Cu-PV final report

4.1. Final publishable summary report

4.1.1. Executive summary

The Cu-PV project aimed to maximize resource productivity and reduce pollution in PV production, through minimizing use of critical resources such as energy (by reducing silicon consumption and improving the conversion efficiency), silver and lead, while simultaneously maximizing recycling possibilities, by introducing design for recycling in this sector, and collaborating over the value chain for improvements in recycling. The project consortium consisted of 7 market stakeholders and research institutes. The participants represent a variety of equipment technology providers, market experts and researchers with in-depth knowledge in PV modules, recycling and waste management and plating technology.

The project focused on solar cell and module technology based on crystalline silicon solar cells with all contacts at the back, since these offer highest power output per unit area, and allow the use of very thin silicon substrates (wafers). Since much of the energy payback time of PV is due to the energy used to produce the silicon wafers, thinner wafers and increased performance were key objectives to effectively reduce environmental impact. Additionally, features to enhance recycling were tested and included, and recycling processes were developed and tested.

LCA – life cycle analysis – data showed that environmental benefits can be achieved by high recycling rates of silicon, silver and glass. While glass is already recycled at large scale, silver recycling is currently considered as uneconomic. The quantities of recoverable silver are too small today and a few PV manufacturers are working on using substitutes to silver in their products.

For two reasons silicon is hardly recycled today: Firstly, the marketability of recycled silicon is very low at present times and secondly, the recycling of the EVA-cell-EVA foil (EVA is the encapsulant used in module production) brings economic and technical challenges.

With the increase in waste quantities in the coming years, quantities of both silver and recyclable silicon will increase. To ensure that these quantities will result in high recycling rates, new technologies both at the production and recycling side need to be implemented.

Key accomplishments of the project are:
High efficiency back contact solar cell technologies were transferred to 120 micron thin substrates (to be compared with present-day typical industrial thickness of 160 micron) and scaled to 6 inch large wafers. Even thinner substrates would be possible, but these are not yet easily available on the PV market. A best conversion efficiency of 22.5% was attained on 180 micron thick substrates (21.5% on 130 micron thin substrates). Several cell processes were developed, with readiness level varying from suitable for industrial pilot production to lower level for the more advanced processes. The most advanced processes save nearly 20% of the currently industrially used silicon (more than 30% compared to project start), and give about 15% or 25% decrease of energy payback time (EPT), respectively (the EPT is of the order of1.5 years for today's modules, with significant variation depending on manufacturing location and process).

The main other two environmentally relevant materials used in silicon PV modules, silver and lead, were also tackled. Lead was virtually removed from the modules by avoiding the use of solder for interconnection of cells. Silver consumption was reduced by developing several seed & electroplate technologies. Also here, a range of technologies with different readiness levels were developed. For application as a drop-in replacement in present industrial metallization by screen printing, seeding with small amounts of silver paste and silver ink was used, with reduction percentages of 70-90%. Alternative silver-free seeding was developed on the basis of laser processing of contact patterns on the back contact cells, followed by deposition of a thin contacting/seeding metal layer stack by sputter deposition. The further metallization of the seed layers was realized by copper or nickel-copper electroplating. Industrial plating equipment was optimized for the handling of the thin cells with high yield, attaining high uniformity, and adjusting the plating process and equipment for bifacial cells.

Recycling processes were developed and compared. While standard modules employ thermosetting encapsulants (EVA), benefit for recycling was demonstrated when using thermoplastic encapsulants. For processing of standard modules, semi-automated equipment for modules with thermoset encapsulants was developed and resulted in recovery of cleaner glass, possibility to recover silver (significant in current modules) and other enhanced recycling opportunities. The recycling processes aimed at thermoplastic encapsulants gave additionally a high yield of recovery of intact wafers.

For the recycling of standard modules, special emphasis was placed on the investigation of methods that allow the non-destructive recovery and reuse of materials such as frame or glass for the manufacture of new panels; other partially destructive ways were tested in order to maximize the recovery of other metals (such as silver) as well.

Finally, destructive tests were carried out to achieve a recovery of materials such as silicon, plastics, glass, directly as a raw material that could be sold on the recycling market today and result in an economically sustainable recycling process.
Recovery of most materials used in the module (apart from aluminium and glass, also silver, copper, silicon, plastics) is possible and the total of recovered materials, together with improvements in their quality and therefore value, is helpful for this economic sustainability.

4.1.2. Summary description of project context and objectives

INTRODUCTION

Solar photovoltaic technology generates electricity from sunlight. The technology is based on installation of large numbers of PV modules of each typically about 250-350 Watt maximum power output (Watt-peak or Wp, the power output under a standardized - very sunny - condition). The modules consist of glass panels protecting the actual semiconductor devices that convert the sunlight to electricity, and are covered on the back, usually by a protective polymer backsheet. They have a size of about 1.5 square meters. The electricity is typically converted from DC to AC, and fed into the grid. The modules can be mounted in residential systems (particularly, on home roofs), or in large utility-scale power plants (on large fields, meadows, deserts, etc.), or anything in-between.

The photovoltaic (PV) market has grown rapidly over the last decades to an annual production of more than 50GWp, equivalent to several large power plants. A large nuclear power plant delivers electrical output of 1 or a few GW. Since the sun doesn't always shine, the yearly energy production by an installed PV capacity of a certain wattage, is however typically less than the production from a conventional power plant of the same wattage. This effect is of course taken into account in calculations of cost and benefits of PV. All predictions and scenarios indicate that there is a strong environmental need for the PV industry to keep growing rapidly, and that this growth will indeed happen.

While photovoltaics is very environmentally beneficial, it's environmental impact is not zero. The Cu-PV project identified the main environmental concerns of photovoltaics, for that part of the PV market that is based on crystalline silicon semiconductor technology (which is more than 90% of the market), to be related to energy consumption in the production of the panels, the big reliance on the use of a scarce material (silver, Ag) for electrical contacting, and the use of a harmful material (lead, Pb) for electrical contacting. Energy consumption during production translates to a CO2 emission per kWh produced over the lifetime of a panel, which is low but not negligible (for PV it is at least about 10-20x lower than fossil fuel kWh's, but of course this number depends on many parameters - electricity from coal or gas, characteristics of the conventional power plant, technology used to produce the PV panels).

This context led to the major objectives of the Cu-PV project: to reduce strongly or avoid the use of Ag and Pb in crystalline silicon based PV technology, and to reduce the environmental footprint of PV technology, the carbon footprint in particular, by increasing the module performance, using less silicon, and providing new technologies for recycling.

One very effective way of reducing the footprint per kWh generated by a PV module, is to increase the performance of that module. Therefore the project focused on high-performance PV technology, providing a high conversion efficiency of power received as radiation from the sun, to electrical power. The vehicle for that high performance are so-called back-contact solar cells and modules, where the solar cells have all electrical contacts on the back side, and have limited or no metal wiring on the front side. For several reasons such cells enable more easily the highest conversion efficiency.

A specific advantage of back-contact technology is that it allows to use even less silicon for the solar cell than would simply follow from the increased conversion efficiency. The reason is that the solar cells experience less mechanical stress during module manufacturing and can therefore be significantly thinner than conventional solar cells. The objective in the project was to reach 22% conversion efficiency, whereas at the start of the project between 18 and 19% was typical for high performance industrial solar cells, and presently first production of advanced so-called PERC cells is trying to establish itself with efficiencies between 20 and 21%. Higher performance back-contact cells and modules in fact exist, from one manufacturer (Sunpower Corp., in the USA), but this is a premium and proprietary product at relatively high price level. The ambition of the project was to demonstrate high performance with more generally available low-cost technology.

In terms of footprint reduction by moving to thinner silicon substrates, the project aimed for a reduction of present solar cell thickness of around 160 micron, to 120 micron or less. The project focused on this thickness of 120 micron, but it must be added that the technologies from the project likely allow even thinner substrates. The objective was a 50% Si and about 30% PV system energy consumption reduction. Silver reduction was another major topic in the project. After the carbon footprint (energy consumption for the production of, in particular, the silicon wafer), silver is in some respects the major environmental impact of PV modules. It is also expensive, which means that technologies to reduce or replace silver will be easier to get implemented in industry. The project investigated several processes, aiming at reduction on short term with technologies that do not deviate from present PV production too much, to complete replacement on longer term, with more drastically deviating technologies. In all cases the principle was so-called seed and plate: providing a contacting seed pattern on the silicon, on which copper is electroplated to provide the required low electrical resistance. The seed would then use a low amount of silver (technology for short term introduction) or no silver at all (for longer term introduction). The target is using 2 mg or less of Ag per Wp power.

Lead reduction was largely accomplished by the change of module technology to the back-contact technology. Most lead in PV modules is used for soldering the cells to connect them to each other, and the outside contacts. In the back contact module technology of the project, other methods for connection of the cell, not relying on lead, were tested in conjunction with the low-silver contacting. Finally, an important part of the project dealt with the environmental impact of end-of-life modules, and the possibilities to reduce environmental impact by re-using more materials from end-of-life modules than presently is the case. In particular re-use of silicon would reduce the carbon footprint of PV significantly. A problem that arises in relation to technology development for recycling of PV modules is the long lifetime of PV modules: typically 30 years or more. Therefore even though on the order of 50 GWp or 4 million tons of future PV waste are already produced each year, it will be many decades before much of that waste will be actually become reality and be offered for recycling. That means there is little incentive for producers to lead the development of recycling-friendly production technologies, or for recyclers to develop recycling technologies: the benefits and available waste volumes on short term will be small. Nevertheless, it is obviously important to develop such technologies. Therefore the project investigated two directions in parallel for recycling: Improve current recycling technologies to recover materials and introduce them back into the cycle of industry from the economic point of view, increasing the value of PV waste making it attractive for recyclers and thereby reduce the carbon footprint. Second, to introduce design for recycling in module production (in particular, in the back-contact module production) and to develop the associated changes enabled by this in recycling technology.
All activities in the project were assessed by economic analysis, and key benefits of the recycling for environmental footprint were analysed by life cycle analysis. Many results of the project were published in scientific literature. Also a policy brief describing the recycling landscape and possible improvements, and an introductory video on the project, were created. A workshop with stake-holders in recycling was organised after 2 years progress in the project.

CONSORTIUM

The project consortium consisted of partners along the value chain (the chain of activities from production of solar cells to recycling), with industrial partners dominating in number. Two non-

commercial research institutes, ECN and Imec, investigated the solar cell technologies (both) and the module and recycling technologies (ECN only) in an integrated approach. One company (Xjet) was involved for the contact seeding technology on the solar cell, and one (Meco, a subsidiary of Besi) for the copper electroplating technology. Unfortunately Xjet abandoned PV activities to focus on other industrial sectors, halfway the project, which necessitated the consortium to somewhat adapt the development plans for seeding technology. For back-contact module production technology, the company Eurotron was involved, and collaborated with ECN on this development. Xjet, Meco, as well as Eurotron fabricate production equipment for PV, so they don't actually produce solar cells or modules themselves.
For recycling technology, the company Technical Plating focused on new processes for todays waste modules, with support from ECN. Technical Plating unfortunately ceased its activities at the end of the project, but the achievements described here will be continued in a new startup company, Solar Recycling SL, created exclusively to develop technology for recycling solar panels.

ECN and Eurotron focused on design for recycling and associated novel recycling technology. The industry association PV CYCLE, which operates a take-back and recycling scheme for nearly all PV manufacturers in Europe, was involved in assessments, dissemination, analysis, etc. The original consortium also included a European module producer, to validate and demonstrate module and recycling technologies, however, this company went bankrupt at the beginning of the project so its tasks had to be redistributed over the other partners.

The technologies are aimed at industrial take-up, and demonstration with tools representative for mass production. Our expectation is that at least several of the demonstrated technologies and concepts will be implemented in pilot production within 3-5 years.

ECN (cell technology)

ECN developed two variations of back-contact cell technology in the project, both incorporating screen printed silver-based contact patterns. The cell technologies were as close as possible to current industrial production (in which ECN has experience based on technology transfer and joint development projects; several advanced cell processes from ECN are in full scale production worldwide). These cells were brought to higher efficiencies and adapted, to result in minimal silver consumption and suitability for electroplating. While the initial plans for the seeding were to use inkjet printing technology from Xjet, finally the development focused on relatively industry-standard screen printing instead of inkjet printing. In addition ECN worked on silver-free seeding technology similar to the technology developed by imec (see below).

The solar cell technologies developed by ECN are known as metal-wrap-through (MWT) and interdigitated back contact (IBC) cell technology. ECN's IBC technology has a specific design feature (a so-called front floating emitter) that allows high tolerance for relatively inaccurate technologies such as screen printing.

IMEC

imec focused on the development of its interdigitated back contact solar cell technology. This had been established in the years before the commencement of this project, with results up to 23.3% reported. The first work was performed on float zone (FZ) silicon wafers, which employed lab-style processing. The cell sizes were 20x20 mm^2, so significantly smaller than the FZ wafer size (4" diameter). In the project this was extended to using solar grade Czochralski (CZ) wafer types, of industrially standard 156x156 mm^2 size, while continuing with the small solar cells. The challenge in the topic over the duration of the project was the upscaling of these small area cells to full size 156x156 mm^2 cells, and to maintain the efficiency and performance that was achieved in the small cells. There were many facets to this task: the processing challenges which arise to realise this target, together with the optimisation of the efficiency potential for a given cell. Replacing the photolithography based patterning that was employed in the small cells required the introduction of laser ablation and screen printing to the process flow. Processes were developed and initially demonstrated on 20x20 mm^2 cells, which attained 22.7% efficient cells. For a solar cell where both contacts are present on the rear side, the definition of the two doped regions on the rear side has great significance – and potential if optimally designed. A schematic design for the solar cell was defined, and this was applied, to achieve a first result on large area IBC solar cells. The efficiency of these cells were improved by several iterative steps, including optimizing the metal-semiconductor contact grid (which reduces the resistive losses). The metal pattern applied initially was based on a sputtered aluminium layer, later a sputtered aluminium-based seed stack followed by a copper plating process. This enabled the cell efficiency to be increased. The final steps in this project involved re-visiting the cell schematic layout, after isolating where the losses were arising, and re-designing to optimise the performance.

Meco

Within the project Meco developed plating processes and equipment improvements for the next generation high efficiency solar cells based on n-type silicon substrates. Plating has the potential to reduce the cost of metallization by more than 65%. The main contribution is material savings by replacing silver with a stack of nickel, copper, and a thin capping layer.

Several alternative routes for cell metallization were investigated which resulted in plating processes for n-type bifacial cells as well as n-type back contact cells. The ITRPV solar industry roadmap shows that both cell types are expected to grow from 10% of the total PV cell production volume in 2015 to more than 20% in 2020. Meco estimates that all tier 1 cell manufacturers (and most tier 2 players) have n-type material in production or will set up manufacturing of n-type production in the near future.

In this project Meco developed specific processes that are optimized for n-type solar cells. It was investigated how Ni and Cu can be plated on different seed layers (screen printed, stencil printed, ink jet printed, PVD-deposited Cu). Three main objectives were better coating uniformity due to improved agitation and shielding, tests with very thin wafer material, and an optimized clip force which resulted in improved wafer handling performance. Since the clips, which hold the cells during processing, are a critical part of the system, Meco developed a clip force tester within this project which was used to measure the repeatability and lifetime of clips. All three topics that were investigated had a positive outcome and can be implemented in future plating systems. The results of the project are already being field tested with one customer.

It is expected that, besides some niche players which are already using plating, more plating will be introduced in mass production the next 1-3 years. The target segment for plating is n-type bifacial and back contact cells.

Eurotron

Eurotron offers fully automated production lines for the assembling of modules with back contacted solar cells. The equipment offers high volume manufacturing with a high degree of automation**,** and can achieve low cost per Wp. The back contact technology offers a number of advantages on cell, module and process level, which are explained in detail later in this report. This type of production platform will likely play an increasingly important role for PV production.

The role and tasks of Eurotron in the Cu-PV project can be divided in adaption of the existing equipment, fabrication of mini (2x2 cells) and full-size (6x10 cells) modules with recyclable materials, development of recycling methods, and Cost of Ownership calculations.

In the project, Eurotron developed and built a machine to provide the possibility for cheaper and more flexible backsheets. The existing module production line was adapted in order to make use of the interconnection method and encapsulant as chosen in the project for reduced environmental impact and to allow recycling. Improved yield in module manufacturing was ensured by an in-line testing system. Module assembly was investigated that enables effective recycling, also with the aim to contribute to establishing standards on this aspect. Alternatives for EVA were studied, in particular thermoplastic encapsulants. When thermoplastic encapsulants demonstrated satisfactory performance, investigation was done for separation of a module by heating, cleaning and re-use of the components. Cost of ownership for the different processes and material options was evaluated.

ECN (module and recycling technology)

ECN investigated the interconnection and encapsulation processes to produce modules from the solar cells produced in the project. The interconnection had to be lead-free, reliable, and allow separation of solar cells in a recycling process. In the encapsulation, the possibility for recycling also played a dominant role. In the project plan it was anticipated that thermoplastic encapsulants would offer benefits over todays thermosetting encapsulants, and this aspect was investigated and developed in detail. Indeed the use of thermoplastic encapsulant turned out to be very beneficial for recovery of complete solar cells from waste modules. It was investigated whether other aspects of design for recycling could also be of benefit, such as design of the metal frame around the glass panel, or the design of the junction box that forms the connection of the module to the outside world.

Continuous assessment of materials by accelerated degradation tests as well as recycling tests (in WP5) was performed. At the end of the project full-size modules were made to demonstrate the integral Cu-PV technologies, and a targeted efficiency of over 19%. The technologies are aimed at industrial take-up, and demonstration with tools representative for mass production.

The focus in recycling technology was on 3 topics: developing recycling technology for current PV modules; developing improved recycling methods for back-contact modules based on the technologies developed in WP4; and assessments of design rules, designs of automated tools, and life cycle analyses.

Technical Plating

The objective of Technical Plating was to develop and test recycling processes that could be applied to todays waste modules (with thermosetting encapsulant and high silver usage) as well as the project’s design-for-recycling modules. The company included evaluation of scaling up and economic aspects. Several processes were studied, treating the modules chemically or thermally. During the project, a mixed mechanical technology combined with thermal treatment turned out to be most promising and was developed and tested further.

With these mechanical processes panels can be disassembled in full, recovering each of the materials making up the panel suitable for reuse or recycling feedstock. Where this is not possible the recovered materials should be ready to be recycled by standard procedures in the industry today.

PV CYCLE

While PV module recycling is already taking place at industrial scale, and between 80 and 90% of a module (by technology and weight) can be recycled, PV CYCLE wants to research into higher-value recycling and new recycling technologies.

With respect to the European WEEE (Waste Electrical and Electronic Equipment) Directive's recycling targets and increasing requirements for design for recyclability, innovative, new processes and techniques have to be investigated.

Today, a high recycling output can be achieved by using the best available techniques from mainly the flat glass recycling industry for silicon based PV modules.

Some materials, particularly the EVA foil (plastic laminate) cannot be further treated at this point and either go into energy recovery or – if applicable – have to be landfilled. On average, about 10% goes into energy recovery and approximately 5% is landfilled today.

With today's low waste streams from the PV industry, landfilling and energy recovery have little environmental impact. As quantities will increase in the coming 10-15 years, PV CYCLE recommends to apply alternatives to these end-processes. Firstly, recycled EVA (or other) will increase in quantity and may attract new businesses for the production of new materials or products and secondly, the environmental impact from landfilling or energy recovery will increase too.

In the project, PV CYCLE provided modules for recycling tests to Technical Plating, arranged contacts with stake holders and participated in the surveys among stake holders, participated in dissemination (in particular, took the lead in the recycling workshop organized by the project, and the policy brief), and participated in techno-economic and life cycle sustainability assessments of the objectives and results of the project.

4.1.3. Description of the main S&T results / foregrounds

ECN (cell development)

At ECN, initial focus was in parallel on bifacial industrial n-type front-and-rear-contact and n-type metal wrap through (n-MWT) cells, with some additional effort on setting up an IBC cell process. The purpose of the work on the front-and-rear-contact cells was to make fast progress in demonstrating the seed and plate technology on industry-standard cells. Results will be described in the later sections on seeding and plating technology.

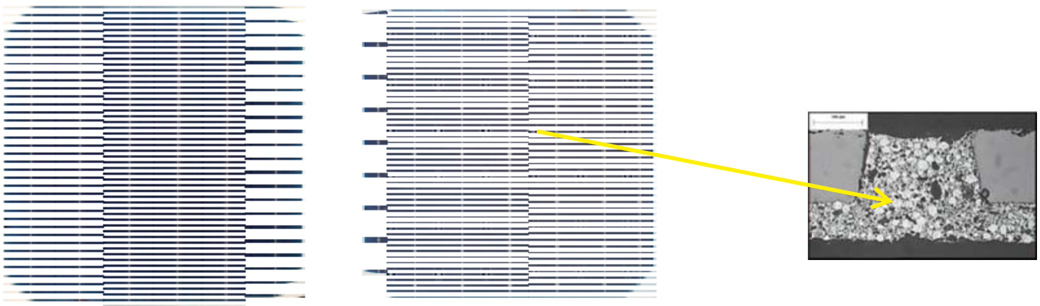


Figure 1: front and back of a high efficiency bifacial metal-wrap-through cell, with cross section of wrap through metal contact

The best n-MWT cell efficiency that was achieved was 20.5% on full size wafers, still based on traditional paste metallisation (large Ag consumption). The smallest cell thickness was 120 micron (um), and the efficiency loss associated with thickness reduction was characterised to be about 0.2%. WP1 provided half-fabricates of n-MWT cells as well as industry standard p- and n-type cells for inkjet and thin screen print metallisation followed by Ni/Cu plating.

The MWT half-fabricates were of thickness 180 and 150 um.

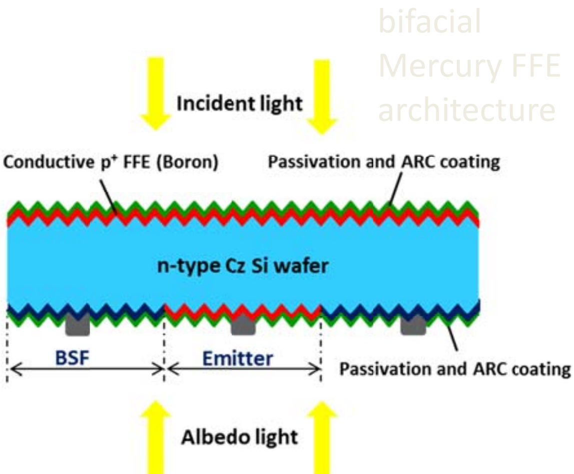
On the bifacial n-type cells we also demonstrated a silver-free rear metallisation of n-type cells, with the same efficiency as with regular Ag-based metallisation. Optimisation of optical properties was done, and a small efficiency increase compared to Ag-based reference process is possible.

n-type MWT cells of 120 micron thickness were fabricated to investigate any processing issues or efficiency penalty. No issues were encountered, and the efficiency penalty appears to be approximately 0.2% relative to standard thickness cells (in agreement with device modelling).

The work was reported in several publications, which are available on the Cu-PV website.

Although the MWT cells reached a cell efficiency of 21% during the project (development work in a parallel project), the project focused from mid-term on IBC cells. The attainable efficiency is higher for such cells, and the advantages from plating are larger, while disadvantages such as front contact widening and ghost plating, are much less relevant. ECN focused on a process with processing steps very similar to the bifacial n-type cell processing (that means a short, industrial, process flow), and the use of a front floating emitter that tolerates very well low resolution patterning with screen printing.

Figure 2a: front and back of a IBC cell with screen printed metallisation. Figure 2b: all-black 2x2 module with these IBC cells.



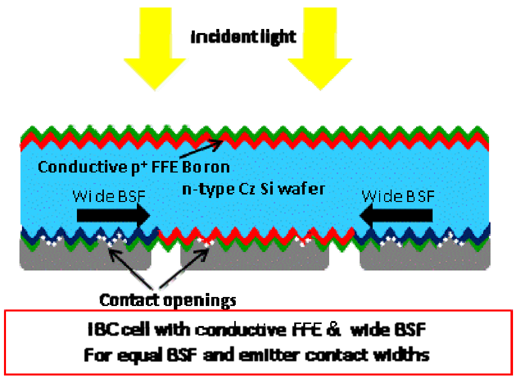


Figure 3a: Left: schematic cross section of the IBC cell with screen printed (seed) metallization. Figure 3b: same solar cell with front floating emitter, but with e-beam evaporated metallization.

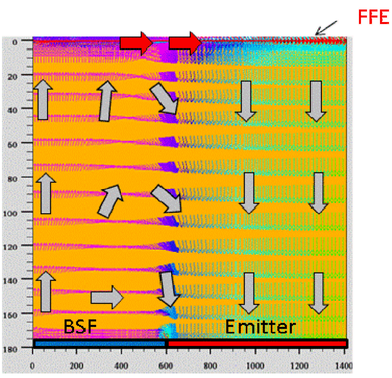


Figure 4: special charge carrier flow in such an IBC solar cell.

Much work was performed on modeling and optimization of the IBC cell design, such as grid design, and process conditions. Importantly, the ECN-designed IBC-grid and the associated ECN-Eurotron module technology used in this project allows high efficiency IBC cells on 6 inch wafers, while the only commercial IBC product presently cannot use industry-standard 6inch wafers but has to be limited to smaller 5inch wafers. With screen printed metallization at ECN a best efficiency of 21.1% was reached (work also supported from other projects). The grid was also optimized for the module technology and for the plating tool. Half-fabricates from this work were provided to WP2 and WP3 for seed and plate tests.

In addition, for this IBC cell development, work was aimed at metallization by aluminium from e-beam deposition (see also next section). This involved investigation of the annealing treatments necessary to restore cell performance after e-beam deposition (it is known that e-beam deposition can degrade cell performance, but the causes of this remain somewhat speculative). It also involved development of processes to pattern and etch the aluminium-based seed stack into a contact grid that could then later be plated. Unfortunately, with available industrial resists and low-cost chemistry, it turned out to be challenging to create a stable and repeatable patterning process, and this work did not result in functional IBC cells.

IMEC

At imec, a baseline high efficiency process has been developed on 2x2 cm^2 cells prior to the commencement of this project, initially using 4 inch FZ wafers. This has since been extended to 125x125 mm^2 (5inch) and more recently onto 156x156 mm^2 (6inch) Cz n-type Si. This process uses extensive cleaning, high temperature oxidations, and lithography patterning to define the doped/contacted regions. This process was used as a starting point for work in this project.

Over the course of the Cu-PV project, the work of imec was to develop a process for large area interdigitated back contacted and thin silicon solar cells, and to deliver such cells for module incorporation at month 30. This deliverable involved several challenges, including an appropriate patterning scheme to enable the boron and phosphorus doped regions to be defined, and contacted independently. As the cells are fabricated on large area wafers, additional challenges were introduced, related to the currents that are produced, and need to be removed from the cell. This could have been alleviated by increasing the thickness of the metal layers, but in turn this creates other issues, namely enhanced metal consumption and cost, and the risk of wafer bowing when the metal thickness is of order 20% of the total wafer thickness. So to effectively remove the current from a thin 6inch IBC solar cell, alternatives to the two busbar configurations were considered. To this end, the cell design needed to be revised and optimised for such a configuration, coupled with a contacting system which is compatible with the conductive sheets used in WP 4.

The first steps to be developed in this project was the development of patterning techniques which are applicable for large area cell production. Laser ablation was selected for defining the p^+ emitter and n^+ back surface field region of the solar cell: a process which involves opening a grid on the rear side of the wafer, consisting of lines of hundreds of microns width. This was done by ablating a series of lines in parallel, and after optimizing the spacing between these lines, together with the laser speed, the required line width could be obtained. This is shown in the images below, where (A) a sequence of dots were ablated, and (B) by reducing the laser line speed this defines a line, while in (C) the line spacing is reduced, until (D) the required line width is defined, and uniformly opened.

A B C D

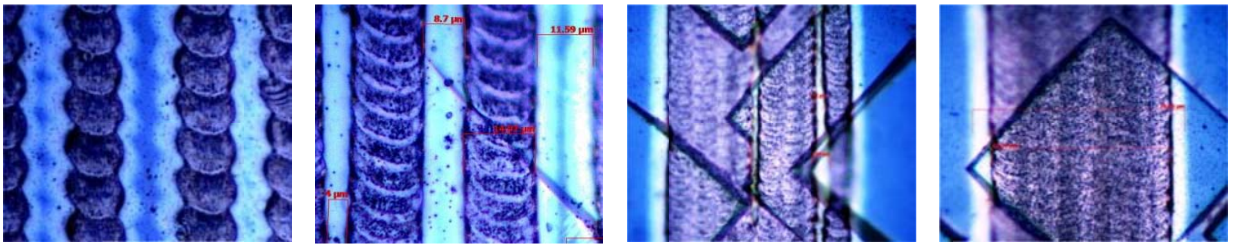


Figure 5: Optical microscopy images of laser ablated oxidised silicon wafers at different processing conditions. The optimum conditions employed are highlighted in (D)

The next step developed was a second laser ablation step, aligned to the step highlighted above, which defined the regions where the metal layer contacted the n^+ and p^+ doped regions. This was performed by opening dots in the silicon dioxide layer, which prevented the photo-generated carriers from being lost before they are collected as the result of the photovoltaic effect. For this reason, these contacted regions had to be sufficiently small to get the carriers out, without generating additional resistive losses but not too large, as this also results in the loss of the carriers – a delicate balance which needed to be optimised. An image of the silicon surface is shown in Figure 6. Also visible are the contact holes ablated in the second patterning step. The density of these holes is significantly higher in the n+ region than the p^+ region, consistent with the ratio of their sizes, together with the resistance of the contact to each region.

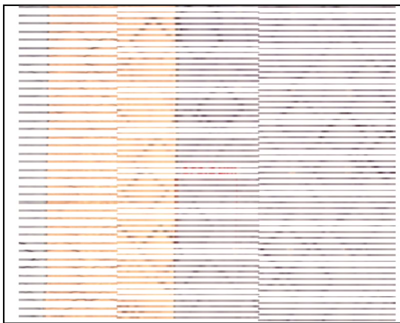


Figure 6: image of the p^+ doped silicon region (blue/grey), and the n^+ doped silicon (light colour) after the first laser ablation step. Also visible are the contact holes ablated in the second patterning step.

In the solar cell process, the next step involved covering the doped regions with a metal layer. This was initially performed using aluminium, which was then etched back to separate the two doped regions. An example of this is shown in figure 7. The n+ and p+ regions have been separated by etching the metal layer between them. In the image the n+ region is depicted towards the bottom (light grey colour), with the contact dots and metal lines visible. The non-uniformity of the electroluminescence image above reveals the resistive losses resulting from the metal layer. The highest signal close to the contact points indicates the impact of finger and busbar resistance losses.

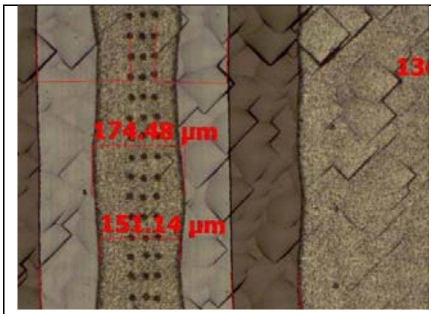


Figure 7a: Image of the metallised solar cell

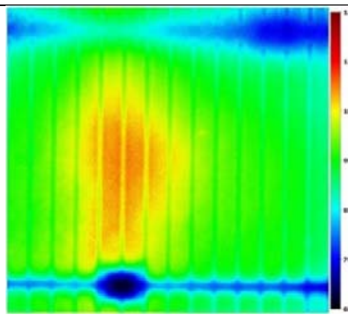


Figure 7b: Electroluminescence image reveals the resistive losses resulting from the metal layer.

Solar cells were fabricated in this manner, and were measured to have 21.3% efficiency. An extensive study of their performance revealed the major loss mechanism arose from the metal layer itself – the aluminium thickness was the maximum possible to avoid significant wafer bowing, but not enough to avoid strong resistive losses. Therefore seeding, and plating with a copper layer, was a suitable choice. A process was developed for this, in particular to engineer where the copper plating happens on the solar cell. To this end, a seed layer is required to define the plated region. This seed layer is a critical component of the cell, and its performance, so a three layer stack was applied in this work. The first layer needs to ensure a good contact to the underlying silicon cell, the second needs to act as a barrier to the copper (which would destroy the cell if it reaches the silicon!), and of course it needs to ensure the copper plating can happen on the seed. The impact of the seed layer deposition on the underlying silicon and doped layers needed to be evaluated, and this is shown in figure 8, where electroluminescence images of first and optimised cells are displayed. In this case, the uniformity of the image indicates the uniformity of the metallisation and the resistive losses, which are high for dark regions in the image, and low for bright regions. After optimising the annealing process, to remove any impact of sputter damage, and ensure an optimum metal-silicon ohmic contact, such cells yielded efficiencies up to 21.9% on 180 µm wafers, or 21.5% on 120 µm wafers.

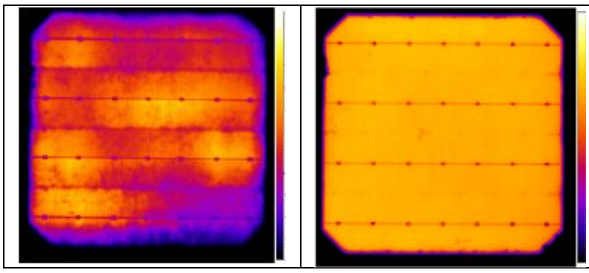
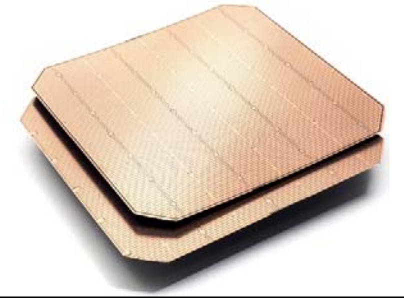


Figure 8: electroluminescence image of solar cell on left with first Cu plated layers, and on right with Cu layers.

At this point, the next step involved a further optimisation of the cell design. This followed a further analysis of the losses present in the cells shown above. The results of this are significant, and depicted in figure 9 below. The difference in the two designs centred on the wafer edges, where the wide loss-inducing regions were significantly reduced. This enabled the cell to generate higher current, and reduce the resistive losses in extracting this current, so combined increase the efficiency to 22.5%, or maximum power output of 5.38W.

	Figure 9: image of a solar cell with the initial (top) and updated (bottom) design.

This work built on a pre-existing high efficiency solar cell fabrication process, and aimed to modify to make viable for processing full size wafers, which has successfully been achieved. However, from an industrialization perspective, the process is still quite extensive and complex. Although not the focus of the work in this project, there is potential to simplify the processing applied to fabricate the cells, in terms of creating the doped layers. This could reduce the number of high temperature process steps, and make the technology more interesting from a cost perspective. The metallisation sequence applied in this work is extensive, and consists of several process steps (deposit seed layer, pattern seed layer, Cu plating, etch seed layer, and anneal). Work is ongoing to simplify this process sequence further, and to apply more cost effective patterning techniques.

Xjet and ECN (seeding)

In WP2 inkjet seed metallisation of n-type cells was established in collaboration between Xjet and ECN, with a consumption of approximately 10 mg of Ag for the front of a bifacial n-type cell and 20 mg of Ag for the rear of such a cell. This results in about 4.5 mg of Ag consumption per watt-peak (Wp), a factor 10 reduction from the present typical 50 mg/Wp. It turned out to be feasible to contact both polarity diffusions in the solar cell (front and back) successfully with inkjetted ink. After Ni/Cu plating the efficiency results of the seeded cells were at the same level as the reference cells with conventional metallisation. Finger width on the front of the cell, before plating, was around 40um, and after plating, was slightly below 55 um.

Xjet constructed an R&D inkjet printer and installed this at ECN. Special designs were applied for a chuck to handle bifacial cells, and for accurate alignment of patterns and re-positioning of the wafer. Also the software for pattern generation for MWT cells was created.

Figure 10: R&D printer from Xjet installed at ECN.

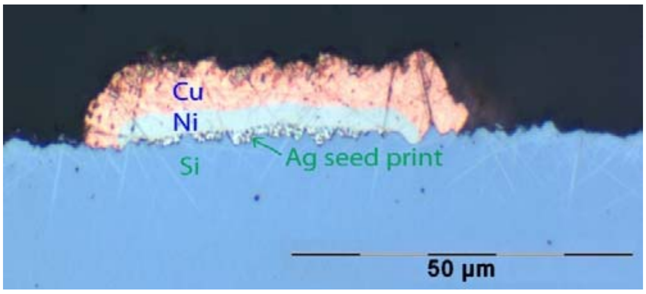


Figure 11: finished seed & plate contact on solar cell. The Ag seed print was deposited by inkjet printer.

After Xjet decided to abandon PV activities, the seeding work package 2 focused on screen print seeding, and the IBC cell type. While screen print seeding cannot easily attain the very high Ag reduction ratios of inkjet (target in this project was 95-99%), it has the advantage of being industry standard and can be implemented in industry by addition of only a plating tool to standard equipment.

Seed & plate of IBC cells has the additional advantage that shading due to finger widening on a cell's front side does not play a role, since there are no fingers on the front side. Also, ghost plating on front side can be more effectively avoided in the plating tool.
The work for the screen print seed & plate of IBC cells involved the following main points:

- adaptation of the metallization grid for full size module technology;
- adaptation of the metallization grid for the plating tool in the project;
- optimization of seed pattern: minimization of laydown and test of uniform plating;
- production of seeded cells.

The demonstrated silver reduction was 71% compared to the normal screen printed mass of silver for these IBC cells. From discussion with the paste manufacturer, 87% reduction should be possible with the same printed volume, by reducing the silver content of the paste.

The cell efficiency of the seeded & plated cells was identical to that of the control group (unplated, normal metallization consumption), at 20.1% average and 20.2% maximum, for 120 micron thin IBC cells.

<u>Meco</u>
In the first task of the plating work package, plating parameters were investigated on Ag-seeded p-type H-pattern cells (both screen printed and stencil printed). These were successfully plated and used for module testing in the module technology work package.

The next task investigated plating parameters for high efficiency n-type back contact cells:

- n-type H-pattern cells were plated with and without Ni diffusion barrier layer and finished with Cu and OSP.
- n-type MWT cells were plated to investigate possible creation of shunt paths related to the MWT vias. Results were positive: only a small and acceptable increase of shunt.
- n-type bifacial cells (H-pattern and MWT) were successfully plated on front and back, and used for module technology tests.
- n-type bifacial cells were provided with different seed layers: stencil printed on the front, screen printed on the rear and inkjet printed on both front and rear.
- n-type back contact cells with printed silver seed were plated successfully with nickel and copper. Alternative capping layers were applied including immersion silver and an organic surface protection.

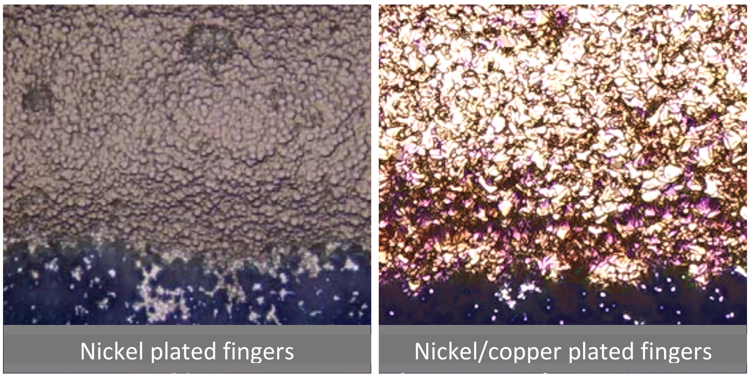


Figure 12a: Nickel plated fingers. Figure 12b: nickel/copper plated fingers

The final task of the plating work package was to develop plating equipment for thin solar cells. Plating on only one side of bifacial wafers was new for Meco and resulted in an artefact of electrochemical attack of the grid on the non-plated side. Also some parasitic (unwanted) plating on the non-plated side took place. The equipment has been modified to avoid this and it was verified that the artefacts were removed successfully.

This modification, however, also led to an unexpected decrease in handling performance. Modifications were implemented in newly built (production) equipment.

The compatibility of grid design with contacting design in the plating equipment was important. The grid pattern was modified to match the available contact on the belt, for several cell types.

Several hardware modifications have been executed for process optimization:

- Clip design: to ensure constant holding force during the lifetime of a belt (typically 30000 open/close cycles, corresponding to 6 months of use). A dedicated clip force measurement setup was developed to study this.

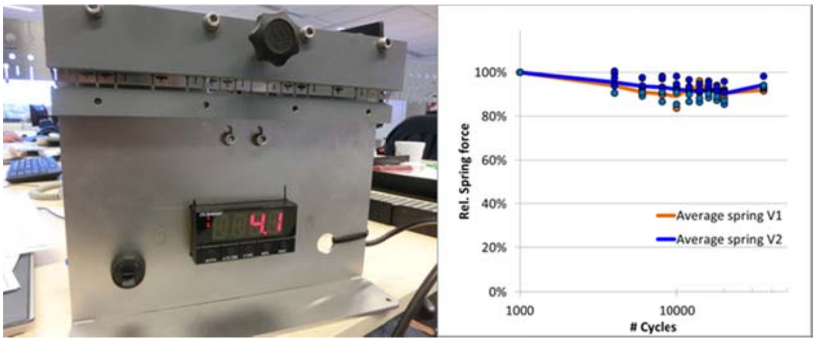


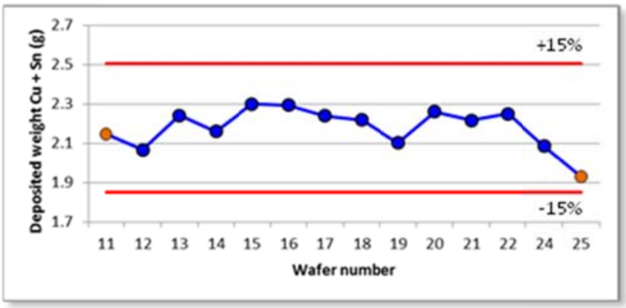
Figure 13. Clip force measurement setup.

Improvements were achieved by:

- reducing the friction by modifying the shape,
- additional winding

Also the tip of the clip was modified to minimize wafer damage and the design was made more compact to enable shorter clip-clip distances.

- Air agitation: To improve transport of copper-ions to the wafer surface.
- Shielding: Tuning of the top and bottom shielding to prevent too high depositions at those locations. The spread within a wafer was minimized to 21%, but needs optimization for each wafer size and pattern design individually. For wafer-to-wafer we achieved a spread of 8.8%. The first and last wafer are expected to be outliers contributing strongly to the overall value.



12%	-15%	-21%	-19%	-8%
-2%	-6%	-7%	-4%	-6%
1%	-4%	1%	-10%	-3%
-3%	-12%	-9%	-6%	-3%
19%	-16%	-9%	-12%	21%

Figure 14: wafer-to-wafer and within-wafer variation of plated thickness.

Significant results include:

- Front inkjet seeded cells, and rear screen printed cells were plated. Resulting cells show approximately equal or better efficiency as reference cells.
- Equipment modifications successfully eliminated artifacts found on non-plated sides of bifacial cells.
- The adhesion between seed and plated metal has been improved by equipment modifications and optimized chemistry.
- Front inkjet-seeded cells with down to 10 mg of Ag for fingers and busbars were plated successfully.
- Rear inkjet-seeded cells with down to 20 mg of Ag were successfully electro plated with Ni and Cu.
- Successfully plated H-pattern cells with cell-to-cell thickness distribution of 7.4%. A series of 664 cells was fed through the plating tool without any breakage (this includes loading, unloading and transport through the process cells).
- Successful plating of 150um thick n-type MWT cells; Demonstrating 11.77% thickness variation.
- Successful plating of 120um thick IBC cells, both on screen printed seed and on PVD-seed. Significant increase of FF, no degradation of cell parameters.
- Thin dummy wafers of 140µm and ultra-thin wafers of only 100µm were fed successfully through the line (this includes loading, unloading and transport through the process cells) with minor breakage. Breakage of 0.15% was achieved at 140µm and 0.1% at 100µm.
- The usual capping layer of Sn (tin) or Ag (silver) has been replaced by a cheaper organic surface protectant (OSP). The contact resistance was successfully tested before and after TC100 (-40°C to 85°C, 100°C/h, under current, IEC61215) and DH500 (85°C/85%RH, 500 hrs, IEC61215).

Figure 15. Cu-plated IBC dummies with different capping layers

- Both the module performance and reliability of these Ni and Cu electroplated cells were proven upto 1xIEC in damp heat and thermal cycle tests.

ECN (module development)

In WP4 module materials and fabrication methods and tools have been investigated, designed and built for the combined objectives of 1) reliable, low-cost, and high performance back contact modules with low or zero consumption of Ag and zero consumption of Pb, and 2) improved possibilities for recycling (improved recovery of valuable or environmentally costly components, reduced cost of recycling). Suitable candidates for these combined objectives were identified. Cell-module interconnection methods were investigated and compared, and interconnection by conductive adhesive was identified as most promising, with interconnection with low-temperature solder as an alternative with some technical issues with respect to reliability. For both techniques accelerated degradation tests and investigations of new materials and technologies, for better performance and environmental footprint, are continuously going on.

Eurotron

The Eurotron equipment is capable of handling all types of back contact cells like P-type metal-wrap-through (MWT) cells, N-type MWT cells, interdigitated back contact (IBC) cells and heterojunction (HJ) versions of these cells, and can produce foil-glass and glass-glass solar modules.
For everyone's understanding, a quick explanation about the typical build-up of the back contact module is given.

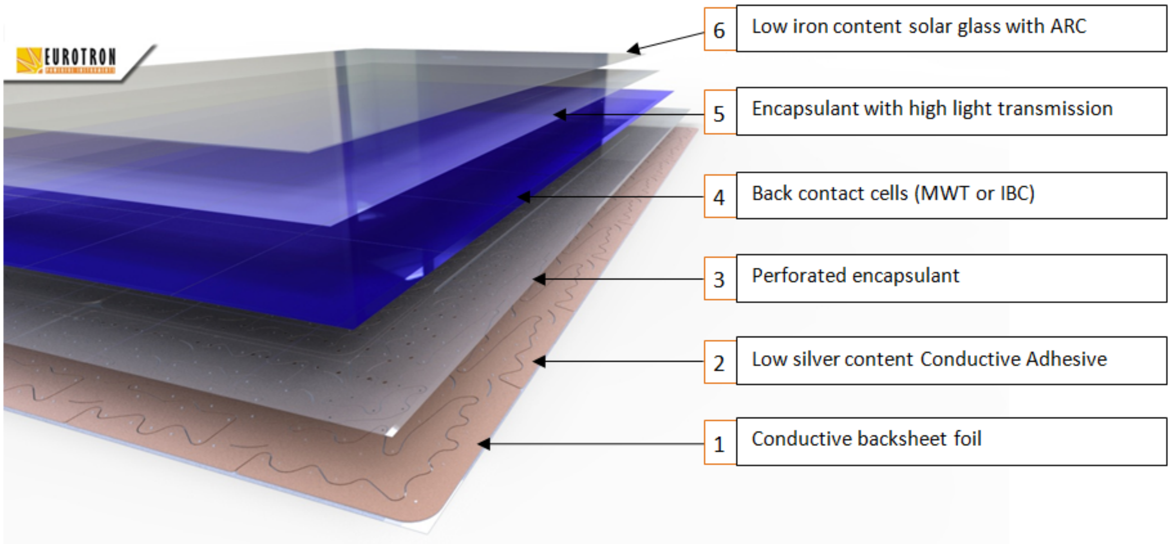


Figure 16: Module build-up

The base layer of the module is the backside contact foil. This foil consists of an electrically conductive metal with a barrier on the back to prevent moisture entering the module. To make the cells' series connection circuit the metal layer is patterned. On top of this backside contact foil small dots of a conductive material are stencil printed which will make the electrical contact between the metal layer of the foil and contact pads on the cell. For a good insulation, between the backside contact foil and the cells an encapsulant with holes is placed. The dots of conductive material will be right in the center of the holes and rise just above the encapsulant. The cells are accurately positioned on top of the conductive adhesive and encapsulation material. The conductive material provides the contact to the metal grid of the backside contacted cell.

The back contact technology offers a wide range of advantages on cell, module and process level:

On cell level this technology allows to increase efficiency and reduce costs. Due to the absence of front busbars and tabs the shading is drastically reduced, resulting in a higher short circuit current. The wafer is responsible for 2/3 of the cell cost, and the fact that the back contact technology is very well suitable for using thinner wafers (single pick and place / no thermal stresses) results in a more efficient use of silicon and cost reduction. It also gives flexibility in amount and position of contact points, in this way the cell grid patterns could use significantly reduced amounts of silver or copper. The multiple contact points also ensure redundancy: if a cell is broken most of it would still be functional.

On module level the foil-based back contact technology ensures a very low series resistance, enhanced reliability and more active area per square meter. The conductive adhesive, which connects the cells with the conductive backsheet, gives a highly efficient and short interconnection. Due to the fact that the conductive adhesive stays flexible over the entire lifetime the reliability is unrivaled. The cell spacing can be small, which leads to a minimum of inactive area of the module, and therefore lower costs for Balance of System (BOS).

On process level this technology has the advantage of flexible equipment with small footprint, minimum amount of operators required, and highest possible yield. Eurotron's equipment is capable of handling different module configurations and sizes. The full automatic line has a capacity of 90 modules per hour with only four operators. The highest possible yield is ensured by the pick and place technique developed by Eurotron.

Project results:
Several machines (“stations”) have been developed and built within the project, while other existing machines had to be adapted in order to handle the new selected materials. These materials and interconnection techniques were first tested on mini-modules, after which full-size modules were assembled with the most promising bill of materials. A proposal was made for an automatic recycling system, of which the most critical parts - especially cutting the embedded cells from the glass - were tested in practice. Cost of ownership for recycling was evaluated, while this calculation was more extensively done for the assembly process.

New and adapted equipment:
Eurotron has developed a novel manufacturing technique for patterning the front side of conductive backsheets, which was successfully tested. This system avoids the environmentally harmful etching process conventionally used for producing backsheets and also allows re-use of the removed copper. The capacity of this Integrated Backsheet Production machine (IBP) is approximately ten sheets per unit per hour.

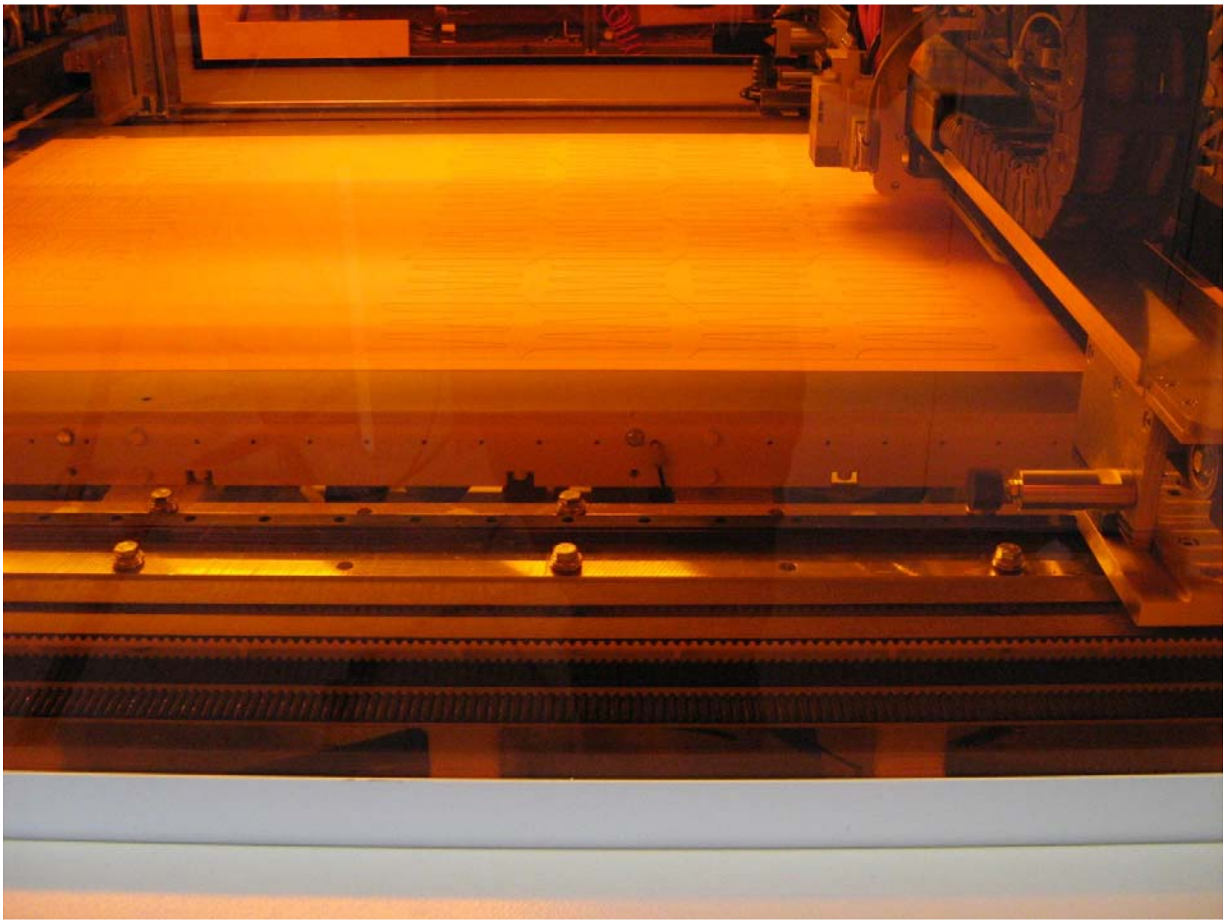


Figure 17 a, b: pictures of the IBP (integrated backsheet production) system

Also a new machine for fast and accurate placement of IBC cells in a full-size module has been built and used, and is ready for implementation in new module lines. This linear-motor-driven machine has an improved accuracy, higher speed and offers more flexibility. The machine contains several vacuum grippers, whereby the cells will be picked up only one time. Cells then pass a vision system which images each cell on proper alignment, based upon the contact points at the backside of the cell. In the same time, a crack detection takes place. Within certain limitations, broken cells will be removed out of the system and be put into one of the bins. Depending on the information from the vision system, proper cells are placed on the module with automatic correction on alignment and rotation angle based upon the contact points.

Figure 18: Picture of the new developed Cell Positioning Unit, particularly suitable for IBC cells and other cells which require extra accurate placement.

Finally, work on equipment and procedures for in-line testing during module fabrication have progressed well. The inline tester will check the module after placement of the cells and before lamination. In this stage it is easy to repair or disassemble the module if faults are detected. The module is checked on alignment and visual defects. When a visual defect is detected the module will be sent to a repair station where the decision can be made if the module will be repaired or disassembled. This system gives a reduced waste of material and creates a continuous quality control.

In order to make the Cu-PV modules, with new module materials, and different types of cells, having novel contact patterns, some existing machines had to be adapted as well. New stencils have been ordered, different opening sizes in the stencils were tested to see how small they could be without compromising module quality. Also new methods for opening the first layer of encapsulant were investigated where finally it was decided to use a laser system to make these perforations in the encapsulant, allowing novel encapsulants to be used.

Module production:
Manufacturing started with production of mini-modules using the interconnection method and encapsulation materials chosen in the other tasks of the project. The interconnection quality was determined from the fill factor of the modules. When satisfied about the bill of materials, a full-size module was made to demonstrate the suitability of the interconnection method and the materials for module manufacturing. One full-size module with IBC cells was manufactured, incorporating 120 um thin cells with printed Ag seed and NiCu plate and OSP capping layer, in combination with recyclable encapsulation materials, thus demonstrating all aspects of the Cu-PV technology in a full-size module.

Several series of modules were made at Eurotron's factory, starting with mini modules containing IBC cells in combination with the standard EVA encapsulant as benchmark. During the second run the EVA was replaced by thermoplastic materials, which gave a recycling friendly module. These modules had an excellent visual appearance and showed good cell alignment. Also the observed cell to module losses were as expected.

Finally a full-size module with IBC cells has been manufactured with a combination of screen printed and NiCu plated cells. These different cells were grouped in three substrings, thus could be measured separately. In this way a direct comparison between the different techniques was created. Only recyclable encapsulation materials were used in this module. A subset of the cells had a thickness of 120 um, without resulting in any issues. The protective capping layer on the Cu metallization of the cells consisted of OSP. In this way, all aspects of Cu-PV technology were incorporated and demonstrated in this module.

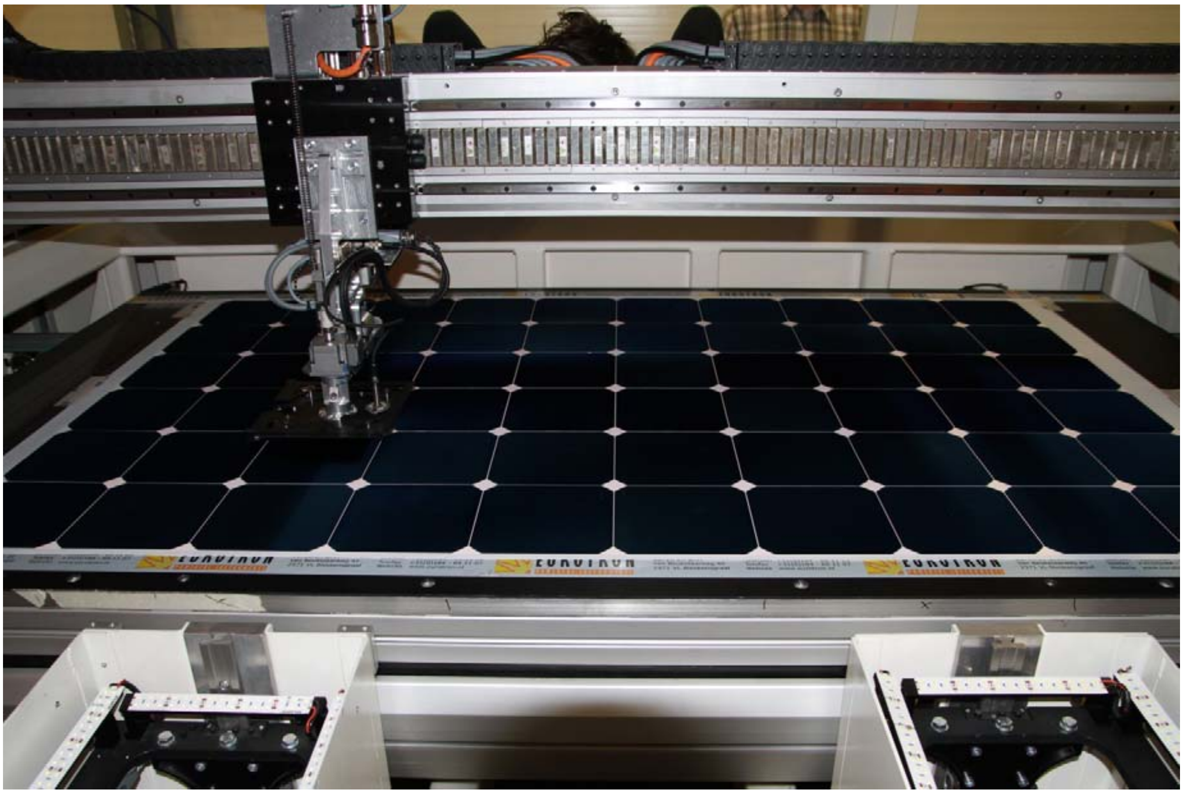


Figure 19: The full size module containing all aspects of the Cu-PV technologies in the pick-and-place cell placement machine.

Recycling

In WP5 surveys and life cycle analyses (LCA) were done to analyse the bottlenecks in present module recycling, and the possibilities and needs for improvements in recycling, and thus improvement of environmental impact of modules. First results were published at the EUPVSEC 2013 conference. The LCA shows that major environmental impact is from the Si wafer, Ag, Cu used for module interconnect, aluminium frame, and glass. For back contact modules, which may use more Cu than conventional modules, recycling of Cu may then become more important than for present modules. From environmental perspective it is valuable to start to recover (additionally to present recycling) in particular the silicon, and additionally to start to recover and recycle in purer format other module materials (in particular fluorinated backsheet, silver, glass, and for as far as not yet done, copper). The surveys to module manufacturers and recycling companies indicated the bottlenecks with respect to recycling. Results are analysed in an evaluation report with recommendations. Cost considerations dominate the feedback, but in general there is interest and willingness to investigate new routes for easier or increased material recovery. Frameless modules would be, for the present state-of-the-art recycling, very unfavourable because the aluminium recovered from the module frames presently provides a large part of the economic business case for recycling.

Also in WP5, development of recycling technology was done. Equipment was set up for recycling of current modules and tests were performed for semi-automated frame removal. Laminate recycling methods based on pyrolysis or chemical dissolution of encapsulant were investigated, but although the preliminary results were satisfactory the low interest in re-using the recovered products directed the research towards novel methods which are described below.

Technical Plating achieved some success in experimental tests for obtaining materials to re-use. A great challenge is the variety of modules (variety of shapes, materials, etc.) to recycle. The end-of-life of the PV modules is not all at the same time, and also the eagerness of manufacturers to improve their technology and performance means that there is no standard in the components; therefore a lot of technologies, brands and models are mixed at the time of recycling, this makes the re-use of components difficult.

The set of materials for re-use appears with large differences in sizes, qualities and thicknesses, not only for the frames but also for the silicon cells. Also models of junction boxes have been greatly modified over the years.

Technical Plating built up a semiautomatic line, based on mechanical separation of the components that allows their easy recycling, although the methods employed are destructive.

Two initial challenges were raised at the beginning of the project: The variety of PV module models on the market that make it difficult to automate processes, and panels arriving damaged (especially, with broken glass) by shock and weather effects. Because of this, it was decided to develop a semi-automatic machine with a high tolerance range, but assisted by people.

The set of technologies described below was developed during the project and introduced on a pilot plant scale production. The process capacity of the existing plant is ten tons per week.

Below the developed successful processes are described in order of execution on the production line:

1. *Separation of the junction box:* A special hand tool was developed for this purpose. It is fast and efficient and readily convertible to full automation, but incompatible with the current design of the production line. Due to major changes needed to be introduced into the line, automation was postponed to the next version.

2. *Removal of aluminum frame:* a machine with hydraulic arms was developed as a multipurpose tool capable of removing the aluminum frame of any current model of PV panel. Glass is not damaged during the process, but it works also even if modules arrive with broken glass. The running time is only a few seconds per module.

3. *Separation of silicon-EVA sandwich, backsheet and glass:* If the glass is not damaged, a continuous process machine, installed after the remover of the frames, is able to separate these three elements in two consecutive steps. Finally the cleaned parts are obtained, while silicon remains enclosed chopped into small pieces in the EVA. The entire process is actually slightly faster than the removal of the frames.

4. *Low temperature incinerator:* At this point EVA-Silicon sandwiches from the separation process 3, and frameless full modules but with the damaged glass, converge. They are introduced separately in a modified gas oven. The flame of oven works for a few minutes as fire starter and EVA works as fuel for the rest of the process. The temperature is controlled by air pressure flows. At the end of combustion a residue of small pieces of silicon and copper ribbons, or the same content mixed with broken glass remains, according to the starting material.

5. *Classification of materials:* The materials obtained in the thermal treatment are processed by screening and air-gravitational systems developed to separate materials in two stages. In the first stage the copper is separated, and then in the second stage if the process began from a damaged glass panel, the glass and silicon are separated.

Other parallel processes have been tested for the processing of copper wires (ribbons) and junction boxes. The manual disassembly of junction boxes and processing by conventional plastic blasting techniques have been successful but it requires a lot of manpower. Machinery for crushing of the junction boxes and the subsequent separation of materials has been developed.

Despite the difficulty of developing machinery that separates the EVA-silicon sandwich from glass without breaking it, the results are very successful. The result of the comparison of the semi-automatic separation of intact glass against directly processing the laminate including the glass in oven, is a great advantage in time, energy and easy handling after processing in the case of separation of the sandwich from glass.

Technical Plating also studied the possibility of recovering silver, and other metals from modules processed as described above. The silver recovery process is technically feasible but economically unattractive for the small amount of silver used in current panels. The large amount of silicon needed makes it difficult to obtain recovery even in specialized chemical plants because of logistical problems. To achieve good results it would be necessary to combine recovery of silver with silicon once decontaminated. This requires the silicon plant and chemical plant to be close.

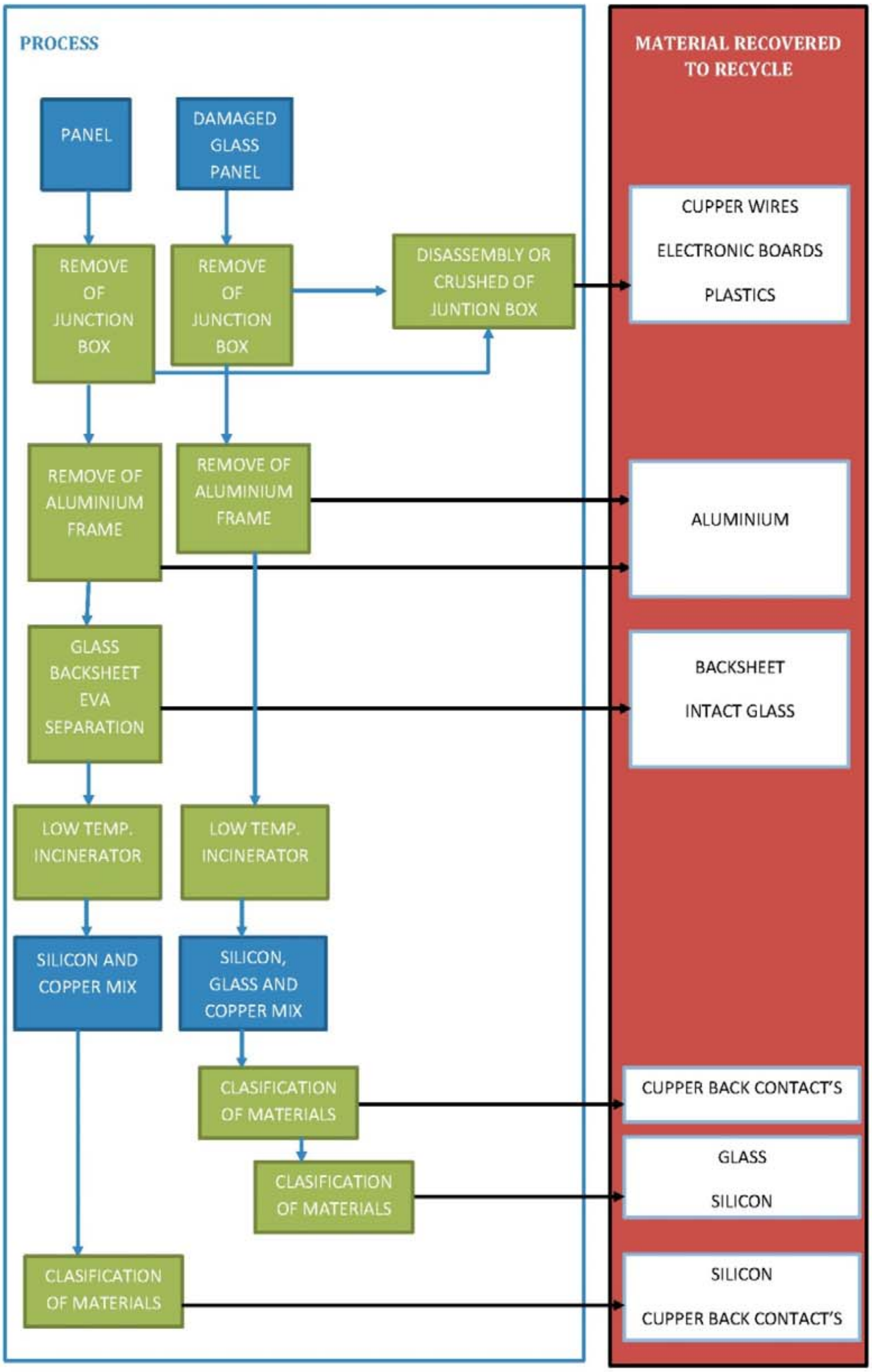


Figure 20. Process flows at Technical Plating for recycling of PV modules with undamaged glass and PV modules with damaged glass.

Figure 21a, b: Disassembled frame from intact and damaged glass panel.

Figure 22: Back sheet (left) and EVA-silicon cell sandwich (right)

Figure 23: Clean cell fragments

Figure 24 a,b: Clean broken glass

Figure 25: Clean full glass

Figure 26 a,b: Recovered copper contacts (ribbons)

In addition, first recycling tests of modules with modified materials and construction aimed at better recycling possibilities were done and showed that glass sheets, cells, and backsheet can be recovered in a simple process with low environmental impact. Further work on the most promising routes is going on.

Modules with thermoplastics
The separation of the PV module components in the case of modules with thermoplastics encapsulants, was executed in two stages. Firstly at temperatures where the thermoplastic material starts to soften, the backsheet is pulled from the PV module. Secondly the temperature is further increased to values where the thermoplastic is highly viscous, but does not start to decompose. At this temperature the encapsulant between the glass and solar cell was cut with a wire saw, thus separating these two materials, resulting in separated glass and solar cells coated with encapsulant residue. The wire saw is developed and tested by Eurotron and can operate at varying sawing frequency and a force of several hundreds of Newton can be applied.

Eurotron has also made a cost calculation for the fully automated equipment needed to recycle foil-based, back contact modules with a thermoplastic encapsulant with this wire-sawing process. Such automated production line with a footprint of approximately 150 square meters is capable of recycling 30 modules per hour. The materials content of these modules is shown in Table 1 below, together with the value of the recovered materials according to the TP process.

The Return on Investment (ROI) takes four years, but it is estimated that this process will give the highest profit at the end compared to other recycling options. This is due to the high value of the extracted solar cells from the PV modules. The CAPEX is relatively high, because it was chosen to use a high degree of automation where a minimum amount of operators is required.

Depending on the application of the recovered glass, the preferable dimension of recycled glass is cullets when used as feedstock for new PV glass production. When the glass is to be directly used in new PV modules, complete glass is required. One of the challenges that needs to be solved in that case is the effects of the environmental and mechanical conditions the glass was exposed to during the life-time. Undefined stress conditions result in glass with an undefined quality. For the time being separation of complete glass plates is especially important for failed modules before leaving the production facility.

With the recycling methods developed in this project, the materials listed in the table below are recoverable. The assumed value of the recovered materials, based on market interviews, is included in the table in the most conservative case (low value of the silicon). Concerning the profitability, initial analyses showed that after upscaling, recovery according to this table will be economically profitable. The quantity of copper in this table is specific for the back-contact modules developed in this project, and is much higher than in the present modules on the market. The quantity of Ag in this table is much lower than in present modules on the market, due to the Ag-reduction in cell and module technology developed in this project. Concerning recovery of silicon the economics of the processes required to remove antireflection coating and junctions was not analysed in this project. The value of recovered silicon will depend completely on its quality control, for which the possibilities vary between the recycling methods. Recovery of full wafers will improve the possibilities for quality control and the value of the silicon.

#	Description	Cost per module [€]	Weight [kg]	Weight percent [%]	Recovery [%]	Weight recovered [kg]	Value [€/kg]	Total value recycled [€}
1	Glass	6,00	12,570	72,69	100	12.570	0,055	0,69
2	Aluminum	8,44	2,000	11,57	100	2,000	0,650	1,30
3	Silicon	9,02	0,601	3,84	70	0,421	2,000	0,84
4	Silver	n/a	0,001	0,01	70	0,0007	445,00	0,31
5	Copper	8,80	0,548	3,38	70	0,384	4,450	1,71
6	Polyester	6,40	0,640	3,70	70	0,448	0,050	0,02
7	Thermoplastic	9,84	0,628	3,63	-	-	-	-
8	Junction box	5,00	0,269	1,56	70	0,188	0,050	0,009
	Total	**53,50**	**17,30**	**100,00**		**16,01**		**4,87**

Table 1. Value of materials to be recovered with the Eurotron/ECN solution.

Cost of Ownership calculations for cell and module production

An extensive Cost of Ownership (CoO) calculation on module-level has been carried out for cell and module production. All back-contact technologies considered in this project (seed-and-plate N-MWT, IBC from both ECN and IMEC) were compared with standard MWT and conventional H-pattern technologies. This includes the influence of the interconnection on module efficiency, expected yield during interconnection, and durability of the module in thermal cycling and damp-heat.

Main conclusions of this CoO study can be summarized as follows:

- Increased efficiency for back-contact solar cells adds to noticeably improved module efficiency (no CtM losses or even CtM gain) and therefore improved module CoO.
- IBC cell technologies enable higher cell efficiencies and is expected to further differentiate H-pattern module technology from foil-based back-contact technology in favor of the latter.
- Costs of BoM (bill-of-materials: all materials used in the module) are by far dominating the production cost on the module level, with the solar cell contributing with 60-70% of the total BoM costs.
- The case for foil-based back-contact modules is already favorable for the assumed rather high costs of the conductive backsheet and ECA per module, which are higher than the combined cost of the backsheet, ribbons and solder for the H-pattern module. Reduction of the costs of the conductive backsheet is expected after scaling up production volume which will further improve the case for foil-based modules.

Comparison between different cell & module technologies - client verification is required							
	P-type mono crystalline cells		N-type mono crystalline cells		IBC (N-type mono crystallinne cells)		
	H-type 3 BB	MWT	H-type 3 BB	MWT N seed&plate	IBC traditional	IBC from IMEC	IBC from ECN
Building cost							
Price of building per m2	€ 200,00	€ 200,00	€ 200,00	€ 200,00	€ 200,00	€ 200,00	€ 200,00
Required m2	7500	5000	7500	5000	7500	5000	5000
Annual cost (15%)	€ 150.000,00	€ 100.000,00	€ 150.000,00	€ 100.000,00	€ 150.000,00	€ 100.000,00	€ 100.000,00
Annual production hours	8600	8600	8600	8600	8600	8600	8600
Annual number of modules	774000	774000	774000	774000	774000	774000	774000
Building cost per module	**€ 0,19**	**€ 0,13**	**€ 0,19**	**€ 0,13**	**€ 0,19**	**€ 0,13**	**€ 0,13**
Equipment cost							
CAPEX glass preparation	na	na	na	na	na	na	na
CAPEX Front-end assembly	€ 2.700.000,00	€ 5.024.000,00	€ 2.700.000,00	€ 5.024.000,00	€ 2.700.000,00	€ 5.024.000,00	€ 5.024.000,00
CAPEX lamination	€ 3.740.000,00	€ 3.740.000,00	€ 3.740.000,00	€ 3.740.000,00	€ 3.740.000,00	€ 3.740.000,00	€ 3.740.000,00
CAPEX back-end assembly	€ 1.850.000,00	€ 1.850.000,00	€ 1.850.000,00	€ 1.850.000,00	€ 1.850.000,00	€ 1.850.000,00	€ 1.850.000,00
	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------
Total CAPEX	€ 8.290.000,00	€ 10.614.000,00	€ 8.290.000,00	€ 10.614.000,00	€ 8.290.000,00	€ 10.614.000,00	€ 10.614.000,00
Equipment cost per module	**€ 2,68**	**€ 3,43**	**€ 2,68**	**€ 3,43**	**€ 2,68**	**€ 3,43**	**€ 3,43**
Labour cost							
price per hour	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00
number of operators for front-end	16	4	16	4	16	4	4
number of operators for lamination	1	1	1	1	1	1	1
number of operators for back-end	16	16	16	16	16	16	16
total amount of operators per shift	33	21	33	21	33	21	21
modules per hour	90	90	90	90	90	90	90
Labour cost per module	**€ 1,83**	**€ 1,17**	**€ 1,83**	**€ 1,17**	**€ 1,83**	**€ 1,17**	**€ 1,17**
Cost Bill of Material							
(conductive) backsheet	€ 6,40	€ 18,00	€ 6,40	€ 18,00	€ 6,40	€ 18,00	€ 18,00
milling & laser cost	na	€ -	na	€ -	na	€ -	€ -
conductive adhesive	na	€ 1,89	na	€ 5,18	na	€ 3,78	€ 3,78
ribbons/soldering	€ 8,00	na	€ 8,00	na	€ 10,00	na	na
encapsulant #1	€ 2,80	€ 3,52	€ 2,80	€ 3,52	€ 2,80	€ 3,52	€ 3,52
cell	€ 86,69	€ 75,69	€ 88,02	€ 79,09	€ 193,59	€ 128,96	€ 100,01
encapsulant #2	€ 2,80	€ 3,52	€ 2,80	€ 3,52	€ 2,80	€ 3,52	€ 3,52
front glass	€ 6,00	€ 6,00	€ 6,00	€ 6,00	€ 6,00	€ 6,00	€ 6,00
tape, frame, corners	€ 10,55	€ 10,55	€ 10,55	€ 10,55	€ 10,55	€ 10,55	€ 10,55
J-Box	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00	€ 5,00
various	€ 1,30	€ 1,30	€ 1,30	€ 1,30	€ 1,30	€ 1,30	€ 1,30
YIELD surplus	€ 1,73	€ 0,38	€ 1,76	€ 0,40	€ 3,87	€ 0,64	€ 0,50
	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------
BoM cost per module	**€ 131,27**	**€ 125,84**	**€ 132,63**	**€ 132,55**	**€ 242,31**	**€ 181,27**	**€ 152,18**
Description							
costs for building per module	€ 0,19	€ 0,13	€ 0,19	€ 0,13	€ 0,19	€ 0,13	€ 0,13
equipment cost per module	€ 2,68	€ 3,43	€ 2,68	€ 3,43	€ 2,68	€ 3,43	€ 3,43
direct labour cost per module	€ 1,83	€ 1,17	€ 1,83	€ 1,17	€ 1,83	€ 1,17	€ 1,17
BoM per module	€ 131,27	€ 125,84	€ 132,63	€ 132,55	€ 242,31	€ 181,27	€ 152,18
	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------
Total cost per module	€ 135,97	€ 130,57	€ 137,33	€ 137,28	€ 247,02	€ 186,00	€ 156,90
Cell efficiency	19,5%	20,3%	19,8%	20,5%	22,5%	23,0%	22,0%
Cell performance in Wp	4,66	4,85	4,73	4,90	5,38	5,50	5,26
Cell price per Wp	**€ 0,31**	**€ 0,26**	**€ 0,31**	**€ 0,27**	**€ 0,60**	**€ 0,39**	**€ 0,32**
CtM losses	3,0%	-2,0%	3,0%	-1,0%	2,0%	0,0%	0,0%
Module performance (Wp)	271	297	275	297	316	330	315
Cost per Wp	**€ 0,50**	**€ 0,44**	**€ 0,50**	**€ 0,46**	**€ 0,78**	**€ 0,56**	**€ 0,50**
Module surface	1,64	1,56	1,64	1,56	1,56	1,56	1,56
Module efficiency	16,54%	19,03%	16,79%	19,03%	20,27%	21,14%	20,22%
CAPEX BoS per MWh	€ 669.410	€ 581.678	€ 659.267	€ 581.647	€ 546.224	€ 523.662	€ 547.465
CAPEX module per MWh	€ 358.073	€ 314.099	€ 356.176	€ 330.215	€ 558.008	€ 402.814	€ 355.244
CAPEX inverter per MWh	€ 142.857	€ 142.857	€ 142.857	€ 142.857	€ 142.857	€ 142.857	€ 142.857
	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------	+/+ -----------------
Total CAPEX per MWh	**€ 1.170.340**	**€ 1.038.635**	**€ 1.158.300**	**€ 1.054.719**	**€ 1.247.089**	**€ 1.069.333**	**€ 1.045.566**

Table 2: Summary of the results of module CoO study for selected cell and module technologies

PV CYCLE

Today, especially the EVA film that laminates cells, backsheet, and other materials, is a challenge to the recycling of silicon-based PV. Built to last 20-25 years, this foil requires micro-recycling in today's applied techniques with higher cost and higher resource input (e.g. electricity to recycle), while the market opportunities for the recovered secondary raw materials are low.

The new methods investigated in the CU-PV project may help to overcome these challenges. The LCA study we conducted together with the project partners identified silicon, silver and glass as the main contributors to environmental impact. The EVA foil with the silicon cells is the most challenging in terms of technology however. Therefore the module technology work package investigated the use of thermoplastics to replace the EVA. Tests showed that by using thermoplastics instead of EVA the recycling rates can be increased. First samples showed that the backsheet can easily be removed from the module. The leftovers of encapsulants on the back contact, back sheet foil and the solar cell can be largely removed using a knife. Further leftovers, on glass for example, could be removed by mechanical cleaning, incineration, or potentially with organic solvents. Follow-up tests in the second phase of the project focused on mechanical cleaning and incineration.

In addition, Technical Plating and Eurotron have further tested automatic or semi-automatic systems for the separation of the frame or the processing of the EVA-laminate to minimize broken cells, for example. Both automatization processes will help to increase recycling rates and decrease environmental impacts. PV CYCLE supplied the tests with end-of-life PV modules from different origins at large scale.

At the beginning of the project, PV CYCLE ran within the CU PV Project a survey amongst PV manufacturers to see to which extent projects for design for recyclability are already taking place and which factors impact decisions for or against innovations.

While few manufacturers responded, the results clearly showed that willingness for design for recyclability is there and cost drives or hampers changes.

A second survey was done amongst recycling companies with the aim of asking the opinion for technical and economic feasibility of new methods. The results were used for a first project report on current recycling methods and opportunities for improvement.

4.1.4. Potential impact and main dissemination activities and exploitation results

ECN

In the R&D vision of ECN as well as the Dutch national Top Consortium for Knowledge and Innovation (TKI) Energy, design for sustainability is an increasingly important characteristic for the innovation of PV technology. ECN will use the results from the research in the Cu-PV project in its exploitation activities. These activities include the technology transfer of cell process technology (for example, the front-and-back-contacted n-type cells such as researched in the first phase of this project have earlier been transferred to industrial production at several international companies, and are still actively being improved and marketed); technology transfer of module process technology (back-contact module technology has been transferred by ECN to international companies as well, but is generally in an earlier phase of the path to mass production); and collaboration with companies along the PV value chain on development, testing, and validation of new and improved processes, tools, and materials.

The n-type and back contact cell and module technologies which formed the core of this project, are becoming an increasingly large part of PV world production. While at the start of the project, three large manufacturers (Sunpower, Panasonic, Yingli) produced n-type cells, and only Sunpower produced back-contact modules, by the end of the project large players such as LG Electronics, and smaller players such as Mission Solar Energy and Megacell, had also started commercial production of n-type modules and are scaling up ambitiously. Also back contact producers have entered commercial production (Sunport), although this technology still has to make its big breakthrough. The ITR PV roadmap consistently forecasts n-type and back-contact technology to grow to a very significant part (30% for n-type, 20% for back contact, in 2025) of world production soon. The project results therefore cover a large potential market. The benefits of the project results also spread to other European companies, such as tool manufacturers, who produce production tools for n-type and back contact cells and modules. Finally, the aesthetic and efficiency advantages of back contact modules can benefit European residential installation (more energy output from a limited roof area; better aesthetics of roof-mounted systems). At least in the Netherlands, there is much commercial interest from industry downstream in the value chain (e.g., system integrators, balance-of-system component manufacturers, architects) for the special advantages of back-contact modules.

The results from the project can be immediately exploited, as discussions on technology transfer of ECN's cell technology and module technology are continuously ongoing. The possibility to use silver printed seed and plate, instead of standard silver screen printing, and the associated cost savings, will be included in ECN's technology propositions. As silver costs are an important part of the total costs of industrial n-type cells with screen printed contacts, the results of the project demonstrate a practical route to reduce cost and increase competitiveness of the n-type high-efficiency cell technologies. The module reliability results are essential in this respect. The demonstrations and reliability tests performed in the project are an important aspect of demonstrating the readiness level of the seed and plate solution.

The possibility to use thin substrates for back contact cells and modules, as demonstrated in the project with little or no performance loss, are also an important factor to make the value propositions for back-contact technology stronger and emphasize the cost-savings which are possible by moving to back-contact technology.

The impact of the project developments in design-for-recycling, and the possibilities for transfer of results to mass production, need more considerations. In contrast to the seed and plate, thin substrate, and back-contact technologies as such, the business case for design-for-recycling likely depends not only on traditional business case variables such as production cost, return-on-investment, technology risks, etc. Additionally, public and industry-wide policies, incentives, public awareness, etc., will be important. The reason is that the economic benefits of this technology may be far in the future, and not even be available to the original producer of the modules. The introduction of design for recycling therefore needs some additional support or incentive for the original module producer. This could be in the form of enhanced repair possibilities for modules that turn out to be defective directly after production, and perhaps the development and demonstration of demountable frames is an example for this. Another benefit that could stimulate design for recycling is if it results in enhanced reliability, as thermoplastic encapsulants in combination with printed seed and plate provided compared to traditional thermosetting encapsulants, in the tests of this project.

ECN Solar has a business development group, with representatives in USA and Asia, which maintains a network of relations with industry throughout the world. Business development visits conferences, workshops, and exhibitions, sometimes uses booth at exhibitions, or organizes workshops to disseminate ECN's technology. For example, during the project, the group has organised a back-contact workshop in China where several project partners presented results.

It is intended that the character of the development collaborations and consultancy that ECN provides will be broadened from very much performance- and cost-oriented to increasingly include the sustainability aspect.

ECN participates in several European and international fora on PV technology, such as the international IEA PVPS task force number 12 on sustainability of PV, the European PV technology platform, the international technology roadmap for PV (ITRPV), standards committees, etc. The need for more attention for sustainability is already well established within these fora; results from Cu-PV will contribute to giving precise and practically founded recommendations and contributions.

The Cu-PV project website and video attract reasonably high attention (1500-2000 page views per month, 300-400 unique visitors per month). The website that was set up at the start of the project in fact has a name and content which is aimed at sustainable PV in general (www.sustainablePV.eu), and the Cu-PV project is only a specific set of pages within that website. The page visits show a slowly increasing trend, and the general pages are visited as well as the project pages, therefore the intention is to keep the project website up-to-date and let it contribute to the wider awareness for sustainability aspects of PV.

The technical and scientific results obtained by ECN and partners in the Cu-PV project, for as far as successful and non-confidential, have been disseminated in presentations at conferences and workshops, and articles in conference proceedings. Many of these articles were peer-reviewed and some proceedings appeared in scientific journals. The proceedings are in nearly all cases open access on internet (sometimes, like for the EUPVSEC, with a delay of 6 months). In addition ECN has made its public contributions available on the project's website.

IMEC

The IBC cell processes developed in this project have been reported in several academic publications over the course of the project timeframe, with iterative steps as summarised above presented as they were developed. At this point, a high efficiency large area IBC cell platform has been established and stabilized, and could provide a framework to test individual processes etc. from other facilities, solar cell manufactures, to quantify their impact on the cell process. This is one of the exploitation activities that is currently being pursued. The developments at imec over the course of the project have been communicated with our partners, which include solar cell manufacturers, material and equipment suppliers, over the course of the project.

The results obtained during the project are some of the highest efficiency, and power output from a single cell, while only Trina Solar have reported higher efficiencies than those reported in this work on 156x156 mm^2 IBC-type solar cells. This points to the potential application of these technology, catered for a high-performance market (for instance, incorporating a 2% cell-to-module power loss a 60 cell module of such cells could generate over 315W).

Before industrialization of this technology, the adopted high-efficiency IBC baseline may need to be simplified, to reduce the number of high temperature steps. This could take the form of replacing the $POCl_3$ and BBr_3 diffusion steps with alternative processes to, preferably, generate one-sided doped layers of the required dopant. These tasks were not addressed in the course of the project, but should be compatible with the processes developed in this project, which when combined could enable higher efficiency, industrially viable technologies.

Xjet

Due to the solar market condition and specifically the solar equipment market conditions, the board of directors of Xjet decided to stop the activity in solar and focus the company on other applications. However, the company is willing to discuss options for application of the technologies developed for solar inkjet printing by others.

Meco

The main impact of the Cu plating processes Meco developed and further improved during the Cu-PV project are twofold:

- A large cost reduction in the metallization process of PV cells can be achieved. This can be attributed to replacement of costly Ag paste not only for the n-type cells of the project but for various cell types: e.g. p-type PERC cells and HJT cell technology. Additionally during the Cu-PV project Meco further refined its copper plating machine platform leading to maximum mechanical yield and minimum consumption of plating chemicals. A competitive machine OpEx (cost-of-ownership) is required to accelerate adoption by the PV industry.
- Copper metallization will enhance efficiency levels of most commonly existing PV cell architectures: plating allows for very fine contact fingers reducing shading losses on the optically active side of the PV cell. Furthermore in more specific PV cell types such as IBC cells copper

metallized contacts lead to generally better contact resistance values ($R_{contact}$) compared to metallization based on screen printing Ag paste. Particularly using screen printed Ag paste on p-doped areas inhibits a favorable $R_{contact}$.

During the duration of Cu-PV project Meco has sold and installed several copper plating tools (pilot as well as HVM tools) at leading PV manufacturers and PV R&D institutes, predominantly in Asia and the US.

Further potential customers are on short term PV manufacturers working on high efficiency (n-type) PV cells where plating is a compelling, and in some cases even mandatory process. On the longer term it is on Meco's commercial roadmap to further expand its installed base in PERC cells and "standard" PV cell technology involving copper metallization on the front side and an Al BSF on the rear. The most competitive results on cost per Wp saving (typically ~ 1.5 US$ct/Wp) and efficiency gain (+ 0.5 – 0.6 % abs.) are achieved in case a laser ablation process is carried out prior to plating. This process sequence also typically requires a NiSi formation step (an annealing step) to improve the Ohmic contact between the nickel layer and the underlying silicon emitter. To achieve a robust process sequence (laser – plating and annealing) further collaboration will be needed with industrial partners (e.g. laser equipment suppliers) as well as R&D institutes.

Meco generally approaches and acquires new PV customers by means of trade shows (EU PVSEC, SNEC PV Power Expo, PV Taiwan), articles and advertisements in relevant trade magazines (Photovoltaics International, PV Magazine) and by direct interactions with potential customers: initially by giving technical presentations followed by plating tests on PV cells provided by those customers. In addition trilateral cooperation between a commercial PV manufacturer, an R&D institute and Meco help accelerate adoption of copper metallization technology.

Figure 27: Meco booth at 30th EU PVSEC (Hamburg, Sept 2015)

Figure 28: Advertisement in Photovoltaics International (30th edition)

Eurotron

The project objectives and results were disseminated by Eurotron on exhibitions, presentations and in personal contact with (potential) customers. For exploitation the activities can be divided in new developed equipment, knowledge about recycling possibilities and improved understanding of CoO calculations. A short description will be given in the next paragraphs.

Several machines were developed by Eurotron in the Cu-PV project.

First, equipment for structuring backsheets with lower costs compared to etching, and possibility of recycling copper chips, has been built. It is based on mechanical milling. This machine (IBP) is ready to use in mass production, however in the meantime also other good (environmentally friendly) techniques were implemented by backsheet suppliers. Nevertheless, in the laboratory line the mechanical milling station is standard used and gives extreme flexibility in design and type of backsheet.

Also a machine with possibility to open the backsheet for interconnection of the junction box has been developed and built. This machine can be implemented in the assembly lines as part of the turnkey solution that Eurotron offers.

Finally a machine for fast and accurate placement of (thin IBC) solar cells with fine grid patterns is up and running. This machine offers advantages such as high throughput and improved accuracy. A better accuracy means smaller contact pads on the cells, thus efficiency increase and reduction of metal consumption. And as the wafer is responsible for 2/3 of the cell cost, thinner wafers result in a more efficient use of silicon and significant cost savings. Also this machine can be implemented in the assembly lines as part of the turnkey solution that Eurotron offers.

General knowledge about recycling friendly materials was gathered. New materials were processed and the machines are now able to handle the different materials. Also a lot of information about recycling processes and the needed equipment is gained.

Knowledge of the module assembly and BoM for Cu-plated cells was obtained and compatibility with copper plated cells was demonstrated. This information is valuable, because it is an evolution in solar cell processing which can accommodate cell designs of the future and enable high-efficiency devices at a reduced cost. Furthermore the interconnection and lamination process does not require any considerable amount of force to be applied and is thus compatible with thinner wafers. For the mentioned reasons we think that future clients will use these techniques.

Finally increased insight in terms of costs is gathered by the extensive Cost of Ownership calculations for several cell designs, material combinations, etc. Input was given by the different partners about several production steps as plating and physical vapor deposition. This gives a clearer view on cell production process and associated costs.

Technical Plating
It has been shown that recycling of PV modules is possible from an economic point of view. Obtaining raw material from modules at the end of their cycle of use can be a profitable venture.

One of the major problems for the profitability of a recycling business is logistics. Due to the weight to volume ratio of modules, transport trucks do not work at 100% capacity when transporting end-of-life modules, since the panels are bulky but light.

Figure 29a, b: Example of one ton of disassembled panels at Technical Plating.

Also at the moment of recovery for recycling, modules are dispersed over areas where they were installed, so collection to a centralized recycling plant from the point of origin would be a major logistical cost.

Another problem is the shortage of current modules offered for recycling. The lack of guaranteed supply prevents the creation of a large-scale recycling plant.

The equipment developed by Technical Plating is light and simple, and even allows installation on mobile platforms, so that dismantling of panels can be decentralized. The disassembly of the modules locally allows for local conversion into heavier and easier to recycle materials, such aluminium and glass, which can be sold at the place of origin. The work of incineration can then be left for a middle-large recycling plant, ideally located near a chemical plant that allows the treatment of silicon, and a silicon producer to reuse the purified silicon.

This distributed configuration may solve both above mentioned problems, allowing recycling with a scalable system that is functional for small amounts of waste modules.

PV CYCLE

PV CYCLE considers that especially the replacement of EVA by thermoplastics can help to improve the overall recycling rate of silicon based PV modules. While the tests are promising and PV CYCLE and its recycling partners strive for greater design for recyclability, the end decision is with the PV manufacturers and customers.

The used thermoplastics selected in the module technology and recycling tasks of this project need to be tested in real-life production and at large scale. It also has to be investigated to which extent the separation of the encapsulants from the back contact, back sheet foil and solar cell can be automated. In the project's tests this was done manually.

A workshop with stakeholders from the PV module as well as the recycling community, and from academia, was organised to disseminate Cu-PV results but also discuss more broadly the needs and bottlenecks in recycling. In smaller groups the question of changes and developments for (more) profitable recycling was discussed from several angles. These angles were:

- profitable treatment solutions;
- profitable materials;
- profitable yielding solutions;
- profitable process design.

The major points of discussion were:

Policies and incentives

- volume of modules for recycling is low, therefore incentives are necessary to motivate industry
- a possible incentive that was considered positively is labelling of environmental footprint of modules
- another possible incentive that looks interesting is to impose mass fractions for recycling per material, instead of one overall fraction. However, this should be done in a staged approach to allow sufficient time to reach a technology readiness.
- difficulty of treating Building Integrated PV (BIPV) will increase as long as there are no appropriate guidelines how to treat the other materials of the building compared to the PV Modules part of the BIPV-system.
- in general, it is important to avoid an overwhelming amount of regulations; preferred option having a staggered introduction of new incentives; and having attention for the practicality of monitoring.

Opportunities for improvement of business case

- Glass: the PV module glass recycling is at the moment not producing a high purity cullet, which results in an economic break-even case of recycling. There is potentially much more value in the recovered glass than currently realized, if purity of the cullet would be high and if it would be available in large quantities.
- Taken into account the value of other materials available in a module but currently not recovered, the recovery of more materials from the module than glass and aluminium alone could lead to a more positive business case.

- A replacement market might improve the volumes for recycling, and therefore the business case, but it is questionable whether the PV market is ready for the existence of a replacement market (i.e., whether PV modules would be replaced before their end-of-life if more efficient or otherwise better modules became available).
- Logistics: the shipping costs of rejected or end-of-life modules are a problem. For historical reasons, the recycling and treatment companies are often not at locations which allow low-cost bulk transport, such as harbours. Optimization of logistics is needed.
- As recycling volumes increase, it may become a problem to find markets for the separated fractions, since presently impurities are dealt with by dilution. Therefore technologies for recovery of materials in higher purity are required.

Opportunities for design for recycling

- In state of the art recycling, glass and aluminium are recovered but silver, silicon and polymer backsheet are not.
- The Cu-PV project presented some results of potential improvements in design, such as use of thermoplastic encapsulant, and framing without adhesive tape or kit. About the use of thermoplastic encapsulant it was noted that the module lifetime should not be affected.
- An alternative or complementary approach to design for recycling is to use minimal amounts of scarce or harmful materials, and simplify components (such as e.g. junction box). The rationale is that if a material is not present or there is no need to recover it, the needs for separation and reprocessing, the costs of recycling, and the environmental impact of the module, will all be reduced.
- It was agreed that design for recycling in c-Si PV modules is presently largely absent. Historically, in other industry sectors design for recycling sometimes originated from economic motivation from within the industry sector, but in other cases originated from policies. For PV it is still open how a design for recycling approach should be stimulated.

PV CYCLE coordinated the writing of a policy brief for dissemination of project results related to recycling, but also sketching the wider context of PV module recycling, and needs and possibilities for appropriate policies.

PV CYCLE plans to disseminate the results and the lessons learned from the Cu PV Project to its members. These are Producer and Importers defined by the national WEEE Laws.
The coming weeks and months PV CYCLE shall inform its members through regular meetings within its Association such as General meetings, Board meetings.

A second level of dissemination constitutes of exploiting the communication channels of the PV CYCLE Association such as the quarterly Newsletter, the monthly Update, the annual report and during presentations and lectures.

IP

Two patents on the module technology developed in the project were filed.

Video

A video introducing the project can be viewed on the project website and on youtube (https://www.youtube.com/watch?v=veTK0g2NaT8)

4.1.5. Address of project website and relevant contact details

Project website: http://www.sustainable-pv.eu/cu-pv
Contact details: info@sustainablepv.eu

ECN
Company website: http://www.ecn.nl/focus-areas/solar-energy/
Contact details: geerligs@ecn.nl

Imec
Company website: http://www.imec.be
Contact details: barry.osullivan@imec.be

Meco
Company website: http://www.besi.com/products-technology/productgroup/solar-plating/
Contact details: info.meco@besi.com

Eurotron
Company website: http://www.eurotron.nl
Contact details: bart@eurotron.nl

PV CYCLE
Company website: www.pvcycle.org
Contact details: jan.clyncke@pvcycle.org or Tel. +32/2 880 72 50