MEGAWATT
OPV Power Plants

- Final Report -

DTU Energy Conversion, Organic Energy Materials (OEM)

EnergiMidt A/S

Gaia Solar A/S

15.03.2014 – 15.03.2017

Index - Final Report

1. Final report

1.1 Project details

Project title	MEGAWATT OPV power plants
Project identification	12144
Name of the programme which has funded the project (ForskVE, ForskNG or ForskEL)	ForskEL
Name and address of the enterprises/institution responsible for the project	DTU Energy Conversion, Organic Energy Materials (OEM) Frederiksborgvej 399 4000 Roskilde
CVR (central business register)	30 06 09 46
Date for submission	13.03.2017

1.2 Executive summary

The overall project objective was in a short sentence: "to find out how big a solar park installation based on OPV should be to reach the objective of a price for 1 kWh of 25 øre". The answer would be substantiated data and experiments from an actual pilot scale installation. Scientifically excellent results were obtained from all work packages (except the management work package). In work package 1 focus was on the solar foil and here the objectives were full met with higher efficiency, several better designs and very fast manufacture. In the second work package where focus was on the installation it was demonstrated that the foil could be installed on a new ventilated/drained surface at high speed and also that it could be de-installed at an equally high speed. In addition we also demonstrated large light weight panels based on thermoplates as an alternative method of mounting. In the work package 3 we focused on operation and have studied several high voltage inverter designs and have developed unique electronics and control systems. We also explored one day energy storage in a hybrid inverter system with a battery. The design of the inverter system yield as low a cost of 266 € per kW (1000 units) in a very compact and simple topology that does not require cooling. We detailed energy production over two years of operation (experiment still running) and found some challenges related to the foil mounting (some were blown away in a storm). The thermoplate mount was more robust but we also lost two plates on a carport demonstration installation during a storm (this latter result was not related to the solar cell but to the carport). Another major result from this work package was a series of analytical tools that demonstrated an asymptotic behaviour in terms of cost of electricity (in kr/kWh) as a function of plant size with a main finding that

already at 50 MW installed capacity no further gain was reached more or less independently of the degradation of the solar cells. The main parameter is thus efficiency and no longer the stability of the OPV devices or put differently the operational lifetime is good enough today for a system to be rentable but the civil works are correspondingly higher for lower efficiency and this is where the large gain can be made. In the final work package the environmental aspects were analysed and the very short energy payback time for OPV was confirmed and environmental leaching studies showed both the impacts of emission to the environment upon simulated failure and established that the technology is benign (even when failing catastrophically and materials emit to the environment and soil). We also found that silver could be quantitatively recovered from the solar cells after end-of-life through incineration. Finally we simulated land filling experiments and found that the effects are benign even though it is not recommended to dispose OPV in a land fill scenario.

1.3 Project results

The MEGAWATT project with its partners from DTU, Gaia Solar and Energimidt built upon the previous project "Grid-connected polymer solar cells" where energy-payback times of less than one year for a complete kW-scaled polymer solar installation had been achieved. The successfully finished MEGAWATT project demonstrates an increased scalable and cost-effective energy production with fast installation/de-installation of polymer solar cell foils and ongoing stable energy production since more than 1.5 years due to improved lifetime and stability of the polymer solar cell foils.

The main objectives of the project were the experimental verification of installation and de-installation of the polymer solar cell foil at 300 meter per minute, one year stable energy production and 3-4 times increase of the energy output per area as compared to what has been achieved in the previous study. The objective of the project was to show a high scalability up to Gigawatt capacity with electricity production costs of 25 øre/kWh including the analysis of the environmental impact and documentation of the energy payback time.

The project comprised five work packages that encompassed the entire value chain from the energy production using on high-voltage based polymer solar cell module technology. The objective and results of each individual work package and their targets will be described in detail.

- WP1 – the solar foil – process and materials development
- WP2 – the installation – improved installation methods
- WP3 – the operation – improved operation lifetime and energy harvest
- WP4 – evaluation – cost analysis and environmental impact analysis
- WP5 – management

1.3.1 Work package 1 – the solar foil

Work package WP1 focused on the further development and improvement of the "INFINITY" production process, whereby the solar foil is entirely based on serially connected cells generating a high voltage – low current photovoltaic system. The objectives of WP1 were increasing the processing width, the area usage, and the processing speed for the foil with applying the best materials and encapsulations that are applicable in this setting.

We have taken a significant step towards increased processing width by testing the individual processes required for manufacturing the INFINITY foil on our 510 mm web-width R2R production machine. The processes tested are flexo printing and rotary screen printing of the two layers constituting the transparent electrode, plus slot-die coating of the active layer and the electron-transport layer (Figure 1).

Fig 1. Rotary screen printing of PEDOT:PSS electrodes on the 510 mm wide machine

All processes were tested with success with similar or higher web speed compared to the standard 305 mm wide R2R machine. An industrial usage of such a wide machine would generate more than 65% larger output by area of produced solar foil, if all processing kept the same. The mechanical/electrical configuration of the machine allowed faster flexo printing of the front silver electrodes and is not limited to just 25 m/min like the smaller machine. Improved oven design with increased time to the first contact of rollers with the printed layer and higher capacity allows faster production speed that can easily fulfil the goal of quadrupling the overall speed to 1.3 m/min and beyond.

Another approach for overall speed improvement is inline processing or the reduction of printed layers. We successfully tested both and the reduction of printed layers was tested with the introduction of a hybrid front electrode that combined silver nanowires (AgNW) and zinc oxide (ZnO) in a single ink mixture that not only saved one print run but also showed higher solar power conversion efficiency compared to other electrode configurations.[1]

The challenge at larger web width in the shrinkage of the foil during the recurring thermal processing and the necessary adaption of the printing forms to compensate the dimensional changes of the prior printing image. The complex research of improved processing protocols, module designs and new materials was therefore carried out on the 305 mm wide R2R printing and coating machine. The 510 mm wide machine with its enhanced ovens was nevertheless in good and frequent use for the thermal pre-treatment of the printing substrate.

Increasing the active area usage (geometrical fill factor) from 50% to 67% on the solar foil was achieved by employing an entirely printed solar module layout where the individual cells are oriented cross-directional (cd) instead along the foil like in the standard INFINITY design (Figure 2). The cd layout requires that all layers comprised in the solar-cell stack can be printed, as coating restricts the layout of the individual cells to stripes oriented along the web. New printable inks[1] have been formulated for the previously slot-die-coated layers; ZnO and active layer. All layers in the solar cells are now printable. The all-printed processing represents a breakthrough with respect to design, as printing allows that any cell layout can be designed and produced. Higher geometrical fill factor close to 85% would be achieved through larger cell sizes and web widths beyond 600 mm.

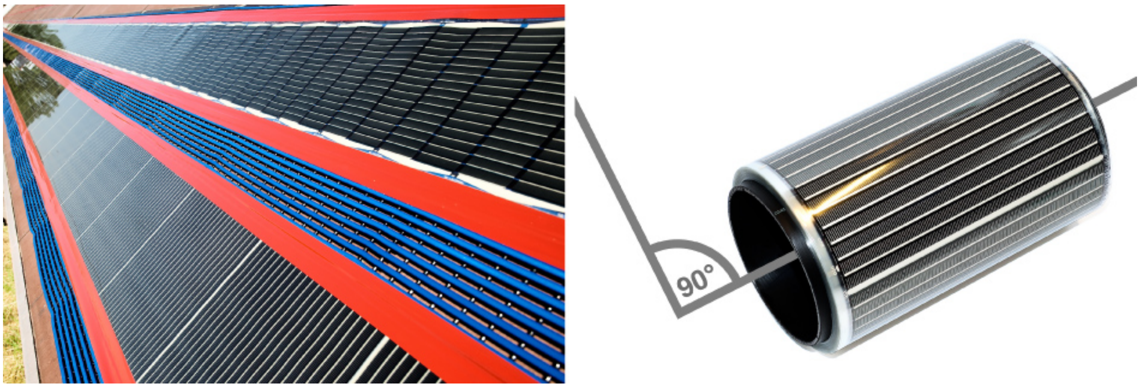

Fig 2. Left: Two versions of the INFINITY foil, the standard (top) and the fully printed cross-directional INFINITY foil (below). The foils are mounted onto a blue flexible plastic mesh to improve water drainage. Right: Roll of fully R2R-printed solar foil with improved perpendicular cell design.

The cross-directional orientation brings several advantages. Firstly, the number of serially connected solar cells per foil length is reduced, and this reduces V_{oc} from 10 kV to 3 kV per 100 m of solar foil. Secondly, the new design allows us to let the active cell area cover most of the foil width. In the original INFINITY design, the areas close to the foil edges are reserved for module interconnects, and the active cell area is correspondingly smaller. Finally, the cross-directional layout was found to be more robust with respect to printing accuracy. Registration is extremely important for the printing of the INFINITY foil with thousands of interconnected cells per 100 m foil and where connection loss between individual cells cannot be tolerated. Where the original layout required precise registration both along and across the web, the cd version requires precise registration only along the web direction.

The highest efficiencies are still achieved using slot-die coating of the active layer due to very high layer uniformity. Extensive processing experience gained

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[1] Development of inks are financed outside the MEGAWATT project

throughout the MEGAWATT project reduced fabrication errors to a minimum and enables repeatable output with a high yield.

The standard INFINITY foil and cross-directional INFINITY foil requires power extraction on each end of the foil that eventually requires 100 m long wires to connect the system to the HV DC/DC converter. We therefore further developed and optimized the module design to enable a scalable single side power extraction at any length but still using the fundamental concept of infinitely serial connected singe cells without embedding current collecting metal bus bars.[2] It only requires a very simple interconnector to allow the current run forth and back on the same solar foil (Figure 3).

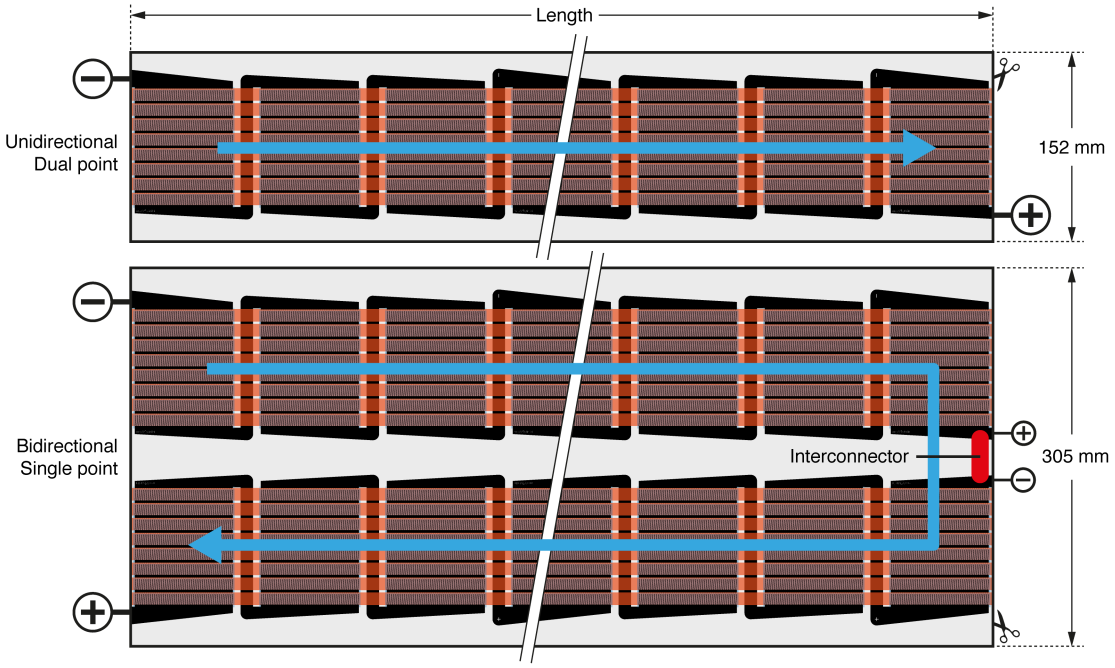

Fig 3. Unidirectional dual point power extraction (above, standard INFINITY foil design) and optimized single point power extraction (below)

The module design has been tested with silver and carbon as current collecting electrodes and does not contain any embedded metal bus bar stripes (Figure 5). The scalability of the design is very high in case printed silver electrodes are used and modules have negligible loss with increasing number of junctions (Figure 4 left). Environmentally more friendly carbon electrodes have been tested in the same layout and it is only efficient for single modules. The higher resistance of the carbon electrodes leads to a major drop in efficiency (PCE) and fill factor (FF) on larger modules (Figure 4 right).

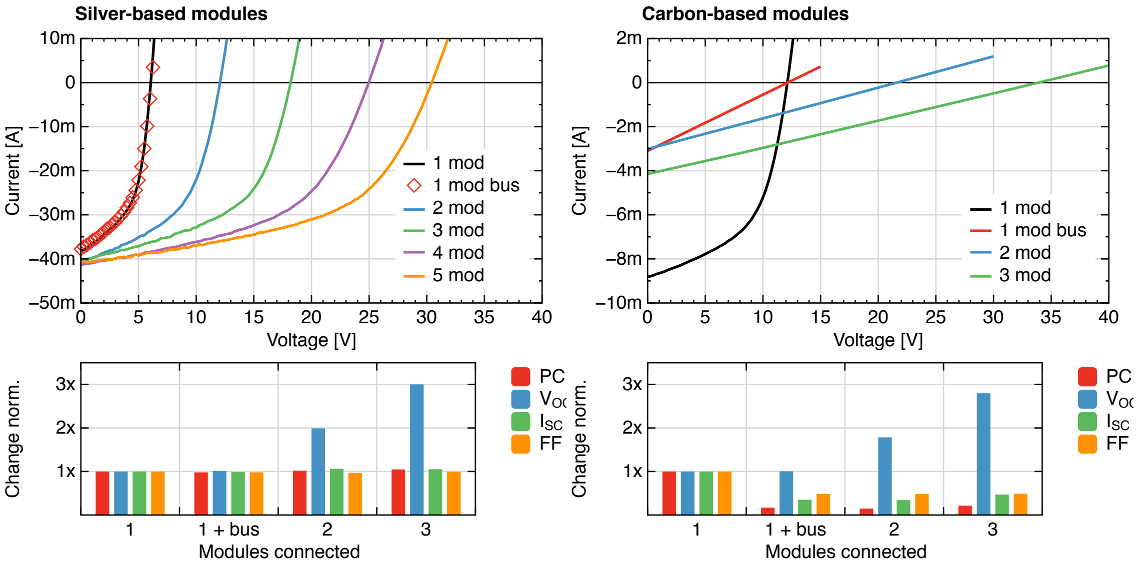

Fig 4. Current-voltage behaviour and parameter scalability of serially connected sub-modules with silver electrodes (left) and carbon electrode (right). The tested cells had a power conversion efficiency of ca. 2%

Based on the experimental results we chose silver over carbon for the fabrication of solar foils for the solar park, although carbon is more environmentally friendly. Nevertheless, studies performed at DTU show that silver in printed organic solar cells can be entirely recycled and extracted up to 100% after its lifetime.[3]

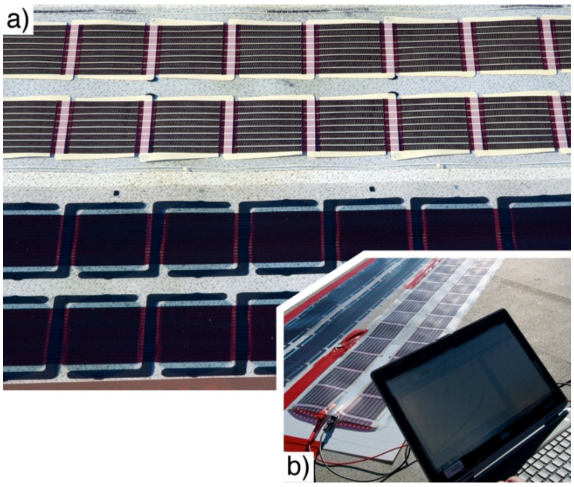

Fig 5. Printed silver electrodes (top) versus printed carbon electrodes

Beside the physical design the stack layout was also optimized throughout the project. The front electrode features flexo printed silver grids and very fast rotary screen-printed silver nanowire transparent electrodes. The transparent electrode stack passes light in a much wider spectrum compared to the former PEDOT:PSS electrode. The lifetime of the solar cells is also improved. The active layer material and its large-scale synthesis has been optimized and allows the fabrication of large-area solar cell modules with efficiencies beyond 4%. High performance active layer materials, cost efficient fabrication, repeatable output, and their availability in large quantity is crucial for the polymer solar cell upscaling to industrial level. Flow-synthesis allows an efficient fabrication of such materials.[4] The initial efficiency of the solar park installation with foil lengths close to 50 m and an overall active area

> 16 m^2 was 3.55% while the alternative installation type based on thermo-insulation plates reached 4% measured in winter at temperatures below zero. The efficiency will be beyond 4% at higher temperatures and better inclination of the sun.

The encapsulation of the solar foil was performed at high speed of several meters per minute using roll-to-roll methods with UV-curable adhesive and pressure sensitive adhesive. The electrically tested solar foils are edge sealed to prolong lifetime and robustness. Part of the improved lifetime to several years are optimized contacting and end-sealing methods that will be detailed in the next section.

The long-term outdoor performance of the rolled-out solar cells is very promising with an extrapolated lifetime of several years based on >15000 hour of continuous recording. The lightweight solar panels based on insulating roof plates are expected to perform even better due to less stress during fabrication and optimized electrical connection. A T80 lifetime of 5 years is expected but outdoor data is currently only available for the winter season 2016/2017. Seasonal increase in efficiency will be observed in spring and summer.

1.3.2 Work package 2 – the installation

The overall goal of WP2 was to increase the installation rate from the current 100 m min^{-1} to 300 m min^{-1} and the de-installation rate from the current 200 m min^{-1} to 300 m min^{-1}. Another target is to demonstrate simultaneous installation and de-installation at the same rates. The essential part was to implement alternative mounting surface with improved water drainage and electrical insulation properties as the INFINITY solar foil concept is a high-voltage installation beyond 10 kV per 100 m long module.

The solar foils are manufactured continuously with length of several hundreds of meters and stored on rolls for further processing. The deployment by rolling out and fixing with tape has been improved throughout the duration of the project. An optimized installation wagon, better tape handling and experience led to installation speed beyond 100 m min^{-1} just limited the human running speed of the wagon operator. Faster speed could be easily achieved by an autonomous installation.

The first solar foils were fixed with tape directly to the wooden plates or PVC plates that did not allow ventilation with the result of water accumulation on the backside of the solar foils. Removing the solar foils was carried out by a very fast roll-up and moving of the wagon. The de-installation speed was at least as fast as installation. A simultaneous procedure is feasible, but was not carried out to avoid eventual damage of valuable solar foils.

An improved mounting surface was found with flexible plastic mesh that had been fixed on top of the wooden plates as can be seen in Figure 2 and 6. This new surface makes the installation process much smoother compared to the wooden surface, that experienced deformation by swelling. The mesh effectively avoids water accumulation on the backside and shows suitable adhesion properties to the tape used for mounting the solar foils. Although the tape shows some optical deterioration, it still holds the solar cells in place after almost 2 years of outdoor operation.

Fig 6. Photograph of the solar park with five lines of bidirectional INFINITY foil mounted on plastic mesh. The four lower ones employ the high-performance polymer.

The electrical connection and sealing methods for the solar foils have improved significantly from the first large solar park installation to the latest deployments. The early solar foils had snap buttons punched through and connected with printed electrode. This leads to mechanical stress around the electrical contacts points and is potentially a starting point for increased degradation. The end of the solar modules was covered with polycarbonate plates and sealed with polyurethane on-site. In the final large-scale roll-out deployment as shown in Figure 6 the solar foils were cut to length and connected in a similar fashion, just indoors. The installation is still in operation and produces energy.

The deployment of solar foils directly from the roll is innovative and fast, but requires optimized mounting surfaces and special equipment for the unrolling. We therefore searched for another procedure to install large areas of polymer solar in a fast and easy way. Our alternative method is based on commercially available thermos-insulating polycarbonate roof plates where we attach solar foils. These lightweight plates are available in virtually any size due to their extrusion-based fabrication method and can have various thicknesses, transparencies and thermos-insulating properties.

We explored several methods for integrating INFINITY solar foils into roof plates. Attaching the foils using pressure sensitive adhesive is the most promising procedure that requires only littles and excludes liquid adhesives, high temperatures and vacuum. It takes only 5 minutes to attach several stripes for further processing on plates with sizes of up to 2.5 x 8 m (Figure 7).

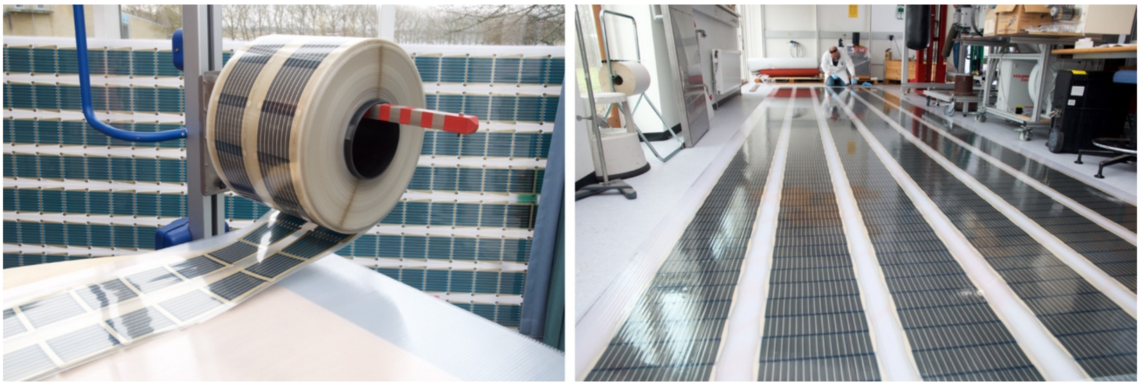

Fig 7. Roll of solar foil that is attached to thermo-insulating roof plates of very large size.

The solar roof plates use the most improved method for contacting and sealing (Figure 8). The electrical contacts at the end of each edge-sealed foil are opened using little to no mechanical stress (e.g. through laser scribing). Short metal bus bars are embedded for serial connection of the ends or to connect external cables.

Only the end of the foils is sealed with a cover foil and light-curable adhesive. This process is very fast and consumes only very little material which lowers cost and environmental impact.

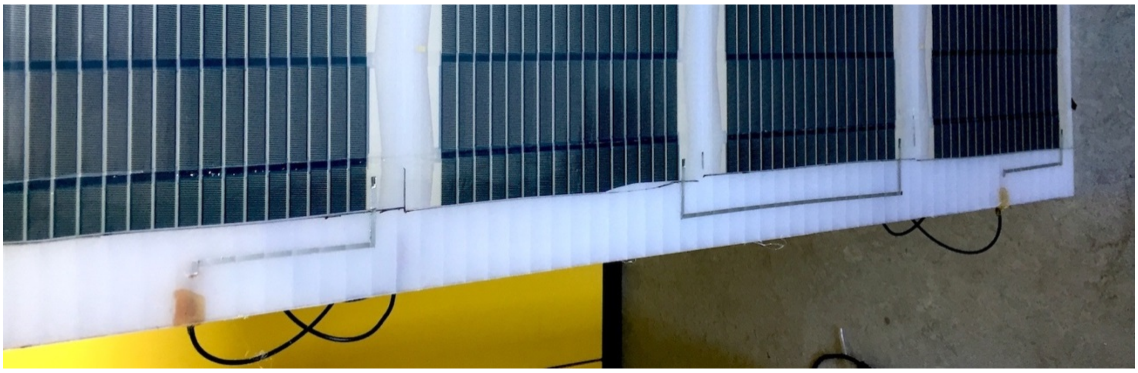

Fig 8. Thermo-insulating roof plate with solar foils and improved contacting through flat metal bus bars and (transparent) cover foil to seal the open ends of the solar foils.

Flat metal bus bars for electrical contacting can also be used to repair the solar foil in case of damages during the operation. Scratches, pinholes, burn marks through hot spots can be bypassed by opening the solar foil at two adjacent electrodes and attachment of flat metal bus bar tape. An additional patch of cover foil hermitically seals the damaged area. Solar panels repaired using this method only loose a minimal portion of active area but fully function without the need of exchanging and disposal of an entire module.

Large-scale grid-connected polymer solar cell installations carried out within the MEGAWATT project are based on rolled-out solar foils (Figure 6) or roof plate solar panels in different sizes of around 3 m^2 to 20 m^2. The panel with a size of 2.5 m x 8 m is by our knowledge the world-largest single-piece solar panel ever produced. Although the size is huge compared to traditional solar panels the weight is very small with some kilograms that allows easy transport (Figure 9). The flexibility of the panels and their integration potential in building structures is demonstrated with a solar carport.

The largest solar installation with four connected stripes of roughly 50 m length has been set up in June 2015 (Figure 6) and is still under operation with good results presented in the next section. Furthermore, 16 roof plate solar panels of various size have been installed during winter 2016/2017 as shown in Figure 10 with grid and battery connection in January 2017. Further long-time outdoor studies are necessary to select the most viable installation method but based on the handling and ease of installation it is potentially the panel based system. It does not require special equipment for installation on-site since all necessary preparation steps are carried out indoors in a safe environment. The solar panels can be tailored to required voltages and allow more freedom in for the deployment.

Fig 9 Solar roof plate panels are lightweight, flexible and fabricated in various sizes.

Fig 10 Various solar roof plate panels installed on wooden scaffolds and utilized as solar carport

Water-based deployment of polymer solar cells has not been addressed due to known risks of destruction at extreme weather condition known from the preview studies, necessary safety measures with respect to high voltage in conjunction with water.

As an additional study, we investigated alternative land-based installations on African homes in Rwanda (Figure 11) in collaboration with Imperial College London (UK). For this purpose, 0.5 m long solar foils were customized and designed for increased mechanical stability and protection to withstand the harsh testing conditions in Rwanda. We chose simple office lamination pouches as environmental protection due to their simple processing and low cost.[5]

The collected data indicates that the modules performed well even though the temperature on the rear side of the modules reached 70°C. It turned out that clear plastic office lamination pouches become brittle under intense sun light and UV irradiation leading to water and dust ingress. It is therefore not recommended as long term encapsulation under extreme climate conditions. The reference samples kept in Denmark did not show such destructive behaviour. Nevertheless, cell area unaffected from damages show only a slight drop in performance after >3000 hours outdoor.

Fig 11. Polymer solar cell foils installed in Rwanda

1.3.3 Work package 3 – the operation

Work package 3 focuses on grid-tied electrical energy production. The installed solar foil resulting from the work done in WP1 and WP2 is evaluated in terms of its ability to produce electricity in large scale. The energy produced has been monitored and supplied to the electricity grid, either directly or after temporarily storage in a battery bank. Grid connection requires down conversion of the high voltage generated by the INFINITY solar foil and inversion to grid standard.

The main technical achievement in WP3 has been the successful development of DC/DC converters with relatively low power that can step down the high voltage generated by the installed INFINITY foil, i.e. voltage in the 1-10 kV range, to DC levels below 1000 V in a safe and efficient way. There is no such high-voltage (HV) converter for photovoltaics available on the market. Stepping down to below 1000 V will allow us to access the grid via commercial PV inverters and thus simplify the connection to the main grid. All HV converters available on the market for more than 1kV are designed for high power ranges, so their sizes and costs are not appropriate for polymer solar cell applications. We designed a specific HV converter following these two goals:

1. Ensure the safety of operation, managing the HV levels from the solar foil modules to safer and usable voltage ranges for typical loads, e.g. direct connection to the LV grid or supply of LV batteries.
2. Optimize cost and efficiency of the power chain, trying to minimize the cost of kWh from OPV as much as possible.

The key idea in the converter design is "splitting the problem", i.e. splitting the voltage down to regimes that can be safely handled by standard electronic components, and thereby avoiding highly specialized, high-voltage components with correspondingly high cost. In the initial phase a 50 W converter prototype for stepping down from 1 kV to 12 V has been designed and built. A 4-stage topology was chosen for this where each stage steps down from 250 V. The 50 W converter was used for monitoring a 1 kV_p capacity installed in the solar park. The converter is also suited for small autonomous OPV systems working with regular 12 V batteries as for example the system tested in Rwanda.

Based on the successful proof of the splitting concept, two larger multi-stage converters were developed with up to 8 kV input and improved transformer design. The HV DC/DC converter prototypes have been tested in the laboratory showing peak efficiencies of up to 97.7% and typically >95% for almost any load condition. This is already at the level of high-end commercial DC/DC converters working in the sub 1000 V range.

To ensure the HV isolation between the primary side (>5kV) and the user or the second power stage, the converter must contain a strong galvanic isolation. Our first large prototype was intended to bear up to 8 kV in the input, so we designed a HV transformer with 25 kV of isolation. However, this level of isolation implies great distance between primary and secondary windings so a high leakage inductance was expected in the HV transformer. To overcome this disadvantage, we chose a LLC resonant topology for the converter. This topology integrates the leakage inductance of the transformer into a resonant tank which is the core of the converter. Switching the input of the converter at the resonance frequency of the resonant tank, the energy is transferred from the primary to the secondary of the transformer with a very high efficiency, typically above 95%. The transformer and resonant tank is designed for an optimum resonant frequency of 100 kHz that allows a compact size of the transformer.

To avoid the use of expensive components, the power stage (resonant tank plus transformer) was designed to bear up to 1 kV at the input with a nominal power of 300 W. Eight identical stages were connected in series at the inputs and in parallel at the outputs. In this way, the eight power stages are switched coordinated and they share the input voltage and the total converter can bear up to 8 kV at the input. The output of the converter is safely isolated. More importantly, we use cheap and available components. For the first prototype the cost per kW for the converter was 352€ (estimated for a production of 1000 units and still including customized HV transformer).

Figure 12 shows the 8-stage prototype installed in the control room near the solar park. The converter is connected to a commercial grid tied PV inverter, which is in charge to inject the energy to the LV grid and track the maximum power point

(MPP) of the solar cells. The system is in trouble-free operation since July 2015 and connected to 4 rolled-out solar foils as shown in Figure 6. A computer with monitoring software specially developed for the converter logs voltages and currents at the input and output side and uses Bluetooth connection to the master controller.

Fig 12. 8kV/1kV HV converter with eight stage and 2.4kW of nominal power.

In the final year of the project we have built and installed a second HV converter prototype. It is almost a copy from the first one but introduces to improvements which makes it a pre-industrial device. The power stages are the same but we have reduced the cost and space per stage with improved integration and use of components.

The electronics and enclosure have been prepared for outdoor conditions with a RS-485 connection instead of Bluetooth. This allows longer communication distances and possible chain-connection for multiple devices. All the HV devices (>1kV) are now placed inside the fence limits increasing the safety of the solar park facility.

The new converter contains a HV isolated feedback loop from the output to the input using a fibre-optic link to place the master controller at the output. This capability allows a better control of the output with improved robustness of the power link to the next power stage and grid-tied commercial inverter. It also avoids the need of a dump load at the output, reducing space and costs, and opens the possibility to more complex control strategies. For this prototype, the cost per kW was reduced to 266 € (estimated for a production of 1000 units). The improved converter (Figure 13) is installed outdoor in the solar park since January 2017 and connected to thermo-insulating roof plate solar panels with 6 kV_p/280 W_p as described earlier.

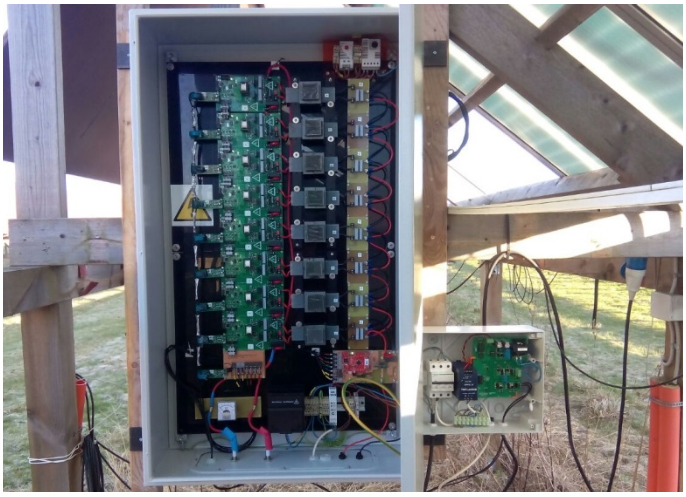

Fig 13 Second optimized HV converter connected to thermo-insulating roof plate solar panels.

In the laboratory, we were simulating the working conditions of the HV converters with a custom-built 2kW/1kV variable load. The load enables the simulation of the electrical behaviour of a battery-bank or the grid-tied inverter. In the solar park the variable load, together with the HV converter, allow us to trace HV current voltage curves from the installed solar foils. This is the very first high-voltage IV curve tracing in the world and an important milestone. A portable version of the HV tracer allows us to measure high voltage solar systems in the field.[6]

To accomplish the one day storage (ODS) battery system, we have setup a commercial hybrid inverter at the output of the HV converter. The hybrid inverter can store the PV energy coming from the HV converter into a 48V/50Ah Li-battery bank or/and inject it to the grid. The setup is running since late January 2017 but requires better weather conditions between spring and summer 2017 to present actual long-term real-world results. The ODS system works well under simulated lab conditions and can also charge the ODS from the connected solar roof plate panels. All incoming data can be remotely controlled through a web interface.

Energy production

The polymer solar cell modules installed in the solar park are fully monitored and more than 100 million data points have been accumulated since June 2015. Logged data includes electrical parameters of the HV solar cells, produced energy (grid connected) and weather conditions (Figure 14). This allows a detailed analysis of the seasonal solar cell behaviour with respect of solar irradiance and temperature. All solar cells are still connected and the HV converter and inverter setup is running without any major problems.

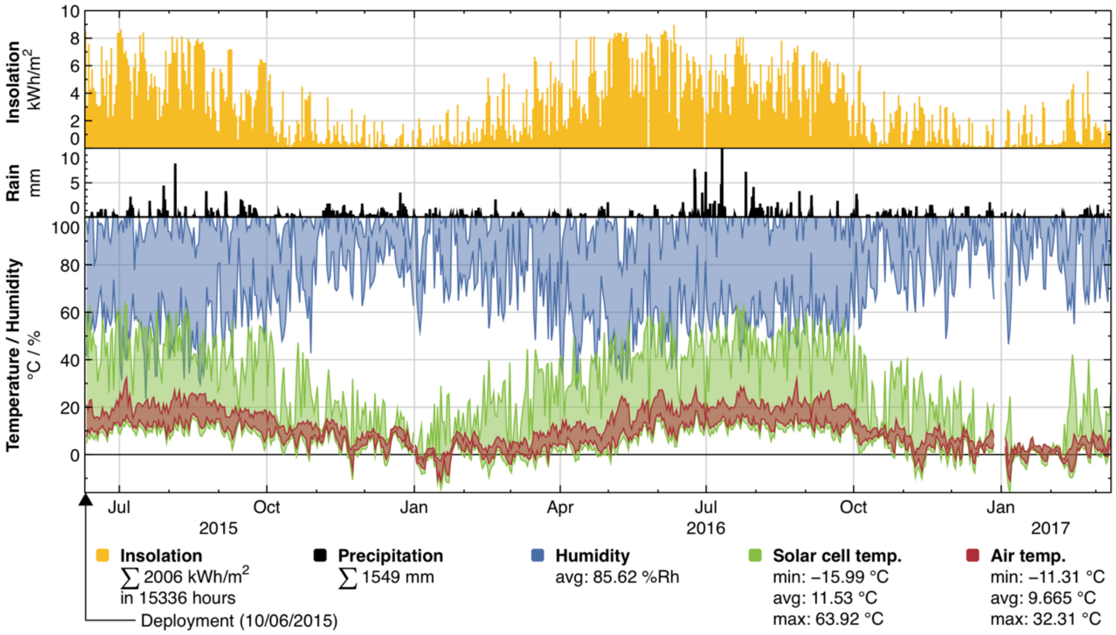

Fig 14. Weather conditions since deployment of solar foils in June 2015

In June 2015, four 30 cm wide solar foils of roughly 50 m length each were deployed and grid connected (Figure 6). The active area was around 16.8 m^2 at start but a major storm damaged one stripe that had to be removed. Therefore, only 75% of the initial setup is grid connected and monitored since December 2015.

From June 2015 to March 2017 the solar cells received an accumulated solar insolation of at least 2000 kWh/m^2 in more than 15300 hours of outdoor operation. More than 1500 mm rain precipitated while the air temperature varied between -11 and +32°C. The solar cells itself reached temperatures between -16°C and +64°C. Contrary to traditional silicon solar cells do polymer solar cells have a positive temperature coefficient and we see the highest performances on very hot days. The solar cell efficiency is strongly related to seasonal changes and we experienced an exceptional recovery close to 95% of the initial measurement between the two summers as can be seen in Figure 15. The trend for the second year is similar and the T80 lifetime is expected to be at least 4 years based on a 5% yearly drop.

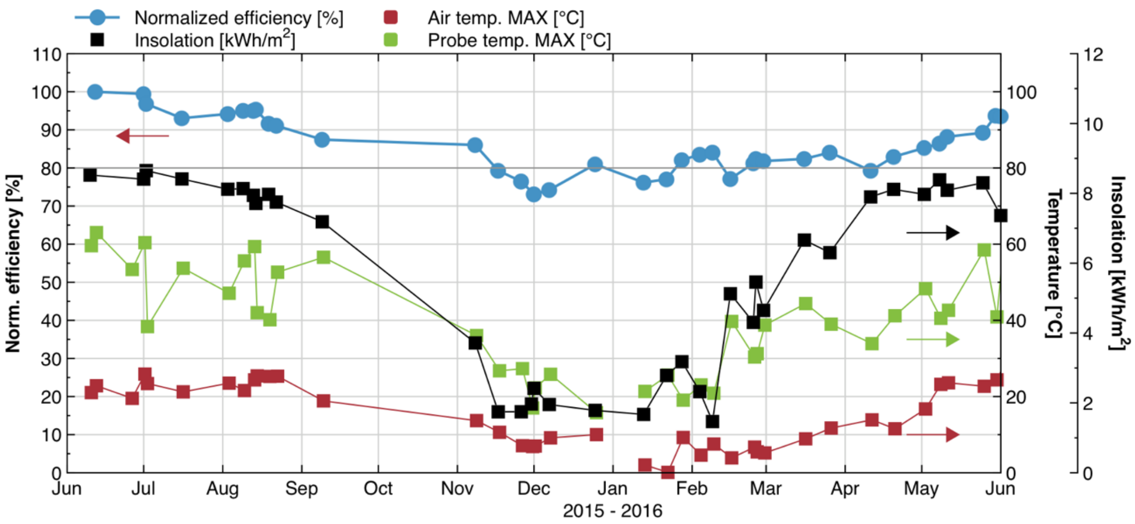

Fig 15. The efficiency of the polymer solar foils is correlated to temperature and insolation. Higher temperature and intense sunshine leads to highest efficiencies.

During the exceptional good and sunny July and August 2015 the power output on the HV side of the solar foils was between 600 and 700 W_p with 100 kWh of Energy produced within a month. The dummy load lowers the received power at the grid-tied inverter that does not operate in its optimal working point at this level of installed solar capacity. The system produces around 20% less energy for the grid. With more solar cells connected and the improved load-free HV converter, we can produce energy the polymer solar foils at a much higher performance ratio.

The rolled out solar foils (Figure 6) with an initial efficiency of >3.5% produced more than 455 kWh since July 2015 and early March 2017 (>14800 hours). During this time, the system was under maintenance with hardware/software improvements and tear-down of one of the four solar foils in November 2015. The weekly and lifetime energy production for the grid is illustrated in Figure 16.

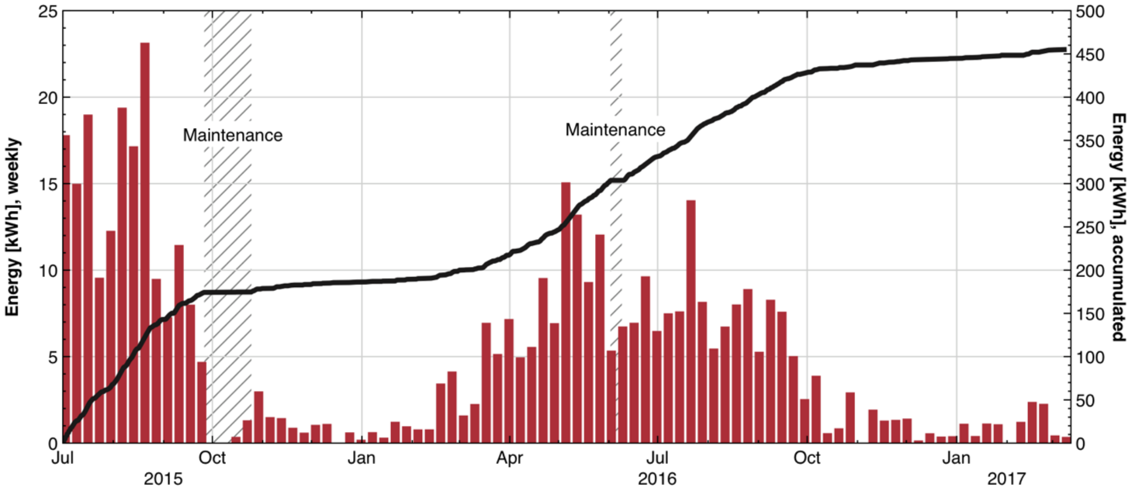

Fig 16. Weekly energy production (red bars) since grid connection of the solar foils in July 2015. Tear down of one out of four solar foils in November 2015 leads to a lower energy output in the second summer period. The active area efficiency just dropped by 5% between the two summers.

The economic feasibility of OPV installation

The economic feasibility of OPV installation at Megawatt scale has been analysed intensively by Gaia Solar and Energiemidt. The two partners developed complex tools to calculate the levelized cost of energy (LCOE) and conclude on technical requirements based on a variety of inputs and assumptions.

In an information-based society technology will tend towards near zero marginal cost and technologies with such development pathways will be preferred.[2] However, the energy density per m^2 of renewable technologies must increase significantly for this to occur.[3] The recent global growth in photovoltaics above 1.3% of global electricity supply confirms that photovoltaics can contribute considerable amount of renewable energy to the energy supply.

The method of economic evaluation enables to benchmark different energy technology investments and scenarios. An Excel tool has been developed to calculate the LCOE based on the characteristics of the OPV, such as high learning curve, lower two-digit annual degradation rate, and autonomous installation and re-installation.

For making the energy transition to a low-carbon society, the levelized cost of energy (LCOE) is a main method of evaluation. The LCOE refers to the cost of generating energy, by accounting for the energy production as well as the projects costs.

$$LCOE = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Energy\ Production}$$

Determining the set of financial assumptions is the priority in applying any economic scenario analysis. The financial assumptions depend on the project, stakeholder's interests, and external factors. The factors include time, investor type, industry, risk profile, immaterial properties and maturity of technology. For a defined project, stakeholders, and periods of time, these assumptions are relative stable, allowing one to assume that the financial assumptions in fact are stable. For this project, the following assumptions will be applied:

- Marginal sales price of electricity: 0.08 €/kWh
- Discounting rate: 2%
- Market inflation: 2%
- Electricity inflation: 2%

The Excel tool shows the simulation results and its correlation with the input parameters. Each aspect of the simulation is divided into descriptive categories such as: project planning, system design, cost-breakdown, OPV module and so forth. Specific to OPV, the degradation rate, redeployment rate and OPV learning rate is of interest.

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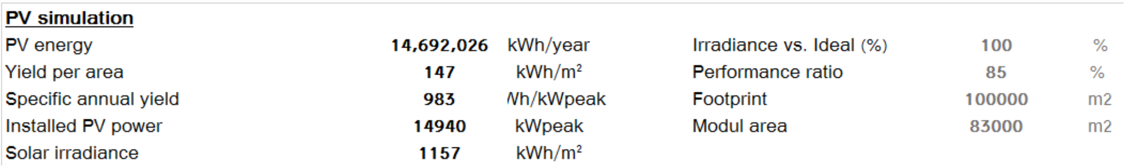
[2] *"Zero marginal cost society", Jeremy Rifkin*

[3] *"Energy Myths and Realities: Bringing Science to the Energy Policy Debate", Vaclav Smil*

For benchmarking the scenarios, the energy yield (kWh/year) of the PV system is simulated. The results of an exemplary PV simulation are as followed:



PV simulation					
PV energy	**14,692,026**	kWh/year	Irradiance vs. Ideal (%)	100	%
Yield per area	**147**	kWh/m²	Performance ratio	85	%
Specific annual yield	**983**	Wh/kWpeak	Footprint	100000	m2
Installed PV power	**14940**	kWpeak	Modul area	83000	m2
Solar irradiance	**1157**	kWh/m²			

For this investigation, the emphasis is on a microeconomic evaluation of the cost-effectiveness of different scenarios. The macroeconomics impacts regarding the composition of the electricity mix will be outside this scope.

The potential knowledge feedback mechanism for product with a lifetime of 5-10 years is inherently high. The OPV degradation rate is specified with of 10% per year. To capture the economics of OPV, or rate of change of economics of OPV, one can describe the learning rate in the following ways:

a) Apply an averaging or selection of learning curves of other relevant photovoltaics technologies and apply it to OPV modules.

b) Consider learning curves in a technological similar industry (e.g. production of displays, printed electronics)

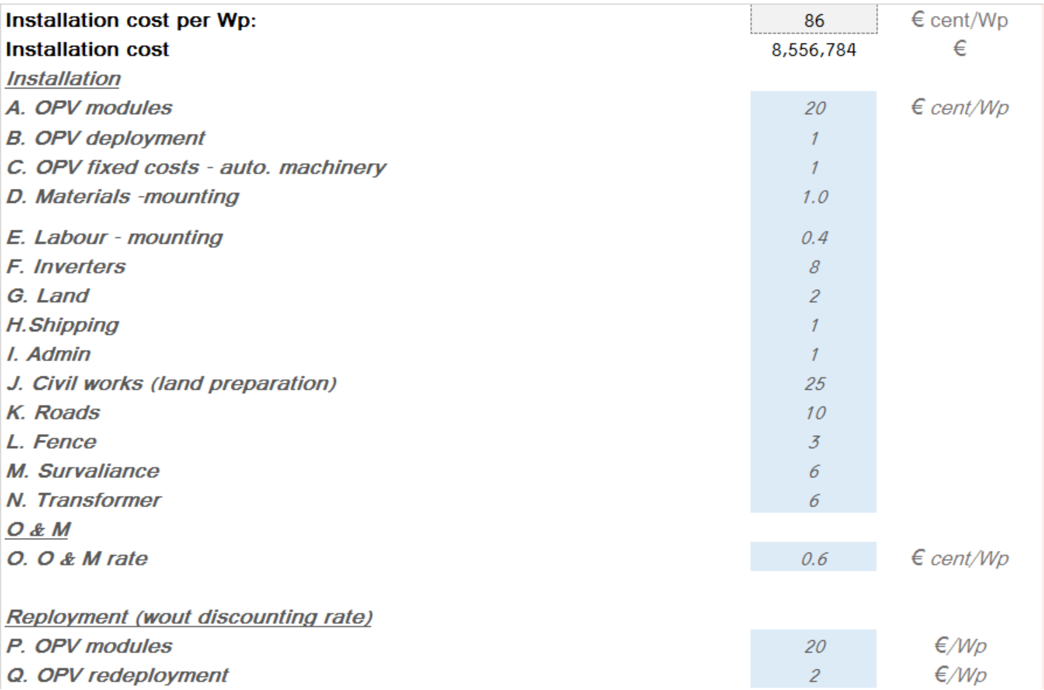
c) Consider learning rate of other roll-to-roll technologies with similar characteristic

d) Split up the learning curve into individual aspects and achieve a combined learning curve, and determine a minimum marginal cost.

Through examination, the learning curve of OPV is best understood as the combined learning curve of 1) research-intensive optimization of the efficiency of OPV in a roll-to-roll process and 2) cost improvements through emerging global market for relevant potentially low-cost raw material input.

For providing a comparison of the cost-effectiveness, two different scenarios are investigated. The scenarios are based on current (100 €cent/W_p) and future expected OPV module costs (20 €cent/W_p). The anticipated results will yield the economic output in terms of the rate of return of the investment (ROI, 5.42%), the payback time of the investment (14.84 yr), and a levelized cost of electricity (5.8 €cent/kWh).

Systems costs are based on specific cost estimation for OPV, relevant reference cost figures for crystalline PV technology, or calculated, where relevant. Figure 17 provides an overview of costs, where the OPV module cost is based on the futuristic assumption of 20 €cent/W_p.



Installation cost per Wp:	86	€ cent/Wp
Installation cost	8,556,784	€
Installation		
A. OPV modules	*20*	*€ cent/Wp*
B. OPV deployment	*1*	
C. OPV fixed costs - auto. machinery	*1*	
D. Materials -mounting	*1.0*	
E. Labour - mounting	*0.4*	
F. Inverters	*8*	
G. Land	*2*	
H.Shipping	*1*	
I. Admin	*1*	
J. Civil works (land preparation)	*25*	
K. Roads	*10*	
L. Fence	*3*	
M. Survaliance	*6*	
N. Transformer	*6*	
O & M		
O. O & M rate	*0.6*	*€ cent/Wp*
Replyoment (wout discounting rate)		
P. OPV modules	*20*	*€/Wp*
Q. OPV redeployment	*2*	*€/Wp*

Fig 17. System cost overview for OPV installations with module costs of 20 €cent/W$_p$

The system cost breakdown (Figure 18) for the installation of 100 €cent/W$_p$ OPV modules show that the OPV modules comprise more than half of the overall installed system costs.

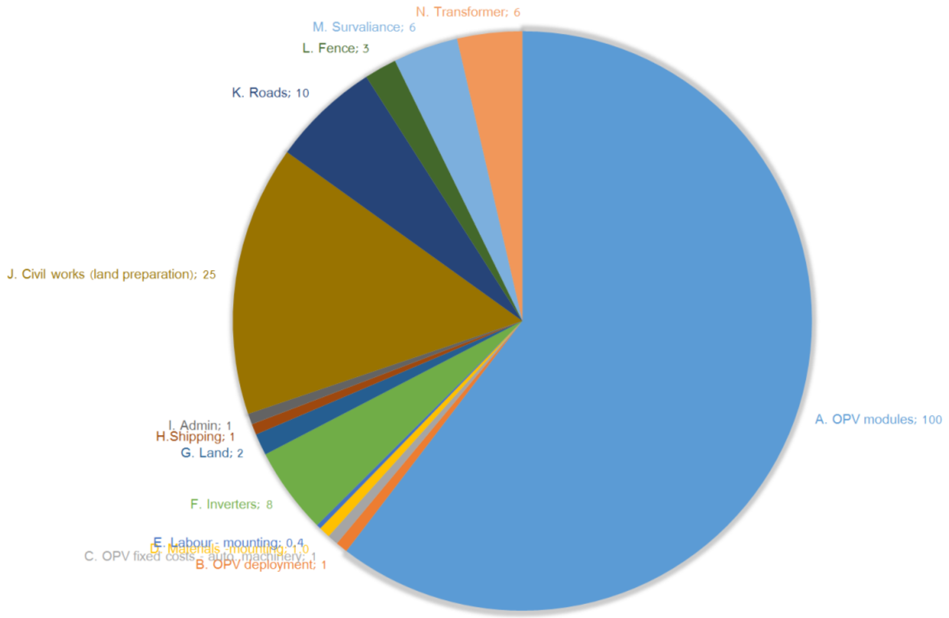


Fig 18. Installed system cost breakdown (in €cent/W$_p$) for 100 €cent/W$_p$ OPV modules

The LCOE equivalent system cost breakdown (Figure 19) considers the lifetime cost of each cost driver. The initial installed OPV modules (100 €cent/W$_p$) together with the redeployed modules compromise an even larger share of the lifetime costs.

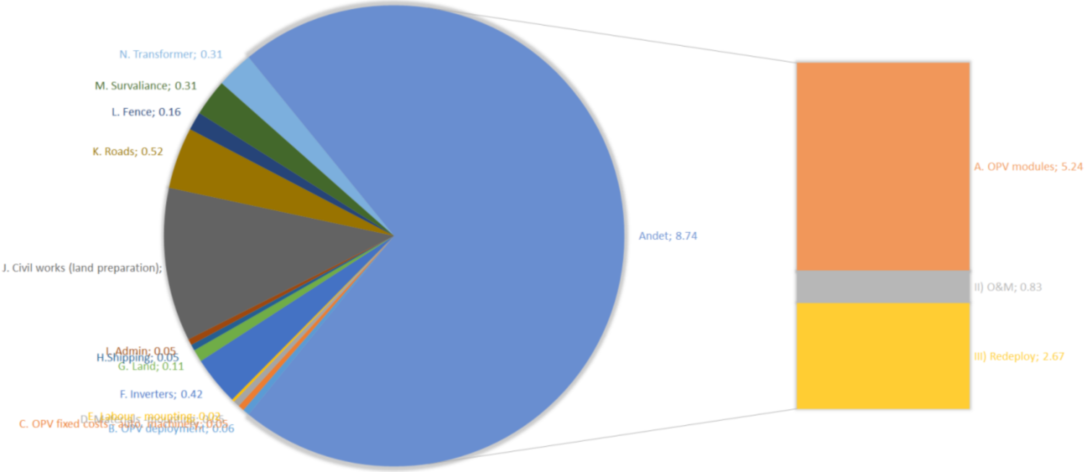


Fig 19. LCOE equivalent cost break down (in €cent/W_p) for 100 €cent/W_p OPV modules.

The cost breakdown for the future OPV module cost of 20 €cent/W_p changes the share remarkably and reveal that civil works and maintenance become the main cost driver (Figure 20 and 21).

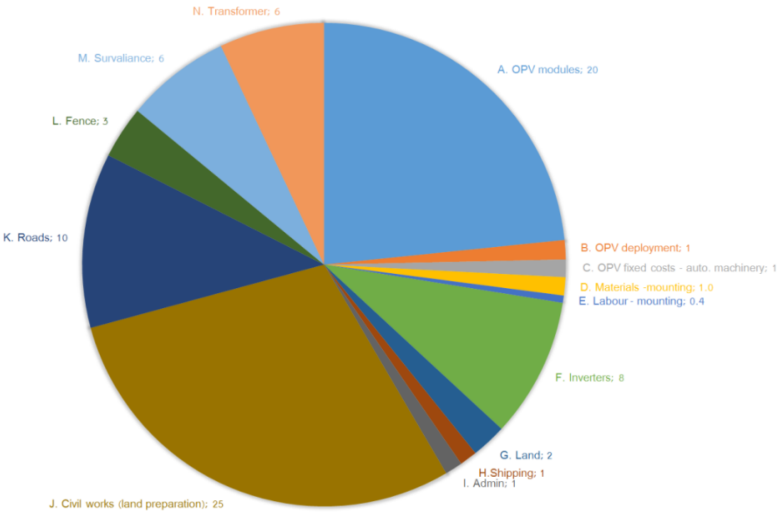


Fig 20. System cost breakdown (in €cent/W_p) for the future OPV module cost of 20 €cent/W_p

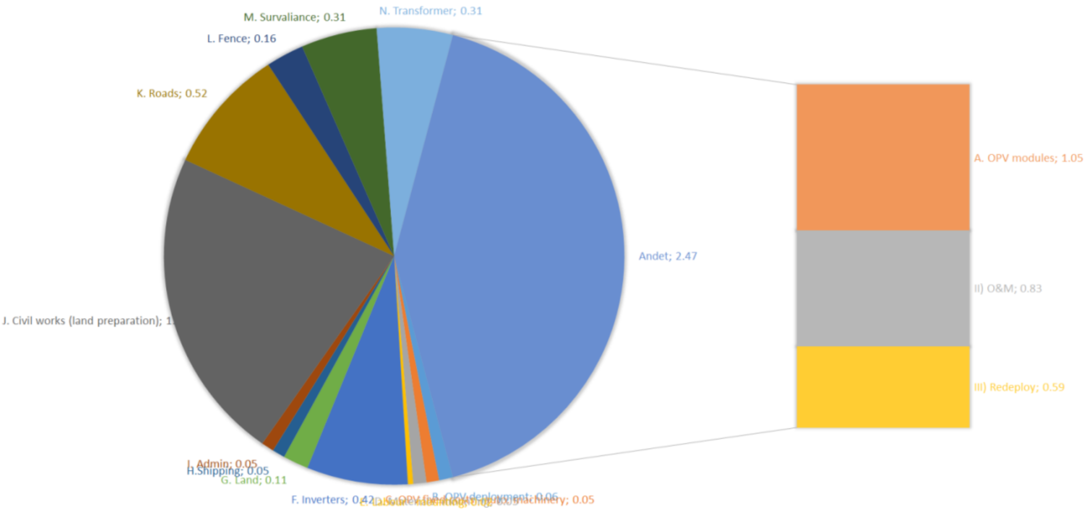


Fig 21 LCOE equivalent system cost breakdown (in €cent/W_p) for future OPV module cost of 20 €cent/W_p

A screening of degradation and efficiency shows the sensibility to LCOE (Figure 22).

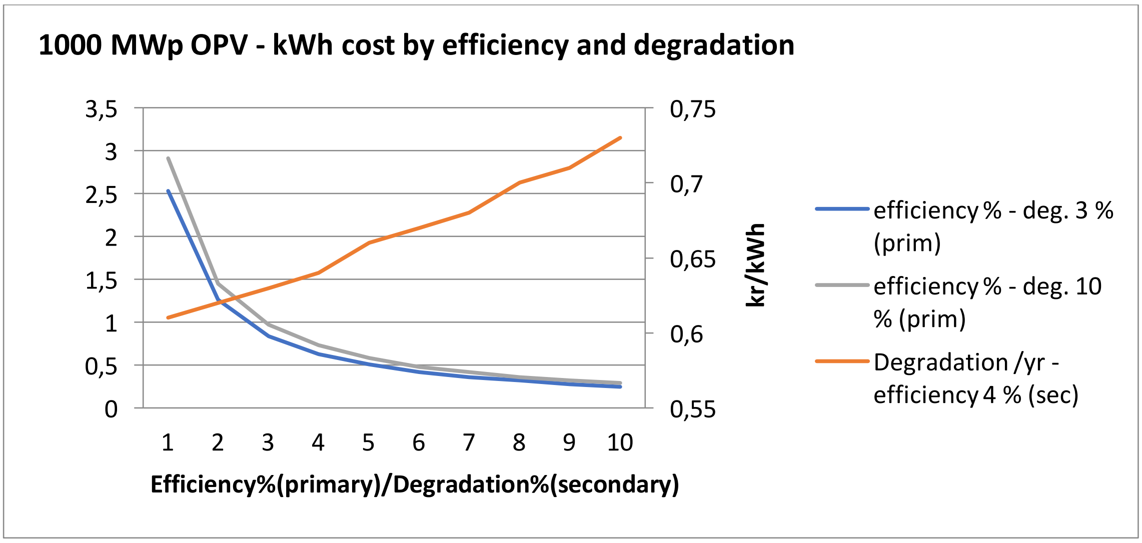


Fig 22. Parameter screening of degradation and efficiency for a 1000 MW_p OPV installation. Cost a given in DKK/kWh.

The blue and grey line in Figure 22 is the efficiency varying from 1 to 10% with a degradation of respectively 3% and 10%. It can be seen there is no big difference in the kWh price even with a more than 3-fold higher degradation. On the other hand, efficiency will impact the LCOE quite dramatically, from 1% to 10% there is a factor 10 in LCOE, going down from 3 to 0.3 DKK/kWh.

From the orange line in Figure 22 it can be concluded that by fixing the efficiency to 4% and changing the degradation input from 1 to 10% the LCOE only changes by around 16% from 61 to 73 øre/kWh. This implies that degradation is not very economic sensitive on the LCOE, if the efficiency is this low (4%).

Based on these results the focus for future projects should preferably rely on efficiency rather than degradation of the OPV modules.

As can be seen on 20 €cent/kW_p pie diagram (Figure 21) civil cost is a huge cost. This is due to the low efficiency that drives down the energy density and thereby the civil costs up. The less efficiency the more land must be occupied and purchased, but all other axillary civil costs (fence, surveillance, roads, buildings etc.) are also driven up due to the size of the plant. Therefore, the efficiency is a very important factor in the LCOE calculation.

In the parameter screening above, a plant of 1000 MW was used. However, it seems that the plant asymptote cost is reached at 100 MW as shown in Figure 23. One could argue it is already be reached even earlier below 50 MW.

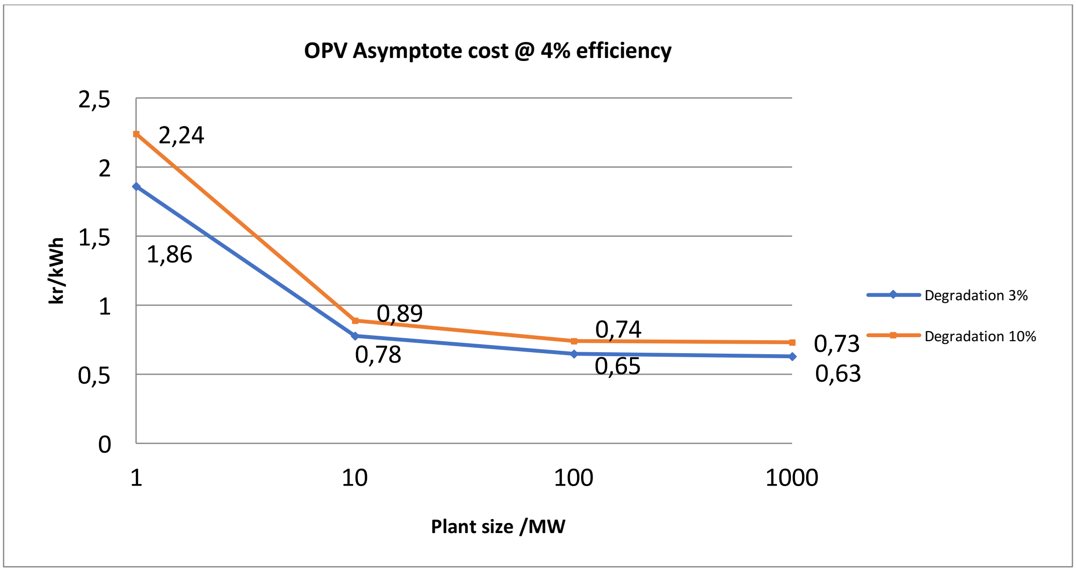
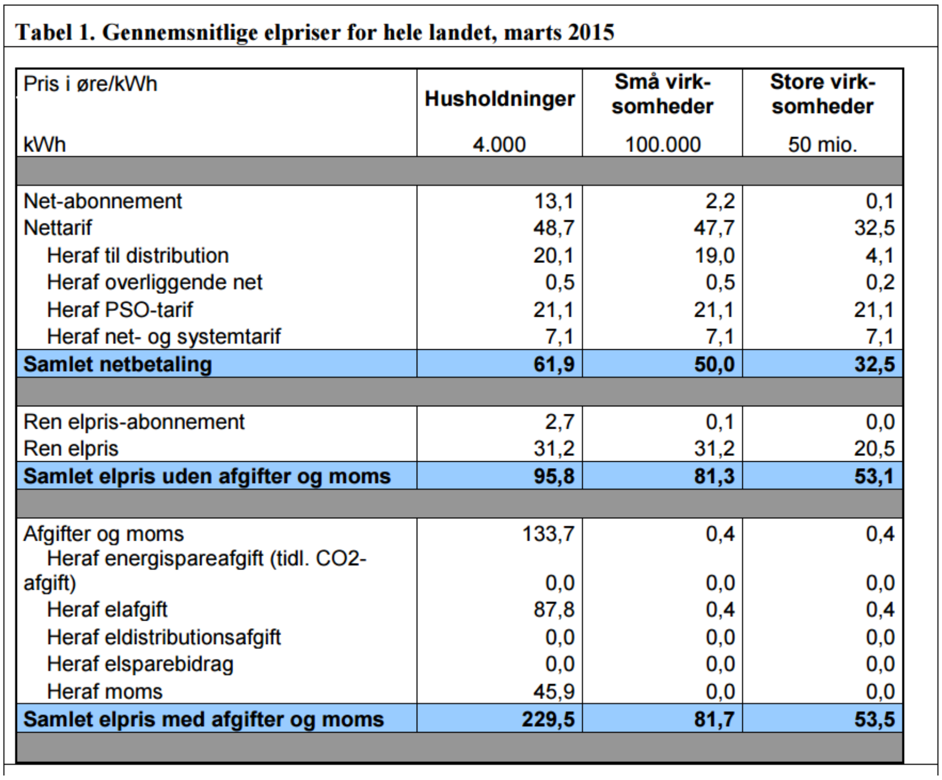


Fig 23 Asymptote cost depending on OPV plant size.

The typical electricity price in Denmark excl. VAT, PSO and energy fees is approximately 8 €cent/kWh (see Figure 24). The electricity price includes the spot price of electricity, cost of subscription, grid tariffs, cost of grid subscription.



Tabel 1. Gennemsnitlige elpriser for hele landet, marts 2015

Pris i øre/kWh	**Husholdninger**	**Små virksomheder**	**Store virksomheder**
kWh	4.000	100.000	50 mio.
Net-abonnement	13,1	2,2	0,1
Nettarif	48,7	47,7	32,5
Heraf til distribution	20,1	19,0	4,1
Heraf overliggende net	0,5	0,5	0,2
Heraf PSO-tarif	21,1	21,1	21,1
Heraf net- og systemtarif	7,1	7,1	7,1
Samlet netbetaling	**61,9**	**50,0**	**32,5**
Ren elpris-abonnement	2,7	0,1	0,0
Ren elpris	31,2	31,2	20,5
Samlet elpris uden afgifter og moms	**95,8**	**81,3**	**53,1**
Afgifter og moms	133,7	0,4	0,4
Heraf energispareafgift (tidl. CO2-afgift)	0,0	0,0	0,0
Heraf elafgift	87,8	0,4	0,4
Heraf eldistributionsafgift	0,0	0,0	0,0
Heraf elsparebidrag	0,0	0,0	0,0
Heraf moms	45,9	0,0	0,0
Samlet elpris med afgifter og moms	**229,5**	**81,7**	**53,5**

Fig 24 Electricity price in Denmark 2015

The LCOE of a OPV solar installation is 5.9 €cent/kWh for the scenario with a OPV module cost of 20 €cent/W_p, module efficiency 12%, learning curve rate of 20%, degradation rate of 10%/year, and re-deployment in 6 year periods. In conclusion, reaching these input parameter, the scenario becomes economic feasible with a rate of return of 5-6%.

Finally, the economy of battery storage (ODS) has been calculated exemplary for the Bulgarian electrical market. The average price estimations for Bulgaria 59,9 €/MWh (between 9:00-20:00) and 25,21 €/MWh (off peak hour). The difference between peak hour and off peak hour is 26,02 €/MWh. If you have one cycle per day (not possible due to lack of PV production) the yearly earnings would maximum be 26,02 * 365 = 9.496,39 €/yr/MWh. With an estimated battery life time of 10 years the lifetime earnings for the battery storage are 94.963,9 €/battery lifetime/MWh.

The target price per kWh to be able to pay back the battery before end of life is then 94,96 €/kWh.

The current estimated price per kWh in large quantities is 800€/kWh and the learning curve for Li-Ion battery-systems is estimated to be 18%. That means the accumulated volume must increase by 10,74 times before there is a business case based on CAPEX for battery systems today. In case the calculations use 250 charge cycles per year it would result in a kWh target price of 65,04 €/kWh with an increase of 12,65 times of accumulated battery volume production.

This calculation only applies to Li-Ion batteries and the Bulgarian electrical market. However, the target price can also be used for other technologies and markets when doing rough calculations.

1.3.4 Work package 4 – evaluation

The aim of WP4 is to deliver a life cycle analysis (LCA) and environmental impact analysis of the INFINITY solar foils in the solar park, with prime focus on the setting defined by the solar park.

The scope of the LCA is to estimate the cradle-to-cradle environmental impact for the solar power plant and their processes defined in work packages 1, 2 and 3. The project's first year has been dedicated to defining the system to be analysed and building the life-cycle inventory, and furthermore to initiate the collection of OPV-specific data required for analysing the environmental impact.

The analysed system comprises four sub-systems: the solar foil manufacturing, the installation, the operation and the disposal, including all the boundaries for each of these systems. The life-cycle inventory gathers all materials and energy needed for producing the INFINITY solar foil, for building the solar park and for installing the foil in the park. Data for processing and feed materials are as far as possible collected from the SimaPro LCA software, but when data is missing in SimaPro, data was extracted from own experiments and made compliant with the SimaPro format.

Calculation for previous solar installation with low-performing solar cells (2%) and estimated lifetimes of 1 year show that the energy payback time (EPBT) including wooden scaffold is 6 month considering an installation in southern Europe (Denmark 277 days).[7] The 1 year lifetime is underestimated and our results from the current installation clearly show a much longer lifetime with a couple of years. Longer lifetimes and still considering 2% efficiency lowers the EPBT to just 0.32 years. During the MEGAWATT project, we more than doubled the efficiency and kept the manufacturing comparable. As a result, the EPBT is likely to be much lower than 100 days.

The most probable biological and environmental impact of the solar park in operation is metal traces that are washed out by rainwater running over the installed INFINITY foil during the use phase. The possible leaching was investigated by collecting rainwater over a period of 6 month and subsequently analysed for trace metals, in this case silver (Ag) and zinc (Zn). The studies also include end-of-life (EOL) management, where different polymer solar cells were buried in soil to simulate uncontrolled or landfilling (Figure 25). All experiments and results are published in detail by Espinosa et al.[8]

Fig 25. Left: Rain run-off leaching setup with different silver and carbon-based solar foils, either intact or damaged on purpose. Right: mobile soil sequestration/leaching setup with solar foil buried in soil, either intact or shredded.

The solar foils tested in all experiments include silver and carbon based devices, that where either fully intact or damaged/shredded to accelerate metal leaching and simulate worst-case scenarios.

In the simulated use phase experiment, we found significant emission of both Ag and Zn for the damaged devices, whereas normally operating devices exhibited no emission, showing that emission-free operation is possible in a properly monitored system and emission can be avoided or significantly minimized if rapid action is taken upon failure. In the land filling scenario, emission of both Ag and Zn was observed, showing that recycling or recovery is mandatory and land filling is not recommended.

The cumulative element leaching (Figure 26) shows a virtually linear release of Ag to the environment from the damaged Ag-OPV modules, reaching 7.9 and 14.3 mg of Ag from 1 m^2 OPV over the six months. This corresponded to about 0.16–0.29% of the total contained Ag. Concerning Zn, the same linear leaching behavior was observed, reaching 65.7 and 79.0 mg of Zn from 1 m^2 OPV, corresponding to the complete release of the Zn contained. Pristine solar cells with intact encapsulation do not release any trace metals until delamination or small damages appear. This suggests a monitoring of damages during the use phase of the solar cells to prevent contamination of the environment.

The landfilling experiment leads to two clear observations: (1) A higher overall amount of Ag reached the soil matrix and leachates in the case of the shredded Ag-OPV, and (2) the deeper column layers showed an enrichment of Ag in the case of shredded Ag-OPV.

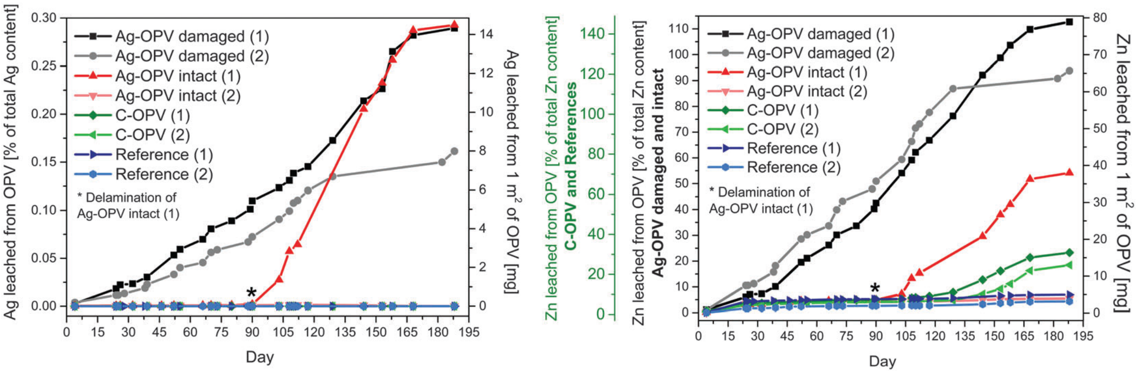


Fig 26. Cumulative Ag (left) and Zn (right) leaching from the samples in the rain run-off experiment conducted in duplicate. The amounts are expressed in mg per m2 of OPV (right axis) and the corresponding share of leached material (left axis). The asterisk "" is the point in time where the Ag-OPV intact sample started to delaminate.*

The homogeneous distribution of Ag and the absence of Ag in the leachate of the intact Ag-OPV soil columns indicates that the soil had a sufficient, inherent capacity of sequestering Ag. The migration of Ag towards the bottom of the column in the worst-case scenario (shredded), however, strongly points towards the fact that the natural sequestration capacity was exceeded, though break-through was not yet reached, even after a year of experiment.

In the case of Zn, we found a low natural content in the soil. Despite this very low content, the release of all Zn contained in the Ag-OPV modules would only increase soil Zn concentration by a factor of 3 to 4, to a concentration between 57–73 µg/kg, depending on the scenario. Since EU top soils contain as much as 52 µg/kg (median), the impact of OPV derived Zn can be considered minor. Similarly, the impact of C-OPV modules regarding Zn addition to soils can be considered minor, since they contained even less Zn than Ag-OPV.

From the leaching study, we derive three major eco-toxicological implications:

(1) Though little Ag was leached during the use phase, peak concentrations occurred after only a few days upon delamination, thus stressing the need to act fast upon failure to limit the release to the environment.

(2) Zn concentrations did not exceed even the most stringent drinking water limits at any time, and Zn is concluded to be of less concern.

(3) A more complete release of Ag occurred when shredded Ag-OPV were incubated in soil (15.7% of the total contained Ag), resulting in critically elevated soil Ag contents, thus highlighting that landfilling is not a viable option and Ag must be recovered from waste.

The threshold value for Ag in drinking water enforced by the World Health Organization (WHO) is at 100 µg/L. In this study, the measured rain runoff Ag concentrations exceeded this limit twice for one of the damaged Ag-OPV foils and the for pristine Ag-OPV after delaminating occurred. All the other Ag concentrations in the rain water remained below the WHO limit. Zn did not exceed any WHO limits.

It is important to point out that the quality of the encapsulation and the edge sealing during an outdoor use phase of OPV are essential both for lifetime performance and environmental concerns. The timely replacement of failed modules is thus not only needed from the electricity production point of view, but also to prevent peak concentrations of metals leaching upon delamination.

For the end-of-life management we also investigated recycling strategies to recover silver after incineration.[3] Recovery of silver from the electrodes of roll-to-roll processed polymer solar cells after incineration (Figure 27) has been performed quantitatively by extraction with nitric acid. This procedure is more than 10 times faster than previous reports and the amount of acid needed for the extraction is reduced by a factor of 100-150. The silver recovery efficiency is 100% compared to 95% by just using shredded cells.

Fig 27. Left: Picture of 1 m^2 of an organic solar cell rolled out on the ground. On the bottom left of the same picture an additional 1 m^2 has been cut into smaller pieces, tied up with heat resistant steel wire and put in a ceramic bowl inside the steel container. Middle: Picture of the oven setup with the steel container placed inside the high temperature oven with a controlled air flow. Right: Pictures of the cut up solar cells before and after incineration.

LCA studies show that the resulting environmental impacts from silver extraction of incinerated ashes are more favorable on almost all standard factors compared to extraction from shredded organic solar cells. The extraction time can also be reduced by a factor of 12. The so lessened environmental impacts by efficient recovery fully justify the use of Ag as an electrode in scaled production of polymer solar cells. Life cycle assessment scenarios show that recycling of silver by extraction from the ash generally has a 20% lower environmental impact compared to extraction from shredded cells.

1.3.5 Work package 5 – management & dissemination

Work package 5 was all about project management and reporting. We frequently met and communicated between the partners to share relevant information to fulfil the targets of the project.

The main results have been shared with the scientific and public community through scientific publications in recognised peer reviewed journals and on conferences:

[1] Hösel, M., Angmo, D., Søndergaard, R. R., Reis Benatto, dos, G. A., Carlé, J. E., Jørgensen, M., and Krebs, F. C., 2014, "High-Volume Processed, ITO-Free Superstrates and Substrates for Roll-to-Roll Development of Organic Electronics," Advanced Science, **1**(1), p. 1400002.

[2] García-Valverde, R., Villarejo, J. A., Hösel, M., Madsen, M. V., Søndergaard, R. R., Jørgensen, M., and Krebs, F. C., 2016, "Scalable single point power extraction for compact mobile and stand-alone solar harvesting power sources based on fully printed organic photovoltaic modules and efficient high voltage DC/DC conversion," Sol. Energy Mater. Sol. Cells, **144**(C), pp. 48–54.

[3] Søndergaard, R., Zimmermann, Y.-S., Espinosa, N., Lenz, M., and Krebs, F., 2016, "Incineration of organic solar cells: efficient end of life management by quantitative silver recovery," Energy Environ. Sci., **9**(3), pp. 857–861.

[4] Helgesen, M., Carlé, J. E., Reis Benatto, dos, G. A., Søndergaard, R. R., Jørgensen, M., Bundgaard, E., and Krebs, F. C., 2015, "Making Ends Meet: Flow Synthesis as the Answer to Reproducible High-Performance Conjugated Polymers on the Scale that Roll-to-Roll Processing Demands," Adv. Energy Mater.

[5] Emmott, C. J. M., Moia, D., Sandwell, P., Ekins-Daukes, N., Hösel, M., Lukoschek, L., Amarasinghe, C., Krebs, F. C., and Nelson, J., 2016, "In-situ, long-term operational stability of organic photovoltaics for off-grid applications in Africa," Sol. Energy Mater. Sol. Cells, **149**(C), pp. 284–293.

[6] García-Valverde, R., Chaouki-Almagro, S., Corazza, M., Espinosa, N., Hösel, M., Søndergaard, R. R., Jørgensen, M., Villarejo, J. A., and Krebs, F. C., 2016, "Portable and wireless IV-curve tracer for >5kV organic photovoltaic modules," Sol. Energy Mater. Sol. Cells, **151**, pp. 60–65.

[7] Krebs, F. C., Espinosa, N., Hösel, M., Søndergaard, R. R., and Jørgensen, M., 2014, "25th Anniversary Article: Rise to Power - OPV-Based Solar Parks," Adv. Mater., **26**, pp. 29–39.

[8] Espinosa, N., Zimmermann, Y.-S., Reis Benatto, dos, G. A., Lenz, M., and Krebs, F. C., 2016, "Outdoor fate and environmental impact of polymer solar cells through leaching and emission to rainwater and soil," Energy Environ. Sci., **9**(5), pp. 1674–1680.

[9] Roth, B., Reis Benatto, dos, G. A., Corazza, M., Søndergaard, R. R., Gevorgyan, S. A., Jørgensen, M., and Krebs, F. C., 2015, "The Critical Choice of PEDOT:PSS Additives for Long Term Stability of Roll-to-Roll Processed OPVs," Adv. Energy Mater.

[10] Hösel, M., Dam, H. F., and Krebs, F. C., 2015, "Development of Lab-to-Fab Production Equipment Across Several Length Scales for Printed Energy Technologies, Including Solar Cells," Energy Technology, **3**(4), pp. 293–304.

[11] Reis Benatto, dos, G. A., Roth, B., Madsen, M. V., Hösel, M., Søndergaard, R. R., Jørgensen, M., and Krebs, F. C., 2014, "Carbon: The Ultimate Electrode Choice for Widely Distributed Polymer Solar Cells," Adv. Energy Mater., **4**(15), p. 1400732.

[12] Carlé, J. E., Helgesen, M., Zawacka, N. K., Madsen, M. V., Bundgaard, E., and Krebs, F. C., 2014, "A comparative study of fluorine substituents for enhanced stability of flexible and ITO-free high-performance polymer solar cells," J. Polym. Sci. B Polym. Phys., **52**(13), pp. 893–899.

[13] Helgesen, M., Carlé, J. E., Helt-Hansen, J., Miller, A., and Krebs, F. C., 2014, "Generic roll-to-roll compatible method for insolubilizing and stabilizing conjugated active layers based on low energy electron irradiation," J. Appl. Polym. Sci., **131**(18), p. 40795.

Conferences & others:

1. Hanne Lauritzen: "Polymer solar cells - A significant player in our future energy supply?" Climate Kick Summer School, Risø, 28. August 2014
2. Markus Hösel, Frederik C. Krebs. Scalable Roll-to-Roll Fabrication for Fully Solution-Processed Polymer Solar Cells from Small-Scale Test Devices to Multi Square Meter Large Modules for Energy Production, MRS Fall Meeting & Exhibit, Boston, 3. December 2014
3. Hanne Lauritzen: "Nye solcelleteknologier: Polymere celler. Filosofien og teknologien bag – samt status: Hvor er vi nu?", Workshop og temadag om solceller, Teknologisk Institut, Århus, 24. November 2014
4. Hanne Lauritzen: "Polymer solceller i stor skala – forskning i plastsolceller", Lys, solceller og facader, Aalborg Universitet, København, 10. December 2014

1.4 Utilization of project results

Research on polymer solar cells in an academic context is with the termination of this project reduced to fundamental materials studies funded by the Innovation Fund Denmark (IFD) through the INKA project (focussed on higher efficiency materials as a highlighted need in this project) and the SEESOL project (focussed on new inorganic absorber materials). The main progress from now and onwards is to prove the commercial viability of polymer solar cells through industrial development. Commercial activities have been initiated by the start-up company infinityPV ApS that has the infinity patent (the patent that describes the infinity connection of OPV and the efficient extraction of power at high voltage). DTU decided to discontinue the maintenance of the series of patents that are now owned by infinityPV ApS. The industrial development must thus be lifted by infinityPV ApS both with respect to manufacture of the OPV solar foil and with respect to development of the high voltage electronics required to make efficient use of the energy harvested. The possibility for new academic research topics may be identified during the effort to commercialize and implement OPV into the system. If when this arise it may form the basis for fundamental research application but the main conclusion is that objectives can be met with OPV and the current need is for industrial development. A stakeholder is already active in this area so the results will naturally be propagated to infinityPV ApS.

1.5 Project conclusion and perspective

The project has been overwhelmingly successful. The MEGAWATT project has brought OPV to the level of a technology that can to be commercialized and implemented. There is no reason that it should be competitive on the market. Highlights are:

- HV solar cell foil can be produced on large scale with high efficiency and improved lifetime
- HV solar cell installation (roll out) works on large scale
- HV to LV conversion is highly efficient
- Grid connected polymer solar cells became a reality, direct or with ODS

- Alternative panel-like polymer solar cell modules potentially better for broader market (no special equipment need for installation)
- LCOE economically feasible for very large installation with very low module cost (20 €cent/Wp) and efficiencies of 12%
- Efficiency has more impact on LCOE than degradation
- Metal can leach in case modules are damaged
- Solar cells can be recycled with 100% silver extraction

1.6 Annual export of electricity (only ForskVE)

Not applicable for MEGAWATT project

1.7 Updating Financial Appendix and submitting final report

Update of Financial Appendix will be submitted within 2 month after submission of the final report.