
Photovoltaic Technology: From R&D to Industry



Andreas Bett

Fraunhofer Institute for Solar Energy Systems ISE

French Technology Academy

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www.ise.fraunhofer.de

AGENDA

- Fraunhofer Institute for Solar Energy Systems ISE
 - Vision and Motivation
- Solar as a Pillar for Solving the Climate Challenge
- Perspectives of Photovoltaics
 - Results at Fraunhofer ISE
 - Industrial production in Europe
- Conclusions

Fraunhofer Institute for Solar Energy Systems ISE

Research for the Energy Transformation



Directors

Dr. Andreas Bett

Prof. Dr. Hans-Martin Henning

Staff

approx. 1200

Budget 2018

Operation € 83.5 million

Investment € 10.8 million

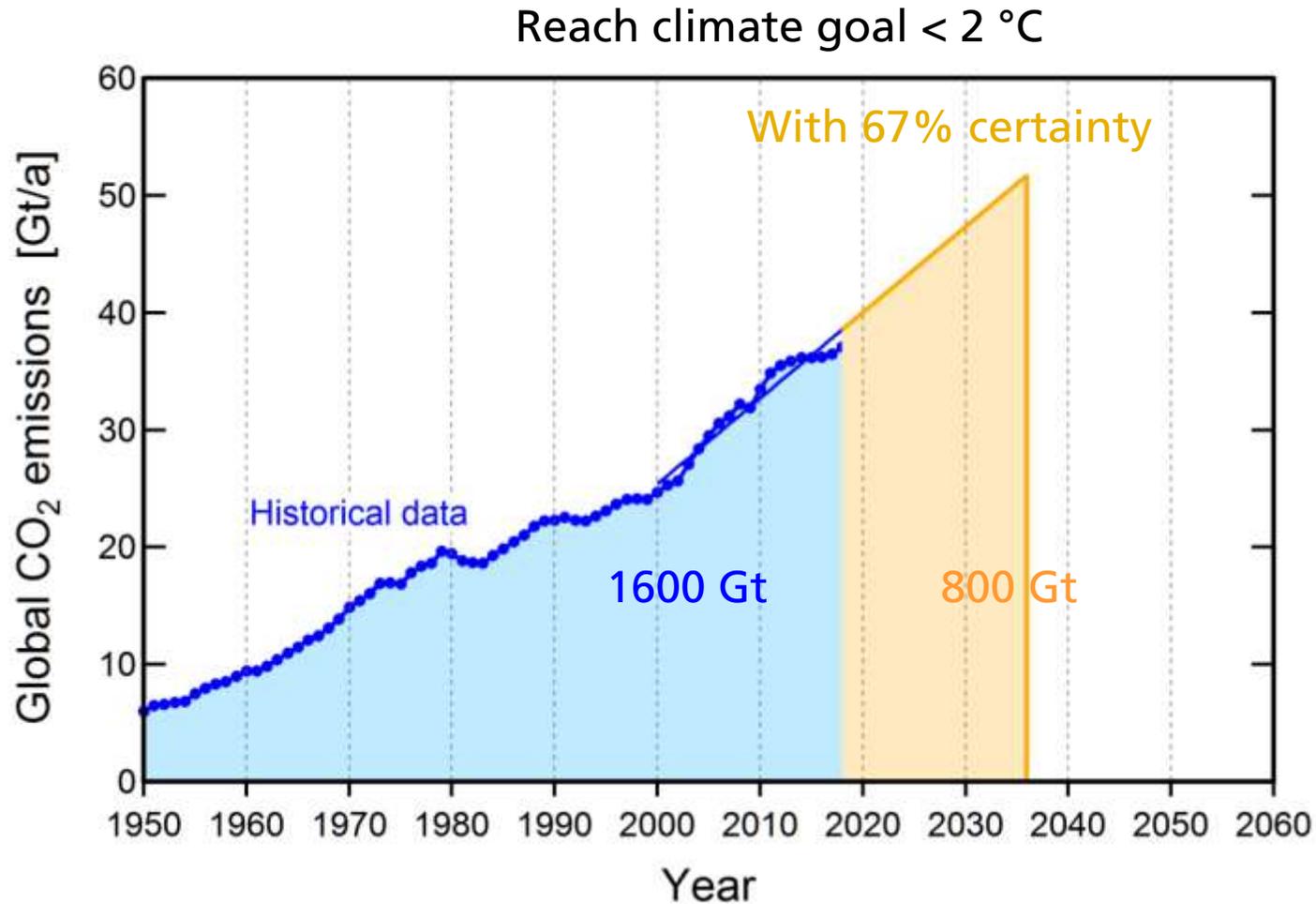
Total € 94.3 million

Our Motivation: Offer Solutions for the Climate Challenge

CO₂-Emission Reduction is a MUST!



Global CO₂ Emissions to Fulfill the Paris Agreement

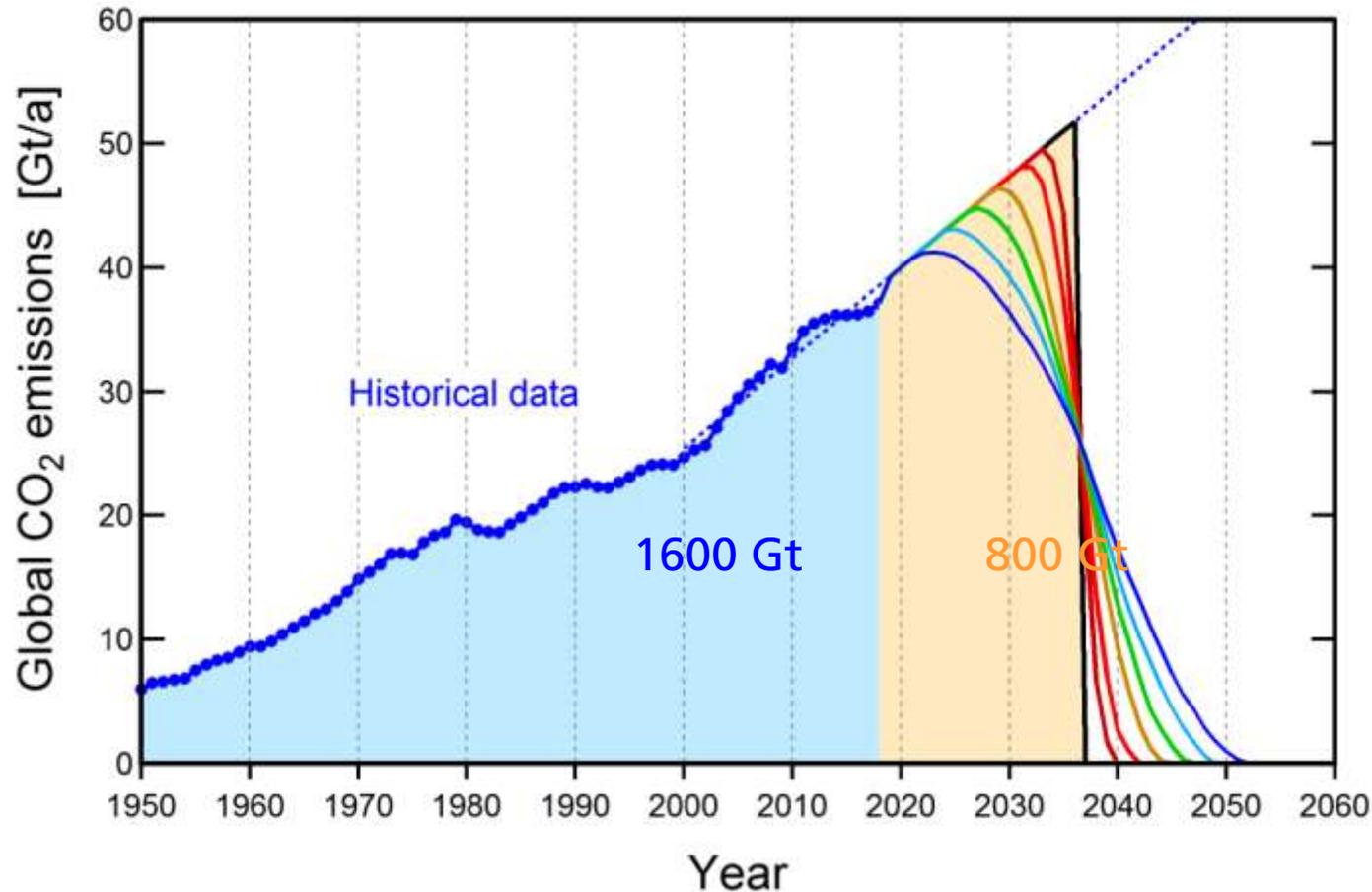


Derived from geophysical models, summarized in [1]

→ 2035 the remaining CO₂-budget is used up!

Global CO₂ Emissions to Fulfill the Paris Agreement

Reach climate goal < 2 °C



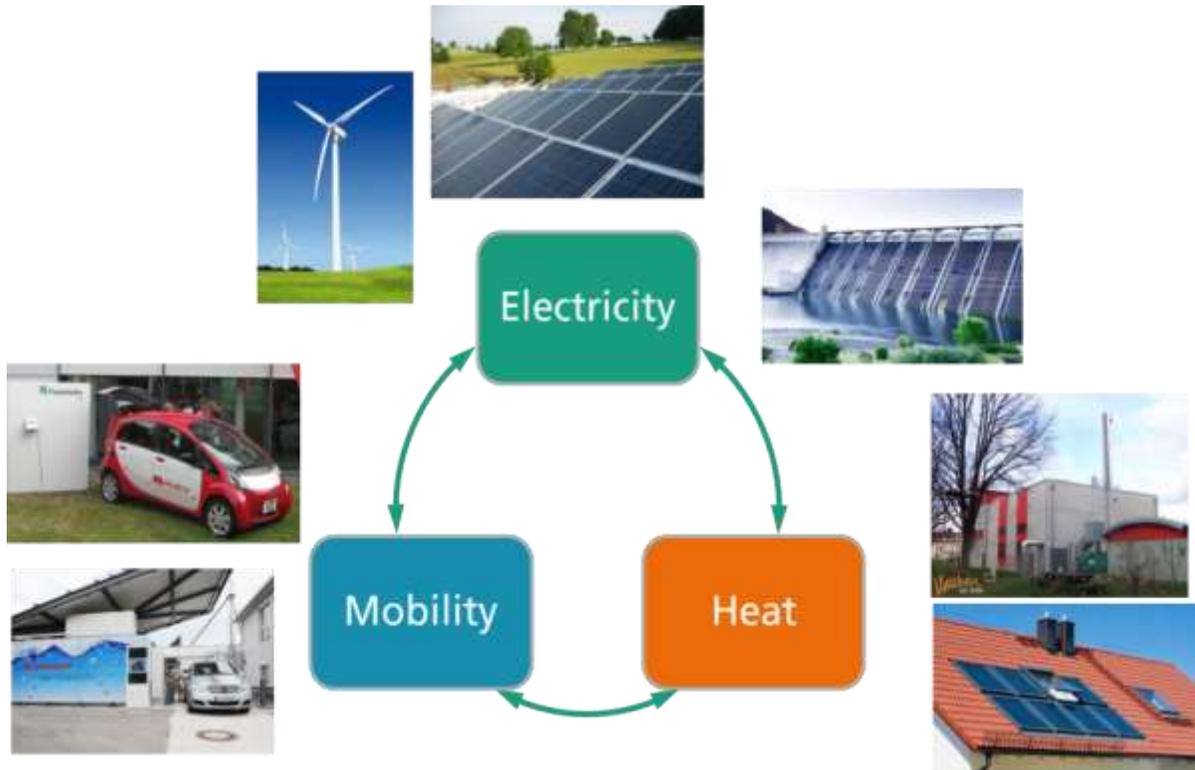
It is still possible!

BUT:
The coming 10 years are decisive

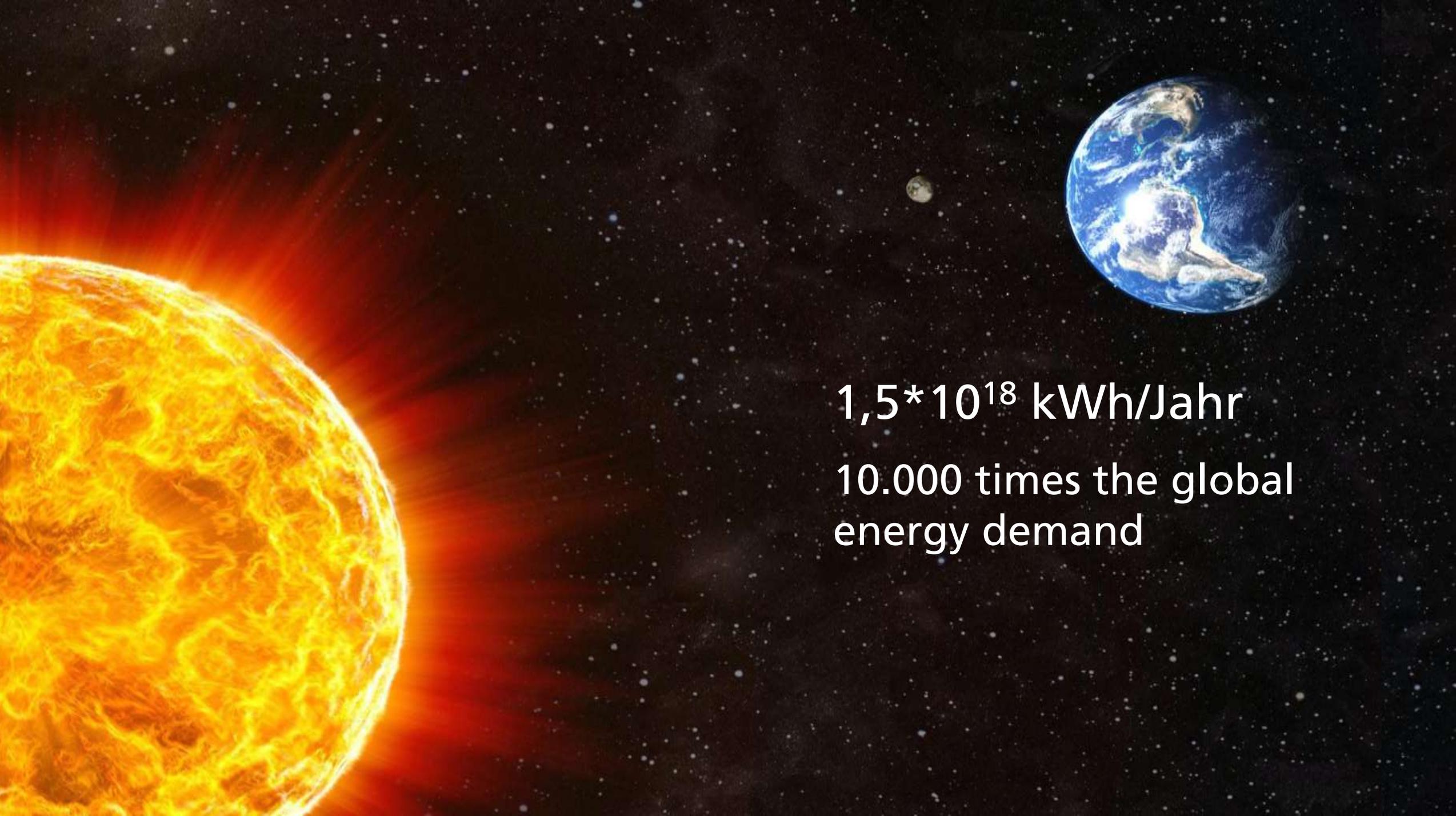
It is urgent to act now!

The »Energiewende« demands for more Electricity

CO₂-Reduction in all Sectors is a MUST!



- Sector coupling in the future energy system demands for more electricity
 - In spite of energy efficiency more electrical energy is needed
 - For Germany:
today: ~ 500 TWh
2030 ~ 750 TWh, 2050 ~ 1400 TWh
- Wind and PV are the pillars of the future energy system



$1,5 \cdot 10^{18}$ kWh/Jahr

10.000 times the global
energy demand

Silicon Photovoltaic R&D: Past and Present

Phase 0:
R&D Fundamental
1839 – ~1990



1839: A. Becquerel:
Photovoltaic effect discovered



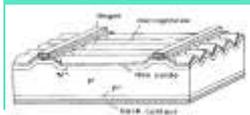
1954 Bell Labs: First Si solar
cell with 6 %



1958: First use of Si PV cells in
Vanguard I



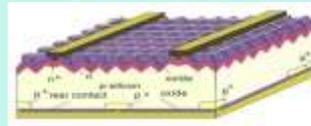
1961: Shockley-Queisser Limit



1986: 20 % mono-Si solar cell

Phase 1:
R&D to approach SQ limit
~1990 - ~ 2017

Better passivation schemes, local
passivation, PERx structures



1999: M. Green first
25 % Si-cell

Heterojunction solar cells
back contact solar cells
passivated contacts



2017: Kaneka 26.7 %

Transfer to industry

New production technologies

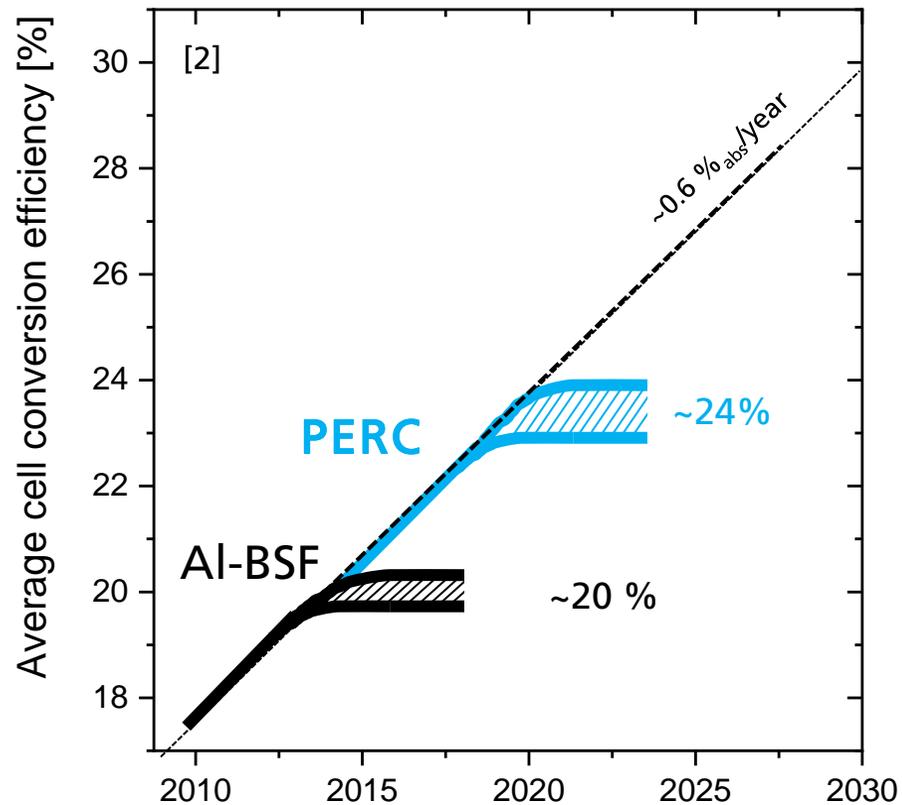
Al-BSF

PERC

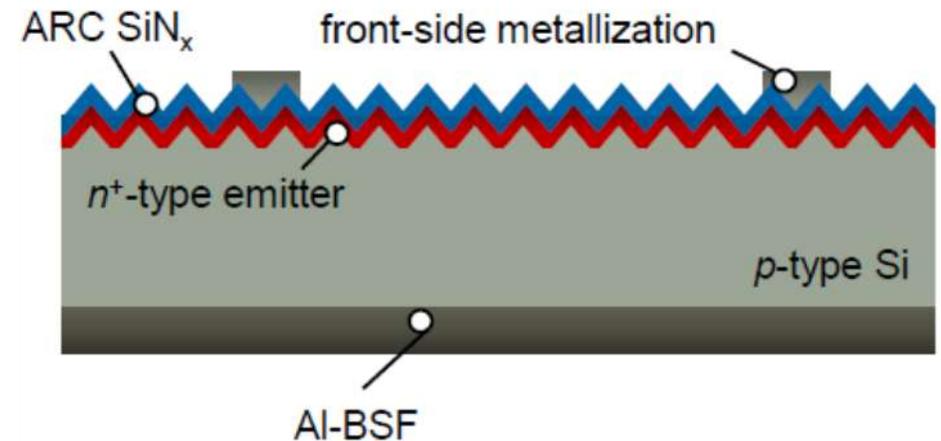
HIT

TopCon

Increasing the Efficiency Industrial Realisation

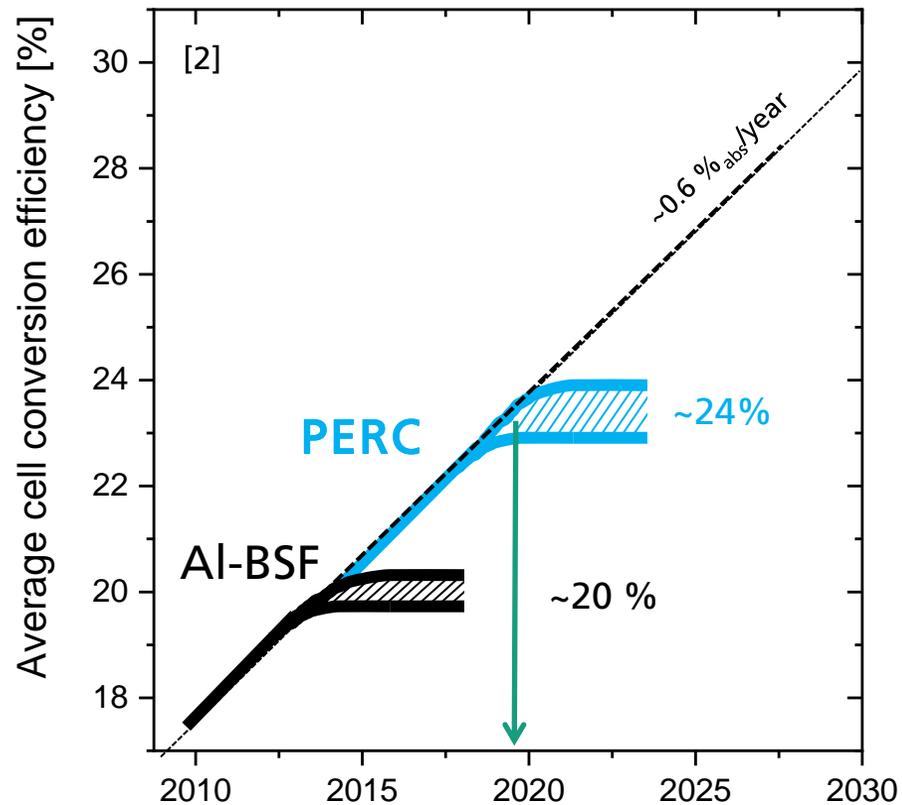


- Now for many years:
Increase of efficiency in industrial production
~ 0,6 %_{abs}/year [1]
- Efficiency limitation due to full area Al-BSF (back surface field) rear side

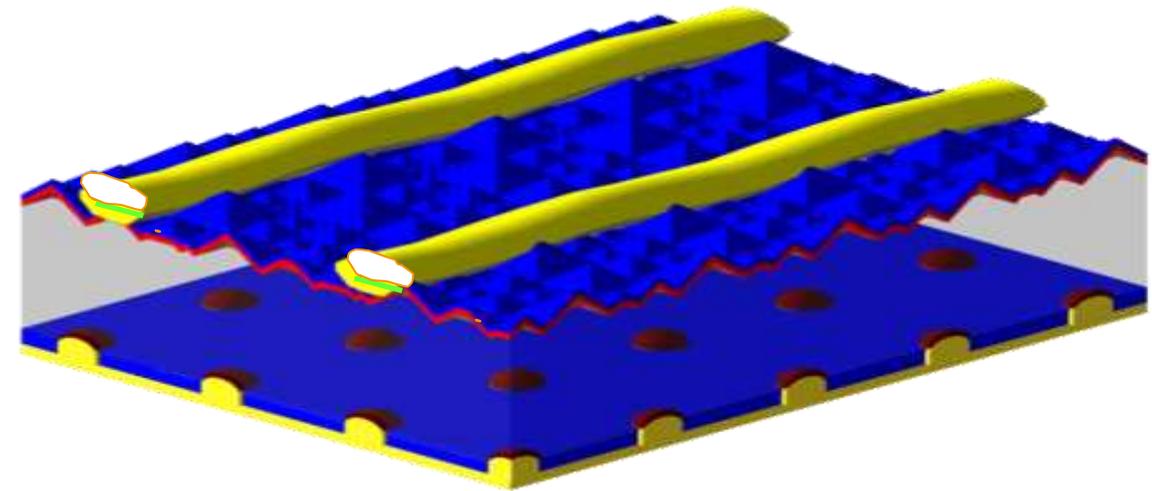


Increasing the Efficiency

Industrial Realisation



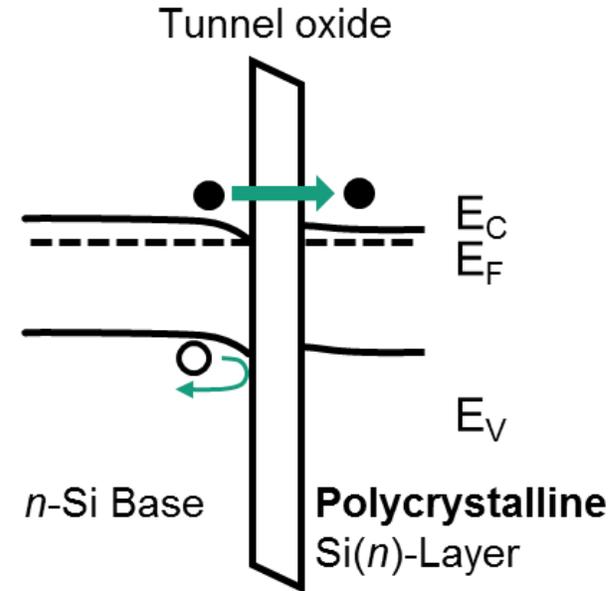
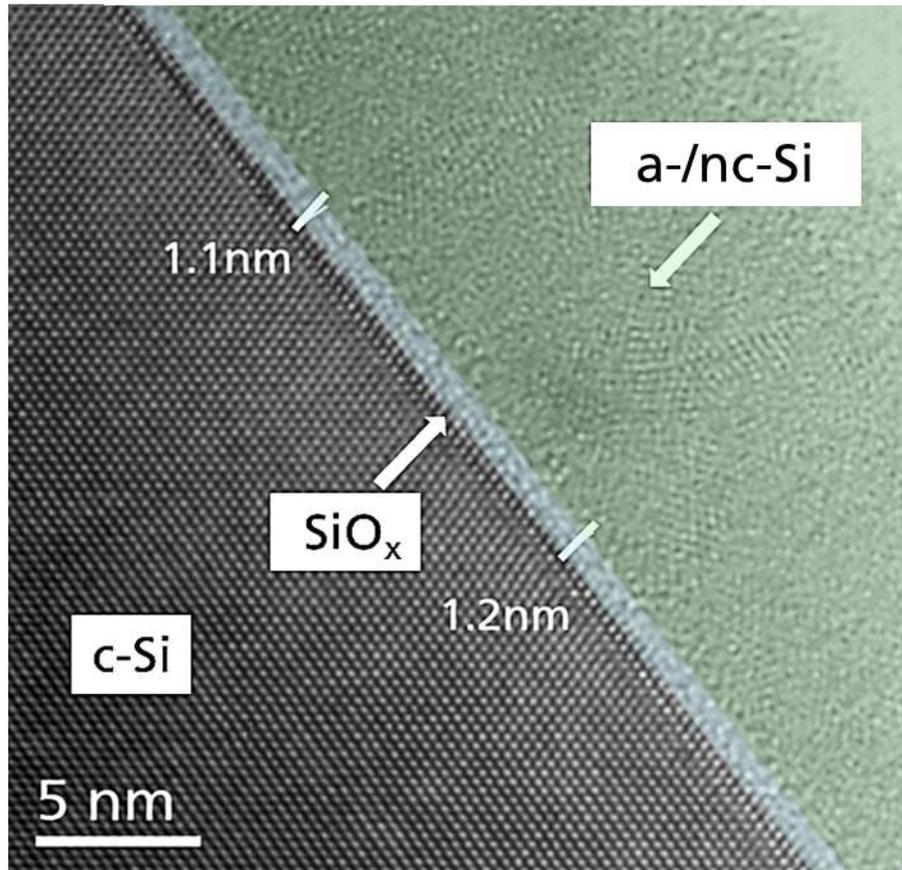
- Now for many years:
Increase of efficiency in industrial production
~ 0,6%_{abs}/year [1]
- Replacement of the full area Al-BSF with a
partial rear contact (PRC)



Increasing the Efficiency: R&D Innovation

Passivating Contacts with Oxide and Polysilicon

TOPCon Structure



Post, IEEE Transactions on Electron Devices (1992)

F. Feldmann et al., *SOLMAT* 120 (2014)

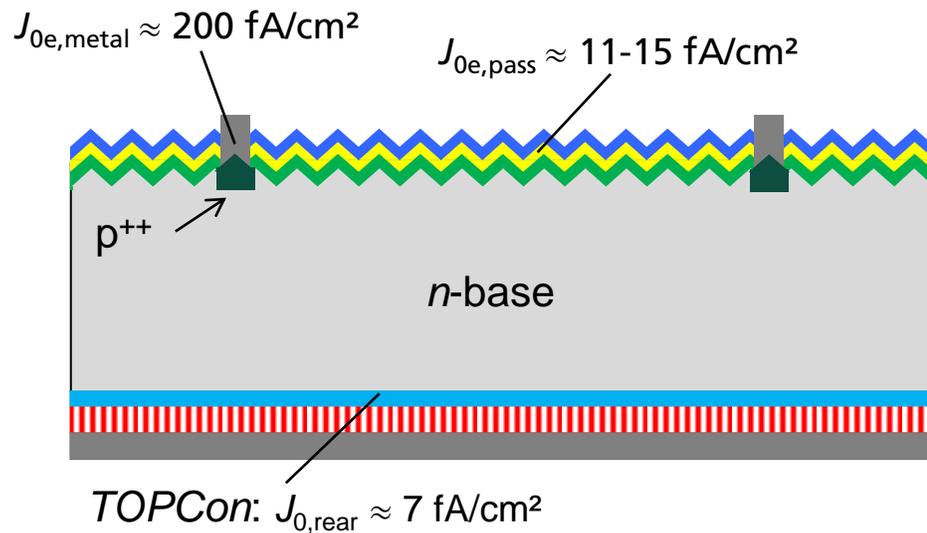
U. Römer, et al. IEEE Journal of Photovoltaics (2015)

D. Yan Solar Energy Materials and Solar Cells (2015)

Present R&D Status

TOPCon Record Cells with Top/Rear Contacts

Material	Area	V_{oc} [mV]	J_{sc} [mA/cm ²]	FF [%]	η [%]
<i>n</i> -type Mono	4 cm ² (da)	724	42.9	83.1	25.8*

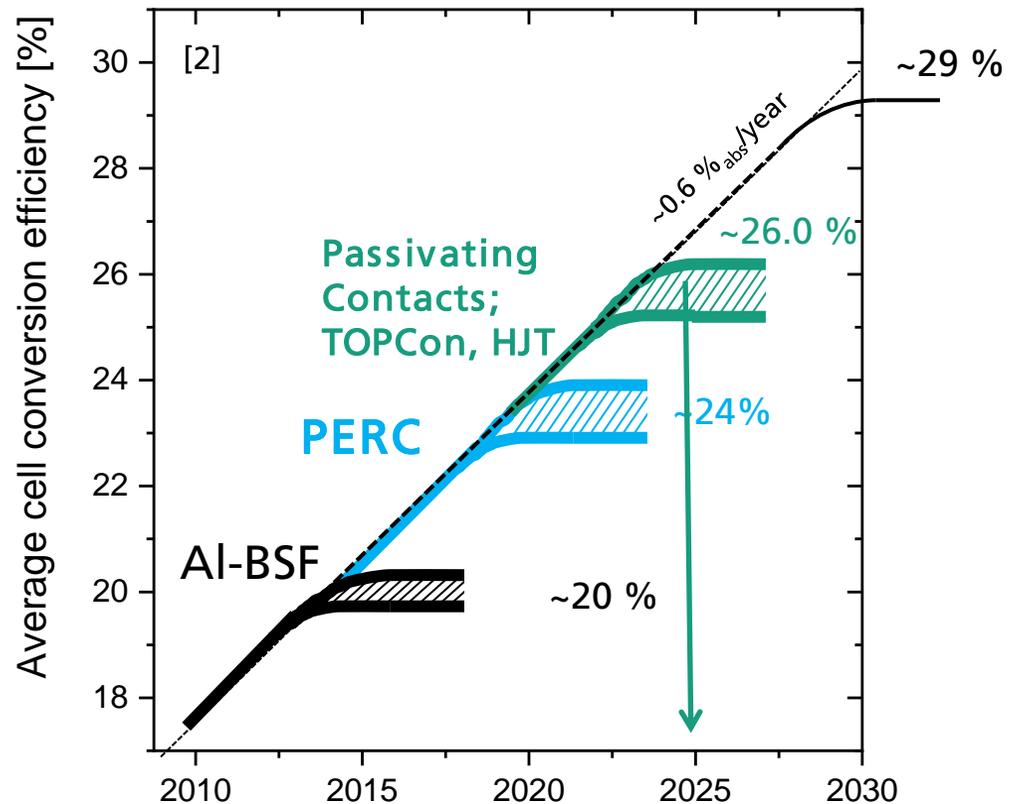


→ World record efficiency of **25.8 %** for both side contacted solar cells

* confirmed by Fraunhofer ISE Callab

Innovations with Respect to Efficiency

Industrial Realisation – A View into the Coming Years



- Now for many years: increase of efficiency in industrial production $\sim 0,6\%_{\text{abs}}/\text{year}$ [1]
- Industrial production with 26% seems possible
- The theoretical efficiency limit for Si solar cells is limited to $\sim 29\%$

What we will see after 2025 in industrial production?

Silicon Photovoltaic R&D: Past and Present

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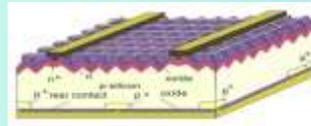
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passivated contacts



2017: Kaneka 26.7 %

Phase 2:
R&D beyond SQ-limit
starting ~ 2017

Technologies for highest efficiency

- III-V on Si
- Perovskite on Si
- Thin-film III-V-based multi-junction

Improve sustainability

Transfer to industry

New production technologies

Al-BSF

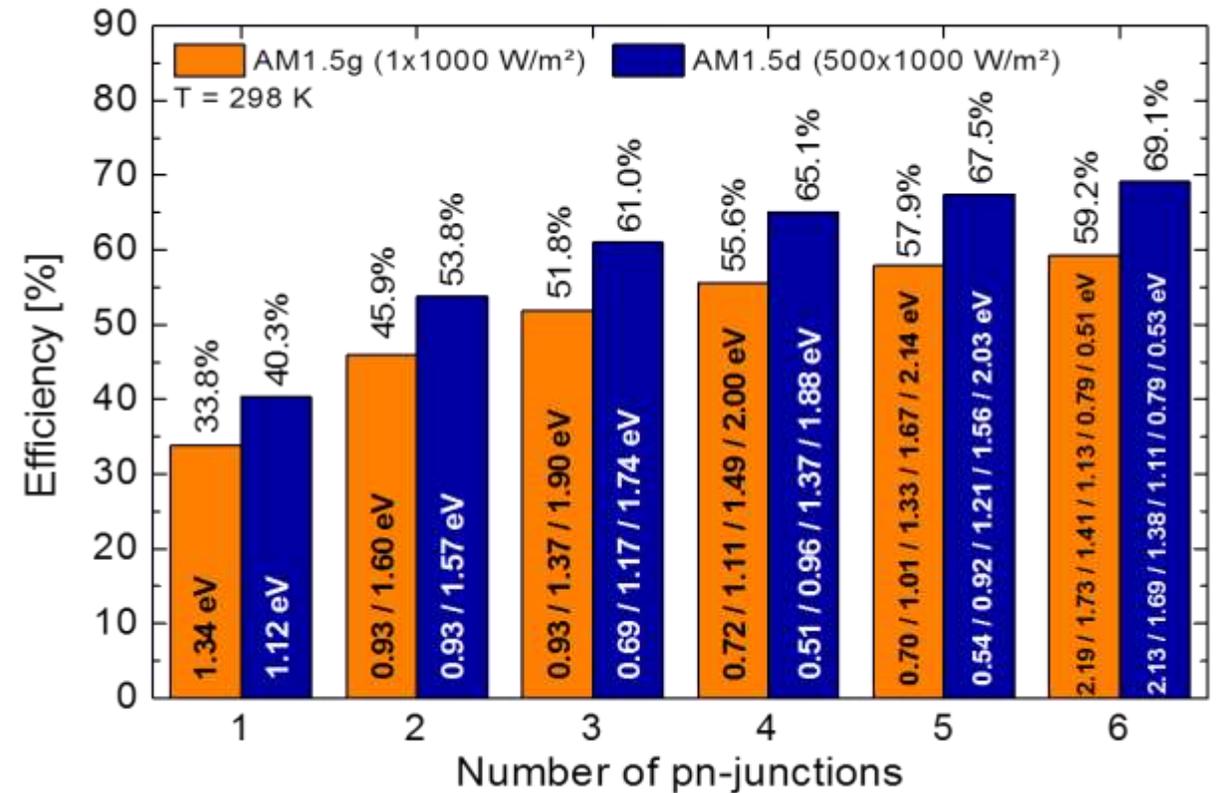
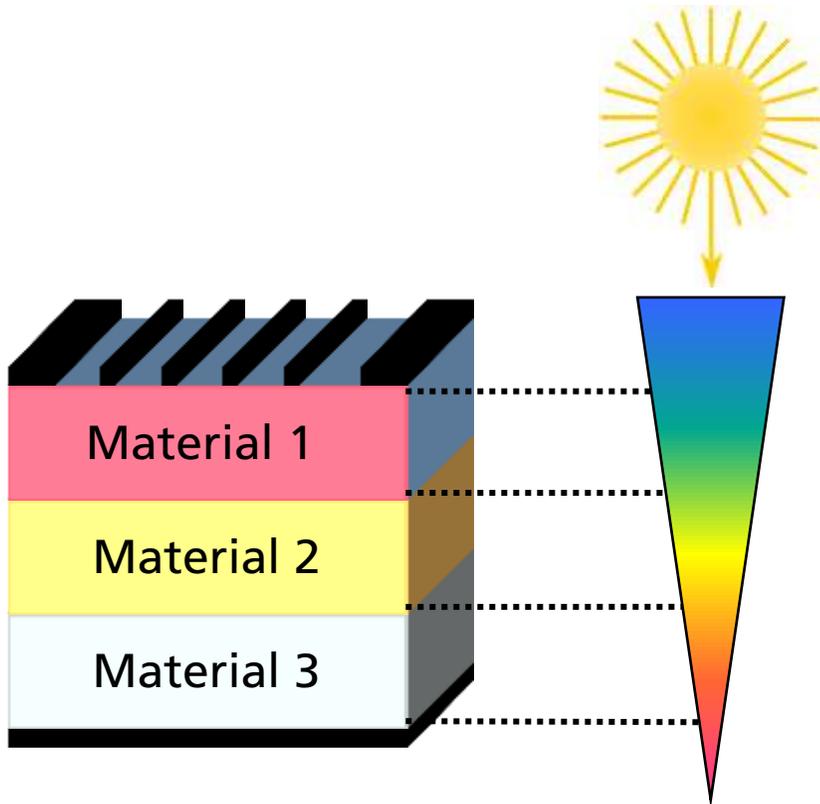
PERC

HIT

TopCon

What can be expected from Multi-junction Solar Cell?

A 50 % Efficient Solar Cells are realistically achievable!

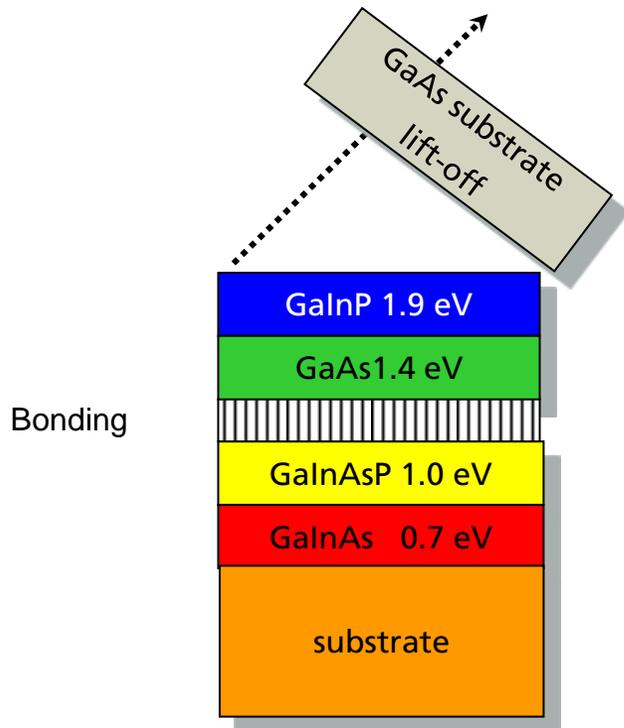


calculation based on Shockley-Queisser approach

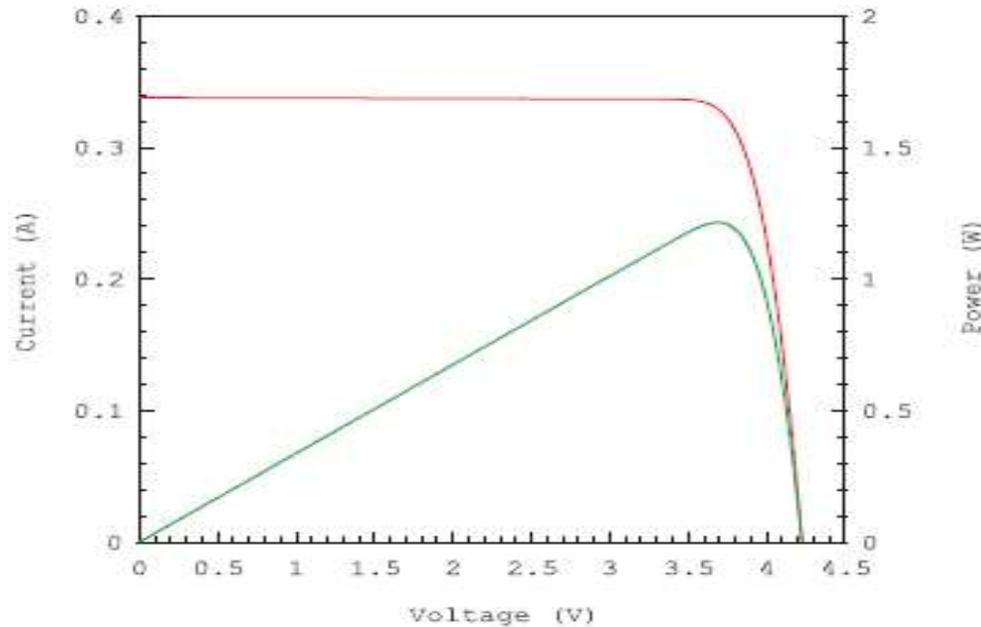
4-Junction Cell Efficiency under Concentration

4-junction bonded to InP

$\eta = 46.0\% @ 500 \text{ suns}$



I-V CURVE
ASTM E927-10 0.0520cm² (designated area) T-HIPSS

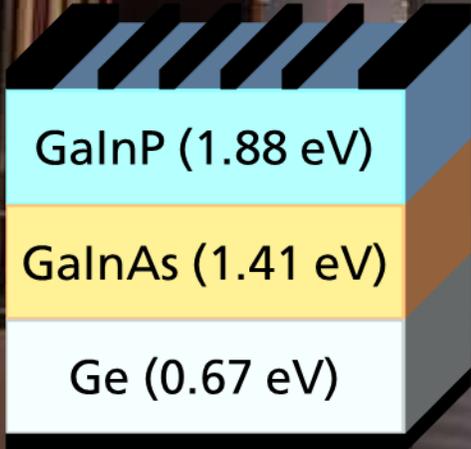


Date : 8 Oct 2014
Data No :
lot21-03-x19y04-01
Sample No :
lot21-03-x19y04
Repeat Times : 9

Isc	337.9	mA
Voc	4.227	V
Pmax	1.215	W
Ipmax	329.8	mA
Vpmax	3.686	V
F.F.	85.1	%
Eff (da)	46.0	%
DTemp.	25.0	°C
MTemp.	24.6	°C
DIrr.	50.8	W/cm ²
MIrr.	50.9	W/cm ² (1st)
	50.8	W/cm ² (2nd)
	50.0	W/cm ² (3rd)
	50.9	W/cm ² (4th)

Scan Mode
Weighted average of
(Isc to Voc) and
(Voc to Isc)



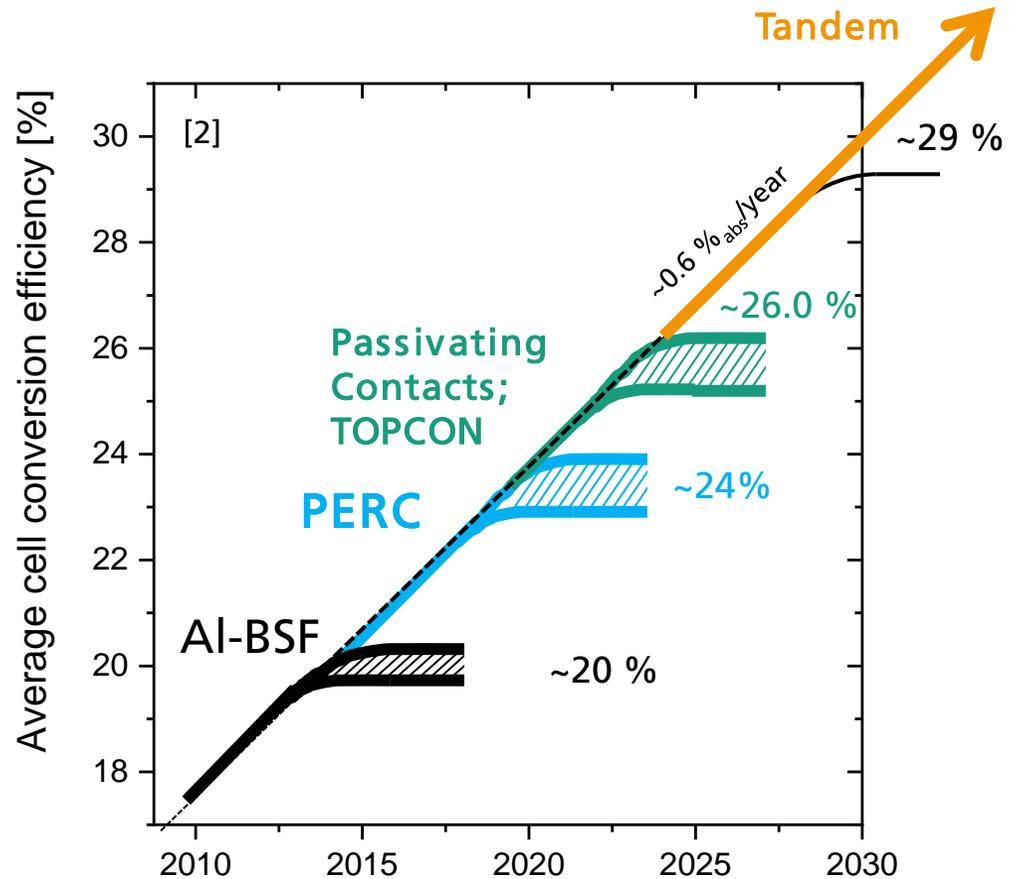


III-V tandem cells a proven space technology

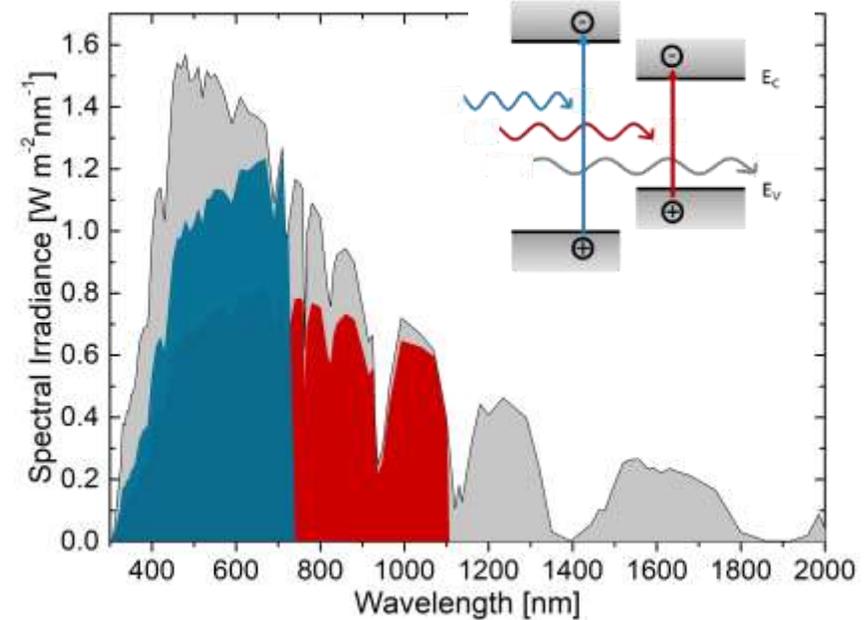
Space Market
< 1 MWp/year
< 2500 m²/year

Beyond the Shockley-Queisser Limit

Tandem Solar Cells on Silicon

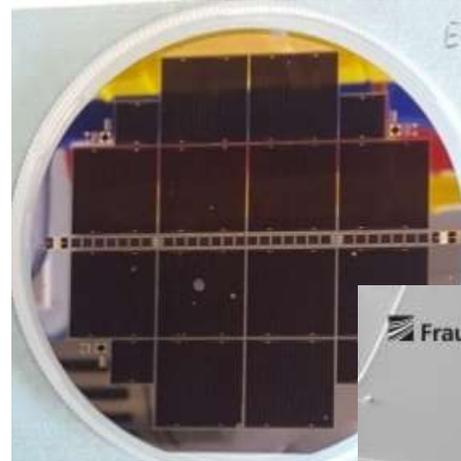
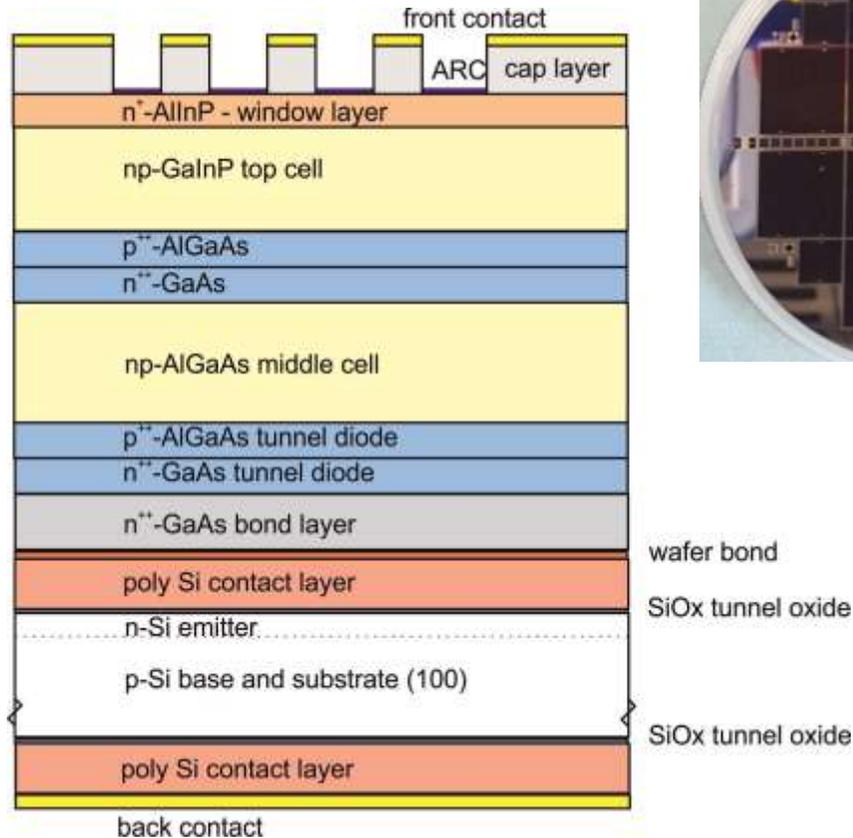


- Tandem cells with silicon as bottom cell
 - III/V top cell
 - Perovskite top cell

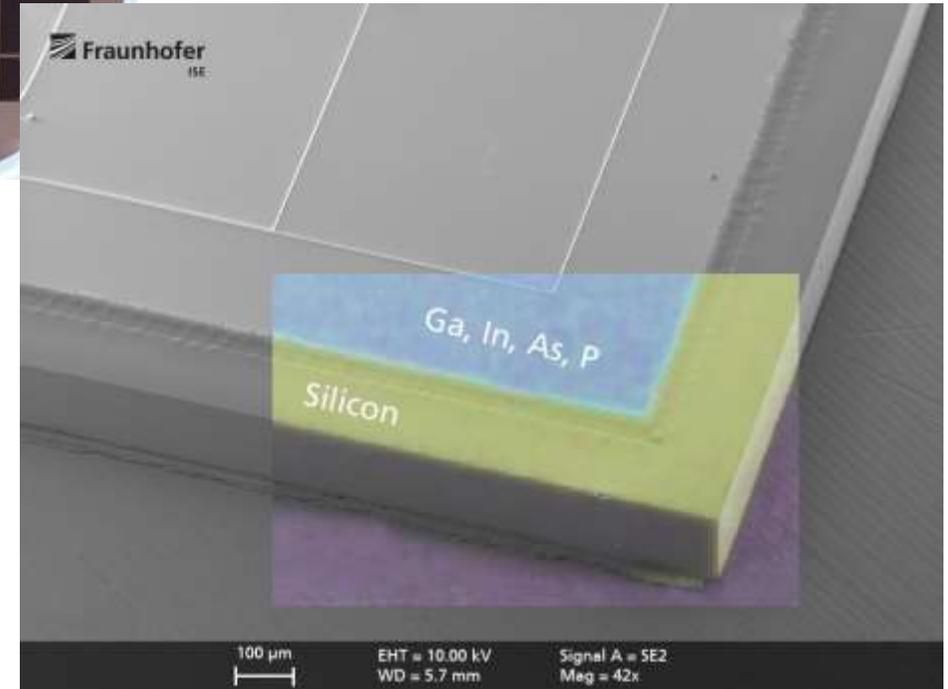


Technology Status 2-Terminal (Monolithic) III-V/Si Tandem

Easy Module Integration by Series Connected Strings



~ 2,5 μm III-V layers on Silicon



Technology Status 2-Terminal III-V/Si Tandem New World Record in 2018

2018

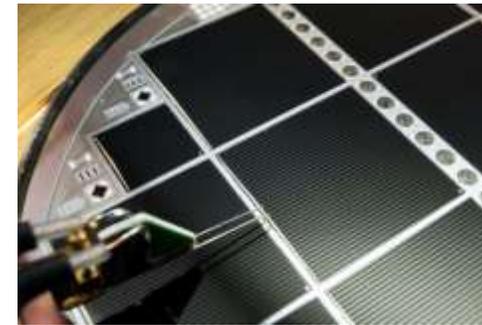
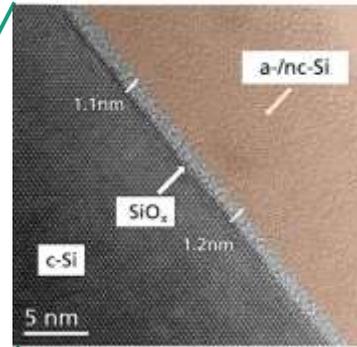
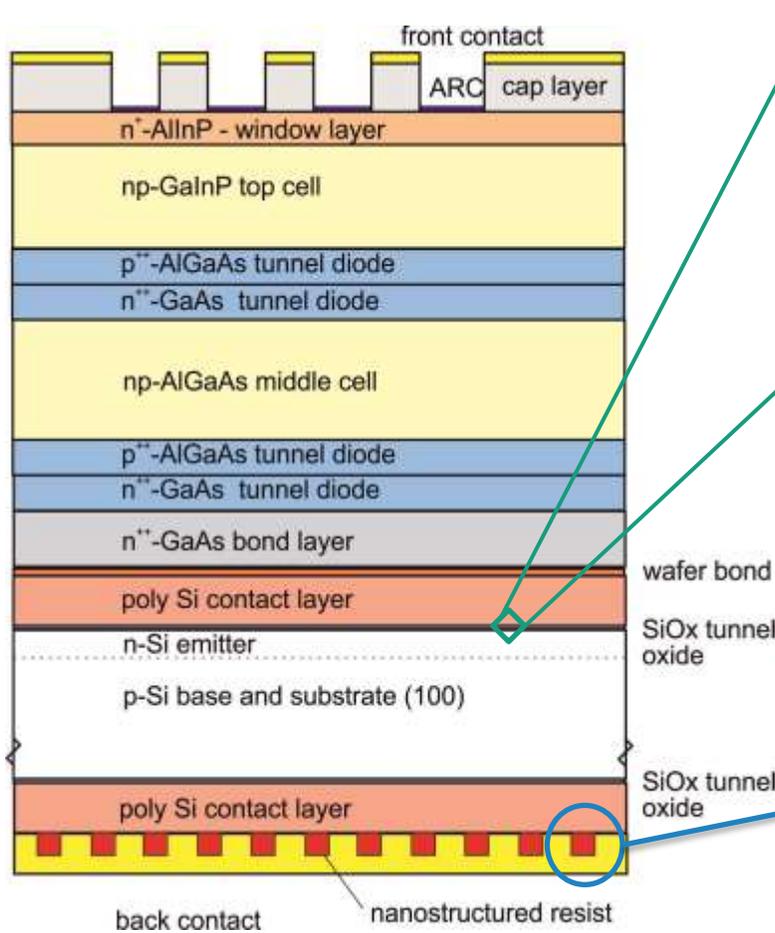
III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration

Romain Cariou^{1,2,3*}, Jan Benick^{1,2}, Frank Feldmann^{1,2}, Oliver Höhn¹, Hubert Hauser¹, Paul Beutel¹, Nasser Razek¹, Markus Wimpfinger¹, Benedikt Bläs¹, David Lackner¹, Martin Herrle¹, Gerald Siefer¹, Stefan W. Glanz^{1,2}, Andreas W. Bett¹ and Frank Dimroth^{1,2}

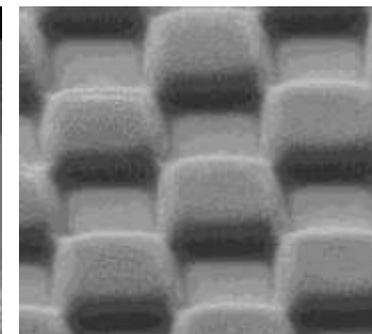
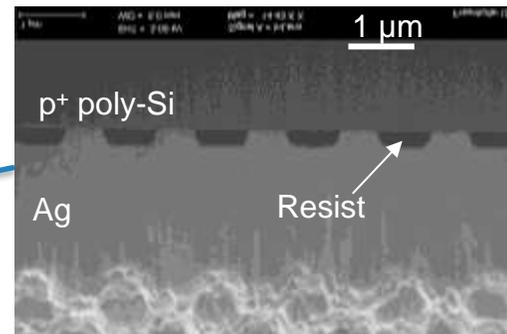
Silicon dominates the photovoltaic industry but the conversion efficiency of silicon single-junction solar cells is intrinsically constrained to 29.4%, and practically limited to around 27%. It is possible to overcome this limit by combining silicon with high-bandgap materials, such as III-V semiconductor, in a multi-junction device. Significant challenges associated with this material combination have hindered the development of highly efficient III-V/Si solar cells. Here, we demonstrate a III-V/Si cell reaching similar performances to standard III-V/Ga triple-junction solar cells. This device is fabricated using wafer bonding to permanently join a GaInP/GaAs top cell with a silicon bottom cell. The key issues of III-V/Si interface recombination and silicon's weak absorption are addressed using poly-silicon/SiO₂ passivating contacts and a novel rear-side diffraction grating for the silicon bottom cell. With these combined features, we demonstrate a two-terminal GaInP/GaAs/Si solar cell reaching a mean AM1.5G conversion efficiency of 33.3%.

Crystalline silicon solar cells have been dominating the photovoltaic market for decades. Today, the overall cost of photovoltaics is driven by system components such as installation, cabling and inverters. One out of three costs are semi-conductor, for a further reduction of the levelized cost of electricity, it is crucial to improve the conversion efficiency. One of the set industrial crystalline silicon solar cells have conversion efficiencies in the range of 20–23% while a few laboratory-type, champion devices reach more than 27%, with 34.7% being the current record efficiency. The theoretical Shockley-Queisser radiative efficiency limit for silicon solar cells with a bandgap of 1.12 eV is 33%. However, due to silicon's indirect bandgap, Auger recombination because the dominant intrinsic loss channel, which reduces the theoretical upper limit to 24.6%. Realistic boundary conditions such as the necessity to attach contacts to the cell and incomplete light harvesting reduce the practical efficiency limit to around 17%. Thus, high crystalline silicon solar cells are intrinsically close to their performance limit, new concepts are becoming crucial.

A well-known strategy for increasing solar cell conversion efficiency is the multi-junction architecture in which a set of semiconductor absorbers with appropriate bandgaps are used. This approach reduces thermodynamic losses arising from the absorption of photons with excess energy compared to the semiconductor bandgap, as well as transmission losses of photons with insufficient energy. Various multi-junction approaches are found in the literature. First, solar cells can be integrated in an optical system, splitting the light into different wavelength bands that are then individualized into solar cells with appropriate bandgaps^{1–3}. Alternatively, multijunction solar cells can be mechanically stacked with separate contacts on each cell, referred to as the multi-terminal approach^{4–6}. By doing so, no subcell current matching is required if every cell has its own electric circuit throughout the photovoltaic module and its own inverter. An efficiency of 35.8% was recently reported for a mechanically stacked two-terminal device (GaInP/GaAs on silicon, 1.2 cm², AM1.5G) by connecting all subcells in series, this device reaches 30.8% efficiency⁷. However, all industrially realized multi-junction cell architectures so far require applications, necessitating photovoltaics or thin-film cells use a two-terminal approach. This is due to the lower complexity of producing these devices and implementing them into photovoltaic modules. Two-terminal cells can be connected by standard series or parallel connection with little space between the cells and with only one electric circuit. Moreover, the parasitic absorption in non-photosensitive layers is reduced (no interdigitated electrodes in the device). Thus, it is expected that two-terminal cells will also be favourable for future applications of high-performance III-V on silicon (III-V/Si), the double dash approach refers to mechanically two-terminal integration (hetero) tandem solar cells. However, it should be mentioned that multi-junctions with high mobility and low cost may enable new architectures for multi-terminal devices in the future. Two material systems are currently discussed as high bandgap absorbers on silicon: perovskite^{8–11} and III-V materials^{12–15}. While the first approach has a clear low-cost potential, its stability and reproducibility are still major issues. In contrast, III-V photovoltaics, while being more expensive, are a proven high-efficiency technology already used in space satellites and concentrating photovoltaics, with champion cell efficiencies up to 38.8% for a five-junction solar cell fabricated at 1 cm² and one cell for a four-junction device measured at 100 suns¹⁶. Experimentally, III-V solar cells achieve the highest spectral efficiency among the high bandgap materials and thus appear as ideal tandem partners for silicon, efficiency wise¹⁷. To apply III-V on silicon, strategies to



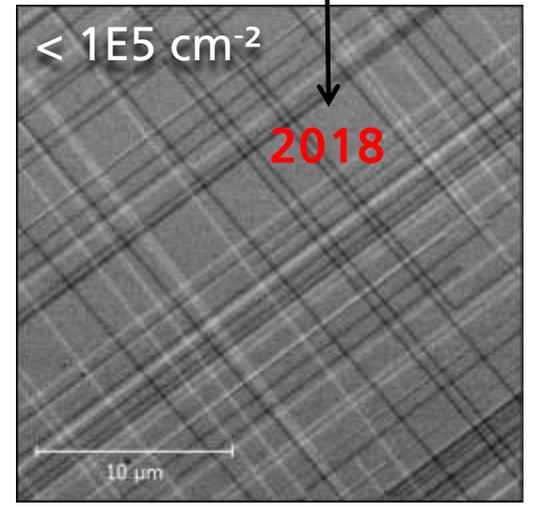
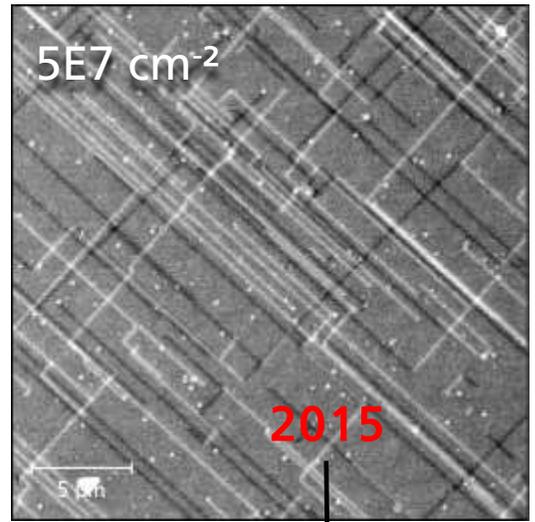
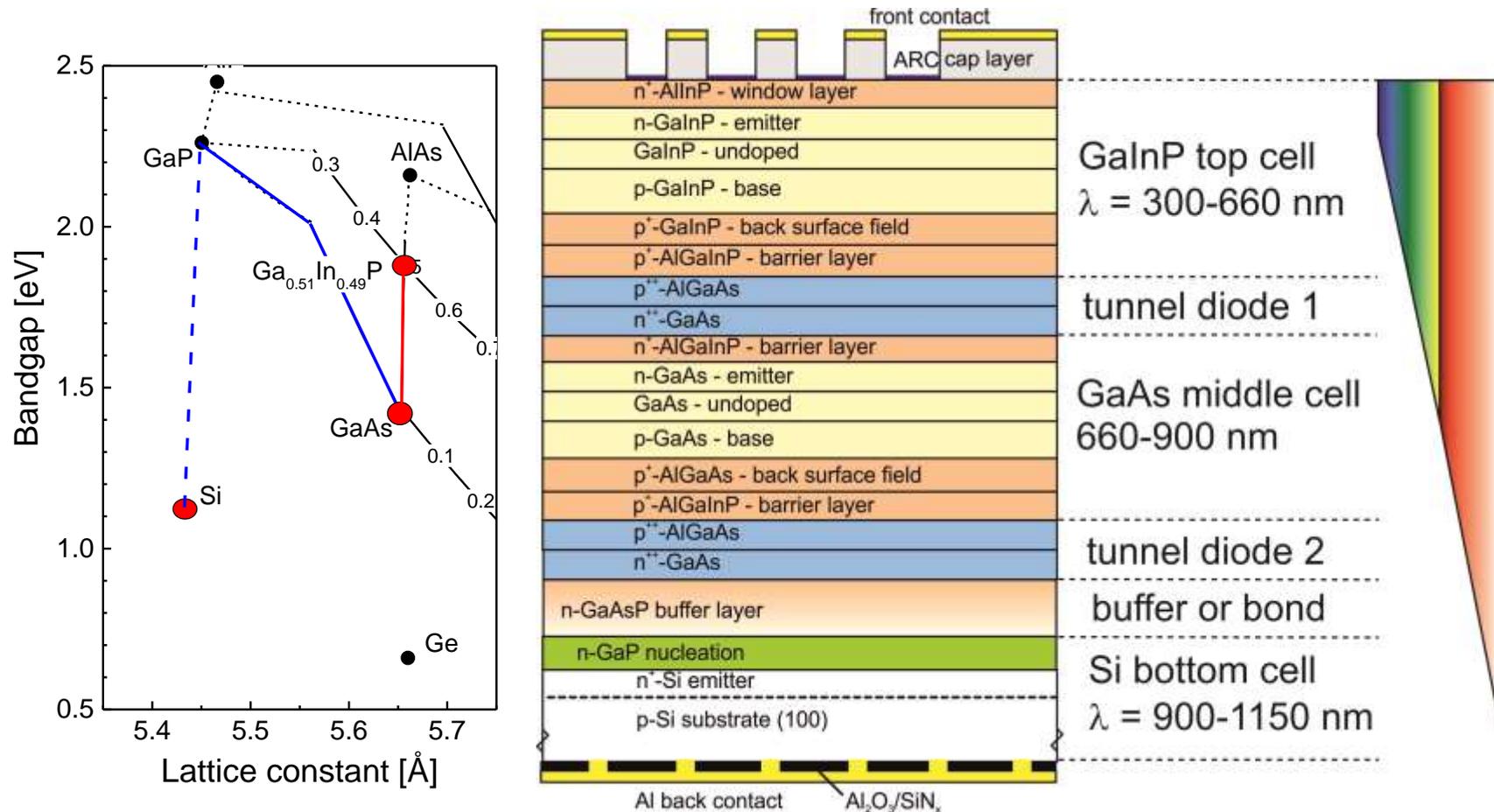
V_{oc} [V]	J_{sc} [mA/cm ²]	FF [%]	η [%]
Gen 3			
3.127	12.7	83.8	33.3



Demonstrated cell efficiency potential > 33%

Technology Status 2-Terminal III-V/Si Tandem

Direct Epitaxy Growth on Silicon



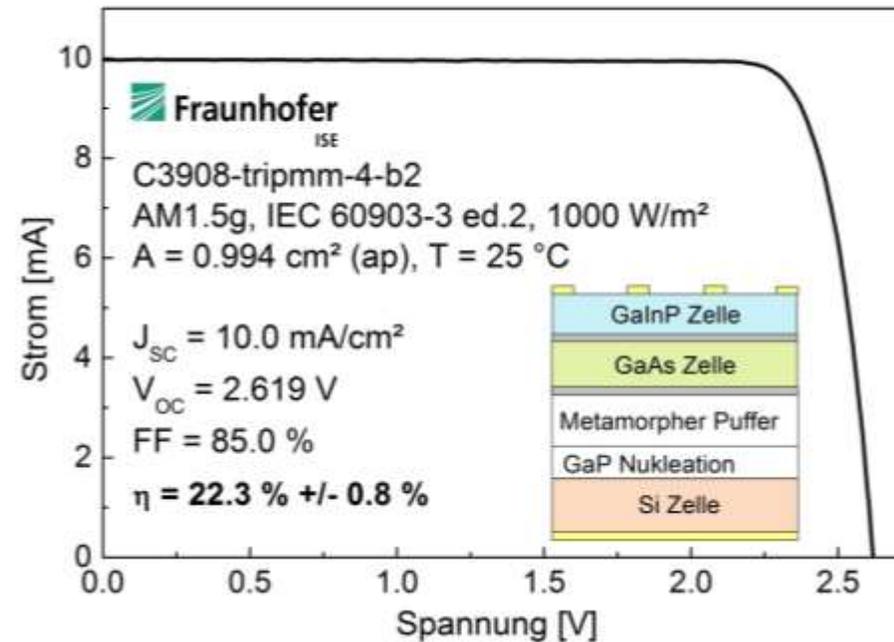
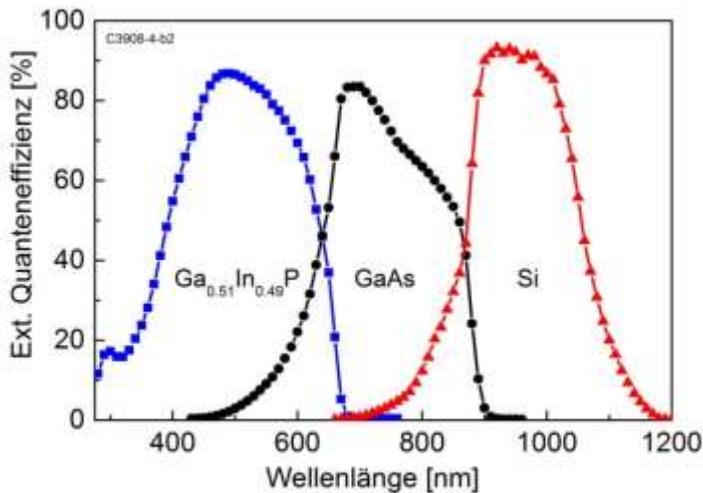
Technology Status 2-Terminal III-V/Si Tandem

World Record for Direct Epitaxy Growth on Silicon

2018



Efficiency > 30 % also realistic for direct growth but further R&D needed



Photovoltaik-Trend Tandemsolarzellen – Wirkungsgradrekord für Mehrfachsolarzelle auf Siliciumbasis

Siliciumsolarzellen dominieren heute den Photovoltaikmarkt aber die Technologie nähert sich dem theoretisch maximalen Wirkungsgrad an, der mit Silicium als alleinigem Absorbermaterial erreicht werden kann. Tandemsolarzellen ermöglichen durch die Kombination von mehreren Absorbermaterialien eine deutlich bessere energetische Nutzung des Sonnenspektrums. Aufgrund des höheren Wirkungsgradpotenzials könnten sie die Basis der künftigen Solarzellengeneration sein. Auf der Grundlage intensiver Materialforschung haben Wissenschaftler am Fraunhofer ISE, gemeinsam mit Partnern, einen neuen Wirkungsgradrekord von 22,3 Prozent für eine Mehrfachsolarzelle aus Silicium und III-V-Halbleitern erzielt. Dabei ist die Besonderheit, dass die III-V-Halbleiterschichten direkt auf das Silicium gewachsen wurden.



Tandemsolarzelle auf Silicium und III-V-Halbleitern ermöglicht eine deutlich bessere Ausnutzung des Sonnenspektrums als heutige Standardzellen.

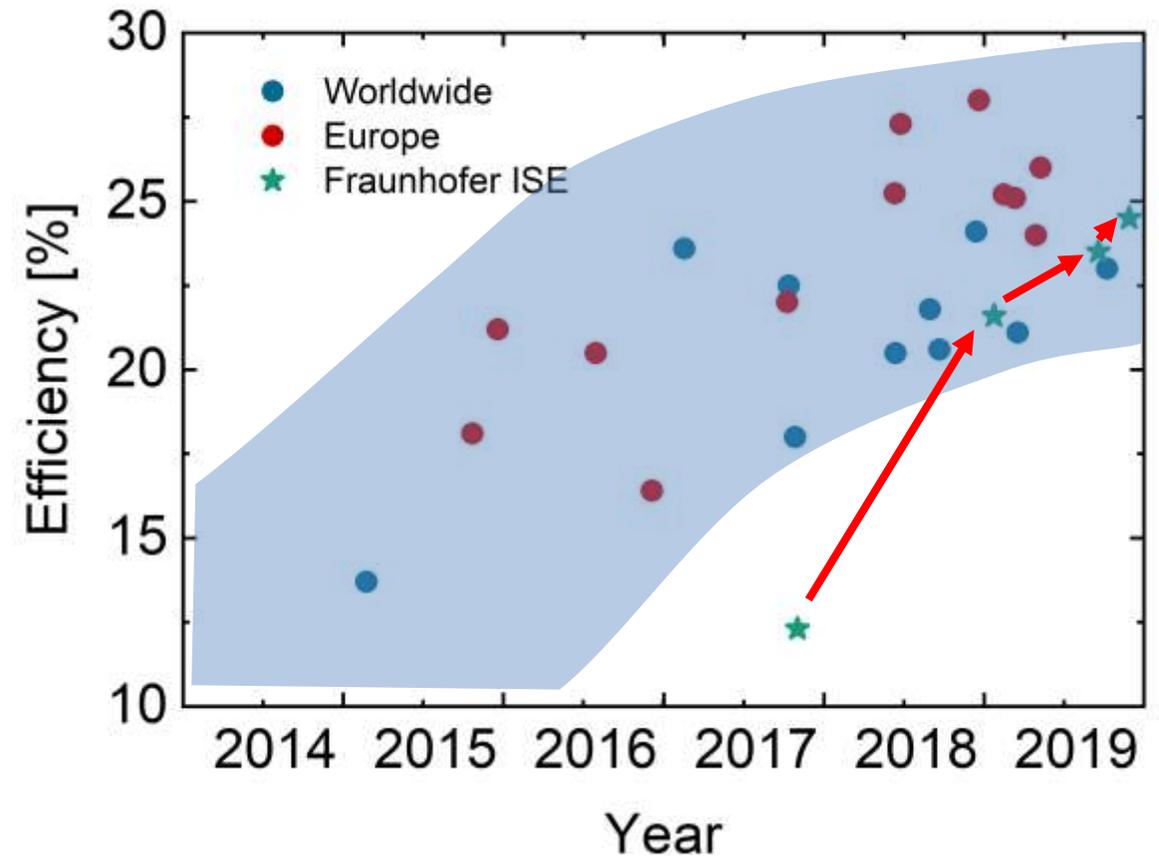


Mit Kombinationen von unterschiedlichen Halbleitermaterialien versuchen Forscher, den theoretisch mit dem Material Silicium erreichbaren Wirkungsgrad von 29,4 Prozent zu übertreffen und damit die Umwandlung von Sonnenlicht in elektrischen Strom noch effizienter zu gestalten. Ein vielversprechender Ansatz ist die Kombination von Siliciummaterial mit III-V-Halbleiterschichten wie Galliumarsenid. Eine Realisierungsoption ist, die III-V Solarzellenstrukturen auf keine Galliumarsenid-Substrate abzuschneiden und diese danach mittels der Halbleiter-Bonding-Technologie auf eine Siliciumsubstrate zu übertragen und das Galliumarsenid-Substrat weg zuätzen. Ein deutlich kostengünstiger Realisierungsweg ist ein direktes Wachstum der III-V Schichten auf die Siliciumsubstrate. Hierzu ist es allerdings notwendig, die atomare Struktur sehr gut zu kontrollieren und zu erreichen, dass die Gallium- und Phosphor-Atome an der Grenzfläche zu Silicium die korrekten Gitterplätze einnehmen. Weiterhin muss der Abstand der Atome in Kristallgitter vergößert werden, um schließlich das Material Galliumarsenid herzustellen. An diesen Herausforderungen arbeiten die Forscher seit mehr als zehn Jahren. Nun ist es ihnen gelungen, die Defektdichten in den III-V Halbleiterschichten auf Silicium deutlich zu reduzieren und so eine III-V-Si-

Technology Status Perovskite/Silicon Tandem Solar Cells

Laboratory Solar Cells

- Only 4 years for increasing the efficiency beyond Si single-junction efficiency
 - small solar cell area !
- Actual record: 28 % (Oxford PV)
- Industrial production started



Center for High Efficiency Photovoltaics ZHS at Fraunhofer ISE Advanced Semiconductor Science and Engineering

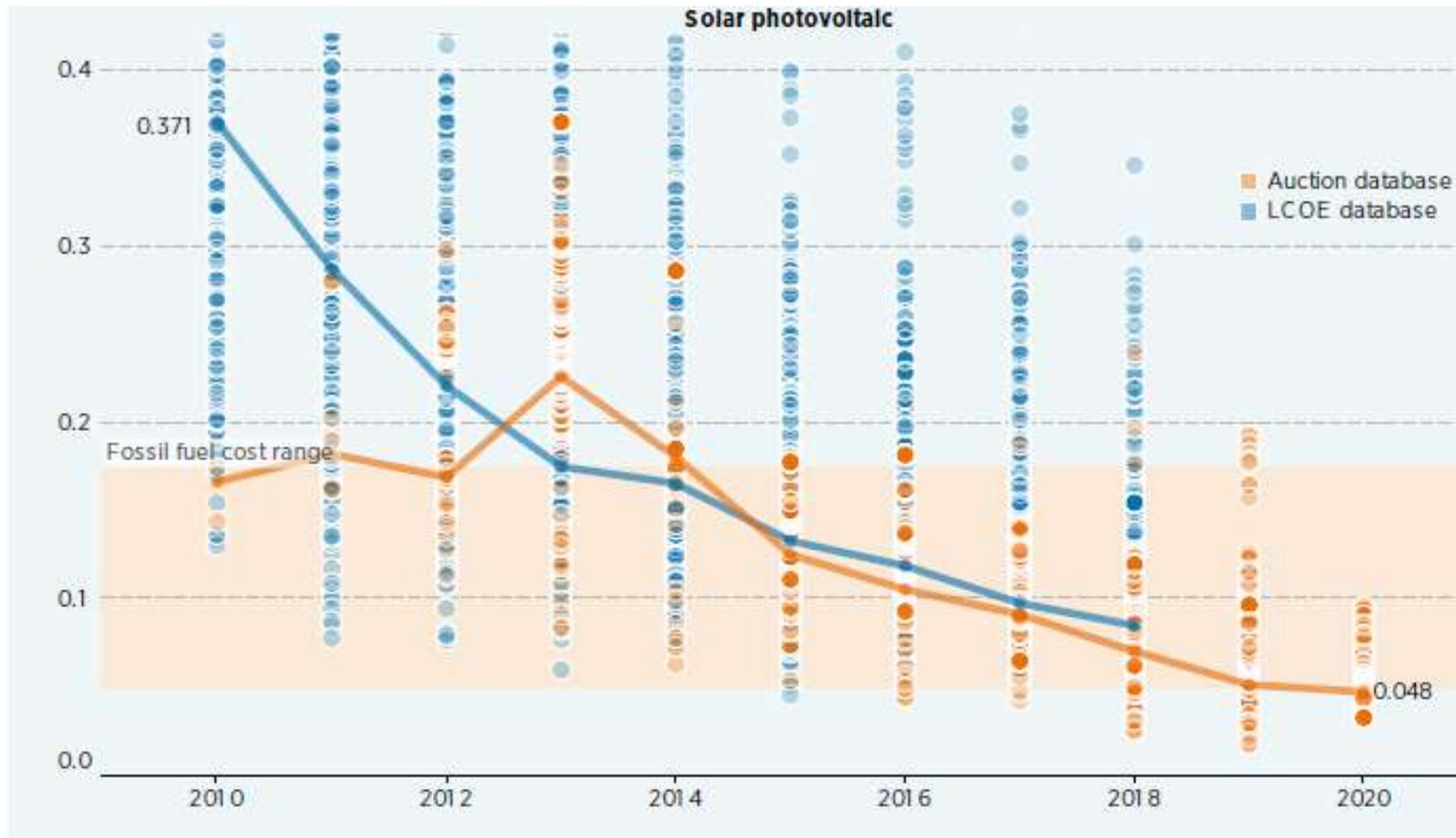
Coming in 2020

400 m² high-tech laboratories

724 m² cleanroom



Electricity by Photovoltaic has today the lowest Costs and Triggers Market Levelized Costs of Electricity (LCOE) in US\$/kWh



The LCOE for projects and global weighted average values for solar PV, 2010–20

Status Quo

Current European c-Si PV Manufacturing Landscape

- Silicon/wafer production in Scandinavia/Germany
- distribution of of small module production plants < 500 MW/a capacity
- almost no cell production capacity

Value chain step

- mg-Si / Poly-Si
- Ingot / Wafer
- Cell
- Module

Factory size

- > 500 MWp
- 100 – 500 MWp
- 50 – 100 MWp

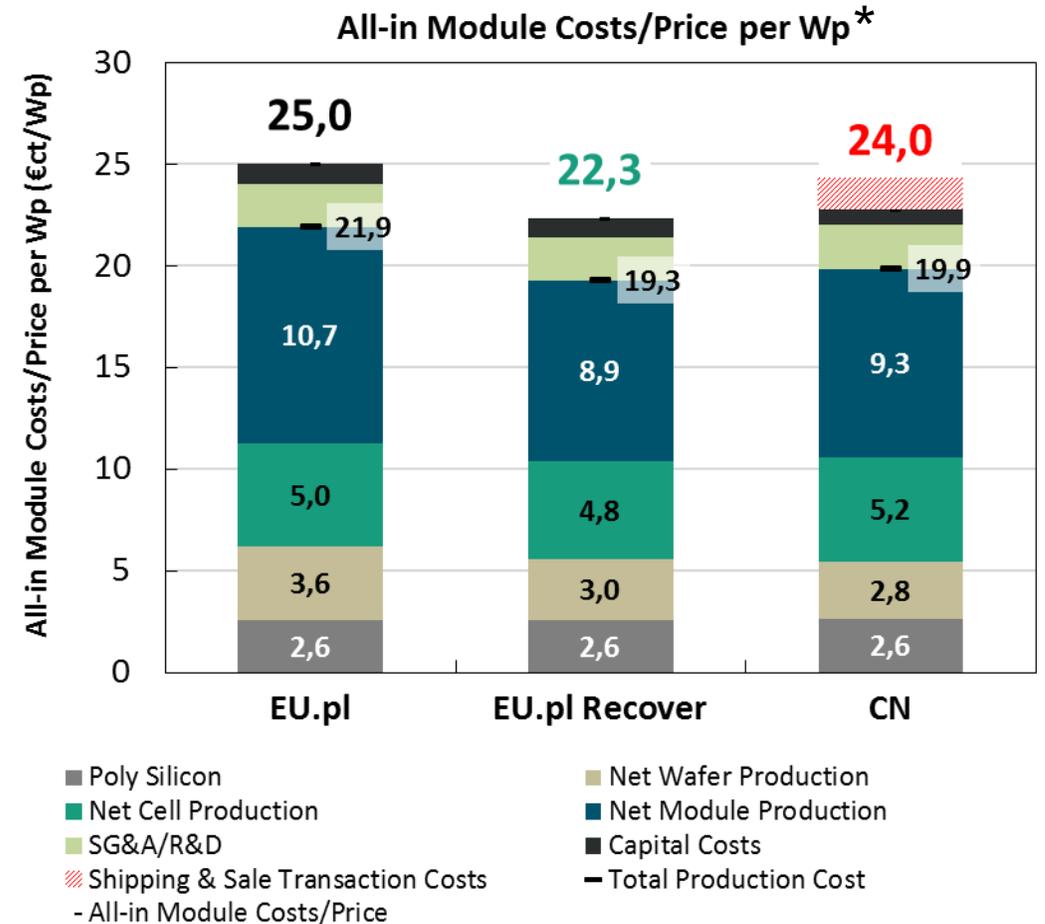


Cost Comparison of Module Manufacturing Europe Versus China

Calculation of Full Manufacturing Module Costs

- Comparison costs for module manufacturing assuming a 1 GW_p manufacturing capacity
 - manufactured in China (as reference scenario)
 - manufactured in Europe with today's European material supply chain (EU.pl)
 - manufactured in Europe with adapted European material supply chain (EU.pl Recover)

→ local manufacturing opens opportunities



Development of Cost in Dependence of Manufacturing Size

Scenario: Europe with Today's Material Supply

■ Production volume

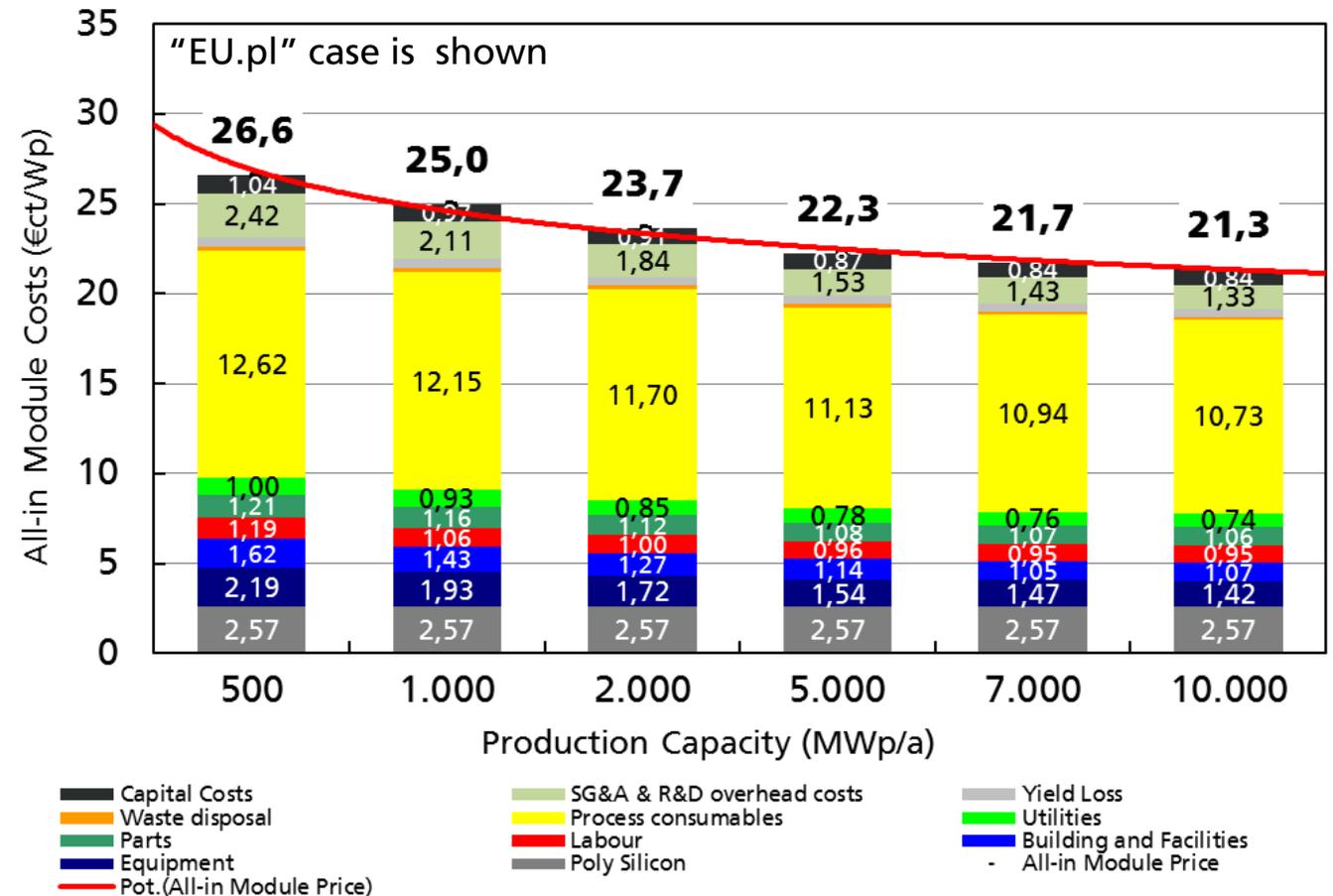
- better line balancing: less equipment, higher utilization, labour decrease

■ Supply chain

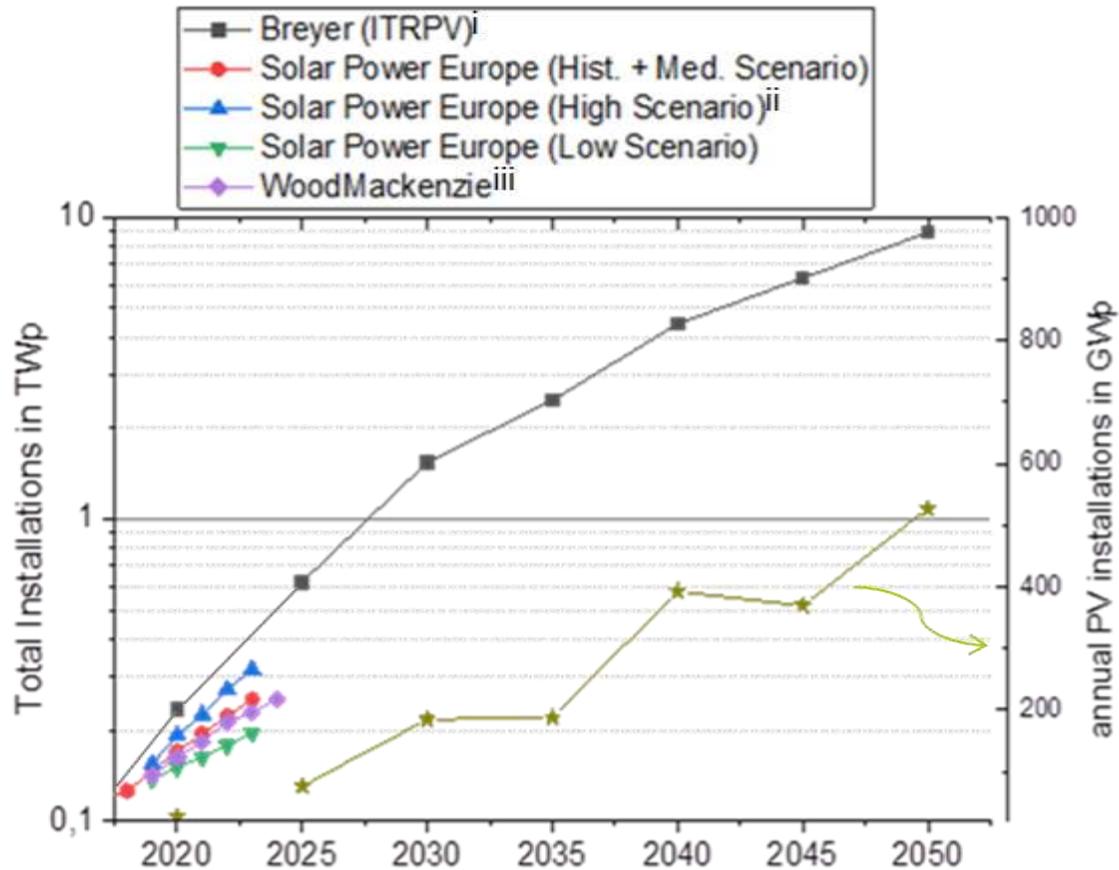
- buying power related discounts

■ Additional scaling effects

- less overhead (diluted SG&A cost)
- lower interest rate with higher corporate value



Growth of the European Photovoltaic Market Expected!



- **Example: Scenario by Solar Power Europe Europe**
 - strong market growth already in 2019
 - future growth to more than 30 GW/ year in 2023
- **Drivers**
 - Binding national targets for renewables in many EU-28 countries.
 - Activities of utilities, corporates, and big funds in Europe who invest in PV as both the lowest cost and most versatile energy generation source.

Costs for Logistics Becomes Notable! More than 10 % of Full Delivery Costs!

1-2 €ct/W transport cost & CO₂ emission

Production cost 2022: ~ 20 €ct/W



[https://de.wikipedia.org/wiki/Containerschiff#/media/Datei:NYK_Virgo_\(8154929586\).jpg](https://de.wikipedia.org/wiki/Containerschiff#/media/Datei:NYK_Virgo_(8154929586).jpg)

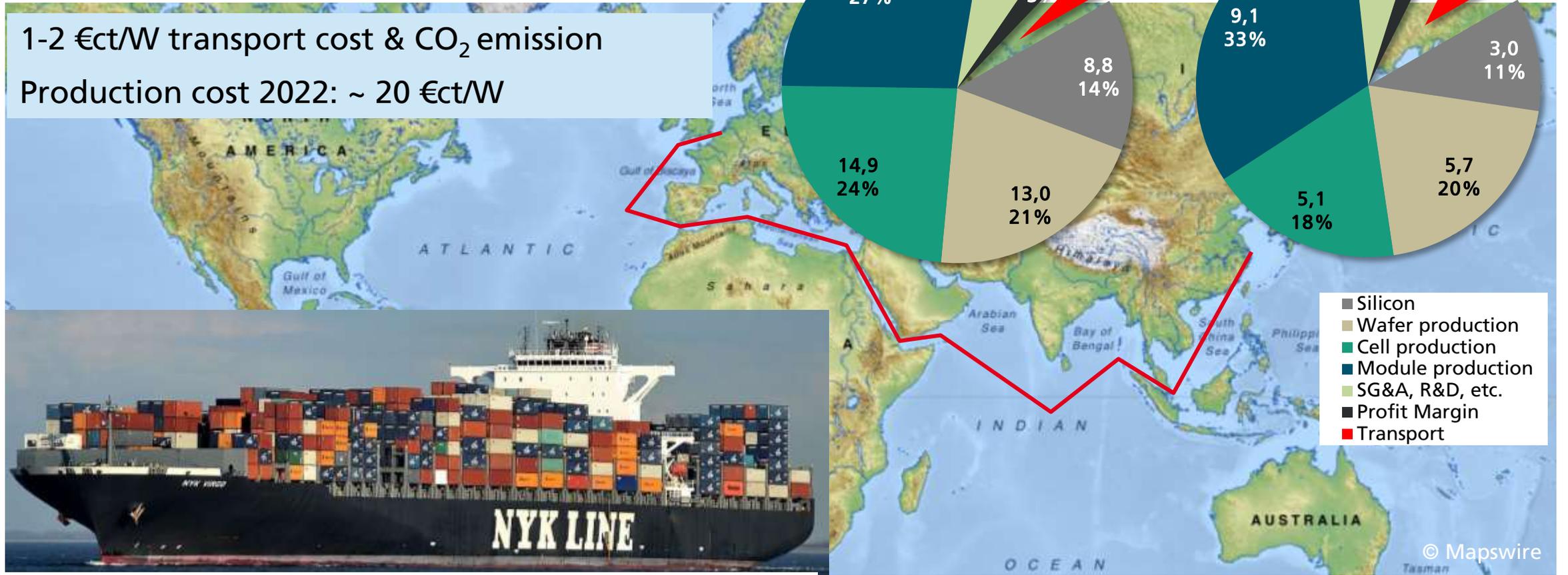
Costs for Logistics Becomes Notable! More than 10 % of Full Delivery Costs!

2014: 62,6 €ct/W_p

2019 / 28,0 €ct/W_p

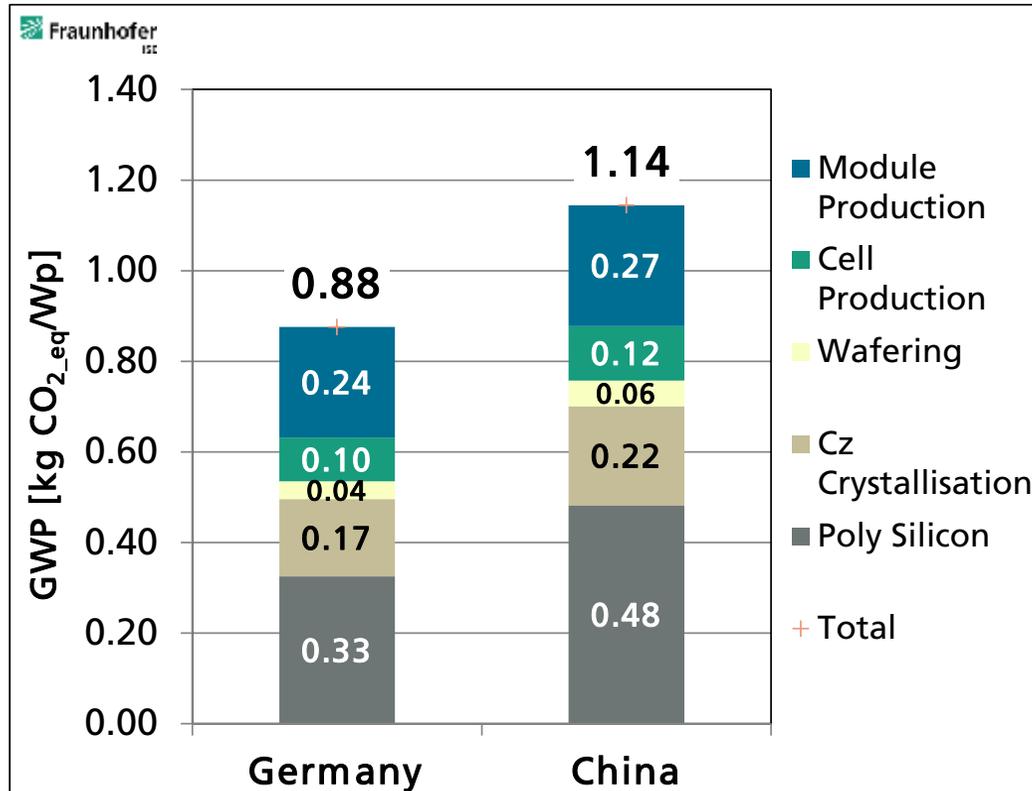
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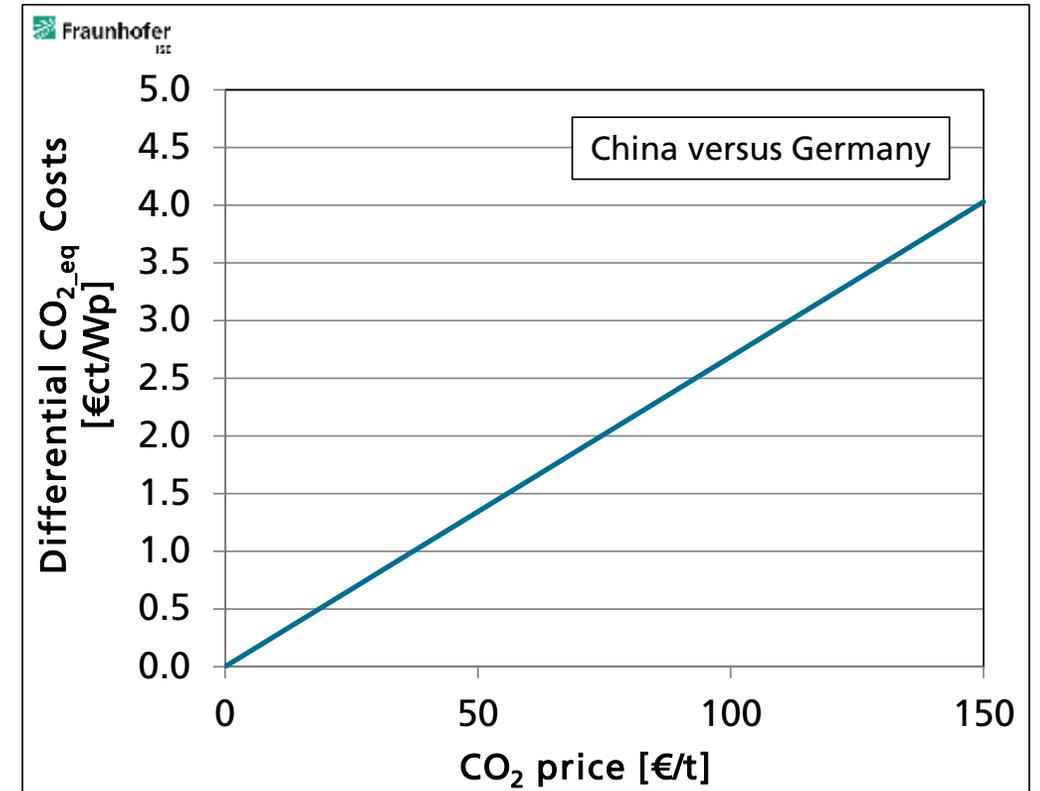


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Carbon Emissions of PV Production and Effects of a Carbon Pricing Scenarios: Germany and China



Carbon footprint of a Cz PERC glass-backsheet module production*

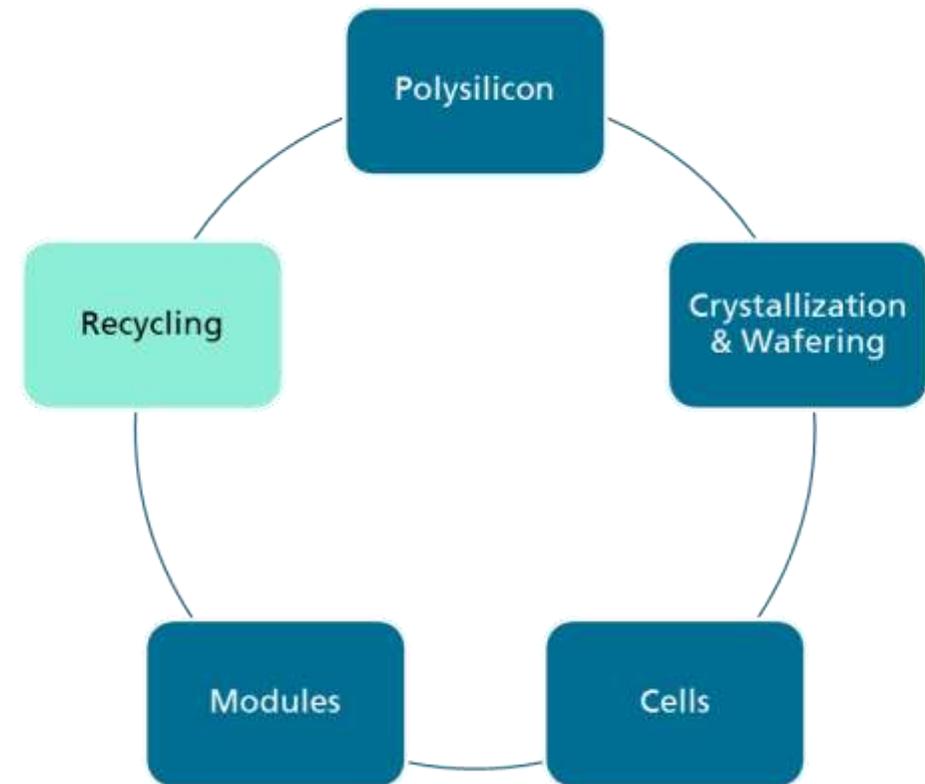


CO₂ cost difference of a Cz PERC module production located in Germany compared to China

PV Market Development, Sustainability and new High-Tech Solutions lead to Novel Chances for PV-Manufacturing in Europe!

- Europe should cover a large share of its domestic energy market with European low carbon footprint products.
- Assets when investing in European PV manufacturing:
 - providing high-tech, high quality products
 - satisfying demand for sustainable products
 - profiting from expertise in R&D and workforce

A vision on **the** circular PV value chain:



The 10 GW GreenFab

Take the Challenge and Make Business

- 10 GW_p fully integrated production in Europe is competitive
- Cost advantages >10 % due to reduced logistic costs
- Production with less CO₂ emission
- Strong growing European PV market

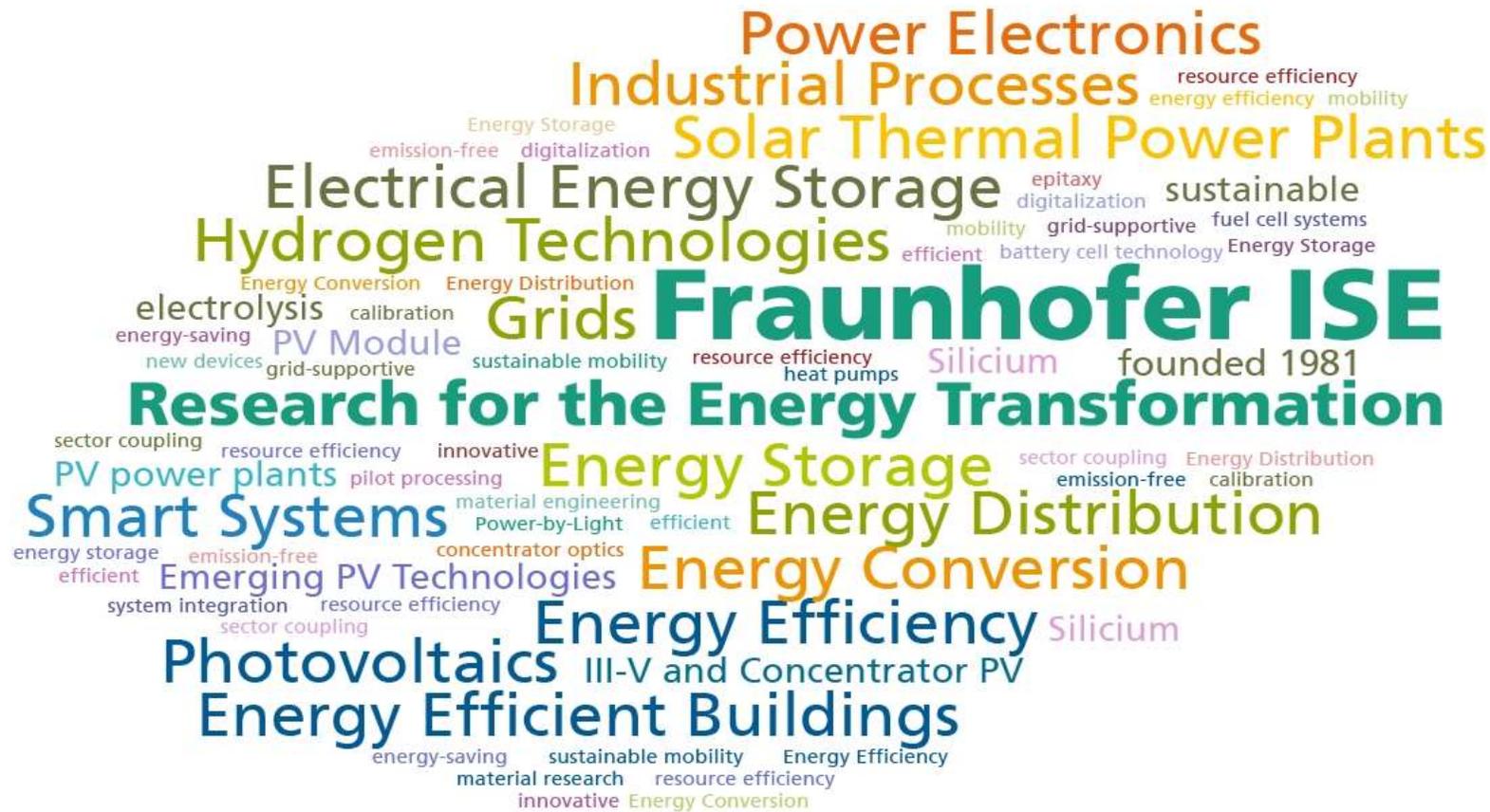


For more see: <https://www.ise.fraunhofer.de/en/renewable-energy-data.html>

Conclusions

- **Photovoltaic technology is the main pillar of the future energy supply**
- Efficiencies of cells and modules are still raising in laboratory and industrial production.
 - Tandem solar cells will bring the efficiency well beyond 30 % in 2030.
- It is time to invest into a **fully integrated 10 GW PV manufacturing line** in Europe.
 - A modern, highly efficient PV manufacturing facility is economically sound and competitive.
 - Producing in Europe with a **GreenFab concept with a small CO₂ footprint** is a strong market differentiator.
 - Transport and logistics cost share increases and opens opportunities for European production.

Thank you for your Attention!



Dr. Andreas Bett

www.ise.fraunhofer.de

andreas.bett@ise.fraunhofer.de