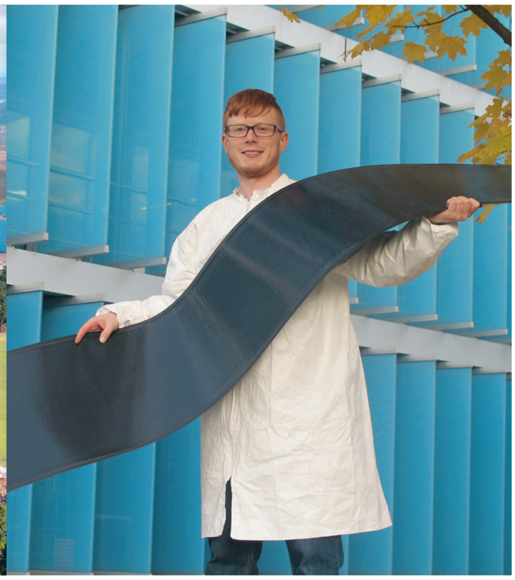
# WHITE PAPER FOR CIGS THIN FILM SOLAR CELL TECHNOLOGY



„The time to invest is now!"

## THE LOW COST HIGH EFFICIENCY PHOTOVOLTAICS TECHNOLOGY

Photovoltaics today is dominated by crystalline silicon (c-Si) technology. Among alternative, thin-film technologies, CIGS is the most advanced and the most efficient. The (PV)modules with CIGS ($Cu(In,Ga)(Se,S)_2$ ) absorbers are very effective in converting light directly into electricity. They are very well positioned in the field of PV technologies with present record efficiencies for small cells of 21.7 % and for production size modules of 16.5 %. Fig.1 indicates that the recent progress at the cell level (black triangles) paves the way for progress at the mini module level (red squares) and towards total area module efficiencies (blue dots) of 18 %. The latter is expected to be realized in the near future through transfer and adaptation of laboratory technology. Low cost CIGS PV modules can provide electricity below € 0.05 / kWh (LCOE) and contribute to $CO_2$ reduction in a significant manner.

### 01 // PRODUCTS AND TECHNOLOGY PERSPECTIVE

The diversification of production and design of CIGS modules offer multiple possibilities for PV power production in the future. CIGS glass-glass products cover the classical application fields of power plants, roof-tops, and building facades. Flexible and light weight CIGS modules currently in production show average aperture area efficiency > 16 %. Achieving high efficiency with such products will open new large scale applications and markets.

In the longer term in combination with suitable wide bandgap absorbers CIGS can be used as bottom cell in tandem devices that enable efficiency values well beyond 30 %. This demonstrates impressively that not only is CIGS a competitive PV technology, but in addition it comprises a potential not yet exploited for further improvements.

### 02 // KEY ADVANTAGES OF CURRENT CIGS MODULES: HIGH ENERGY YIELD AND OUTDOOR PERFORMANCE

A low temperature coefficient, a favorable spectral response and high efficiency under low light conditions are the reason for excellent energy yields and hence low levelized costs of electricity under most climatic conditions (Fig. 2). Furthermore, the thin film module design based on monolithic interconnection results in intrinsically reduced sensitivity to shading. Lower temperature coefficients, higher shading tolerance and a good low light performance are also key requirements for building integrated PV applications.

### 03 // SUSTAINABILITY: LOW ENERGY CONSUMPTION, SHORT ENERGY PAYBACK TIME AND MINIMIZED MATERIAL CONSUMPTION

Based upon the intrinsic features of thin film solar cells – short energy payback time and minimum use of high purity materials – thin film solar cells produce electricity at cost below conventional energy sources. If the carbon footprint is also taken into account there is a clear advantage of thin film solar cells and a real chance for providing a truly sustainable energy source. Complete recycling of end-of-life modules is technically feasible and will be exploited in future once significant volumes are available. This combination makes CIGS one of the most sustainable solution for PV volume production.

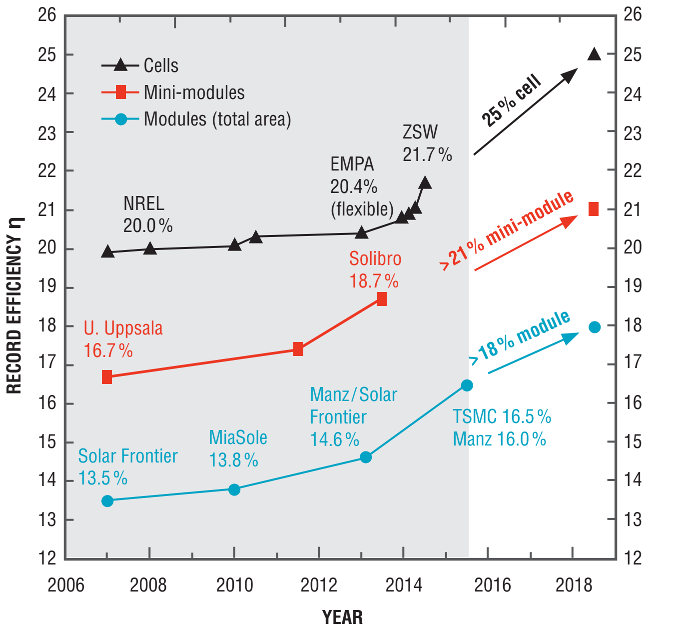



Fig. 1: Evolution of record efficiencies highlighting a steeper increase since 2014; 2016–2019 projections based on current R & D projects.

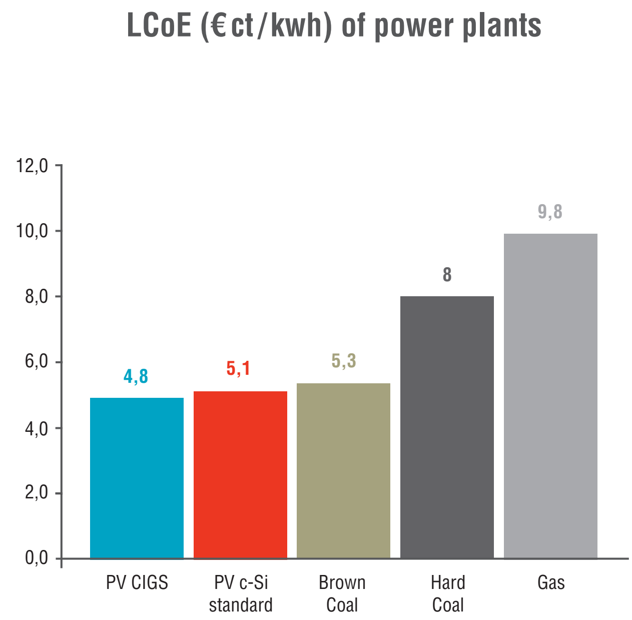



Fig. 2: Levelized cost of electricity for different technologies [1)]

## 04 // PROVEN RELIABILITY

Glass-glass CIGS modules with monolithic series connection of the individual cells demonstrate inherently superior stability over soldered or bonded cell strings. At present, CIGS modules from mass production guarantee a high level of reliability proven by extensive endurance and long term field tests in numerous installations and climatic conditions with independent verification [2)].

## 05 // HIGH PRODUCTIVITY AT THE GW PRODUCTION LEVEL

Currently the biggest production units, ranging in capacity from 100 to 1,000 $MW_p$ / a, are located in Germany and in Japan, These are operated at high yields well beyond 90 % over the whole value chain. At present, the total world-wide CIGS production capacity is about 2 $GW_p$ / a. Although companies use different fabrication methods, all of them show excellent results, demonstrating that CIGS production technology has reached the first stage of industrial maturity. Even when using non-abundant elements like indium, a supply limitation is not expected below a production volume of 100 $GW_p$ / a. The latter is due to continuous reduction of the amounts of Indium needed in combination with progress in recycling. Nevertheless, further cost reduction potential is expected to be exploited within the next decade if supported by continued, effective R & D activities.

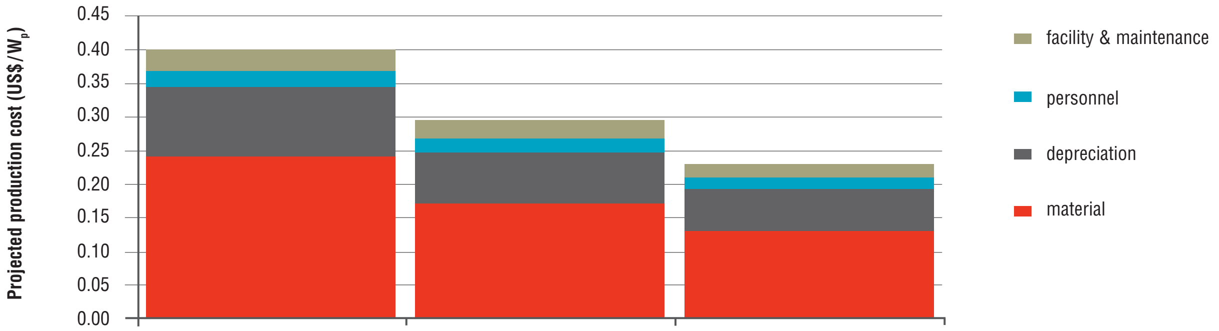
## 06 // PRODUCTION COSTS

Today´s CIGS production costs are already comparable to crystalline Si albeit at lower accumulated production volume – from 2008 to 2014 roughly 3 $GW_p$ CIGS modules were shipped worldwide. This means that CIGS has just started the learning curve typically seen for comparable thin film technologies such as flat panel display or glass coating. Large area deposition and accelerated processing combined with new CIGS facilities have the potential to yield total cost of ownership of 0.40 US-$ / Wp even at productions capacities as low as 150 $MW_p$/a (Fig. 3).

It is important to mention that the capex for thin film modules includes the whole value chain from glass input to the finished module. Given the already low cost level of CIGS today we see an enormous potential for cost reduction with CIGS technology. Fig. 3 shows the present status and the effects of learning by further scaling and upgrading module efficiencies. Multiple activities are

1) Source: Fraunhofer ISE / IPA Dec. 2013 „Study for planning and construction of a xGW factory for the production of forward looking PV products in Germany, data calculated for 0.5 $GW_p$ / a. Ref. location PV Sevilla / Spain: 1.880 kW / m2*a. Note: in this study, PV costs are projected for products from a $GW_p$ fab, the costs for fossile driven power plants are today's.

2) See for instance data from the independent DKASC outdoor test site in Alice Springs (http://www.dkasolarcentre.com.au) where commercial CIGS modules have been benchmarked favourably over many years.




| | Present fab | Next gen fab | Upgrade & scale next gen fab |
|---|---|---|---|
| **Capacity** | 150 $MW_p$/a | 250–500 $MW_p$/a | 500–1000 $MW_p$/a |
| **Average efficiency** | 14.3 % | 16 % | 18 % |
| **Reductions versus present fab** | | material -20 %<br>capex -20 % | material -30 %<br>capex -30 %<br>f&m -20 % |

Fig. 3: Projected CIGS production cost using presently available technology and leveraging further cost reduction potential

ongoing with the focus to transfer the high-efficiency lab results to production.

Costs will be continuously reduced by improving module efficiency from 14 % up to 18 % (see Fig. 1) and by scaling effects reducing the bill of materials (purchasing large volumes, reducing layer thicknesses and using less pure materials) and capex. Improved productivity by next generation equipment (improved throughput, yield and availability), minimized energy consumption and optimized infrastructure will also contribute to the cost decrease. Summarizing all reduction potentials, and scaling to the multi $GW_p$/a level, CIGS technology will be able to reduce costs by another 25 % up to 40 % within the near term.

„The time to invest in CIGS technology is now!"

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