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Executive Summary

The vision to use photovoltaics (PV) as a decentralized and sustainable source of energy in their products is shared by thousands of designers, architects and manufacturers world-wide. In principle PV can be integrated directly in products, such as devices, vehicles and buildings.

Nowadays the development of photovoltaic modules is still primarily driven by the idea of economies of scales which leads to unvaried PV modules that are only good for large-area installations. These photovoltaic modules are not suitable for the integration into building skins, roof tiles or electric devices because of their rigidness and their electrical constraints. Even companies which could provide a solution for these applications (flexible thin-film PV firms) are not providing customized PV modules because of the associated set-up times.

The SolarDesign project addresses these obstacles by the development of novel solar cell materials, manufacturing processes and supportive actions to improve communication in the design value chain.

One key technology is a novel monolithic interconnection process for thin- film solar cells that simplify the production of thin-film modules and allows adjusting the essential properties of a PV module “on-the-fly” without excessive set-up times. It allows adjusting the electrical properties of a given PV module on the fly as well as the production of fully customized photovoltaic modules in respect to size, shape and patterns. Combined with an optimized solar cell performance, the pliability given by the flexible substrate and the encapsulation these novel PV modules provide the necessary variability and performance ability for design-driven solar solutions. Based on the innovative thin film solar cell technology, the scientific basis for optimized designs of photovoltaic cells and modules was made for different application fields and associated necessary adaptations of involved materials and process parameters were explored.

The novel PV material was demonstrated in design driven prototypes ranging from solar charged mobile devices, solar lighting and building integrated PV to full integration in smart textiles.

Project Context and the Main Objectives

ONE SIZE DOESN´T FIT ALL

Photovoltaics is widely recognized as one of the key technologies for the future energy supply. The photovoltaic industry has successfully achieved a sharp reduction in manufacturing costs over the course of the last 10 years that is also reflected in declining market prices. The cost reduction is a result of the utilisation of learning effects, expansion of production capacities, extensive automation and standardisation efforts.

The growth of the PV Industry has produced falling prices for photovoltaic installations despite some shortages in the supply chain between 2005 and 2008. However, despite these achievements, the result has been standardised production processes and product lines that fail to respond to varying customer requirements. Conventional mass produced photovoltaic modules are in most cases not suitable for the integration into surfaces of facades, roof tiles or electric devices due to their rigidness, appearance and electrical constraints.

Nevertheless, the demand for aesthetically integrated photovoltaic materials is growing steadily in many industries. A growing number of designers, architects and industrial manufacturers across the world share a common interest in using Photovoltaics (PV) as a decentralized and sustainable source of energy in their product designs. Developing markets such as sustainable housing, temporary building structures, outdoor activities, electro-mobility and mobile computing drive the demand for decentralized, attractive energy solutions. Indeed photovoltaic modules are the only viable renewable energy solution that can be integrated directly into objects such as devices, vehicles and buildings.

CURRENT NEEDS FOR NEW PV APPLICATIONS

Required solutions for these PV integrated product solutions are customisable shapes, sizes, colours, transparencies or specific electrical properties, which have a decisive influence on the acceptance on the market. Therefore a new breed of solar technologies was necessary. These technologies provide the right photovoltaic solution for the given requirements in respect of appearance, easy system integration and technical constraints. To achieve this goal it was needed to develop new flexible production processes and materials.

Furthermore the designer or architect who wants to incorporate solar electricity into his work needs a service environment to be assisted in the creative process. Tools should support the designer in conceiving, planning and producing the SolarDesign products. This project addressed the above mentioned challenges by exploring and developing new materials, manufacturing and business processes in PV powered product design and architecture.

To show the application range of customizable and flexible solar cells, prototypes in different markets have been developed. Each application has special requirements towards the solar modules, such as shape, flexibility, weight and I/U characteristics. The areas covered are building integrated photovoltaics (BIPV) and solar powered consumer products.

SCIENTIFIC AND TECHNICAL OBJECTIVES OF SolarDesign

The scientific and technical objectives of this project were to develop:

- A flexible scribing and printing technology that allows producing a given photovoltaic module according to specific design requirements "on-the-fly". This flexible interconnection was applied on the solar foil (i.e. an endless solar cell) and allows curved solar cells and interconnection patterns.
- Novel materials for the underlying flexible solar cell technology to extend the design related degrees of freedom and to optimize the materials used for integrative solar applications.
- Novel materials for satisfying design related requirements on solar module level (the part that is most visible for the beholder). Focus was laid on materials for the electrical conducting front grid to allow a high design freedom of patterns and colour variations, as well as using of different novel encapsulants allowing custom designed visual appearance.
- A methodological toolbox to provide design rules for the best solar cell super-structure and module design layout for a given application by using numerical modelling and simulation. A product development process assisted the designers in all aspects of the SolarDesign process (visualisation, determination of electrical specifications, calculation of expected energy yields, and interface with rapid prototyping equipment).
- New design oriented applications for decentralized solar power generation ranging from low-power demand to high power applications. The developed technologies were demonstrated by Building Integrated Photovoltaics (BIPV) and Product integrated Photovoltaics (PIPV).
- Design-driven solar products are often operated in subpar angles to the sun and without any back ventilation. Therefore, solar cell efficiencies are not only optimized in respect to standard tests conditions but also to the specific conditions of solar integrated solutions.

CUSTOM DESIGNED SOLAR MODULES

Solar thin-film is still a promising field of innovation which is dominated by the desire to drive down costs on the basis of economies of scale. Most of the thin-film technologies and companies compete fiercely with conventional silicon solar cells and to some extend with upcoming technologies like organic photovoltaics. Flexible thin-film solar cells have the intrinsic advantages of flexible thin-films such as aesthetic appearance (smooth surfaces, no crystalline impression), pliability and the possibility to adjust the voltage by an integrated solar cell interconnection are not exploited today after all. For design-driven solar applications a novel "PV material" is necessary that gives the creator full control over shape, size and electrical properties.

Sunplugged's flexible CIGS solar cell (Solar Foil)

Besides costs, efficiency is a key metric for PV modules used in terrestric applications. Crystalline silicon PV modules are still leading with efficiency on module level, followed by CIGS thin-film. Due to their appearance and mechanical flexibility thin-film PV and organic PV are often cited as ideal candidates for PIPV and BIPV. In reality both technologies are currently widely manufactured in such a way, that no adaptation of any sort can be applied.

SolarDesign approach: Photovoltaic modules that can be modified "on-the-fly"

In order to meet the requirements as expressed by architects and designers, the SolarDesign approach is similar to that adopted by a tailor in the manufacture of bespoke, "made-to-measure" garments. The fabric, or basic material, is an endless thin-film solar cell. This solar cell can be cut according to the size and shape stipulated by the user and a flexible interconnection can be applied to obtain the required electrical specifications. This innovative approach provides a great deal of flexibility across four dimensions: mechanical, electrical, size and shape thereby providing new possibilities for PV integration into products.

A novel manufacturing process enables the adjustment of all properties of a thin-film module on-the-fly and facilitate the production of customized photovoltaic modules with the desired voltage, size and shape. Combined with the material characteristics given by the underlying thin-film solar cell technology a new-breed of design-led, sustainable and decentralised energy solutions can be realized.

Typical requirements of design driven solar applications, addressed by SolarDesign:

- Fully pliable,
- Any voltage can be defined on-the-fly during production,
- Any shape can be applied (round, triangular, etc.) as long as the serial interconnection can be applied,
- Holes can be applied, as long those holes are isolated by the flexible interconnecting pattern,
- The printing process of the interconnection allows the application of distinct patterns; the colour of the printed interconnection can vary depending the design requirements ranging from nearly indiscernible (the invisible solar cell) to decidedly eye-catching,
- No restrictions whatsoever; basic material is 300 mm wide endless foil.

INNOVATIONS ON THE SOLAR CELL LEVEL

The basic material for SolarDesign approach is an endless solar cell based on CIGS (copper indium gallium di-selenide) absorber layer. CIGS solar cells have the highest potential efficiency of all thin-film technologies. This solar cell is optimized for the requirements of design driven and integrated photovoltaic solutions. SolarDesign cell contains no toxic materials (conventional high efficiency solar cells contain cadmium or other toxic materials), has got a good response under diffuse light conditions and comparably low losses at high temperatures. Design-driven solar products are often operated in subpar angles to the sun and without any back ventilation. Therefore, SolarDesign cell efficiencies are not only optimized in respect to standard tests conditions but also to the specific conditions of solar integrated solutions.

INNOVATIONS ON SolarDesign MODULE TECHNOLOGIES

SolarDesign interconnection allows full customization of the PV module. The basic fabric in SolarDesign is an endless produced solar cell. The project made use of a fundamentally new way of how to interconnect solar cells to a final PV module (which is the end product and therefore of interest for the designer and end-user).

In doing so micro-scale grooves were applied by an ultra-short pulse laser process into the solar foil. With the help of this laser process the edges of a given PV module were isolated and the thin-film layers were ablated selectively so that the rear contact (which is initially covered by several thin functional layers) and the transparent front contact of the solar foil were electrically interconnected. The electrical interconnection itself can be then printed virtually in the same production step. To do so a novel adjustable solar cell interconnection needed to be developed which gives full freedom of design. To make this novel interconnection possible, a thin-film solar cell stack and short-pulse laser scribing process had to be developed.

One core innovation of this project is a flexible interconnecting scheme that allows the separation of all solar cell related processes from all processes related to the solar module production. This novel approach enables the flexible production of custom-made photovoltaic modules. Thin-film solar modules are usually interconnected by three scribing steps of the different thin-film layers. Within the scope of the project all three scribing steps were brought together in one laser process which is simultaneously combined with a printing process. This approach cuts dramatically production costs, increases efficiencies and facilitates the flexible production of custom-made photovoltaic modules.

The technique used for the interconnection and the metal grid are screen printing and partly dispensing and inkjets. The technologies at our disposal for the printing were screen printing and dispensing. For very small scale production (lot size below 200) screen printing is unsuitable because every pattern requires its own screen. Also after the printing of the isolation paste a thermal curing needs to be applied. Therefore a dispensing process was developed to complement the production for specialised modules. This involves the evaluation and adaption of electrical isolation and conductive pastes and the development of the dispensing process. Therefore two dispensers were integrated into an existing laser scriber/screen printer and test the system in comparison with screen printed modules. The main advantage of the dispensing technology is that it can be fully digitised and a “lot size one” is possible. It is an addition to the screen printing to fulfil customer demands regarding design for reasonable costs.

CUSTOM DESIGNED ENCAPSULATIONS FOR CIGS SOLAR MODULES

Encapsulants for CIGS solar modules require a very important attention. The selection of the potential solution is a compromise between several technical and economic constraints: it has to be thin, flexible and transparent. It needs to protect the solar cell against external shocks and mainly against moisture according to the international standards.

The development of an encapsulation solution satisfying all the specifications (e.g. barrier performance, cost, photo-chemical stability) can unlock entire market segments for thin film flexible PV panels based atmosphere sensitive components. The products available on the market do not lead to a complete set of solutions which was required within the project SolarDesign. Conventional encapsulants do not have tailored properties: thickness, colour, mainly and conventional encapsulants are not textured on back side in order to increase the light entrapment for increasing the module efficiency. Even without developing new material within SolarDesign, it was important to make an complete benchmark on existing solutions on the market, make characterization and finally propose evolutions (like texturing) in order to even improve and tailor the properties.

DEMONSTRATION OF THE NEW PV TECHNOLOGY: APPLICATION LEVEL

To demonstrate the practical use in real-world applications and get a good understanding of the applicability the thin-film solar modules have been used in totally differing areas. The applications are the following:

- Solar charging of electronic devices
- Integration of PV in Textile Support
- Urban Design/ Solar Lighting
- Building Integrated Photovoltaics

Description of the Main S & T Results/Foregrounds

1. Custom designed PV modules based on flexible scribing and printing technology

The production of custom designed thin-film Cu(In,Ga)Se2 (CIGS) PV modules based on flexible scribing and printing technology is the broad objective of the SolarDesign project. It was achieved through number of steps, described in the other chapters, including optimization of the technology and introduction of new materials, implementation of laser scribing and printing technology into the industrial scale production line. The progress in these steps was supported by means of numerical simulations.

In order to meet the requirements as expressed by architects and designers, the SolarDesign approach was similar to that adopted by a tailor in the manufacture of bespoke, "made-to-measure" garments. The fabric, or basic material, is an "endless" thin-film solar cell. This solar cell can be cut according to the size and shape stipulated by the user and a flexible interconnection can be applied to obtain the required electrical specifications. This innovative approach provides a great deal of flexibility across four dimensions: mechanical, electrical, size and shape thereby providing new possibilities for PV integration into products.

A novel manufacturing process enables the adjustment of all properties of a thin-film module on-the-fly and facilitates the production of customized photovoltaic modules with the desired voltage, size and shape. Combined with the material characteristics given by the underlying thin-film solar cell technology a new-breed of design-led, sustainable and decentralised energy solutions can be realized.

Competitive advantages of this approach is in the economic viability even at low quantities. Additionally, it is much more aesthetically appealing in contrast to existing solutions (right size allows seamless integration). Integration of laser ablating/printing technology is compatible with existing manufacturing concepts and can be easily implemented in the industrial line.

By separating vacuum processes (for producing an endless CIGS solar cell) and module processes (interconnection by laser and printing), the production of fully customized photovoltaic modules with a desired voltage, size and shape was made possible. Combined with the pliability and the high yields of the underlying CIGS based solar cells such PV modules are ideal candidates for a multitude of applications ranging from PV-integrated products (sensors, chargers, lighting) to the use in BIPV products.

The process runs in a large vacuum chamber, in which all components are integrated for the production of CIGS absorber. Up to 500 meter of substrate film (metal foils or high-temperature-resistant polymers) can be used in one production cycle on the internal roll-to-roll system. The chamber includes three sub-segments for CIGS manufacturing, each consisting of sputtering and evaporation components and precisely adjustable heaters. An exact control of all parameters, like voltage, current of the sputtering magnetrons, evaporation rates, temperatures, and film speed is essential for the quality of the process output.

The custom designed PV cells were implemented in seven product prototypes developed by the "design partners" in the SolarDesign consortium, each of them demonstrating a different aspect and application of the technology.

2. New materials for the flexible CIGS technology

One of the objectives of SolarDesign project was to optimize the growth procedure of the CIGS film and buffer layer necessary for the creation of the PN junction. In particular, the deposition procedure of CIGS thin film had to be adapted to the specific request of photovoltaic modules on flexible substrates for Building Integrated PV system, (BIPV) Product Integrated PV systems (PIPV) and Textile Integrated PV system. Additional goals were to increase cell efficiency in non-optimal insulation application, and to reduce of the environmental impact and the used material quantity and the introduction of new non-toxic materials.

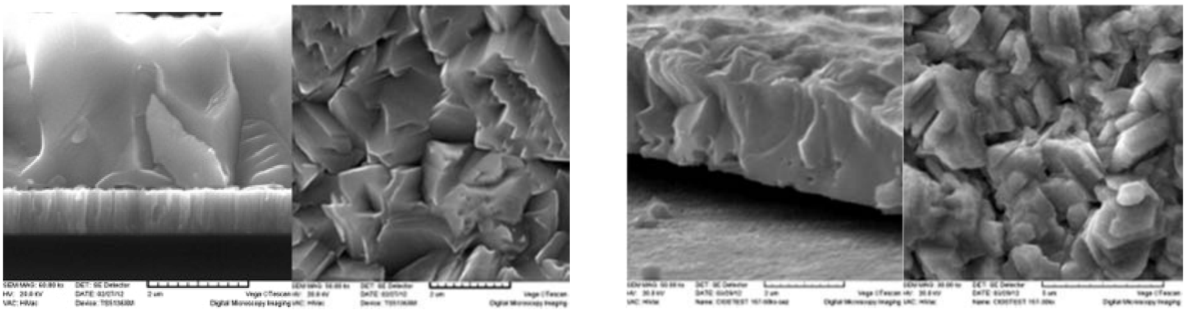
Thin film CIGS solar cells have drawn considerable attention as a cost-effective candidate for BIPV and PIPV applications due to its higher efficiency respect to others thin film solar cell technology. Most of the applications in BIPV and PIPV, however, require the use of a flexible support. Moreover, insulating low cost flexible substrate allows roll-to-roll (R2R) manufacturing, thus reducing manufacturing costs and increasing throughput and process yield, and allowing monolithic module fabrication.

The most interesting materials as flexible substrates are stainless steel and polyimide. The use of stainless steel substrate is known to cause impurity diffusion (mainly iron) from the steel foil into the CIGS, which leads to a degradation of the solar cell performance. Therefore, an impurity diffusion barrier is conventionally used to ensure negligible impurity concentrations in the absorber layer. Polyimide is an alternative substrate material, which is insulating and has high temperature stability up to 450°C. Due to absence of iron, no barrier layer is necessary on polyimide. Therefore, in order to employ these plastic substrates, the reduction of the deposition temperature below standard 550° C is needed as well as the optimization of such process.

The process setup at SUNPLUGGED CO. for CIGS production is based on a patented two-step method based on sputtering of CuInGa-precursor and subsequent selenization under high temperature conditions at atmospheric pressure. The equipment allows to change annealing temperature, ramp up and ramp down time (and respective temperature profiles), annealing time, and selenium amount and species in gas atmosphere.

For the improvement of the material deposition process, new target materials for CuInGa-precursor deposition have been developed and tested. They allow for example to increase Ga content of the CIGS absorber or to avoid sputtering of pure indium, which is known to potentially decrease cell efficiency compared to evaporated indium.

One of the advantages of the CIGS based absorber is the possibility of spatial band-gap tuning. The value of the band gap is simply changed by tuning of the Ga/(In+Ga) ratio within the absorber. The normal grading contains an increase of the band gap towards the back contact, while the double grading is a profile with a minimum amount of Ga in the middle of the CIGS layer and an increased band gap towards the back and the front contact. From the simulations the beneficial effect of a double grading in the solar cell performances was found out and the deposition process was improved to comply with the simulation guidelines.



Scanning Electron Microscopy images of the section and the surface of Sunplugged´s CIGS film deposited on glass (left) and flexible substrate (right) in the laboratory of UNIMIB

New buffer layer

The role of the buffer layer in the CIGS solar cells is related to the adjustment of the parameters between absorber and window layers. From this point of view, the importance of the buffer layer refers to the electronic, structural and chemical issues. In general, the CIGS solar cells are fabricated using cadmium sulfide (CdS) as buffer layer. More recently, different deposition methods were employed to deposit the buffer layer, in order to protect the junction region from the sputtering damage that can occur during the deposition of subsequent undoped and aluminum doped zinc oxide (ZnO). In order to achieve an optimal buffer, i.e. high optical transmittance with minimal resistive loss in the band gap, the thickness should be as thin as possible.

CdS is widely used as a buffer layer in solar cells. With respect to this, the easiest way to deposit CdS is via chemical bath deposition (CBD). Additionally, the CdS layer needs to be pore free so that it could shield the CIGS material from ZnO deposition damage. Furthermore, CdS can protect the CIGS from the damage caused from the deposition of ZnO, while the S atoms diffuse into CIGS and passivate the surface to reduce the surface recombination, thus increasing the carrier lifetime.

However, there are few concerns regarding the toxicity of the CdS and the implementation of chemical bath deposition technique in an industrial process. Also the quantum efficiency of CdS/CIGS solar cell drops at short wavelengths due to the optical absorption losses from the CdS layer. This implies that further improvement in the short circuit current (Jsc) can be archived by replacing CdS with another appropriate wider band gap buffer material. The use of a buffer without cadmium is well introduced into the philosophy of a green economy.

Several materials have been tested as an alternative buffer layer: ZnS, $ZnSnO_3$ (ZTO), In_2S_3, ZnSe. Numerical models were set-up for the simulation of different aspects of solar cell/module technology. Amongst them, the effects of the CIGS solar cell parameters due to the use of new buffer layers were investigated. In the CIGS technology a new buffer layer is suitable due to the following reasons: the expected environmental risk due to use of Cd, the technological problems caused by a non-vacuum CBD process in a vacuum line, the potential of increasing the current generation in the spectral region between 350 nm and 550 nm.

Both measurements performed in UNIMIB and the simulations in TUW have shown that using the technique of growth adopted in SolarDesign project, the most promising buffer layer is the ZTO, as Cd-free buffer layer for CIGS solar cells.

Important compatibility with industrial applications. Targets of the chosen materials were fabricated and tested. Thanks to the simulation analysis and the experimental data it was possible to conclude that the even more interesting material as Cd-free buffer layer is Zn_2SnO_4.

Characterization

The materials characterization was an important part of the project. Different characterization techniques on CIGS samples grown at laboratory level and at pilot line level were used. The key to high-efficiency CIGS solar cells is the quality of the CIGS absorber layer itself, as it is the most complex layer. All the characterization and skill so far used have been put at the disposal of SUNPLUGGED CO. for the pilot line optimization.

The applied methods for the analytical investigation deliver information about the composition, surface morphology and the microstructure of the CIGS layers. To measure the composition of CIGS layers produced by SUNPLUGGED CO., a XRF (X-ray fluorescence) spectrometer and an EDX (energy-dispersive X-ray) spectrometer were systematically used. To obtain information about the surface morphology of the CIGS layers, mainly two different methods have been used. In general, SEM images (Scanning Electron Microscope) of every analysed sample have been taken with three different magnifications. These images have helped obtaining a clear idea of the shape and size of the CIGS grains. In order to gather additional information about the morphology, particularly in z-direction, atomic force microscope (AFM) has been employed, here again with 3 different magnifications. 3D Data from AFM images made it possible to calculate the roughness of each sample.

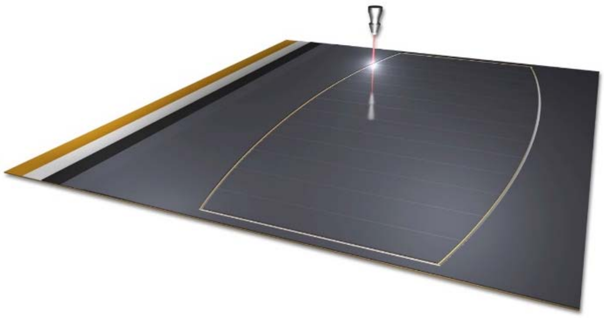
Furthermore, cross-section SEM images provided information about the crevices observed in the bulk of the layers and allowed for determining the thickness of the CIGS- and molybdenum layers. Additionally, X-ray diffraction (XRD) has been employed in order to determine the existing crystallographic phases in the CIGS layers and the preferred crystallographic orientations.

3. Freedom of design through flexible cell patterning

Laser scribing

In order to achieve a freedom of design of photovoltaic cells/modules a technique of laser scribing had to be developed. Therefore a process window for the selective laser scribing of the different thin-film layers of the solar cell without causing much damage to the solar cell and the flexible substrates had to be found. This was achieved by investigating the selective ablation of the films. MUAS performed a number of tests in order to establish the suitable process window. Effects of laser fluence, wavelength, pulse duration, pulse overlap and spot size on selectivity in layer ablation were examined. These parameters guarantee a desired functionality of the structured trenches. The ablation process was optimized for three different trenches formation, with different number of layers needed to be removed. By the successive placement of the trenches, the current flows from the front contact of one cell to the back contact of the next cell, thus creating a “monolithic serial interconnection”.

Besides the quality of the trenches, the process speed is an essential factor for an industrial application of the laser structuring processes. To increase the process speed, the repetition rate was increased, while the focus beam radius was kept constant at the previously determined value. In consequence, the process speed was increased, while the quality of ablated lines was sustained. Entire solar cell module layouts were structured on glass and on polyimide substrate. The obtained trenches were analysed by light and by confocal microscopy.



Laser scribed isolation trenches enable flexible cell shape and size

Flexible interconnection

Flexible interconnection is achieved through a high-precision, large scale printing technology that enables the exact printing of interconnection layers (one isolation layer and one conducting layer per interconnection) into the laser scribed micro grooves. This includes the definition of potential materials, processes and combinations for the conductive and non-conductive layers.

Based on the basic process determinations fundamental parameters for the pre- treatments, printing and drying processes were developed and are the foundation for the merging of the flexible interconnection and the laser scribing on an industrial scale.

In principal a multitude of techniques are suitable for the deposition of conductive and non-conductive layers onto CIGS solar cells. In consequence of the implicit combination of the printing process with the laser processes developed only atmospheric deposition techniques were considered (screen printing, dispensing and inkjet printing). The necessity of an atmospheric deposition is also strengthened by fact that the deposition needs to be geometrically aligned with the microgrooves applied in the preceding laser process and should allow a high freedom of layout design coupled with low set-up times. The selection of the optimal technique was done according to several parameters: flexibility, efficiency, expandability, material and production costs.

The tests have been carried out in order to determine the optimum parameters for the printing/dispensing of several commercial silver-polymer pastes/inks, as well as the optimum curing temperature conditions. The goal was to develop conductor lines with high conductivity, low dimensions and different and customizable shapes. Specific contact resistivity of conductive lines printed on top of ITO layer was measured, and it was found that the introduced contact resistivity does not affect the overall serial resistivity of the fabricated PV cells.

As a digital printing process, inkjet printing was selected as the most suitable and cost effective deposition process for the “on-the-fly” SolarDesign approach, since the printing pattern can be changed during the process. It is also a fast and accurate process to deposit materials on selected coordinates on the substrate. Dynamic adaptation of the printed pattern dimensions and alignment are possible due to the digital nature of the process, for e.g. compensation of distortions in the substrate during previous processing steps. The non-contact nature of the process also lends itself to depositing material on non-planar topographies (e.g. trenches, steps) on flexible as well as rigid substrates. The materials selection for inkjet is wide covering inorganic nanoparticle inks as well as polymer based organic inks.

Upscaling

After the basic developments in the field of laser processing and printing of flexible interconnections, the upscaling of all developed technologies into the pilot production line of SUNPLUGGED CO. was the next step, so that the flexible CIGS photovoltaic foils can be produced. The set of optimized laser scribing parameters was successfully transferred to SUNPLUGGED CO. Solar modules were structured by the machine designated for the up scaled process. These customized photovoltaics foils need to be encapsulated in a durable packaging.

Out of the various inkjet printing processes, an industrial multi nozzle piezoelectric inkjet printing was selected because it has the most potential for integration into a fast industrial process. A viable experimental printing system was developed and coupled with the short-pulse laser process.

R2R Pilotmachine for the upscaled Roll-to-Roll deposition of CIGS semiconductors based on a novel hybrid Sputtering-Evaporation process

4. Numerical modelling and design rules toolbox

In order to improve the current fabrication technologies and allow the exploration of new cell/module concepts while meeting specific requirements, simulation on the composite materials used in thin film solar cells were indispensable. A variety of modelling and simulation work has been done to understand the internal operation of inorganic thin film solar cells; however interpretation of these results is often difficult, because of the lack of precise models. Analytical models are possible only under certain simplifications and this is the reason why numerical simulation is better choice for modelling of CIGS devices. The numerical models were calibrated taking account the measured properties of the materials and the devices under standard test conditions. By numerical modelling, the impacts of different material parameters on the solar cell key performance parameters (Voc, Jsc, FF, η) were studied.

A design rules toolbox (better understanding of the module performance versus material composition) has been established by taking into consideration all the simulation results joined together. From this “service” all CIGS producers (companies), indirectly also end-users for PiPV and BiPV, as well as the research centres working on CIGS development could benefit. Since the CIGS market grows, such a toolbox could be particularly interesting for BiPV applications.

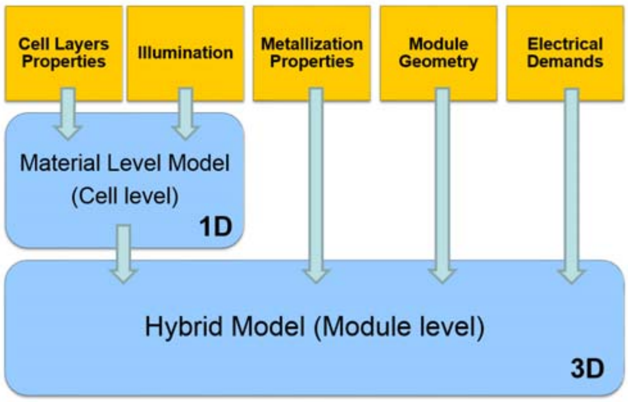
Generic CIGS solar module numerical model enables following benefits:

- Significantly reduced time and cost for the product development,

- Meeting of desired electrical module characteristics (power, voltage etc.) for each application respecting module design, temperature- and illumination conditions,
- More freedom in the design of PV modules,
- Technological flexibility and - adaptability to the integration of PV module to PIPV or BIPV in respect to the requirements of creative industry.

Description of models

For the module level simulation a 2-step model was implemented. The model uses the results from the material/cell level simulation as an input parameter, and together with the specified module geometry inputs, calculates the module output parameters.



Schematic of the two-step cell/module simulation

The cell level simulation was carried out in one dimension, in the direction orthogonal to the cell layers (vertical). In this simulation were modelled the processes of charge generation, charge movement through the cell layers and their recombination. The movement of the charge in the horizontal (lateral) direction is not considered, as the cell is thin (few microns) and it is presumed that the charges move through the cell in the shortest path. As the result of the cell level simulation output I-V curve of the cell is calculated. From this result all the important parameters like Voc, Jsc, Vmp, Jmp, FF and η can be extracted. The results of the cell level simulation, besides the property of the cell layers, also depend on illumination and temperature.

Lateral (in the horizontal plane) movement of the charges is present in the conductive layers of the cell, which include bottom and top electrodes. Bottom electrode is typically made of molybdenum. Top electrode must be transparent in order to pass the sunlight into the active layers of the cell. For the top electrode transparent conductive oxide (TCO) materials have to be used. As the resistivity of molybdenum is much lower than the resistivity of TCO, resistive losses caused by lateral current flow through the molybdenum electrode can be neglected. Therefore, the simulation of the horizontal plane (charges movement in the lateral direction) of the solar module is based on the simulation of the electrical currents through the top TCO electrode.

The improvement of the conductivity of the top electrode was done with the addition of highly conductive metal lines (usually referred to as “fingers”), which is patterned on top of TCO layer. However, metals are opaque and prevent the transmission of sunlight into the cell interior. This is referred to as metallization shading. Therefore, special care must be taken when designing the pattern of metallization lines to improve the conductivity of the top electrode, while allowing the cell to receive as much sunlight as possible.

As it was described, two kinds of losses are present on the module level, which do not exist on the solar cell level: electrical (resistive) losses and optical (shading) losses. It was shown that these two losses are opposite to each other, and reducing of one type of loss causes the other loss to increase. Thus, the configuration where the combination of the two losses is at the minimum must be found in order to have an optimized device.

Potential distribution along the horizontal surface on TCO and metallization layers was simulated. Generated photocurrent at each point of the cell depends on the local voltage value between the electrodes of the cell. Generated photocurrent was introduced in the model in the form of normal current component entering the bottom side of TCO layer. How the photocurrent depends on the applied voltage was determined in the first simulation step using one-dimensional modelling software, which is based on the measured parameters obtained by characterization of real cells.

Input parameters: I-V curves on the cell level (illuminated and dark), conductivity of TCO and Ag paste, Ag contact resistance, geometry, geometry of metallization, Output: IV curve of cell/module, potential distribution on TCO.

Metallization optimization

By the preliminary simulation it was concluded that there can be two different paths for optimization. For the cells of small widths (w<10 mm), no additional metallization is needed (except the interconnection metallization used for monolithic integration of the cells). Even the most distant points on the cell are close enough to the current collection line (interconnection) on the other edge of the cell, so that there is no significant voltage drop that would reduce photocurrent generation.

For the large-width cells (w>10 mm) some kind of additional metallization is needed to more efficiently collect the generated current. The more of the active area is covered by metallization, the more current is collected from the neighbouring area. But the area directly under the metallization is in the dark, and does not generate any photocurrent. The optimization in this case is done by finding the best geometry of the metallization layer.

Flexible solar cells

One of the advantages of thin-film photovoltaics is their flexibility. For some applications, like BiPV and PiPV this possibility is of great importance. In the previous simulations, only flat panels were considered. To simulate curved panels, several changes had to be introduced in the model. First, due to its curvature, different parts of the module have different incident angles of sunlight. These angles can differ in a large amount, even to 180°, in some cases. The following improvements of the model were done in order to meet the desired needs:

Simulation of power on a daily basis

For the applications of PV in stand-alone off-grid devices, it is beneficial to estimate the daily power yield of a module. In order to assess the daily power yield the following steps were done:

- Calculate the Sun position for several moments during a day (for example, every 2 hours), and for every of these positions do all the following steps,
- Based on the Sun position, calculate the illumination level on an arbitrary position (azimuth and tilt) of the flat module,
- Carry out cell level simulation based on the calculated illumination and obtain the I-V curve,
- Define scaling function according to curvature of the module,
- Carry out the module simulation based on input data from all previous steps.

Using the developed numerical models an optimisation of the module design, e.g. geometries (shape, size) of single cells in modules, interspaces between cells, resistivity of the transparent front window and the interconnections between the cells, was made for defined irradiation fluxes. Furthermore, the sensitivity of module characteristics on the variation of various technological and geometrical parameters has been made.

User oriented software tool

According to the architect and designer needs related to software tools for SolarDesign, the main requirements were identified to address the development of the software tool. The main requirements were grouped in five groups: interface requirements (e.g. need of user-friendly and intuitive interface), input requirements (e.g. need of reliable import of 3D geometry, need of reliable and transparent default values which can be easily modified, accurate and accessible weather data from referenced sources, which can be easily adjusted to local conditions), output requirements (e.g. graphical and numerical output, comparability among outputs related to design alternatives, information about result accuracy, evaluation of solar potential on user defined surfaces (insolation, irradiation) over time, estimation of energy production by the PV systems, interoperability requirements (e.g. interoperability with CAD software) as well as requirements related to needed accompanying documentation (e.g. transparency about algorithms used in calculations, tutorials and manuals).

The user/target group of the software tool was identified in architects, designers and students who need an easy tool for fast estimation of the system energy performance during the early design phase.

An easy-to-use user oriented software tool was developed within SolarDesign project. The tool takes into consideration all the parameters for the establishment of a numerical modelling and simulation tool that allows gathering the necessary information about energy yields, performance, electrical and optical characteristics during the design process. For this tool open standards are used and a friendly and easy interface.

Following three principles: early and continual focus on users; empirical measurement of usage; and iterative design involving the user in the process, within GAIA the Living Lab methodology has been followed, which involves end-users and distinguishes the following levels of user involvement:

- The user not only supplies information to the developers, but also is part of the development team generating ideas and prototypes,
- Users can test products for instance at home or in a real environment,
- Users are invited to focus groups,
- We ask and listen to what the user thinks to the product or service,
- We imagine what the user might think and make assumptions based on our knowledge of, belief in or know-how of the matter.

It is a key challenge to carefully balance energy performance/standardization needs and architects/designers, professionals and students desired freedom. For this reason, a multidisciplinary approach following a user-driven design methodology fosters the collaboration between “creative partners” and “technician partners”.

The development of the user oriented software tool was based on the Life Cycle Assessment concepts. The main focus on the identification of Life Cycle Assessment concepts and parameters in renewable energy products like thin-film modules is the design for minimum energy-payback times and maximum savings potential regarding greenhouse emissions.

The actual innovation of the software tool is that it enables the user to calculate solar radiation received on any shape, being no problem to simulate any scenario on a complex shape. The user oriented software tool provides design rules for the best solar cell super-structure and module design layout, and addresses the efficiency in the incorporation of thin film to the different products or structures designed. The tool allows users to calculate a performance simulation to subsequently design the electronic and pattern for production process.

A second innovation is that, rather than being just focused on the designer's or architect's side, the software also treats the other side of the application: the manufacturer's point of view.

5. New design oriented applications for the decentralized solar power generation

One of the main objectives of SolarDesign project was to develop several prototypes of products with design driven applications. The first step towards this objective was to achieve the definition of the general requirements and to explore the design possibilities for Building Integrated Photovoltaic (BIPV) and for Product Integrated Photovoltaic (PIPV), addressing the system design with strong participation of designers and architects belonging to the consortium (F3, SIARQ, INN, SUN) since the very first stage of the development process. A key challenge of this step lies in the careful balancing of energy performance/standardization needs and architects/designers' desired freedom. For this reason, a multidisciplinary approach has been adopted, fostering the collaboration between "creative partners" and "technician partners".

The first part of the activities was focused on the identification of needs and barriers that designers/architects are facing in incorporating PV systems in their design and in using software tools for SolarDesign. Additional to the activities within the consortium, these analyses were based on the results of an international survey, which involved ca. 600 designers and architects, carried out in the context of the IEA Task 41 project "Solar Energy and Architecture".

In order to demonstrate the different applications and possibilities of self-powered autonomous (and semi-autonomous) PIPV and BIPV devices based on flexible CIGS photovoltaic technology seven product prototypes were designed and fabricated throughout the SolarDesign project. Those prototypes are the following:

- Building skin for BiPV geodesic structure (SIARQ)
- Solar street lighting system –FASCOM (SIARQ)
- Solar Powered Tablet Charger –SUNHUB (F3)
- Solar Powered Audio Device – JUNE (F3)
- Solar powered lamp –LYSARK (F3)
- Wireless sensor network –WSN (INN)
- Integrated PV in textile support (INN)

Building skin for BiPV geodesic structure

Nowadays there are many companies offering BIPV products for its use as a skin, but all of them have standard PV crystalline panels or thin film solutions as a flat module integrated in facades or roofs. Due to the difficulties of designing a customized installations, there is a gap between the designers and the PV manufacturers.

The innovation of the SolarDesign BiPV prototype was in a sophisticated solution for the customized modules (in shape and area) for a geodetic or parametric architecture. This is possible thanks to the process, that studied the needs of the clients (geodetic or parametric structure developers companies, architecture practices or building companies specialized in cladding) and developed the necessary steps to design the required on-the-fly modules. The final prototype developed within the SolarDesign consortium was the demonstrator of the feasibility for the specific custom designed module technic.

Competitive advantages of this approach are seen in the fact that there are many architects, designers and constructors that would like to add photovoltaic technology to their projects but they do not find the way how to do it with modules available on the market.

The principal advantages of SolarDesign approach are: migrating from the square/rectangular solar module by using PV as a versatile building integrated component, improving the efficiency of the PV module by integrating in new morphologies, increasing the receiving surface by escaping from the concept of “optimal orientation” and increasing and improving the participation of the PV manufacturer in all the process. The SolarDesign approach provides the characteristics that are not available in the same product or service: PV modules on-the-fly that could be integrated in complex architecture. In addition to producing electricity, this kind of BIPV installations adds structural value and can enhance a building’s aesthetic quality and design (colours, customization and at the same time remain cost competitive).

A functional demonstrating prototype has been developed for the geodesic dome, which represents a first step for integrating PV technology in complex structures (triangular PV modules). The final solution consists in a customized solar kit, encapsulated in a flexible polymeric substrate, composed of CIGS-based photovoltaic triangles. Several kits have been developed: all the kits are based on the manufacturing of a CIGS triangle, encapsulated in a flexible substrate; a “unique PV triangle” that fits in three geodesic domes with diameters of 6, 7 and 9 meters. The kit is composed by five of the triangular PV modules which can be placed in six possible locations of the geodesic cover skin.

The pentagonal substrate is made by white PVC material. From the point of view of the aesthetics and the performance of the system, the use of the same material as the dome guarantees a good integration and the same behaviour in terms of durability. The adhesion of the five triangular demonstrators has been realized by a technical glue special for PVC materials. In this way is possible to achieve a uniform adhesive layer along the demonstrator surface that ensures a good integration with the pentagonal PVC substrate. In order to obtain a complete union between the triangles and the PVC surface, five openings in the pentagonal substrate for the location of the junction boxes added on the lower side of the PV demonstrators are needed.

Triangular modules and Solar Pentagon for geodesic domes application (SIARQ)

During the project a BIPV triangle was manufactured and assembled at CEA-INES site. The parametric tests realized by varying the slope of the BIPV triangle permitted to obtain thermal, meteorological and electrical data. A good power output for the triangular module has been reached and CIGS thin film technology has been properly demonstrated in a “non-classical” shape.

Through SolarDesign Project, the contacts with the main geodesic domes manufacturers were established. These companies had positive feedback regarding the SolarDesign solution both from the economic and the integration point of view.

Solar street lighting system (FASCOM)

Increasingly restrictive legal requirements have been adopted in the past years, with ambitious targets regarding energy saving and reduction of greenhouse gas emissions. Lighting demands represent around 30% of total electric consumption in developed countries. Substitution of conventional luminaires by LED lighting has been proved to offer large energy savings. Retrofitting programs are being undertaken on a worldwide basis. However, PV powered streetlights, which could further improve the net energy balance, are not being considered for such retrofitting. In developing countries, there is also a need for stand-alone street lighting at affordable costs, as grid-connection is not available or highly unstable.

Regarding the innovativeness introduced compared to already existing product, there are several advanced concepts implemented in the design of the solar street lighting system. A compact concept is applied to the solar streetlight: incorporation of the PV module, lithium-ion batteries, electronics and luminaire within a single, dome-shaped element, while keeping aesthetics and adaptation to the environment at a high level. The curved receptor surface maximizes PV production independently from the orientation. Lightweight materials provide weight reduction and reduced costs in transport and installation. Compact integration reduces vandalism. Intense expected use as a substitution product, by incorporating the designed luminaire to existing mast structures. The product have been prepared with different photometries composed by a modular system, LEDs and optics, in order to satisfy different markets and typologies of lighting exterior urban spaces.

While standard solar streetlights are based on crystalline silicon, thin film CIGS solar cells were incorporated in FASCOM streetlight, providing better performance against shades, miss-orientations and diffuse light. Nowadays, all solar streetlights strongly depend on PV module orientation. So big PV module should be orientated always towards the sun, but errors of orientation during the installation are very frequent, disabling and reducing the calculated performances of the solar lamp. The solution of the FASCOM streetlight prevents this problem.

There are several benefits of the developed street light system, as a value proposition for the customer: a reduction of costs in purchasing and installation compared with standard PV lighting solutions, all in one (the customer does not have to worry about different elements on the installation), long last use on low irradiation, reduction of CO2 footprint, optimal integration of technological and aesthetical values, easy to maintenance, orientation free due to the circular shape of the dome, long

SIARQ’s Solar street lighting system

lifetime designed to fulfil the more severe climates and conditions.

The domed PV module represents the main component of the Compact Photovoltaic Streetlight. The challenge was to produce a double bended PV module and demonstrate the feasibility of the integration of the on-the-fly thin film cells. After three years of design and testing and thanks to the manufacturing process of the CIGS cells deployed by SUN and the application of the adequate technique for encapsulation gave us the possibility to fulfil the objective and show the result as a success. Geometrical characteristics of the module include a configuration composed of 18 trapeze-shaped mini-modules, covering a domed shape.

Other mechanical parts of the solar streetlight system (cap and base of the dome) have been designed and fabricated in order to comply with the requirements of effective thermal dissipation and simplicity of assembly and maintenance. A deep research has been conducted in order to select the most appropriate battery technology that is able to fit better with the requirements of the compact solar streetlight. $LiFePO_4$ and Lead Crystal technologies have been selected and should be able to cover the large majority of the possible scenarios.

The power electronics consists on a multiple maximum power point tracker (MPPT) and a charge controller to manage the battery and lighting control. The MPPT was specifically designed for this non-standard, dome-shaped application, taking into account the expected variable and non-optimal working conditions, the potential appearance of local maximum power points inside the PV panel, and the particularities of CIGS. Its objective is to obtain the maximum power from every section of the solar street light in a low-cost and reliable way.

The lighting system is composed of several LED modules that allow to perform different photometry according to the application, being able to adapt to a wide range of lighting requirements by changing/combining the optical lenses. For the prototype symmetric oval photometry has been mounted. The lighting system is equipped with a motion sensor module, which are used to dim the light intensity of the streetlight when no one is detected in the proximity of the lamp, in order to utilize the generated energy efficiently.

Solar Powered Audio Device, Solar Powered Tablet Charger and Solar Powered Lamp

When designing solar powered products the freedom of design is often limited to the dimensions and specifications of the solar panels available. All the products still need a decent power source while having size vs. usage context and the aesthetics of the dominating panels in mind. The design freedom acquired from the SolarDesign’s roll-to-roll production from Sunplugged, has made it possible to design products with curvatures, cutouts and profiles that has never been seen before while maintaining high level of aesthetics. F3 has developed three concepts to demonstrate the technology aimed for the consumer’s market: an audio device, a tablet charger and a lamp. All three concepts are developed to approach the segment of buyers that would possibly weigh design more than green consciousness, that at present time only products with conventional solar panels offer. All concepts are subject to be adjusted in certain directions according to an eventual demand in specific sectors such as outdoor or low budget. This adaptability of the Solar cells from Sunplugged, enable a less risky and easier way into different market segments.

Both the functionality of the designs and the electronics developed in F3 have been tested and proven, as well as the possibility to define and integrate the CIGS solar panels from Sunplugged. in several shapes, sizes and geometries. This is an option not normally possible using commercially available products. Available Photovoltaic Panel (PV-panel) do not offer these customizable features which would make the designs from F3 impossible or at least not feasible to realize. This opens up for an entirely new market and ranges of products within high levels of design, but also with the promise of a competitive prices, compared to existing market solutions.

The designs have gone through many iterations to the final prototypes in order to achieve the best possible design for manufacture, aesthetics, functionality and simplicity. The electronics developed in F3 was adapted and created specifically to make the prototypes run from solar energy alone, and to optimize the energy harvested from the PV-panels.

Solar powered audio device, Solar powered tablet charger and Solar powered lamp (Faktor 3)

JUNE™ / Solar Powered Audio Device

JUNE™ is a Bluetooth speaker, designed to decrease the product footprint in order to take up the smallest space possible while the PV-panel still be effective. The PV-panel area is on the front and the back of the device, with the angle of the PV panels optimized for primary use near windowsills and domestic outdoors. Simulations of the solar panels integrated into the prototype confirmed that the PV-panels are able to deliver enough power for the intended uninterruptible application, which means that the audio device can generate sound at a normal listening volume for approximately 2 hours a day. The optimum hours of operation for the device is from 8 to 10 hours.

An important design feature of JUNE™ is the detachable panels for personalization and expanded life cycles. The two solar panels of the JUNE™ can be changed or replaced if the user wants PV with other colours, textures or if the PV is damaged and should be replaced.

The panels demonstrate a concave shape with cutouts for the speaker in the front and a custom conductive snap-lock system specially developed for the concept.

The cabinet is raised to separate the cabinet from the elements and to move the sound source closer to the user when placed on sand or grass. The space between the panels underneath the cabinet safely protects phones and other streaming devices from the sun. The actual audio device can also be used separately, giving the end user a wider range of usage, increasing mobility and usage in tight spaces.

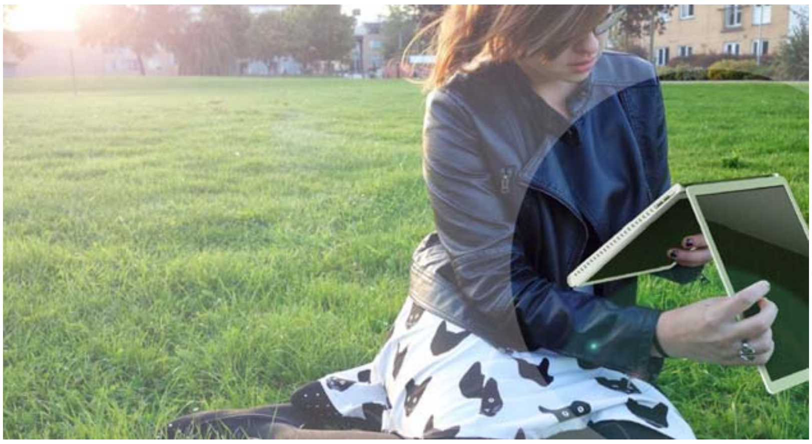
SUNHUB™ / Solar Powered Tablet Charger

There are very few successful solar powered tablet chargers on the global market today. The Apple iPad is one of the most successful consumer products in modern history. The SUNHUB™ is fitted for the iPad Air 2.

Compared to the two other F3 prototypes, the concept design and market success of the SUNHUB™ depend upon the existing tablet. Although the SUNHUB™ PV-panels are limited to the tablet's physical dimensions and their usage, it would still have enough power to extend battery operation considerably, and in some cases being able to run completely from solar power, thus eliminating the need for electric grid power.

The cover has integrated MPPT (Maximum Power Point Tracking) solar power optimizer, batteries and feedback light communicating the power status.

While inserted and having the PV-cover closed, the iPad is fully drop and scratch protected while being charged. Because of the two panels either fully unfolded or hand-held the SUNHUB™ can charge no matter what side is facing towards the sun. A modern tablet is designed for people from all walks of life and the SUNHUB™ gives the end user a simple and an effective environment friendly charging solution.



Solar Powered Tablet Charger in use

LYSARK™ / Solar Powered Lamp

LYSARK™ is designed to have a large PV-panel surface area while maintaining small a footprint and not compromising its core functionality.

To make a solar powered light source as universal as possible, it is important that repositioning and transport is easy. That means size and weight is limited for what an average person is able to handle. The most optimal shape for the PV-panels in most cases is a flat surface that follows the sun during the day. In that case it would take up too much space in the expected usage context.

LYSARK™ has three different standing positions and two hanging positions. In other words the device is designed in a way that it is impossible to positioning it wrongly. LYSARK™ has a parabolic shape, with PV-panels on the both side of the device and light source from the inner surface of the parabola and on the outer surface next to the PV-panel.

LYSARK™ is far from the most common interpretation of what a conventional lamp looks like, but this device is aimed for not only being a source of light but also moving the consumer perspective of aesthetically pleasing solar lighting.

Wireless sensor network (WSN)

The main idea of this demonstrator prototype was to integrate flexible solar cells in the sensors belonging to a WSN to be used in the plantations of added value cultivations like vineyards or fruit trees where the control of parameters like temperature, humidity or radiation is necessary to ensure the proper cultivation process.

Since these kinds of plantations are located in the countryside, there's a clear limitation of installing these sensors due to the lack of electricity and the difficulty of replacing batteries every week. The sensors, for this use, need to be self-maintained and the solar energy can facilitate that. The use of flexible solar cells also allows the integration of the PV modules in the same box of the sensors device having a stand-alone and simple implementation.

Other important application is the monitoring of forest areas to prevent and control forest fires. These sensors can alert about any temperature increase caused by the start of a fire allowing having a fast response. They can only alert about high temperatures and low humidity in case of high possibilities of fire.

The developed WSN system consists of two types of devices: coordinators and sensing nodes. The sensing nodes consume less power and they have a limited functionality: measure a physical value and send it to a neighbour node. On the other hand, the coordinator nodes are more complex. They have to start the network, permit other devices to join, hold a list with all the nodes, receive the data from all the sensor nodes and send the information to a server via GSM communication.

Both types of device are powered by one cell Li-Po battery. The PV module is connected to a single cell battery solar linear charger targeted at space-limited portable applications that is mounted in the same board. This regulator carries an input voltage regulation loop with programmable input voltage regulation threshold that makes it suitable for charging from alternative power.

The enclosure design for the sensor and coordinator node were developed bearing in mind two special requirements. On the one hand, the solar cell must be placed easily on the enclosure and it must harvest as much solar energy as possible. On the other hand, the device must be versatile enough to be placed on different trunks (in case of agriculture monitoring) and supports. In addition, the box should be as reduced in size as possible, having enough space to include the electronics and the battery inside and the solar cell outside. Two iterations of design process were concluded, and the final design of the coordinator node is presented in the following picture.

After the work carried out within the SolarDesign project, InnovaTec has succeeded in developing an innovative and appealing product in comparison with other products already in the market. After doing a market research, most of the systems already available don't present the solar cell integrated on the same case or they are not as compact as the product InnovaTec is about to launch to the market.

Wireless sensor network node (InnovaTec)

Integrated PV in textile support

Currently on the market there are no available photovoltaics integrated in natural or acrylic textile supports using textile coating technologies. The main goal of this demonstrator was to find the best alternatives that can be used in order to implement and to integrate solar CIGS technology within an industrial manufacturing process without altering the current process itself. This phase which has been developed by InnovaTec, was divided into four sub-phases:

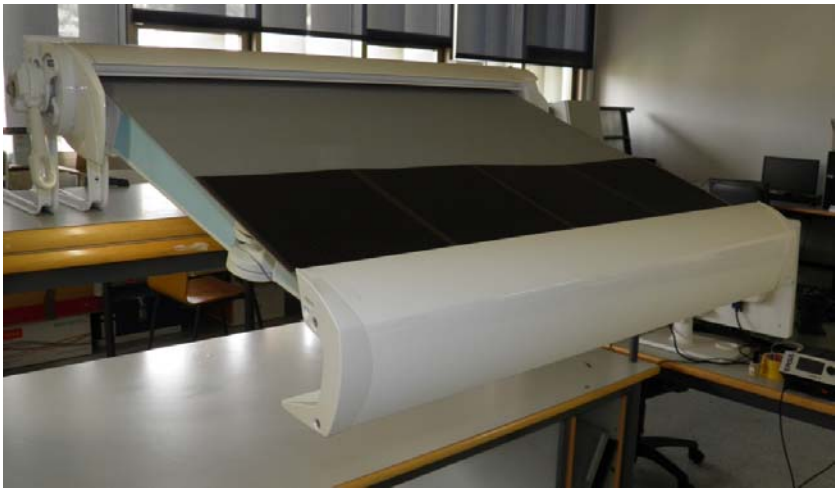
- Analysis and selection of the adhesive. In this phase different adhesives used in textile sector were analysed. An adhesive should provide a high bonding rate between the fabric and the encapsulant without losing the flexibility property inherent to the fabric.

- Selection of the textile substrate. This is one of the most important choices since the textile substrate provides greater flexibility and strength to the product. In order to obtain the final textile substrate, many variables were taken into consideration, for example: the composition of the substrate sheet, the fabric structure, the density and the suitable finishing.

- Selection of the system to apply the adhesive. Within this phase, a research and a selection to find the system that best suits the bonding process of the encapsulant and the textile were carried out. After having selected the mechanism that enables the uniform deposition of the adhesive and the subsequent bonding of both materials, various tests were conducted to define the variables and the optimal conditions for the joining process.

- Final product characterisation. In this last step the final product was verified, with the completion of the relevant tests necessary in order to validate the resulting prototype.

As an example of application the awning was developed by InnovaTec with PV cells integrated on it. The main functionality of this prototype is to store and use the energy obtained during the day in the rolling awning to feed the illumination system placed in those awnings used at night in restaurants, terraces or homes.



Solar powered retractable awning (InnovaTek)

6. Monitoring and validation of solar integrated products

Monitoring and validation of solar integrated product prototypes has been carried out on several levels. First, the different aspects of the prototypes, such as electrical and mechanical properties have been continuously validated during the product development cycle within the companies they were developed. Also thermal properties and exposition to the atmospheric conditions have been tested. The tests performed on the batteries have been designed to check the capacity and performance of the storage component in different climatic situations. These tests also gave the information needed to simulate the performance of the battery.

Additional specific feature modules, such as touch panels, audio amplifiers and Bluetooth audio streaming, all present in F3 Solar powered Audio Device have been separately tested, as well as the optic systems present in SIARQ FASCOM and F3 Solar Powered Lamp.

Lamination and forming tests have been performed by CEA using laminator with curve guide in order to optimize PV stack encapsulation and avoid possible wrinkling of the product with curved design.

For the purpose of BiPV prototype monitoring an evaluation laboratory has been assembled in EURAC. INTENT (**INT**egrated **EN**ergy walls **T**est facility) is a laboratory that can evaluate, either in dynamic or static mode, the thermal and energy performances of building envelope systems, such as walls and floors that integrate active solar systems for energy production or radiant circuits for heating/cooling.

The laboratory includes calorimeter, steady-state sun simulator, hydraulic measurement circuit and a detailed monitoring system. During the tests, the BiPV sample was inserted into a frame surrounded by thermal insulation, located between the cold and a hot box which is constituted of a guard chambers. The hot box reproduces the interior room conditions, while the cold box reproduces the outside ambient conditions.

The solar simulator reproduces the irradiation conditions on the external surface of the test sample. The glazed panel at the bottom of the cold-box allowed us to keep the desired climatic conditions in the cold chamber and at the same time guarantees the needed transparency for the irradiation of the sample.

The temperature values are acquired with 70 surface thermocouples (Type T) and 40 air thermocouples (Type T). The metering box is equipped with a heating device. The guard and the cold chambers have air conditioning systems. The ambient temperature within the three climatic chambers (guard, metering and cold), is controlled using PT100 temperature sensors distributed within them. The air velocity can either be mechanically regulated by varying the dimensions of the channels in which the air is conveyed or automatically by regulating the speed of the installed fans. The moveable anemometer allowed us to check the air velocity field within the air stream channels. The irradiance was measured with a pyranometer placed on the same plane of the PV modules. All measured values were continuously controlled and acquired, with 1 minute interval.

Main aim of the test was to evaluate and monitor the thermal impact of the PV integration in the geodesic dome by measuring the temperature distribution of BIPV triangular module integrated in the PVC building envelope under different environmental conditions (i.e. typical winter and summer day in Bolzano and Barcelona). Moreover, the temperature data were used to calibrate the simulation model. Additional measurements were performed with an infrared thermal camera to evaluate the temperature homogeneity on the specimen.

In the framework of SolarDesign project, outdoor tests on BIPV elements were planned. The tests consist of thermal and electrical analyses of a BIPV triangle mounted on a PVC substrate in situ at CEA- INES site. The objective was to estimate the impact of parameters such as the BIPV triangle slope on its constituting layers temperature and its electrical behaviour under exterior conditions. The results permitted to have an overview of suitable location of PV triangles on the geodesic dome in cold season.

Project Impact, the Main Dissemination Activities and the Exploitation of Results

PROJECT IMPACT

The project addresses major challenges that Europe faces like the need for reduction of our energy use and associated emissions. It provides European creative industries and manufacturing firms with a long awaited PV material for a user centred Ecodesign and helps to stop the dislocation of traditional industries on one hand and improves the global competitiveness on the other. We Europeans can either wait and see how competition from low wage countries cannibalizes our industries (and not only the PV industry) with suboptimal mass products or take the opportunities that lie in the SolarDesign project. The design-driven prototypes, tools and processes developed within the project can be applied to a vast array of sectors.

STRATEGIC IMPACTS

Novel materials and products where the design and the advancement in the properties of the materials are a key factor for success

The project addresses creative industries and adjacent industries alike. The creative industry receives novel materials and an unknown freedom-of-design for the development of solar powered products. Manufacturing industries can upgrade their products and productions by full integration of PV materials. In case of Sunplugged as prospective European solar cell manufacturer with focus on bespoke PV solutions the project is decisive for bridging the gap between proof-of-concept and industrial production. Sunplugged has already set-up a pilot production line for flexible CIGS solar cells with an annual production capacity of 2 Megawatt peak.

From the end-users (designers) the following impact is expected and is exemplary for the creation of new opportunities in the creative industries:

The development of a Compact Solar Lighting System is crucial for SIARQ as a company in the solar lighting market. SIARQ has already gained certain notoriety in developing smart- looking solar street lighting systems during these last 10 years.

The development of a low cost Compact Solar Lighting system as a high quality and performance solar product, helped the company to set up an assembling facility as well as introduce the solar product in the market of urban areas. The market studies have shown that this ambitious and new generation product can be sold not only in Europe but worldwide due to its price and technical characteristics.

SIARQ introduced the new smart solar street light systems in the cities as a new smart city lighting solution that permits a creation of a family of products, and also developed smart solar lighting systems for private use.

The SolarDesign project opened new product and design possibilities for Faktor 3 company. It made possible to offer innovative, unique and efficient consumer products on the market.

Especially the flexibility in form and size of the new solar cells makes Faktor 3’s power management electronics more attractive to customers. It is possible to integrate solar cells into existing products of customers. This allowed Faktor 3 to break into new markets and product groups. The development of a solar fabric integrating the thin-film technology created a new production and commercial line for Innovatec that manufactures solar fabric and, with the fabric, the development of customised textile products like blinders, roller blinders, awnings, tents, etc. that uses fabric with solar cells integrated on it.

Boosted dynamism of innovation in the fields of the creative industry

Attention to materials and manufacturing is a fundamental concern in architecture and industrial design. The use of PV by designers is limited by the current generation of photovoltaic modules and the underlying materials and production processes used to produce them. Today aesthetic, ergonomic and multifunctional aspects have to be neglected for achieving a required amount of energy. An international survey among architects and designers carried out by the IEA Task 41 experts has underlined that one of the main barriers which hinders the spread of PV systems integrated in buildings is the lack of suitable products developed to satisfy the architects' needs for high quality, formal and conceptual architectonical integration.

Improved communication between actors in the innovation chain also in view of novel consumption patterns

Ultimately designers, not scientists are the ones to decide on the use of resources, consumption modes and the life cycles of buildings, vehicles or devices. The project identified major obstacles and problems that product designers have when developing solar powered products in terms of available know-how, methodology and tools. SolarDesign provided solutions to overcome these obstacles (i.e. simulation, design assistance and modelling). SolarDesign has provided a market pull innovation, meaning that unfulfilled market needs were the guiding direction of the innovation efforts and the creative industry was involved from the very beginning of the project.

By having architects, designers, researchers and developers of solar technologies involved in the project the consortium has learned about the needs within various market segments. In addition knowledge about the way the product is used was also key for the development of solar powered products. Within the project a knowledge base covering typical usage patterns and situative conditions for all applications covered in the project have been developed.

Contribution to achieving EU policies, particularly the Europe 2020 and the Innovation Union goals as well as those of the initiative addressing the creative industries.

Common goals of all EU member states is to limit climate change, enhance energy security and generate jobs as well as a green economy in Europe. The European Union has therefore established a number of directives like the Ecodesign Directive and the Energy Performance of Buildings Directive. Those policies represent major milestones to achieve the associated objectives. For instance the Energy Performance requires that all new buildings have low energy standards by 2020. Photovoltaics is of course one major technology to achieve this objectives stated in the directive. Design is an important and so far underestimated acceptability factor. Improved design can improve the acceptability of PV technology.

SolarDesign has been conceived in line with targets set by the European Union and its member states to increase the share of renewable energy and to accelerate the uptake of low-carbon technologies (SET plan). Furthermore our approach supports initiatives towards a sustainable and decentralised energy infrastructure at a Europe -wide level. The project contributes to Europe 2020 targets by providing a solution to integrate solar power in a multitude of applications thus increasing energy efficiency and the use of renewable energies and lowering greenhouse emissions.

Reduced environmental impacts, improved safety for users and workers

All commercially available thin-film solar cells are using amounts of toxic materials like lead, silicon tetrachloride or cadmium within production processes. CIGS solar cells contain normally a thin cadmium-sulphide layer as a so called buffer layer. Cadmium can cause lung and kidney damages and can be fatal in large quantities. The project results offer solutions to eliminate cadmium completely from the solar cell by using novel, non-toxic buffer layers. This eliminates the hazardous risks for workers and for users.

Indium supply for the fabrication of CIGS modules

Approximately one third of the CIGS absorber consists of Indium. In other words with current available processes and production technologies at Sunplugged's pilot line 100 square meter of solar foil can be produced with one kilogram of Indium. Converted in Watt-peaks 100 square meter equal 12.000 Watt-peaks (assuming an average efficiency of 12%).

With a current Indium price of around 500 Euro per kg Indium accounts for 4-5 per mille of the total costs. Even a sharp increase in Indium market prices would not affect dramatically the production costs. Furthermore Indium suppliers like the Indium Corporation are stating that Indium resources are sufficient and sustainable for the decades to come. Data from the U.S. Geological Survey shows that indium exists in the earth's crust in quantities approximately three times that of silver which is currently extracted at 60 times the rate of indium.

Generally, this production processes are neither optimised in terms of sputtering yields nor is the solar cell itself optimised in respect to raw material consumption. Nevertheless within the SolarDesign project the consortium strived to reduce the Indium content by thinning the precursor layer of the CIGS absorber.

IMPROVED COMPETITIVENESS FOR EUROPEAN INDUSTRIES

Transforming traditional industries

SolarDesign team was focused on uniqueness as well as core competences, which is by far more important than market position when aiming for sustaining success. By creating a new "PV material" as well as flexibility in terms of shape, size, and electricity, we provided designers and architects with a high degree of transferability of solar technology to a variety of untouched markets and hence applications.

New Business models for regional production and global market niches

Business concepts in the photovoltaic market are driven in most cases by achieving cost leadership. Like in other industries this leads ultimately to price wars and decreasing profit margins. Within the last several years the wholesale PV modules prices dropped considerably from €3 to about price today € 0.50 per Watt-peak. China's strongly subsidised solar production has gained a dominant global market share. This major player is dramatically pushing the prices below profitability levels of EU firms. SolarDesign is not about David against Goliath (in form of Chinese mega factories). It´s about cultivating markets that lie fallow and cannot be addressed by production lines which can only operate profitable due to economies of scale. The SolarDesign approach enables not only new product designs but allows full integration of the technology into existing production processes. For the PV industry and OEM´s who want incorporate photovoltaic modules in their products. The project enables supply industries to upgrade their products with integrated photovoltaic modules. In respect to industrial implementation the SolarDesign approach enables full product and production integration. It is conceivable that the solar foil (solar cell) is delivered as semi-finished product and the solar module tailoring can be integrated in the production process of the respective manufacturer. This can facilitate the manufacturing of sustainable products and lower the total production costs.

Mass-production vs. Tailor-made-production

Today most tailor-made PV-Modules are made still of crystalline silicon solar cells. The three-step monolithic interconnection that is used in solar thin-film factories was not suitable for swift changes in the production set-up. The deposition processes and scribing processes are too much intertwined that a change in certain module specifications (e.g. cell width) would result in economically unsustainable set-up costs.

The following examples of specific designer requirements illustrate that the SolarDesign approach allows not only freedom of design but is also superior in terms of costs in comparison to existing solutions.

One major advantage of the SolarDesign approach is the strict separation of solar cell processes (deposition) and solar module processes. This lays the groundwork for a novel production approach that allows the unification all back-end processes.

High-added value products for PIPV and BIPV

The SolarDesign Project addresses the “long tail” of the total PV market. The special needs of a multitude of niche markets cannot be satisfied by mass-produced standard PV modules. We saw a strong demand for PV in upcoming markets like Passive Houses, E-mobility and the powering of energy-efficient small electric devices. SolarDesign solves a specific problem. For this reason we believe that the price is not the decisive factor and we can even charge a premium for providing a tailor made solution. Furthermore we can expect high customer retention in markets that are not depended on subsidies.

The need to dramatically increase the renewable part of our energy supply, stated in two important Directives such as the EPBD recast 2010/31/EU and the RES 2009/28/CE, is now pushing to maximize the PV use in building skins, making architectural integration a key issue.

Thus there was a need for product development which would suit the needs of architects, offering them the possibility to use PV as a “material” or building component in the design process, providing a flexible product able to easily change in size, shape and appearance.

A great application of PV integration lies for example in retrofit systems, where flexibility of shapes, colours, sizes and patterns are an essential point considering that every building is unique and different from another one.

Many surfaces are suitable for PV integration in the built environment, and the characteristics of pliability, transparency, possibility to choose different shapes and patterns are necessary for achieving high quality solutions. The new technology developed in this project could be easily applied in different ways to suit the different buildings typologies and shapes.

The “BIPV potential” for Central Western Europe was quantified by an analysis carried out within the project IEA-PVPS T7: the study shows that there is an high potential considering the actual building stock, i.e. 18 m^2 per capita for roofs and 6.5 18 m^2 per capita for facades. Also new architecture needs new products to be developed to integrate PV in the building skin: contemporary architecture is in fact exploring new shapes and surfaces which not always match with the available PV products.

Product Integrated Photovoltaic (PIPV)

As technologies advance, the energy consumption of products (e.g. LED lights, power-optimised processors, passive houses) is decreasing. Together with the fully customisable PV modules new applications for solar integration have become feasible. Solar designed products leverage solar power to advance energy efficiency and ease the deployment of operation. These attributes opened the door for different and new usage models. A conservative estimate suggests that around 200 -300

MW-peak were integrated into consumer products in 2010 alone. SolarDesign innovations have the ability to spark an explosion of solar-powered products. The advantage developed within SolarDesign is not only the provided “freedom of design” but even more crucial, the process of customized solar integration itself was made simple and therefore feasible.

EUROPEAN APPROACH

Supporting and linking of cultural and regional distinctions

Integrating photovoltaics in architecture and industrial design is in its infancy and taking into account different European perspectives is crucial for its success. This is especially true for Building Integrated PV where legal conditions like construction codes or feed-in regimes are differing from one European country to another.

By seeing design from a stylish or sensory perspective, regional characteristics exist. Taking product designers and PV experts from different European countries ensured the incorporation of varying design manifestations.

Landmark for European wide adoption of Photovoltaic integration in sustainable design

The project addressed a need of European Designers and SMEs who want to create sustainable products and differentiate themselves from the competition of low-wage countries. This urge is not confined by any national boundaries or regional climatic conditions.

The objects and activities of the SolarDesign project catalysed a widespread uptake of solar powered sustainable designed products. These products were developed and showcased in different locations all over Europe, to further inspire the utilisation of integrating photovoltaics in sustainable designs.

Bringing together scientists, integration experts and designers

The project has established and enhanced a firm foundation for technological developments in the photovoltaic sector and in the greening of European products and buildings.

Therefore the SolarDesign consortium was composed of 11 partners from Austria, Denmark, France, Germany, Italy and Spain. Each partner provides specific expertise in his or her domain spanning from fundamental photovoltaic cell research, material sciences, nano and micro technologies, solar integration and design. On a national or regional level such a well-defined partnership is hardly possible because only few European nations would have the necessary resources. Moreover by adopting different European perspectives, the project has incorporated cultural varieties not only from the designers’ point of view, but from stakeholders from a various European regions.

DISSEMINATION AND EXPLOITATION OF THE SOLARDESIGN RESULTS

Dissemination is a horizontal activity and was concentrated on disseminating the results of SolarDesign project itself to a wide range of existing or potential stakeholders. SolarDesign Consortium has identified and organized the activities to be performed in order to promote commercial exploitation of the project’s results and the widest dissemination of knowledge from the project. The plan was expanded in two directions: towards the marketing activities in order to enhance the commercial potential of the products and towards the notification of the project’s results in the scientific and non-scientific public.

Regarding dissemination, there were two fundamental objectives: the increase of general dissemination (broad public) activities for the project and the intensification of scientific dissemination in international events. All the industrial SolarDesign partners focussed their actions on the first objective while partners of academic nature made an effort to participate in events and to publish specialized articles with more scientific content. Accordingly, a wide range of dissemination, which reaches the diverse audiences interested in knowing the different aspects of SolarDesign project's results, was carried out.

Dissemination activities included:

- The strategy to ensure proper dissemination of the generated knowledge, related to confidentiality, publication and use of the knowledge,
- Individual dissemination plans and schedule of activities among partners,
- Numerous scientific (peer reviewed) publications,
- Active participation in events, conferences, workshops, fairs,
- Networking with other European platforms and with related EU projects,
- Contribution of SolarDesign Consortium in Creative Cluster activities within EC,
- Open Project Workshops,
- Personal meetings/discussions with Industrial Representatives (end-user stakeholders),
- Establishing of the Project Webpage. The consortium has registered the domain http://www.solar-design.eu/ in order to facilitate the access to project information using the internet,
- Identification and classification of target stakeholders to be addressed (not only for dissemination purpose but also for the identification of final potential users of the project results),
- Publication of various dissemination materials (e.g. newsletters, project flyer, general poster, press releases) and specific associated activities (dissemination in each partner web pages, public newspapers etc.),
- Education and training of students in the field of SolarDesign,
- Presence of the project in Social Media (Twitter, Facebook, LinkedIn etc.).

SolarDesign partners promoted participation of young female researchers in meetings, workshops, conferences and other dissemination activities. GAIA promoted the participation of women in SolarDesign, in launching specific actions but also analysing the different effects of a system or product on women and men. A specific element of the project action plan related the public image presented by the project through its dissemination activities within the international scientific and wider community. All material gave a balanced representation of all social groupings to prevent any "gender stereotyping". It was essential that any gender implications in this area were assessed and clearly understood before any public statement was made.

Clear channels of communications between the project partners themselves as well as with the wider community played a crucial role in the success of the project. The internal communication infrastructure had to include provision of convenient and appropriate mechanisms for facilitating the free flow of information across SolarDesign project site.

Ecosystem and networking activities:

- Integration of regional innovation initiatives in Europe (technology suppliers, final users, industries and promoters) into the photovoltaics environment in order to build up a sustainable ecosystem for the SolarDesign Project.
- Downstream activities oriented to the establishment of a sustainable ecosystem surrounding the project, conceived to outlive beyond the end of the project as a key factor to enable wide adoption in the market and obtain business impact.

Exploitation activities included:

- Identification of the scientific and technical knowledge, products and services of the project
- Identification of the project results and classify them according to their commercial potential, as a first step towards the exploitation of the project results
- The creation of detailed and regularly updated product descriptions for the SolarDesign Project's results that allowed the intensification of the exploitation tasks
- Risk Grading Matrix and action plan to manage the potential risks
- The consolidation of the project's Interest Group, which encompassed, public bodies, research institutions, universities, companies and people/professionals potentially interested in the SolarDesign project

Market and Competitive Analysis

- Identification of relevant target markets and target groups
- Positioning of the expected results of the project within the target markets/ groups identified
- SWOT analysis of the project itself
- Detect new trends and possibilities
- Constitution of an industrial User Group

Business Modelling and Licences

- A consistent project exploitation strategy delivered
- The rules and ways the results of SolarDesign have been brought to the different markets
- Finalized agreements between partners including intellectual property agreements covering patents, copyright, trademarks and intellectual property rights

Business Planning

- Exploitation strategy outlined both at a consortium level and at individual partners' level
- Guidelines have been established to the commercial deployment of the products/services the consortium and the individual partners exploited
- Two open workshops for industry and research have been organized

Patent issues

- An extended patent research was conducted and IPR matters were reviewed on an ongoing basis throughout the project
- List of applications for SolarDesign patents, trademarks, registered designs (2 patent applications, 3 registered designs, 3 trademark protections)

Life Cycle Assessment (LCA)

- For the achievement of the SolarDesign objectives, the LCA analysis were taken into consideration for the design and manufacturing of the photovoltaic cells

Standards and standardisation as tools for the implementation of research results

- Circulating of new measurement and evaluation methods, implementation of new processes and procedures created by bringing together all interested parties such as manufacturers, researchers, designers and regulators concerning products, raw materials, processes and services
- Include sessions on standardisation in the frame of meetings for increasing the internal and external awareness of the topic

List of project partners:

1. TECHNISCHE UNIVERSITAET WIEN (**TUW**), Austria
2. SUNPLUGGED - SOLARE ENERGIESYSTEME GMBH (**SUN**), Austria
3. FAKTOR 3 APS (**F3**), Denmark
4. INNOVATEC SENSORIZACION Y COMUNICACION, S.L. (**INN**), Spain
5. STUDIO ITINERANTE ARQUITECTURA SL (**SIARQ**), Spain
6. RHP-TECHNOLOGY GMBH & CO KG (**RHP**), Austria
7. EUSKAL HERRIKO ELEKTRONIKA ETA INFORMAZIO (**GAIA**), Spain
8. FACHHOCHSCHULE MUNCHEN (**MUAS**), Germany
9. ACCADEMIA EUROPEA PER LA RICERCA APPLICATA ED IL PERFEZIONAMENTO PROFESSIONALE BOLZANO (ACCADEMIA EUROPEA BOLZANO) (**EURAC**), Italy
10. UNIVERSITA' DEGLI STUDI DI MILANO-BICOCCA (**UNIMIB**), Italy
11. COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (**CEA**), France