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PROJECT FINAL REPORT

Grant Agreement number: 228743

Project acronym: NOVA-CI(G)S

Project title: Non-Vacuum processes for deposition of CI(G)S active layer in PV cells

Funding Scheme: FP7-NMP-2008-SMALL-2

Period covered: from January 1st 2010 to June 30th 2013

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Project website Error! Bookmark not defined. **address: www.novacigs.info**

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

4.1 Final publishable summary report

4.1.1 EXECUTIVE SUMMARY

Current production methods for thin film photovoltaics typically rely on costly, difficult to control (over large surfaces) vacuum-based deposition processes that are known for low material utilisation of 30-50%. NOVA-CI(G)S proposes alternative, non-vacuum ink-based simple and safe deposition processes for thin film CI(G)S photovoltaic cells. The low capital intensive, high throughput, high material yield processes will deliver large area uniformity and optimum composition of cells. The project objectives are to achieve competitive about 14% small area cell efficiency and to demonstrate the processes at high speed on rigid and flexible substrates while maintaining acceptably high efficiencies. The processes reduce cost of the CI(G)S layer by 75-80% in comparison to the evaporated CI(G)S, which translates into a 20-25% reduction of total module cost. Major scientific breakthroughs of the project include improved materials control in novel precursor materials by using nano-sized particles of specific chemical and structural characteristics and innovative ink formulation, to enable coating by simple processes while avoiding the use of toxic gases in subsequent process steps. This industry-led project constitutes the first essential step for a fully non-vacuum, roll-to-roll process aimed to achieve the solar module production cost substantially below 0,8 €/Wp.

- WP1 (Umicore as leader): Precursor materials and ink formulation
- WP2 (ZSW as leader): CI(G)S layer deposition and activation
- WP3 (TUC as leader): Large area deposition and annealing of CI(G)S layer
- WP4 (WERes as leader): Exploitation & Dissemination
- WP5 (Umicore as leader): Management

Developped technology will rely upon the use of inks prepared from particles, considering the following requirements and benefits:

- Typical particles we consider are partly based on metal oxygen-bearing derivatives
- Particles prepared using Umicore’s competences on wet-phase chemistry
- Inks prepared according to end-application specifications
- 2 materials systems selected for further optimization
- Move away from resort to H_2Se or harsh selenization conditions

Many particle-based precursors were prepared and evaluated and it was decided to focus efforts in an optimization phase on 2 chosen promising precursor materials systems. These precursors can be prepared easily in a controlled fashion (while the technology being industrially scalable and exploited) and delivered on all typical quality control dimensions (particle composition & morphology, phase formation, formulation, deposition, conversion). Formulation efforts were also carried out to reduce the amount of carbon which needs to be removed during/before conversion to the CIGS absorber layer, improve ink stability and versatility. Currently available formulations prepared within the consortium can be printed using lab-scale standard equipment and can be converted, following a sequence of post-deposition steps, to a functional CIGS absorber layer with cell efficiency up to 8%.

Information can also be found at www.novacigs.info
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4.1.2 SUMMARY DESCRIPTION OF PROJECT CONTEXT & OBJECTIVES

The goal of NOVA-CI(G)S is to develop an ink based non-vacuum simple and safe deposition process of the CI(G)S absorber layer for highly efficient low cost solar cells. CI(G)S has high cost savings potential, coupled with the highest operating efficiency of all TF PV. In a CI(G)S device, the absorber layer is the single most scientifically challenging one and with the biggest impact on materials cost. The project aims to demonstrate the following:

1. Non-vacuum deposition of the CI(G)S layer is possible whilst maintaining acceptably high efficiency
2. Non-vacuum deposition of CI(G)S layers can be realized at high speed (30m^2/min) on rigid substrates whilst maintaining acceptably high efficiency on assembled cells
3. Non-vacuum deposition of CI(G)S layers can be realized at high speed (100m^2/min) on flexible substrates replicating similar dried CI(G)S (pre-annealing) characteristics as for rigid substrates

The overall aim is for sure to make a significant impact on reducing the cost (€/Wp) of the CI(G)S layer and pave the way to addressing the device's adjoining layers with a similar fully integrated low cost deposition process ultimately achieving a CI(G)S TF module cost substantially below 0,8 €/Wp. Non-vacuum deposited CIGS would then become more competitive versus the strongly positioned CdTe thin film PV technology.The ambitious but realistic initial objectives of NOVA-CI(G)S are given in Figure 1.

General CI(G)S layer deposition process performance
Total CI(G)S layer cost (capital, process, materials) reduced by 75-80% (reference section 3.1) versus cost of vacuum technology
Material utilization of more than 90% up from current 30-50%
Elimination of hazardous materials
Cell & module performance (rigid substrates)
Printed CI(G)S small area cell efficiencies of about 14%
Module efficiencies of at least 70% of small area efficiencies
Deposition productivity of 30m²/min, with structural characteristics equivalent to the optimized lab layer (prior to annealing)
Cell & module performance (flexible substrates)
Printed CI(G)S small area cell efficiency 90% of cell efficiency on rigid substrates
Module efficiencies of at least 70% of small area efficiencies
Deposition productivity in the 50 – 100 m²/min range with structural characteristics equivalent to the optimized lab layer (prior to annealing)

Figure 1. **Objectives of NOVA-CI(G)S**

As far as cell efficiency objectives are concerned, the objectives of reaching 14% on small area rigid substrates and 12-13% on small area flexible substrates remain relevant in the context of the scientific & technological challenges that need to be tackled by the different partners. Comparing to cell efficiencies recorded for vacuum-deposited CIGS, the objectives as stated herein can be considered a first step in the good direction with however a clear need to go in the future beyond the objectives described herein.

The shift to non-vacuum technology also has serious consequences in terms of dealing with issues as to resource efficiency and sustainability. Indeed, non-vacuum technology will enable a material utilization of more than 90% compared to current typical 30-50% for vacuum-based technologies. Although it is now agreed by many that indium should not face major supply risk in the near future, the reduction of material utilization is a clear advantage here. In term of susbtainability, one of the objectives of the project is to keep away from using toxic, harsh chemicals for the deposition and conversion/selenization steps. No resort will be made to compounds such as H_2Se, hydrazine and its toxic derivatives, … One consequence of the choice of the 2 precursor materials systems developped at Umicore is that the source of selenium would actually be embedded (experiments conducted until now still rely upon the need for a separate selenization step until selenium inks are fully developped) already into the ink to discard the need for a separate selenization step or at least reduce strongly the amount of Se used in that step.

The work plan strategy is based on a step-by-step selection of technology combinations limiting complexity of the project, optimising resource investment and reducing technical risks. The main steps are: Initially start lab-scale deposition using rigid substrates only to develop and select precursors and deposition technologies. Upon reaching certain milestones, RTD lines for large-area deposition will be started, followed by tests on flexible substrates.

The overall strategy, timeline and milestones of the NOVA-CI(G)S project are clearly depicted in Figure 2 below.

Initially, RTD will focus on rigid substrates only, using a standard soda-lime glass substrate without barrier layer. Such rigid substrates allow higher efficiencies (due to higher temperature annealing step), while simpler deposition reduces technical complexity. Secondly, focusing on one substrate type limits workload on testing ink and deposition technology combinations.

For deposition, ink-jet and gravure printing have been identified as 2 technologies that are representative of high throughput potential techniques (1 contactless medium-high throughput / 1 contact very high throughput). A brief comparative study will be kicked off early on and the most suitable technology to be used for the ongoing lab work will be determined in month 4 (MS1).

Right at the project start, and parallel to selecting the standardised lab based deposition technology mentioned above, doctor blade will be used to allow initial tests of 4 families of precursors and derived inks. The system has low productivity, but is simple, flexible and expected to deliver required control over layer deposition for preliminary testing. Further, it requires limited investment as WP2 partners have experience with the technology and equipment available.

Upon selection of the lab-scale deposition technology, a standardised laboratory set-up will be installed at Umicore (WP1) and ZSW and EMPA (both WP2). The standardised set-up will allow WP1 to make initial analyses of the deposited layer, so feedback-loops are short and the number of samples that are selected for further processing by WP2 remain limited. Using the standardised set-up at WP2 ensures verification and copy of WP1 results.

In an iterative process, ink routes will be further developed on the selected deposition technology. Interesting CI(G)S layers will be activated by traditional methods and laser annealing (by ZSW) and in parallel by furnace RTP (by EMPA), until halfway of the project.

At month 18, the goal is to have achieved 50% of the target efficiency for a small area cell printed on rigid substrate (MS2). At this moment, the work plans and focus will be revised to focus on the most promising approaches. The overall strategy of the project will be assessed if goals are not met. At month 18 as well, the 2 best precursor / technology combinations and derived inks will be selected for further improvement in the lab on rigid & flexible substrates (MS3). Parallel to that, a proof of concept study will be conducted for large-scale printing on rigid substrate (MS4) (study will aim at printing on a rigid substrate at a throughput of 30 m^2/min a layer replicating the lab-based pre-annealed layer produced by WP2) as be the basis for selection in month 31 of either ink-jet or gravure deposition technique for the feasibility study for large-scale printing on rigid substrate (MS5). In light of results obtained until now, the MS2 will be postponed by 6 months until M24 and activities on flexible substrates could only, at best, start after M24. More details are provided in section 3.2.3 of the present report.

If 50% of the target efficiency for a small area cell printed on flexible substrate is achieved (MS6), the decision will be taken, at month 31, to proceed with proof of concept study (MS7) for R2R (ink-jet, gravure) large-scale printing on flexible substrate. Study will aim at printing on a flexible substrate at a throughput in the 50 – 100 m^2/min range a layer replicating the lab-based pre-annealed layer produced by WP2. Over the duration of the project, the integration of annealing into large-scale printing will be examined (MS8).

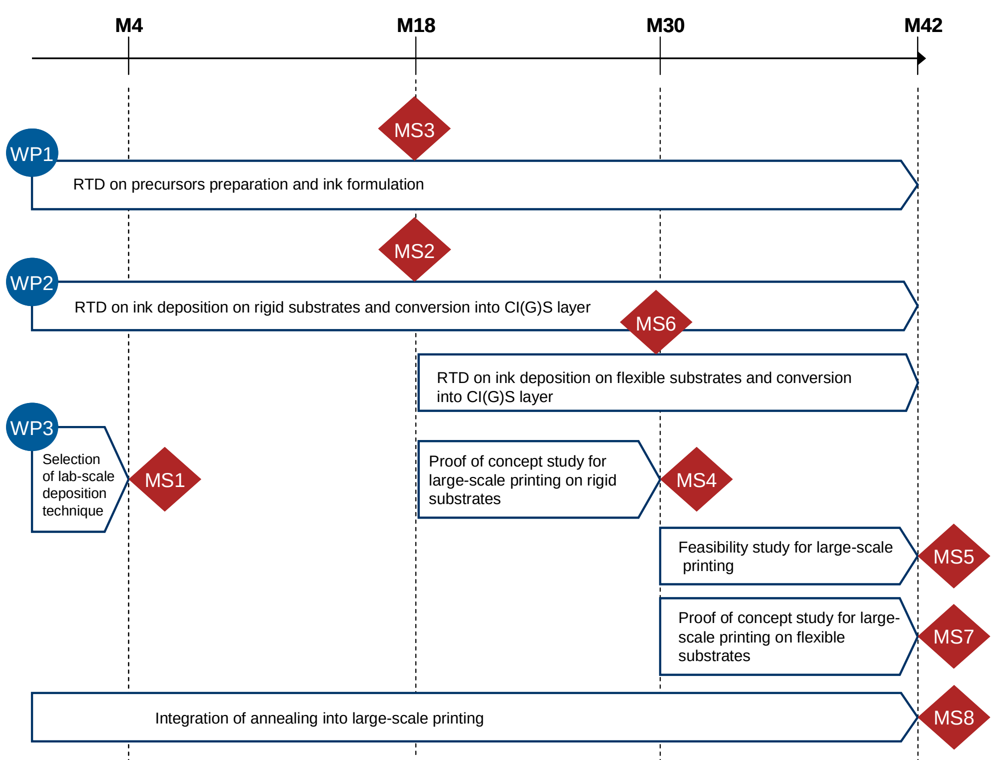
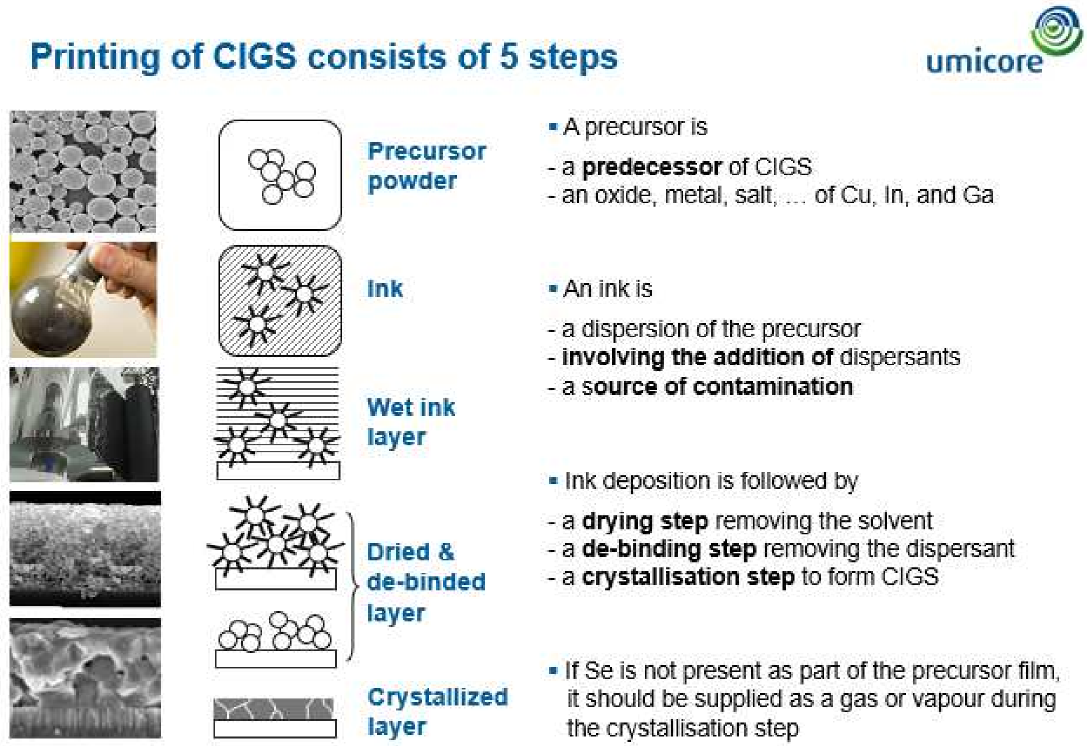
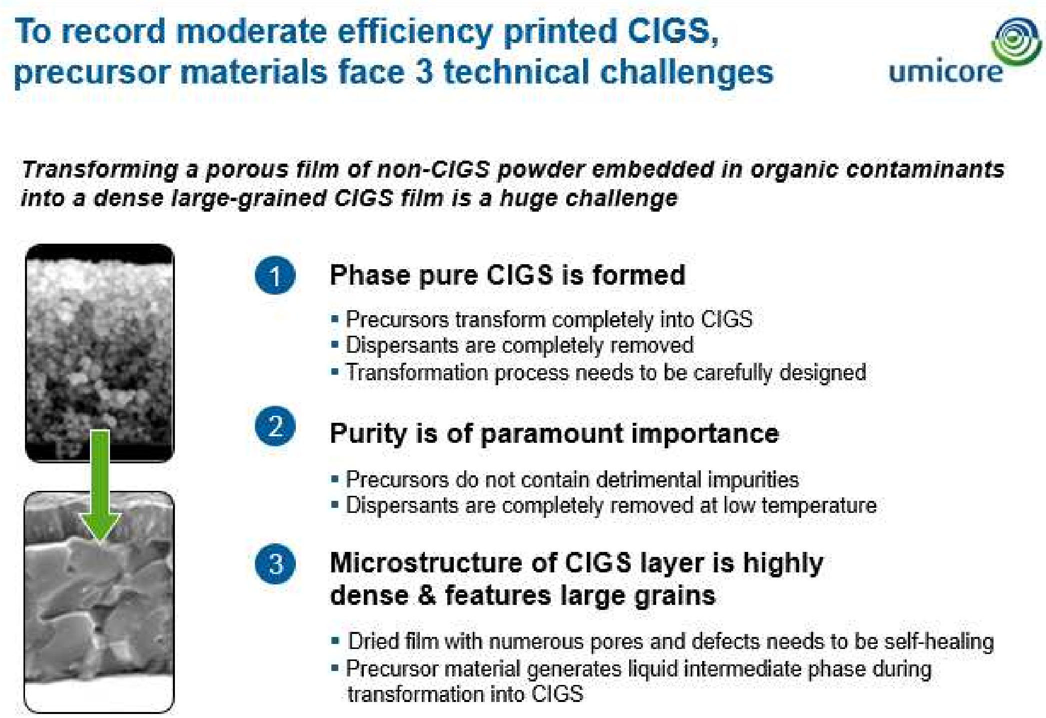


Figure 2. **Overview of NOVA-CI(G)S strategy & milestones**

4.1.3 MAIN S&T RESULTS / FOREGROUNDS





General Process: CIG precursor → solar cell

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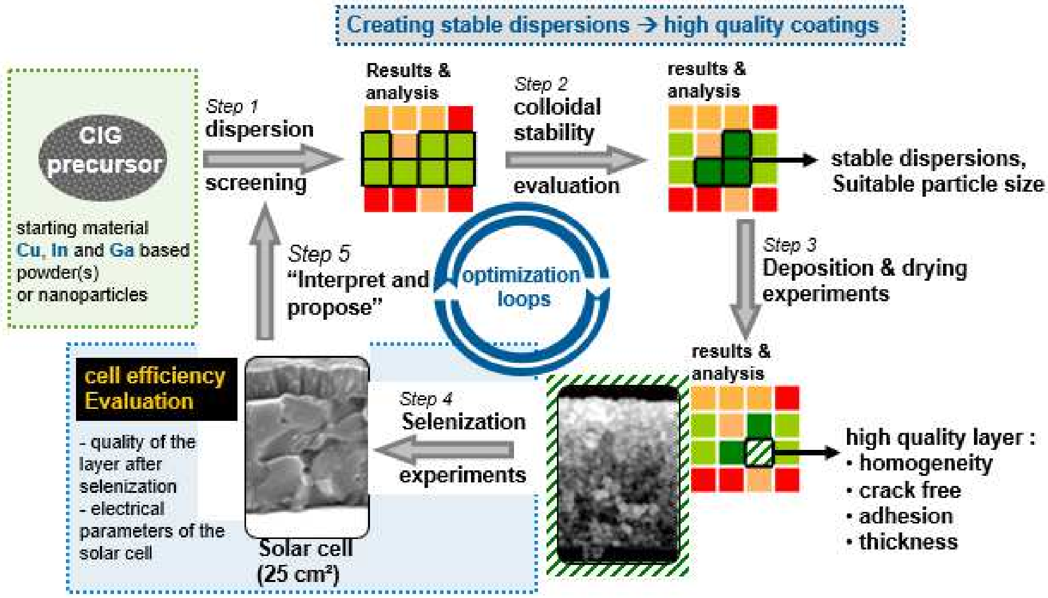

The 3 technical challenges (that precursor materials are facing) have been partially met

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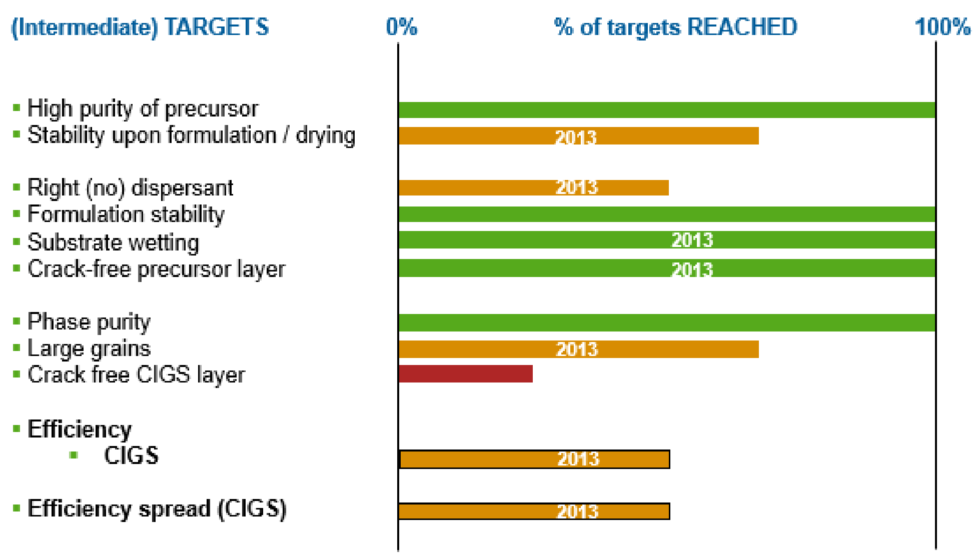

Printing equals moderate efficiency, but moderate efficiency is no longer acceptable

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Now	2015		2020
8%	10%	defin	20%
& insight in technological challenges	Possible but irrelevant		Moving target Highly unlikely / impossible

- Focussing on current targets/parameters
- More time/resources

- Increasing efficiency gap to bridge
- Deep understanding of electronic properties required
- And even if the understanding is there:
printing driven by thermodynamics / too limited control

4.1.4 POTENTIAL IMPACTS

Initial market assessment proved interesting although already considered risky (refresher 1/2)

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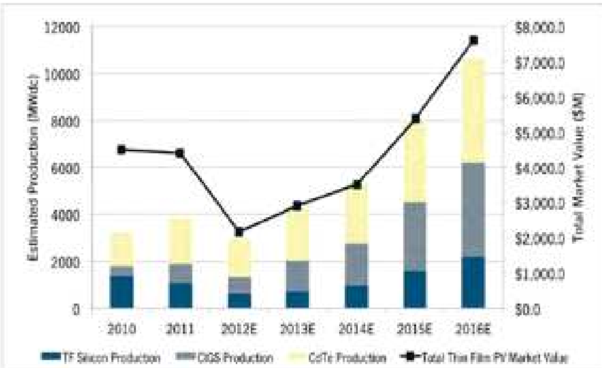

Estimated Production (MWdc)	2010	2011	2012E	2013E	2014E	2015E	2016E
TF Silicon Production	1395	1101	633	711	992	1562	2177
CIGS Production	400	779	712	1351	1735	2954	4059
CdTe Production	1456	1991	1594	2181	2589	3462	4405
Total	3251	3871	2939	4243	5316	7978	10641
Total Thin Film PV Market Value	$4,525.3	$4,431.3	$2,166.1	$2,903.5	$3,520.3	$5,400.2	$7,601.3

Source: GTM Research

- **Market for CIGS absorber materials originally estimated at:**
  - **280 M€ (360 M$) by 2016**
  - **could double by 2020**
- Estimate based on (in 2016)
  - 0,09 $/Wp CIGS materials cost (for module producer)
  - 4 GW_p annual CIGS module production
- **Survival of CIGS and other TF technologies depends on industry developing**
  - **efficiency: 15% by 2016**
  - **economies of scale: >200 MW_p**
- Penetration of printing in CIGS module production is difficult to estimate

Initial market assessment proved interesting although already considered risky (refresher 2/2)

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- Compared to vacuum based CIGS technology, printing of CIGS can allow for
  - Up to 20-25% CAPEX reduction
  - Up to 20-25% increase in material utilisation
  - Up to 15% decrease in module production cost
- **The accesible market are the new plants. The incentive for switching to printing are**
  - **A technology adoption at new or expanding operations**
  - **Additional advantages (larger area uniformity, patterning, and increased flexibility)**
- CIGS inks could be priced at the same level as CIGS materials for vacuum technologies with CAPEX gain given to customers as incentive for technology adoption
- In case market is approached in late 2016, CIGS materials pricing could correspond to 0,07 €/Wp
- **At an evaluated 5 GW_p market increase between 2016 and 2020 * and provided printing dominates CIGS production, the maximum CIGS inks market could be 350 M€ in 2020**

CIGS efficiency to grow further to compete with c-Si The train is accelerating, will printed CIGS ever catch up is highly uncertain !

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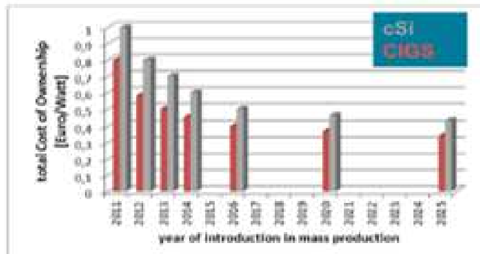
Total Cost of Ownership: possible roadmap

manz passion for efficiency

Business Case updated 2013: total cost of ownership (TCoO)

To stay competitive TCoO of CIGS has to be reduced to

- **0.45 - 0.5 €/W in 2013**
- **0.4 - 0.45 €/W in 2015**
- **below 0.4 €/W until 2018**



Realistic potentials of efficiencies (apa), targets in running fab:

	2012	2015	2020	2025
CIGS	13-13.5 %	15-16 %	16-17 %	17-18 %

If these targets will not be reached, thin films probably will drop out of the energy market (competition with cSi + BOS penalty)

CIGS industry is also looking at standardized production equipment, thinner and lower purity films, … Printing of CIGS is not enabling that move

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Scaling in size and Upgrading with cost potentials Potentials to be gained with realistic numbers

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Module efficiency: linear influence on cost, targets of 15 – 16% have to be realized within next five years to be competitive with cSi

Capex:

- next gen equipment has to be standardized and will have much higher productivity; throughput increase by factor of 5, working/product area increase by factor of 2 and high performance/yield (~ 95%), etc.)
- Bigger fab sizes (200-500 MW/a)

→ **capex reduction by 30% in mid and 50% in long term**

Material cost:

- Increased material purchase: reduction of cost by ca. 30% plus purchase e.g. in low prize regions
- Qualification of upgrades (thinner films ca. -30%, lower purity, packaging and JB)

→ **material cost reduction by 50% in mid term**

As a conclusion …

- The market risk is considered much higher (smaller market, in hands of few, innovation adoption risk high, will be pressure on margins, …)

- The technology risk is considered much higher (technical challenges partially met but whereas stretching to 10% cell efficiency is feasible, stretching to 20% seems unfeasible in present context)

- Risk versus Opportunity seems quite unbalanced