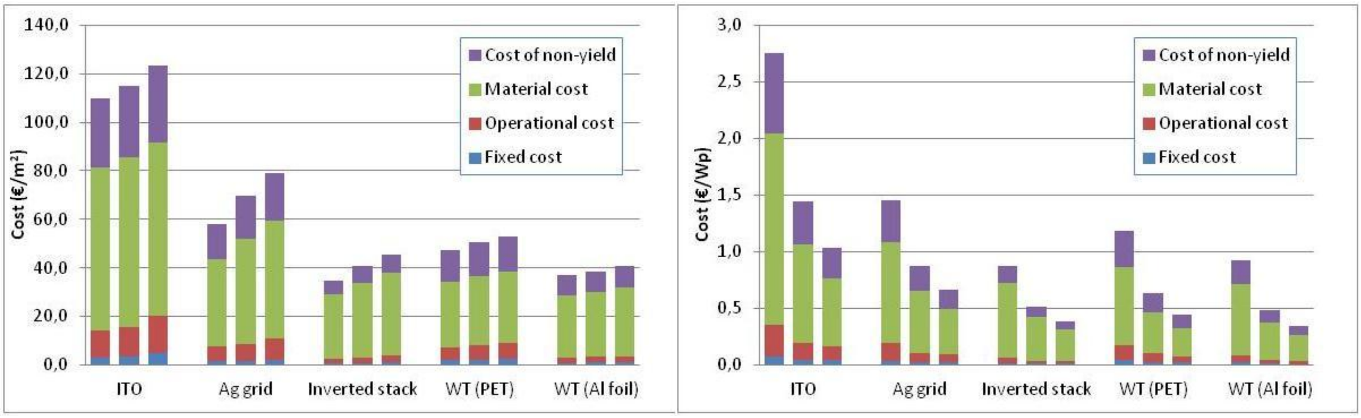

Figure 17 *Cost calculation of ITO based and ITO free based design inEuro/m2 and Wp s(Ag Grid = ASP; Invertedstack =AlCr and WT) for 4(left) 8(middle) and 12% (right column) cell efficiency.*

The most important lessons that have been learned from the cost and life cycle assessments carried out in Hiflex are:

Costs

- Cost reductions of > 50% are feasible when ITO is replaced by alternative electrodes
- The OPV part in the OPV powered targeted laser pointer is lower than 1 Euro per device
- Photoactive and electrode layers have no significant contribution to the costs, <10 €/m^2
- Replacement of Silver by Carbon leads to further cost reduction
- Most of the cost in the ITO free OPV modules is attributed to front and back PEDOT: 40-50 % share
- Further reductions in materials costs (i.e PEDOT, photoactive layers) can be expected if economies of scales are considered
- Materials costs dominate the total module cost for these OPV device structures (see figure 16)
- The wrap through design on a metal foil carrier obtains the lowest cost per Wp (0.34€/Wp) for a cell efficiency of 12%. The main drivers for the cost reduction from the Ag grid design to the wrap through design on Al foil are the replacement of PET foil with the barrier to a metal foil (-23%) and the replacement of Ag by cheaper metal electrodes (-19% for 4% cell efficiency to -33% for 12% cell efficiency).

Life Cycle assessment

The life-cycle assessment (LCA) was carried out on the credit card sized OPV modules powering the laserpointer demonstrator as shown in Figure 1, in which the ITO back-contact electrodes are replaced by alternative electrode configurations developed in HIFLEX. In figure 18 the embedded energies are shown for the selected device types and encapsulation scheme and compared to a comparable ITO based OPV device. For the latter system, a minimum and maximum value was taken based on the range of embedded energy values for ITO on PET that have been reported in the literature (40-250 MJ/m^2) , and are related to the assumed power efficiency of the sputtering tools that are used for the deposition of ITO.

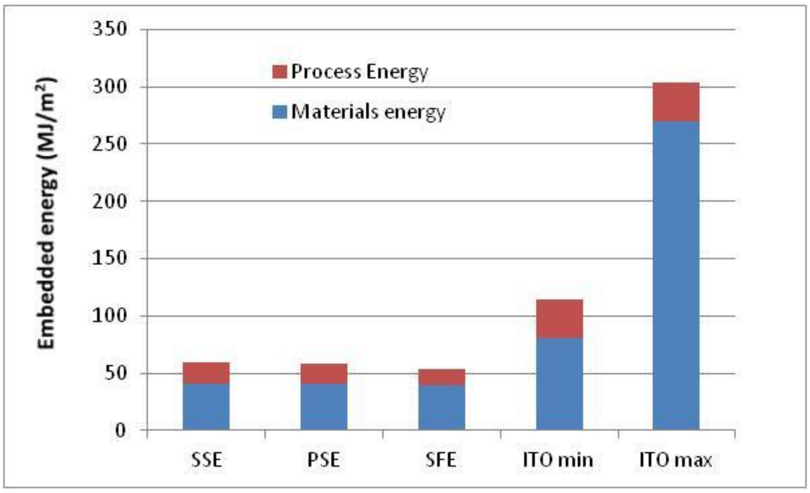

Figure 18. Embedded energies in MJ/m^2 for the module manufacturing divided into a materials and processing contribution.

The most important lessons that have been learned from the life cycle assessments carried out in Hiflex are:

- Embedded energies for ITO free electrodes based on Ag and/or Graphite are much lower (~ 5 – 7 MJ/m^2) than for ITO based electrodes (>42 MJ/m^2)
- Embedded energies for OPV are in general much lower than for competing inorganic PV technologies, resulting in very low energy pay back times and attractive environmetal profile
- The overall embedded energy of the OPV modules is very low in the range up 60 MJ/m^2. Corresponding values for other thin-film PV technologies are ≥ 800 MJ/m^2, but glass-based encapsulation schemes are typically applied in these modules (unlike in the HIFLEX modules). Even when accounting for the differences in the encapsulation schemes by incorporating weathering foils like ETFE , the conclusion remains valid that the HIFLEX OPV technology incorporates a uniquely low embedded energy. This is thanks to the absence of vacuum and high temperature processing.
- Graphite electrodes are identified as the best choice in terms of the environmental profile, because they outperform the Ag electrodes in a number of environmental impact categories (other than the embedded energy). Most importantly, the impacts associated with ”carcinogens” in the life-cycle profile of the electrodes are practically absent for graphite, while for silver they are the largest contributor in the ”eco indicator” analysis that was carried out Furthermore, the carbon footprint of the devices with graphite electrodes is also substantially lower, by almost 30%, than for devices with Ag electrodes.
- Regarding the transparent ITO electrode, the replacement of this compound by alternative electrode materials - which are not based on indium - is desirable, primarily from the point of view of indium scarcity. Such alternatives should ideally not be based on silver though, which is expected to face its own critical supply/demand imbalances in the near and longer term future as well. Therefore, graphite electrodes as mentioned under point 3) are ultimately the best choice form an environmental point of view.

WP6 Dissemination and Exploitation

- To assure that the results of the project will be disseminated to Industry
- To assure that there is an on-going communication between the consortium and the general public
- To assure that the project results are adequately protected

Details of HIFLEX dissemination activities – publications, presentations, disseminations materials, etc. - can be obtained through the website www.hiflexopv.eu. The website has been kept up-to-date with the consortium's publication activity and event attendance. Technical sections of the site have been updated and dissemination materials are available to download through the site.

A significant number of dissemination activities have taken place during this final period of the project. Most of the events attended have been a mixture of scientific conference and industry meetings. In particular these include key conferences relevant to the project – MRS, E-MRS, EU PVSEC, LOPE-C and others.

The HIFLEX project culminated in a final dissemination event held jointly with the ISOS summit (International Summit on Organic Photovoltaic Stability) at which the key successes of the HIFLEX project were presented to an audience of over 70 people from universities, research technology organisations, OPV product developers and manufacturers, materials suppliers, manufacturing and test equipment suppliers and prospective end users. Further details can be found at the HIFLEX website or at the dedicated wiki page http://isos-5.wikispaces.com/.

A final comprehensive press release was published in March 2013. This was distributed to various audience including technical and industry publications but also none technical national and local press.

A range of exploitable technology has been developed during the project although most of the details of this remain confidential. One patent application from the HIFLEX technology has been submitted to date by ECN & Holst, patent application number WO2012154045: Method for forming an electrode layer with a low work function, and electrode layer. A significant amount of know-how (or trade secret) has also been developed from the project work and by knowledge-transfer between the partners due to the close collaborative nature in which the project has been undertaken. Know-how is particularly important to OPV and related organic electronic R2R coating and printing technologies as subtleties in a process and knowledge of the 'black art' can make the difference between whether a production process is successful or not. i.e Knowledge of materials, designs and processes obtained from patents is often not sufficient to be able to reproducibly manufacture products without first investing a significant amount of time to investigate and optimise a process. Therefore the consortium are in a strong position to exploit this IP either by using this knowledge to manufacture their own commercial products within the existing companies or through the establishment of a new HIFLEX company or through partnership and licencing deals with external companies.

Potential impact

A Vision for Photovoltaic Technology – some history

In 2005 the European Photovoltaic Technology Research Advisory Council (PV-TRAC), prepared the report "A Vision for Photovoltaic Technology" with the purpose of contributing to the rapid development of world-class, cost–competitive European Photovoltaics (PV) for sustainable electricity production. This report identified the major technical and non-technical barriers for the uptake of PV and outlined a strategic research agenda designed to ensure a fast breakthrough of PV and an increase in deployment in the Union and worldwide. This Strategic Research agenda appeared in June 2007 under the auspice of the EU PV technology platform and was followed soon by an Implementation Plan describing how to put into practice the SRA's findings and recommendations.

The SRA stated that the end-user of PV focus primarily on the following parameters, irrespective of the nature of the PV technology:

- the price per watt-peak of module
- the energy yield per watt-peak under field conditions
- the module's efficiency and reliability
- size and weight of the module
- flexibility or rigidity
- Visual appearance including aspects like semi-transparency, form-freedom, color variety
- recycling scenario's

There is a large portfolio of different PV technologies, each with their own specific advantages and disadvantages but they will all be evaluated in terms of the parameters mentioned above. For the R&D community, it is crucial to get a sound understanding of all the different cell and module technologies resulting in the different work programs to achieve the required cost reduction, performance enhancement and improved aesthetical and environmental profiles.

It became clear that different technologies require their own research and development activities, although they have a number of issues in common.

1. Wafer-based (mono and polycrystalline silicon)
2. Existing thin-film PV technologies like thin film Silicon, CIGS, CdTe with the prospect of achieving lower production costs due to efficient materials utilization
3. Emerging and novel technologies (including "boosters" to technologies in the first and second category) representing super low cost and/or super high efficiency concepts

While the common R&D issues can be generalized as:

- Improvement of efficiency, energy yield, stability and lifetime
- High productivity and low cost manufacturing, including in-process monitoring & control
- Environmental sustainability
- Integration

It is expected that this broad variety of technologies will determine the PV technology portfolio on the longer term, depending on the specific requirements and economics of the various applications. The different PV technology families are developing in parallel *from generation to generation* – in the sense that cost per Wp is falling and efficiencies are continuously improving. And as the technologies develop, new potential applications gradually continue to appear and emerging technologies will take over some market share from other technologies.

In the last category of emerging and novel technologies, the focus is on realizing very low cost approaches at moderate efficiencies and/or high efficiency approaches at moderate costs. It is the first

category where Organic Photovoltaics could play an important role. In these type of cells, the photoactive layer consists completely or partly on organic molecules or polymers. They offer the prospect of achieving very low materials and substrate costs, low energy input by high throughput atmospheric production methods and easy up-scaling. This should finally lead to costs significantly lower than 0.5 Euro/Wp.
The potential of OPV was also recognized within the emerging research **Organic Large Area Electronics** (OLAE), where a strategic research agenda was made under the auspice of the Coordinated Action OPERA, Organic Electronics Association and the technology platforms EPOSS and Photonics 21. This SRA will guide the developments in the following sectors: Lighting, **Organic Photovoltaics**, Displays, Electronics and Integrated Smart Systems and define the research programs for the next HORIZON research programme.

Market potential of Organic Photovoltaics

To enable long term use of OPV to replace conventional electricity generation, e.g. in grid-connected or stand-alone roof top applications, significant progress in efficiency and especially lifetime is needed. For this reason it is projected that large-area, high-efficiency applications will not become feasible before around 2020 Nevertheless, due to a continuous progress in device performance and processing technology and profiting from the "unique selling points" of OPV like flexibility, semi-transparancy, form-factor, sustainability and aesthetical profile, the OPV market will grow continuously in size over the next years and will follow a "stepping stone approach" via different product generations first entering into (niche) markets for mobile electronics applications.

Table 4 provides a tentative timeframe for applications of OPV in short, medium and long term that can be expected from successful R&D and knowledge exploitation in this field. It represents a very general picture and guideline on how OPV is expected to penetrate the markets progressively via the different segments.

Table 4. *Tentative application roadmap of OPV*

Time frame	**Short-term 2011-2013**	**Short-term 2012-2014**	**Medium-term 2015-2019**	**Long-term > 2020**
Application Area	**Mobile Electronics**	**Outdoor recreational remote**	**Off grid power and Building Integrated PV**	**Roof top grid-connected, bulk power generation**
Product generation	**Gen1: Flexible, low weight modules, product lifetime 1-2 years Lower efficiency**	**Gen2: Flexible, low weight PV, product lifetime 3-5 years Moderate Efficiency**	**Gen3: Flexible/rigid low weight modules, product lifetime 10-20 years Moderate Efficiency**	**Gen4: Flexible/rigid low weight modules, product lifetime >20 years**
Typical applications	Low-power applications for indoor electronic devices and portable consumer products(e.g. PDAs, laptops, navigation systems, mobile phones, MP3 players, toys, remote controls)	Shading elements ("powerbrellas", awnings, parking lots), tents, sails, bags and backpacks	Stand-alone outdoor applications, e.g. solar-homes, rural electrification; building structures such as windows, skylights, facades, roof's, and walls.	Established competitive solar technique for 4 out of 5 PV market segments

Commercial status, OPV based demonstrators and products

Within the family of OPV, one may distinguish between devices that are based on organic semiconductors applied from solution or vacuum or “hybrid” technologies based on a combination of organic and inorganic components, such as the Dye-sensitized Solar Cell (DSSC). There is a growing industrial interest across the whole value chain to start R&D in this field from materials to manufacturing, but there are only a few OPV producers to date that officially have commercialized the OPV technology. Flexible DSSC and solution processed Polymer PV modules manufactured by resp. G24i and Konarka with power conversion efficiencies up to 3 % and limited product lifetimes up to a few years, have been integrated into bags for charging applications [refs. 7, 8] and are commercially available since 2010. These first “stepping stone” applications target the low-power consumer market segment as indicated as the first entry market in Table .

Continuous development of the production processes towards large areas could lead to several new large volume applications, inspired by the unique properties of OPV like its flexibility, power-to-weight ratio, good low-light performance, semi-transparency and color tunability. This has already led to first, large area demonstrations by Konarka of flexible and/or semi-transparent OPV integrated in BIPV applications behind glass (like curtain walls), shading structures and greenhouses (see Figure ..).

Figure 1. *Examples of Large area demonstrations utilizing OPV panels. Left: curtain wall with OPV behind glass. Middle: OPV integrated in a shading structure providing both power and natural colling. Right: semitransparent OPV integrated in a greenhouse (Courtesy: Konarka),*

Regarding small molecule OPV, Heliatek currently ramps up world’s first vacuum-roll-to-roll OPV production line. First pilot products are still foreseen for end of 2012 / early 2013. These products will be on PET substrates, to deliver flexible, light-weight products. As expected, bringing the significant gap between R+D and first industrial production challenging for SM-OPV as well, but so far very promising.

Within the scientific and technical community, DTU has produced larger series of polymer modules integrated into functional demonstrators (like a solar hat, laser pointer and solar lamp) and disseminated this to the public. The most important learning points that came out of these studies were the (sometimes unexpected) response of end users to the technology as well as the fact that integration of the solar cell/module into a product requires more attention to get it as fast as the processing of the solar modules itself. The conclusions from these studies is therefore to involve end-users and end product design in a very early stage of the complete process, so that full profit can be made from the anticipated product versatility as is always mentioned as one of the unique assets of OPV.

Players active in the value chain

Inspired by the long term potential of OPV as a low cost, flexible and versatile PV technology, many companies stepped in the development of OPV technology covering the whole value chain from materials to equipment and finally end manufactures.
Hereunder follows a non-exhaustive list of companies which are now active in the field:
Merck, BASF, Solvay, Agfa, Polyera, Plextronics, Sumitomo and Mitsubishi chemicals have dedicated material development programmes for OPV.

Other SME's and larger industries are amongst others Kroenert (Germany, equipment), Mekoprint (Denmark, production), Graphisk Maskinfabrik (Denmark, equipment), Coatema (equipment), 3DMicromac (equipment), Solarpress (UK, technology development for production), Disasolar (France, production), Eight19 (UK, production), Thyssen Krupp Steel (Germany, OPV on steel), PolyIC/Kurz (Germany, production), Solarmer energy (materials, production), Heliatek (Small molecule OPV, production).

Konarka Technologies (US) was the very important frontrunner and the first company that succeeded in the roll-to-roll production of first generation ITO based polymer based OPV modules, where all layers are deposited by printing and coating methods at high speed and high yield. Konarka was the first OPV company that shipped their Power Plastic® thin film PV modules to external customers as was mentioned earlier in this report. In June 2012 they filed for bankruptcy. However in October 2012 it was announced that Belectric have taken over the European operations of Konarka GmbH adding OPV to Belectric's PV technology portfolio.

Impact of HIFLEX

At the start of the project in 2010 and as shown in Table 4, mobile ICT applications were considered as the most likely early adopter of OPV technology and this was taken as the most important focus of the R&D work in HIFLEX. The general objective of HIFLEX was:

to develop a cost-effective **Highly Flexible Printed ITO-free Organic Photovoltaics (OPV) module technology** matching the particular requirements of mobile and remote ICT applications, delivering the required efficiency under different light conditions, sufficient lifetime, acceptable cost structure, appropriate power-to-weight ratio and fit-to-purpose mechanical flexibility.

The key achievements of HIFLEX have been summarized in earlier sections of this report and it has been shown that the overall objectives have been fullfilled, i.e. a low cost, scalable processing OPV technology free from Indium and even silver with performance characteristics that are compatible with a number of mobile and remote ICT applications under different light conditions.

These achievements are of crucial importance for further dissemination and exploitation to accelerate the uptake of the OPV technology as a viable PV technology for several application areas, with the mobile ICT as the first stepping stone in the application roadmap.

As was indicated in the WP6 summary, a range of exploitable technology has been developed during the project of which most of the details remain confidential but can be summarized as:

- Fabrication technologies (S2S and R2R) for optimized designs of ITO free transparent and conducting flexible electrodes and module designs
- Optimized highly conductive PEDOT formulations by Agfa
- The automated inspection equipment for OPV /OLED production by Dr Schenk

A significant amount of know-how (or trade secret) has been developed from the project work and by knowledge-transfer between the partners due to the close collaborative nature in which the project has been undertaken. Know-how is particularly important to OPV and related organic electronic R2R coating and printing technologies as subtleties in a process and knowledge of the 'black art' can make the difference between whether a production process is successful or not. Knowledge of materials, designs and processes obtained from patents is often not sufficient to be able to reproducibly manufacture products without first investing a significant amount of time to investigate and optimise a process.

Therefore the consortium are in a strong position to exploit this IP and knowledge either by using this knowledge to manufacture their own commercial products within the existing companies or through the establishment of a new HIFLEX company or through partnership and licencing deals with external companies.

As an important add-on of the project, the consortium has investigated the environmental and cost profile as well as product integration requirements and the market readiness of the developed technology for four selected applications with good commercial potential in the mobile electronics market segment: a Laser pointer, a flexible charging panel, a Helmet and Shop price displays.

More broadly the HIFLEX project will positively impact upon:

- the industrialization of OPV technology
- Europe's position as a leader within the emerging OPV and organic electronics fields and more widely within ICT ensuring Europe remains industrially competitive
- progress in ICT developments for the benefit of European citizens

Dissemination activities

The consortium followed a policy of active dissemination of knowledge and results which was realised by the following actions:

- Exchange of scientific staff took place with the aim of increasing the scientific output, propagation of "best practices", side-by-side comparisons of different technologies and preparation of integration;
- Scientific publications in relevant journals
- Contributions to conferences (orals, posters, exhibitions)
- Cross fertilization with related EU projects in ICT and other frames or thematic areas like NMP and Energy
- Organisation of a final dissemination event with around 70 attendees from academia, research institutes and industry.

List of beneficiaries

List of beneficiaries and contact persons

1.	ECN Solar Energy	Dr. J. Kroon (j.kroon@ecn.nl)
2.	Fraunhofer ISE	Dr. Birger Zimmermann (birger.zimmermann@ise.fraunhofer.de)
3.	Holst Centre	Dr. Yulia Galagan (yulia.galagan@tno.nl)
4.	DTU	Prof. Frederik Krebs (frkr@dtu.nl)
5.	Matri	Dr. Stephen Ryley (stephen.ryley@pera.com)
6.	Dr Schenk	Dr. Stefan Gritsch (stefan.gritsch@drschenk.com)
7.	Agfa Gevaert	Dr. Dirk Bollen (dirk.bollen@agfa.com)

Website

www.hiflexopv.eu

4.2 Use and dissemination of foreground

A plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) shall be established at the end of the project. It should, where appropriate, be an update of the initial plan in Annex I for use and dissemination of foreground and be consistent with the report on societal implications on the use and dissemination of foreground (section 4.3 – H).

The plan should consist of:

- Section A

This section should describe the dissemination measures, including any scientific publications relating to foreground. **Its content will be made available in the public domain** thus demonstrating the added-value and positive impact of the project on the European Union.

- Section B

This section should specify the exploitable foreground and provide the plans for exploitation. All these data can be public or confidential; the report must clearly mark non-publishable (confidential) parts that will be treated as such by the Commission. Information under Section B that is not marked as confidential **will be made available in the public domain** thus demonstrating the added-value and positive impact of the project on the European Union.

Section A (public)

This section includes two templates

- Template A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Template A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[3] (if available)	Is/Will open access[4] provided to this publication?
1	*ITO-free flexible polymer solar cells: From small model devices to roll-to-roll processed large modules.*	*FC Krebs (DTU)*	*Organic Electronics*	*Volume 12, nr. 4*			*2011*	*pp. 566-574*		No
2	*Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment.*	*FC Krebs (DTU)*	*Energy & Environmental Science*	*4(10):*			*2011*	*3741-3753*		*No*
3	*An inter-laboratory stability study of roll-to-*	*FC Krebs (DTU)*	*Solar Energy*	*95(5)*			*2011*	*1398-1416*		*No*

[3] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[4] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

	roll coated flexible polymer solar modules.		*Mater Solar Cells 2011*								
4	*The OE-A OPV demonstrator anno domini 2011.;*	*FC Krebs DTU)*	*Energy & Environmental Science*	*4(10):*			*2011*	*4116-4123.*		*No*	
5	*ITO-free polymer solar cells.*	*FC Krebs(DTU)*	*J Appl Polym Sci*				*2012*	*Doi: 10.1002/app.38854*		*No*	
6	*(All solution processing of ITO-free organic solar cell modules directly on barrier foil.;:.*	*FC Krebs (DTU)*	*Solar Energy Mater Solar Cells*	*107*			*2012*	*329-336*		*No*	
7	*(Life cycle assessment of ITO-free flexible polymer solar cells prepared by roll-to-roll coating and printing.;:*	*FC Krebs (DTU)*	*Solar Energy Mater Solar Cells*	*97*			*2012*	*3-13.*		*No*	
8	*TOF-SIMS investigation of degradation pathways occurring in a variety of organic photovoltaic devices - the ISOS-3 inter-laboratory collaboration*	*FC Krebs (DTU)*	*Physical Chemistry Chemical Physics*	*14(33)*			*2012*	*11780-11799*		*No*	
9	*Solar cells with one-day energy payback for the factories of the future.;:*	*FC Krebs(DTU)*	*Energy & Environmental Science*	*5(1)*			*2012*	*5117-5132.*		*No*	
10	*Stability of Polymer Solar Cells.*	*FC Krebs (DTU)*	*Adv Mater*	*24(5)*			*2012*	*580-612*		*No*	
11	*Investigation of the degradation mechanisms of a variety of organic photovoltaic devices by combination of imaging techniques-the ISOS-3 inter-laboratory collaboration*	*FC Krebs (DTU)*	*Energy Environ Sci*	*5(4):*			*2012*	*6521-6540.*		*No*	
12	*Roll-to-roll fabrication of polymer solar cells.*	*FC Krebs (DTU)*	*Materials Today*	*15(1-2):*			*2012*	*36-49*		*No*	
13	*The ISOS-3 inter-laboratory collaboration focused on the stability of a variety of*	*FC Krebs (DTU)*	*Rsc Advances*	*2(3)*			*2012*	*882-893*		*No*	

	organic photovoltaic devices.									
14	On the stability of a variety of organic photovoltaic devices by IPCE and in situ IPCE analyses - the ISOS-3 inter-laboratory collaboration	FC Krebs (DTU)	Physical Chemistry Chemical Physics	14(33):			2012	11824-11845		No
15	Low-cost upscaling compatibility of five different ITO-free architectures for polymer solar cells.	FC Krebs (DTU)	Journal of Applied Polymer Science	(accepted manuscript)			2013.			No
16	OPV for mobile applications: An evaluation of roll-to-roll processed indium and silver free polymer solar cells through analysis of life cycle, cost and layer quality using inline optical and functional inspection tools OPV for mobile applications….	FC Krebs (DTU)	Journal of Materials Chemistry A	1			2013	7037-7049		No
17	Inkjet printing of back electrodes for inverted polymer solar cells. 2013	FC Krebs (DTU)	Advanced Energy Materials	(peer reviewed, final decision pending).			2013			No
18	Scalability and stability of very thin, roll-to-roll processed, large area, indium-tin-oxide free polymer solar cell modules	FC Krebs (DTU)	Organic Electronics				2013		Doi:10.1016/j.orgel.2012.12.033	No
19	Roll-to-Roll Inkjet Printing and Photonic Sintering of Electrodes for ITO Free Polymer Solar Cell Modules and Facile Product Integration.	FC Krebs (DTU)	Adv. Energy Mater.,	3			2013	Pp 172-175	doi: 10.1002/aenm.201200520	
20	Photonic sintering of ink-jet printed current collecting grids for organic solar cell applications	Y. Galagan (TNO/Holst)	Organic Electronics: physics, materials, applications	14 (1)	Elsevier		2013	pp. 38-46	http://www.sciencedirect.com/science/article/pii/S1566119912004788	
21	Evaluation of ink-jet printed current collecting grids and busbars for ITO-free organic solar cells	Y. Galagan (TNO/Holst)	Solar Energy Materials and Solar Cells	104	Elsevier		2012	pp. 32-38.	http://www.sciencedirect.com/science/article/pii/S0927024812002152	

22	Current collecting grids for ITO-free solar cells	Y. Galagan (TNO/Holst)	Advanced Energy Materials	2 (1)	WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim		2012	pp. 103-110.		
23	ITO-free flexible organic solar cells with printed current collecting grids	Y. Galagan (TNO/Holst)	Solar Energy Materials and Solar Cells	95	Elsevier		2011	pp. 1339-1343	http://www.sciencedirect.com/science/article/pii/S092702481000468X	
24	Aerosol printed grids	B. Zimmermann (ISE)	Solar Energy Materials and Solar Cells	107	Elsevier		(2012)	252–258		
25	Electrical modeling of polymer solar cells	LH Slooff (ECN)	Energy Procedia	Accepted			2013			

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[5]	Main leader	Title	Date	Place	Type of audience[6]	Size of audience	Countries addressed
1	Press release	ECN		Jan 2010		General public		Worldwide
2	Press interview	ECN	+Plastic Electronics	Feb 2010		Organic electronics industry	100,000	Worldwide
3	Press release	Dr Schenk		Feb 2010		Organic electronics industry		Worldwide
4	Presentation*	ECN	MRS spring conference	April 2010	San Francisco (US)	Advanced materials research community & industry	2,000	US, worldwide
5	Presentation & paper	Holst	LOPE-C 2010	June 2010	Frankfurt (Germany)	Organic electronics industry	1,000	Europe, Worldwide
6	Presentation	ECN	OLAE cluster meeting	June 2010	Brussels (Belgium)	Organic electronics research community	60	Europe
7	Presentation	Holst	EU PVSEC	Sept 2010	Hamburg (Germany)	PV solar research community & industry	2,000	Europe, Worldwide
8	Workgroup	ECN	OE-A Green working group	Sept 2010	Dresden (Germany)	Organic electronics research community &	25	Europe

[5] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[6] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible.

						industry		
9	*Stand & demo**	*MaTRI*	*ICT 2010*	*Sept 2010*	*Brussels*	*ICT research community & industry*	*1,000*	*Europe*
10	*Presentation*	*Holst*	*Dutch Solar Energy R&D Seminar*	*Sept 2010*	*Utrecht (NL)*	*Solar energy research community*	*425*	*Netherlands*
11	*Presentation, workgroups*	*Risø, ECN, Holst, ISE, Agfa*	*ISOS 3, DTU*	*Oct 2010*	*Roskilde (Denmark)*	*OPV research community & industry*	*75*	*Europe, worldwide*
12	*Stand**	*MaTRI*	*K 2010*	*Oct 2010*		*Materials processing industry*	*220,000*	*Europe, worldwide*
13	*Presentation*	*ECN, Holst*	*MRS spring conference*	*April 2011*	*San Fransico (US)*	*Advanced materials research community & industry*	*2,000*	*US, worldwide*
14	*Presentation*	*ECN*	*E-MRS 2011*	*May 2011*	*Nice (France)*	*Advanced materials research community & industry*	*1,000*	*Europe*
15	*Presentation (oral)*	*ECN, Holst*	*LOPE-C*	*June 2011*	*Frankfurt (Germany)*	*Organic electronics industry*	*1,000*	*Europe, Worldwide*
16	*Presentation (oral)*	*ECN, Holst*	*EU PVSEC*	*Sept 2011*	*Hamburg (Germany)*	*PV solar research community & industry*	*2,000*	*Europe, Worldwide*
17	*Presentation (oral)*	*ECN*	*Organic Photovoltaics 2011*	*Sept 2011*	*Wurzburg (Germany)*	*OPV community*	*200*	*US, Worldwide*
18	*Presentation (oral)*	*Holst*	*Low Carbon Earth Summit (LCES-2011)*	*Oct 2011*	*China*	*Low carbon economy community*	*1,000*	*China, Worldwide*
19	*Press Release*	*Dr Schenk/DTU*		*April 2012*	*All*			*Worldwide*
20	*Presentation (oral)*	*ISE*	*MRS Spring Conference,*	*April 2012*	*San Fransisco(US)*	*Advanced materials*	*2,000*	*US, worldwide*

						research community & industry		
21	Presentation (oral)	ISE	E MRS	May 2012	Strassbourg (France)	Advanced materials research community & industry	100	Europe, worlwide
22	Presentation (poster)	ECN	LOPE-C	June 2012	Munich (Germany)	Organic electronics industry	1,000	Europe, Worldwide
23	Presentation (oral)	ISE	LOPE-C	July 2012	Munich (Germany)	Organic electronics industry	1000	Europe, Worldwide
24	Presentation (oral)	Holst	EU PVSEC	Sept 2012	Frankfurt (Germany)	PV solar research community & industry	2,000	Europe, Worldwide
25	Presentation (oral)	ECN	OLAE cluster meeting	Okt 2012	Dresden (Germany)	Organic electronics research community		Europe
25	Presentations (oral)	ECN, ISE, DTU, Holst	HIFLEX, ISOS	Dec 2012	Eindhoven (NL)	OPV research community & industry	50-100	Europe, worldwide
26	Technical symposium	European Coatings Show	European Coatings Show	March 2013		Coatings & printing industry	20,000	Europe, worldwide
27	Press release on final achievements Hiflex	ECN, Matri		Planned March 2013		General public		Worldwide
28	Presentation (oral)	ECN	Sophia	June 2013	Munich (gGermany)	PV solar research community & industry	<50	Europe
29								

* HIFLEX included as part of presentation