4.1 Final publishable summary report

Executive 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

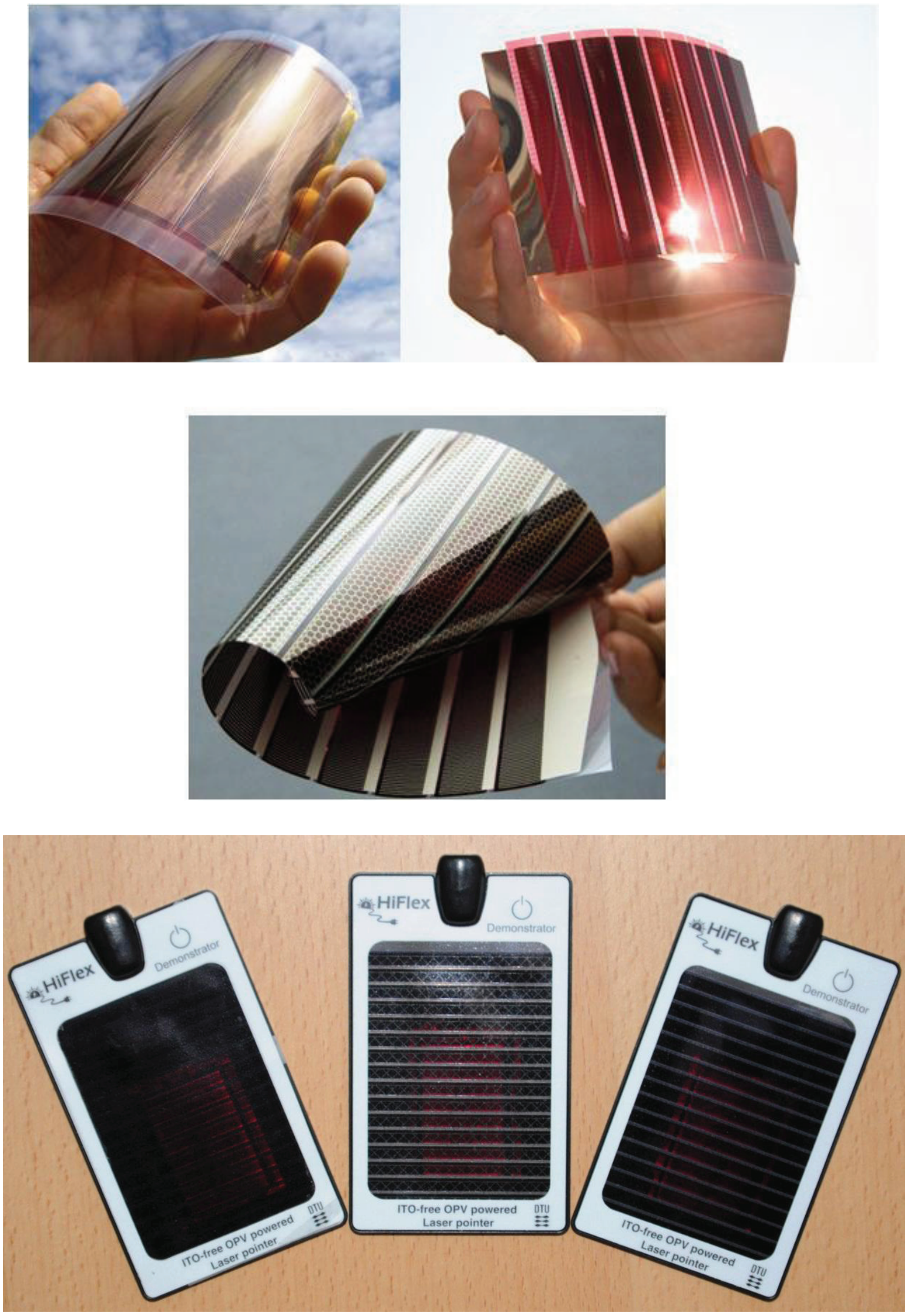


Figure 1 *Pictures of S2S processed (Top) and R2R processed ITO free modules (middle) and three variants of ITO free powered laserpointer demonstrators*

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.

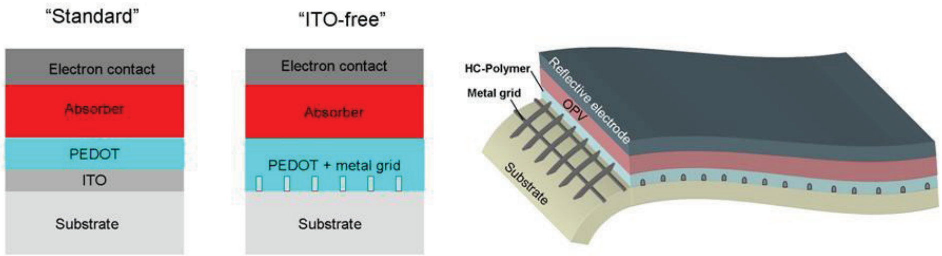
The unique thin film thicknesses employed in OPV devices (in the order of a few tens or hundreds of nanometres) are one prerequisite to achieve the high flexibility and high power-to-weight ratio. However highly mechanically stable electrodes and barrier layers, as well as higher power conversion efficiencies 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.

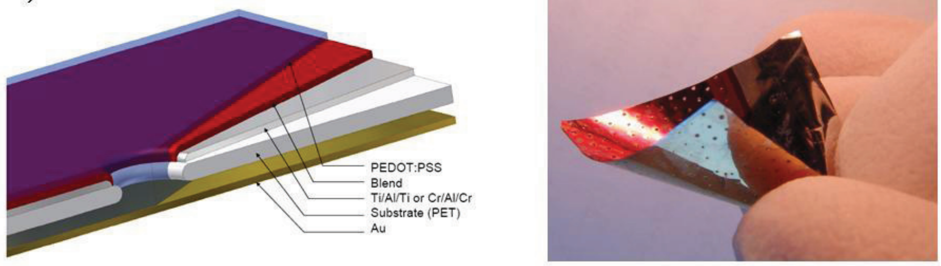
In HIFLEX, <u>an application-driven research</u> approach was followed by investigating two key technologies as a starting point enabling the manufacturing of ITO-free solar cell modules by roll-to-roll production:

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



a)



b)

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**esearch line)
WP2: Module Engineering and prototypes (**R&D** line)
WP3: Envelope (substrate/encapsulation) development
WP4: Upscaling and Large Area printing (**D**evelopment 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.

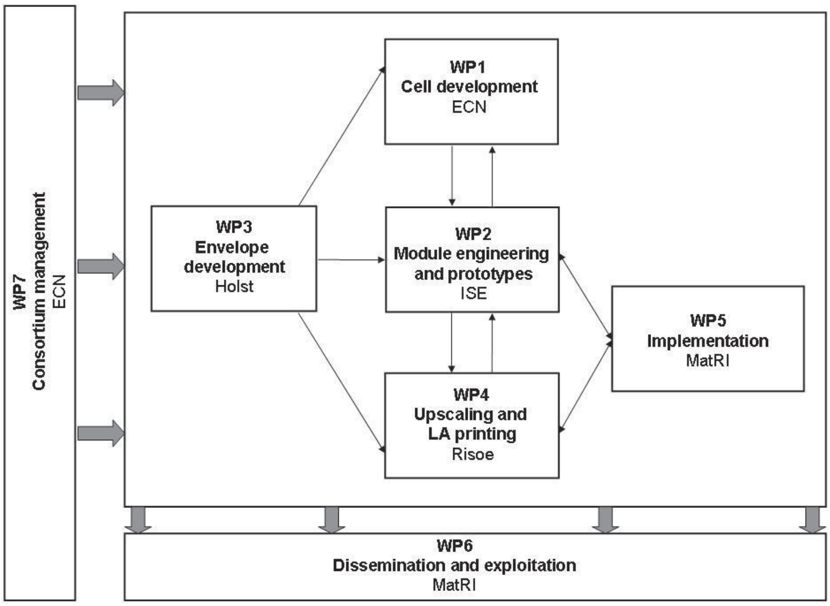


Figure 2 *Project structure showing the interdependencies between the work packages*