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Future Emerging Technology
Collaborative Project

ASPIS

Active Solar Panel Initiative

Final Publishable Summary Report

Start date of Project: 01 January 2009
End date of Project: 31 December 2011
Duration: 36 months

Project Summary

The basis of ASPIS is a novel suspension technology concept that supports flat, fixed solar panels with internal concentration and dynamic sun tracking. By means of a ten-fold reduction of amount of silicon, costs of the Active Solar panels will be reduced compared to conventional PV modules.
The aims of the project include prototyping and verification of the technology, as well as development and verification of cost-efficient manufacturing techniques and dissemination of knowledge among European manufacturers. The project also aimed to lay the groundwork for the next generation of Active Solar technology that will enable an additional drastic increase in residential solar generation efficiency through use of the highly efficient multi-junction cells in flat, fixed rooftop-mounted panels.

The consortium managed to define, design, simulate and finally manufacture three completely new solar module generations from sketch within 33 months.

The internally named Early Prototype (EP) was a first setup for proof of concept. Every EP module consists of three main units (Cells on Back Plate, Fresnel Optics and Mechanical Subsystem) that finally had to be assembled. Close collaboration between the partner and beyond

Based on the promising test results were gathered, the consortium started investigating in a further prototype, named Integrated Prototype IP. The major aim was the increase of output power per module. Therefore, the amount of cells nearly doubled from 222 in EP to 432 in IP modules. The overall concept remains the same. The thin monocrytalline cells were positioned and glued on a massive Al plate as back panel. A supporting steel frame rims the lenses and operates as link between optical subsystem and the mechanical one for repositioning. To avoid significant sagging, the frame had to be stiff without adding too much weight.

During the phase of design and construction, the scale up resulted in significant challenges mainly with the mechanics which were redesigned to lower the costs. As an enhancement compared to the EP, the first version of the tracking subsystem based on a prototype printed circuit board was assembled and operated the actuators for (re-) positioning of the lenses.

The major aim of the third generation of ASPIS prototypes laid in reducing the complexity of the suspension system on the one hand as well as the reduction of weight on the other. A complete redesign was performed to meet these challenges. The concept of a fixed base plate hosting the cells with moveable lenses on top, covered by an additional sheet of glass, completely been crushed and renewed. The new system now consists of a base frame hosting the suspension subsystem, a moveable plate with glued on encapsulated cells and just one sheet of glass with molded on Fresnel lenses. In addition to this conceptual change, all mechanical parts were reviewed and redesigned according to the needs of weight reduction. The usage of stiff but lightweight aluminum honeycomb structured material paved the way for success. The latest examinations showed that the FIP modules not only will pass standard tests like damp heat testing and electrical performance tests but also will be able to supply the predicted output after considering all boundary conditions.

Project Context and Main Objectives

The main objective of the S&T program is the development of methods and technologies leading to a working prototype of the first-generation Active Solar panels. The prototype will use silicon cells designed and produced by a partner in the consortium and uni-directional Parallactic Tracking. Use of readily available monocrystalline silicon (m-Si) material will help reduce technological risks related to new materials. While a wide range of concentration ratios is possible, a concentration ratio of 10 was chosen as a trade-off, due to the following reasons:

- This concentration ratio is high enough to reduce the amount of silicon by 90%, to a level where silicon ceases to be a major part of the panel cost, while meeting the key cost goal of the Strategic Research Agenda[1]
- It is low enough to use the ubiquitous monocrystalline silicon PV cells, eliminating the need to resort to exotic and expensive PV materials and/or multi-junction cells
- It is low enough to allow use of appropriate passive cooling[2] rather than expensive and complex active cooling
- It is high enough to keep the concentration within low panel profile (resulting in a “flat” panel)

In the course of the project several technologies will be developed in order to overcome challenges posed by the Active Solar implementation. The following challenges have been identified:

- *Advanced optical design for Parallactic Tracking* supporting a large angle focusing range and an evenly spread solar illumination. This includes an innovative design of a unique Fresnel lens array capable of focusing light impinging on the aperture at a wide range of angles. Moreover, the optical design is required to support an even illumination of the PV cells at the full range of aperture insolation angles.
- *PV Cell design*. Dedicated elongated, narrow monocrystalline cells produced using 10% of the amount of silicon used for conventional cells will be designed so as to take a full advantage of the Parallactic Tracking technology and achieve a 90% silicon cost advantage.
- *Design of Parallactic Tracking control subsystem.* The robust, self-sufficient embedded closed loop control subsystem will be implemented to enable internal sun tracking and efficient focusing by the optical array under a variety of weather conditions, latitudes and rooftop slopes.

[1] “A Strategic Research Agenda for Photovoltaic Solar Energy Technology”, the European Photovoltaic Technology Platform, 2007, ISBN 978-92-79-05523-2

[2] Mallick et al., 2007, “Using air flow to alleviate temperature elevations in solar cells within asymmetric compound parabolic concentrators”, Solar Energy, 81, pp. 173-184

- *Design of advanced durable optics*. In order to ensure low production cost and longevity of the optical subsystem, the optical layer will be implemented using a durable low-cost sol-gel or other material.

- *Advanced interconnection of cells.* The project will demonstrate how larger quantities of small cells can be reliably and efficiently interconnected. This will also have a considerable technological spillover impact on standard module interconnection methods.

- *Advanced thermal design.* Dissipation of heat resulting from focusing concentrated light on a narrow cell area must be achieved using inexpensive passive convection. An integrated finite element model for optics and heat transfer[3] will allow detailed analysis of the spatial variation of solar energy flux in the system resulting from conductive, convective and long-wave radiative heat transfer.

- *Mechanical design*. This includes creation of durable enclosure and Parallactic tracking suspension and actuator subsystem that will sustain a 20-25 years lifetime.

- *Design of manufacturing methods*. A preliminary design of mass production methods, including prototype-level tooling and automation, will be undertaken.

The Project will use a successive prototyping design methodology whereby three prototypes will be developed:

- *Early Prototype (EP)* will include integrated optics, photovoltaic arrays and manual tracking. Its area will be about 50% of that of the fully integrated final prototype. The EP will be tested and used to mitigate technological and subsystem durability risks.
- *Integrated Prototype (IP)* will integrate also the electronic tracking control sub-system and the mechanical tracking subsystem. The main use of the IP will be verification of functionality of tracking and suspension subsystems and their reliability. Its size will be identical to that of the final fully integrated prototype.
- *Fully Integrated Prototype (FIP)* will include all subsystems in a sealed enclosure. The FIP will be tested extensively on all parameters including performance and reliability.

[3] Mallick et al., 2005, “Validation of a unified comprehensive model for a photovoltaic concentrator”, 20th EUPVSEC, Barcelona, Spain, 472-475

Main S&T results / foregrounds

The major aim of driving European consumer premises' power generation to cost parity with grid electricity could not be achieved by the ASPIS project. The reason therefore is mainly to be seen in the drastic cost break for poly silicon in 2008-2009.

The whole ASPIS concept is based on the reduced need for silicon due to the slim lines of active solar area. During the proposal phase (2008) and also during the first months of the ASPIS project, the price for Si at stock market were at a height of up to 460$/kg. Due to the reduction of Si prices ($/kg) as depicted in figure 1, the fundamental setup was crushed. Today's spot market price for poly-Si is approx. 32$/kg (Feb. 2012). Due to the planned reduction of Si needed for ASPIS modules, the savings should still outflank the additional costs for the additional parts, like actuators, sensors and lenses.

The drop in $/kg for solar Si, due to the ramp-up of capacity especially by the major players Hemlock Semiconductor, Wacker and MEMC, was for the benefit of the whole PV industry on its way to grid parity, for sure. Nevertheless, in the same way, it was the knock out for the ASPIS concept if seen strictly from the point of costs.

Nevertheless, at the end of the ASPIS project, the consortium not only builds up 12 prototypes (4 modules of each evolution), it also gained a lot of new experiences and knowledge that can be retransferred into other research or industrial projects. The main S&T results per field of knowledge are further explained in the following chapters.

1. General achievements on system level

The major visual achievements are for sure the three generations of prototypes that have been built up in the course of the project.

Starting with the Early Prototype (EP) as the basis for proof of concept, the IP has been a further step towards an increasing size and power output. Several challenges that occurred and had to be tackled were the reason for a complete paradigm shift concerning the suspension and mechanical system. The development, design and construction of the third and last prototype within ASPIS therefore had the major aim to reduce weight and costs.

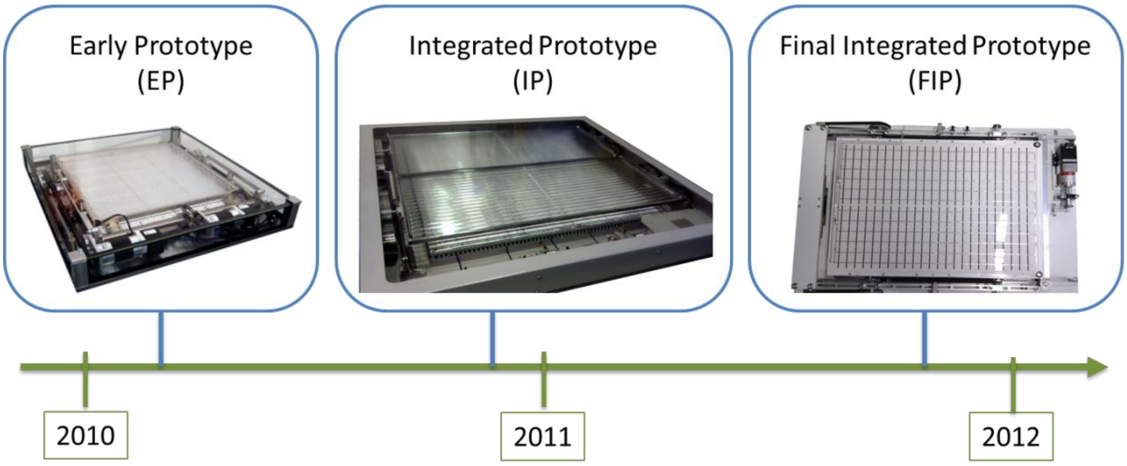


Fig. 1: Timeline of prototypes

Counting from the official start date of the project (01st January 2009) it took the partner only 14 months to finish all necessary tasks for the complete development of a completely new system, never been set up before. Four functional prototypes were built up for further investigations and measurements.

Every EP module consists of three main units that finally had to be assembled. Close collaboration between the partner and beyond the range of single Work Packages was needed and performed to be able to succeed.

- Cells on Back Plate
  As a basis, 222 tiny cell stripes (60x2mm) had to be prepared by separating them from a monocrystaline Wafer. They were glued on an Al cooling device which also serves as back plate supporting the whole structure.

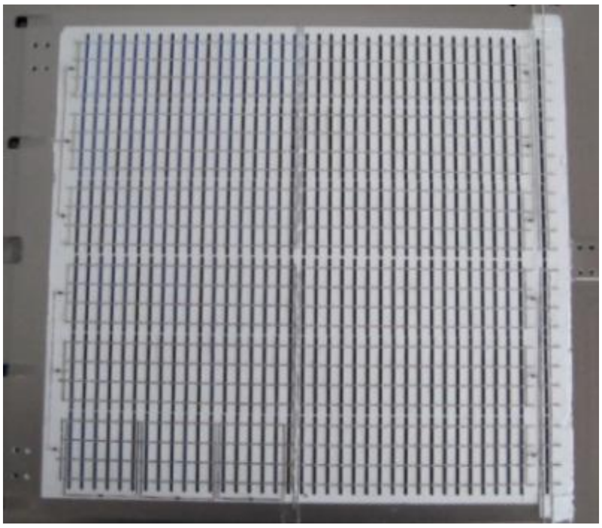


Fig. 2: Cell Plate EP

- Fresnel Optics
  To achieve the low concentration of sun light that is desired (approx. 10x) the consortium decided on using Fresnel Optics. The structured lenses, able to be variable positioned according to the inclination of the sun, focus the sun light directly onto the active cells array.

Fig. 3: Fresnel lenses EP

- Mechanical Subsystem
  A mechanical subsystem is connecting the optics with the back plate and enables the flexible positioning and focusing (so 2D) according to the inclination angle of the sun light.

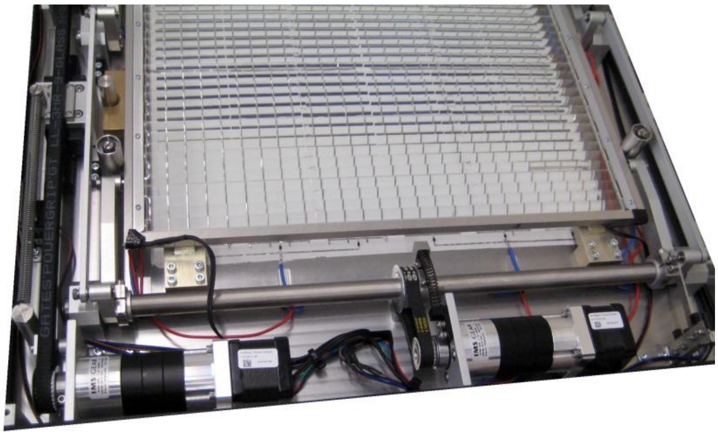


Fig. 4: Mechanics EP

Integrated Prototype (IP)

Based on the promising test results we were gathering, the consortium started investigating in a further prototype, named Integrated Prototype IP. The major aim was the increase of output power per module. Therefore, the amount of cells nearly doubled from 222 in EP to 432 in IP modules. The overall concept remains the same. The thin monocrytalline cells were positioned and glued on a massive Al plate as back panel. A supporting steel frame rims the lenses and operates as link between optical subsystem and the mechanical one for repositioning. To avoid significant sagging, the frame had to be stiff without adding too much weight.

The whole module is covered by a solar grade glass sheet glued into a lid. Overall, the IP generation modules have a dimension of 1,1 x 1,1 m² and a weight of appox. 46kg. Similar to the EP manufacturing, 4 identical systems were built up and tested mainly on performance parameters.

Fig. 5: Assembled IP

During the phase of design and construction, the scale up resulted in significant challenges mainly with the mechanics which were redesigned to lower the costs. The new concept no longer foreseen a subsystem based on gears, shafts and multiple gear rods but was based on leaf springs and wires transmitting the forces necessary for moving the optical frame. Due to the fact that leaf springs can't be compressed to a altitude of zero, the whole base framing subsystem had to be adopted accordingly by implementing an additional socket to guarantee a range of movement similar to the one in the EP (50mm in Z direction).

As an enhancement compared to the EP, the first version of the tracking subsystem based on a prototype printed circuit board was assembled and operated the actuators for (re-) positioning of the lenses.

Final Integrated Prototype (FIP)

The conclusion that have been drawn by the consortium after presentation of the testing were quiet drastic. The growth in size without rethinking the whole conceptual design of each single subsystem didn't seem to succeed. The major aim of the third generation of ASPI prototypes laid in reducing the complexity of the suspension system on the one hand as well as the reduction of weight on the other.

A complete redesign was performed to meet these challenges. The concept of a fixed base plate hosting the cells with moveable lenses on top, covered by an additional sheet of glass, completely been crushed and renewed. The new system now consists of a base frame hosting the suspension subsystem, a moveable plate with glued on encapsulated cells and just one sheet of glass with molded on Fresnel lenses. In addition to this conceptual change, all mechanical parts were reviewed and redesigned according to the needs of weight reduction. The usage of stiff but lightweight aluminum honeycomb structured material paved the way for success.

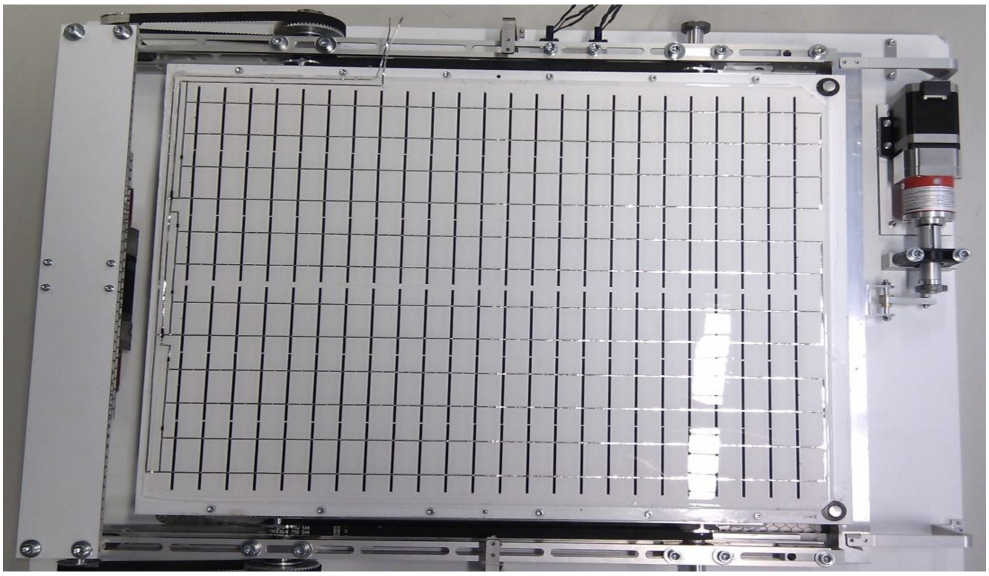


Fig. 6: Assembled FIP

The latest examinations showed that the FIP modules not only will pass standard tests like damp heat testing and electrical performance tests but also will be able to supply the predicted output after considering all boundary conditions.

Each partner involved in the ASPIS project gained further knowledge, not only in his dedicated field of operation. After finishing the project each partner was asked to answer the following two questions:

1. Which major benefit (if any) could your organization achieve?
2. Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

The statements given were the following:

Fraunhofer IPA:

Which major benefit (if any) could your organization achieve?

The handling of fragile substrates such as PV cells is a major objective at Fraunhofer IPA. The experiences gained throughout the project therefore perfectly fit in our strategic agenda. Additional knowhow could be attained in micromanufacturing and –assembly.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

Several industrial as well as research projects, dealing mostly with handling and automation in PV as well as with all kinds of micromanufacturing, already benefit from the knowhow gained during ASPIS.

Solecta:

Which major benefit (if any) could your organization achieve?

Significant advancement of knowhow and technology experience required for Solecta's core business.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

Likely to use the knowledge in next generation products of Solecta

Narec:

Which major benefit (if any) could your organization achieve?

Within the ASPIS project Narec was able to continue to employee R&D staff in a very turbulent time in the CPV industry. The major technical benefit was the research and development of a novel cell technology that allowed enhanced yields (and testing capabilities) for long thin solar cells. These cell types could be useful, for example, in luminescent solar concentrator systems.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

The work from ASPIS is rolled into the continued success of the Narec Solar spin off business to develop commercial concentrator silicon solar cells. FDT, emitter and aluminium optimisations as well as the design work helped introduce applicable practical skills and knowledge which built on the baseline yield of the LGBC technology.

Heriott-Watt University:

Which major benefit (if any) could your organization achieve?

New thermal modelling tool for CPV systems and a generalised temperature co-relation for solar cells was developed.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

The modelling tool has secured funding from Energy Technology Partnership-NaREC funding in non-uniform modelling of CPV cells, in addition, the collaborative knowledge have secured funding from UK-India BURD project.

ACI ecotec:

Which major benefit (if any) could your organization achieve?

In all related areas (definition of cell design, manufacturing and processing) we were able to improve our capabilities. Especially the process was helpful for us to understand the different needs of each process step and the execution of the process steps for high quality results.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

Up to now not directly but we are in contact to especially provide our solution for cell separation which is a very stable and reliable technology to partners and interested industry. The different handling requirements and experiences for thin and fragile parts (most likely cells and tabs) can be used in both future industrial and special development projects – but currently we do not have such projects.

Austrian Institute of Technology:

Which major benefit (if any) could your organization achieve?

General adjustment of test set-ups to be more flexible concerning what types of modules (technology, size, ratings, concentrated systems,…) can be characterized. Increase of in-house knowledge concerning the characterization and validation of concentrated pv technologies.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

The improved analysis methods were already used in the course of several other research as well as industrial projects.

IMOS-Gubela:

Which major benefit (if any) could your organization achieve?

IMOS got the knowledge to produce much larger optical structures than before. The silicone on glass technology also seems to be optimal for the production of optical microstructures or even nanostructures.

Are there any projects (industrial / research) in which you could use the knowledge you gained during ASPIS?

There is the plan to investigate in some optical nanostructures out of silicone on glass.

2. Achievements on subsystem level

The achievements on system level are based on the developments and results gained on subsystem level. For an optimized workflow, the workpackage structure was directly related to the single subsystem development. The major R&D achievements of each of the sections

- Cells
- Thermal Modelling & Simulation
- Optics
- Interconnection & Assembly
- Sun tracking and control
- Testing

are explained in the following.

2.1 Cells

Narec utilises a laser grooved buried contact (LGBC) process in the manufacture of its silicon solar cells [1]. This is a versatile cell structure for concentrator module's cells as the direct write lasering aspect of the finger and bus bar patterning allows for ease of optimisation in gridline density to reduce cell wiring series resistance thus providing a simple way of producing cells for a wide range of concentrator application from 2x to 100x. In addition, the LGBC's intrinsically higher efficiency and the higher conductivity of the plated copper LGBC grid lines compared with silver grid lined used in standard screen printed cell solar cells provides overall an high efficiency solar cell.

For the ASPIS project, the cell requirements were stringent: high efficiency, low cost, long and thin cell for 10x concentration. Traditionally these criteria are not compatible. Due to edge recombination effects, long thin cells are inherently poorer in efficiency. Also costs of LGBC concentration cells can be comparable but the additional handling requirements of the smaller cells could present a longer manufacturing time and/or lower mechanical yield hence a higher overall manufacturing cost.

The challenge for Narec was therefore in the areas of cost (including mechanical yield) and cell efficiency all within the design constraints of a long, thin cell.

The initial project goal was of 1mm by 120mm with the aim of reducing the raw material silicon usage. As will be seen in Section 5, mechanical testing showed the low mechanical yield of the very thin long cells (1mm x 120mm). Any thickness of 2mm or wider yielded greater than 95% mechanical yield. The mechanical strength was a significant factor in cell size choice. There were also benefits to more relaxed placement tolerances that assisted the lens and interconnection (by project partners) so not solely a Narec choice.

2.1.1 Front Dicing Technology

In a silicon solar cell, the maximum energy is achieved by optimal collection of all generated energy carriers within the cell. Any reduction in this maximum amount is due to recombination of these carriers within the semiconductor material itself.

While these recombinations may happen anywhere within the cell, there is a concentration of defects inherent within the silicon edges of a silicon solar cell due to the laser induced damage at the isolation process. In an LGBC process, the isolation of a solar cell is carried out at the final part of the cell production process. A Nd:YAG 1035nm laser is used to cut approximately half way through the cell around the edge of the cells. This cut is used as a physical seed for final breakthrough which, at Narec, is made through manually applying pressure to each edge of the cut. This deterioration in performance at the edges can be illustrated quantitively using internal Quantum efficiency spatial mapping on Narec's Semitool LBIC (laser beam induced current) analysis of the solar cell.

To boost the efficiency of the ASPIS cell, a cell manufacturing solution was required that did not damage the cell edges or alternatively repaired any damage made through etching or high temperature annealing of the silicon material. The standard process steps for LGBC are shown schematically in figure below. As can be seen, the final step is the laser isolation of the cell edge (from the rear surface).

Due to plasma etching, chemical polishing and plating on the rear surface, any change to the sequencing of the isolation step on the rear of the cell would be potentially abraded somewhat away. The proposal therefore was to change the isolation process to pattern the front of the cell. The concept is shown in a schematic cross-section comparison below.

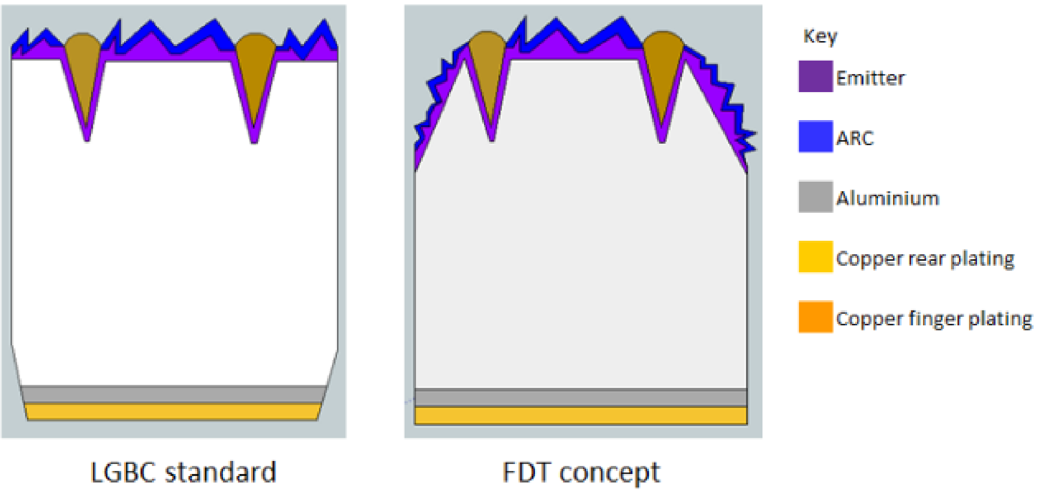


Fig. 7: Comparison of cell processing concepts

This front dicing step was proposed to be carried out as the initial step in the cell production process.

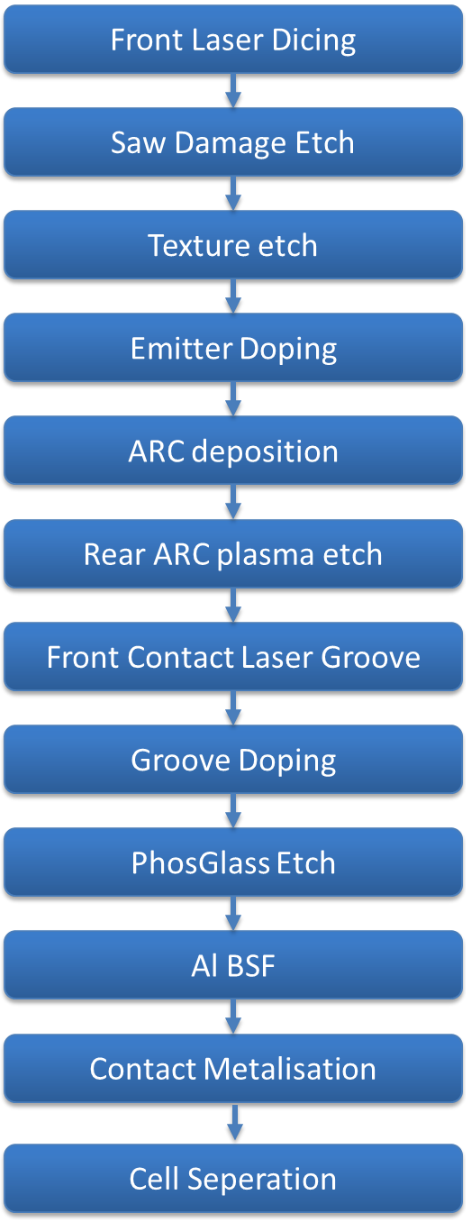


Fig. 8: Process flow of ASPSI cell production

Several challenges, like Mechanical fragility or Insufficiency or too much depth of cut at the end of production, were overcome by extensive investigations of the newly developed process.

Narec's standard cell processing conditions have been established over time involving experimentation on the effects of process variation, for example in doping levels of the emitter step. For ASPIS, the most sensitive aspects of production were varied on the ASPIS cell design under production conditions and the cells tested and analysed for performance. Cells were tested under 1SUN and design concentration conditions. The conclusions from this work were that the processing conditions utilised for the final prototype were optimal.

At the end, the best in calls cells with a dimension of 60x2mm achieved efficiencies of more than 18.2% under 10x sun.

2.2 Thermal modelling & simulation

For the thermal management of the system, extensive numerical simulations of both 2-D and 3-D have been carried out for the ASPIS system with and without passive cooling arrangements. The comparison of 2-D and 3-D has been carried out for with and without fins case and deviations are given as 8.3 % and 7.5 %. Based on that, the effect of other influencing parameters such as, ambient temperature, solar radiation and focal length on solar cell temperature have also been predicted for the ASPIS system. The efficiency of the ASPIS single solar cell is obtained as 14.91% at 25°C.

Based on that, the maximum power of the EP and IP were predicted. The detailed analysis of effect of ALUCORE material on solar cell temperatures was also carried out. First, various geometrical cases with constant porosity and constant permeability value have been taken to study the effect of ALUCORE on solar cell temperature. A particular case has been taken with constant porosity and different permeability values to see the effect of solar cell temperatures. Second, cases with constant permeability and different porosity values have also been carried out in this study. It was clearly observed that the porous medium of low permeability can be used to reduce the solar cell temperature. Based on this present simulation, ALUCORE material with low permeability and porosity for aluminium back plate can be used effectively in the ASPIS project.

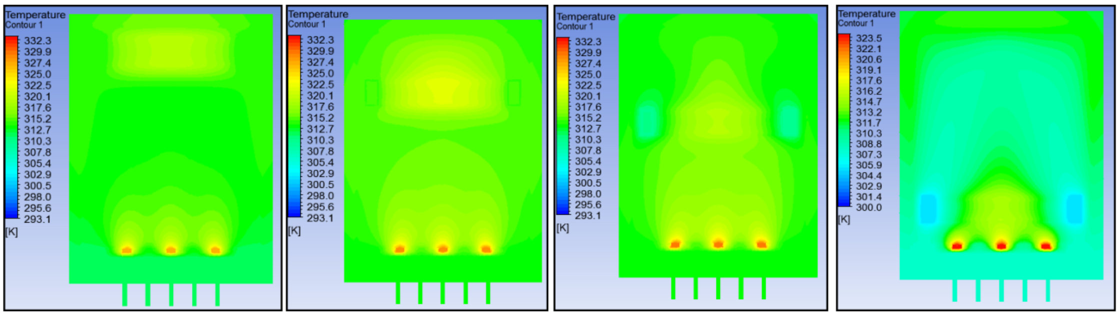
In addition to that, porous material analysis of IP and experimental analysis of EP were also carried out. The present thermal model of cell temperature predictions for WOI and WI of EP gives better agreement with experimental results. Thus, the developed thermal and electrical model can be effectively used to predict the performance of the ASPIS systems.

2.1.2 Modelling setup & Results

The geometries of the present model were created in ANSYS, Workbench. ANSYS 12.1, CFX package was used to develop the thermal simulations for different focal lengths to predict the temperatures of the system. Grid independent study was carried out and the optimum mesh size of the geometry has been obtained with 401 thousands tetrahedral nodes. The continuity, momentum and energy equations were solved with convergence criteria of 10-4. High resolution advection scheme has been selected to discretize pressure, velocity and temperature terms. The global dynamic model controls were adapted for solving the continuity, momentum and energy equations.

The temperatures of the different components (solar cell, lens, Aluminium frame, back plate, and fins) of the system were predicted for different position (41, 33, 25, 5 mm) of the focal lengths. In order to see the effect of cooling fins, first simulation was carried out for the system of 41 mm focal length without cooling fins. Remaining simulations were considered for the system with fins.

With respect to system without fins, it can be seen, that the use of cooling fins with the heat transfer coefficient of 5.8 W/m²K at 41 mm focal length reduces the cell temperature to 3.2°C. It is also noted that the cell temperature is first increased and then decreased. Similarly, the lens temperatures is also first increased and then decreased for different values of the focal lengths. Due to circulation of the hot air by natural convection effect, the lens temperatures are higher than the solar cell temperatures. Aluminium frame, cooling fins and back plate temperatures are almost same for different focal lengths.



(a) (b) (c) (d)

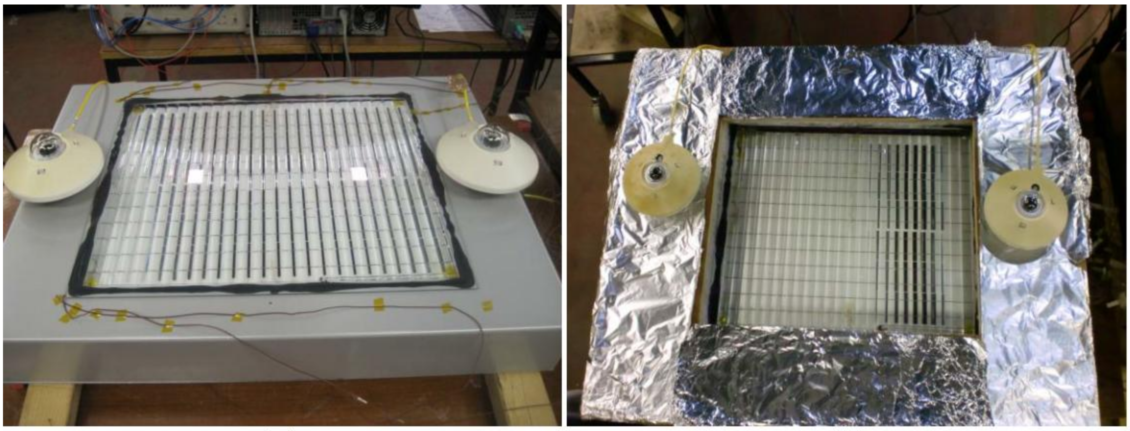
Fig. 9: Temperature of the EP ASPIS system without insulation for focal length of (a) 41mm, (b) 33mm, (c) 25mm and (d) 5mm respectively

The experimental analyses of the ASPIS were carried out in two different places; Solecta- and AIT. Three calibrated thermistors were placed (at point closest to the solar cells, optical lenses on the optical frame, back plate fins) to measure the temperature of the solar cells, optical frame and fins. It is observed that the cell and lens temperature prediction based on the present numerical model shows good agreement with solecta measurements. The maximum and minimum deviation of 3.8 % and 17.9% were observed. On the other hand, the model deviates maximum 16.9% with AIT measurements.

Based on the validated thermal model, further numerical studies were dedicated to next stage of the prototype, integrated prototype (IP) of the ASPIS.

Three different types of ALUCORE honey comb composites panel arrangements are placed at the base of the system to see the effect of cell temperatures. To compare our previous simulation, few cases were also carried out with TCA (Thermal conductive adhesive) and aluminium back plate to predict the solar cell temperatures of the system. Different cases were considered to predict the thermal performance analysis of the solar cell. In addition, the effect of material thickness, effects of fins as cooling arrangements and different geometries were considered.
The outcome in general was that the use of porous medium with high permeability value in the ASPIS project will not reduce the solar cell temperatures. At the same time, the use of ALUCORE may reduce the cost and total weight of the system.

The experimental characterisation of the FIP system with and without insulation at Heriot-Watt University is shown in Fig. 10. The bottom of the back plate is insulated with glass wool. The top cover of the metal frame and other four sides are insulated with the thermo-cool. In addition to this, an open wood plate is covered for avoid burning of the thermo cool at high energy flux. All side temperature are monitored to make sure less heat leakage to the ambient. Twenty eight thermocouples are used for measuring the temperatures of the cell bed, bottom of the cell bed, inside lens and 6 sides of top cover metal plate.



(a) (b)

Fig. 10: FIP system under experimental test at HWU for the system of (a) without insulation and (b) insulated at the side and rear plate

Although similar temperature profiles were found in the start of the experiments, the maximum and minimum temperature differences were 12°C at the steady state conditions. It is clearly indicated that the maximum temperature difference occurred when the solar cell plate is 5mm away from the optical frame plate. This is due to the trapped air within the region acts as an insulator, which increased the operating solar cell temperatures.

2.3 Optics

The idea of the parallactic tracking which is used in the ASPIS project is a unique concept and differs a lot from other concepts that are used in concentration optics. Linear fresnel lens arrays are used for the concentration in the parallactic tracking. The optical design included exhaustive raytracing simulations in order to proof the optical concept and to predict the efficiency of the optical system. The goal of mechanical design of the optics was to integrate the lens array in the suspension system within the desired tolerances. IMOS Gubela was responsible for producing the special optics for the ASPIS modules. The optics of all three prototypes were produced in polymers but switched to a new technology between the EP and the IP. The new silicone on glass technology promised more potential for the production of the concentrator lenses. The silicone on glass technology was successfully introduced in the project and was the basis for the good quality of the lenses of the IP and FIP.

The raytracing was performed with the commercial ZEMAX software. The optics of the ASPIS project is very unique so the capabilities of ZEMAX were not sufficient for effective simulations. IMOS developed a matlab toolbox that extended the possibilities of ZEMAX and allowed them to perform the simulations that were required in the ASPIS project. The target parameter for the optimization was the overall efficiency of the optical subsystem. The challenge in this task was the varying angle of incidence. For conventional CPV panels the panel is tracked and the incidence angle is constant for every time and every day of the year. For the ASPIS panel there is no external tracking and therefore there are different angles of incidence during a day and during the year. The focus is moving with the incidence angle, this is compensated by the parallactic tracking. The simulations (Fig. 11) show the required movement of the lenses to keep the focus on the cells. Additionally there are lens aberrations for skew incidence. These lens aberrations widen the focus and therefore are the limiting factor for the concentration ratio.

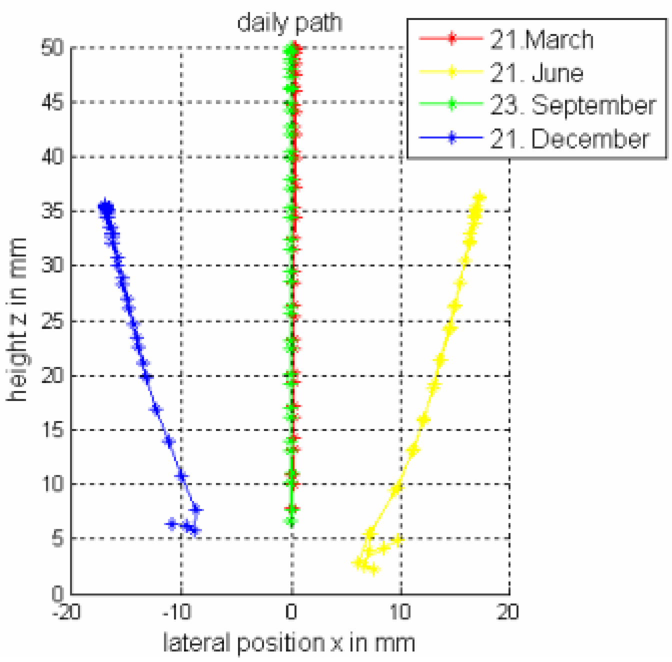


Fig. 11: Position of the focus during a day for the ASPSI module

Numerous simulations have been performed for many times a day and many days per year to predict the overall optical efficiency over a period of a whole year. The results allowed a comparison of different kinds of designs and to choose the optimal lens equation for the Fresnel lens. The design of the EP had the best efficiency but only a concentration of 5x while the IP and FIP had a concentration of 10x. The IP and FIP had the same specifications although the FIP had a little bit less efficiency. The reason for this is that the FIP has the structure on bottom and not on top of the glass. Anyhow, this design has been chosen since it has advantages in the system point of view that compensate the disadvantages. The results from the simulations were also the base for the construction of the mechanical subsystem since the movement of the focus defines the maximal travel distances of the parallel tracking. Furthermore the results from the optical simulations determine the maximum system tolerances that can be accepted without significant losses of energy.

The optics of all three prototypes were manufactured from polymer with moulding techniques. Conventional polymer lenses and rotational symmetric Fresnel lenses are suitable for fast prototyping. These prototypes are usually done by diamond turning. This approach was not possible for the ASPIS project because of the complex geometry and the large size of the arrays. Thus there had to be built a mould for each prototype. The essential part of the mould is thereby the optical template.

The EP lens array consisted out of several lens arrays which were produced in PMMA by injection moulding. The single lens arrays were assembled together and put on a glass which was inserted into the frame.

For the IP IMOS manufactured 4 lens arrays per module in silicone on glass technology. The four lens arrays than were assembled in one metal frame. The silicone on glass technology required a complete new mould design and also the diamond cutting process of the structure template had to be changed.

The FIP lens array was manufactured in one piece in silicone on glass. We optimized the silicone on glass technology that we used for the EP further for the production of the FIP. Also a new mould including a new structure template was built. All prototypes were measured and the optical performance was tested. The lens profile and the surface roughness were tested with a profile stylus measurement system from Vecco. The focal length was determined with an auto-collimating measurement system. A measurement of the lengths and positions of the lenses was also done. It turned out to be necessary that we optimized the mould after the first measurement to correct tolerances and optimize the quality of the lens arrays.

All three optical prototypes yielded good results regarding the focal length and the surface profile of the optics. The inspection of the IP lens array by the AIT showed some surface defects and defects at the border of the structure. These visual defects could be reduced considerably with the optimized production process of the FIP. To draw direct conclusions from the results of the AIT about the performance of the lens was quite difficult since there are too many components that influence the efficiency of the panel.

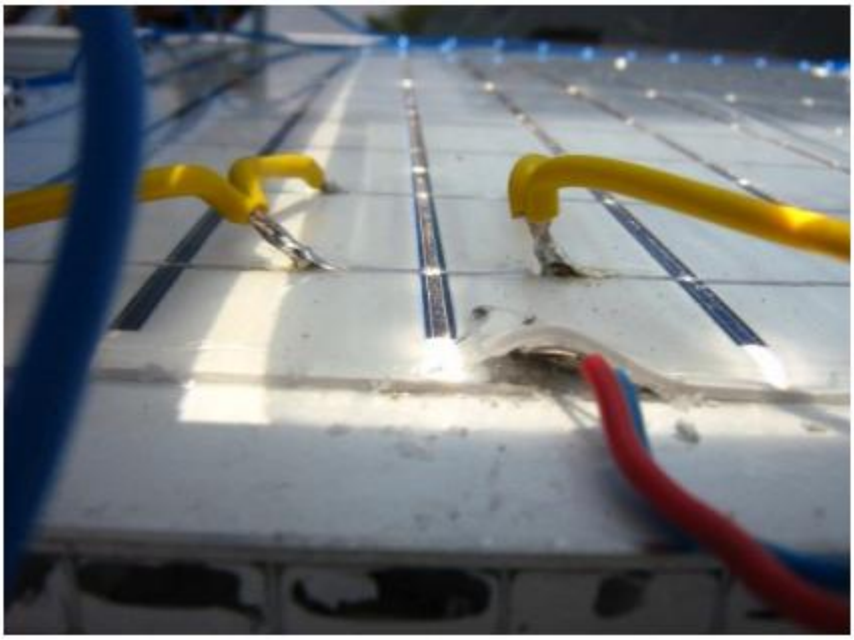


Fig. 12: focused sunlight on cells of FIP module

Therefore the consortium decided to perform a test with just one cell. In this configuration it was ensured that underperformance due to misalignments between the cell and the lens will not affect the test results. The measurements were done by the AIT on 03.10.2011. The power output of the cell was exactly the theoretically expected output. This test confirmed the good quality of the FIP lenses confirmed the measurements that IMOS did internally.

2.4 Interconnection & Assembly

For the EP several cell concepts have been proposed by Narec. All different cell types were narrow (from 1 to 3 mm) and long (either 60 or 120 mm). Facing the challenge if interconnection these very fragile cells to long strings, the idea was to put as little stress as possible in the cells for interconnection.

Therefore Day4 ecoTec proposed to use electrically conductive adhesive (ECA) for interconnection. Based on this idea all supporting tools (cell separator, cell interconnection plate, stringing plate) were designed to support this technology. Based on the requirements of the partners the interconnection design was proposed. Influencing factors for this were not only the gained current and power but also the ability of specifically measurable areas for some partners. In Picture 1 the final EP interconnection design is shown. The module consists of 4 quarters each measurable separately. For supporting the positioning of the lens frame an additional string where the cells are positioned side by side was placed at the bottom of the module.

The manufacturing of the interconnection itself was performed in the Day4 ecoTec Technology Centre. The quarters were packed and delivered to the Fraunhofer IPA where the integration of the quarters to the module was performed as the full assembly was executed there.

The precision of aligning the cells was seen to be one of the most critical issues during the EP assembly process. To check the quality of the handling and fixation on the cell plate, random measurements of the accuracy of cell positioning were performed on a Kugler Microgantry Micro 3X equipped with an highly accurate positioning system (scaling down to 0.0001 mm).

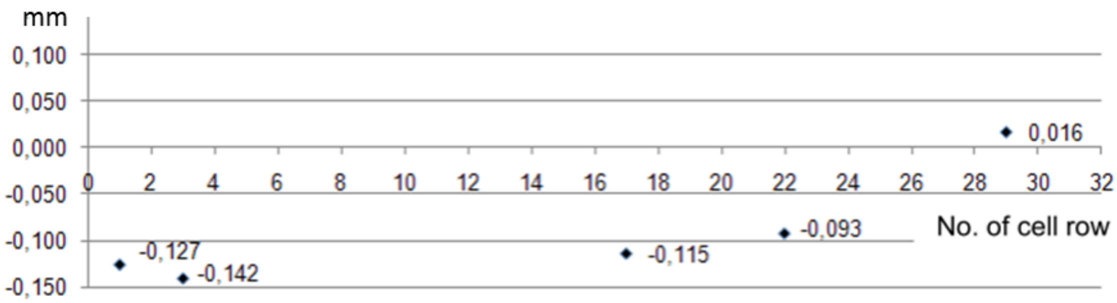


Fig. 13: Accuracy of cell positioning

The results of the EP with regard to the interconnection technology looked very promising. This did not make any changes necessary. Therefore the technology for the IP interconnection design was as well ECA. Due to the changes in size (12 x 36 cells) as well as due to the changes in distance from cell to cell (20 mm instead of 10 mm) the supporting tools had to be redesigned to fulfil the needs. Day4 ecoTec decided to implement the ECA dispensing onto a linear high precision axis not only to achieve comparable ECA amounts for each connection but also to improve the positioning accuracy of each dot.

Additionally to the automated dispensing process the redesign of the supporting tools had extensive impact on the assembly of the cell interconnection. The cell separator was improved to process the Narec cells sunnyside up (see front dicing technique in the related Narec report) and the cell tabbing plate needed a new design because the distance of the cells had changed. To avoid the cells from sticking with the ECA at the dispensing needle a fixation plate was added to the cell tabbing plate as well as to the stringing plate. Furthermore a pressure plate for the fixation of the tabs at optimal height to the cell was developed for the cell tabbing and the stringing plate.

The experiences of EP and IP had shown that the fixation of the tabs with ECA to the cells was a quite fragile connection. Therefore Day4 ecoTec decided to follow the revolutionary approach for the interconnection technology as other partners did for their work. Examinations were started for bonding and soldering as possible other approaches. Following further investigations, soldering was chosen as interconnection technology for the FIP module assembly. Furthermore the decision was made to perform the integration of the strings at the Day4 ecoTec facility to the cell back plate. This was meant to avoid additional transportation stress to not completely fixed sub-parts of the ASPIS module.

During the assembly process further improvements for the supporting tools were made and a new string gripper for improved string positioning was developed. The gripper allows the handling of 12 cells at a time with only eight connection points.

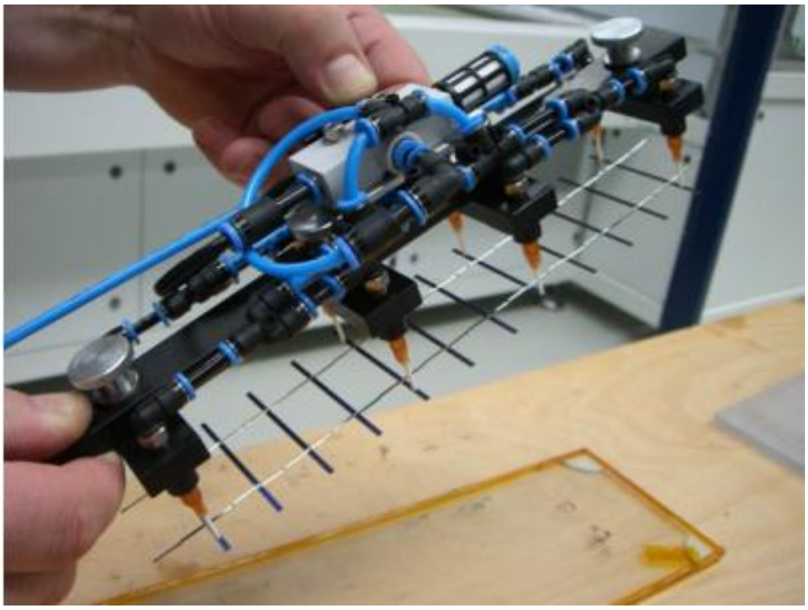


Fig. 14: Semi automated gripper for FIP cell strings

The assembly of the several subsystems was the final stage during the development of each module. All subsystems were mounted according to the predefined construction layouts. The way each prototype had to be assembled differs a lot form the others. Several unpredicted challenges had to be covered. The development of the FIP modules therefore took the concerns of assembly into consideration right from the beginning. The usage of standardized components and spare parts in combination with assembly friendly positioning were the major aims towards mass manufacturability.

2.5 Sun tracking and control

The Electronic control unit was implemented in three stages each of which corresponded to the respective ASPIS pane prototype: the EP, the IP and the FIP.

Solecta therefore focused on the following subjects:

1. Finding the optimal combination between off the shelf electronics and the electronics that need to be developed in house
2. Finding the optimal microcontroller in terms of cost
3. Investigating for the optimal control algorithm taking into account the specific needs and design of the ASPIS panel

The EP was operated manually and smoothly from the first try. The suspension could be moved in both dimensions along the designed range. Velocity and power consumption of the motors were measured and the conclusions were subsequently used in the IP design. The concept of using a combination of off the shelf and in house electronics proved to be efficient. The control subsystem was used to measure the output power of the panel as a function of the position of the optical frame above the cells backplane. This data was subsequently used for theoretic analysis of convergence performance of the various candidate algorithms.

For the IP modules, the control hardware was integrated and embedded in the panel. For the first time the in house designed electronics operated the motors. The current provided to the motors was adequate for smooth movement and the concept of adding heat sink to the driver chips proved successful. The external computer was no longer used for operation (but was still used for debugging) and the embedded microcontroller successfully controlled operation, data collection and the manually operated control algorithm.

Since the FIP electronic hardware was very similar to that of the IP (except for newly manufactured printed circuit board) the main challenge was the final selection, integration and testing of the Parallactic Tracking control algorithm.

Following a MATLAB simulation and the integration with the ASPIS panel, three control algorithms were tested experimentally:

- Simplex (based on triangle) - more than 20% power loss
- Powell-Fletcher (based on gradient vector in each direction separately) - more than 20% power loss
- Heuristics (Gauss Seidal) (based on gradient vector in both direction) - less than 10% power loss

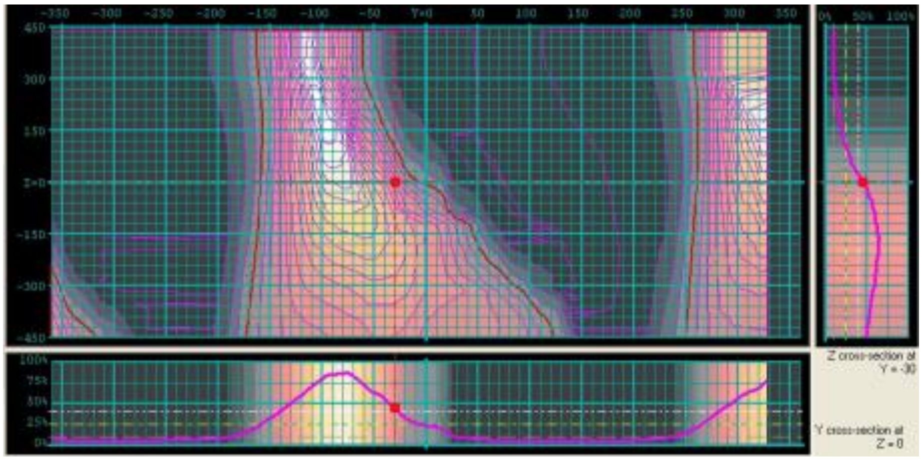


Fig. 15: Experimentally determined optimization cost function and algorithm convergence curve

The Gauss Seidal search algorithm was found to be optimal for the FIP due to its efficient handling of mechanical suspension backlash movements. In order to optimize the control algorithm further research is needed. The possible optimization includes study of optimal values of motor steps as these affect the motor power consumption, the convergence speed and the maximal achieved output power. Another area of optimization may be a combined open loop/closed loop tracking control, using known astronomic values in order to speed convergence of the algorithm.

2.6 Testing

Besides some small test setups like single cell strings or smaller test versions of the prototypes there were 3 generations of the ASPIS prototypes. The first prototype, the Early Prototype – EP, was built and tested during the first half of 2010. The lessons learned from this prototype were considered during the conception and construction of the Integrated prototype – IP. This prototype was built and tested during the second half of 2010 and the first quarter of 2011. The analyses of the IP prototypes identified general needs to change the mechanical set-up of the prototype and the tracking system. The EP and IP prototypes had a fixed cell plate (= back plate of the module), a fixed front side glass and a moveable lens plate in between. The last prototype, the Fully Integrated Prototype – FIP, was built with the lens plate integrated into the housing and replacing the fixed front side glass. The cell plate was separated from the back plate and was then made the moving part in the tracking system. This overview about the prototypes and results will show the technological progress the project consortium was able to achieve and the major issues left before a mass manufacturing could be started.

The performed tests at AIT were mostly taken out of the type approval standard for concentrated PV-modules IEC 62108:2007-12 Ed.1.0. Besides these standard tests additional examinations of the prototypes were done. The most important of these tests were performance measurements at various conditions, electroluminescence measurements and analyses of the mechanical tracking system.

Two EP prototypes were delivered to AIT for testing – EP1 and EP3. Among others, the following tests were performed on the EP prototypes:

- Visual inspection
- Insulation test
- Electrical performance indoor (STC) & outdoor
- Hot spot endurance test
- Electroluminescence measurements
- Infrared measurements
- Temperature measurements (cells, optical frame, fins)

The results gathered of those tests were first of all a proof of concept, since nobody ever tried before; no one has known if the concept of a combined tracking and concentration would work out. The results also highlighted the potentials of optimization and were therewith a very valuable input for the further development.

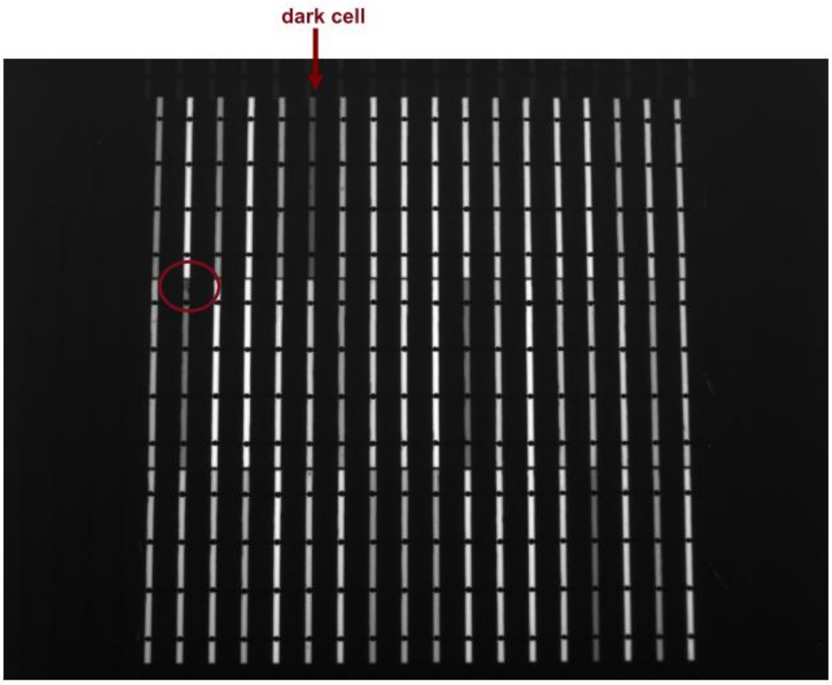
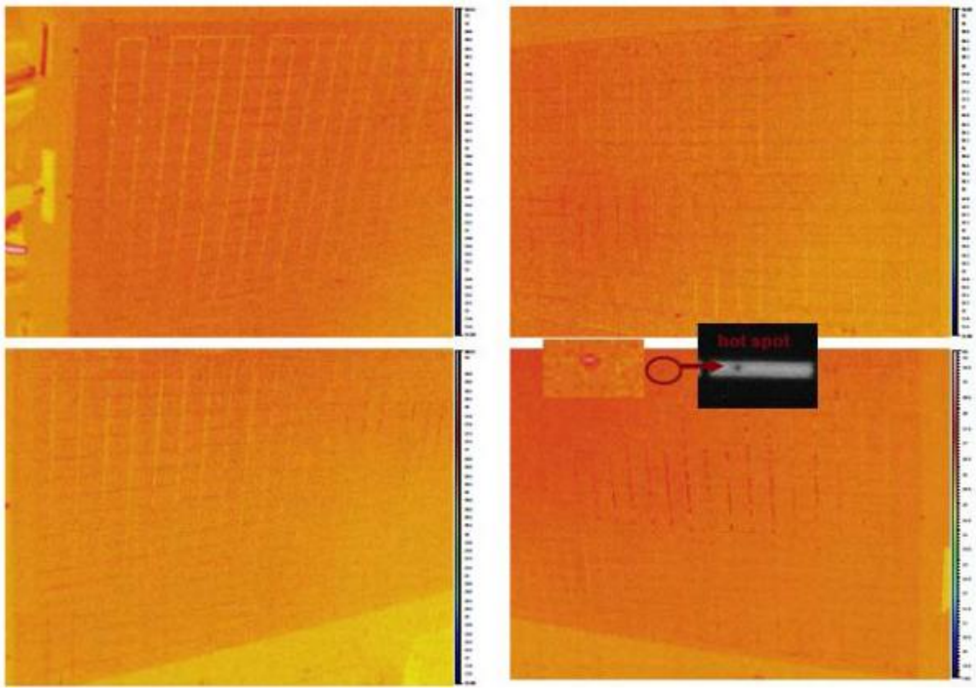


Fig. 16: Electroluminescence measurements of EP module

For testing the IP, two modules of the second generation prototype, where sent to AIT for the verification of the operation of the suspension system and the parallactic tracking system as well as general performance measurements and quality analysis.

To check the operation of the suspension and the tracking system the whole mechanical system was inspected thoroughly and tests were performed to check the ability to move the lense plate - precision, smoothness, power consumption, function of motor control and limit switches. Most of the tests performed to check the overall quality of the prototypes were taken out of the type approval standard for concentrated photovoltaic systems – IEC 62108:2007-12 Ed.1.0 Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval. Besides this additional tests / analysis outside the scope of the type approval standards were chosen to get a better understanding of the internal mechanisms leading to the results found during the above mentioned tests. For this purpose the following analysis methods were used: Electroluminescence imaging, infrared thermography, temperature measurements and performance determinations under various conditions.



Fig, 17: IR-measurements of IP

The major issues for the forthcoming prototypes identified during the analysis at AIT were:

- Find a mechanical system for the movement of the optics which is more robust and precise.
- The power consumption of the motor control system must be decreased.
- Try to get better ratios of power per area (module efficiency) and power per weight.
- Improve the soldering technique to get less short circuited cells and loose contacts.
- Improve method of placing the cell strings on the back plate to get a more precise alignment of the individual cell rows.
- A insulation barrier between life parts and the back plate must be found capable to resist voltages of at least 500V.

The results gathered while the testing of the IP in combination with the experiences gained during the assembly ended up in the decision of a complete new design and concept for the FIP.

Two modules of the third generation prototype, the Final integrated prototype - IP, where sent to AIT to perform exhaustive tests and validate if the open tasks from the former prototypes could be sufficiently addressed. The tests and analysis used for this purpose were the same like AIT performed on the previous prototypes to get comparable results. Hence the following overview about the test methods was taken out of a previous deliverable: To check the operation of the suspension and the tracking system the whole mechanical system was inspected thoroughly and tests were performed to check the ability to move the lens plate - precision, smoothness, power consumption, function of motor control and limit switches. The test performed in detail were quiet the same as for the IP modules.

The comparison of the test results showed improvements on all component levels and also the overall concept of the prototype could be substantially improved compared to the IP prototype.

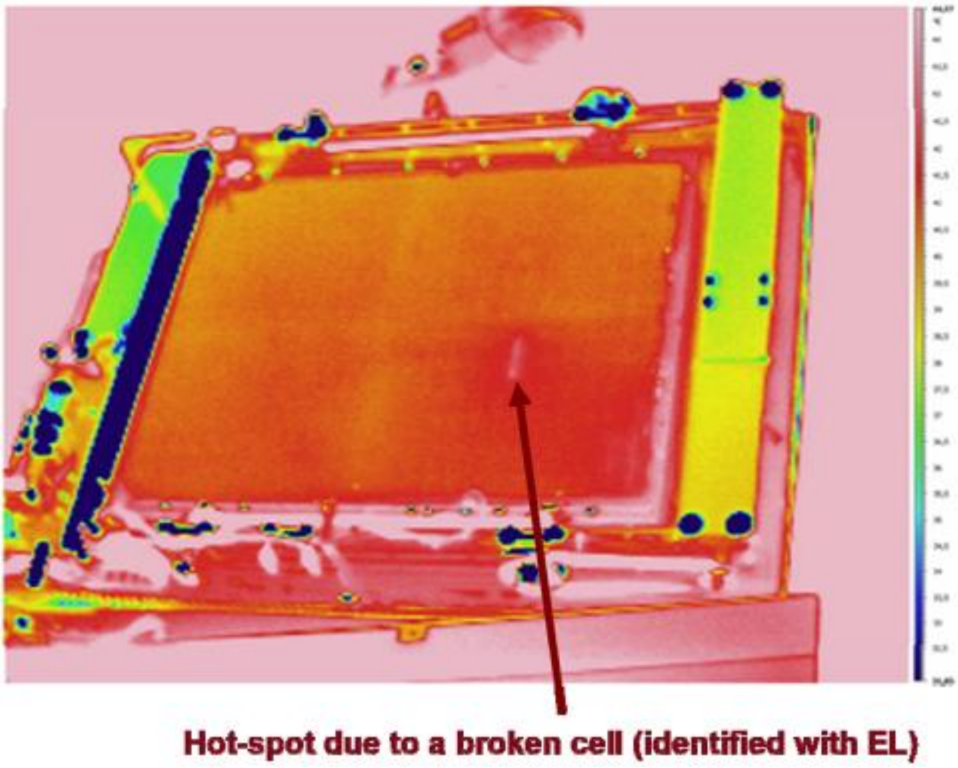


Fig. 18: IR-measurements of FIP, Isc operated under natural sunlight

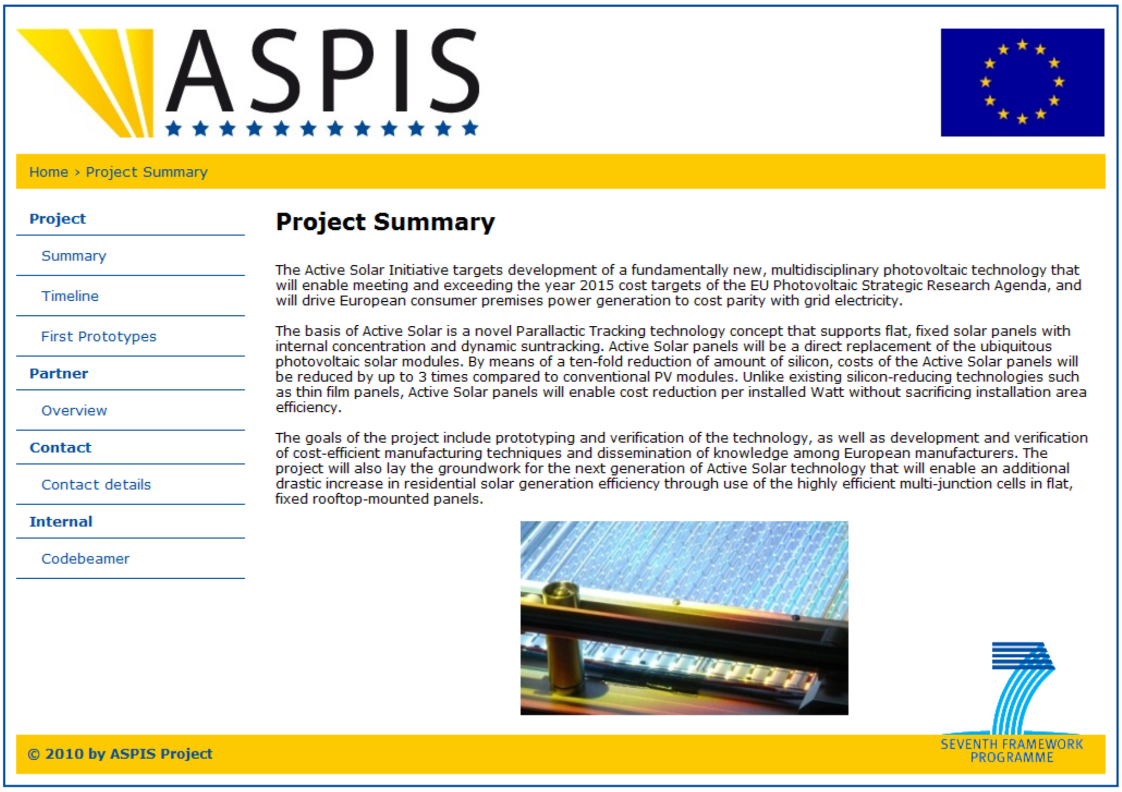
Dissemination and Exploitation

Several dissemination activities and exploitation have been carried out to produce interest on the one side and to demonstrate the scientific aspects on the other.

Website

The project website (www.aspisproject.eu) was launched in project month 4 (April 2009) and since then updated ongoing. The current version is structured into 4 main areas:

- Project
  This section gives an overview of the aim of the project and describes the technical aspects as well as the timeline to achieve this.
- Partner
  A hyperlinked table gives an overview of the participating companies / institutes / university.
- Contact
  Coordinator's contact details ensure quick and easy ways of communication for further information about the project.
- Internal
  This section is a direct link to the projects internal collaborative platform which is used for hosting and sharing all project relevant documents.



www.aspisproject.eu (status: Feb 2012)

Flyer

A flyer was designed and printed in project month 8 (August 2009). Compromised on a tri-folded leaflet it summarizes the most valuable information about the project aims, the partners and the possibilities to learn more about it. Every partner received 100 copies to use them for marketing issues on conferences / exhibitions. Fraunhofer, for example, used it for advertisement during several conferences, exhibition and in-house marketing.

Flyer frontside

Flyer backside

Papers

Several (partly peer-reviewed) papers, addressing the different R&D topics within the ASPIS project demonstrate the scientific relevance and quality of the results gathered.

Year	Author	Title	Source, Location
2010	Drew, K.; Cole, A.; Brown, L. M.; Heasman, K. C.; Bruton, T.	Front Dicing Technique for Pre-isolation of Concentrator Silicon Solar Cells	6th PVSAT, Southampton, UK
	Drew, K.; Brown, L. M.; Cole, A.; Heasman, K. C.; Bruton, T.	Front Dicing Technique for Pre-isolation of Concentrator Silicon Solar Cells	25th EUPVSEC, Valencia, Spain
	Mallick, T. K.; Natarajan, S. K.	Heat transfer modelling of a novel concentrating Photovoltaic system	International Heat Transfer Conference-14, Washington DC, USA
	Wertz, R. on behalf of the whole consortium	ASPIS - Concentrator PV for Rooftop Applications	25th EUPVSEC, Valencia, Spain

2011	Drew, K.; Brown, L. M.; Cole, A.; Heasman, K. C.; Bruton, T.	Design Considerations for Silicon Solar Cells as Part of the Aspis Concentrator Concept	7th PVSAT, Edinburgh, UK
	Drew, K.; Brown, L. M.; Cole, A.; Heasman, K. C.; Bruton, T.	Design Considerations for Silicon Solar Cells as Part of the Aspis Concentrator Concept	26th EUPVSEC, Hamburg, Germany
	Natarajan, S. K.; Katz, M.; Ebner, R.; Weingaertner, S.; Wiechers, O.; Cole, A.; Wertz, R.; Giesen, T.; Mallick, T. K.	Experimental validation of a heat transfer model for concentrating photovoltaic system	Applied Thermal Engineering, 33-34, pp. 175-182
	Natarajan, S. K.; Katz, M.; Ebner, R.; Weingaertner, S.; Wiechers, O.; Cole, A.; Wertz, R.; Mallick, T. K.	Validated Thermal Model for CPV System	7th International Conference on Concentrating Photovoltaic Systems, Las Vegas, USA
	Natarajan, S. K.; Mallick, T. K.; Katz, M.; Weingaertner, S.	Numerical Investigations of Solar Cell Temperature for Photovoltaic Concentrator System With and Without Passive Cooling Arrangements	Int. Journal of Thermal sciences, Vol 50, pp. 2514-2521
	Natarajan, S. K.; Mallick, T. K.	3-D Thermal Model for an Integrated Prototype of an ASPIS System	Photovoltaic Science and Technology Conference, Edinburgh, UK
	Natarajan, S. K.; Mallick, T. K.	Thermal Model for an Early Prototype of CPV for ASPIS	Photovoltaic Technical Conference, 25th to 27th May, 2011, Centre de Congress; Aix En Provence; France
	Wertz, R.; Giesen, T.; Aßländer, O.; Weingärtner, S.; Verl, A.	Challenges during assembly of ASPIS low-concentrator prototype module	26th EUPVSEC, Hamburg, Germany
2012	Mallick, T. K.; Natarajan, S. K.	Integrated Optical-Thermal-Electrical Model for Concentrating Photovoltaic Systems	Targeted Journal will be Solar Energy, Time scale early 2012
	Mallick, T. K.; et al. (includes all other member from the consortium)	Experimental Validation of in-house developed thermal model for concentrating Photovoltaic system	Targeted Journal to be decided later, time scale Early 2012

Exhibitions & Conferences

The ASPIS project and its results have been actively presented on several exhibitions and conferences.

- 24th EUPVSEC, Hamburg, Germany
- International Heat Transfer Conference-14, Washington DC, USA
- 25th EUPVSEC, Valencia, Spain
- 6. Workshop Photovoltaik-Modultechnik TÜV Rheinland
- 7th International Conference on Concentrating Photovoltaic Systems, Las Vegas, USA
- 7th PVSAT, Edinburgh, UK
- Photovoltaic Technical Conference, Aix En Provence, France
- 26th EUPVSEC, Hamburg, Germany

Further Publications / Media

Publications in other media as already mentioned above shall ensure the wide speeded distribution of the project objectives an results among the scientific community, industry as well as civil society and policy makers.

- International Innovation: EuroFocus edition, April 2012 Something new under the sun
- Clean-Tech Initiative, Kataster (http://www.cleantech-initiative.de/kataster/projekt.php/445-aspis, status 02/2012)