Photovoltaic Technology: From R&D to Industry

Andreas Bett

Fraunhofer Institute for Solar Energy Systems ISE

French Technology Academy

Paris, 8th January 2020

www.ise.fraunhofer.de

AGENDA

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

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Fraunhofer Institute for Solar Energy Systems ISE
Research for the Energy Transformation

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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

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Our Motivation: Offer Solutions for the Climate Challenge

CO_2-Emission Reduction is a MUST!

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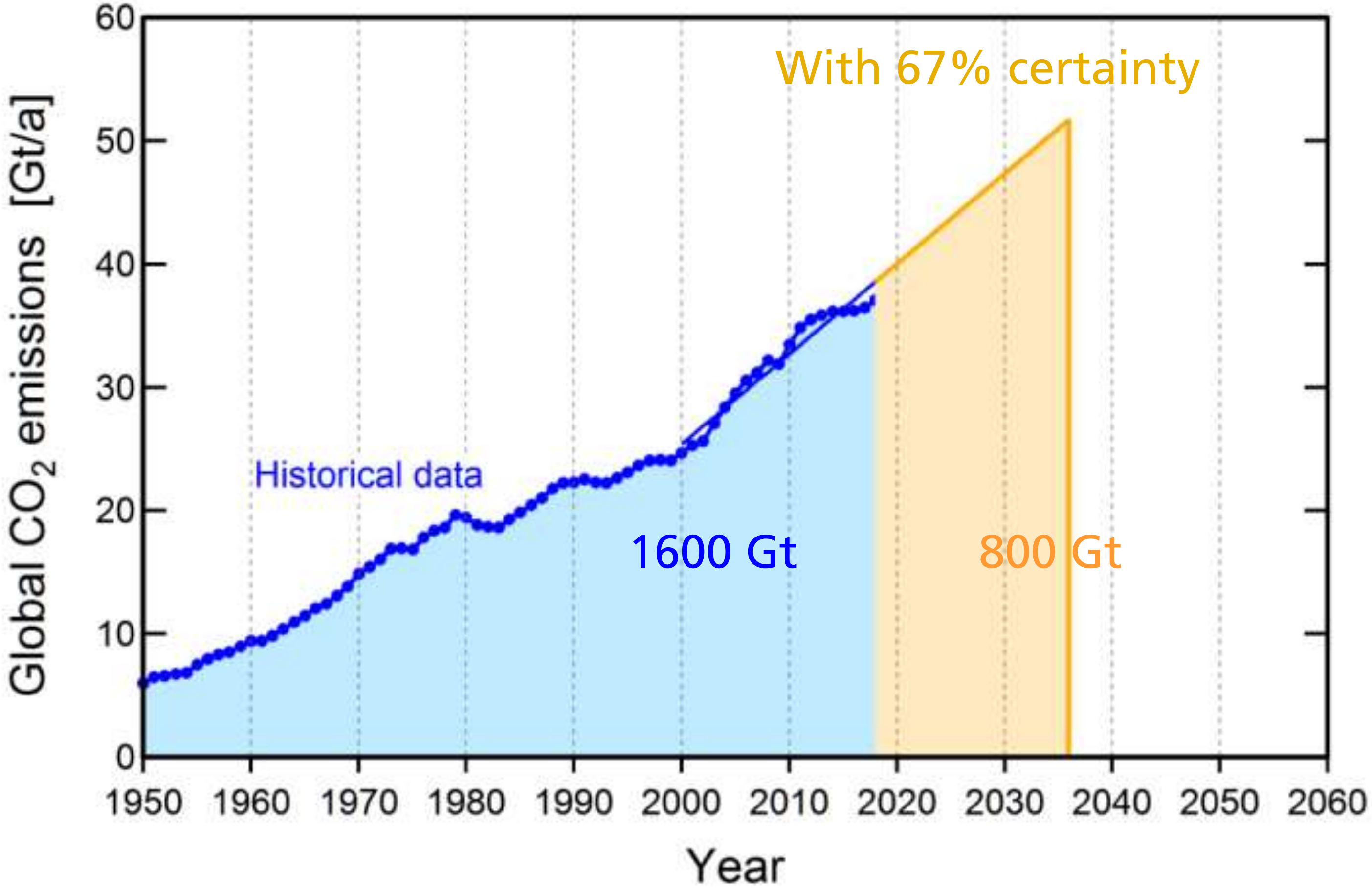
Global CO_2 Emissions to Fulfill the Paris Agreement

Reach climate goal < 2 °C



Derived from geophysical models, summarized in [1]

→ 2035 the remaining CO_2–budget is used up!

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Credit to Pietro Altermatt, Trina Solar

[1] G. Luderer et al, Nature (climate change) 8, 262 (2018)

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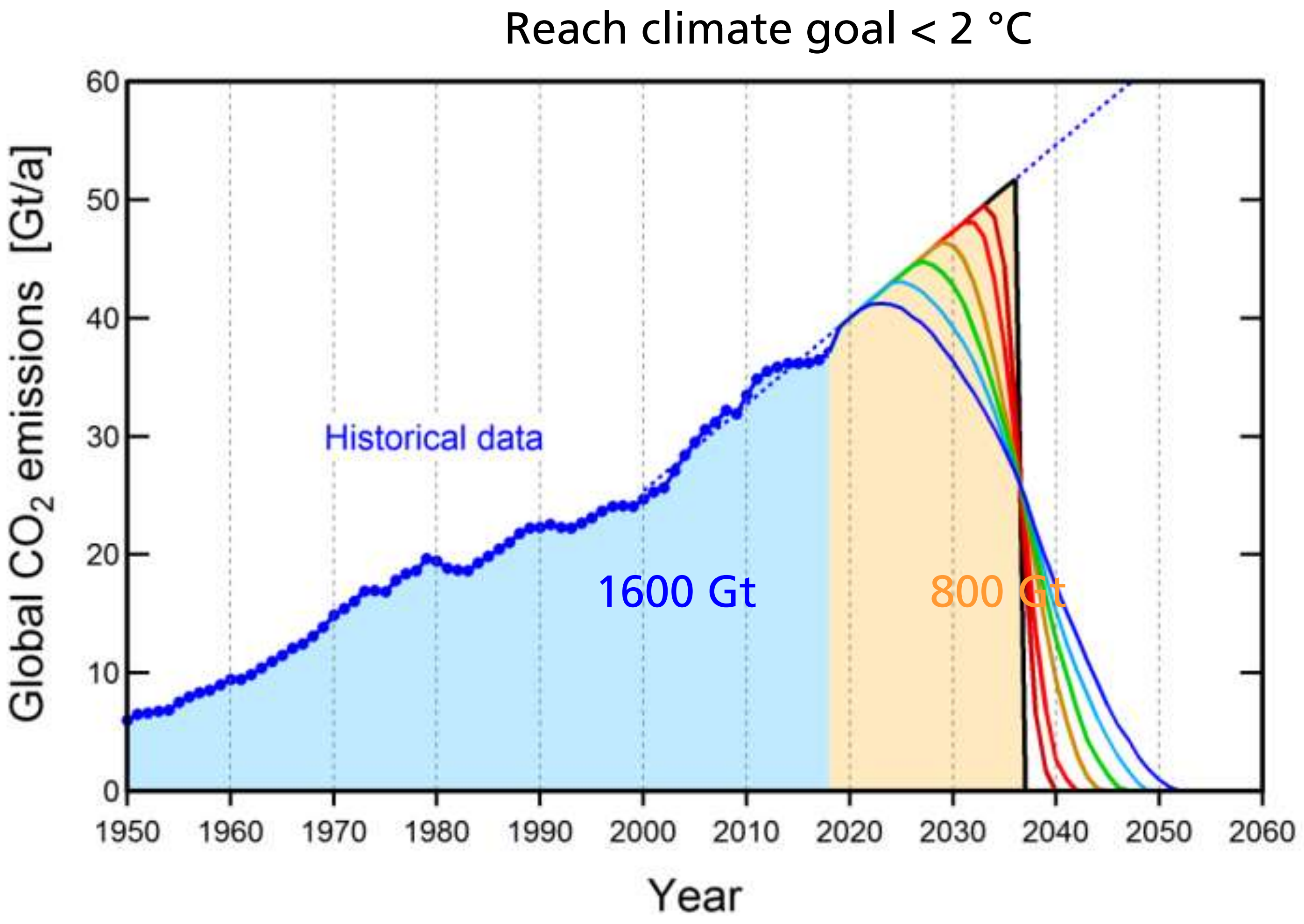
Global CO_2 Emissions to Fulfill the Paris Agreement



It is still possible!

BUT:
The coming 10 years are decisive

It is urgent to act now!

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Credit to Pietro Altermatt, Trina Solar

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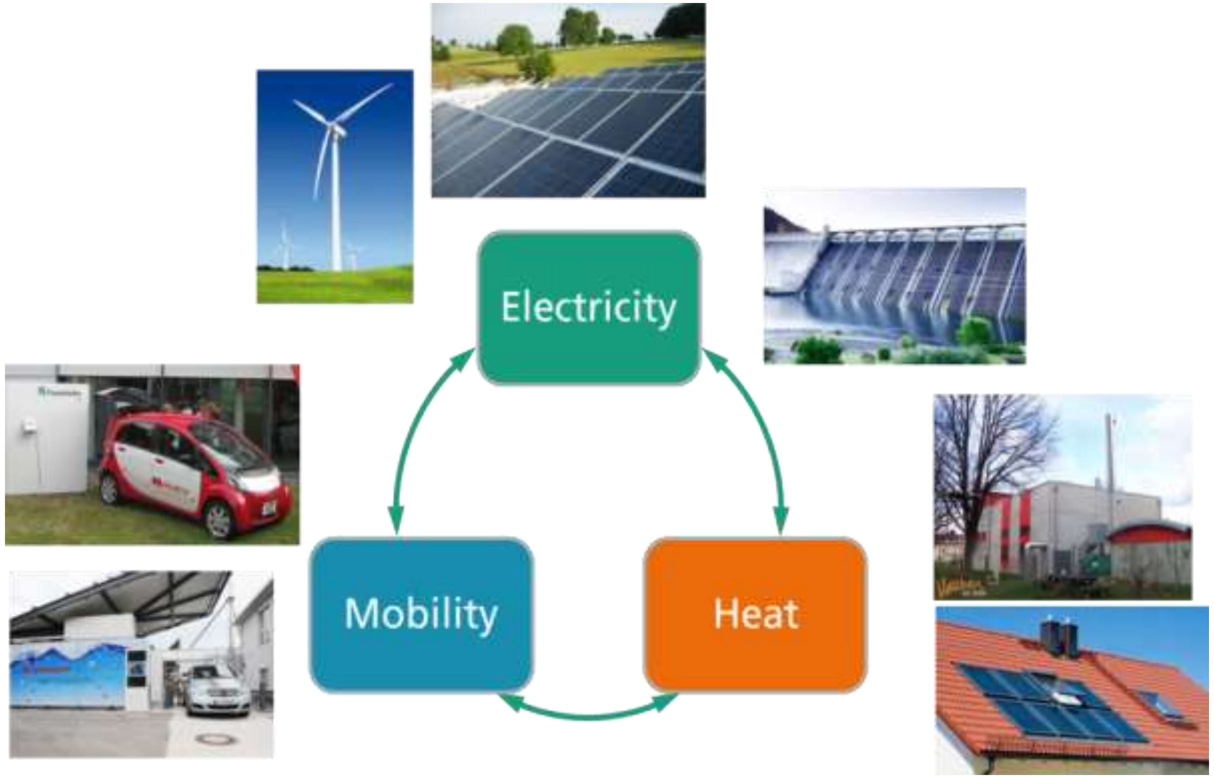
The »Energiewende« demands for more Electricity

CO_2-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

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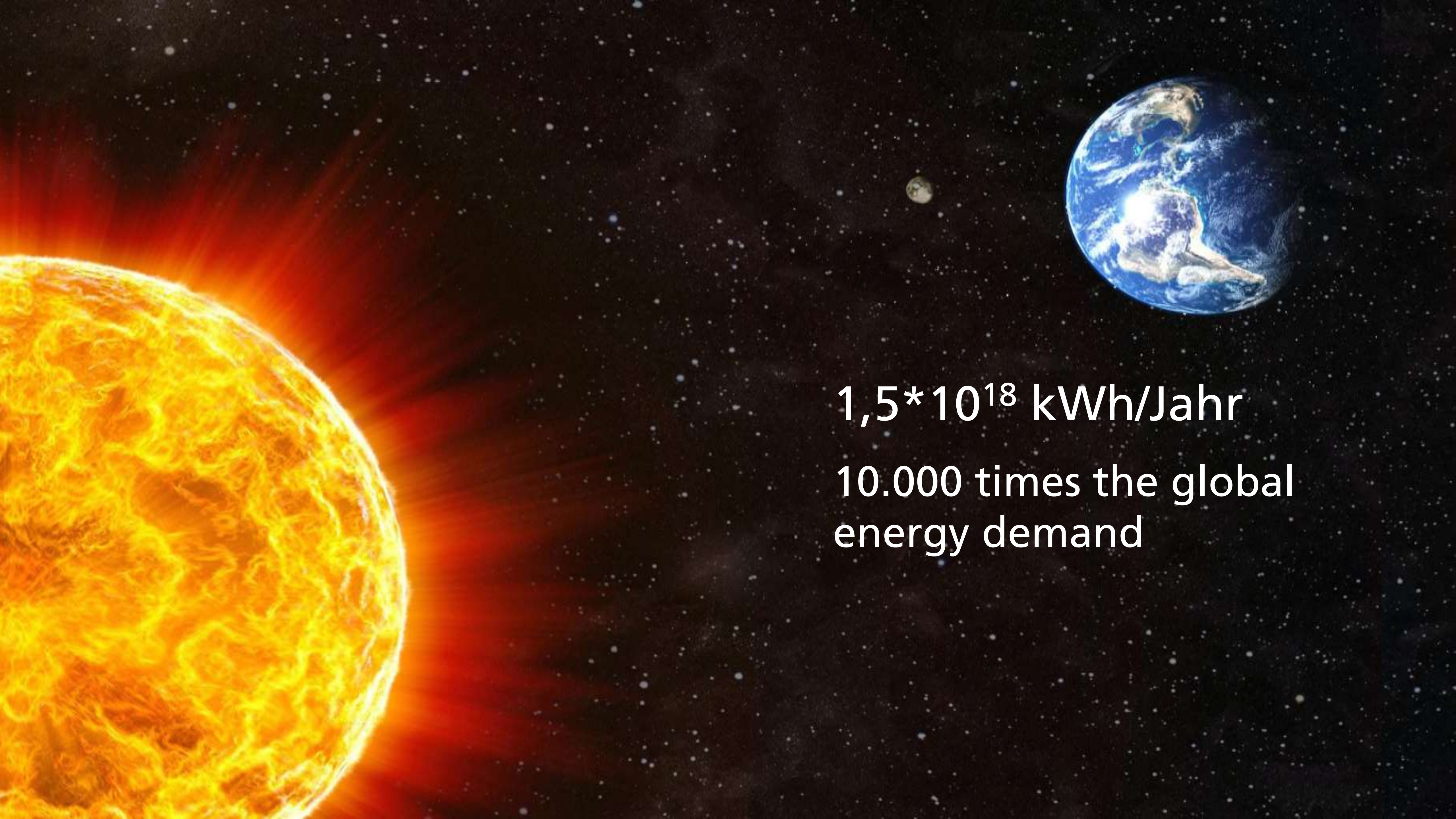

1,5*10^{18} kWh/Jahr
10.000 times the global energy demand

Silicon Photovoltaic R&D: Past and Present

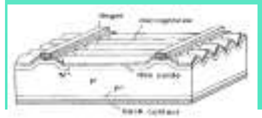
Phase 0:
R&D Fundamental
1839 – ~1990

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

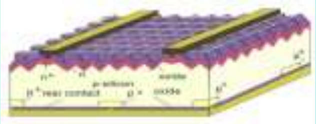
1961: Shockley-Queisser Limit



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

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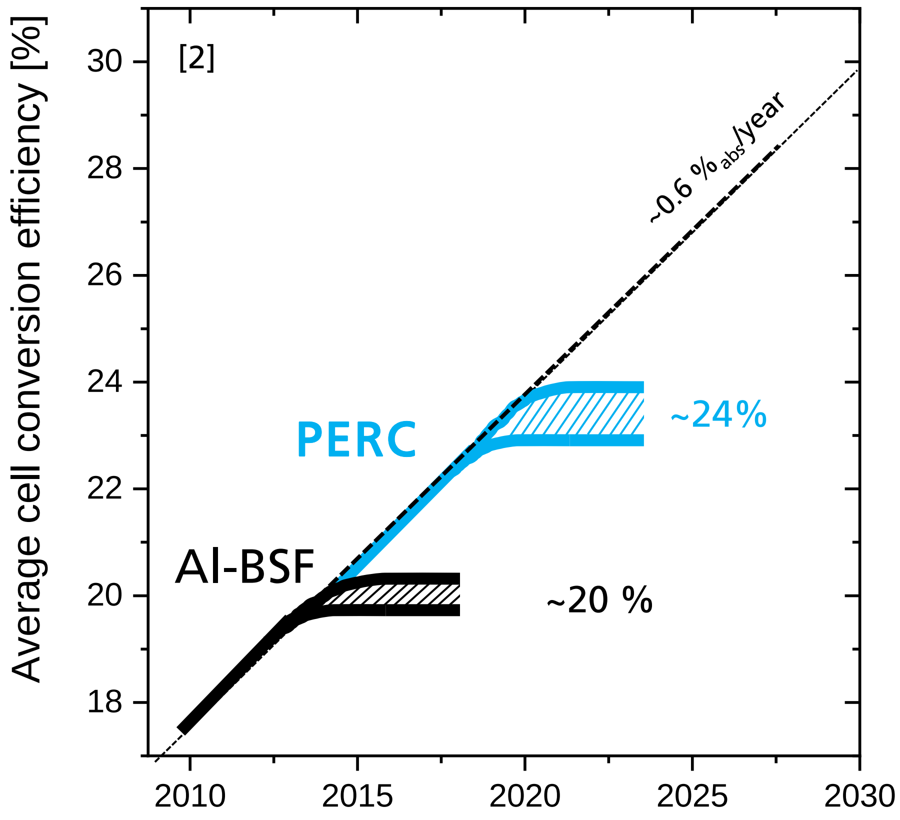
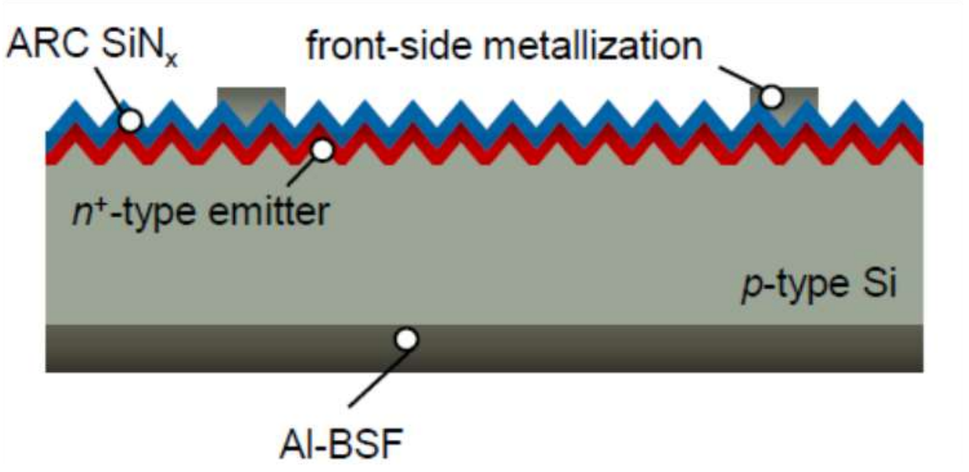
Increasing the Efficiency
Industrial Realisation



- **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



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[1] F.Fertig et al. Silicon PV 2019 and 2017
[2] M. Hermle, ETIP PV, PV Manufacturing in Europe, 2017, Brussels

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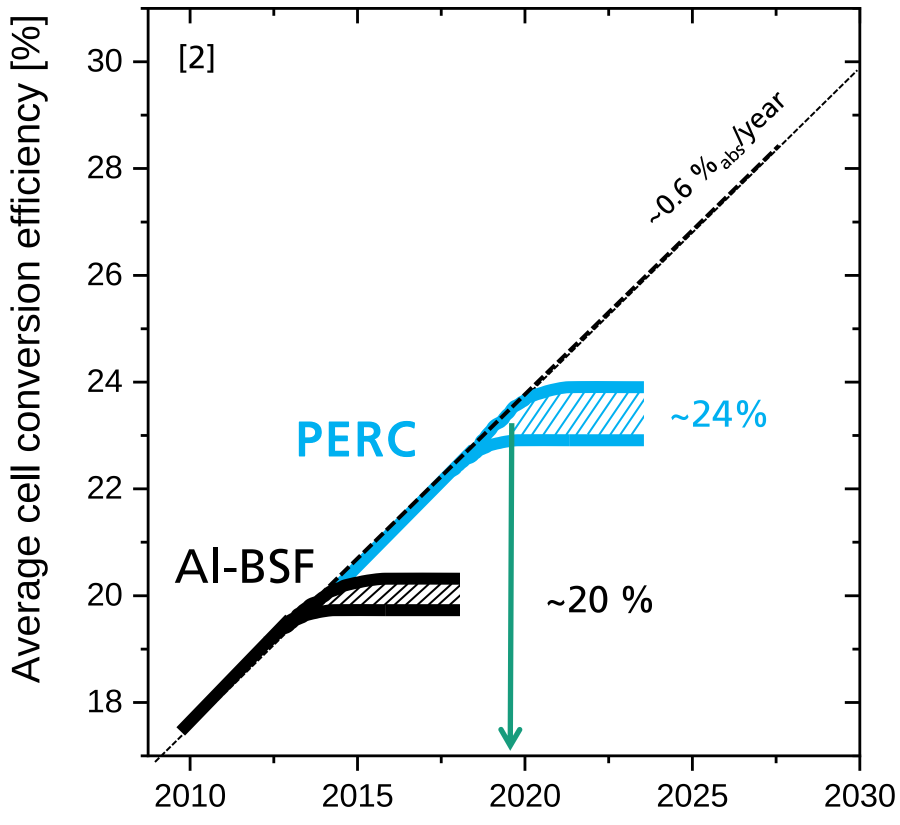
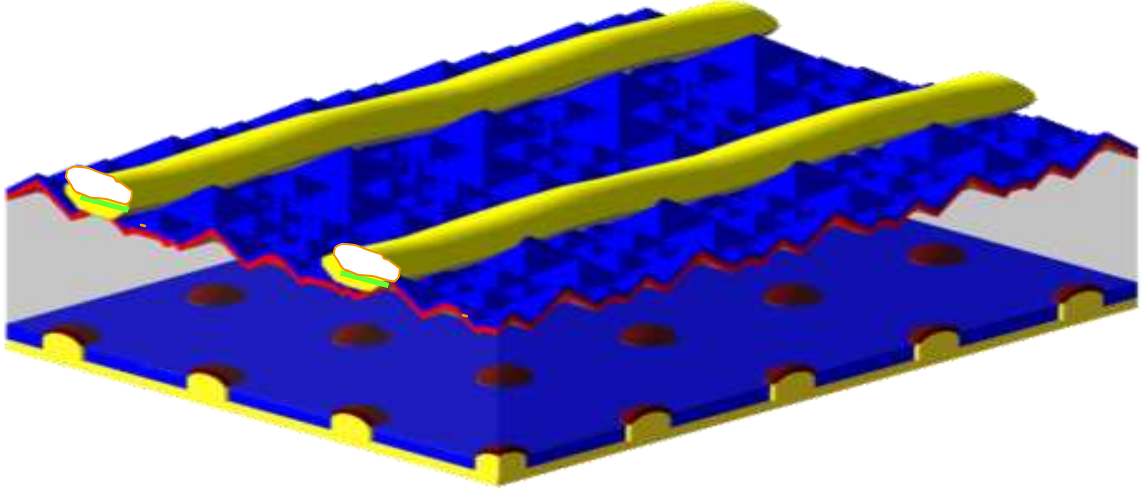
Increasing the Efficiency
Industrial Realisation



- **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)**



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[1] F.Fertig et al. Silicon PV 2019 and 2017
[2] M. Hermle, ETIP PV, PV Manufacturing in Europe, 2017, Brussels

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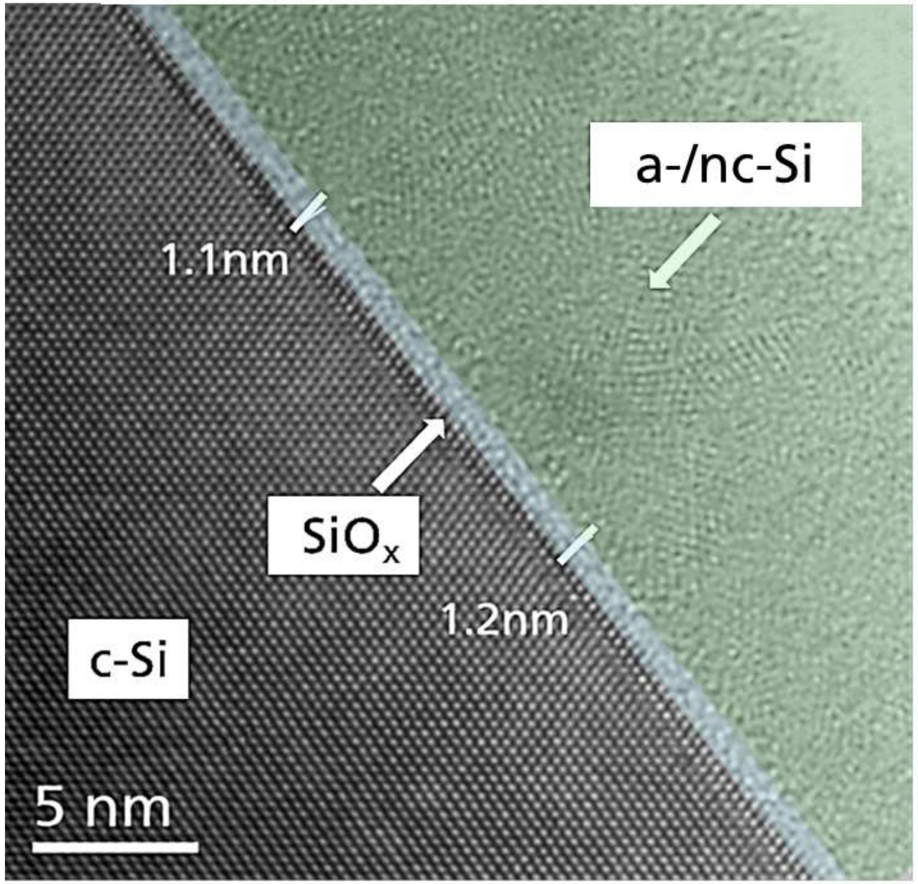
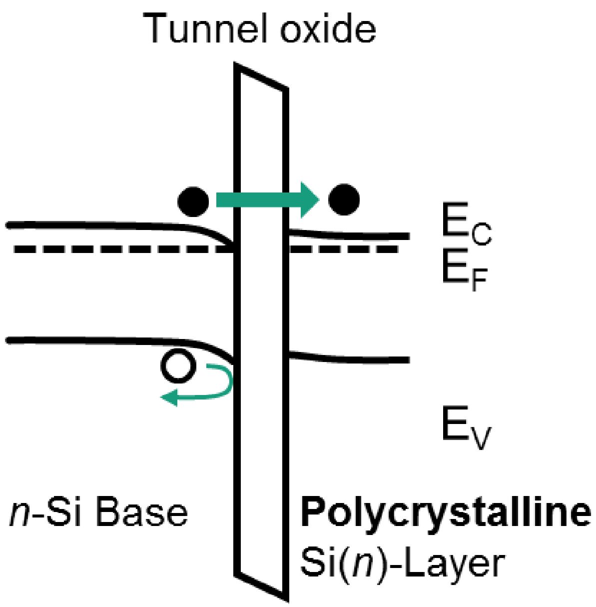
Increasing the Efficiency: R&D Innovation
Passivating Contacts with Oxide and Polysilicon

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)

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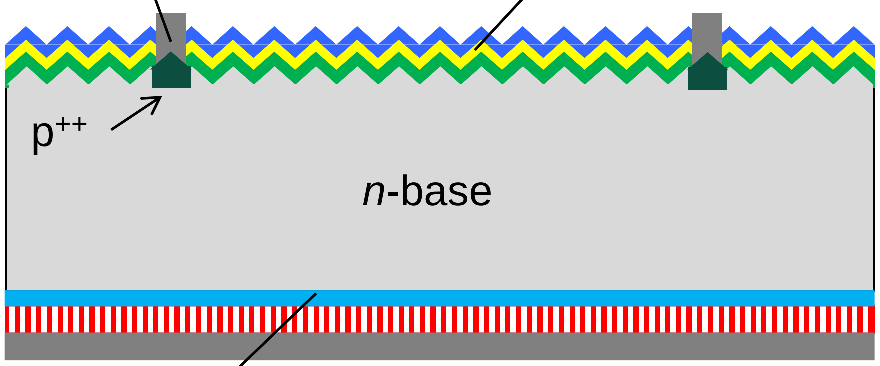
Present R&D Status
TOPCon Record Cells with Top/Rear Contacts

Material	Area	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
n-type Mono	4 cm² (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

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A.Richter *Silicon Solar Cells with Passivating Rear Contacts* 7th Silicon PV, Freiburg, Germany, April 3, 2017

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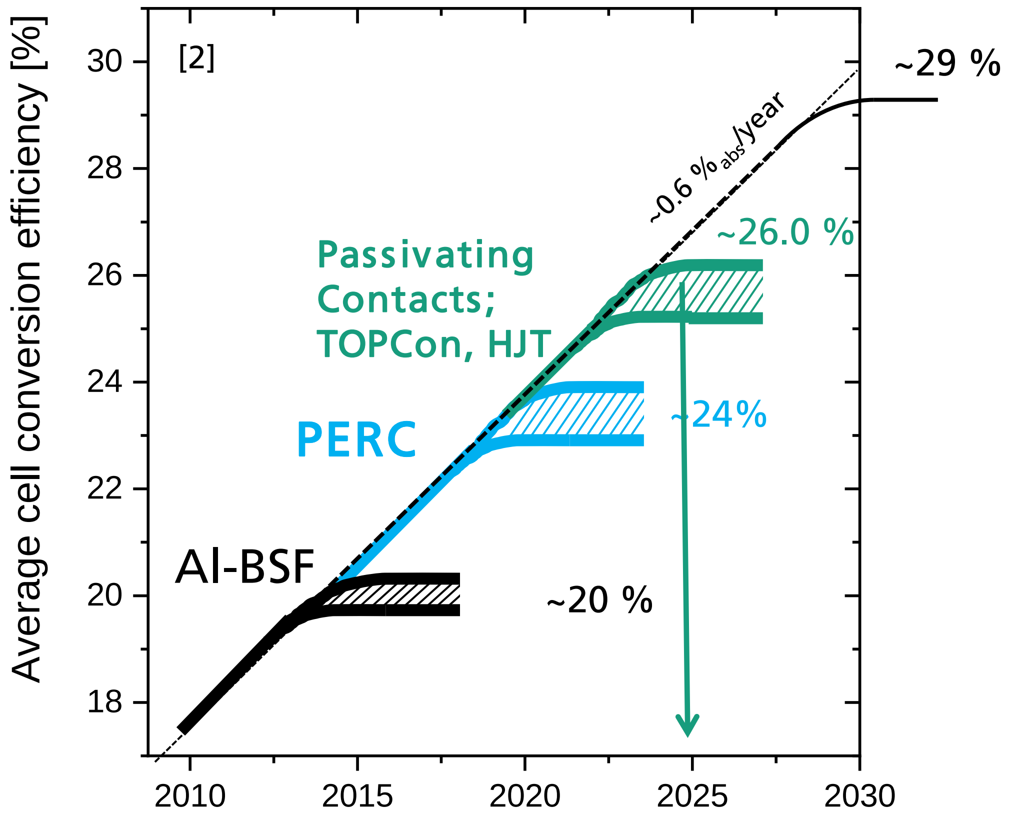
Innovations with Respect to Efficiency

Industrial Realisation – A View into the Coming Years



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

What we will see after 2025 in industrial production?

[1] F.Fertig et al. Silicon PV 2019 and 2017
[2] M. Hermle, ETIP PV, PV Manufacturing in Europe, 2017, Brussels

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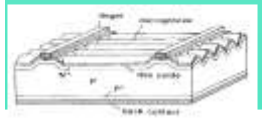
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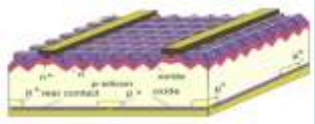
Phase 1: R&D to approach SQ limit ~1990 - ~ 2017

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 %

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

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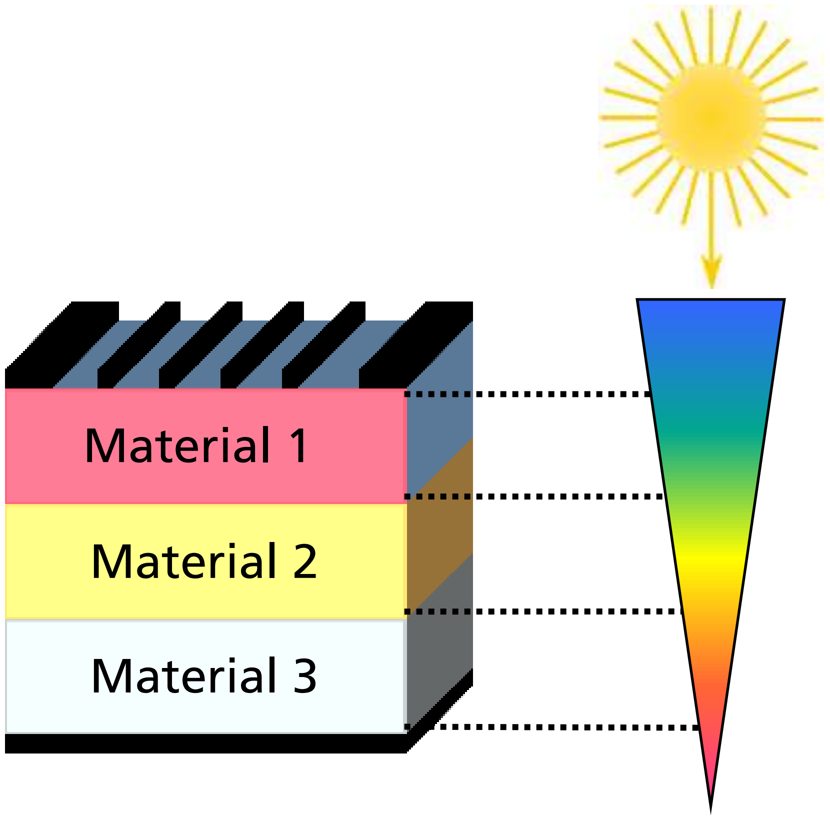
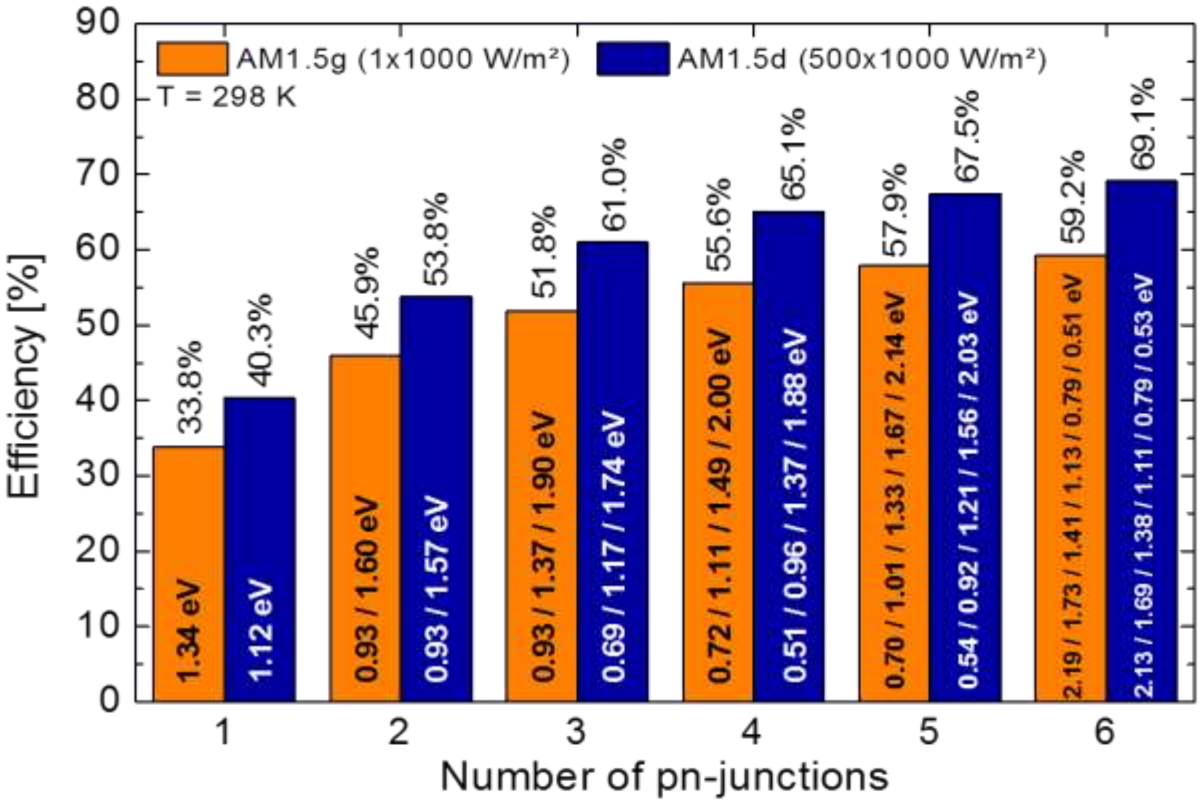
What can be expected from Multi-junction Solar Cell?

A 50 % Efficient Solar Cells are realistically achievable!





calculation based on Shockley-Queisser approach

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S.P. Philipps and A.W. Bett, in: Advanced Concepts in Photovoltaics, A, J. Nozik et al (eds.), Cambridge: Royal Society of Chemistry (2014).

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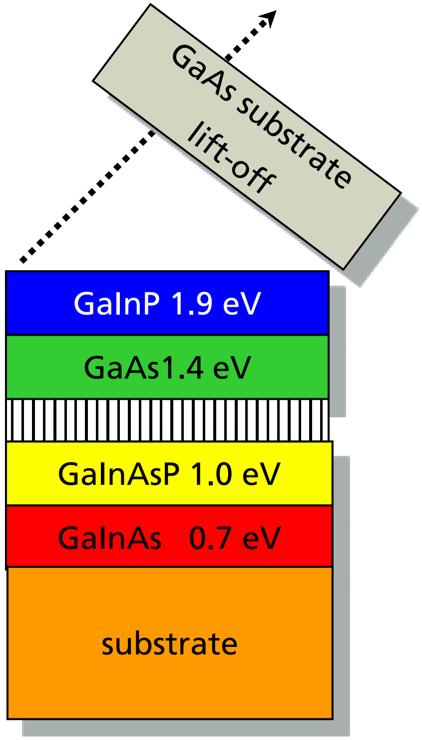
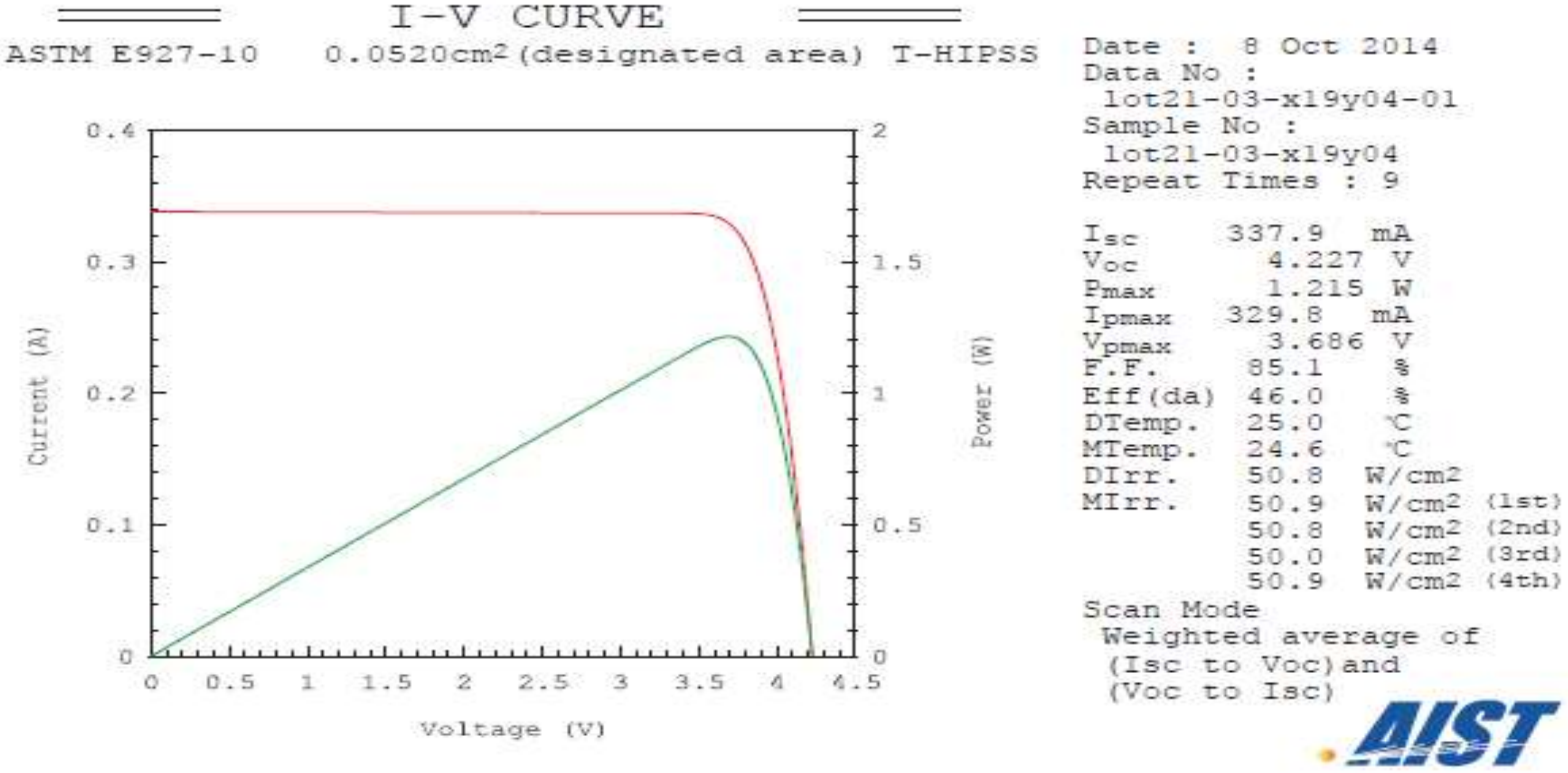
4-Junction Cell Efficiency under Concentration

4-junction bonded to InP

Bonding



η = 46.0 % @ 500 suns



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T.Tibbits, Proc. 29th EU PVSC, Amsterdam (2014)
Solar cell efficiency tables, Prog. Photovolt: Res. Appl. 2015; 23:1–9

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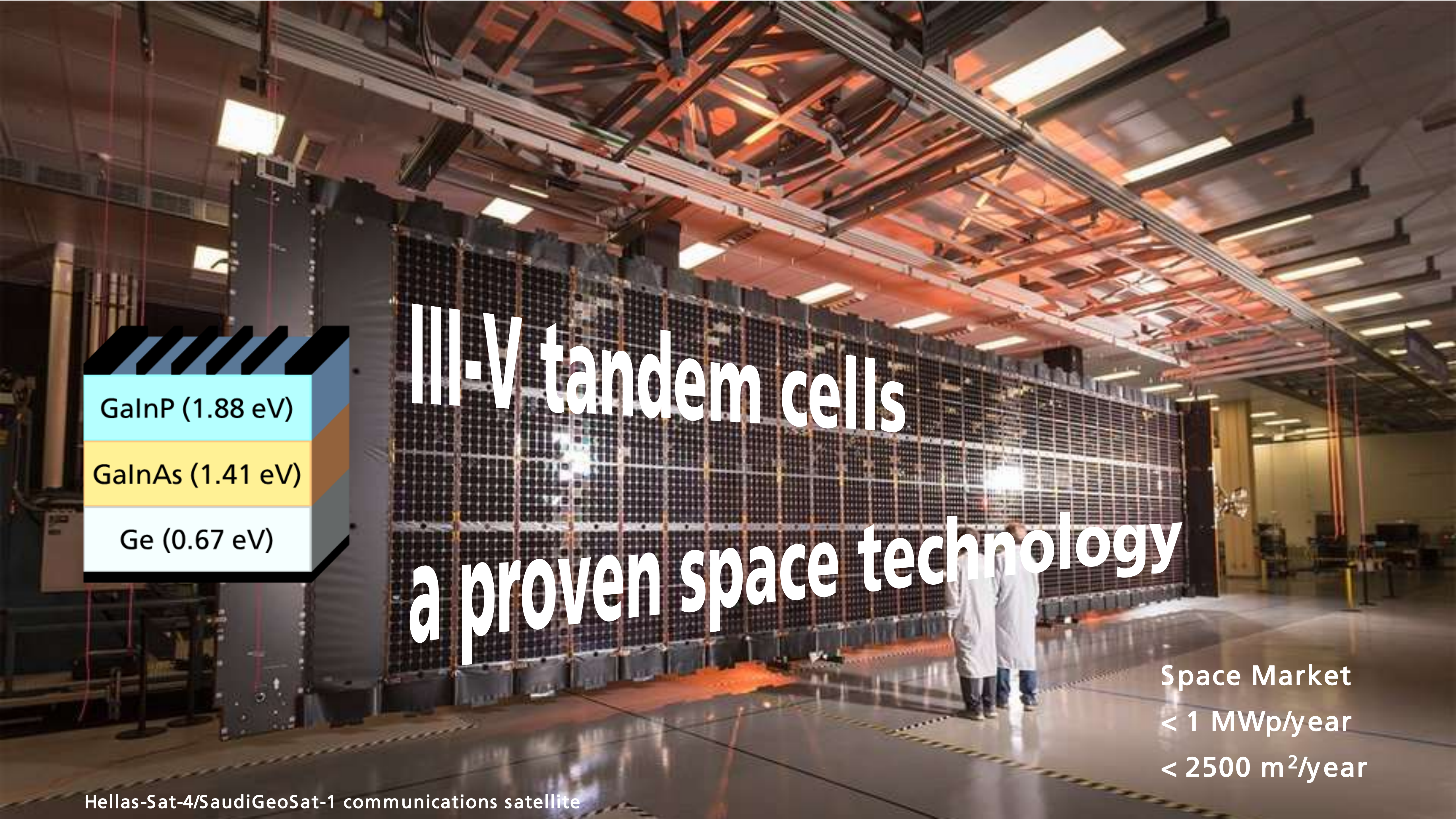
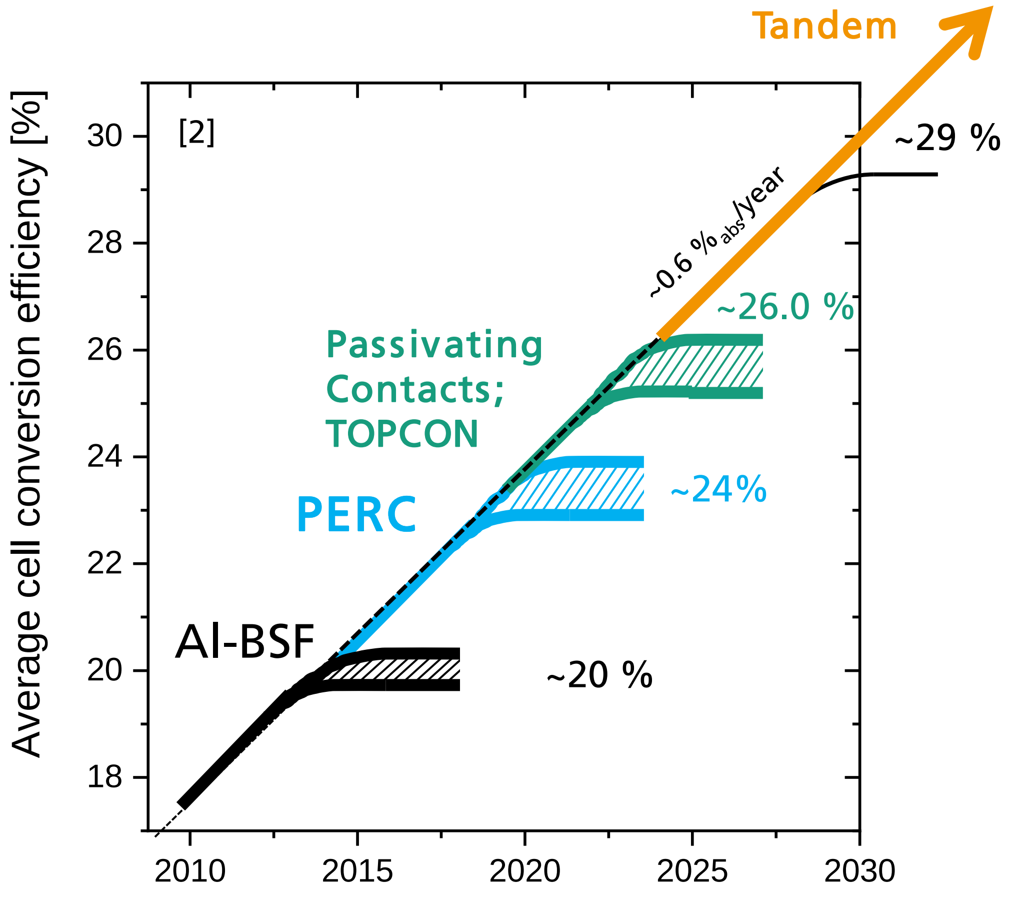
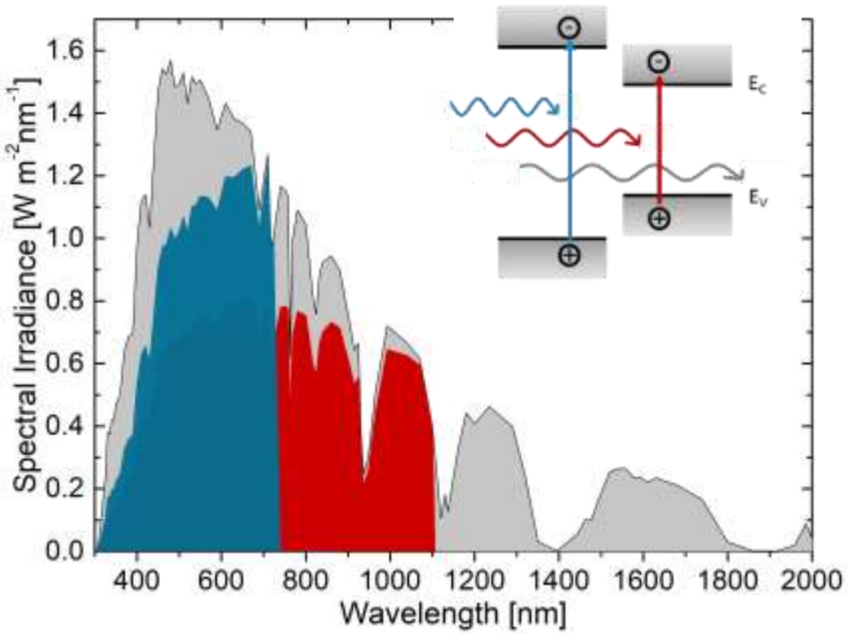

GaInP (1.88 eV)
GaInAs (1.41 eV)
Ge (0.67 eV)
III-V tandem cells
a proven space technology
Space Market
< 1 MWp/year
< 2500 m²/year
Hellas-Sat-4/SaudiGeoSat-1 communications satellite

Beyond the Shockley-Queisser Limit
Tandem Solar Cells on Silicon



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



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[1] F.Fertig et al. Silicon PV 2019 and 2017
[2] M. Hermle, ETIP PV, PV Manufacturing in Europe, 2017, Brussels

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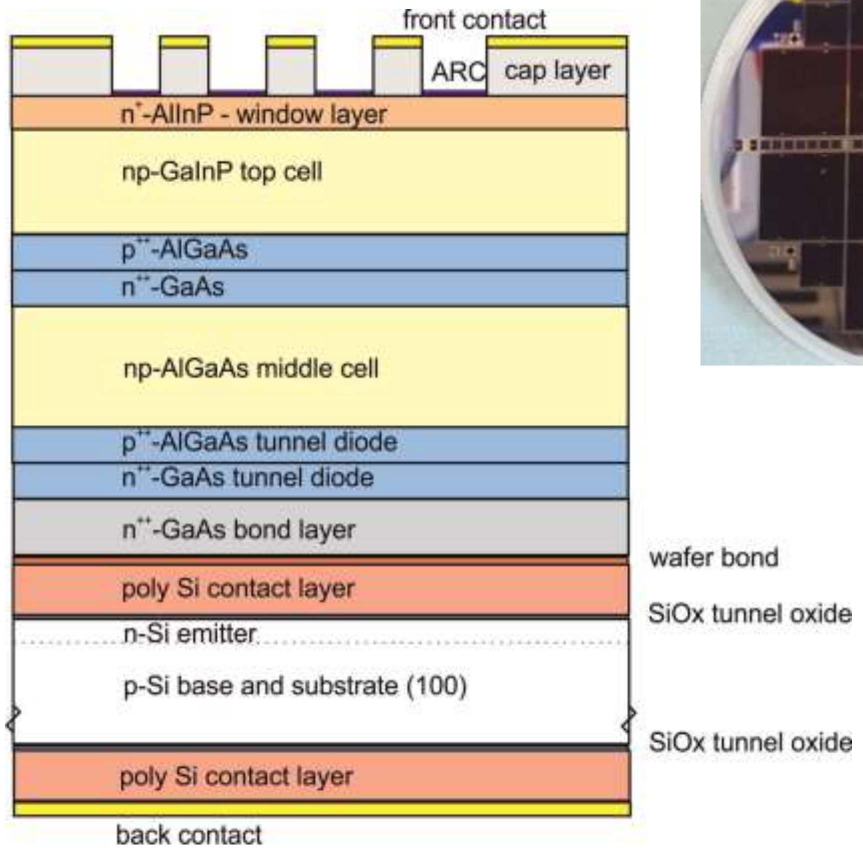
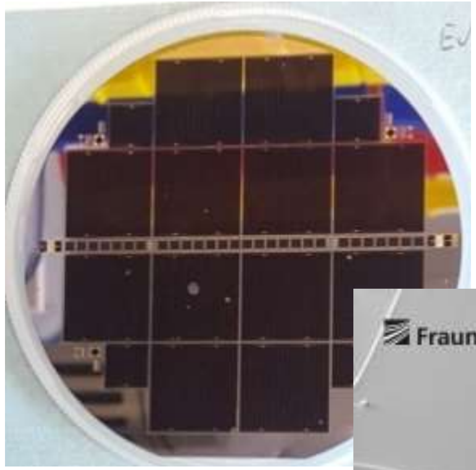
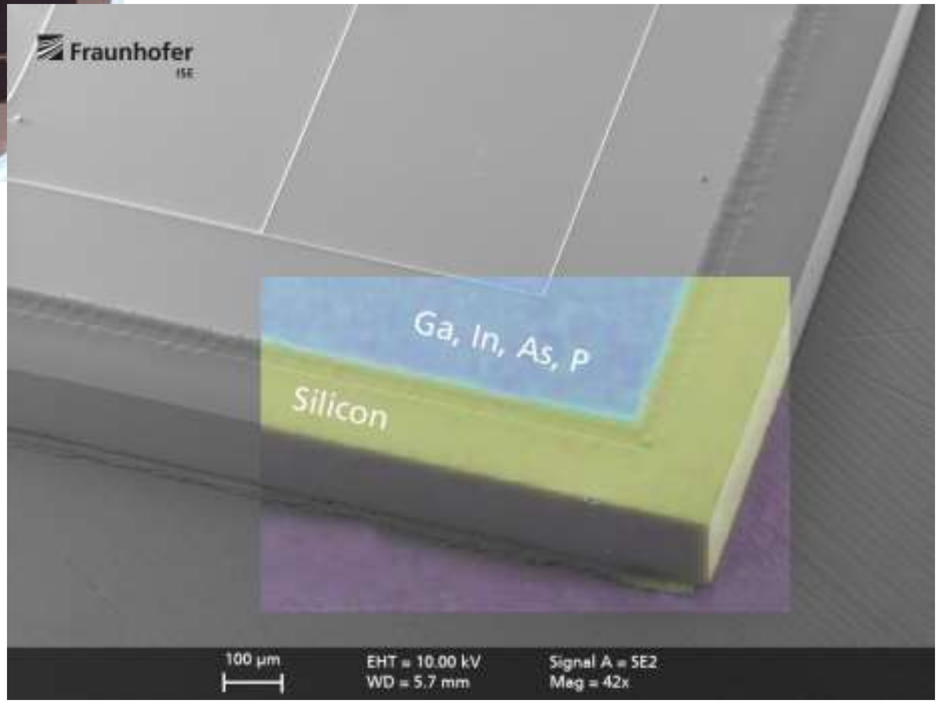
Technology Status 2-Terminal (Monolithic) III-V/Si Tandem

Easy Module Integration by Series Connected Strings





~ 2,5 µm III-V layers on Silicon



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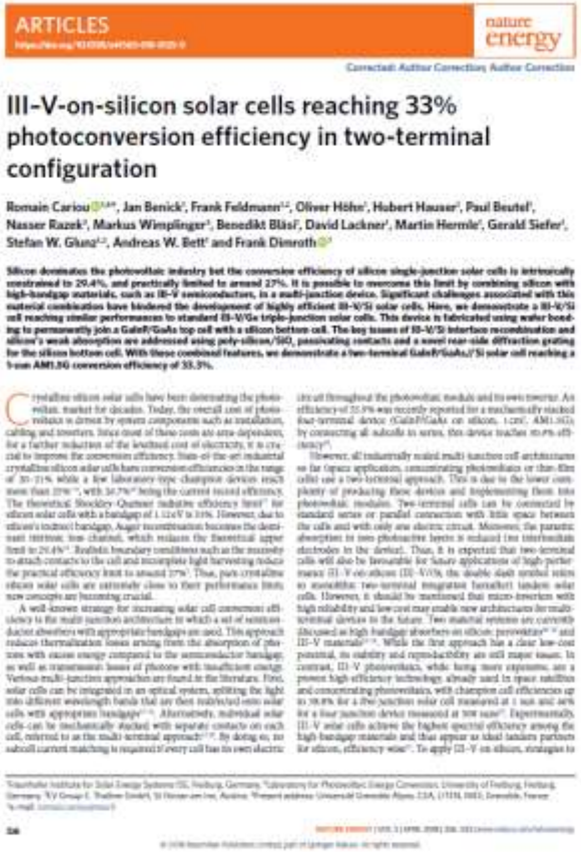
Technology Status 2-Terminal III-V/Si Tandem

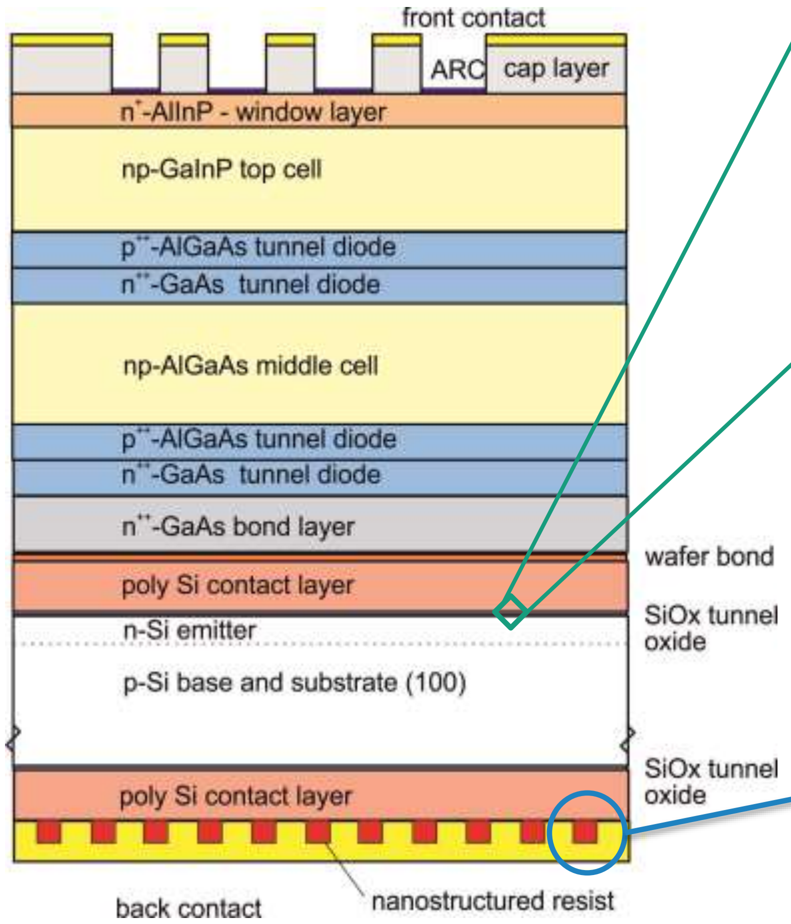
New World Record in 2018

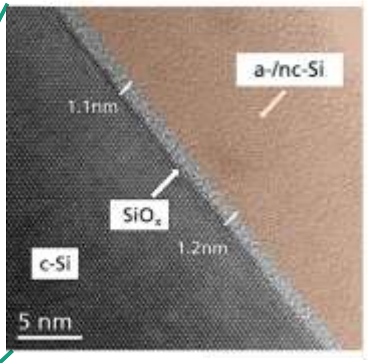
2018


ARTICLES
nature energy

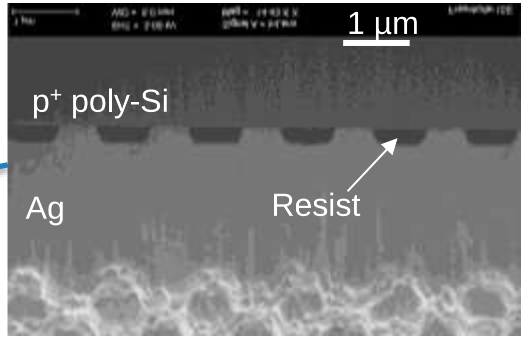
III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration

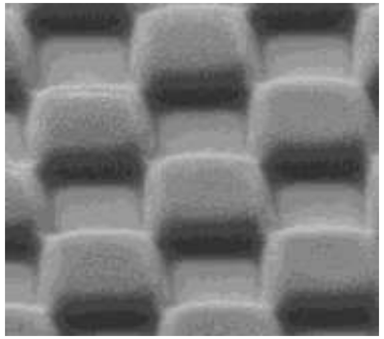
Romain Cariou, Jan Benick, Frank Feldmann, Oliver Höhn, Hubert Hauser, Paul Beutel, Nasser Razek, Markus Wimplinger, Benedikt Bläsi, David Lackner, Martin Hermle, Gerald Siefer, Stefan W. Glunz, Andreas W. Bett and Frank Dimroth





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%

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R. Cariou, Nature Energy (2018) doi:10.1038/s41560-018-0165-5

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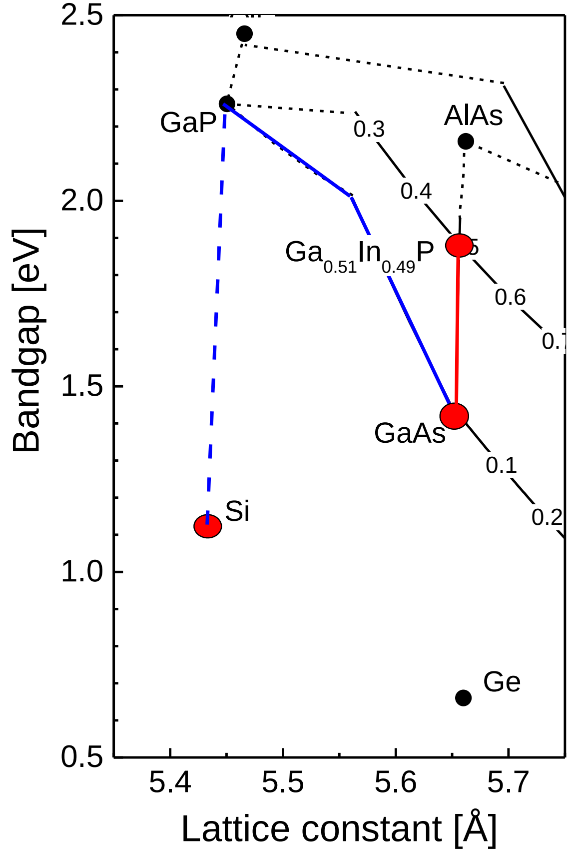
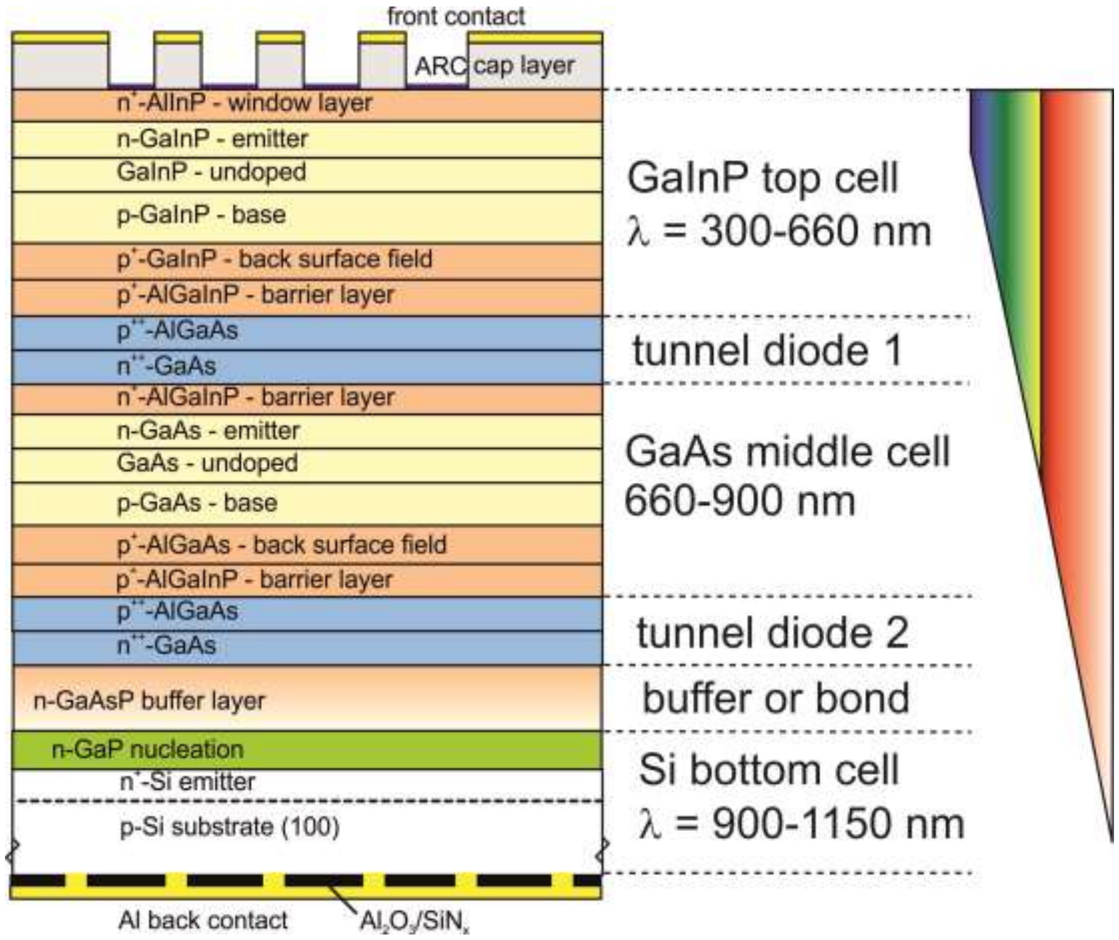
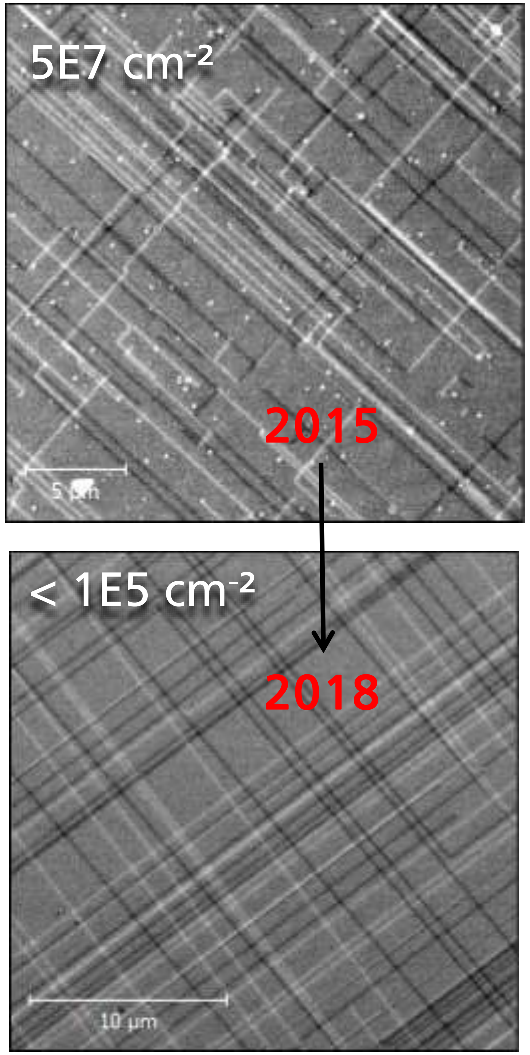
Technology Status 2-Terminal III-V/Si Tandem

Direct Epitaxy Growth on Silicon







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Philipps Universität Marburg

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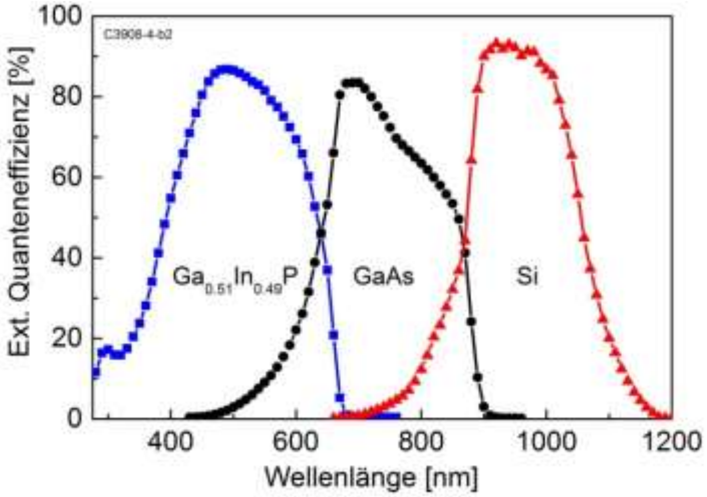
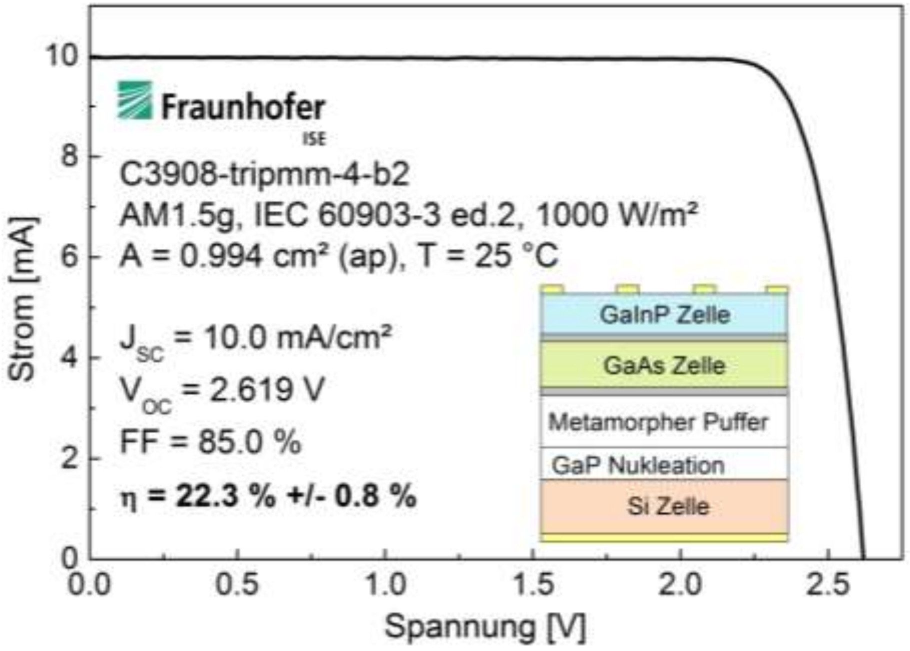
Technology Status 2-Terminal III-V/Si Tandem

World Record for Direct Epitaxy Growth on Silicon

2018

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





Presseinformation #1

Photovoltaik-Trend Tandemsolarzellen – Wirkungsgradrekord für Mehrfachsolarzelle auf Siliciumbasis

7.1.2019

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.

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-Halbleiterverbindungen wie Galliumarsenid. Eine Realisierungsoption ist, die III-V Solarzellenstrukturen auf teure Galliumarsenid-Substrate abzuscheiden und diese danach mittels der Halbleiter-Bondingtechnologie auf eine Siliciumsolarzelle zu übertragen und das Galliumarsenid-Substrat weg zu ätzen. Ein deutlich kostengünstiger Realisierungsweg ist ein direktes Wachstum der III-V Schichten auf die Siliciumsolarzelle. 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 im Kristallgitter vergrößert 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-

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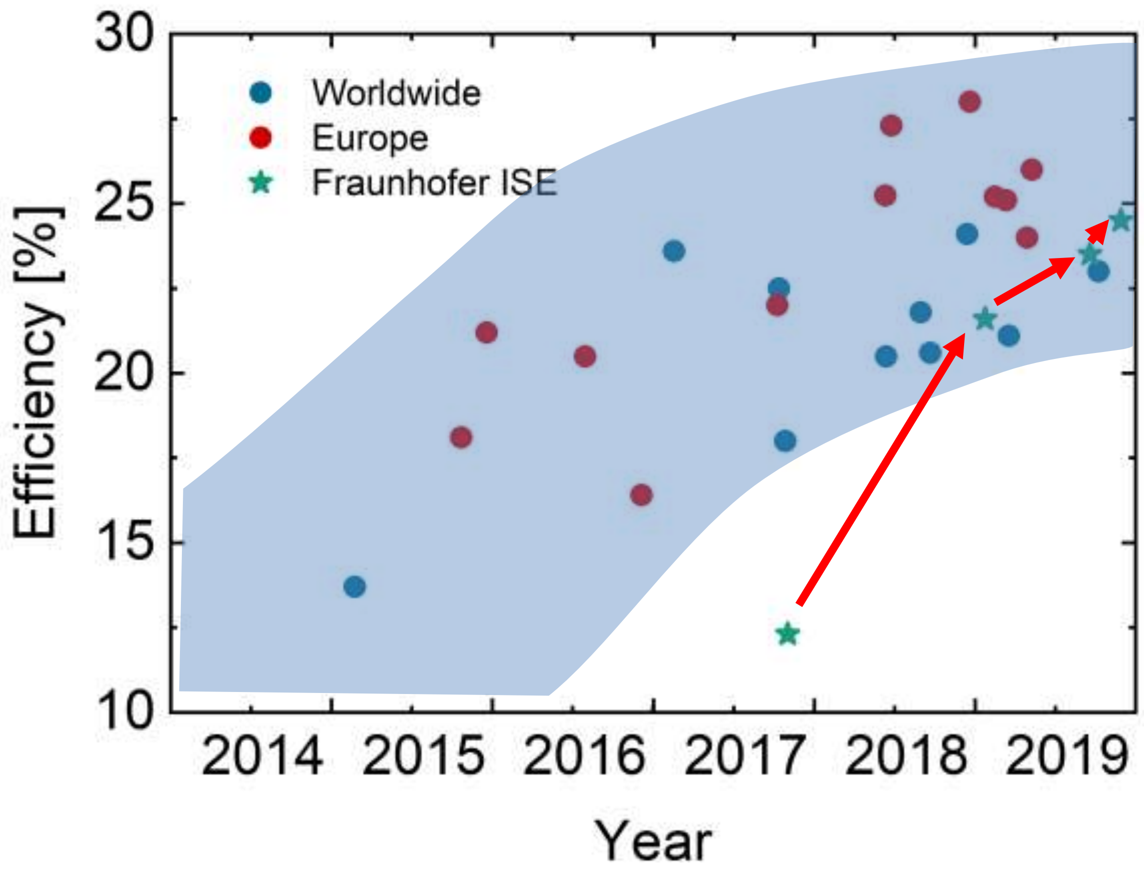
Technology Status Perovskite/Silicon Tandem Solar Cells
Laboratory Solar Cells

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



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Center for High Efficiency Photovoltaics ZHS at Fraunhofer ISE

Advanced Semiconductor Science and Engineering

Coming in 2020

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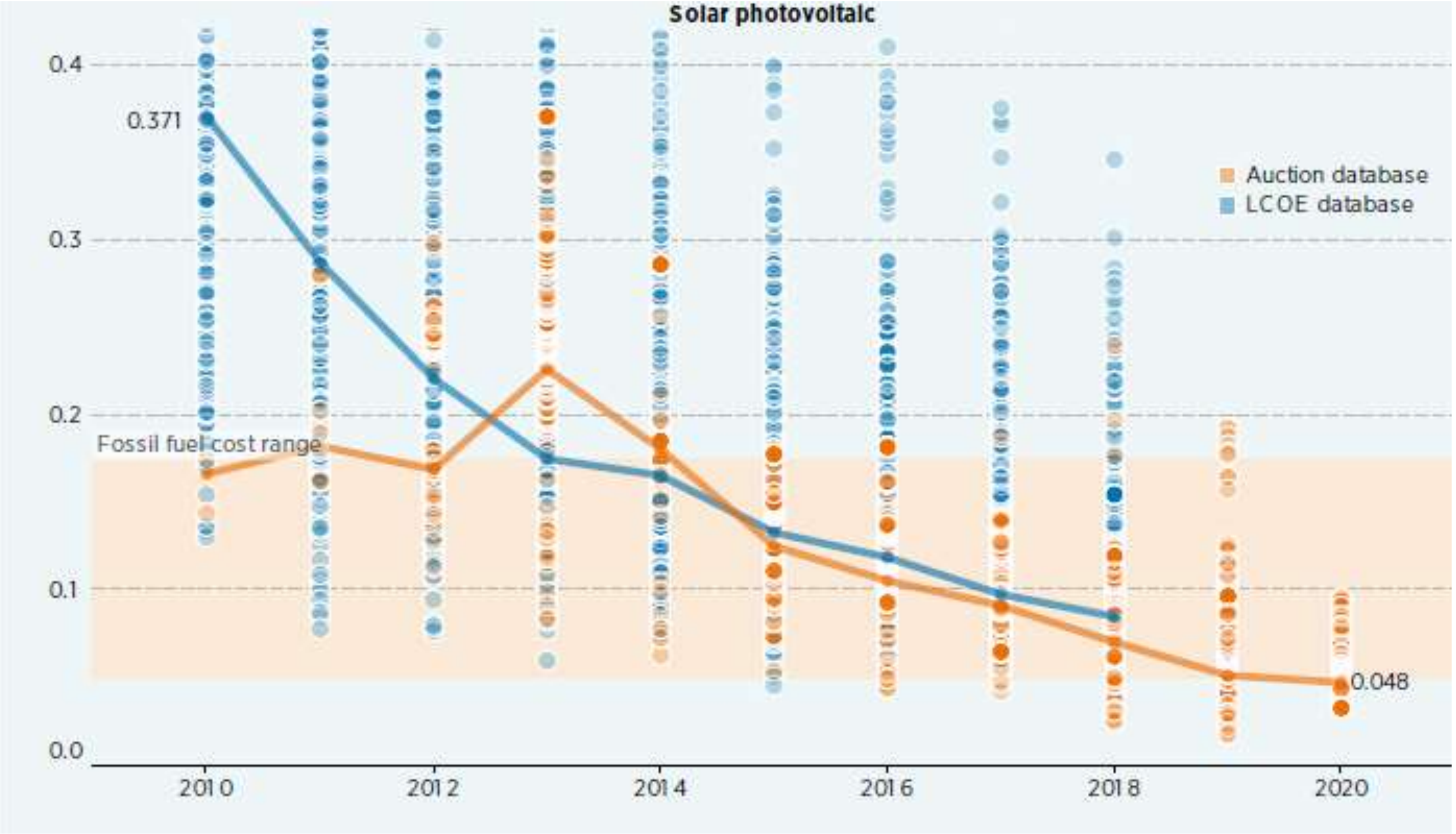
Electricity by Photovoltaic has today the lowest Costs and Triggers Market

Levelized Costs of Electricity (LCOE) in US$/kWh



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

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Future of Solar Photovoltaics, Report, IRENA, 2019

Status Quo

Current European c-Si PV Manufacturing Landscape

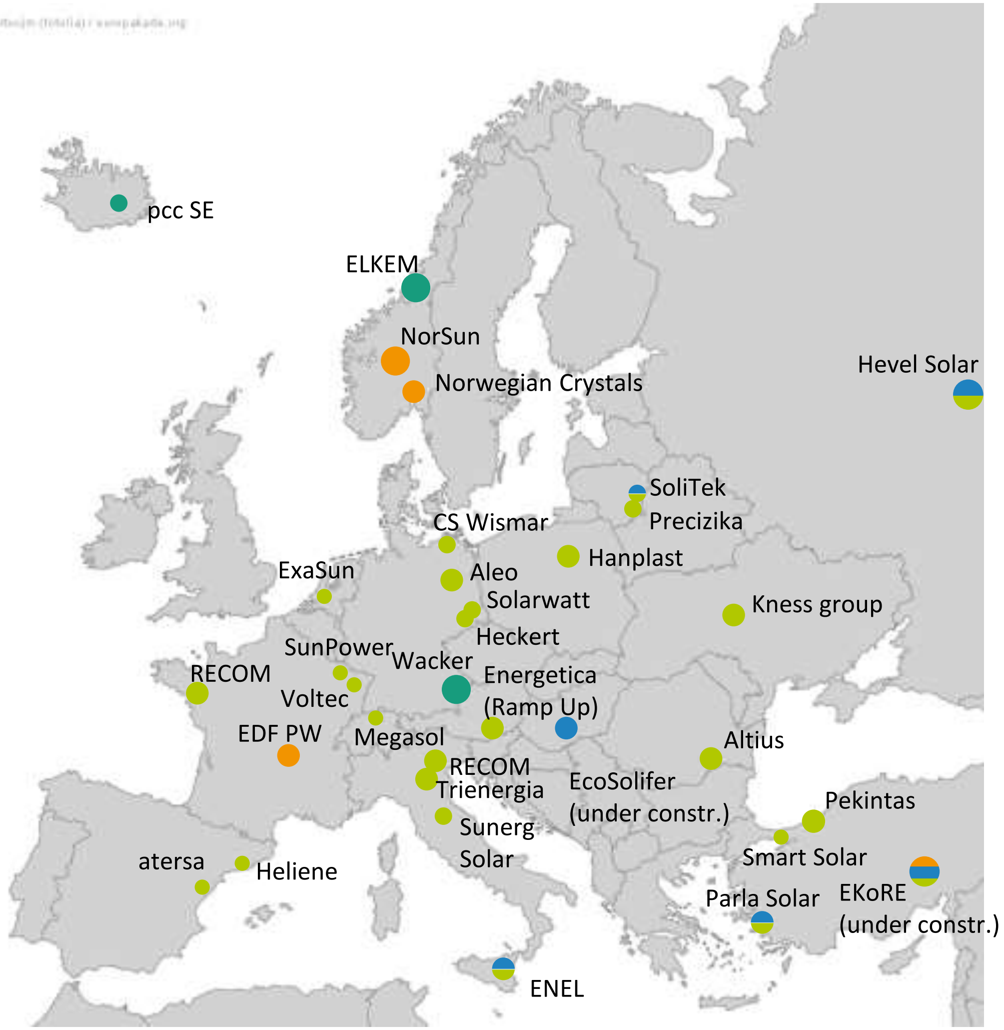
- Silicon/wafer production in Scandinavia/Germany
- distribution of of small module production plants < 500 MW/a capacity
- almost no cell production capacity

Value chain step

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

Factory size

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



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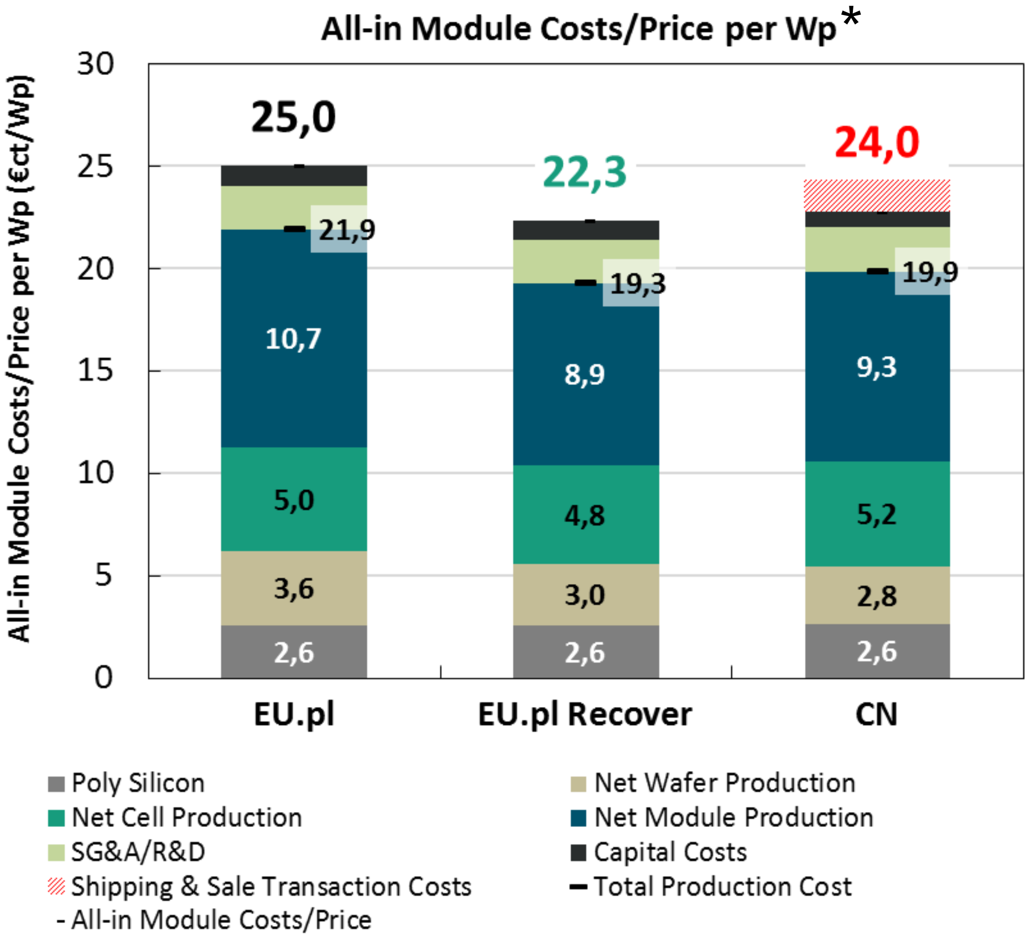
Cost Comparison of Module Manufacturing Europe Versus China

Calculation of Full Manufacturing Module Costs

- Comparision 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**



*Ref: J. Rentsch, et al, *Competitiveness of a European PV manufacturing chain*, Photovolt. Int., Vol. 43, p. 29-35, 2019

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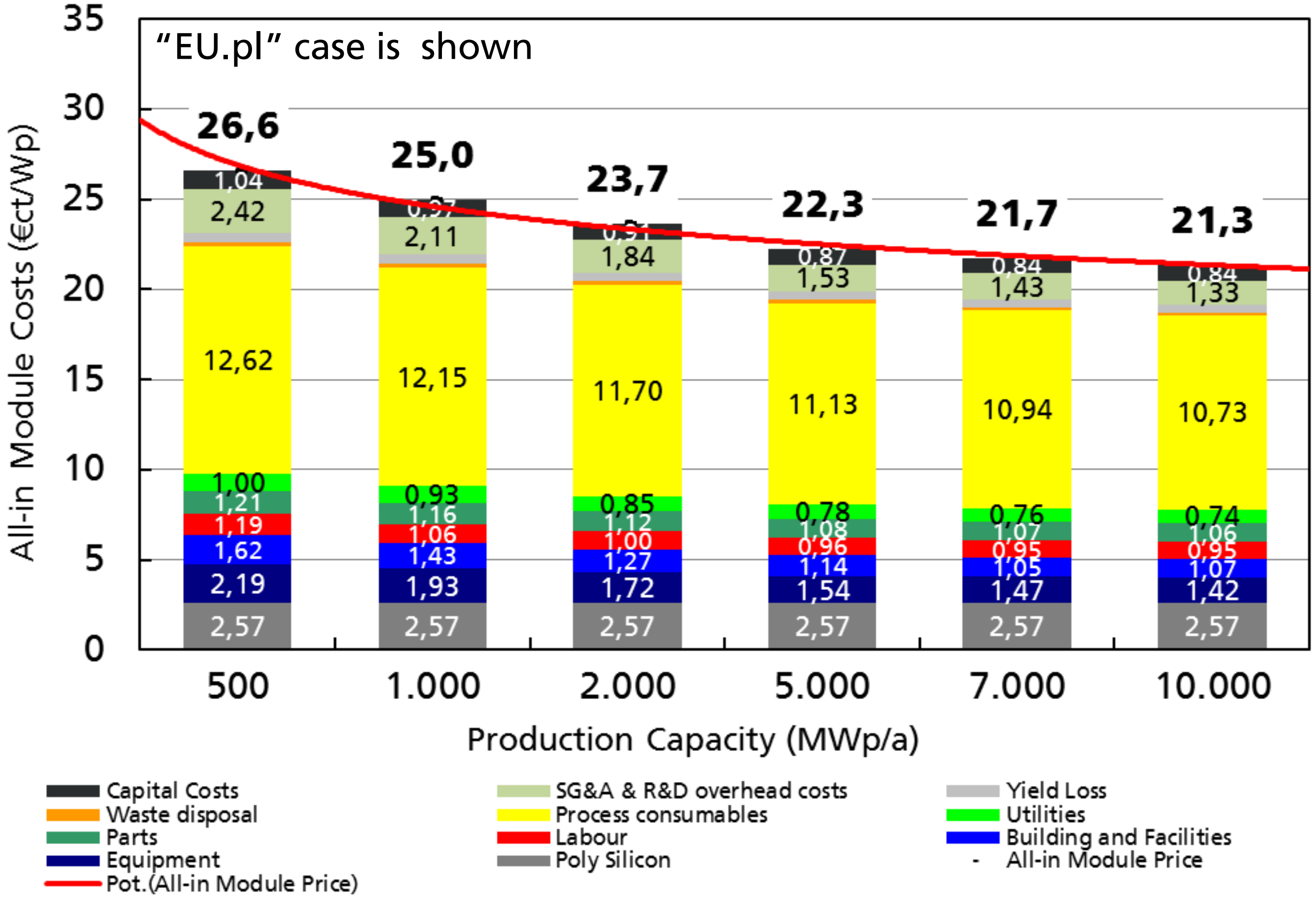
Development of Cost in Dependence of Manufacturing Size

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



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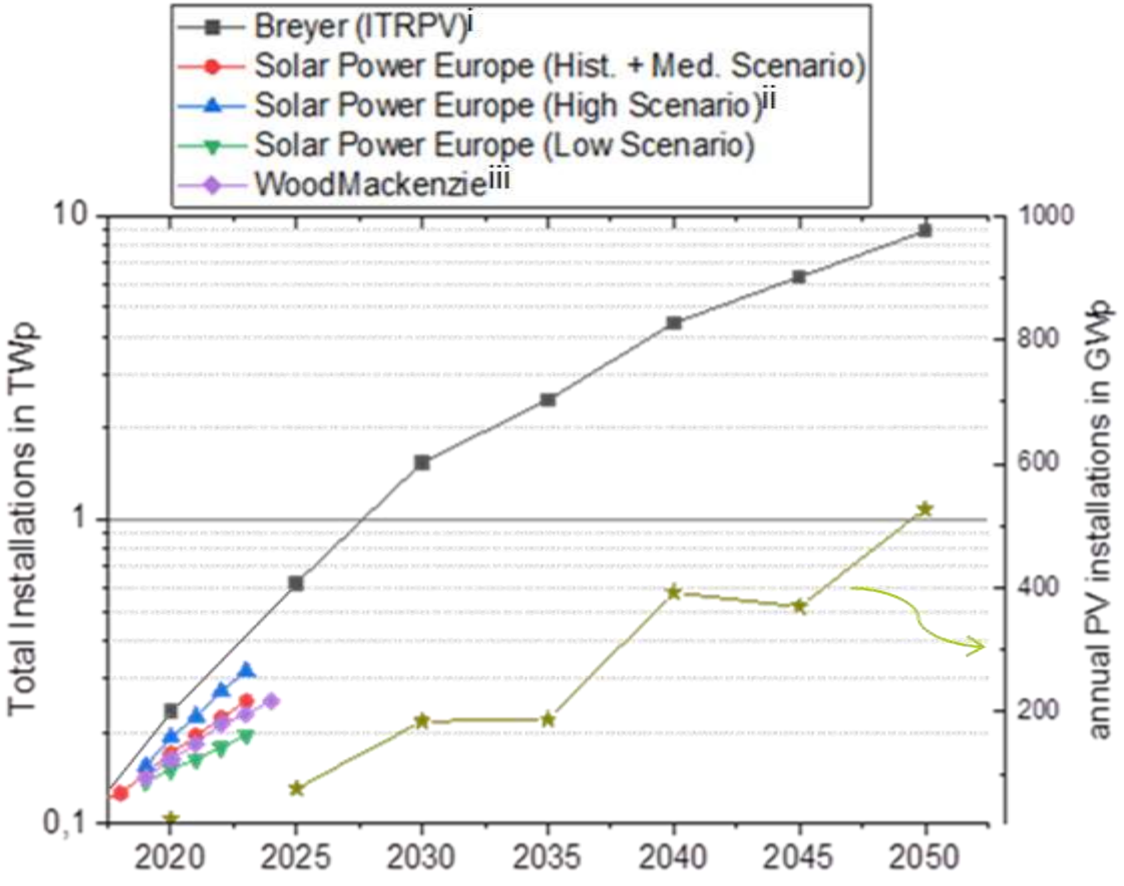
Growth of the European Photovoltaic Market Expected!



- **Example: Scenario by Solar Power 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.

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i) M. Ram et al, Global Energy System based on 100% Renewable Energy - Power Sector (2017); Lappeenranta University, Finland;
ii) SolarPower Europe, Global Market Outlook for Solar Power, 2019-2023;
iii) Wood MacKenzie, Europe solar PV outlook, 2019

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Costs for Logistics Becomes Notable!

More than 10 % of Full Delivery Costs!

1-2 €ct/W transport cost & CO_2 emission

Production cost 2022: ~ 20 €ct/W

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

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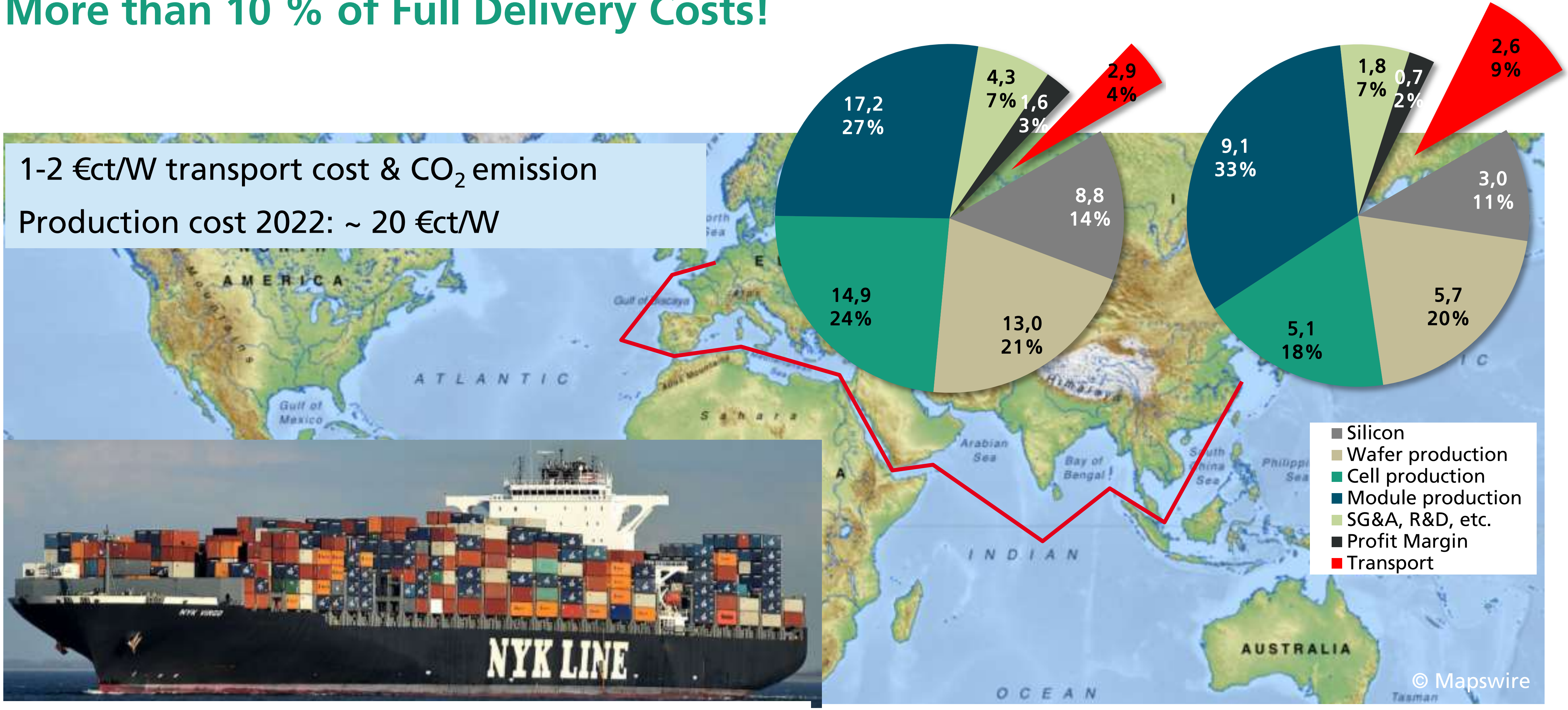

https://de.wikipedia.org/wiki/Containerschiff#/media/Datei:NYK_Virgo_(8154929586).jpg

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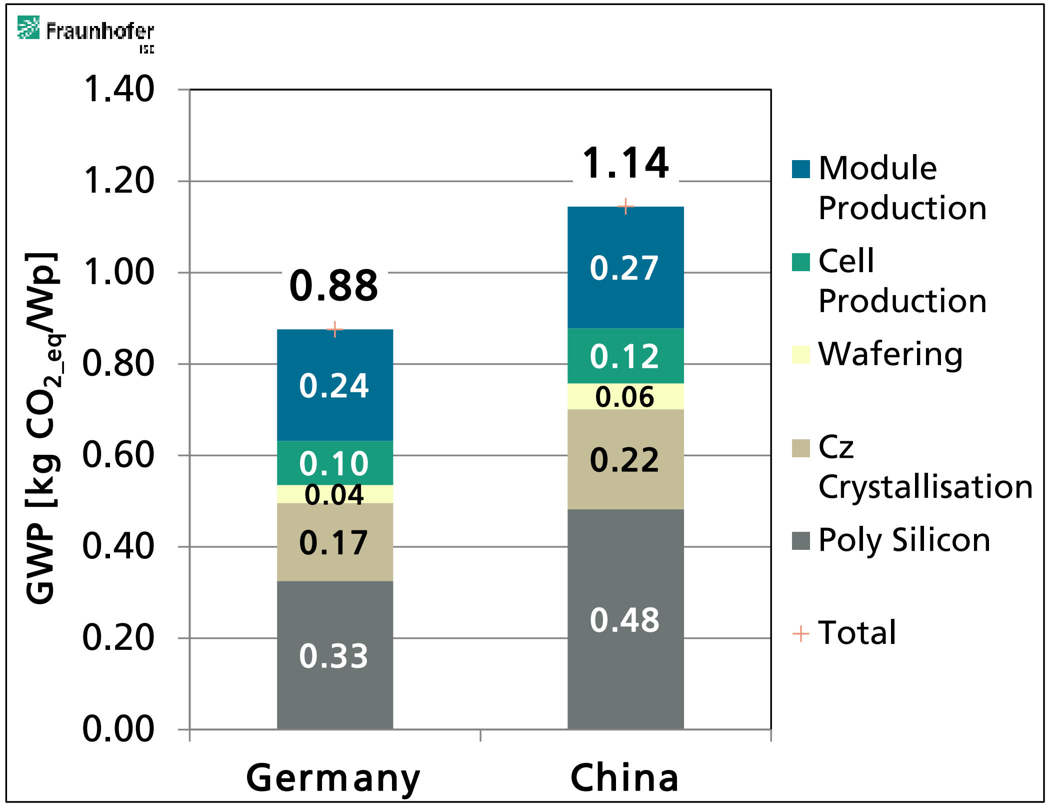
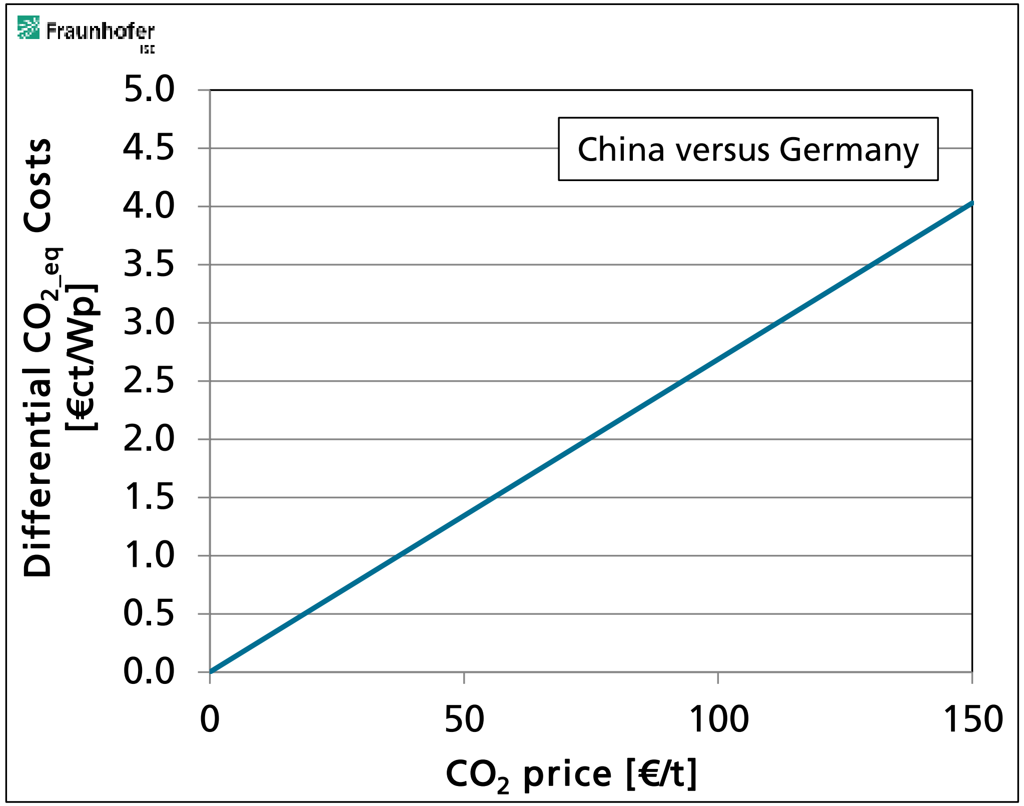
Carbon Emissions of PV Production and Effects of a Carbon Pricing

Scenarios: Germany and China



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



CO_2 cost difference of a Cz PERC module production located in Germany compared to China

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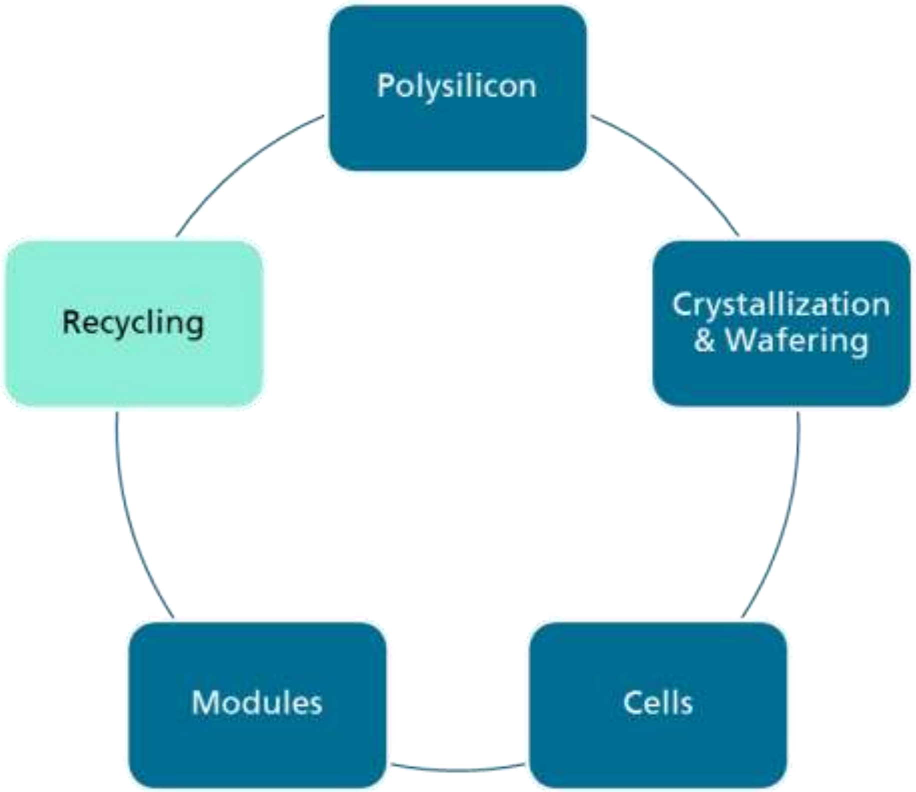
PV Market Development, Sustainability and new High-Tech Solutions lead to Novel Chances for PV-Manufacturing in Europe!

- 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:



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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 CO_2 emission**
- Strong growing European PV market

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

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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 CO_2 footprint** is a strong market differentiator.
    - Transport and logistics cost share increases and opens opportunities for European production.

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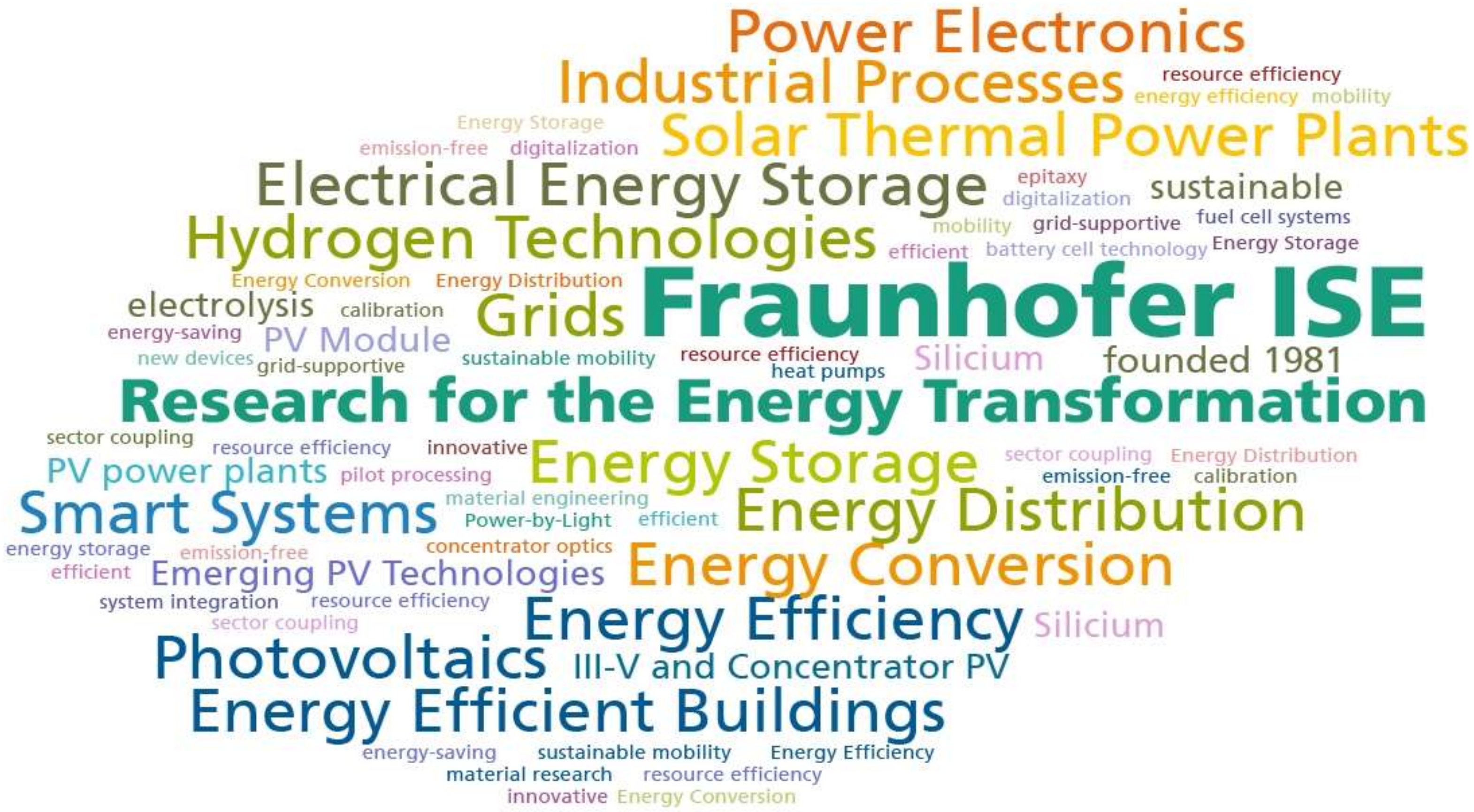
Thank you for your Attention!



Dr. Andreas Bett

www.ise.fraunhofer.de
andreas.bett@ise.fraunhofer.de

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