PUBLIC

SE-POWERFOIL	**Roll-to-roll manufacturing for high efficient multi-junction thin film silicon flexible photovoltaic modules**
Project: SE-Powerfoil	**Contract number: 038885 (SES6)**

Deliverable number: SEPF5.1-DEL-20090928-Publishable Final Activity Report

PUBLISHABLE FINAL ACTIVITY REPORT

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Author(s):	Edward Hamers (HLT), Jaap Struijk (UNI)

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Sixth Framework Programme

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CONTENT

0 Executive Publishable Summary

0.1 Project Objectives

SE-PowerFoil focuses on high efficiency flexible thin film Silicon PV modules, produced in a roll-to-roll process on metal foil (in the superstrate or pin configuration). The objective was 12% (tandem or triple junction) aperture area stabilized PV foil modules, with more than 20 years outdoor lifetime and a proven outlook towards manufacturing costs below € 0.5/Wp once scaled up to mass production. This constitutes radical innovations over the state-of-the art thin film silicon PV on glass panels (which is batch-wise, with efficiency in production nominally 6 - 8%, at ~ 2.5 € /Wp production costs at beginning of the project).

The Scientific and Technical Objectives are:

Device potential:
High efficiency, *i.e.* 12% (tandem or triple junction) thin film silicon laboratory devices (= Demonstrators on 10x10 cm^2 substrates) using innovative, batch type, laboratory deposition processes, among others by:

- Development of new device architectures based on comprehensive optical light management model: optical grading and smoothing, functional nanometer thick interlayers, smart textures, nanostructuring of active layers;
- Development of novel high transmission (< 5% absorption), high conductivity (<10 Ohms/sq) natively textured, reactive hydrogen resistant, multilayered transparent conductive oxides by means of stable high throughput atmospheric CVD processes: multilayer with graded refractive index from 1.5 (top) to 2.0 (at TCO – top cell interface;
- Research on innovative fast and inexpensive deposition technology (Hot Wire CVD) for high quality and highly stable (<8% light induced degradation) active proto- and micro-crystalline silicon layers with lower intrinsic stress on foil substrates;
- Technology transfer from laboratory technology to both 30 cm roll-to-roll pilot line and 120 cm industrial manufacturing width.

Manufacturing potential:

- High rate (1 - 3 nm/s) industrial plasma deposition technology for high performance micro-crystalline silicon layer deposition (high pressure depletion RF/VHF, new electrode with optimal gas flows, novel efficient powering);
- Innovative deposition technology in the pilot line for novel TCO in high throughput thermal CVD deposition process, leading to substantial efficiency increase in pilot line process. (50% improvement of throughput per injection head, 50% longer uptime between cleaning cycles);

Outdoor lifetime and economic potential:

- Accelerated lifetime testing of high efficiency pilot line modules to demonstrate excellent stability in climate stability tests according to a/o IEC 61646 standard for thin film PV modules;
- Prototype flexible module (= Demonstrators) installed in representative outdoor monitoring stations for lifetime monitoring, demonstrating less than 2% performance decrease per year (based on stabilised performance specification) and improved yield (kWh/(kW_p*year) compared to existing PV technologies;
- Full economic assessment of €/kWh potential (< 0.10 €/kWh) of project results (aiming for maximum attainable efficiency, low cost production PV laminate technology (≤ 0.5 €/Wp) and long lifetime (≥ 20 yr).

0.2 Contractors Involved

The consortium (8 participants, representing 5 EU Member States and one Associated Member State) comprises one European manufacturer of flexible PV foils and modules, a company specialized in chemical vapour deposition technology, a company specialized in innovation management and new business development, two research institutes and three universities each with their own expertise in thin film silicon photovoltaic research and process technology.

Participant name (short name)	Country	Business Activity/Main Mission /Area of Activity	Contact persons / addresses
Helianthos B.V. (HLT)	NL	High tech company; 100% subsidiary of Nuon NV, a Dutch energy company. Main mission is to develop high-performance flexible thin film PV modules based on roll-to-roll manufacturing technology.	Dr. Edward Hamers Nuon Helianthos Westervoortsedijk 71k, 6827 AV Arnhem (Visit) Postbus 2134, 6802 CC Arnhem (mail) The Netherlands www.helianthos.com
CVD-Technologies Ltd. (CTEC)	UK	Small high-tech company (SME) specialized in thermal CVD deposition techniques and processes	Dr. David Sheel CVD Technologies Limited Cockcroft Building University of Salford Salford M5 4WT - United Kingdom http://www.cvdtechnologies.co.uk
Forschungs zentrum Jülich-Institute of Photovoltaics (FZJ-IPV)	DE	Research institute; Part of Forschungszentrum Jülich GmbH. Main mission is to develop highly efficient silicon thin film PV cells.	Dr. Friedhelm Finger Wilhelm-Johnen-Strasse 52425 Juelich – Germany http://www.fz-juelich.de/portal/
Institute of Physics, Academy of Sciences of the Czech Republic (IPP)	CZ	Leading university in the area of optical, electronic and structural characterization of layers and complete device structures, optical modeling	Prof. Dr. Milan Vanecek Cukrovarnická 10 CZ-16253 Prague 6 - Czech Republic www.fzu.cz/departments/optcryst
Laboratoire de physique des interfaces et couches mines (CNRS - LPICM)	FR	Leading research institute in the area of polymorphous top cells.	Prof. Dr. Pere Roca Route de Saclay 91128 Palaiseau- France www.lpicm.polytechnique.fr
Uniresearch B.V. (UNI)	NL	R&D and business development company (SME)	Dr. Jaap Struijk Uniresearch B.V. Elektronicaweg 16c 2628 XG Delft The Netherlands www.uniresearch.nl

University of Salford (USAL)	UK	Leading university in the area of fundamental studies of gas-phase and surface phase CVD for preparing novel materials such as TCO's.	Dr. H.M. Yates Engineering and Physical Sciences University of Salford Newton Building Salford M5 4WT - United Kingdom
University of Utrecht (UU)	NL	Leading university in the area of hot wire CVD techniques and triple junction cells	Prof. Dr. Ruud Schropp Princetonlaan 4 3508 TA Utrecht – The Netherlands www.phys.uu.nl/SID

0.3 COORDINATOR CONTACT DETAILS

Co-ordinator name	Dr. Edward Hamers
Co-ordinator organisation name	Nuon Helianthos B.V.
Co-ordinator email	edward.hamers@nuon.com
Co-ordinator phone	+31 26 365 1121
Co-ordinator fax	+31 26 365 1250

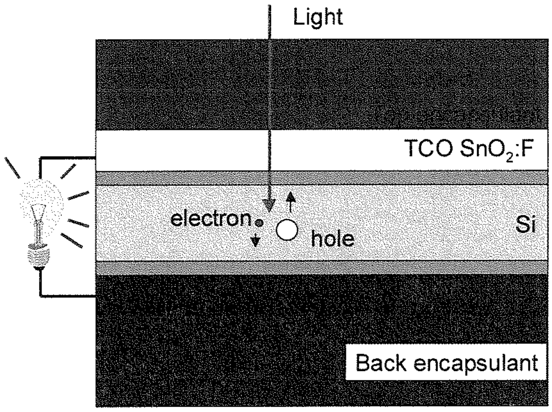
0.4 Work performed and End Results achieved

SE-PowerFoil aimed at the development of roll-to-roll manufacturing technology for production of high-efficiency flexible photovoltaic (PV) modules. The overall objective is 12% (tandem junction) aperture area stabilized PV foil modules, with more than 20 years outdoor lifetime and a proven outlook towards manufacturing costs below € 0.5/Wp once scaled up to mass production.

The workplan focused on the following key issues: a) use of low-cost base materials and minimal materials consumption for devices and improvement of the efficiency; b) reduction of the production costs and c) accelerated lifetime testing (acc. IEC 61646) and outdoor monitoring.

A. Thin film Si cell efficiency

All thin film Si solar cells, flexible or rigid, have a common working principle. A schematic of the simplest thin film Si solar cell is given in Figure below. Such solar cells are essentially built up by only a few component layers. We will very briefly describe these layers, and their relevance to the objective of this project.



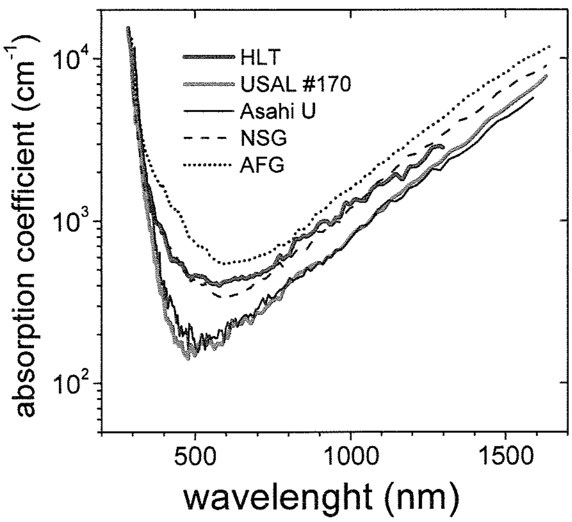
Structure of a photovoltaic cell and its principles of operation

The active Si layer stack is the heart of the photovoltaic device, in which the light is absorbed and converted into electrical energy. The most widely used thin film Si devices make use of amorphous Si (a-Si) layers. These can be found in a-Si cells or a-Si/a-Si tandems. If the ma terial is grown under yet different conditions, thin film Si with varying degrees of crystallinity (microcrystalline Si) can be deposited Micro-crystalline Si (µc-Si) has a smaller bandgap than a-Si. Thus, with microcrystalline silicon layers a larger part of the solar spectrum can be absorbed. Microcrystalline silicon layers (µc-Si) can be combined with a-Si:H layers to form a **micromorph** (microcrystalline/amorphous) or '**hybrid**' tandem cell.
A drawback of using µc-Si is that the thickness of the thin film Si cell is enlarged by a factor 3 to 4 or even more. Given the significant extra capital investment needed to produce a tandem or triple device as compared to a single cell, it is always essential to ensure that the extra cost of the thicker stack is outbalanced by the higher cell efficiency. For this reason work on µc-Si has been combined successfully with research towards higher deposition rates (see also the next section, on production cost).

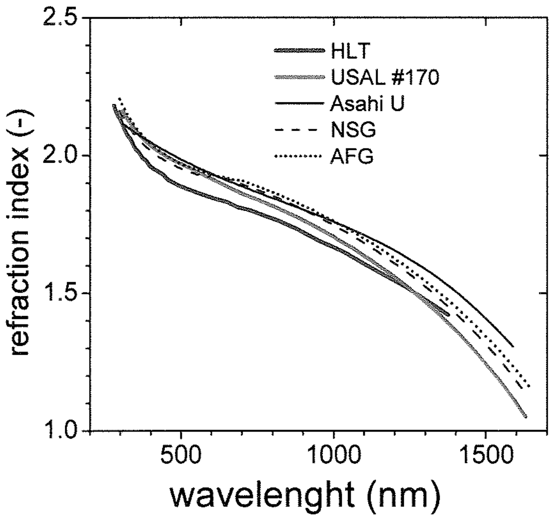
Two electrode layers are needed to conduct the generated electricity to the 'outer world'. At least one of these contact layers is a transparent conductive oxide (TCO) window layer. Since this electrode layer is facing the sun, it must be transparent, thus excluding the use of metal layers. A trade-off is always necessary between the TCO's optical transmission and its electrical conductivity. For pin structures, an additional challenge for the deposition of the TCO layer is to obtain sufficient electrical, optical *and* morphological properties. Surface morphology has a large direct influence on module efficiency, and hence on kWh cost. This is because a rough, textured, surface morphology will introduce light scattering that enhances the optical path within the Si layer. Although a lot of research has been done in this field the overall influence of the TCO morphology on cell efficiency is only partially understood on a fundamental level. The most common TCO materials used are: SnO_2:F, ZnO:Al and ITO. Apart from these electrical, optical and morphological demands, it is also necessary for the TCO layers to remain stable over the lifetime of the PV module. The back contact is usually a highly optically reflecting combination of metals and ZnO. The former layers conduct the electrical current, whereas the latter enhances the reflection of that part of the light that has not been absorbed in the Si layers during the first pass of the light. Hence, one can achieve much higher efficiency values by effectively controlling and optimizing the light scattering and reflecting properties of the front and back electrodes. This approach is sometimes called 'light management'.

2.1 Light management through improved light scattering by front and back electrodes
The light management has largely been devoted around the TCO development. On glass many different SnO2:F recipes have been deposited and their structural, electrical and optical properties characterized. This resulted in a-Si:H solar cells with efficiencies in the range of cells made on Asahi-U, but nevertheless still a few tens of a percent lower 9.1 vs 9.5%. However, growth rate and film structure are fundamentally related and a compromise required. A key aspect of the technology targeted for development within this project, was that it be based on high growth rates compatible with in-line production and lowest manufacturing costs. In this part of the work extensive sample exchange has been made between the different partner institutes

The light management has largely been devoted around the TCO development. On glass many different SnO2:F recipes have been deposited and their structural, electrical and optical properties characterized. optimal deposition conditions as far as the absorption loss in TCO were identified, results are better that comparable industrially available TCOs. nevertheless, the light scatteing properties has to be further optimized, some direction how to do it were suggested. Resulted a-Si:H solar cells have efficiencies in the range of cells made on Asahi-U.



Comparison of absorption coefficients of USAL, HLT and some commercial SnO_2 materials.

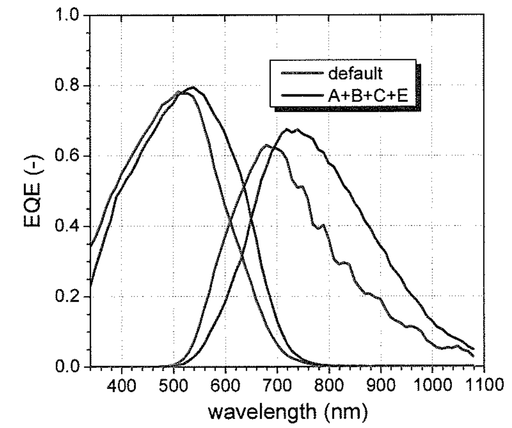


Comparison of refraction indices of USAL, HLT and some commercial materials

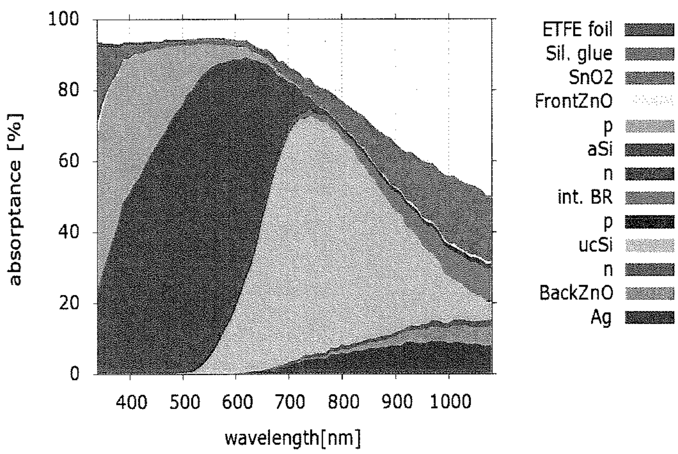
Although improvements have been made, the work on stable tandem modules on foil substrates has been shown the necessity to further improve the robustness of the module manufacturing process. Especially the interconnection process appears to be rather sensitive to the material structure and thicknesses of the different partner samples, resulting that on every sample the interconnection must be optimized individually. As a result the interconnection has often been a limiting factor for the performance. Light beam induced current measurements proved to be an efficient tool to monitor laser scribing and cell quality in the vicinity of laser scribbed lines.

The modeling work on light management and direct assesing of absorber material quality by Fourier transform photocurrent spectroscopy has shown that the quality of amorphous and microcrystalline silicon does not deteriorate due to deposition on Al foil (compared to the standard deposition on glass). It can be even better, compared to deposition on glass.

If we put together all improvements developed within this project simultaneously and successfuuly (and with a high reproducibility), we would come (results of modeling) to the short circuit current 12.1 mA/cm^2 and the cell efficiency 11.3%, as it is shown on Figures below.



EQE of 'best' structure with all improvements, after the current matching.



Absorptance diagram of 'best' structure with all improvements, after the current matching

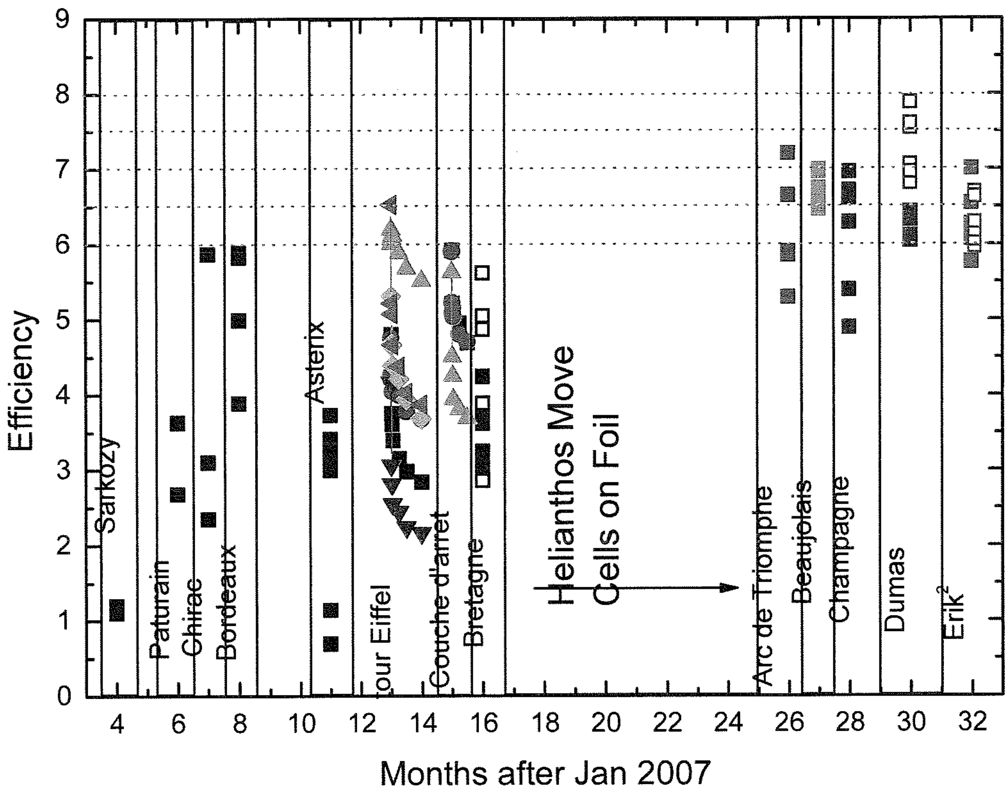
2.2 Foil modules with stable top cells

The goal of this task was to fabricate cells and modules made out of hydrogenated polymorphous silicon (pm-Si:H) and using the temporary foil substrate concept. This material is known to result in photovoltaic cells whose efficiencies possess superior stability when light-soaked. Work which was executed as part of the SEPowerfoil project included cell study/optimization which occured in-house at the LPICM, as well as studies that involved the cooperation of the project partners.

The primary efforts that involved project partner cooperation were the fabrication of pm-Si:H modules and cells on temporary foil substrates. This involved the production of the foil+TCO substrates at HLT, deposition of the active layers at LPICM, and the subsequent back reflector deposition and module processing steps being done at HLT. These cells were then tested at HLT for their PV characteristics, and the most promising samples were light-soaked to evaluate the changes in their performance during light-induced degradation. Over the course of the project, a total of 13 foil batch exchanges were performed, and these resulted in a total of 84 foils being processed at HLT after deposition at LPICM.

The table below displays the tremendous progress made within this Task. Each exchange of sets of foil substrates was given a nickname to aid in the rapid recollection of important elements that were learned at each step. Initial efforts to combine the two technologies – foil-substrates and pm-Si:H - were disastrous, and resulted in module efficiencies below 1.5% due to delamination and shunting problems in the cells that remained testable. Subsequent process improvements to ensure lamination and reduce shunting produced a jump in efficiencies, and by foil batch "Tour Eiffel", initial efficiencies above 6% were achieved.

However, variations within each batch resulted in the decision to use a "Cell on Foil" design, wherein individual cells rather than modules were produced and analyzed. This design process and an accompanying optimization programme at the LPICM during the HLT shutdown (indicated on the graph) resulted in dramatic improvements in cell efficiencies.



The foil batch exchange that was executed immediately after the HLT group had moved to their new location immediately reaped the benefits of the efforts of the partners on both sides of the cooperation. Efficiencies above 7% were observed for pm-Si:H devices for the first time, and clearer relationships between process conditions and cell performances started to emerge. Through further optimization and adjustment of the pm-Si:H process conditions to the foil substrate, the foil exchange "Dumas" resulted in an initial cell aperture area efficiency of 7.88%. These cells were left un-encapsulated to enable the changes in their performance over time, and by applying the gains in cell efficiency typically seen upon encapsulation, one can estimate an active area efficiency for these cells of 8.3%. Nevertheles, by project end, the measured value of 7.88% remained the highest efficiency achieved for pm-Si:H cells deposited on temporary foil substrates.

2.3 Micromorph lab modules on foil

The task in WP2.3 was to fabricate thin film silicon tandem modules on a lab scale (10x10cm²) by integrating all optimized building blocks which constitute the module and which are from pre-existing know how or developed with the individual tasks in the project. With this a world record efficiency of 12% stable for such an encapsulated module is aimed at as an ambitious goal. The individual building blocks include:

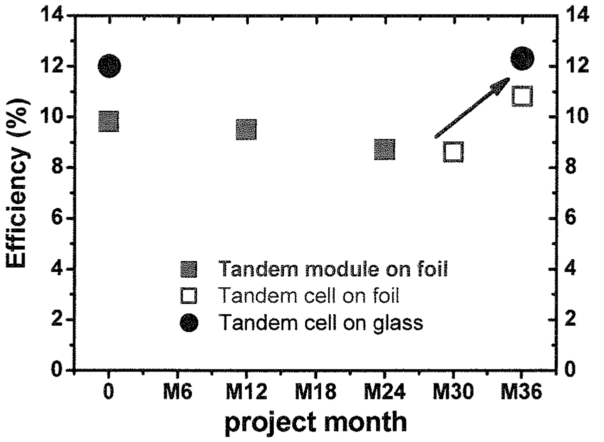
- transfer of a high quality tandem cell recipe from a rigid glass substrate to a flexible metal foil
- high quality transparent conductive oxides (TCO) with cost effective process technology
- optical layers, window layers, intermediate reflectors, back reflectors for enhanced photon harvesting
- stable top cell with polymorphous silicon absorber material
- maintain or increase deposition rates for active layers by PECVD and HWCVD processes
- modelling of the optical and electronic properties of tandem cells as an optimization tool with predictive power
- development of an infrastructure for fabricating fully encapsulated modules in a batch process as a tool for optimization of roll-to-roll (r2r) processes.

The starting point of this task concerning efficiency was a high standard a-Si/µc-Si tandem cell prepared at FZJ on commercial (Asahi Type-U) or in-house (texture-etched ZnO) TCO which yields efficiencies of > 12% initial and 11% stable at deposition rates of 0.15 nm/s for the top and 0.5 nm/s for the bottom cell active layers. Based on this process a flexible module on temporary Al foil substrate from HLT had been fabricated prior to the POWERFOIL project with an initial efficiency of 9.4 % for a 60cm² size module. This result had given confidence that further improvement in the efficiency should have been easy to achieve by integrating further optimized building blocks into the device. Within the project these individual tasks were worked on at different partner institutes:

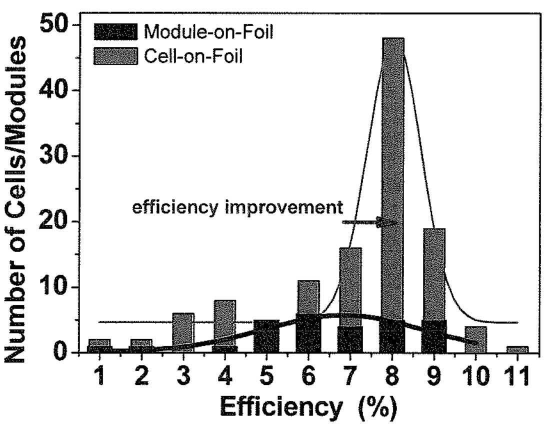
- deposition of a-Si/µc-Si cell structures at FZJ
- evaluation of new TCOs in solar cells and modules at FZJ
- development of new TCOs at USAL
- stable top cells at LPICM
- evaluation of optical properties of materials and modelling as assistance to above developments at IPP
- high deposition rates at UU and FZJ
- providing TCO-covered Al foil and finalizing device structures into modules by encapsulation, etching, and laser patterning the interconnects at HLT

For the latter task an important challenge was the fact that the process at HLT runs and is optimized for r2r while at FZJ and other partners only batch processing of the flexible substrates are available. Therefore first a standard for sample geometries, foil mounting, foil handling (packing, sending, measurement) was developed. At FZJ this includes a frame for foils and a holder which can accommodate up to four frames for deposition in a 30x30 cm² area system. The logistics was optimized for weekly operation starting with deposition on TCO covered Al foil substrates at FZJ (similar at LPICM and UU) sending foils (in frames) to HLT for fabrication into modules and measurements, evaluation and planning of the next process. The procedure was named the Module-on-Foil (MoF) Day which allowed to increase sample through-put and process yield from 65 % to 78 %. Nevertheless it was experienced that the laser patterning step for module interconnect was still a serious bottle-neck for systematic development. This process

step, optimized and used for the r2r pilot line at HLT needed to be adjusted for each module – on foil from the batch process from FZJ, UU and LPICM as here different layer thicknesses, different materials and dimensions are used. In addition development was hampered by the move of HLT to its new compounds. During this period the efficiency could not be improved but stagnated at below 10% initial. Integration and evaluation of the newly developed building blocks with respect to improvement of the module performance was not possible. It was therefore decided in the final year of the project to develop a Cell-on–Foil (CoF) structure as a new optimization tool which would avoid the critical interconnection step and ultimately allow complete fabrication of devices on foil at the partner facilities without need of HLT.
With this device considerable improvement was made in the final year with a maximum efficiency of initial 10.8% for the CoF structure. Details are described in the respective deliverables. The Figures below show the development of device efficiency over the project period. Note the progress made in the final year. There is however still a strong degradation of these devices. Future development will have to focus on this problem together with the integration of the new and improved other functional layers.



Efficiency of the best cells/modules on glass and on Al-foil obtained in the project



Efficiency distribution of tandem solar cells for MoF (in M1-M24) and CoF (in M25-M36) structures

One of them is the newly developed TCO prepared with cost effective APCVD processes at USAL With the TCO prepared at USAL highly efficient solar cells were fabricated at FZJ with 9.2 % for a single junction and 11.1 % for a tandem junction with similar or better performance as compared with high quality Asahi-U TCO. After transferring this TCO process to Al foil, first promising device efficiencies of up to 7.5% where achieved for a tandem CoF structure.
Results for the best cells are summarized in Table 1.

Cell-Type	Eff. (%)	FF (%)	V_{oc} (mV)	J_{sc} (mA/cm^2)	Substrate
a-Si:H	**9.2**	75.5	841	14.53	Glass
a-Si:H/µc-Si:H	**11.1**	76.1	1367	10.26	Glass
a-Si:H/µc-Si:H	**7.5**	61.3	1290	9.53	Al-foil

Table 1: Solar cell parameters for devices on glass and Al-foil with APCVD-SnO_2 prepared at USAL

In parallel work was performed on new materials for optical layers like windows, intermediate reflectors, and back reflectors in the tandem solar cells. The focus here was on µc-SiC:H prepared with HW-CVD and μc-SiO_x:H with PECVD. The development resulted in excellent performance solar cells with μc-SiC:H window with exceptionally high short circuit currents and blue light response with efficiencies of 9.2 % for a single junction μc-Si:H cell. The intermediate reflector in a tandem cell allows redistributing the current contributions from the bottom into the top cell which will allow reducing the top cell thickness for better stability against light induced degradation. Using such a reflector a tandem cell with 12.3% efficiency was prepared on glass. Both materials are ready for transfer and application in the flexible Helianthos module.

Work on high deposition rates were performed in a state-of-the-art multi-chamber deposition system at FZJ. However for the application of PECVD processes the system was found to limit further progress beyond the already high value of about 1 nm/s with which a world record efficiency of 10.3 % for a μc-Si:H single junction cell had been obtained. As a consequence a new CT system was developed and commissioned with adapted technology for high deposition rate processes. Excellent homogeneity over 10x10cm² at up to 1.4 nm/s is already obtained during the installation process. The system will be available for deposition on foils soon.
In summary WP2.3 has seen a development of a sophisticated infrastructure and logistics with a newly developed tool for optimization of flexible solar modules in r2r processes while using batch systems for the individual processes. The know-how shall be of high values for similar projects and developments in the future where flexible modules are seen as a unique feature of the thin film silicon PV.
The very ambitious final efficiency target for a flexible module was not achieved. Nevertheless considerable progress in the device development was made especially in the last project months allowing us to expect further improvement in the future.
This hope is supported by the excellent performance of newly developed TCOs and optical materials which are ready or have already been tested in the flexible devices. Optical modelling performed in WP2.1 further supports the potential of the concept based on already existing materials. Deposition rates for actives layers are very likely to be further increased with new and adjusted deposition equipment.
All in all the work on flexible lab modules has collected tremendous know-how on development and optimization for a very promising solar module with unique application potential.

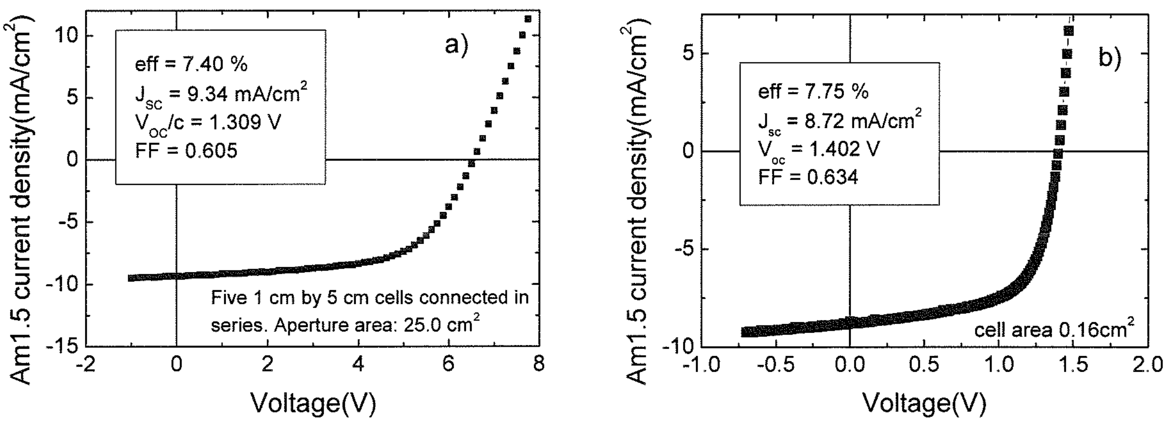
2.4 Hot wire micromorph tandem and triple cells on foil

Hot-Wire CVD is unique compared to plasma-based (RF or VHF etc.) CVD techniques. The deposition process does not involve energetic ions and the decomposition process in HWCVD is electromagnetically independent of the substrate. At Utrecht University, we have been developing materials and devices on flexible substrates using hot-wire deposited hydrogenated amorphous (a-Si:H) or protocrystalline Si:H, and nanocrystalline silicon (nc-Si:H) as the absorber layers, and we achieved AM1.5 a stabilized efficiencies η of 8.5% [1] for single junction nc-Si:H solar cells and an initial efficiency 11% (stabilized 10.6%) [2] for triple junction nip cells, using a conventional structure (no sophisticated back reflector and intermediate reflector etc. were used). Compared to solar cells with an identical structure but with absorber layers made by (RF/VHF) plasma CVD, the triple junction cells show an impressively high stability, due mainly to the protocrystalline structure of a-Si:H and a-SiGe:H and the rather small thickness of the absorber layers in these cells.

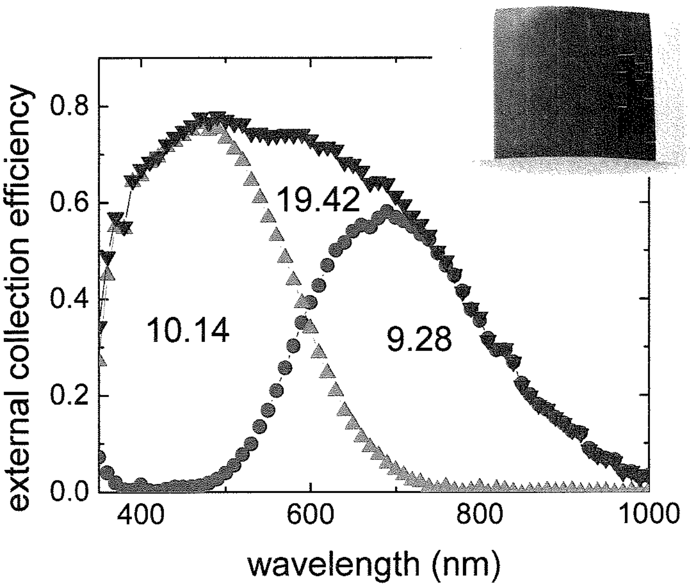
Our target in this project was to demonstrate the high efficiency potential of the Hot Wire CVD technique on a laboratory scale, exceeding present day performance of a-Si/μc-Si cells on foil. To be able to achieve the objectives, we conducted research along two research lines: 1) Deposition and optimization of HWCVD μc-Si:H material at a high deposition rate (rd); 2) Deposition and testing of the technology of solar cells with hot-wire deposited absorber layers for the first time using the HLT transfer process.

Hydrogenated thin film silicon materials deposited by HWCVD at a high deposition rate, around or above 1 nm/s, have been extensively studied in this project [3]. We have taken the route of increasing deposition rate by increasing filament temperature. To avoid substrate overheating due to filament irradiation at the elevated filament current, active substrate cooling was introduced. The materials thus made were characterized using structural, optical and electrical characterization methods such as Raman spectroscopy, Fourier Transform Infrared spectroscopy, Reflection/Transmission, electronic activation energy, and photosensitivity measurements by determining the dark conductivity and the photoconductivity under AM1.5 illumination. Subbandgap defects were characterized by means of Constant Photocurrent Method and Photothermal Deflection Spectroscopy. Increasing the substrate temperature as the deposition rate is increased was found to be beneficial for the material quality. At a substrate temperature of around 360 ºC, nc-Si:H materials with a photosensitivity above 100 and activation energy around 0.6 eV could be obtained near the phase transition regime (X_c = 0.45-0.65), indicative appropriate quality for solar cell application.

In collaboration with Heliathos b.v., we have developed solar cell tandem mini-module containing slicon absorber layers deposited by Hot-Wire CVD. An aperture area efficiency of 7.4% was achieved for a 25-cm^2 cell on HLT aluminium foil (Figure on left) [4]. The cell structure is a micromorph tandem structure with two hot-wire deposited absorber layers: hot-wire deposited proto-Si:H as the top cell i-layer and µc-Si:H as the bottom cell i-layer. The reference cell on an Asahi U-type superstrate showed a slightly higher cell efficiency (Figure on right, η = 7.8%), which means that the quality of the solar cells with hot-wire deposited absorber layers is essentially unaffected by the change in the type of superstrate (from TCO glass to Al foil). Note that this result was achieved immediately when using HLT foil and HLT processing. The fast transfer from glass superstrates to foil superstrates is due to the unique characteristics of hot-wire chemical vapour deposition, namely, the absence of an RF electromagnetic field during deposition and the low stress in the silicon layer stack.



AM 1.5 J-V characteristics of micromorph tandem cell with hot-wire deposited silicon absorber layers prepared on: (a) Helianthos foil; (b) Asahi-U substrate. V_{oc}/c was calculated from the module V_{oc} divided by the cell number (5).



ECE of a micromorph tandem mini-module with hot-wire deposited silicon absorber layers prepared on Helianthos foil. Inset is a picture of such a module (25 cm^2 aperture area).

In earlier work, we have shown that H_2-profiling brings large improvement to the μc-Si:H cell [1,2]. By using this technique, the efficiency of tandem cells deposited on Asahi-U type glass substrates was further increased to over 9.5% (up from an efficiency of 7.8%, as shown **Error! Reference source not found.**). Tabel 2 shows the detailed parameters for tandem cells containing H_2-profiled bottom i-layer. The large increase in solar cell efficiency is due to the increased material quality of the absorber μc-Si:H i-layer in the bottom cell. Note that all tandem cells are designed using a conventional structure, without sophisticated substrates or intermediate reflector.

Table 2 Detailed parameters for tandem cells containing H_2-profiled bottom i-layer.

	Subst.	Top cell thick. (nm)	Bottom cell SiH_4 flow (sccm)	Bot. thick. (nm)	J_{sc}^{SR} top (mA /cm^2)*	J_{sc}^{SR} bottom (mA/ cm^2)*	Eff (%)	J_{sc} (mA/ cm^2)	V_{oc} (V)	FF	R_s (Ω cm^2)	R_p (Ω cm^2)
Best in the series	ASAHi -U	350	5.2→5.1→ 5.0	2.5 μm	9.58	10.01	9.51	10.8	1.355	0.650	12.47	1434
Ref.	ASAHi -U	250	5.3→5.0	2.0 μm	9.11	10.15	9.28	9.96	1.423	0.655	14.97	1601

*: J_{sc}^{SR} is the integrated current density obtained from spectral response measurement. Due to the limited spectral range and integration step used, it shows a smaller value than the J_{sc} obtained from the J-V measurement with solar simulator (AM1.5).

The 25 cm^2 mini-module showed an initial efficiency of 7.4% (Table 3, line 1) in the year 2007. It was laminated in October 2007, but subjected to light soaking only in June 2009. Due to the delayed lamination of the mini-module, the module efficiency had decreased to 6.7% (measured in October 2007, line 2 in Table 3), mainly because of a decrease in V_{oc} [5]. After it was laminated however, the module efficiency decreased only marginally over the two years storage on the shelf. Just before the start of the light soaking test, the sample showed an efficiency of 6.4% (Table 3, line 2). After 120 hours of light soaking under open circuit conditions, under AM1.5 illumination at 60% intensity and at 50 °C, the module efficiency did not decrease at all. Instead, its efficiency increased to 6.86%, due to a recovery of V_{oc}. This is even better than the efficiency measured in 2007 right after lamination. These results prove that the micromorph tandem module made by hot-wire CVD is indeed very stable against light soaking.

Table 3 Light soaking result of a 25 cm² mini-module with an i-layer made by hot-wire CVD with a constant H_2 dilution.

	Eff. (%)	*J_{SC} [mA/ cm²]*	*V_{OC} /c (V)*	*FF*	*R_S (Ω cm²)*	*R_P (Ω cm²)*
No lamination (HLT, 2007)	7.4	9.34	1.309	0.609	24.9	1020
Laminated (2007)	6.72	9.28	1.187	0.610	21.0	1806
0 hr (2009)	6.42	9.07	1.193	0.593	23.26	2064
120 hr (2009)	6.85	8.98	1.263	0.604	22.9	1760

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B. Production and integration cost

Processing technologies

Flexible solar cells

Thin film solar cells, based on Si or other materials, can be made by batch or continuous processes. The present thin film PV modules on the market are mostly produced in batch processes on glass panels.
The two main advantages of flexible solar cells are:

- Flexible PV modules enable roll-to-roll manufacturing, which offers the advantage of a cheaper and intrinsically more stable continuous process.
- Easier integration and installation of the PV product in the application (for instance for building integrated PV). Integration and installation costs are sometimes overlooked, but they do add considerably to the overall price of solar electricity (up to 40%!).

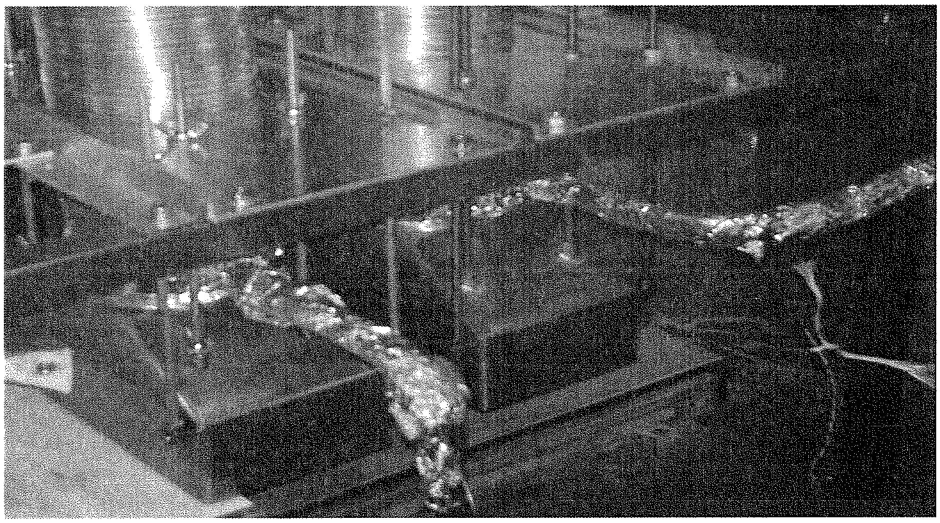
On the other hand, flexible PV modules require more complicated encapsulation. Conventional rigid thin film PV modules can make use of the excellent, low-cost protecting properties of the glass panels. For flexible PV modules more expensive fluoro-polymer systems are usually employed for encapsulation. Still, this disadvantage is easily outweighed by the advantages mentioned.

Fast deposition technologies

For any production process, be it batch or continuous, it is essential to have fast deposition technologies if one really wants to obtain low production costs.
At present, TCO layers can be deposited in a high-throughput APCVD process such as used in the float-glass industry for energy efficient windows (static deposition rates of 10-100 nm/s). Hence, the cost of this process is acceptable at the moment. As outlined in the light management paragraph, for a true TCO optimization, it will be necessary to implement more advanced materials or multilayers to satisfy the conflicting electro-optical and morphological demands. Of course, such improvement should not go at the expense of increased TCO production costs. For that reason, process capabilities will be developed and tested in the project that allow for multiple reaction chemistries, either simultaneous (stannates, other ternary materials) or sequential (combinations of different layers).
In a throughput-matched production process the Si deposition requires a very significant fraction of the capital investment. If the deposition speed of the Si layers remains unchanged, the capital investment needed for, e.g., an aSi-μcSi tandem with its greater layer thickness will even be higher. For this reason, it is essential to include research on technologies for higher Si deposition rates in the project.
All thin film Si layers are usually deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD). This is the present-day, vacuum based, most frequently used deposition technique, which has a relatively low throughput (static deposition rate 0.1-0.5 nm/s). With the VHF-plasma CVD process which is applied by several of the project, partners (FZ Jülich, University of Utrecht) the deposition rates are already improved (on lab scale) with respect to the standard PECVD process (0.5-1.5 nm/s). Even at these rates, the capital investment needed for deposition of Si layers in a micromorph tandem is so dominant that there is a need for improvement.
From the available technologies, we have selected Hot Wire Chemical Vapor Deposition (HWCVD) because this technology has recently shown high quality (laboratory) cells that are deposited at 5-10 times higher rates for both protocrystalline and μc-Si silicon. Therefore, one of the research objectives is to explore a radically new, high throughput continuous deposition technique that is compatible with roll-to-roll mass production of thin film silicon solar cells.

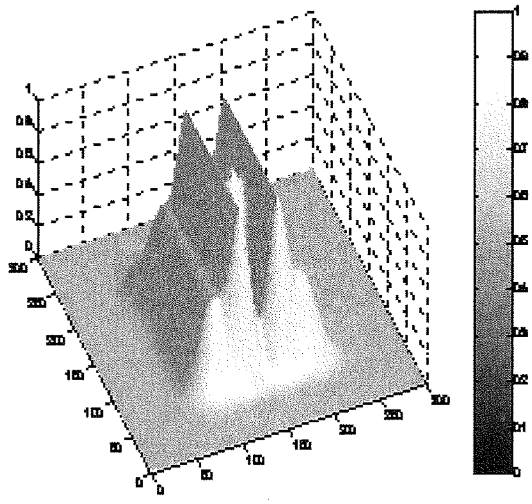
3.1 Fast deposition technology for high performance TCO

The TCO deposition technology work at CVD Technologies focussed on developing and building of an in-line TCO coater. In the first thrust of the work, a new design of high throughput CVD lab experimental coater was developed to accelerate materials evaluation. This was successful in both increasing throughput by an order of magnitude but equally importantly, by enhancing significantly the reproducibility of experimental conditions and more accurately defining trends. In the second thrust was targeted at upgrading the designs of CVD coater heads to achieve higher growth rates without compromising properties or increasing costs substantially. A completely new coater head design was developed which met and exceeded our targets.



The work also developed a new approach to monitoring of reactions in-situ within CVD reactors. The concept was to establish the feasibility for 3D monitoring of the reaction space with the CVD system. This was particularly challenging given the restricted space available in the designs being considered (where the substrate to coater head gap is small) and the temperatures are typically >500C. A laser based (NIR) multi-wavelength and multi-point design concept was developed. In addition a capability to "scan the laser measurements in 3 dimensions directly through the reactor space was integrated.

The concept feasibility was developed, (in collaboration with Manchester University, Dr P Martin) group, tested successfully using a laser based mechanically scanning system, monitoring HCl concentration in-situ in the reaction zone of the CVD system.
The results were successfully used to advance understanding of the CVD system operation and design.



Modelled 3D HCl concentrations under CVD head
based on laser diode measurements

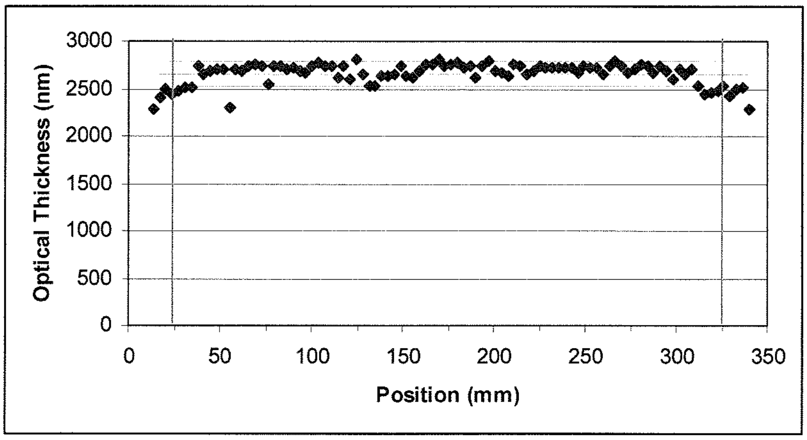
In TCO materials tudies, Salford University have had two primary thrusts to their work. Starting with the CVD lab high throughput systems designed and built by CVD Technologies, firstly, exploration and optimisation of Fluorine doped tin oxide was undertaken. The objective was to maximise light coupling into the cell via TCO whilst avoiding loosing the key benefit of atmospheric pressure CVD i.e. that very fast growth rates can be achieved and this can lead to high volume manufacturing and lowest costs. New growth chemistries and pre-and post treatments were developed which substantially upgraded the performance of the TCOs produced compared to the original starting point. A significant number of cells were supplied to partners for evaluation and testing. Cell performances significantly in excess of those achieveable by Glass line based technology were demonstrated.
In a second thrust, Salford University explored the potential of other TCO materials. Tin doped indium oxide (ITO), doped zinc oxide and p doped TCOs were explored.
Comparative performances of each TCO material (under similar growth technology conditions) were determined. Further studies, based upon progress made within the project, are now underway to advance this work.

3.2 Fast deposition technology for active silicon layer

The main deliverables within this task were related with demonstrating how to produce the a-Si:H and especially the μc-Si:H layers on an industrial scale. The work started with developing the technology on 350 mm wide and scaled it to >1200 mm width in the later stages of the project.

A major result is shown in the Figure on the next page where the homogeneity is shown of a μc-Si:H layer deposited in a batch reactor on 350 mm wide Al foil. The growth rate of this layer is about 0.86 nm/s. As is demonstrated excellent homogeneity at these high growth rates are achieved.
This task made it possible to make the equipment specifications for the 350 mm wide roll-to-roll pilot line tandem deposition equipment.

Much work has gone into the development of a PECVD reactor capable of depositing on 120 cm wide foil. A-Si:H layers have been successfully deposited. As main deliverable >0.3 nm/s a-Si:H with homogeneity better than 95% was achieved. Furthermore considerable progress was made on the high rate deposition of μc-Si:H layers on this scale. The high power density required for the high rate depositions of μc-Si:H requires good solutions for thermal management.



Homogeneity of optical thickness of a μc-Si:H layer deposited with a deposition rate of >0.8 nm/s. The vertical green lines indicate the boundary of 30 cm width. The solid horizontal lines indicate the ±5% in-homogeneity boundaries.

C Lifetime

Obviously, a module's lifetime affects the kWh cost as directly as its efficiency. To protect solar modules from environmental attack, and thus to increase the module's lifetime, barrier 'encapsulation' layers are applied both at the back and front side of the thin film solar cell. Because of its direct influence on the product performance, a very significant research effort has already been dedicated towards encapsulation at Helianthos. A good encapsulation system is a crucial to the first generation a-Si product as it will be to the high efficiency SE-PowerFoil modules. Hence, such a system must and will be developed, well before SE-PowerFoil's end date, at Helianthos separately, *in parallel to but outside this project*. Yet, to enable a true evaluation of the economic potential of thin film Si flexible PV one needs to monitor the long-term power output in the field as well as measure the expected lifetime in standard accelerated lifetime tests. These monitoring and measurement tasks will be performed on modules produced within the project in the Helianthos pilot line, using the state-of-the-art encapsulation process developed outside the project. For comparison, modules produced both at the start of the project and around mid-term will be used.

4.1 Transfer of know how from lab to roll-to-roll

Structured research and development that results in new baselines with better performance has been an ongoing activity. Sharpen the understanding of the processes by a multidisciplinary team is a continuous learning cycle. The insights that the SE-Powerfoil project have given on the solar cell technology on laboratory scale have also had its influence on the 350 mm wide pilot line. Through the years a tremendous progress has been made as is demonstrated in the Figure below where the progress in Helianthos module sizes is shown.

The different a-Si:H module sizes from the roll-to-roll pilot line: 8x7.5 cm^2, 28x30 cm^2, 28x90 cm^2, 28x600 cm^2 and two integrated 28x600 cm^2 modules.

Preparations to implement the a-Si:H/μc-Si:H device in the Helianthos 350 mm pilot line are in a far stage. The experiences from the device performance in the lab equipment as well as the development of the technology on the required substrate sizes allowed to make the specifications, design and constructing of equipment necessary for this technology.

4.3 Accelerated lifetime assessment according to IEC 61646

Accelerated lifetime testing of high efficiency pilot line modules were done to demonstrate the stability in the climate stability tests according to (a.o.) the IEC standard for thin film PV modules. The thermal cycling test and the damp heat climate test have showed that it is possible to have modules with excellent stability. The yield however varies and requires attention. Especially failing modules out of the damp heat climate test show severe degradation. The root cause of this lifetime issue has been tracked down and mitigated.

4.4 Outdoor monitoring

During the SE-powerfoil project several tests regarding lifetime and outdoor monitoring were running. In the first year a-Si:H pilot line modules from the beginning of the project failed severely in the outdoor test, probably due to improper mounting. A new set of state-of-the-art modules were evaluated over one year outdoor from august 2008 to 2009.
At the end of the project also tandems on foil from the lab line were placed outdoors. Within three months there were no other effects than the Staebler-Wronski effect visible.

4.5 Exploitable benefits/Overall economic assessment of devices, technology and lifetime

Economics are key in the development of new technology. Based on the experiences on the device structure of the tandem, as well as the experiences with the deposition of μc-Si:H on 350 mm and 1400 mm width a cost price model has been developed for the PECVD equipment. This model allows to compare the costs of a-Si:H technology with the a-Si:H/μc-Si:H technology. The outcomes have shown that the business case for the tandem device is much better than the a-Si:H device, despite the higher investment costs required to make the device as well as the higher variable costs required associated with the thicker silicon layers. As would be expected increasing growth rate has been shown to be beneficial for the business case as the PECVD equipment is the most expensive equipment that is needed.

0.5 Degree to which the Objectives were reached

At the 36M Final meeting in Arnhem, an evaluation was held.

Huge progress has been made in the past three years and most scientific and technical objectives have been reached. At project start, efficiency for the tandem was less than 7.2%. Now, the record initial efficiency is close to 11% though, still significant future challenges lie ahead with respect to the stabilizing of the initial efficiency.

The targets for the deposition rate of active silicon were partially reached. HLT will continue with the R&D on improving the deposition technology after the ending of the project.

All partners including the coordinator acknowledged the excellent cooperation, the fine work and results achieved in the round the table.

Some success factors mentioned:

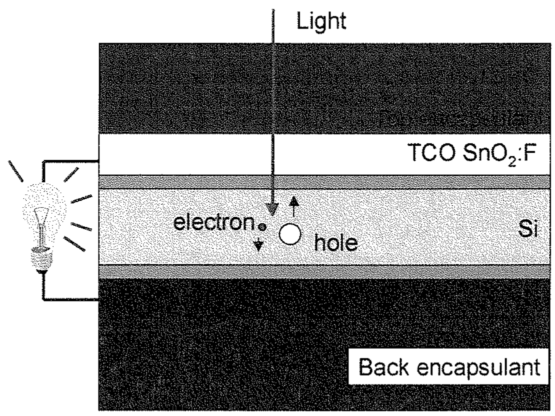
- Solid preparation in the pre-stage of the project (e.g. consortium agreement in place);
- Consortium composition (vertical structured, no overlaps in technology/know how);
- Strong technology-pull based coordinatorship by HLT;
- Adequate management support.

0.6 Methodologies and Approaches Employed

Below, a short introduction is provided that addresses all the scientific and technological issues related to thin-film silicon PV modules, high-throughput roll-to-roll manufacturing technology and lifetime aspects. Subsequently, the structure of the workplan and the overall methodology used to achieve the objectives are presented and explained, followed by an graphical presentation (GANTT chart) of the major components (tasks) of the workplan, their timing and the interdependencies between the major components (tasks).
Part A, B and C of this text can also be found as separate introductions to the work described in section 0.4, but for completeness it is presented here.

A. Thin film Si cell efficiency

All thin film Si solar cells, flexible or rigid, have a common working principle. A schematic of the simplest thin film Si solar cell is given in the Figure below. Such solar cells are essentially built up by only a few component layers. We will very briefly describe these layers, and their relevance to the objective of this project.



Structure of a photovoltaic cell and its principles of operation

The active Si layer stack is the heart of the photovoltaic device, in which the light is absorbed and converted into electrical energy. The most widely used thin film Si devices make use of amorphous Si (a-Si) layers. These can be found in a-Si cells or a-Si/a-Si tandems. If the material is grown under yet different conditions, thin film Si with varying degrees of crystallinity (microcrystalline Si) can be deposited Micro-crystalline Si (µc-Si) has a smaller bandgap than a-Si. Thus, with microcrystalline silicon layers a larger part of the solar spectrum can be absorbed. Microcrystalline silicon layers (µc-Si) can be combined with a-Si:H layers to form a **micromorph** (microcrystalline/amorphous) or '**hybrid**' tandem cell.

Two electrode layers are needed to conduct the generated electricity to the 'outer world'. At least one of these contact layers is a transparent conductive oxide (TCO) window layer. Since this electrode layer is facing the sun, it must be transparent, thus excluding the use of metal layers. A trade-off is always necessary between the TCO's optical transmission and its electrical conductivity. For pin structures, an additional challenge for the deposition of the TCO layer is to obtain sufficient electrical, optical *and* morphological properties. Surface morphology has a large direct influence on module efficiency, and hence on kWh cost. This is because a rough, textured, surface morphology will introduce light scattering that enhances the optical path within the Si layer. The most common TCO materials used are: SnO_2:F, ZnO:Al and ITO.

Apart from these electrical, optical and morphological demands, it is also necessary for the TCO layers to remain stable over the lifetime of the PV module. The back contact is usually a highly optically reflecting combination of metals and ZnO. The former layers conduct the electrical current, whereas the latter enhances the reflection of that part of the light that has not been absorbed in the Si layers during the first pass of the light. Hence, one can achieve much higher efficiency values by effectively controlling and optimizing the light scattering and reflecting properties of the front and back electrodes. This approach is sometimes called 'light management'.

B. Production and integration cost

Flexible solar cells

Thin film solar cells, based on Si or other materials, can be made by batch or continuous processes. The present thin film PV modules on the market are mostly produced in batch processes on glass panels.

The two main advantages of flexible solar cells are:

- Flexible PV modules enable roll-to-roll manufacturing, which offers the advantage of a cheaper and intrinsically more stable continuous process;
- Easier integration and installation of the PV product in the application (for instance for building integrated PV). Integration and installation costs are sometimes overlooked, but they do add considerably to the overall price of solar electricity.

On the other hand, flexible PV modules require more complicated encapsulation. Conventional rigid thin film PV modules can make use of the excellent, low-cost protecting properties of the glass panels. For flexible PV modules more expensive fluoro-polymer systems are usually employed for encapsulation. Still, this disadvantage is easily outweighed by the advantages mentioned.

Fast deposition technologies

For any production process, be it batch or continuous, it is essential to have fast deposition technologies if one really wants to obtain low production costs.
At present, TCO layers can be deposited in a high-throughput APCVD process such as used in the float-glass industry for energy efficient windows (static deposition rates of 10-100 nm/s).

As outlined in the light management paragraph, for a true TCO optimization, it will be necessary to implement more advanced materials or multilayers to satisfy the conflicting electro-optical and morphological demands. Of course, such improvement should not go at the expense of increased TCO production costs. For that reason, process capabilities have been developed and tested in the project.
All thin film Si layers are usually deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD). This is the present-day, vacuum based, most frequently used deposition technique, which has a relatively low throughput (static deposition rate 0.1-0.5 nm/s). As the Si deposition represent a significant fraction of the capital investment, extensive research has been performed on technologies for higher Si deposition rates in the project.

C Lifetime

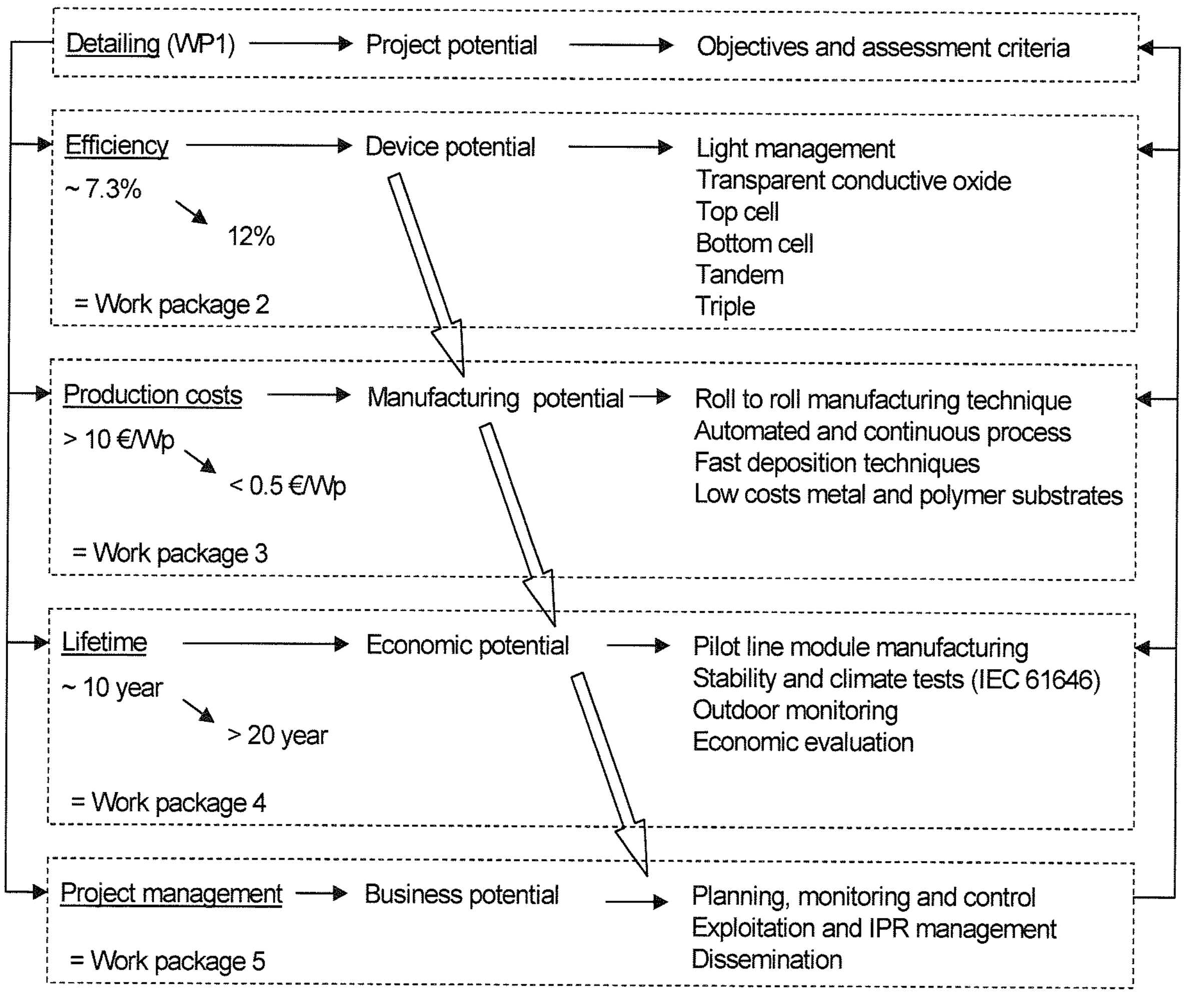
Obviously, a module's lifetime affects the kWh cost as directly as its efficiency. To protect solar modules from environmental attack, and thus to increase the module's lifetime, barrier 'encapsulation' layers are applied both at the back and front side of the thin film solar cell.

A good encapsulation system is a crucial because of its direct influence on the product performance. The research on encapsulation has been carried out by Helianthos separately, i.e. in parallel to, but outside this project.

In order to enable a true evaluation of the economic potential of thin film Si flexible PV, the long-term power output in the field has been monitored and the expected lifetime has been determined in standard accelerated lifetime tests.

In summary, the SE-POWERFOIL project focused on the development of tandem silicon PV laminate and the underlying scientific know-how and technology thereof. The key objectives were to significantly increase module efficiency and to lower the production cost by developing multi-junction, multi-bandgap thin film silicon solar cells using innovative high rate deposition processes, on improved TCO layers.

In order to realise the concept and objectives described above, the project workplan consisted of three main workpackages: The logical interaction between the workpackages is schematically shown in the Figure below, and a summary of workpackage contents is given on the next page.



Overall structure of the Workplan (Task flow diagram).

WP1 - Activity type: Research related activities
At the beginning of the project, a small work package WP1 was devoted to **detailing** the specifications of the high performance flexible PV modules and underlying systems. The work package also served to ensure uniform sample handling and measurement procedures among the partners.

WP2 - Activity type: Research
In work package 2 the full **efficiency** potential of flexible thin film Si PV modules was explored on lab scale. The challenge in this WP was to assemble all individually optimized building blocks of a micromorph device and drive their cooperative performance in an actual flexible module to an high stable efficiency. The basic approach was to pursue parallel research on the individual building blocks (top and back electrode layers, intrinsic, doped and buffer layers in both top and bottom cell) and to systematically measure the progress by integration into complete flexible micromorph modules.

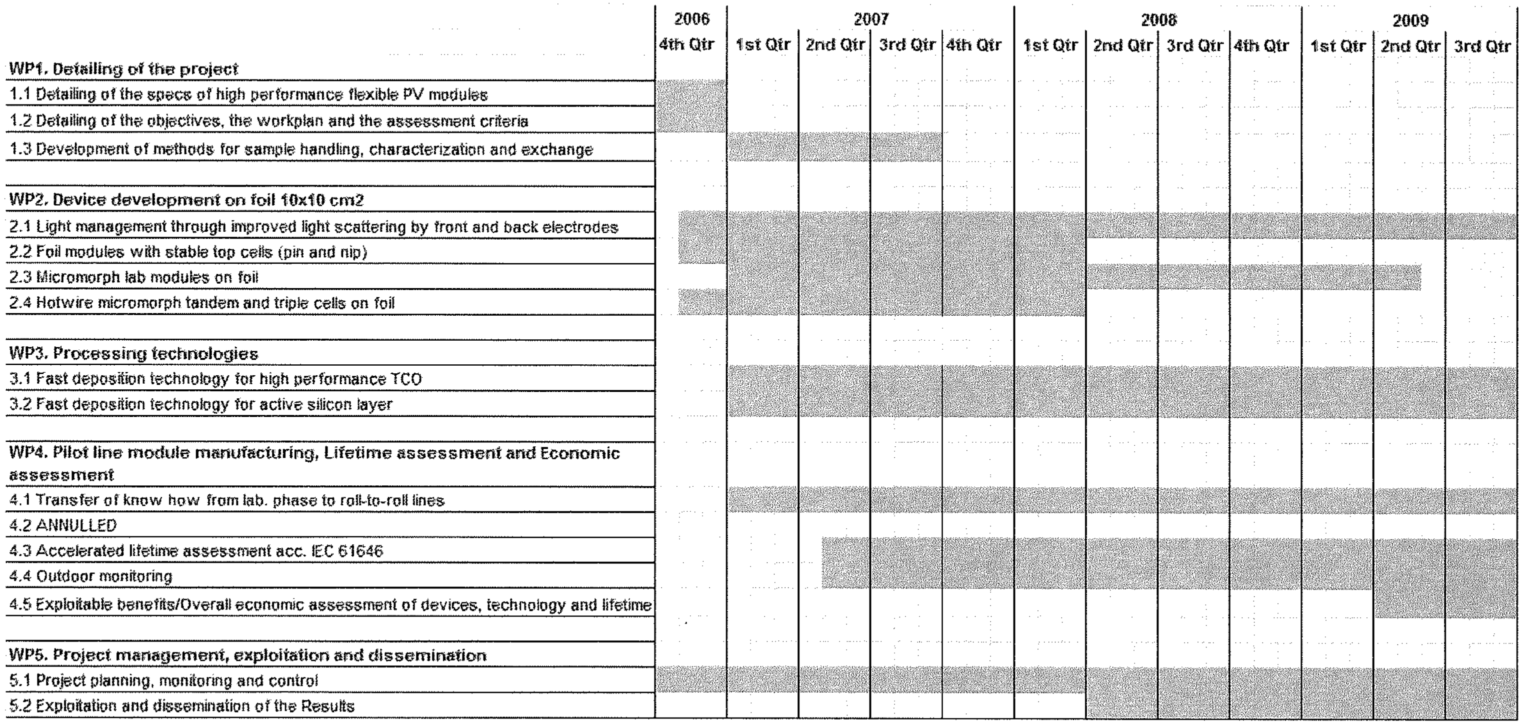
WP3- Activity type: Research and Technological development
Work package 3 dealed with the **production cost** of flexible thin film Si PV modules. Focus was on the crucial production steps of the applied roll-to-roll processing technologies. This includes the development of large scale, reliable, fast, homogeneous deposition technologies for the high performance TCO and for the active silicon layer. Obviously, the development in this work package closely followed that of WP2. For instance, newly developed TCO (multi-) layers from WP2.1 were tested on manufacturability in WP3.1.

WP4- Activity type: Technological development and innovation-related activities
In work package 4 **pilot line** PV flexible thin film Si PV modules were exposed to outdoor climate conditions for true power **output monitoring** at the start of the project as well as at mid-term PV modules from the pilot line. This work package also dealed with **accelerated lifetime** assessments according to IEC standard 61646.

Combination of the results of WP2 (efficiency), WP3 (crucial elements of production cost) and WP4 (pilot line manufacturability, monitored output and accelerated lifetime) allowed for a realistic **overall economic assessmen**t (in terms of Euro/kWh) of flexible thin film Si PV modules produced in a full production plant.

WP5- Activity type: Management and innovation-related activities
The supporting work package 5, **project coordination**, secured the necessary exchange of research information between project partners, monitored and controlled the progress of the project and took care of the disseminating of the project results.

A specific project's website/intranet (**http://se-powerfoil.rtdproject.net/**) was launched-composed of two separate areas: a public area and a restricted area. The public area was/is meant for: promotion and dissemination of the scope of the project and to get into contact with other experts, potential partners, *etc.* The restricted area was/is meant for the consortium partners only. This part comprised amongst others an archive, shared harddisk (comparable with MS explorer), a communication tool and a progress monitoring tool.


2006
2007
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4th Qtr
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3rd Qtr
WP1. Detailing of the project
1.1 Detailing of the specs of high performance flexible PV modules
1.2 Detailing of the objectives, the workplan and the assessment criteria
1.3 Development of methods for sample handling, characterization and exchange
WP2. Device development on foil 10x10 cm2
2.1 Light management through improved light scattering by front and back electrodes
2.2 Foil modules with stable top cells (pin and nip)
2.3 Micromorph lab modules on foil
2.4 Hotwire micromorph tandem and triple cells on foil
WP3. Processing technologies
3.1 Fast deposition technology for high performance TCO
3.2 Fast deposition technology for active silicon layer
WP4. Pilot line module manufacturing, Lifetime assessment and Economic assessment
4.1 Transfer of know how from lab. phase to roll-to-roll lines
4.2 ANNULLED
4.3 Accelerated lifetime assessment acc. IEC 61646
4.4 Outdoor monitoring
4.5 Exploitable benefits/Overall economic assessment of devices, technology and lifetime
WP5. Project management, exploitation and dissemination
5.1 Project planning, monitoring and control
5.2 Exploitation and dissemination of the Results

0.7 ACHIEVEMENTS OF THE PROJECT IN RELATION TO THE STATE OF THE ART

The PV market is dominated for 80% by the crystaline silicon solar cells, whereas thin film PV on glass has 18% market share. The remaining 2% are for thin film PV that is roll-to-roll produced. The main players in this segment with silicon based technology are for the moment UniSolar (about 90 MWp/yr), Fuji Electric (ramping up to about 40 MWp/yr) and Flexcell (ramp up to 25 MWp/yr). Thin film CIS players are amongst others Global Solar and Nanosolar.

The state of the art regarding roll-to-roll manufacturing for high efficient multi-junction thin film silicon flexible photovoltaic modules is not changed significantly. At the same time, fast progress toward large-scale market entry is seen for all existing flexible thin film Si producers (expansion of Unisolar, new manufacturing facilities for Fuji and VHF technologies). Within the FP6 project Flexcellence – in which VHF-technologies participated - a 9.8% active area stabilized efficiency of a-Si:H/µc-Si:H solar cells on a PEN substrate has been reported [Publishable Final Activity Report FP6-019948]. World record stabilized efficiency for such a tandem device on glass is 11.7% made by Kaneka. [Prog. Photovolt: Res. Appl. 2009, 17: 320-326]

The efficiencies that have reached on flexible substrates within the SE-Powerfoil project in the last year: 10.3 to 10.8% (initial active area of 5 to 7.5 cm^2) from HLT and FZJ respectively, show clearly the potential of the technology. Furthermore the differences between tandems made on the glass substrates and the flexible substrates are becoming smaller. As the SE-Powerfoil project ended on a rather step part of the learning curve we expect that significantly higher efficiencies are within reach.

Although the Helianthos product is not yet commercially available the efficiencies will allow it to compete with other flexible thin film silicon solar cell products. Also from a cost point of view (Euro/Wp) the technology still looks promising in comparison to other silicon based technologies.

0.8 IMPACT OF THE PROJECT ON ITS INDUSTRY OR RESEARCH SECTOR

Large-scale use of solar PV power generation will prove necessary for a smooth energy transition during this century. Solar energy can become the major source of renewable energy during the coming 50 years.

For thin film silicon based flexible PV technologies, *i.e.* roll-to-roll manufacturing of PV laminates on kilometre long substrates followed by simple gluing on building materials, forecasts indicate that amorphous silicon based on flexible PV laminates with moderate efficiencies of 5 - 6% energy efficiency already will be capable to lead to turnkey system prices between 2.5 - 3 EUR/Wp. The efficiencies of thin film tandem silicon solar modules on flexible foil that will result from the current project will have a high potential for cost effective power generation as the costs in EUR/Wp will decrease with respect to the lower efficiency a-Si:H modules.

A "passive" means of dissemination is the project website, available under:
http://www.se-powerfoil.eu

1 PUBLISHABLE RESULTS OF THE FINAL PLAN FOR USING AND DISSEMINATING THE KNOWLEDGE

1.1 EXPLOITABLE KNOWLEDGE (PUBLISHABLE RESULTS) AND ITS USE

1.2 DISSEMINATION OF KNOWLEDGE

Dissemination takes place through a special website (www.se-powerfoil.eu) designed for this purpose and through the articles/technical papers in scientific journals and contributions to international conferences.

Overview table

Planned/actual dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible/involved
From November 2006 onwards	Public part of project website www.se-powerfoil.eu	public	World-wide		UNI/HLT
March 2007	Exchange of results with Flexcellence project	Flexcellence consortium		20	HLT
April 2007	Mat. Res. Soc. Spring Meeting, San Francisco, USA – oral presentation (Tutorial)	Industry, academia, research institutes	Worldwide	200	FZJ
August 2007	22nd Int. Conference on amorphous and microcrystalline semiconductors, Colorado, USA	Industry, academia, research institutes	World-wide		IPP
September 2007	22. European Photovoltaic solar energy conference in Milan, Italy	Industry, academia, research institutes	Worldwide	>2000	All, for contribution IPP see below
September 2007	ProFlex 2007, Vacuum Roll-to-roll processing of flexible materials, Dresden (G)	Industry, academia, research institutes	Worldwide	150	HLT
12 October 2007	Exchange of results with Flexcellence project	Consortium and Flexcellence project	CZ, DE, FR, NL, UK	10-20	All
March 2008	Mat. Res. Soc. Spring Meeting, San Francisco, USA	Industry, academia, research	Worldwide	200	FZJ

	– oral presentation	institutes			
April 2008	PVSAT 4, Bath, UK – oral presentation	Industry, academia and research institues	European countries	100	USAL
May 2008	EMRS Spring Meeting –	Industry, academia and research institues	European countries		LPICM, FZJ
May 2008	Societé Francaise de la Physique: Congrès Plasma	Industry, academia and research institues	French institutes		LPICM
June 2008	ICCG, Eindhoven (poster)	Industry, academia	Worldwide		USAL/CTEC
June 2008	European Physical Society Meeting (EPS 2008, Crete)	Industry, academia and research institues	European countries		LPICM
September 2008	23rd EU-PVSEC Valencia (2008)	Industry, academia, research institutes	Worldwide	>3000	HLT,LPICM
September 2008	23rd EU-PVSEC Valencia (2008)	Industry, academia, research institutes	Worldwide	>3000	HLT
September 2008	Joint Seminar of FZJ and HZB, Hirschegg, Austria, oral presentations	Research institutes	D	60	FZJ
October 2008	TCO-2008, Crete – oral presentation (invited)	Industry, academia, research institutes	Worldwide	200-300	USAL
December 2008	HGF-TÜBITAK Workshop 2008 Istanbul-Gebze, Turkey, oral presentation (invited)	Academia, research institutes	D, TR	150	FZJ
January 2009	PVSEC 18, Kolkata-oral presentation (invited)	Industry, academia, research institutes	Worldwide	300	FZJ
April 2009	2nd International Workshop on Thin Film Silicon Solar Cells, Berlin Ger-	Industry, academia, research institutes	Worldwide	200	HLT

	many				
April 2009	Materials Research Society Symposium (MRS 2009, San Francisco)	Industry, academia, research institutes	Worldwide		LPICM, UU
August 2009	ICANS 23, Utrecht, NL, - oral presentation, poster	Industry, academia, research institutes	Worldwide	300	FZJ
September 2009	CVD network, UCL, London –(posters)	academia,	UK	30	USAL
September 2009	EPVSEC, Hamburg (posters)	Industry, academia, research institutes	Worldwide		USAL/CTEC, FZJ
September 2009	1st SiNEP, Vigo, Spain – oral presentation (invited keynote lecture)	Industry, academia, research institutes	Worldwide	50	FZJ
September 2009	University do Minho, Portuga, orals presentation (Seminar)	Academia	P	30	FZJ
October 2009	EUROCVD 17 + ECS, Vienna, Austria – oral presentation	Industry, academia, research institutes	Worldwide	>1000	USAL

1.3 PUBLISHABLE RESULTS

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2. J. Holovský, A. Poruba, J. Bailat, M. Vaněček, Separation of signals from amorphous and microcrystalline part of a tandem thin film silicon solar cell in Fourier Transform Photocurrent Spectroscopy Proceeding of NUMOS - International Workshop on Numerical Modelling of Thin Film Solar Cells, Eds. M. Burgelman, M. Topič, Gent, Belgium, 28-30 March 2007, pp. 249-255, ISBN: 978-90-382-1109-1.
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6. D.W. Sheel,H.M.Yates, P.Evans, U. Dagkaldiran, A. Gordijn, F. Finger, Z. Remes, M. Vanecek, Optimum Performance Solar Cells using Atmospheric Pressure Chemical Vapour Deposition deposited TCOs, TCO-2008, Intl. J. NanoTechnology, 6 (2009) 816-827.

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8. Ü.Dagkaldiran, A. Gordijn, F. Finger, H.M. Yates, P. Evans, D.W. Sheel, Z. Remes, M. Vanecek, Amorphous silicon solar cells made with SnO_2:F TCO films deposited by atmospheric pressure CVD, Maters.SciEngB 159-160 (2009) 6-9.
9. J. Holovsky, A. Purkrt, A. Poruba, Z. Remes, M. Vanecek, D. Semerel, A. Borreman, E. Hamers, F. Finger, U. Dagkaldiran, H. Yates, Comprehensive study of single amorphous and tandem micromorph solar cells and modules on flexible aluminum superstrate prepared in roll-to-roll process Proc. 23rd European Photovoltaic Solar Energy Conference, Eds. D. Lincot, H. Ossenbrink, P. Helm, 1-5 September 2008, Valencia, Spain, pp. 2309-2312, ISBN: 3-936338-24-8
10. An alternative precursor for APCVD deposited F doped SnO2 TCO for solar cells', H.M.Yates, P.Evans, J.L. Hodgkinson, P. Sheel, D.W. Sheel, U. Dagkaldiran, A. Gordijn, F. Finger, Conference proc. PVSAT5, Wrexham, April 2009.
11. Optimization of Solar Cell Performance using Atmospheric Pressure Chemical Vapour Deposition deposited TCOs', H.M.Yates, P.Evans, D.W. U. Dagkaldiran, A. Gordijn, F. Finger, Z. Remes, M. Vanecek, ECS Transactions - Vienna, Austria" Volume 25, EuroCVD 17/CVD 17. publ9/09
12. Smirnov, V., Das, C.; Melle, T.; Lambertz, A.; Hülsbeck, M..; Carius, R.; Finger, F. 'Improved homogeneity of microcrystalline absorber layer in thin-film silicon tandem solar cells'
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14. T. Chen, A. Schmalen, J. Wolff, D. Yang, R. Carius, F. Finger, Aluminium doped silicon-carbon alloys prepared by hot-wire chemical vapour deposition, Accepted for publication in Phys. Stat. Sol. C
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18. Proc. 24th EUPVSEC, Sep 2009, Hamburg, Germany
19. Erik V. Johnson, Ka-Hyun.Kim, and Pere Roca i Cabarrocas, In-Situ Observation of High Deposition Rate Hydrogenated Polymorphous Silicon Cell Degradation through Variable Intensity Method Measurements, Amorphous and Polycrystalline Thin-Film Silicon Science and Technology - 2009 (Mater. Res. Soc. Symp. Proc.) A7.9.
20. E.V. Johnson, F. Dadouche, M.E. Gueunier-Farret, J.P. Kleider, and P. Roca i Cabarrocas, Open-circuit voltage increase dynamics in high and low deposition rate polymorphous silicon solar cells, Physica Status Solidi (c) 'current topics in solid state physics', submitted 2009.
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