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Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK

**Bundesamt für Energie BFE**
Sektion Cleantech

**Schlussbericht** vom 22.12.2017

# Pilot production line using innovative R2R manufacturing processes for flexible and lightweight CIGS PV-Modules

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**Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.**

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# Zusammenfassung (Abstract)

In the course of this project, the results from the Flisom development line, located in Dübendorf on the Empa campus, and more than 10 years of research cooperation on national and international level get transferred into a 15 MW pilot production line to demonstrate the market readiness of commercially viable large volume (100MW plus) production plants.
Key target is to demonstrate fully industrially functionality of the pilot production plant producing IEC qualified solar modules, which are of relevant interest to the market. This will enable Flisom to enter in the commercialization phase and to generate growing revenues to become self-sustainable.
During the whole project a very close collaboration between Flisom and Empa was desired and required on regards of process development. With Empa‘s vast experience in the $Cu(In,Ga)Se_2$-technology the transfer from development to production will be accelerated to the benefit of Flisom. Further Empa’s large analytical experience and capabilities in this material family will easily help to identify areas of improvement for further progress.
For the year 2016 the goals have been to start up the equipment in the Niederhasli facility achieving required tool and process conditions which allow the transfer of the Flisom technology developed on a 50cm wide flexible polymer substrate at the development line in Dübendorf. To show the readiness of the equipment process relevant parameters have to be achieved. Beyond setting the tools to the desired conditions the ramp-up of the pilot production line has to start and first products and production relevant results will be demonstrated. The focus here is to ensure a smooth transition of the process from development to production. This means beyond pure production related parameters also improvement on the equipment and processes must be continued to ensure best results.
In the year 2017 the focus has been on ramping up production without ignoring improvement of the processes. In addition, development and manufacturing of product and gaining international certificates for this product is equally important. During the whole project work improvement of module efficiency is continuously worked on. Production capabilities of the line have shown continuous improvement over the course of the months and reliability and stability of equipment and process continuously improved. Also product development has shown very good progress with developing three different platforms, which allow to serve three market segments of high interest: building, mobility and special applications. During the project first orders have been received and a first installation of totally 30kW was realized partially on a façade and a roof. Besides commercial projects also a small installation of 2.5kW at the Flisom building was set-up to collect outdoor data and investigate the performance of the modules.
Although not all milestones have been reached as planned the project is considered successful as it helped Flisom to expedite its way into commercialization and the orders and inquiries received are prove for this success.

# Inhaltsverzeichnis

# Abkürzungsverzeichnis

| | |
|---|---|
| BC | back contact |
| BE | back end |
| CBD | chemical bath deposition |
| CdTe | Cadmium Telluride |
| CIGS | $Cu(InGa)Se_2$ |
| CW | continuous wave |
| DD | Dübendorf |
| DOE | design of experiments |
| Empa | Eidgenössische Materialprüfungsanstalt |
| ETH | Eidgenössische Technische Hochschule |
| EQE | external quantum efficiency |
| FC | front contact |
| FE | front end |
| GW | Gigawatt |
| IEC | International Electrotechnical Commission |
| IR | infrared |
| IV | current-voltage |
| MW | Megawatt |
| NH | Niederhasli |
| P1 | laser patterning line 1 |
| P2 | laser patterning line 2 |
| P3 | laser patterning line 3 |
| PV | photovoltaic |
| R2R | roll-to-roll |
| Se | Selenium |
| TCO | transparent conductive oxide |
| Voc | open circuit voltage |

| | |
|---|---|
| W | Watt |
| WP | work package |
| XRF | X-ray Fluorescence |
| ZnO | Zinc Oxide |

# Ausgangslage/ Initial Position

Flisom AG is a Swiss spin-off company from ETH founded in 2005. The company develop and still continues to improve a novel production method for high efficiency flexible thin film CIGS solar modules. The technology is based on a technology transfer from Empa, who holds a world record of 20.4% efficiency for these flexible CIGS solar cells.

The business approach of Flisom is to develop and own proprietary equipment and production knowhow for large scale roll-to-roll factories producing flexible high efficiency GIGS PV products. Based on this knowhow and technology PV modules will be manufactured and commercialized on the global PV marketplace. According to the current planning, first income from technology sales will be generated from 2018 onwards.

In 2015, Flisom has taken into operation a 4500 m$^2$ industrial technology up-scaling facility in Niederhasli (ZH). The total investment for this was of approximately CHF 20 million in equipment and infrastructure. The planned nominal annual production capacity of this facility is of 15 MWp, or approx. 100’000 m$^2$/year.

Manufacturing of solar photovoltaic modules in the world is dominated by silicon wafer technology with more than 90% share of production shipment. High volume production of such modules by mainly Chinese companies have brought down the module production cost and propelled global deployment.

On the other hand, thin film photovoltaic technologies offer distinctive advantages associated with large area high throughput coatings and laser patterning for monolithic interconnections, leading to low manufacturing cost and lower energy payback time. First Solar and Solar Frontier have already succeeded in achieving >GW yearly production capacities with CdTe and CIGS thin film solar modules on

**Figure 1: Examples of metal roof tops in Switzerland ready for Flisom solar modules**

glass substrates. Further cost reduction in manufacturing of solar modules and completely installed systems could be achieved with more innovative manufacturing technologies for high performance thin films solar modules.

R2R manufacturing of high efficiency and stable flexible and lightweight thin film solar modules opens new directions for reaching to low cost energy efficient systems and new applications. Developments of advanced manufacturing technologies, which can bring down the solar electricity cost by increasing module efficiency and decreasing material and process costs are of great importance. Innovative photovoltaic technologies for achieving these requirements are being developed here in Switzerland at Flisom and Empa research lab.

Flisom has installed a pilot-production plant for R2R manufacturing of cost effective high performance lightweight flexible CIGS solar modules. This pilot production line will serve as a blue-print for multiplication to larger production capacity plants. Flisom`s disruptive technology of lightweight and flexible solar modules of different types for building roofs, facades and many more applications, like mobility opens new paradigms and allow to use solar in a way it has never been used before.

As there is no supplier for manufacturing plants with proven process and equipment for flexible CIGS modules Flisom is working to capture this unique opportunity for a hugely untapped market. The flexible solar modules offer various application and cost advantages, which open additional markets that cannot be served by traditional PV technologies.

Within this project, Flisom will start, ramp-up and optimize the pilot production plant for demonstrating a novel disruptive photovoltaic technology for industrial usage, serving as a base for large production factories at a later stage. The commercialisation of the flexible, light-weight CIGS technology can only proceed, if the achieved results in R&D, innovative equipment, process and solar module development, can be demonstrated on a pilot production scale. This up-scaling phase is challenging for a technology venture like Flisom on various levels:

- Development of innovative equipment for larger substrate size
- Process transfer from development to pilot production line
- Process development aligned to new and large equipment for industrial pilot production
- Investments of multiple million CHF for innovative equipment
- Hiring and training of new employees
- Expansion into a new location with 4500 m2 and large utility spending

Setting up a new and highly innovative pilot production of a new technology inherits larger financial investments at a high level of risk. Within this project Flisom has received financial support to set up and start a worldwide unique technology facility for lightweight flexible solar modules. The basics of technology have been developed initially at ETH Zürich and then championed at Empa with world record efficiencies cells. Flisom has systematically developed innovative equipment and processes for industrialization.

Now Flisom is facing the final challenges to successfully transfer the research excellence in solar production solutions exemplifying unique Swiss high tech solutions in clean tech sector. Over the years, Flisom has made remarkable progress on development of innovative manufacturing tools and processes and with this project the final push is given to demonstrate the functionality of pilot-production plant and show success in commercialisation of Flisom products.

# Ziel des Projekts/ Project Goals

Within this project, the results from the Flisom development line and 10 years of national and international research cooperation get translated into a 15 MW pilot production line to demonstrate the market readiness of commercially viable large volume (> 100MW) production plants. This 15 MW pilot production line for processing substrate of 1 meter width is designed as a fully functional demonstrator for a large industrial production plant: For a low cost production at least a 100 MW capacity plant it is required to benefit from scalability and supply of low cost materials and components. The pilot production line will be a blue-print for such a large capacity plant allowing detailed analysis of processing parameters and validation of cost assumptions based on key parameters of the business plan during production. However, overcoming of some key technological challenges related to machines and processes are of paramount importance.

Key target is to demonstrate fully industrially relevant functionality of 15 MW pilot production plant producing IEC qualified solar modules. This will enable Flisom to enter the commercialization phase. Further, the right choices of low-cost material, superior production processes and innovative module architecture enable the Flisom CIGS production technology to be competitive with silicon solar modules on a global level. This production plant will demonstrate that a commodity like solar modules can be produced in Switzerland for global markets.

To achieve the key target the following goals and objectives have to be achieved, which in parts requires a close collaboration with Empa as well:

Goal 1: The pilot production plant demonstrates feasibility as an operational production line with IEC certified solar modules and a continuous improvement program.

1. Optimize tools and equipment for robust production as per technical milestones for achieving industrially relevant reliable processing of high efficiency modules.
2. Establish and optimize production process for 76% line yield and 700 kW monthly output.
3. Achieve 15% cell efficiency with CIGS deposition tool on 1 m web width.
4. Reach production readiness for a certified CIGS solar modules with 12% module efficiency.

Goal 2: Process speed enhancement of CIGS deposition and laser patterning process to achieve needed throughput for 15 MW capacity.

1. Improvement of CIGS deposition machine and processes to achieve 30 cm / min web speed
2. Improvement of laser patterning process and tool to achieve >30 cm / min web speed for processing of high quality scribes with small dead area loss (<350 micro meters)
3. Adapt the world record efficiency cell processing of Empa's research lab on industrial machines and collaborate for device processing cross-checks and improvements, and in-depth detailed characterization of layers, interfaces and devices.

Goal 3: The economic feasibility of the pilot production plant as an operational demonstrator for subsequent larger scale industrial production plants of 100 MW to GW capacities is assessed.

1. Running the pilot production line to demonstrate the industrial like production possibility
2. Real time production relevant parameter acquisition for estimation of throughput and yield for assessing the limitations and potentials.
3. Detailed analysis of production parameters and costs for CAPEX and OPEX optimization validating business model assumptions for larger capacity (100MW – 1GW) plants.

# Grundlagen – Randbedingungen/ Background – Boundary Conditions

In the years before the project started Flisom AG developed a proprietary CIGS thin-film solar technology in Dübendorf on a development line in close partnership with the thin film laboratory of Empa (Swiss Federal Laboratories for Materials Science and Technology). Empa is Flisom's close research

**Figure 2 1kW Outdoor Installation in Dübendorf**

partner and achieved 20.4% world record thin-film solar cell efficiency and >16% monolithically connected sub-module efficiency on flexible plastic foil. Flisom converts the innovative research excellence of Empa into an industrial production environment and with the aspiration to manufacture and sell lightweight and flexible CIGS PV modules for different applications worldwide.

In 2015 Flisom has finished the installation of a pilot production line in the city of Niederhasli, ZH. This line was set-up to demonstrate industrial manufacturing of lightweight and flexible CIGS thin film PV modules. Coating of the photovoltaic films is done using roll-to-roll coating tools based on processes using a polymer substrate of 1m width. In addition to the pilot production Flisom was already operating a development line for all manufacturing processes in Dübendorf at the Empa campus. This line was continuously used for experimental purpose to further develop the technology and the solar modules and laid the basis for each development work in the new pilot production line. In this line the substrate width is 50cm, which is a good start for the ramp-up of the new pilot production line. In Dübendorf all process steps are performed and small size prototypes of module are manufactured to gain experience and do reliability testing. Also a small installation of about 1kW on the roof was set-up to start collecting outdoor data (see Figure 2).

At start of project all the equipment was installed and operational. The production line has to main areas, the front end and the back end. In Figure 3 the different process steps of the production line are shown. It is clear that all the coating process steps are done in the Frontend whilst the Backend is reserved for the module manufacturing and quality controls. The equipment as installed in 2015 was operational. However, some of the tools required adjustments to make them suitable for optimum process conditions. In case of the CIGS co-evaporation equipment the uniformity of the evaporation sources had to be improved using simulations to test new designs. Further the scribe recognition of the laser patterning tool needed modification to work reliable and fast enough for different CIGS compositions at the required scribing speed. Mechanical changes made to the CBD equipment, which is coating the buffer layer, were needed to achieve the required coating uniformity of the layer.

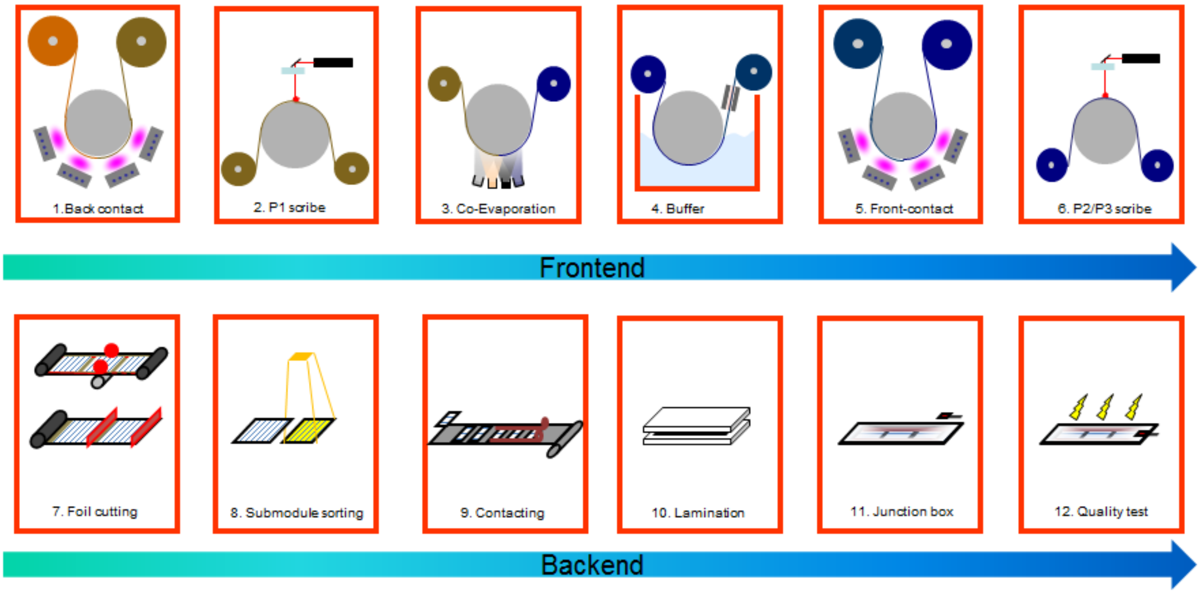



**Figure 3 Process flow of Flisom production line**

Besides improving the equipment the individual coating processes had to be transferred from the Dübendorf to the Niederhasli equipment to define a starting process on which further optimization could start. Transfer the deposition and module manufacturing processes was one of the main challenges of the project. After successful completion on this task the equally demanding work of optimizing the individual production processes to an overall process delivering good quality semiconductor coatings on the substrate and stable, lightweight and flexible PV modules. At the same time improvement of the production performance indicators is required to show industrial style mass production.

This project is understood as an accelerator on the way to commercialization of Flisom, therefore the focus is not only on production parameters but also on product development and hence IEC certification of product as prove of a minimum quality standard. To pass the well-known IEC certification special care is required to choose suitable encapsulation material. Further, extensive in-house tests must be done prior to turn in modules for the official certification. Failure of the certification process will lead to huge costs, which has to be avoided.

# Vorgehen – Methode/ Approach

The project is divided in four phases, which follow each other. At the beginning all tools and equipments haven been acceptance tested by Flisom engineers with the different equipment suppliers. All externally purchased equipment was installed as per Flisom`s specification and tested on proper mechanical, electrical and process function. With a function test the acceptance is officially reviewed and confirmed. All purchased equipment are then ready to run substrate without damaging the substrates. This was be the starting point of the project.

**Phase 1: Individual production tool qualification and process transfer**
Functions, software and machine settings of the tools were studied by the responsible engineers. They identified basic equipment settings and operation to get the tools started in basic process windows. Therefore the technical specifications for 0.5m web width from the development line in Dübendorf have been implemented on the pilot production line tools.

**Phase 2: Overall line integration: Integrated process and tool optimization to manufacture 1 m web width solar module**
After successful qualification of the individual tools, the next tasks required tuning the individual tools into a common production flow of 1m web width. Started substrate have been processed in the individual tools with variation of the process windows. In between the production steps, the substrate was characterized with internal measurement tools and external device analysis by Empa thin film laboratory. For these tests substrate rolls of up to several hundred of meters of length have been processed. The pilot production line is based on same technology as the development line, but the tools are modified to larger dimensions and in requirements for high material throughput. The different geometries of the lager equipment required adjustment of process parameters and settings.

**Phase 3: Stabilization of production process**
The target of this phase was the stabilization of the test runs and to reach uniform product performance on 1 m web width. Therefore it was necessary to execute matrix experiments with interacting process steps. For this purpose process parameters of individual process steps have been varied as it is known that a parameter change at one process will affect the result of another process step. This way adjustments of process parameters for optimized process stability was done. Furthermore a standard for the first generation of test module has been defined.

**Phase 4: Pilot test runs**
Target of this phase was the execution of pilot production runs on the line. Production related data for evaluation and analysis of efficiency, throughput, reproducibility and yield have been gathered in several pilot test runs of the overall line. Furthermore the pilot production line has been characterized, monitored and optimized under real production conditions.

During optimizing process parameters and with ongoing R&D support from development line and innovation from Empa the need of some upgrades or redesigns of the CIGS and other tools has been identified and implemented.

**Work Packages**
Seven WP have been defined to cover individual tasks of the four phases and to ease the overview of the tasks to be worked on. Individual WP have been defined for very sensitive tools and processes. All WP are linked together and finalize in WP7 Test Production. The structure also indicates nicely how work on different production steps can influence previous and the subsequent production steps. The WP structure is shown in Figure 4.

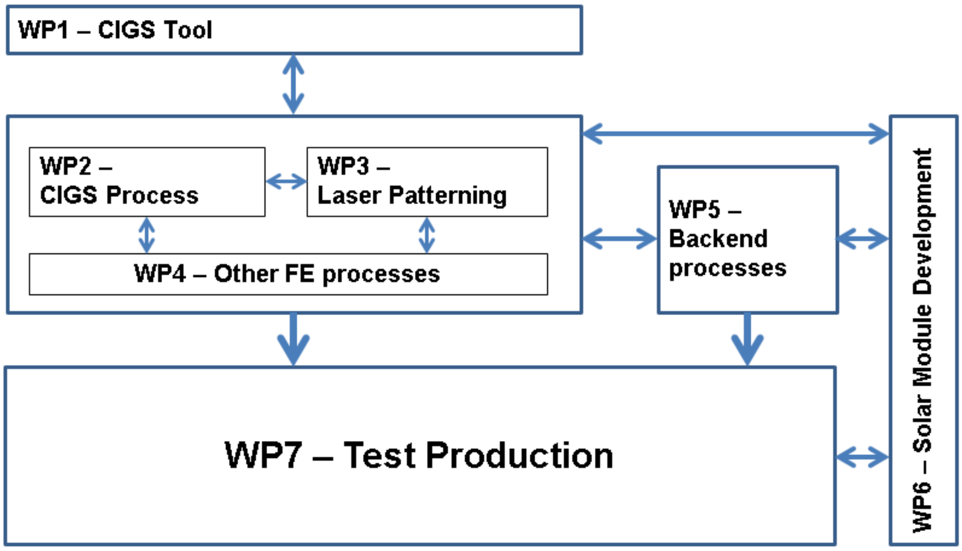



**Figure 4 Interconnection of work packages**

For each WP a responsible person – the WP leader - has been assigned to ensure the progress towards meeting the defined milestones. A list of milestones for the individual WPs has been compiled as well as the timeline defining the duration of the four phases and individual tasks of the WPs. The defined milestones are given in the table below.

**Table 1 Defined milestones per WP**

| Milestones | | | | |
|---|---|---|---|---|
| | **End Q2 2016** | **End Q4 2016** | **End Q2 2017** | **End Q4 2017** |
| **WP1: CIGS tool development** | process speed of 5cm/min;<br><br>base pressure of 10-6mbar | metal evaporation sources ready for uniform coating (±10%) over 1m web width | wrinkle free winding and unwinding with process speed of 20cm/min at 300-400°C | wrinkle free winding and unwinding with process speed of 30cm/min at 300-400°C |
| **WP2: CIGS process** | process transfer for minimum cell efficiency 10% | | process transfer for minimum cell efficiency 14% | |
| **WP3: Laser patterning process** | patterning at web speed of 5cm/min over 1 m width | scribing accuracy of ±40um over one meter web width;<br><br>patterning at web speed of 15cm/min | Dead area total scribe distance <350um | patterning at web speed of > 30cm/min |

| Milestones | | | | | |
|---|---|---|---|---|---|
| | | **End Q2 2016** | **End Q4 2016** | **End Q2 2017** | **End Q4 2017** |
| **WP4: Frontend processes** | | Back contact: sheet resistance 16mΩ square and thickness uniformity ±10% over 1 m web width;<br><br>Buffer: Uniform coating (±10%);<br><br>Front contact: Sheet resistance of 10-12 W square and light transmission of 80-85% | | Optimized processes of buffer layer, front contact and back contacts for compatibility with high speed deposited CIGS (key features: minimal stress, delamination-free, minimal defects check with EL and Thermography) | |
| **WP5: Backend processes** | | Bubble free laminate, demo up to 3 m2 | Fully integrated module with all electrical connections | | |
| **WP6: Solar module development** | | | Internal qualification for IEC certification standards | 1-3 $m^2$ solar module ready for IEC certification | IEC certification for 1-3 $m^2$ solar module with minimum 12% module efficiency |
| **WP7: Pilot test runs** | **Line Yield** | ---- | 55% | 67% | 76% |
| | **Started area** | | 27551 | 42325 | 46084 |
| | **Laminated area** | | 14457 | 27167 | 34200 |
| | **Module Eff** | | 9-10% | 10.7 - 11.2% | 11.6 - 12.2% |
| | **demonstrated kW** | | 1298 | 3017 | 4117 |

**Table 2 Overall project timeline**

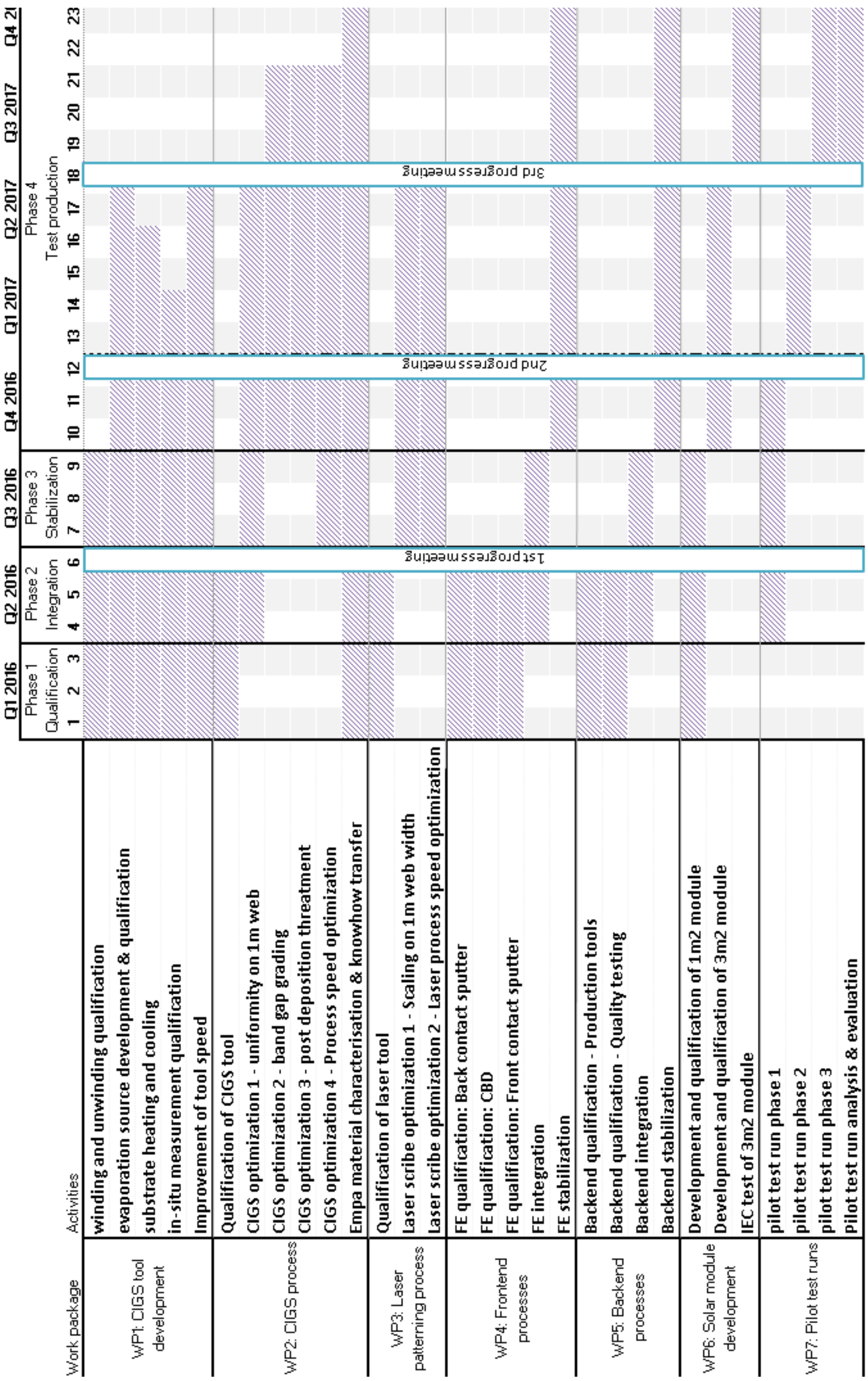



Table 2 represents the time line in form of a Gant Chart. It is clearly shown that in all WPs tasks are worked on almost from the beginning until the end of the project. Even WP1, which covers all the required development and improvement work of the CIGS tool is not finished before three quarters of the project term. On the other hand pilot test runs already start after one quarter into the project. Each WP has different tasks which need to be worked on to achieve the final goals and most of them can be worked at in parallel. The project plan nicely illustrates this time optimized way of working.

In the timeline is already reflected that qualification of the individual FE processes (WP 4) can be done fast and thereafter only variations to optimize the overall process are required. Further not a lot of development and improvement work is expected at the tools. In WP1 however it is clearly stated that the CIGS tool will need intensive improvement as this equipment is a first of its kind and the only one worldwide. As the CIGS layer (WP2) in the solar cell structure gives live to the solar modules development and optimization of this process requires a lot of attention and is also most crucial regarding efficiency and stability of the solar modules. Further, to show scalability of the technology for large scale production the throughput of the process must achieve a certain number. This however may affect the quality of the layers therefore increasing process speed without loss of efficiency requires constant attention. In WP3 the laser tool has to be qualified, scaled to 1m wide web and the speed has to be optimized to achieve the required throughput. Although the laser process is defined by Flisom the tool requires more attention as the scale-up step in this case is quite large. In the Dübendorf development line only a lab set-up allowing scribing of max.12x36cm mini-modules was available. Now the scribing of P1, P2, and P3 was extended to 90x86cm.

WP5 and WP6 cover development of larger scale PV modules, which also requires external IEC certification. To be able to manufacture PV modules the BE line was qualified and the individual process steps have been matched to each other. Development of modules required testing of many different materials at each process step. This way the team became familiar operating the tools and is developing product at the same time.

All the work done in WP1 to WP6 focused on running the whole production line at each process step. It was not only about operating the tools and manufacturing modules. Also critical production parameters are tracked and have been improved throughout the different pilot production phases. To improve operational parameters detailed analysis of what is limiting progress was done on a regular basis and appropriate action was planned and executed to improve the numbers over time.

Progress of the project was reported to the BFE on a semi-annual basis in meetings and reports presenting the progress towards the milestones defined in Table 1.

# Ergebnisse/ Results

An official inauguration in 2015 marked the end of the installation of all the production tools needed to industrially produce lightweight and flexible PV panels based on the proprietary CIGS-technology using the R2R technology developed by Flisom in cooperation with ETH and Empa during the last ten years. All the production equipment is designed to operate with a flexible polymer substrate of a width of 1m.

This project started in December 2015 at a status when the tools have been fully operational however, still needing improvements and adjustment to reach the goals lined out for the project. As described in the previous section the project is structured into seven WP, each covering a certain area of the overall production process and they are closely linked together. Individual work packages have been defined for very sensitive tools and processes. The general way of working towards the defined milestones follows four phases:

a. Qualification of individual production tool and transfer process from development line to the new tool.

b. Overall line integration: process and tool optimization to manufacture working solar modules on a 1m wide Polymer web.

c. Stabilization of overall production process.

d. Execute pilot production test runs.

During first phase the tasks of the WP are independent from each other, however in the following phase the interaction between the different work packages starts as the process conditions and substrate quality of each tool influences the performance and quality of the subsequent or even later processes.

Table 3 gives an overview of the achievements towards the milestones. Detailed discussion of the results and findings of the individual WPs will be found in the relevant sections.

**Table 3 Overview of achievements towards milestones**

| | Q2/2016 | Q4/2016 | Q2/2017 | Q4/2017 |
|---|---|---|---|---|
| **WP1: CIGS tool development** | | | | |
| **Milestones** | process speed of 5cm/min; | metal evaporation sources ready for uniform coating (±10%) over 1m web width | wrinkle free winding and unwinding with process speed of 20cm/min at 300-400°C | wrinkle free winding and unwinding with process speed of 30cm/min at 300-400°C |
| **Status** | Achieved<br>30 cm/min | Achieved<br>± 7% | Achieved<br>30 cm/min | Achieved<br>30 cm/min |
| **Milestones** | base pressure of 10-6mbar | | | |
| **Status** | Achieved<br>Pressure is reached in 10h | | | |

| | Q2/2016 | Q4/2016 | Q2/2017 | Q4/2017 |
|---|---|---|---|---|
| **WP2: CIGS process** | | | | |
| **Milestones** | process transfer for minimum cell efficiency 10% | | process transfer for minimum cell efficiency 14% | |
| **Status** | Achieved 14.7% | | Achieved 16.5% | |
| **WP3: Laser patterning process** | | | | |
| **Milestones** | patterning at web speed of 5cm/min over 1 m width | scribing accuracy of ±40µm over one meter web width | Dead area total scribe distance <350um | patterning at web speed of > 30cm/min |
| **Status** | Achieved Overall speed 14.5cm/min | Achieved ± 15 µm | Achieved Avg. 333 µm | Achieved Speed >40cm/min tested |
| **Milestones** | | patterning at web speed of 15cm/min | | |
| **Status** | | Achieved Overall speed 15.3cm/min | | |
| **WP4: Frontend processes** | | | | |
| **Milestones** | Back contact: sheet resistance 600mΩ square and thickness uniformity ±10% over 1 m web width | | Optimized processes of buffer layer, front contact and back contacts for compatibility with high speed deposited CIGS | |
| **Status** | Achieved 600mΩ at ±5% | | Achieved Submodules at 13% eff | |
| **Milestones** | Buffer: Uniform coating (±10%) | | | |
| **Status** | Achieved ±10% | | | |
| **Milestones** | Front contact: Sheet resistance of 10-12 Ω square and light transmission of 80-85% | | | |
| **Status** | Achieved 8 Ω square at >80% trans. | | | |
| **WP5: Backend processes** | | | | |
| **Milestones** | Bubble free laminate, demo up to 3 m2 | Fully integrated module with all | | |

| | Q2/2016 | Q4/2016 | Q2/2017 | Q4/2017 |
|---|---|---|---|---|
| | | electrical connections | | |
| **Status** | Achieved | Achieved<br>Gen1 8x1 module manufactured | | |
| **WP6: Solar module development** | | | | |
| **Milestones** | | Internal qualification for IEC certification standards | 1-3 $m^2$ solar module ready for IEC certification | IEC certification for 1-3 $m^2$ solar module with minimum 12% module efficiency |
| **Status** | | Achieved<br>Gen1 8x1 module is IEC certified | Achieved<br>Gen2 4x1 is ready for certification | Achieved<br>Gen2 4x1 has passed all tests successfully |
| **WP7: Pilot test runs** | | | | |
| **Milestones** | Line yield: | 55% | 67% | 76% |
| **Status** | | Not Achieved<br>about 30% | Not Achieved<br>about 30% | Not Achieved<br>about 40% |
| **Milestones** | Started area: | 27551 | 42325 | 46084 |
| **Status** | | Achieved<br>32’062 $m^2$ started | Not Achieved<br>About 20’000 $m^2$ | Not Achieved<br>About 38’600 $m^2$ |
| **Milestones** | Laminated area: | 14457 | 27167 | 34200 |
| **Status** | | Not Achieved<br>about 3’000 $m^2$ laminated | Not Achieved<br>about 5’000 $m^2$ laminated | Not Achieved<br>about 17’000 $m^2$ laminated |
| **Milestones** | Module efficiency: | 9-10% | 10.7 - 11.2% | 11.6 - 12.2% |
| **Status** | | Achieved<br>Range 9 to 11% | Achieved<br>Range 10.5 to 11.5% | Achieved<br>Range 11.5 to 12.4% |
| **Milestones** | Manufactured kW: | 1298 | 3017 | 4117 |
| **Status** | | Not Achieved<br>about 20 kW | Not Achieved<br>about 53 kW | Not Achieved<br>about 520 kW |

## WP1: CIGS Deposition Tool Development

With the CIGS co-evaporation tool Flisom has entered in the area of machine building, as this equipment is completely designed and set-up in-house. This includes a vacuum system, the control software, the design of the web transportation system, the in-situ measurement of evaporation rates, and the design of the evaporation sources.

To achieve good process conditions the evacuated tool must reach a defined base pressure. After installation and assembly of the tool the first task is to apply vacuum, identify leaks and seal them. Despite the large dimension of this tool even small vacuum leaks needed to be localized and sealed. There are multiple reasons for small vacuum leaks, starting from small scratches on sealing surfaces to cable feedthroughs guiding electrical connections from the air to the vacuum side.

Vacuum technology offers standard leak testing methods which have been used to detect all leaks. Once the leak is identified it will be sealed by appropriate measures depending on the origin of the leak. Having fixed all leaks the base pressure of $10^{-6}$ mbar can be reached within a few hours of pumping time. As the deposition tool has a large dimension evacuation is not completely uniform and pressure differences can be seen throughout the vessel. Important is to reach the required vacuum regime in time before the process can be started. Detailed of the pumping characteristic can be seen in Figure 5. This achievement was a very important first step on the way to operate the equipment successfully and allowing for good efficiencies. This result also reached a milestone of WP1.

A very important process parameter for each coating process is the deposition speed as this defined the capacity of the tool. The plan for the NH production line is based on a deposition speed of 30cm/min. Developing the process for the final deposition speed can be done approaching the target value in multiple steps optimizing process and material each time. However, if the substrate transport system and the evaporation sources are able to work at the target speed it is most efficient to aim for the highest speed and optimize the process from the beginning. During commissioning of the tool after some satisfying test it was decided to start process optimization with the maximum deposition speed of 30cm/min. Plan B was to work with slower deposition speeds if the desired results on CIGS coating and substrate quality cannot be achieved.

At the start of process development no reference process was established in the NH line. Therefore the quality of the coatings was compared to the films deposited in the DD development line. For the process it is important to achieve a certain thickness and composition of the CIGS layer. The composition has to follow defined coating profiles to achieve the desired grading of the band gap in the final absorber semi-conductor. These parameters are measured in-situ and ex-situ with XRF. The ex-situ measurement allows for space-resolved two dimensional mapping of the thickness and composition of

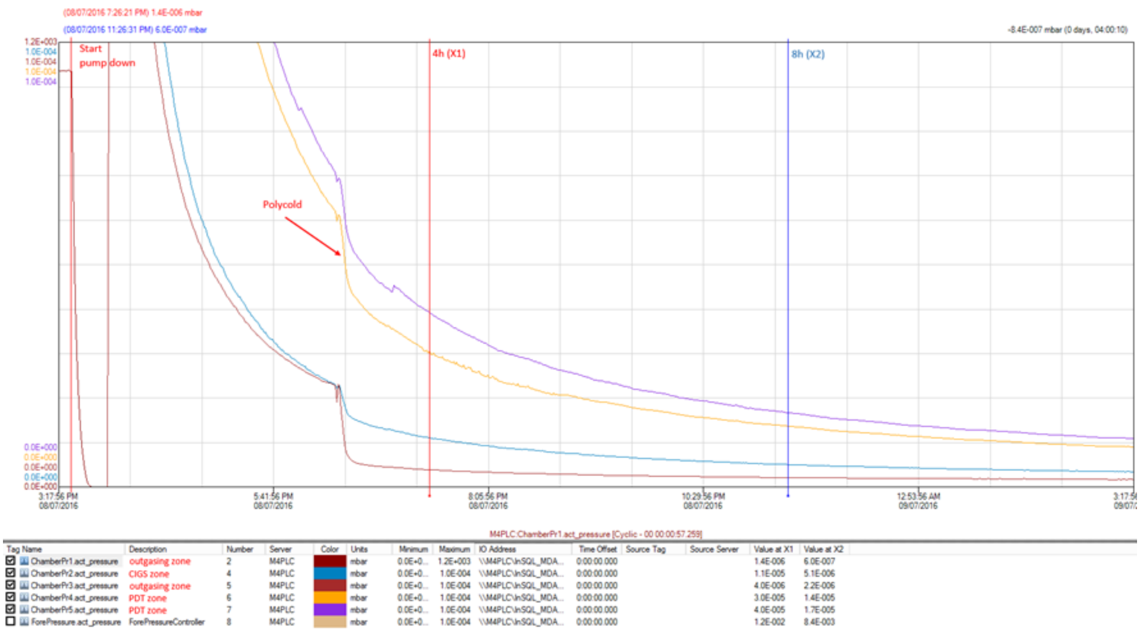



**Figure 5 Pump down characteristic of CIGS evaporation tool**

the whole substrate roll. The in-situ measurement consists of four positions in the chamber at different positions in the deposition are. Each position is equipped with 2 detectors to have some lateral resolution. With this set-up it is possible to measure the composition and the thickness of the absorber at different stages of the process, which is required to influence the efficiency of the solar modules.

To adjust thickness and composition the evaporation rate of individual evaporation sources has to be adjusted, which is done increasing or decreasing the temperature of the source. The challenge for this milestone was to reach the evaporation rate at each source which will result in the desired absorber thickness of approx. 2µm at the deposition speed of 30cm/min. In parallel the transport system has to move the substrate foil continuously without interruptions being exposed to the heat of the sources and the material coatings, which will accumulate not only on the substrate but also on the transport system and protective cover sheets. To achieve the desired results, multiple runs have been done increasing the evaporation rates from run to run to test the evaporation sources and to reach the desired thickness without any equipment failures.

Successful operation of the tool at the deposition speed of 30cm/min was achieved very early in the project and thus this major milestone of WP1 was reached. With this deposition rate small solar cells have been manufactured with efficiencies according to the plan. Details thereof can be found in section WP2 CIGS Process.

Evaporation sources have to fulfil three purposes during the process. First the evaporation rate has to be high enough to grow the desired material thickness on the substrate at a given substrate speed de-

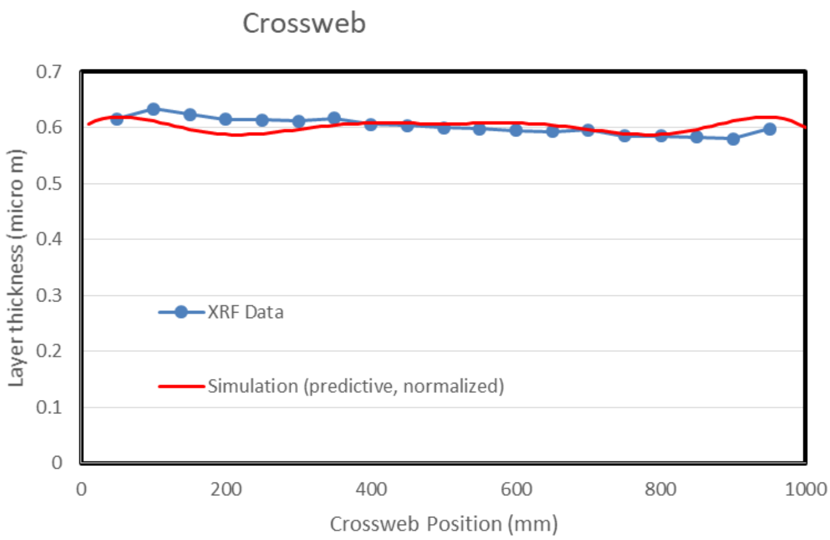



**Figure 6 Generation 10 source initial test, homogeneity of +-3%**

fining the deposition speed. This is done controlling the heating power. Second the homogeneity of the evaporation rate has to be very uniform from one side to the other to ensure the material quality over the whole width of the web. And third long term stability is required to ensure continuous operation for several days. These three items have been addressed and improved in multiple generations of design.

The way of working follows a straight process. First a new design is drafted. The new concept of the evaporation source is then used to simulate the expected deposition characteristics. One of important milestones in WP1 is a thickness uniformity of at least ± 10% over 1m substrate width. Simulation of the evaporation characteristic of the sources allow to evaluate a new design before money and time is spend on manufacturing parts for a new source. If the simulation shows the desired results the source will be manufactured and tested. For testing sources a specific test chamber has been designed allowing to characterize the evaporation rates and uniformity of one source at a time. The milestone of ± 10% has been well reached with a uniformity of ± 3% at the end of the first year and the results can be seen in Figure 6. The uniformity of the evaporation sources can also be seen nicely looking at the composition data of the CIGS absorber across the substrate width. These numbers are measured on each coated roll to control the process and ensure experimental rolls show the desired composition profile. The very good result of the composition uniformity, which is achieved at the fast speed of 30cm/min is displayed in Figure 7. The section in the red rectangular is the relevant section for the process. The areas outside are related to ramp-up and ramp-down of the evaporation sources.

Improving the quality of the evaporation sources required multiple generations, which have been manufactured and tested. The major changes in the evaporation sources have been the heating and evaporation nozzles to ensure uniform and stable evaporation rates without clogging of the sources. As the level of the evaporation material changes substantially over a long deposition run it is important that

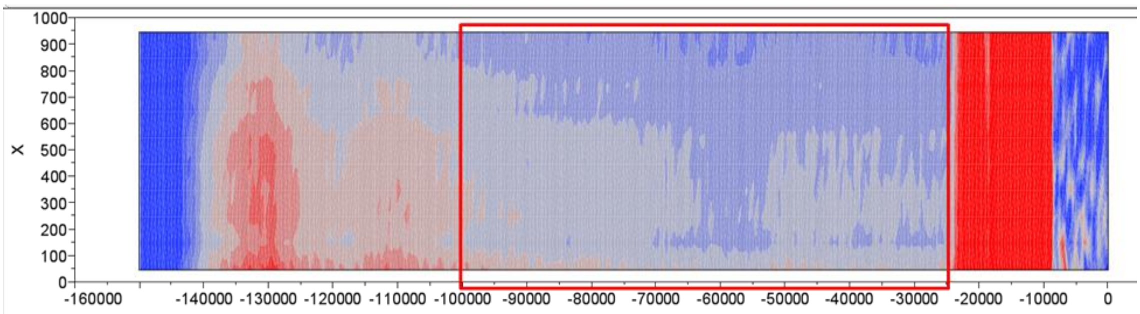



**Figure 7 2D measurement of metal ratio uniformity of substrate**

the evaporation rate stays constant and the uniformity does not change. These challenges have been successfully solved.

In addition to the deposition rate and uniformity of the coating the transport system of the tool is of major importance. This part of the tool moves the substrate at the correct speed without causing and mechanical damage at fairly high substrate temperatures. Wrinkles in the substrate have been a major issue in the evaporation tool of the DD line and therefore much attention has be put on the design for the equipment in the pilot production line. Wrinkles lead to damage in the semiconductors and cause sever shunting or non-functional solar modules. In both cases the modules are waste and reduce production capacity and yield. Much care was taken to investigate reasons for damage, change and improve design of the transport system to a status where the substrate runs flat through the evaporation tool thus not causing any wrinkles on the roll. To reach this status multiple modification on the transport and clamping of the substrate haven been required. Several generations of transport clamps have been designed, manufacture and tested until the edge quality was as desired. Also protective shields in the transport section have been installed to allow for reliable movement of the substrate even after many hours of continuous operation.

Besides flatness of the substrate and deposition speed the length of the roll is also important for the transport system as reliable transport has to be ensured for many continuous hours. The longer the roll the less time is lost interrupting the process and changing rolls. At the beginning of the project the length of a roll was only about 250 to 300m. This length was extended to about 650m quickly. For whole 2017 this has been the standard length to operate the line. The capabilities of the transport system are of this kind that besides operating wrinkle free also the edge accuracy (telescoping) is about ±0.2mm. An example of bad telescoping is shown in Figure 8. It is obvious that substrate wound in this way is not usable in the next production tool, therefore such a behavior needs to be avoided.

It must be noted that out of each roll approx. 100m in total are so called design scrap, which is due to ramp-up and ramp-down of the process and equipment. A sudden start of the process is not possible as the evaporation sources have to heat up and stabilize before the process will produce usable PV film. Also the sources have to cool down after the process to stop the evaporation process. This loss is taken fully in the yield calculation and will improve once the length of a roll will be extended.

Reporting of the results in this chapter show all milestones defined in Table 1 have been achieved during the project period of two years.

**Figure 8 Example for bad telescoping**

## WP2: CIGS Process

With the CIGS co-evaporation equipment operational the development of the CIGS process and consequently the integration of all deposition processes started. The solar module efficiency is mainly influenced by the quality of the CIGS absorber layer. Flisom has long standing experience in optimizing CIGS absorbers in its DD development line. Also the very close collaboration with Empa's Laboratory of Thin Films and Photovoltaics is of significant importance for this work package. Process development started based on initial settings for each coating tool determined during the activities in WP3 and WP4, which started in parallel to the work on WP1 and WP2. Close interaction with Empa on regards on material characterization, exchange of samples and scientific discussion completed the development activities. Even with all the combined material knowledge and experience of Flisom and Empa, development work in this area is still quite iterative and improvements require multiple experiments at one tool with subsequent optimization at other process steps. In addition to the experiments and measuring the direct impact on cell efficiency also extensive material characterization is needed to understand were differences between absorbers of Flisom and Empa are. Empa is very well equipped with analytical tools for this kind of material analysis and because the team also knows the materials very well themselves they are the ideal partner to support Flisom in this task.

After qualification of individual coating tools as described in WP3 and WP4 the next step was manufacturing first rolls with all the layers coated in NH. At this time working with sub-modules was less important as first IV results on small cells are giving a good indication of the material quality. For these tests also the coating uniformity was not critical as small samples of some square centimetres have been used. The process speed used from the beginning was set to 30cm/min. With the experience of the Flisom team and the good support of Empa very soon first results significantly above 10% have been reached. Intensive experimental and analytical work led to a cell efficiency of 14.6% after approx. 5 months into the project indicating successful transfer of the deposition technology from DD to the production line of NH.

In Figure 9 the relevant IV curve is shown. Also shown is the EQE of a Flisom cell in comparison to an Empa cell used as reference. The comparison clearly shows that there are still differences in the material band gap, however the overall quality of the EQE is already comparable. With this comparison the experts of Empa and Flisom are able to identify the differences between the materials and which parameter need to be adjusted. In this particular case the bandgap of the NH cell is still lower than the

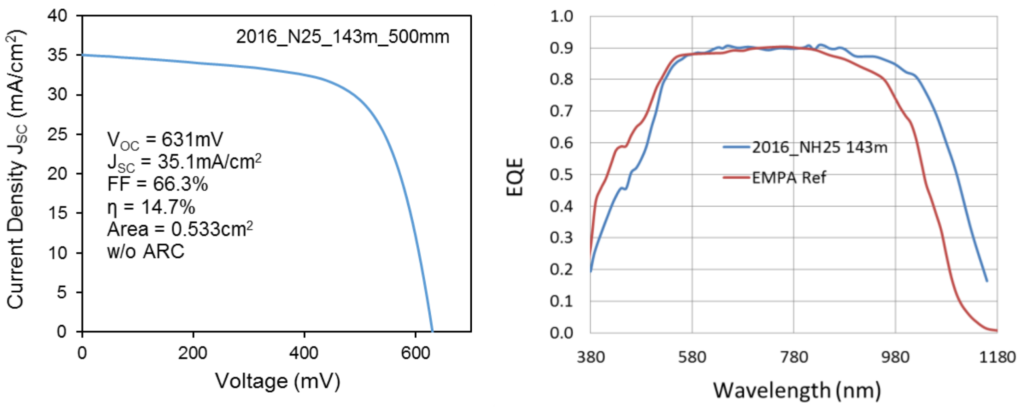



**Figure 9 IV measurement of solar cell and comparison of external quantum efficiency**

one from Empa and requires adjustment through the settings of the In and Ga ratio during the CIGS evaporation.

To achieve these results many experiments have been executed adjusting the temperature settings of the individual evaporation sources to form the desired band-gap grading in the absorber material. In-situ process control with the XRF is used to control composition on the substrate at different times through the deposition process. It must be noted that an important process parameter is the Se pressure as the amount also affects the evaporation rate of the other sources. This means the Se pressure needs tight control to allow for reproducible processing. In addition to the XRF composition measure-

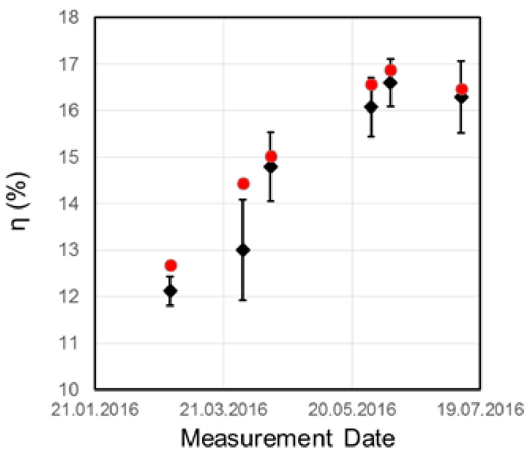



**Figure 10 Progress of efficiency development on cell level**

ments further analytics to characterize the layer quality has been done. For example absorber layers from Flisom have been processed at Empa to deposit the buffer and TCO layer. This way the quality of the absorber was analysed based on known buffer and TCO layer. This way also the influence and quality of the buffer and TCO layer from the NH line was compared with the known Empa layers and adjusted to match these characteristics. Another important analytical tool during this period was the electron microscope, which allows to compare the crystallinity of the absorbers from different processes and the Empa with each other. Although only microscopic areas are investigated the optical impression of the surface and cross section will give a good indication if there are fundamental differences how the layers grow during the process.

To drive the efficiency to levels comparable to the results achieved in DD development line many runs to optimize the settings of the different evaporation sources and also the substrate temperature were needed and have been done. As pointed out earlier the reliability of the tool was not very good at the beginning, therefore many runs had to be aborted due to equipment failures and needed to be repeated.

Continuous operation of the tool and improved understanding of the process setting eventually lead to a reliable process and baseline. In the second half of 2016 a solid baseline at an efficiency on cell level of around 16% has been established as it is shown in Figure 10.

With the demonstrated results of process development the technology transfer from DD to NH was successfully accomplished and all WP2 milestones have been achieved. The basis for reliable manufacturing of modules was set this way.

## WP3: Laser Patterning Process

Laser patterning is a very important process in module manufacturing. This process allows the monolithical interconnection (i.e. interconnection on the substrate) of solar cells to form sub-modules. This is an important advantage of the Flisom technology as there is no need to cut out individual cells and string them together. The monolithical interconnection is done with a proprietary laser process developed by Flisom. Details of the patterning, also called scribing, are given in Figure 11. It is nicely shown that with three scribe lines a series connection of a number of cells will be realized defining the Voc of a submodule.

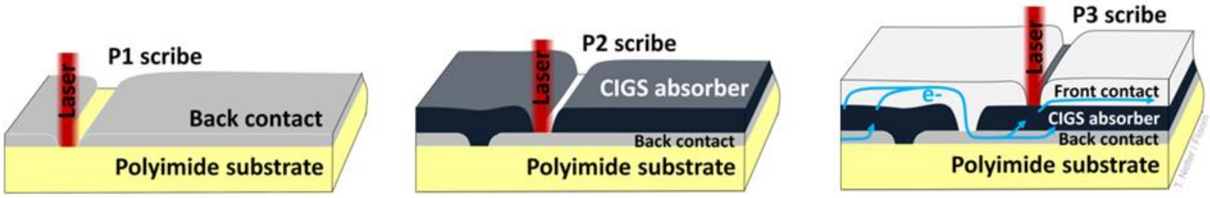



**Figure 11 Scribing sequence for Laser Patterning process**

The important parameters which define this process are the parallelism of scribe lines and the scribing speed. The scribing speed is affected by both, process settings for a given material mix and ease of recognition of the P1 line by the image processing unit. The direction of scribe lines is perpendicular to the transport direction of the substrate, meaning they run cross-web. To achieve very high parallelism of the P2 and P3 line along 1m width of the flexible substrate registration of the P1 line for alignment is required as often as possible. Limitations by computation hardware currently only allow registration every 5 to 10 cm.

The setting of the substrate illumination as delivered by the manufacturer was from the front, which did not allow for fast and reliable recognition of the P1 line in many cases. Low contrast between the P1 line and the surrounding material made it very difficult for the image processing system to reliably identify the P1 line. As the surface morphology of the modules was changing strongly between individual coating runs the optical situation was always different and the P1 recognition proved to be difficult and sometimes not possible at all. This situation was limiting the throughput of the tool and causing erroneous scribe lines. To improve this situation eventually a modification of the illumination was required. The light source was transferred to the back switching from visible to IR light as the CIGS absorber is transparent for IR light. As the Molybdenum back contact is removed at the P1 line the IR light is shining through at these positions creating a strong contrast to the dark surroundings. This improvement made the scribe recognition system more tolerable to changes in the material composition resulting in a much improved processing speed.

In addition to the P1 recognition also parameters and settings of the transport system needed to be updated for faster processing. In a first step the processing speed of around 15cm/min was achieved as presented in the first progress report in Q2/2016. Further the process speed was maximized by experimenting the laser parameters like pulse energy, pulse frequency, and peak power the find the fastest possible process, which sill delivers good patterning lines.

To avoid dead area on the module positioning of individual scribe lines needs to be as precise as possible as well as the overall scribing width – distance between P1 outer border to P3 outer border – has to be as small as possible. The goal for both parameters in this WP are ±40 µm for positioning accuracy and <350 µm of scribing width.

The distribution of P1-P1 variation shown in Figure 12 is taken from more than 300'000 measurements and indicates a very tight distribution in the range between +3 and -18 µm. In total >99.99% of all measurements lay within the tolerance of ±40 µm showing the very high precision of the laser tool. The high precision of the tool is also found in the overall scribing width. The width is measured between the most outer P1 line and the most outer P3 line. The definition of scribe width is shown in Figure 13. This measurement is not taken automatically therefore manual analysis was done to evaluate the scribe width on several locations over one production roll. The measured results are shown in Table 4. Precise measurement on the width is quite difficult therefore there is a certain variability in the number. However, it is clearly seen that besides some outliers above 350µm distance the average measurement is well below the targeted value, a clear indication of the good quality of the tool and the

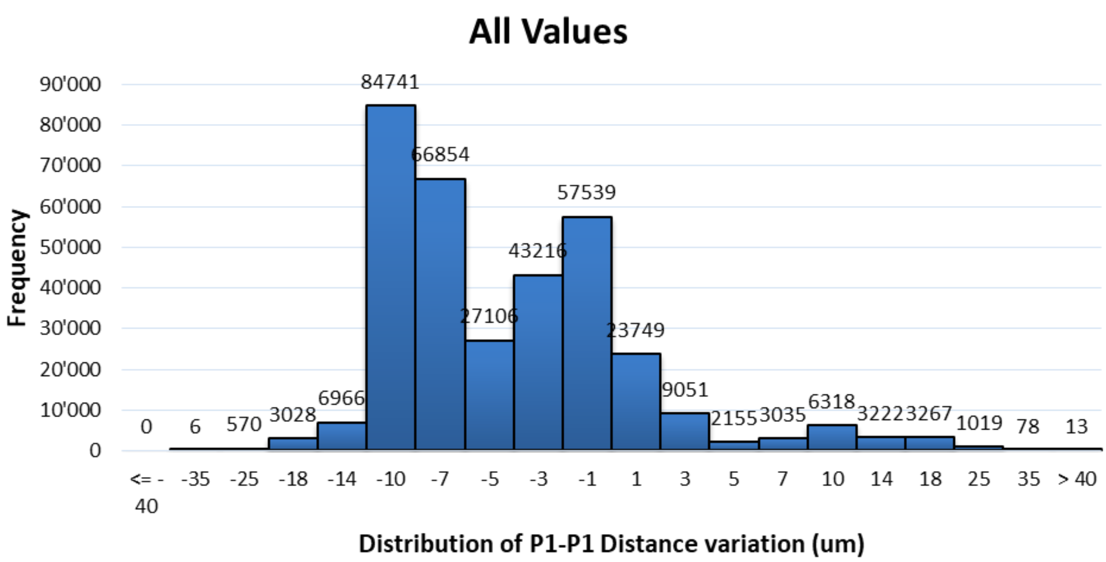



**Figure 12 Distribution of P1-P1 distance variation**

defined laser process.

**Table 4 Measured distance on different locations on one roll**

| | P1-P2 | P2-P3 | P1-P3 |
|---|---|---|---|
| | 143 | 171 | 314 |
| | 160 | 205 | 365 |
| | 165 | 205 | 371 |
| | **154** | 171 | 325 |
| | **148** | 165 | 314 |
| | 171 | 165 | 336 |
| | 131 | 154 | 285 |
| | 160 | 160 | 319 |
| | 143 | 205 | 348 |
| | 148 | 217 | 365 |
| **AVG** | **151** | **181** | **333** |

The goal of this WP was to improve the process speed to 30cm/min for all three scribing processes together. A lot of adjustment of the testing of different process settings has happened and the speed of 30cm/min is possible. To achieve this process speed different settings of the laser have been tested on different substrate rolls. Besides pulse energy, peak power also the operational mode has been

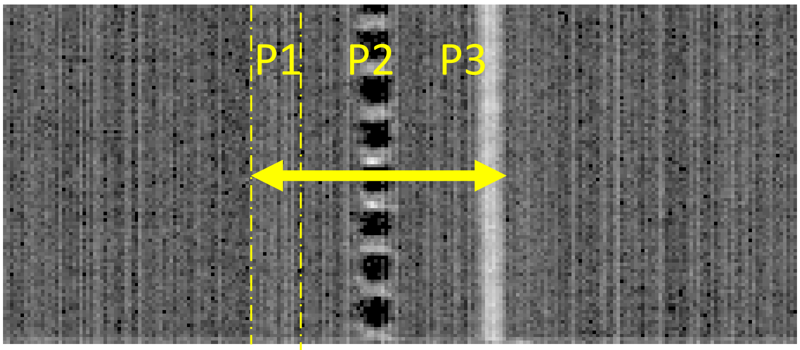



**Figure 13 Definition of scribe width**

switched from pulsed at different frequencies and CW operations. However, unfortunately all tests did not lead a repeatable process suitable for production. At the end the decision was taken to work with the best settings which are usable for production without sacrificing quality and reliability of the process. With these process settings an overall process speed of 22.15 cm/min has been achieved. This is about 32% more than the first milestone speed. Details of this calculation are given in Table 5.

There are possibilities how the gap between 22 and 30 cm/min can be closed and for a large scale production these solutions will be considered according to what makes most economic sense. One possibility would be stronger lasers, which will allow to increase the speed, however this may have some effect on the process. The easiest solution however will be multiplication of the tool and designate a tool to a specific process. This will reduce the cost per tool as only one type of laser will be installed. Another reason for the slower speed can be found in the current submodule design. If this would be larger the processing time can be reduced as well. However, this is not planned for the time being.

In case of this project the laser tool was chosen with the knowledge that there might be limitations on throughput, but the financial situation did not allow for a second tool, which clearly would have given the chosen capacity and beyond. It is important to say that the choice of tool and manufacturer is clearly the correct one as all other important specifications are fulfilled and the support is very good.

**Table 5 Final laser process parameters**

| Process | Process Speed (cm/min) | Overall Tool Speed (cm/min) |
|---|---|---|
| P1 | 48 | 22.15 |
| P2/P3 | 44 | |
| PT | 630 | |

## WP4: Frontend Processes

To manufacture the solar modules there are three further deposition processes: back contact where the Molybdenum back contact is deposited by sputtering directly on the polymer web substrate, CBD where a thin, 30 to 50nm thick, buffer layer is deposited on top of the CIGS using a chemical bath deposition process which is modified to work on a R2R application, and front contact where the ZnO front contact is deposited as final layer on top of the stack. In all three cases the equipment was chosen from experienced suppliers and no real issues on the functionality have been expected. The main work was to develop and optimize process parameters in combination with the CIGS process to achieve the highest possible cell and module efficiency. It turned out that in case of the CBD equipment certain adjustments to the mechanical set-up were required to meet the specified uniformity. During process development it was recognized that the flow of the chemical solution was quite non-uniform across the substrate, which resulted in film uniformity outside the desired specification. To overcome this equipment deficit the infeed of the solution was modified several times to get a uniform flow of the solutions over the whole substrate width. Each change of infeed resulted in several experimental runs to test the changes in film uniformity and reproduce the same. Also the transport system was improved several times to make sure the substrate is transported through the tool without causing damage to the substrate or even rupture it. To achieve this improvement the side guides of the transport had to be modified and thus tested. As a process normally lasts for a few days long term stability was quite important.

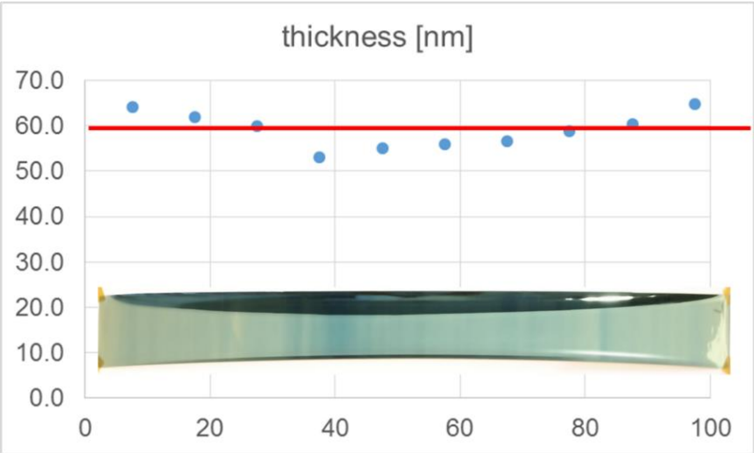



**Figure 14 Thickness uniformity of CBD deposition**

Changing the solutions flow and some optimization in the transport system fixed this issue and uniformities in the range of ±10% are achieved as expected and aimed for (see Figure 14). For this process the thickness is less critical therefore a lax target of ±10% can be accepted without further improvement. The optimization of the transport system not only improved the uniformity but also solved some mechanical issues causing bubbles and wrinkles on the substrate. The bubbles and wrinkles are responsible for damage to the substrate.

In case of the front- and back-contact the sputtering equipment is working as expected. Minor adjustments to uniformity were possible. To improve the uniformity experiment changing the distribution of the sputter gas along the rotary cathodes have been done. This is a common practice at large area sputtering. This is a very empirical approach. The gas distribution will be changed locally at the targets adjusting the gas flow at the flow meters and afterwards the thickness and sheet resistance of the back or front electrode on the substrate will be measured. If needed multiple experiments will be done to reach the desired uniformity. The achieved results in a first round of optimization have all been within the milestone targets. The sheet resistance of Mo-layer is around 600mΩ□ with a uniformity of ±10% as it can be seen in Figure 15. In the case of Mo the most important parameter is the sheet re-

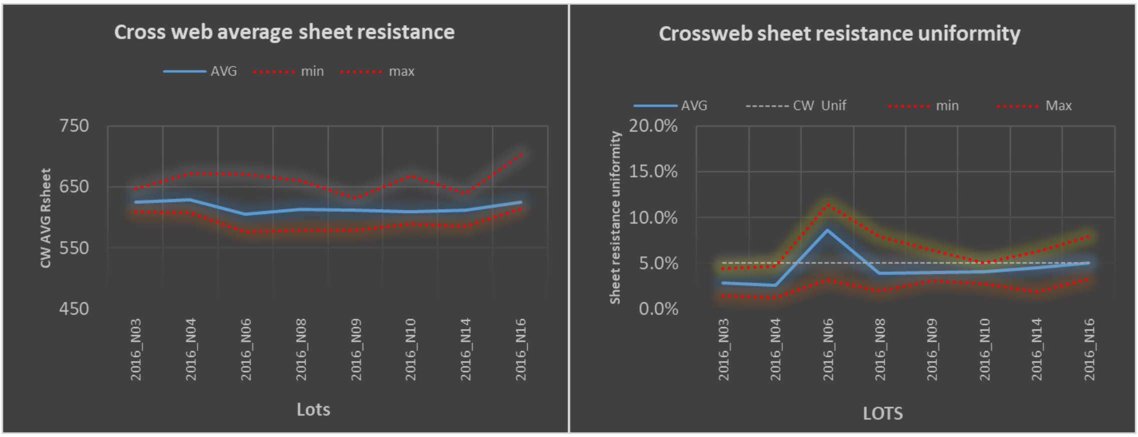



**Figure 15 Deposition characteristic of back contact process according**

sistance and not the thickness.

In the case of the front contact it was found that the sheet resistance of the TCO-layer is depending of

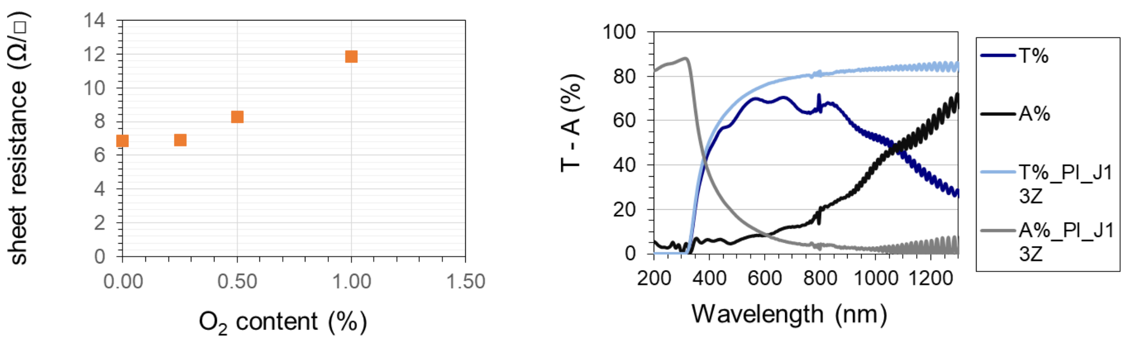
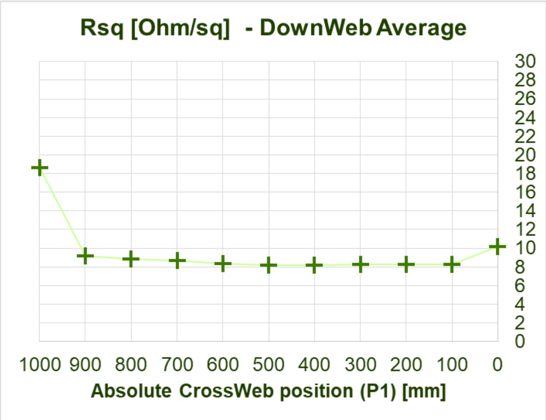



**Figure 16 Effect of $O_2$ ratio in sputter gas to sheet resistance and relative transmission of ZnO**

the $O_2$ content in the sputter gas and can vary in the range from 7 to 12 Ω□. The relative light transmission of the TCO layer has been measured >80% as shown in Figure 16. The goal is to have a sheet resistance as low as possible in combination with a transmission as high as possible so the process setting was chosen accordingly. The process optimization of the TCO was more laborious as more parameters affect the quality of the layer. The $O_2$ content in the sputter gas influences the layer properties as well as the substrate temperature, which has a strong influence on the sheet resistance. Also pressure of the sputter gas adjusted in the process chamber has influence on the transmission and sheet resistance. Therefore multiple experiments have been done optimizing the individual settings of the process parameters. As more than one factor are of importance and the correlation of these have to be investigated using DOEs helped to achieve results much faster than only testing individual changes of the different parameters.

The uniformity of the front contact was achieved as targeted, which is shown in Figure 17. The data points at the position 0 and 1000mm can be ignored as these reflect the physical edge of the substrate and will not be used for any module manufacturing at all. Like in the case of the back contact the adjustment of the uniformity was done by varying the gas flow at the cathodes to achieve laterally slightly different deposition rates leading to improved or worse uniformity. Also in this case multiple experiments coating TCO on the plain substrate have been required. At the end the results are very good and uniformity of the TCO is not indicating to cause any problems for large area modules.



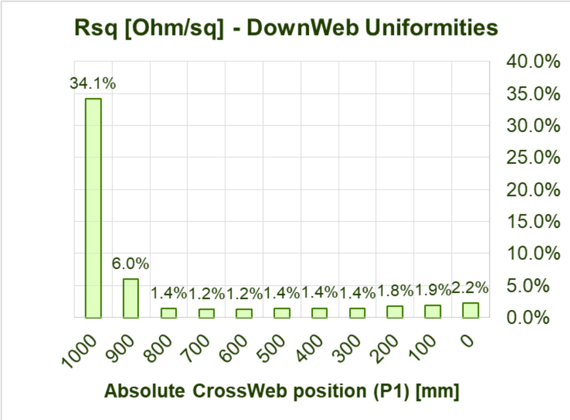




**Figure 17 Sheet resistance and uniformity of front contact**

According to the milestone plan all initial requirements of WP4 have been fulfilled thus a successful deposition of all the layers of the pilot production will be possible. In the following months experiments have been done optimizing process parameters at the different deposition steps to achieve best efficiency results of the modules manufactured in the line. From the beginning all the FE processes have been optimized for maximum deposition speed of 30cm/min. With this basis the integration work started and first trials have been done processing substrate rolls through the whole production line. During the different experiments process parameters of the CIGS process have been adjusted to achieve higher efficiencies on finished cells or modules. In succession also process parameters of the other processes have been adapted. Especially the sputter pressure of the back contact was adjusted many times as this parameters strongly affects the stress within the back contact layer. For best results the back-contact may not any cracks. This can be achieved by choosing the sputter pressure and thus reduce the stress in the layer.

Further also the TCO process was optimized for higher efficiencies varying also the deposition conditions. As the quality of the TCO is not only depending on the sputter pressure but also on the substrate temperature variation of this parameter have been done using substrate already coated with CIGS. In comparison with the tests done on bare substrates at the same process setting the temperature of the absorber with CIGS coating will be different, which has an effect on the performance of the modules. This means fine adjustment of the process always requires experiments with all the coatings on the substrate followed by measuring the efficiency and thus finding the most optimum process settings for each process.

The major influence on module efficiency was found to be adjusting the process settings of the CIGS equipment. In the first half of 2017 the line was operating with a process giving approx. 10% efficiency modules. Unfortunately this process was not reliable. As mentioned earlier the reliability of the CIGS tool was not very good at the beginning. The stability of the evaporation rate of the sources was changing from run to run as well as during the run. This shortcoming was fixed in many iterations by making changes to the evaporation sources to increase the process stability.

Table 6

*Before*

| | Sample | Voc | Jsc | FF | Eff. | Rp | Rs |
|---|---|---|---|---|---|---|---|
| N65B | Empa Reference Thick | 0.627 | 33.8 | 69.0 | 14.6 | 1817 | 1.2 |
| | Empa Reference Thin | 0.618 | 33.0 | 62.3 | 12.7 | 632 | 1.1 |
| | Empa Recipe / NH Ingredients | 0.612 | 33.0 | 67.7 | 13.7 | 1275 | 1.1 |
| | NH Recipe / NH Ingredients | 0.645 | 29.0 | 59.3 | 11.1 | 301 | 1.1 |

*After*

| | Sample | Voc | Jsc | FF | Eff. | Rp | Rs |
|---|---|---|---|---|---|---|---|
| N61 | Empa Ref Thick CdS | 0.631 | 30.3 | 61.9 | 11.8 | 376 | 1.1 |
| | Empa Ref Thin CdS | 0.636 | 33.3 | 68.2 | 14.5 | 857 | 1.0 |
| | NH 50cm/min | 0.629 | 33.9 | 70.2 | 15.0 | 987 | 1.0 |
| | NH 40cm/min | 0.635 | 33.6 | 69.3 | 14.8 | 909 | 1.3 |
| | NH 50cm/min & 10% less flow | 0.633 | 34.4 | 72.1 | 15.7 | 1772 | 0.9 |
| | NH 40cm/min & 10% less flow | 0.630 | 35.4 | 71.3 | 15.9 | 1387 | 0.9 |
| | NH 40cm/min & 10% less flow after TCO | 0.612 | 31.1 | 71.6 | 13.6 | 1266 | 0.9 |
| | NH 50cm/min & 10% less flow after TCO | 0.608 | 30.9 | 70.9 | 13.3 | 1794 | 0.8 |

However, reproducibility can also be affected by other steps. After thorough investigations and different test it was found that the CBD process was done in a different way as the Empa process. As this was the only clear hint of a difference the process was changed to match the Empa process and the results were very encouraging. Since this adaption the reproducibility of the process was very much improved and also the efficiency per module was raised to about 11%. In Table 6 it is demonstrated how the effect of the ingredients was excluded and only the recipe was identified as the source of difference (red circle). It is also shown, that the process speed and flow of solution has no significant effect on the results (green circle). These improvement on the CBD process resulted in a much more reliable production and reproducibility in efficiency as is shown in Figure 18.

With these results the successful production of larger numbers of modules became possible and the

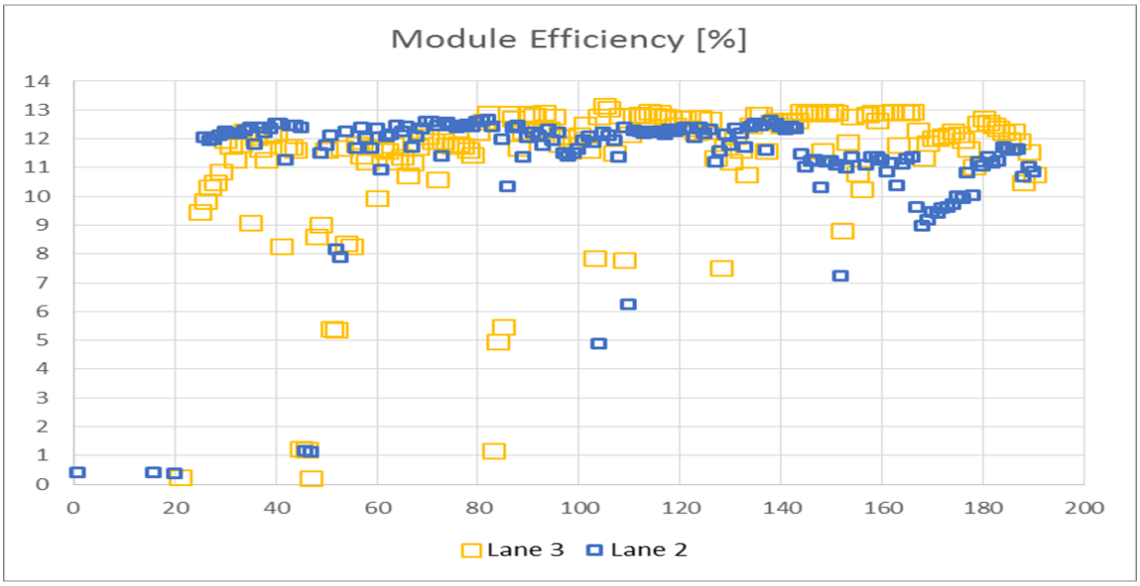



**Figure 18 Efficiency reproducibility of modules along the position of one roll of 200m length**

number of modules manufactured was rising. This progress will be described in the section WP7. Given the presented achievements it is clear that the milestones of this WP have been reached and allowed to progress towards a regular industrial production.

## WP5: Backend Process

Backend is the area where all the rolls coated with all the active PV layers will be cut into submodules. Then the submodules will be used to manufacture encapsulated PV modules. These modules may contain one or more submodules. The equipment installed in the backend cuts submodules of different sizes from processed rolls, strings them together and does the lamination to form a module. Further the flasher for final electrical qualification of the modules is situated in this area. During the first year of the project all the equipment was successfully commissioned and tested for the different working steps. All backend equipment is dimensioned to handle modules up of 1x3m$^2$ size (see **Figure 19**). During testing the line was stressed with dummy submodules and modules of different sizes and encapsulation materials. This way confidence was built that the equipment is working well and having a product platforms based on different encapsulation materials is no general issue. The backend tools and processes work easily with different materials on different sizes.

**Figure 19 1x3m module laminated**

The milestones of the WP include laminating a 3m$^2$ module and manufacturing of fully functional modules with all electrical connections on the Niederhasli backend line. At the beginning of the project no PV foil was available to produce working modules. Therefore, all activities at this time have been done

**Figure 20 Two different types of modules of 3m length and 1m module shown front and back with junction box**

using dummy material. However in the second half of 2016 PV material from the Dübendorf line was used to test the processes also with working submodules to see if there is any detrimental damage caused by the equipment. The modules shown in **Figure 20** are all working as they have been manufactured with submodules from the Dübendorf line. The roll width of the Dübendorf line is only 50 cm so the width of the module is limited as the submodule size is limited to about 37cm. The edges of the roll need to be cut off for uniformity reasons.

To define the different processes in the back end experiments with different parameter settings at the different tools have been done. In particular the lamination and lane cutting process required optimisation.

In case of the laminator the temperature of the heating plate, the evacuation time, the pressure pressing the laminate and the pressing time had to be adjusted in multiple iterations to achieve modules without any wrinkles and folds showing a uniform appearance on the front. Besides the equipment parameters also different tests with structured mats have been done to choose a pattern, which leads to a slightly matt finish of the surface. This way reflections are avoided and the whole appearance of the module is very agreeable.

More detailed tests of the backend equipment was consequently done during the phase of product development, which is part of WP6. In this case also reliability studies are done to ensure the longevity and reliability of the modules.

# WP6: Solar Module Development

The focus of this work packages is on development of PV modules which will pass all reliability and stability relevant criteria. This required extensive testing of different encapsulation materials as well as understanding potential degradation effects, which may not only be related to the encapsulation but also to the semiconductor layers as well. The common standards of the industry for thin film modules are IEC 61646 and IEC 61730. Flisom owns most of the equipment which is required to do in-house IEC testing. In other cases testing was be done at relevant institutions to ensure proper execution.

During this WP Flisom not only worked on testing suitable encapsulation materials but also did some market research to get a better understanding what are the requirements of the customer. These findings strongly influenced the product development work. At the end of the project three product platforms have been developed, whose key characteristics are described in
Table 7. For the semi-flexible and flexible modules the choice of encapsulation materials is with focus on long durability of the modules to withstand environmental impact and to generate power reliably for more than 25 years. The rollable module follows the same principle of encapsulation. However, for this product the mechanical flexibility and lightness is more important, therefore the choice of material is different to allow for different mechanical properties.

All three platforms can easily by manufactured in one width of approx. 42cm and in four different lengths (0.8m, 1.5m, 2.3m, and 3.0m) determined by the number of submodules included in each module. The width of 42cm allows for submodules of 80 cells which deliver a total Voc of around 50V suitable for most off-grid applications as well as in grid connected installations. In case the standard sizes will not work for a customer Flisom is also able to offer customized solutions to enable PV in different applications.

**Table 7 Description of three product platforms**

| Product Type | | Key Characteristic |
|---|---|---|
| Semi-flexible |  | Thin metal back sheet, which provides structural support for semi-flexible character |
| Flexible |  | Uses plastic back sheet for flexible character |

| | | |
|---|---|---|
| Rollable |  | Uses light plastic sheet encapsulation for rolla-ble character. |

All platforms follow the same principle of encapsulation as shown in Figure 21. The lamination foil which will go between the front sheet and the solar film and likewise between the solar film and the back sheet is missing in the figure for clarity.

Another result of the market research and contact with many potential customers in the last few months allows Flisom to refine the market segments in which Flisom's products will have a benefit above the standard rigid and heavy solar technology using Si wafers or thin films coated on glass. As a result, Flisom is now focusing in three market segments to provide solutions for energy needs:

a. **Buildings and Infrastructure** - the largest market segment
b. **Transportation** - where Flisom will offer solutions for passenger and commercial vehicles and has started working with a premium car manufacturer to evaluate the challenges and possibilities for integrating solar panels on car roofs
c. **Special solutions and custom applications**. In this segment Flisom has successfully worked on different projects which require lightweight and flexible modules. For example, Flisom has de-signed a custom module for the largest Swiss Gondola company, to be integrated in rope way gondolas to power battery for safety devices. In a second project, Flisom has developed an ex-tremely light-weight module to be used in high-altitude air ships. A result of this development is a

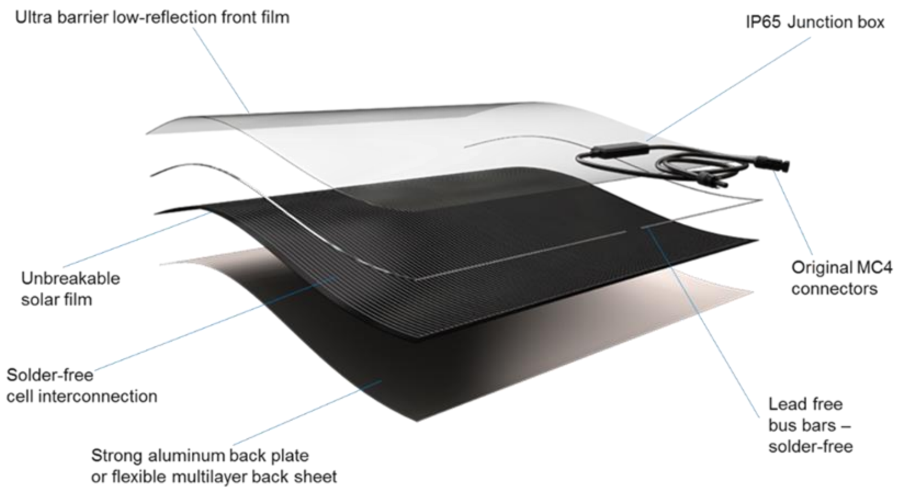



**Figure 21 Exploded view of Flisom modules without encapsulant**

module with a weight of less than 200g/m2 and a power density of approx. 780W/kg was designed. A larger quantity of these modules are now being manufactured for installation on a high altitude airship and drone.

TÜV InterCert SAAR

CERTIFICATE

*Certificate No.* 16-PPV-0000006/01-TIC

WE HEREBY CERTIFY THAT THE PHOTOVOLTAIC MODULES WITH THE MODEL

**Flisom / SF Series**
(Tested Types)
And with Types extended for similarity*
- See Annex –

| LICENSE HOLDER: | | MANUFACTURER: |
|---|---|---|
| Flisom AG<br>Überlandstrasse 129,<br>8600 Dübendorf, Switzerland | & | Flisom AG<br>Gewerbestrasse 16<br>8155 Niederhasli, Switzerland |

IS IN COMPLIANCE WITH THE REQUIREMENTS OF

IEC 61646 : 2008
Thin-film terrestrial photovoltaic (PV) modules. Design qualification and type approval
&
EN 61730-2:2007**
(Photovoltaic (PV) module safety qualification)
To be used in plants at a total voltage up to : 1000 Vdc (application Class A)

AS RESULT OF THE TEST IN OUR APPOINTED LABORATORY
EA ACCREDITED LABORATORY N. 0192

REPORT No. TIC- PVQ01 17116-160023 & TIC- PVS201 17116-160023
&
THE MANUFACTURING INSPECTION ON THE DATE 10th JUNE 2016 WITH
REPORT No. RFI-0616-PPV-TIC-0000006-16

*Expiring date* 01.07.2021
(Providing that the testing basis continues unchanged)

DAkkS Deutsche Akkreditierungsstelle D-ZE-16012-01-00

Bonn, 02.07.2016

Ing. K. Lindenblatt
TÜV InterCert Certification Body

TÜV InterCert GmbH - Group of TÜV Saarland - Am Bonner Bogen 1 - 53227 Bonn GERMANY
www.tuv-intercert.org

CERTIFICATE • CERTIFICATO • ZERTIFIKAT • SERTIFIKA • CERTIFICADO • شهادة • ΠΙΣΤΟΠΟΙΗΤ

**Figure 22 IEC Certificate for first module type**

Results of environmental testing with the first encapsulation platform were very encouraging therefore an official IEC certification was started at TÜV InterCert. The module with 0.4 x 1.0m size, Al back-sheet and 33W power was fully IEC certified by mid-2016. This result proves that the chosen materials and processes for encapsulation are of the right kind and ensure good protection and stability of the PV modules. In-house DH test have been done more than three times the IEC requirements also showing good stability (see Figure 23).PV modules.

IEC certification of 3m eMetal and eFlex was started in summer 2017 and all critical tests have been passed successfully. The plan was to have the testing sequence finished before end of 2017. However there have been some delays, but generally the tests have all been passed successfully. These status is acknowledged in the declarations shown in Figure 24. To receive the certificate a factory inspection has to take place as well and then certificate will be issued some weeks thereafter.

With the results reached the milestones of WP6 have been achieved. The size of these large modules is about 1.2m$^2$, which according to our market research is sufficient for the customers. The length is limited by the lamination tool and the width giving 80cells is fine for most product requirements.

Data sheets for all module platforms can be found on the Flisom website under https://flisom.com/products/.

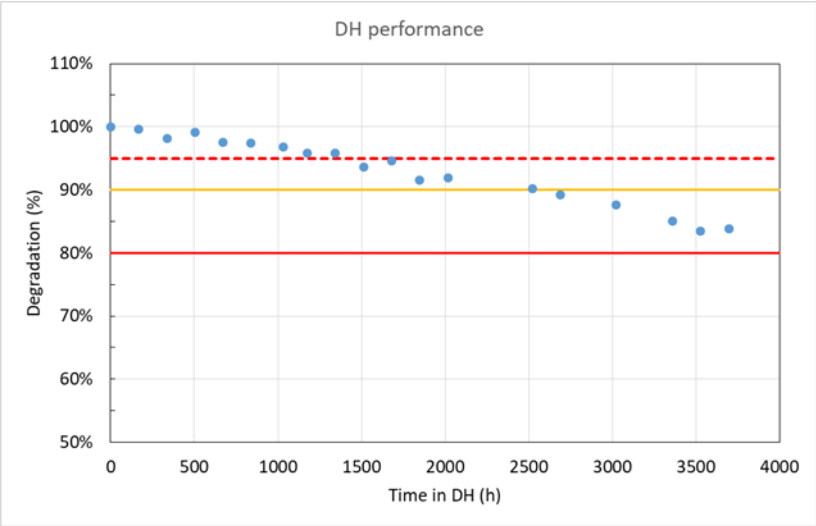



**Figure 23 Long term degradation of modules in DH**

Eurotest Laboratori

DECLARATION

EuroTest Laboratori S.r.l.
via Marconi, 23 – 35020 Brugine (PD) – Italy

Subject: PV conformity tests of 3m modules (e-metal and e-flex) from Flisom

It is declared that 3m modules of Flisom are under testing as per CEI EN 61646 and CEI EN 61730-1/2 standards and per related IEC standards.
All the tests are successfully completed except for sequence of 50 Thermal Cycles+10 Humidity Freeze Cycles and similar tests for e-flex modules which are expect to be completed before December 24th, 2017.

Brugine, November 13th 2017

Alberto Chinellato
Technical Laboratory Manager

Eurotest Laboratori

DECLARATION

EuroTest Laboratori S.r.l.
via Marconi, 23 – 35020 Brugine (PD) – Italy

Subject: Status of PV conformity tests of Flisom e-flex modules

It is declared that Flisom e-flex modules are under testing as per CEI EN 61646 and CEI EN 61730-1/2 standards and related IEC standards.

As per IEC standard, all the climatic tests (50 and 200 Thermal Cycles, 10 Humidity Freeze Cycles, Damp Heat Test) are successfully completed.

We expect that the remaining tests will be completed within the next few weeks, depending on the actual weather conditions.

Brugine, January 15th 2018

Alberto Chinellato
Technical Laboratory Manager

**Figure 24 Declarations of Certification Institute about successfully passed tests.**

# WP7: Pilot Test Runs

At the beginning of the project real production was not in the focus. The most important tasks have been optimizing process conditions and operations of the coating tools and the backend line. Once submodules with good efficiencies have been manufactured regularly pilot production started. The goal of this WP is to achieve defined production measures like line yield, started quantity of substrate area, laminated quantity of substrate area, average module efficiency and production quantity in kW.

The production throughput was continuously increased over the last 18 months. The goal was to start as many meters of substrate as possible and to process as many modules through the whole line. At the beginning the quantities were very limited as reliability issues of the CIGS tool required many interruptions and a lot of material had to be rejected. Over time the root causes for equipment and process trouble have been eliminated and the number of finished modules increased. To ensure stable and reliable production regular maintenance procedures have been developed and implemented.

During the whole period of the project more than 90’000 m$^2$ of substrate have been started in the production line (see Figure 25). At the beginning for the project about 20’000 m$^2$ have been used for deposition experiments during process development of the individual tools. This amount was not use for module production at all. For manufacturing of modules about 70’000 m$^2$ in total have been started.

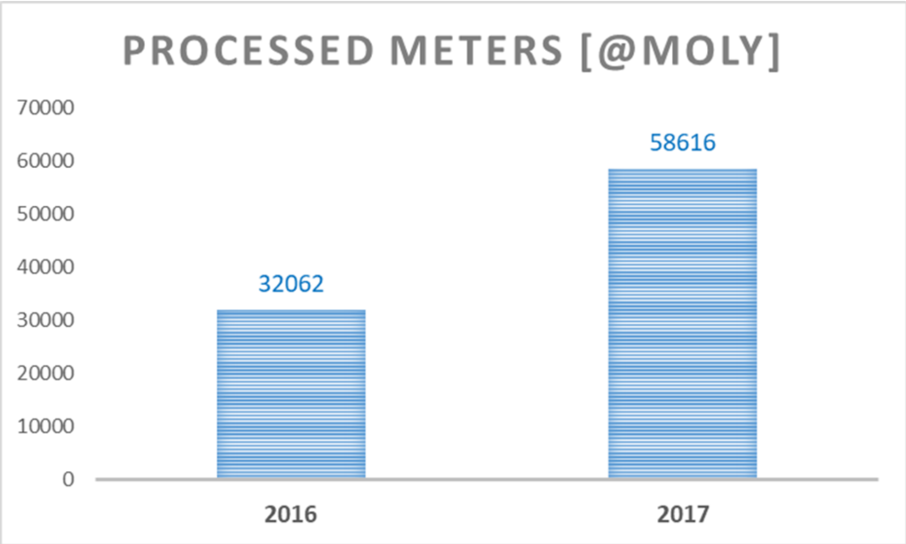



**Figure 25 Started length of substrate at BC**

Due to different reasons the planned production yield could not be achieved. One major reason for consequently lower than targeted material yield can be found in the way of yield calculation. Yield calculation includes non-usable areas related to process and technology limitations, the so called design loss. This is shown in Figure 26 where all the orange coloured area is non-usable for product and accounts for design loss. In the R2R process a ramp-up section at the start and a ramp-down section at the end of a roll is needed to start-up and stabilize the process and to cool-down the process and equipment. This causes material loss which is independent of the length of a substrate roll. Subsequently, in case of a short roll the percentage wasted is much higher than for longer rolls.

At start of project a roll was about 300m long. A value which was doubled in the first half of 2017 when operation of equipment and process was improved and more reliable.  With these inherent design plus the operational losses caused by equipment failures, process instabilities and operator errors the material yield of the line is about only half of the aimed value. However, ignoring design loss the line end

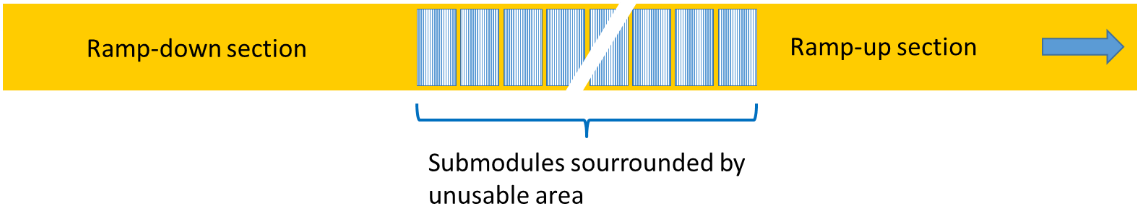



**Figure 26 Distribution of submodules on roll**

achieved at the end of the project is in the range of 80% and even more. This number for the real operational yield is very good.

Taking the design loss as a yield number is an internal convention. This loss could also be considered material cost, which would lead to generally higher yield. However, in this case the material costs have to be in more focus. At the end this loss has to be minimized. Extending the length of a roll is one approach and the final goal is to run rolls of about 2000m. Further this loss will be reduced by extending the usable area of the web width further. At the end of the project the used width is only about 74cm. This number will be extended to at least 92cm in the first few weeks of 2018. The reason for the reduced width are mechanical unevenness in the border area. With some additions to the transport system this deficit will be fixed. In addition to extending the usable width also the distance between submodules will be dramatically reduced. Currently the alphanumeric serial number of the submodule is written in the space between two submodules. The location will be changed towards the border than the distance of 4cm can be reduced to 5mm, also a dramatic improvement in material usage and reduce yield loss.

Regular processing of finished modules started when a level of approx. 10% efficiency has been reached. At the beginning the average efficiency on a month to month base was around 10% ±1% for the year 2016. In 2017 a positive development towards higher efficiencies was achieved. At the beginning of the year rolls with above 13% eff. have been produced. However these process parameters did not allow for reproducible roll to roll results, so the process required further improvement. To ensure a reliable and stable production the reproducibility of the process is crucial. Therefore the focus shifted for the time being away from increasing eff to stabilizing the process and roll performance. This caused a slight drop in efficiency however improved reliability substantially. Based on a stable process increasing efficiency is much more effective. During all the time development work on the processes was supported by the team from Empa, which was a gr eat help to identify possible cause of variability


**Figure 27 View in the production: back-end on the left, front-end on the right**

and ways how to improve much faster than without. Not only the large pool of analytical tools helped, but also the extensive material knowledge of the team.

Manufacturing continuously even small number of modules allowed Flisom to install a small 2.5kW array (see Figure 28) at its building façade on the South side in spring of 2017. With this installation outdoor data will be collected to investigate the performance of the modules.

Production quantities increased in the second half of 2017 as the quality of the PV films became better and efficiencies allowed to manufacture modules, which could be used as sample to ship to customers. The increased quantity also coincides with the first real project Flisom had to deliver. It was a project of around 30kW (see title photo), which was delivered in July 2017. Installation of the system was a big success and step forward for Flisom and was celebrate in September 2017. The installation is adjacent to a system made with standard c-Si modules and in comparison the Flisom modules perform at least as good as the c-Si ones as it is seen in Figure 29. Both systems went online on August 18$^{th}$, 2017 and the graph shows the energy yield per installed kW, which is calculated for the period since then until end of December 2017.

**Figure 28 Facade installation at Flisom building**

In 2016 no noteworthy quantity of modules was produced due to the low production throughput and low yield. This changed in 2017 as efficiencies and yield improved. The increased production quantities lead to the two installations mentioned above and many other orders, which have been shipped to different customers. At this point it must be highlighted that one very interesting shipment was specially designed modules with very low weight of approx. 200 g/m2. The application for these modules is a high-altitude airship cruising in an altitude of approx. 20km to act as a communication hub for internet connections.

The quantity of modules produced from start of continuous production in Q3/2016 to end of Q4/2017 was increased by a factor of more than 10. This was only possible with many improvements in the equipment availability and process improvements during these months. Continuous collection of data in the database to identify the most significant relations between process parameters and efficiency and variations of those throughout a process. Reducing the source of variation is one major improvement in improving process reproducibility. Regarding equipment reliability preventative maintenance procedures are improved as new learnings happen. Additionally design of some equipment parts may not be suitable for longer and longer use. If parts fail after regularly after a certain process time the design was and will be improved to ensure reproducible results even on longer runs.

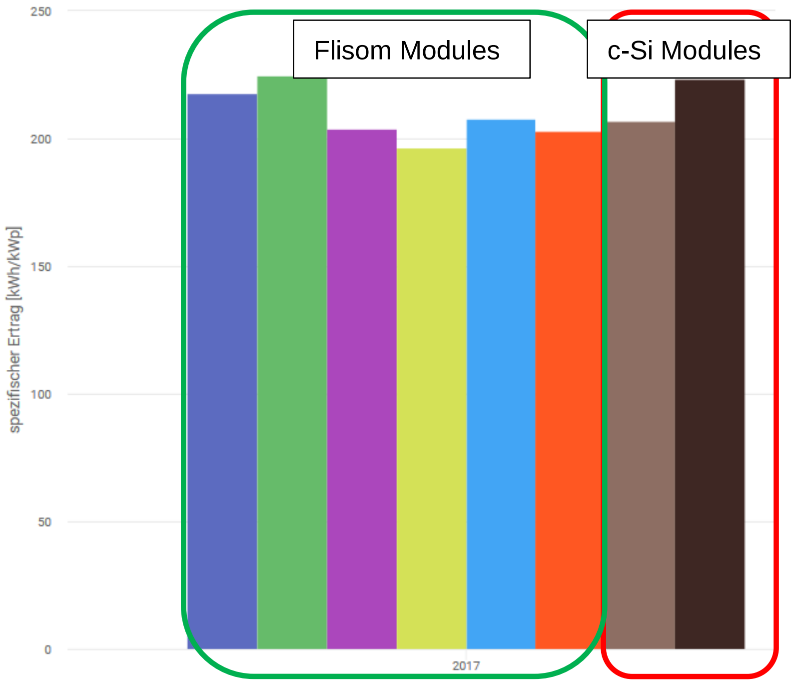



**Figure 29 Comparison energy yield of Flisom and c-Si modules**

During the course of 2017 planning on a large scale production started to evaluate the investment and cost structure of such a project. Based on assumptions taking into account the learnings of the NH production line it became clear that a large scale production will be economically worthwhile starting at annual production capacities about 100MW. Therefore the planning focused on multiple expansions of a large production of around 100MW annual capacity. This expansion is required to ensure sustainable long-term cash flow positive results of the company.

## Missed Milestones

Obviously not all milestones of WP7 have been achieved. The general overview is given in Table 3. In particular, milestones related to production quantities have been missed. At a closer look all these milestones are related to each other.

Earlier the yield calculation was explained in detail. Missing the yield milestone is mainly related to the way of calculating yield numbers. The major single reason for yield loss is the so called design loss, which is process inherent. Flisom is working on minimizing the design loss in different ways: - reduce the spacing between submodules, - increasing the usable substrate width, and increasing the length of the substrate rolls to change the ration between ramp-up/ramp-down section and active area. These activities have been successfully started during the project but putting the focus on technical challenges in other areas have slowed down progress. The CIGS co-evaporation tool needed much more attention as originally anticipated. As this is the first and only tool of its kind and completely designed and installed in-house the need for more intense improvement did not come as a complete surprise. The major issues have been process reliability and repeatability. The weak points have been the transport system and the stability of evaporation sources. Both topics have been intensely addressed and improved because without reproducible and stable processing continuous processing did not make sense. Equipment and process problems and interruption related to stability issues of the transport system and the evaporation sources also caused significant reduction of yield. Further the efficiency of the submodules on the roll are also a reason for yield loss as the process reproducibility affects the efficiency. Only submodules with efficiencies >10% have been chosen for further processing, which further reduced the yield.

Consequently the milestones of started substrate area have been missed for the reason to save material cost. Management decided to rather focus on fixing the stability and reliability issues noted above than to start as much substrate as possible and waste good material and money. Resulting from reduced amounts of started substrate less material delivered to the back-end for lamination thus missing out on the milestones on laminated areas as well as on manufactured kW as they are directly related to the laminated area. The manufactured number of kW is also depending on the module efficiency. As here progress was as planned and all milestones have been met, therefore only the reduced number of manufactured modules is the reason for the low production numbers.

Although many production milestones have been missed key production indictors show a clear trend of improvement and there are no signs technology related reasons will limit progress in production capacity and yield in the future.

# Diskussion - Würdigung der Ergebnisse – Erkenntnisse/ Discussion – Appraisal of the Results - Insights

Flisom started the ramp-up of its pilot production line to demonstrate the feasibility of industrial production applying its proprietary R2R CIGS thin film process. The pilot production line will be a blueprint for a large scale production of at least 100MW with which not only the technological but also commercial feasibility can be shown prior to investing. Further, the project was also intended to help Flisom progress on the way to commercialisation.

The results achieved during this project clearly show that the technology transfer and scale-up from Flisom's development line in Dübendorf was successfully accomplished according to the planned timeline and the given milestones. As expected some modifications to the equipment were required as well as a lot of process optimization to achieve the eventually reached level of module efficiency.

There are many learnings coming from this project, which will help to further scale up the pilot production line in Niederhasli as well as any large scale production in the future. Transferring technology requires a very close look to details and processes have to be copied as close as possible to achieve similar results. In this particular case the different geometries of the equipment required by double the substrate width compared to the development line have some influence on process parameters. Also faster production speed requires adjustment of process parameters to achieve the required material characteristics. It is very important to exactly know the material property of the final product to be able to adjust the process settings in different equipment. To save time in the ramp-up of a large production this means to copy as close as possible the equipment of the pilot production. However, all technical improvements, which are required to optimize the process and increase reliability of the equipment in the next production line must be incorporated in any new tools to have a better starting point for a new production.

One very important knob for scaling up the coating technology is uniformity of the coatings. A good uniformity is most important to get good efficiencies on large areas. Further, this will also help to reduce cost as more area of the coated substrate can be used to manufacture product. If the variability of the uniformity is too large either the overall efficiency of the modules will suffer or material utilization will go down as material needs to be trashes.

In day to day operations it became clear that a production line works best if there is minimum disturbance and changes from the standard processes. Reproducibility of production runs and thus yield and efficiency will always benefit. If experimental work has to be performed to improvement the efficiency or to solve issues causing loss of product it is important to build on a standard process, which is reliable and predictable. If this process does not exist it must be establish to enable further improvement of the product quality. After initial difficulties finding the right balance between experiments and standard production this was much improved during 2017 resulting in higher production quantities as well as more reproducible and constant efficiencies. For the future this means there will always be period with almost not experimental work to stabilize the production line followed by some substantial changes to find process improvement towards higher efficiency, better quality or reliability. Once these changes are defined the line needs time to stabilize again before the next round of improvement should be started.

For quickly ramping up a production a very good collection of process and product data is inevitable. Only if correlations between process settings and product measurements can be made easily sources for instability in the process can be determined. Further, a good data base with easy access will also help to monitor production progress as well as production yield. In case of Flisom this kind of data base was developed in-house, which has multiple advantages. The whole system is tailor made to the very need of the company. Software errors can easily be fixed without and improvements and additions are possible much faster as there is no waiting time for the availability of any programmer of a commercial supplier of such a software. The database enables process engineers as well as production management to always access the most recent status of the production floor, which allows very close monitoring and help to identify out of control events very fast. Ideally an automatic tracking is built in the data base and will raise an alarm if any out of control event is detected. Only with very fast response larger loss of material and thus money can be avoided.

Product development for this pilot production turned out to be an ongoing task. Once the earlier described product platforms have been developed it became obvious that the market not only has an interest in the standard modules but also is approaching Flisom with many new and very custom inquiries. As Flisom has the option to be very flexible, not only on the mechanical characteristic of the product but also in form factor, any customer requests will be accepted if there is commercial sense behind it. Customers must be willing to pay for the development of special solutions then Flisom will develop such a solution. This way two specific solutions have been developed and delivered in 2017:

1. Very lightweight module (<200g/m2) for usage on a high altitude (Stratosphere) airship, which will act as communication hub in the stratosphere. In the trail there is a project for the same modules for an airplane drone with a similar usage also in the height.

2. A small specially shaped module, which is integrated in a rope way gondola to power safety and communication equipment in the gondola. Prototypes have been developed and currently undergo testing.

In both cases Flisom was able to develop a solution well accepted by the customer and consecutive orders are announced and expected. In addition to these very specific requests a first larger scale installation was manufactured and sold. It consists of a 5kW façade part and a 26kW roof-top part. In this case the roof was not able to take the load of standard c-Si modules and Flisom was able to install a product which fits the tight weight requirements. At this point it has to be highlighted that the projects have been done by Flisom without covering even the cost.

**Figure 30 5kW facade installation with Flisom modules**

Looking back at the challenge of transferring the process to new and large equipment, with some never being built before the achieved results are very good and encouraging to go for a large scale production in the future. Although the production performance developed less beneficial as planned for the continuous progress gives the security which is required to take a positive decision for such an important step. Also the very promising start of commercialisation in different sectors is very promising and shows that Flisom is progressing well and is able to penetrate the market in different segments where standard solutions will be difficult to find.

During the project Flisom already started sales activities to push commercialisation forward. Therefore several exhibits have been attended. Flisom's product raised a lot of interest and many inquiries about potential project have been issued. Currently Flisom is working to fulfil some commercial projects and to intensify other contacts for future projects.


**Figure 31 Flisom booth at Intersolar trade fair in Munich 2017**

# Schlussfolgerungen/ Conclusions

During this project Flisom demonstrated the successful transfer of its proprietary thin film CIGS technology from the development line in Dübendorf to the new pilot production in Niederhasli. All process steps were successfully in the scheduled time. The tools of the new line, which have been already installed at the start of the project were working as specified. However, in the case of the in-house manufactured CIGS deposition tool some modification have been needed to ensure better uniformity and flat substrate transport. In case of the CBD and laser tool also some minor modification have been done to make operations more reliable and reproducible.

After a short time of start-up of individual tools and setting of process parameters cells with efficiencies around 14% have been made and process optimization on the large area started. In parallel work on product development started as well as understanding market requirements to develop the desired product. Continuous improvement of the production parameters and increasing reliability of the production runs enabled to start manufacturing larger numbers of modules used for testing of different encapsulation materials and to develop three different product platforms as offer for customers.

A first product received the IEC certification early in the project and modules of 3m length are currently undergoing IEC certification, which will be finished in early 2018. In 2017 shipment of first product started in small numbers. Also a first installation of 30kW was delivered and installed. Further, some large orders have been received, which will be delivered and installed in 2018.

Although production ramp-up was slower as planned the progress is still remarkable and shows continuous improvement in all production and module parameters. With the work accomplished during the project Flisom clearly went long ways on the road to commercialisation and became very visible in the international PV market. Two exhibits at Intersolar in Munich also helped to raise awareness of potential customers about Flisom’s products and technology. Production performance is still increasing and with the orders received the need to successfully produce good product is very present. The increasing number of incoming inquiries for orders indicate the interest of the market for these kind of products and the future for Flisom is not only in the classical PV market, but also in market segments, which have not used PV before or in only small quantities and picking up now.

# Ausblick, nächste Schritte nach Projektabschluss/ Outlook, Next Steps after Project end

Clearly Flisom will progress on the way to commercialization increasing the activities in customer acquisition and loading its production. There is the need to generate more revenue to increasingly cover the cost, which also means Flisom has to focus more and more in market areas where the price pressure is less crucial than in the building market. Generally these are market segments like aerospace and others where the needed quantities of modules are much less. Therefore Flisom will also market in the segment of buildings and construction to keep the flow in the production running. One big advantage of Flisom at this time is the flexibility towards different customer demands, this opens numerous opportunity to provide PV in way it has never been before.

As it will be difficult to maintain a sustainable business on Flisom's current scale an investment for a large production of about 150 to 200 MW is evident. At this time the search for investors has started and the planned start-up of the large production is in the second half of 2019.