

CIGS Thin-Film Photovoltaics

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White Paper for CIGS Thin-Film Solar Cell Technology

This website highlights the CIGS Whitepaper written by 30 renowned experts from CIGS industry and research institutes. It was first conceived in 2015 and has been updated in February 2019 (publication pending).



CIGS building-integrated facade with CIGS modules by (image: Manz AG)

CIGS White Paper Initiative

More than 10 CIGS module producers and equipment manufacturers as well as more than 10 CIGS research institutes have contributed to various versions of the CIGS White Paper:

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- Ayodhya N. Tiwari (Flisom, EMPA)
- Esko Niemi, Eric Jaremalm (Midsummer)
- Markus Beck (Siva Power)
- Chris Eberspacher (Solopower)
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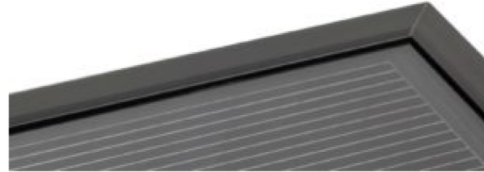
About CIGS

Copper indium gallium selenide (CIGS) is a highly stable, high performance, and mature thin film PV technology. The CIGS semiconductor composition has not been substantially altered since 1986, although advances in production technology have enhanced efficiency over this period.

That the semiconductor composition has remained fundamentally unchanged over 30 years stands testament both to its stability and reliability, and also indicates the potential for future fundamental 'step change' improvements in production cost and conversion efficiency – as a result of continuing R&D efforts and deployment in large-scale manufacturing.

As of 2019, CIGS cell efficiencies have surpassed all other thin film PV technologies, achieving 23.35% on the cell and 17.5% on the module level. CIGS has also been deployed in ultra-high efficiency tandem cells, with the potential to achieve 30% efficiency. Perovskite/CIGS tandem cells have been produced, and there is significant potential for future efficiency development through band-gap tuning in such applications.

Why Invest in CIGS Thin-Film Technology?



Framed CIGS thin-film solar module

The global solar photovoltaics (PV) industry has entered a new phase. In 2019, it is cheaper for many homes and businesses to generate solar electricity on their rooftops than to purchase from their utility. In large-scale applications, power generation from PV is competitive with a range of conventional sources in terms of levelized cost of electricity (LCOE).

The 2018 Bloomberg NEF New Energy Outlook forecasts that **wind and solar PV will account for 50% of the world's electricity generating capacity by 2050**. In an emissions-constrained energy economy, high volume, energy efficient, and environmentally friendly PV manufacturing and production will play a central role.

This emerging cost paradigm will also open up new opportunities for solar deployment. While established rooftop and utility-scale solar applications will continue to increase in size and number, **PV will play a vastly increased role as an integrated element in our built environment, appliances, and mobility solutions.**

To meet the needs of this rapidly emerging development, efficient, environmentally friendly, reliable, flexible, lightweight, recyclable, and cost efficient technologies will be required. **Copper indium gallium selenide (CIGS) thin film PV is ideally positioned** to fulfill this role based on its inherent advantages and ongoing R&D activities.

CIGS White Paper 2019

Introduction

The global solar photovoltaics (PV) industry has entered a new phase. In 2019, it is cheaper for many homes and businesses to generate solar electricity on their rooftops than to purchase from their utility. In large-scale applications, power generation from PV is competitive with a range of conventional sources in terms of levelized cost of electricity (LCOE).

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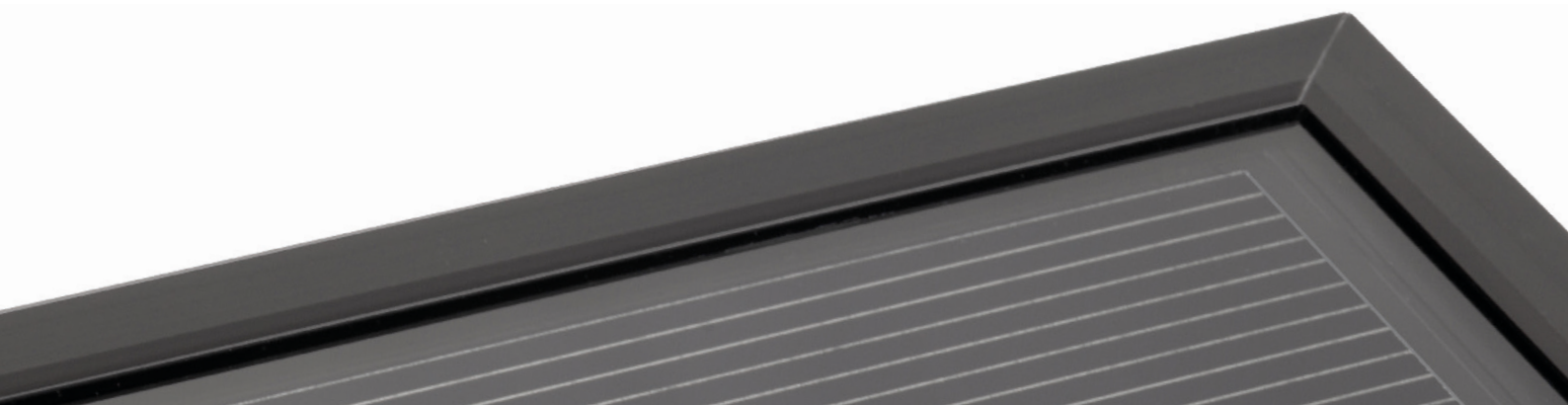
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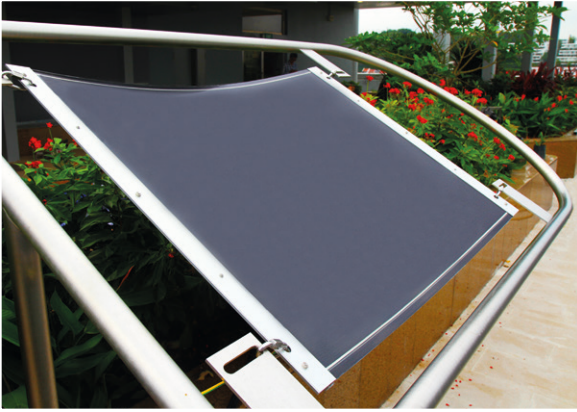
To meet the needs of this rapidly emerging development, efficient, environmentally friendly, reliable, flexible, lightweight, recyclable, and cost efficient technologies will be required. **Copper indium gallium selenide (CIGS) thin film PV is ideally positioned** to fulfill this role based on its inherent advantages and ongoing R&D activities.

Unique features of CIGS

- *CIGS exhibits **high conversion efficiencies**, both in the laboratory and in production. This high efficiency, coupled with long-term stability, makes it uniquely positioned to play a central role in the global renewable energy sector. When its high performance is considered in conjunction with its other inherent advantages, CIGS is clearly a PV technology set to **dominate fast-emerging PV market segments such as building-integrated photovoltaics (BIPV)**.*
- *The production costs of CIGS solar modules are highly competitive with other PV technologies on a capex basis. Furthermore, and due to the inherent advantages of thin film solar production, CIGS has substantial cost advantages and a **compelling cost-reduction potential on an opex basis** – particularly when large-scale manufacturing is achieved.*
- *The **environmental advantages of CIGS are unparalleled**. It has an extremely low CO₂ footprint and is a material suitable for high-value recycling.*
- ***Visually, CIGS is far superior to alternative solar technologies**. This is true both in 'standard' module form, when its monolithic, all black appearance is most striking, as well as in colored or patterned modules.*

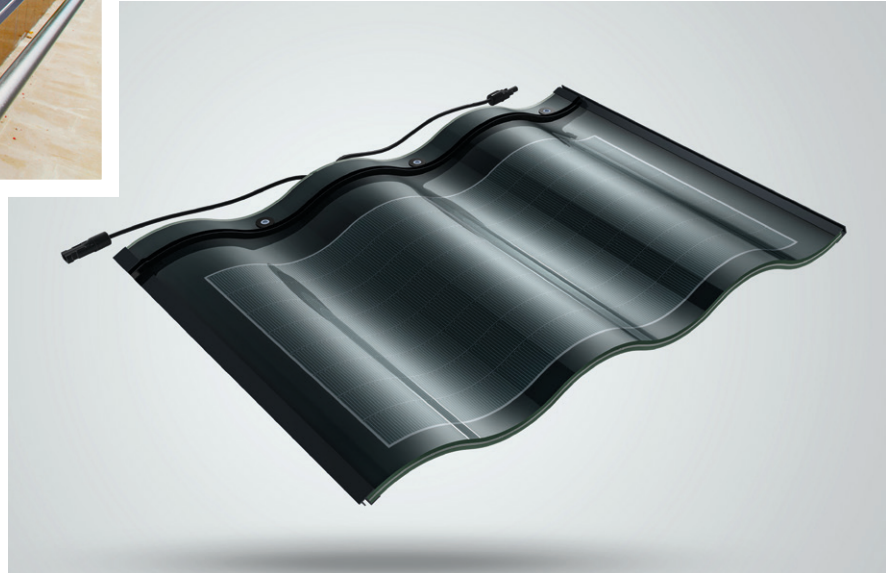
This document will describe these advantages, making clear that CIGS technology presents a highly attractive business case for investors today, to meet the clean energy needs of tomorrow!





◀ Monolithic CIGS on a flexible substrate, installed in Singapore.

Flexible CIGS modules are lightweight and can be incorporated onto vehicle roofs and structures for which heavy PV modules are unsuitable. ▼



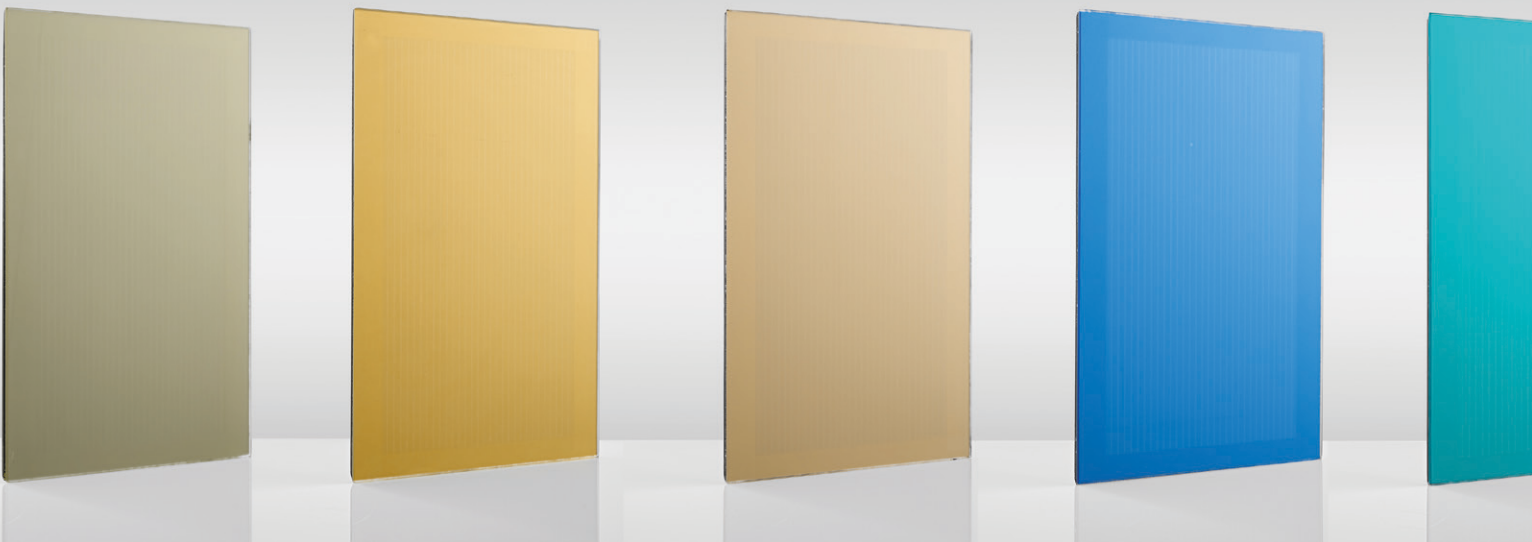
efficient
stable
beautiful
flexible

Applications

CIGS is a **stable and proven** PV material, with low technology risks for investors. CIGS is a high-performance PV technology, both in terms of relative conversion efficiency and absolute energy yield. There is a long track record for CIGS in both utility-scale and rooftop applications – including in some of the world’s most demanding climates.

At utility scale, CIGS PV has a proven track record and has demonstrated **superior performance in diffuse light conditions and at high temperatures**. Degradation that can occur in high efficiency crystalline silicon technologies does not occur in CIGS modules.

Avancis has produced a series of colored modules and is working to optimize different colors with power output. ▼



In rooftop applications and when incorporated into the built environment, CIGS has the additional advantage of being **aesthetically pleasing, due to its monolithic 'all black' deposition**. Architects are increasingly responding to frameless CIGS modules, incorporating them **seamlessly into building facades**. Beyond electricity production, CIGS modules are a high quality, high value, and attractive building material.

Colored and patterned CIGS modules can also be produced and are ready for incorporation by architects in even the most ambitious and visually appealing building projects.

CIGS is suitable for the production of **lightweight, flexible, semi-transparent, and custom-shaped** solar products. These can be deployed in an incredibly wide range of solar products.

Construction materials such as building facade glass and windows, and fully integrated PV roofing materials are proven applications of CIGS modules. Building-integrated photovoltaics (BIPV) and building-applied photovoltaics (BAPV) may be niche applications today, but they are expected to become commonplace in a carbon constrained near future. An estimated 90% of electricity consumption occurs in large cities, making the production of energy on-site both practical and cost effective. In BIPV/BAPV applications, diffuse light conditions, high temperatures, and partial shading are more commonplace than in conventional ground-mounted or rooftop PV applications, making CIGS the best-suited PV technology, in addition to its obvious aesthetic advantages.

Alongside glass, the photovoltaic CIGS semiconductor stack can be **deposited onto flexible substrates**, such as stainless steel and polyimide films. These can then be incorporated into PV modules that are lightweight, flexible, and robust – ideal for electric cars, buses, trucks, trains, and membrane roofing structures. Flexible mini-modules can also be incorporated into consumer electronic devices, including chargers and accessories – such as luggage and backpacks.

Driven both by regulatory frameworks and economic necessity, PV's ubiquity in the built and lived environment will undoubtedly grow. CIGS is poised to fulfill these applications as they rapidly evolve into mainstream market segments – alongside established rooftop and utility-scale solar arrays.

The **proven performance of CIGS technology in conditions of diffuse light, high temperature, and partial shading** makes it ideal for a wide range of applications for which other PV materials would be unsuitable.

Copper indium gallium selenide (CIGS) is a highly stable, high performance, and mature thin film PV technology. The CIGS semiconductor composition has not been substantially altered since 1986, although advances in production technology have enhanced efficiency over this period. That the semiconductor composition has remained fundamentally unchanged over 30 years stands testament both to its stability and reliability, and also indicates the potential for future fundamental 'step change' improvements in production cost and conversion efficiency – as a result of continuing R&D efforts and deployment in large-scale manufacturing. As of 2018, CIGS cell efficiencies have surpassed all other thin film PV technologies, achieving 23.35% on the cell and 17.5% on the module level. CIGS has also been deployed in ultra-high efficiency tandem cells, with the potential to achieve 30% efficiency. Perovskite/CIGS tandem cells have been produced, and there is significant potential for future efficiency development through band-gap tuning in such applications.



Manufacturing

Over the past two years, CIGS has been the **fastest growing thin film PV technology**. Driving this uptake is its suitability in a wide range of applications, but also its compelling cost competitiveness – both in absolute and in relative terms.

Japan's Solar Frontier is currently the largest CIGS producer, with 1 GW of production capacity and 5 GW of modules deployed globally. A wave of new, large-scale investments in CIGS manufacturing from major energy and industrial players is currently underway, primarily in China. Around 600 MW of CIGS production capacity was added in 2018 with expansion plans for multiple gigawatts of production.

Chinese construction materials and engineering company CNBM, electricity equipment supplier Shanghai Electric, and subsidiaries of mining and generation giant China Energy Investment Corporation (formerly Shenhua Group) have made strategic investments in CIGS technology and production equipment. China's Hanergy is currently pursuing a production ramp of around 600 MW of CIGS capacity in both flexible and on-glass formats. In other words **the journey to large-scale CIGS manufacturing is well underway**.

Currently the most profitable PV manufacturer globally is a thin film PV producer with production facilities in the United States and Southeast Asia – an often-overlooked feature of the global solar marketplace. All thin film technologies share similar intrinsic advantages when economies of scale are realized – including low-cost production, low-material consumption, and fast energy paybacks.

Fully vertically integrated production facilities – glass in, PV module out – can be realized with CIGS technology, resulting in cost competitiveness with crystalline silicon (c-Si) PV at the megawatt scale. When the complete c-Si value chain is considered, including polysilicon, ingot, wafer, cell, and module, CIGS production represents a very attractive investment opportunity in terms of both capex and opex. Additionally, CIGS is well suited to manufacturing with high levels of automation and Industry 4.0 approaches.

CIGS production can be highly automated and is Industry 4.0 ready. ▶

Solar Frontier supplied 23MW of its CIGS modules to this project in Ube, Japan. ▼



CIGS technology has proven to deliver **highly stable power output**, with the semiconductor stack exhibiting dynamic properties – and as such it can be considered a ‘smart material’. Consequently, while other high efficiency PV technologies are prone to degradation, particularly when exposed to light and elevated temperatures, CIGS exhibits an increase in power output after months of light exposure.

Additionally, CIGS technology has a **low temperature coefficient**, meaning its efficiency does not decrease as quickly as c-Si when in high temperatures – making it ideal for installation in the fast-growing solar markets of the Sun Belt region. Coupled with superior performance in diffuse light conditions, CIGS PV remains a high yield technology even in less than ideal environments.

European production equipment suppliers have established **peerless expertise in CIGS tooling** and key production processes. Many are currently supplying and profiting from the CIGS manufacturing cycle underway in China today. These European technologists are developing what can be described as next-generation CIGS production processes for the deposition and treatment of the semiconductor stack, which show promise in reducing both capex and opex costs in the future.

There exists an **unparalleled network of CIGS research institutes and endeavors** in countries including Germany, France, Switzerland, the Netherlands, Sweden, and Spain – making Europe the leading international center for CIGS technology development. When this fundamental expertise is combined with the established network of advanced production equipment suppliers, Europe has the ideal ecosystem for CIGS technology development – with laboratory developments readily transferable into scale production machinery and solutions.

Feedback loops from local manufacturers, with bidirectional knowledge sharing between lab and fab, could further enhance Europe’s leading position in CIGS technology. The stage is set for Europe to take the lead in establishing decentralized, competitive, and energy efficient CIGS production and machinery supply for the new global energy economy.

**GW-expansion
underway**

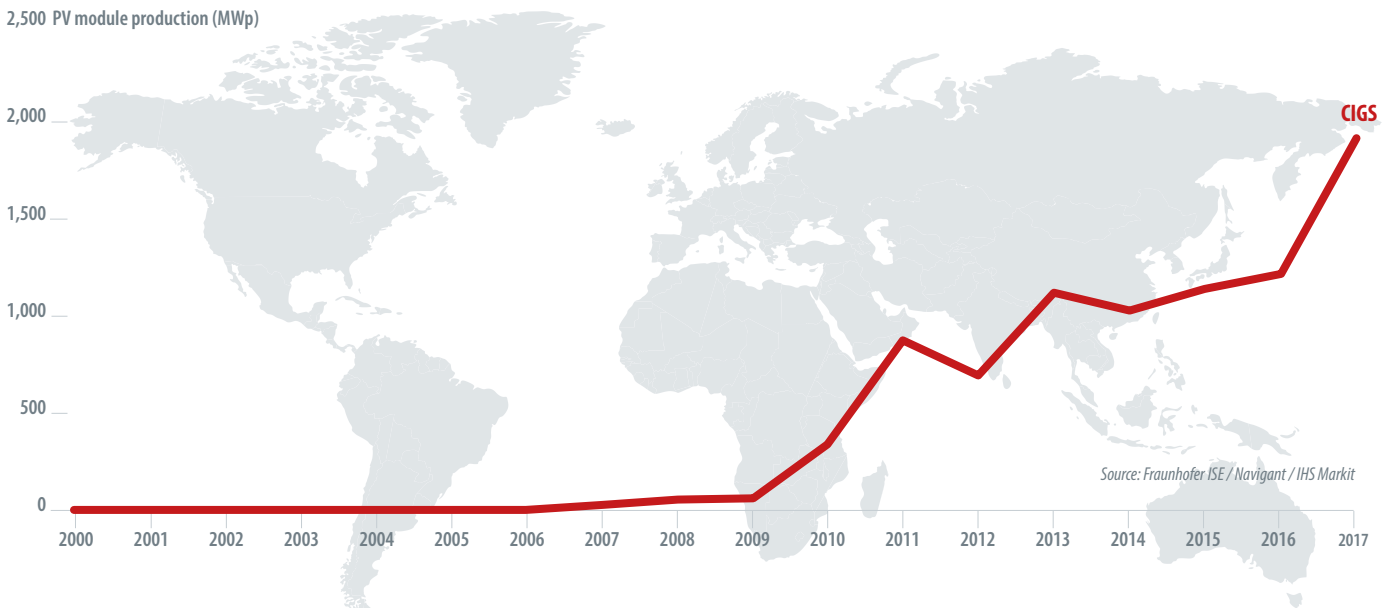
scalable

capex efficient

‘smart’ technology

Annual global production: CIGS thin film modules

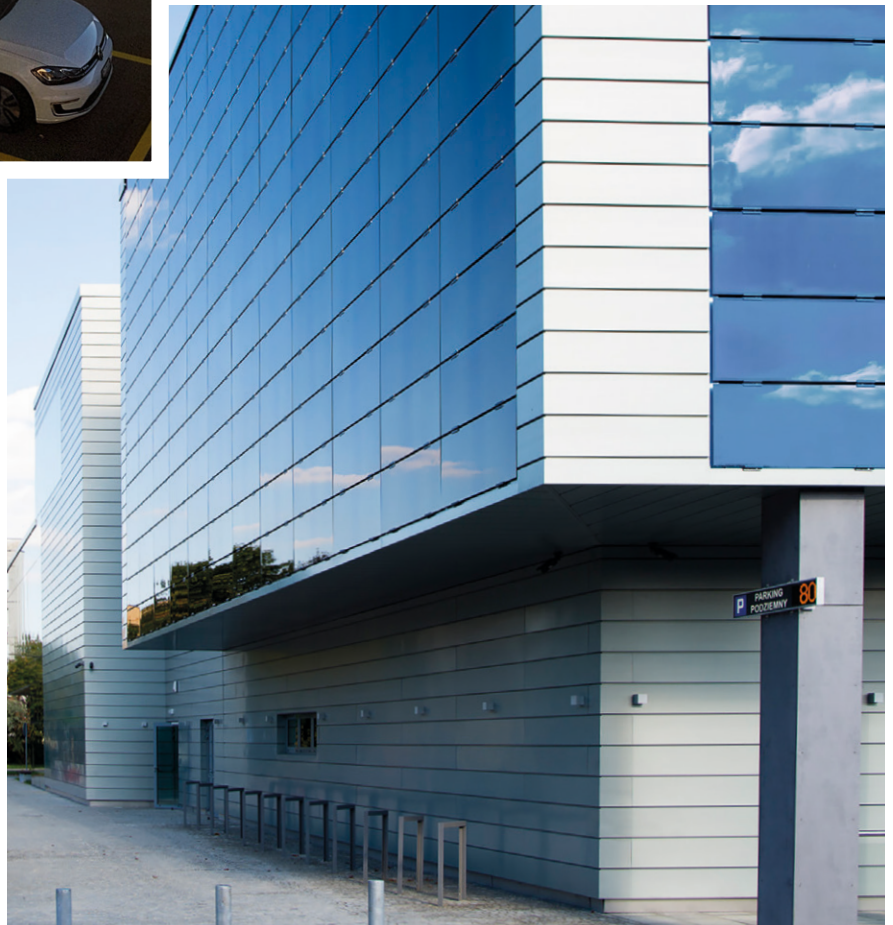
2,500 PV module production (MWp)





◀ Flexible CIGS modules can be curved over structures such as solar carports.

Frameless CIGS is ideally suited for architectural applications. ▼



- eco-friendly**
- high material efficiency**
- low carbon footprint**
- recyclable**

The environment

The global solar market has grown at a compound annual growth rate (CAGR) of 24% between 2010 and 2017. There is an undeniably leading role for solar PV as one of the central pillars of the global energy system of the future. Decentralized PV generating capacity is quickly becoming an integral feature of our built environment and mobility infrastructure.

To fulfill expected end market demand for PV modules and products, and for countries to meet their climate-protection goals, global solar manufacturing capacity will have to be vastly increased from the approximate 120 GW in place today. The need for **low cost, high throughput, high yield, and energy efficient PV production technologies**, in particular CIGS, is becoming increasingly urgent.

Thin film PV, and CIGS in particular, offers one of the most efficient semiconductor materials for the conversion of sunlight into electricity. Thin films require around **one hundredth of the semiconductor material when compared to crystalline silicon (c-Si)** – including polysilicon losses through mechanical sawing of silicon wafers: 2 micrometers (μm) of semiconductor material compared to 180 μm . CIGS PV's material usage is thus low, presenting an inherent advantage to it and other thin film technologies.

Thin film PV exhibits an **energy payback time of less than 12 months** in most parts of the world, and six months in the Sun Belt region. This is a significant improvement on c-Si, which achieves an energy payback time of between 12 and 18 months.

In terms of **carbon footprint, thin film PV has a very clear advantage** over c-Si. While commoditized mono c-Si has a carbon footprint of 50–60 g CO₂ equivalent/kilowatt hour of electricity, the carbon footprint of thin film PV is only 12–20 g CO₂ equivalent/kilowatt hour.

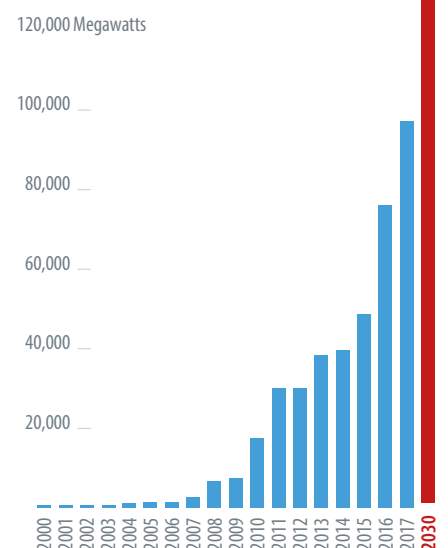
This approaches the carbon footprint currently achieved by wind power of 10–12 g CO₂ equivalent/kilowatt hour – a significant milestone, particularly given the wide range of applications for which solar PV is suitable.

Recycling and end-of-life issues are becoming increasingly important as the global PV industry continues to scale. **CIGS recycling processes are low impact and high value.** The European Union, through its member states, is currently leading the way in providing a legislative and regulatory framework to close the loop in terms of PV module lifecycle management. Following a pattern established in other industries, it is likely that other jurisdictions will follow suit in the coming years. CIGS is ideally positioned to fulfill these end-of-life standards.

The efficiency credentials of CIGS technology continue to improve through the efforts of the global R&D community. In January 2019, scientists from Solar Frontier achieved a conversion efficiency of 23.35% on a 1 cm² cell. It has not only been demonstrated that single junction CIS technologies easily get into the range of top c-Si record efficiencies, the technology has also proven again, that material and device innovation also enable the substitution of cadmium sulphide in this efficiency range. This shows the importance of framework conditions which enable continuous innovation and efficiency improvements in photovoltaics. In order to find the best solution, it is essential not locking out certain material pathways, but rather empowering researchers to develop efficiency pathways in conjunction with assessing all potential material alternatives.

Solar power installed

Source: BP (historic data) / LONGi (forecast)



Supported by:



Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

This document has been prepared with input from the attendees of the IW-CIGSTech9 conference, hosted by ZSW and HZB. Detailed contributions were made by (in alphabetical order):

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Conclusion

The energy system of the future will undoubtedly look very different to that of today. **Efficient and proven PV technologies** will be needed to fulfill solar's role as one of the pillars of a carbon-constrained global economy.

Given this pressing need, successful PV technologies will have to be **widely applicable and cost effective in traditional rooftop and ground-mounted PV applications**, as well as in the built environment, as they are integrated into public and private mobility solutions. The required production processes will have to be scalable, with low material consumption, and be suitable for high value recycling at end of life.

CIGS is ideally positioned to meet these needs today, with its role in doing so set to grow in the future.

Momentum is building behind CIGS technology, with new developments demonstrating its inherent advantages alongside innovative new applications.

A window of opportunity presents itself for investment in CIGS technology today to fulfill the needs of the carbon constrained global economy of tomorrow!



The ZSW institute's building in Stuttgart-Vaihingen features a striking CIGS facade. ▲

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