NEUE PHOTOVOLTAIK-TECHNOLOGIEN FOCUS: PEROVSKITE SOLAR CELLS (PSC)

A new approach for photovoltaics

Dr. Andreas Hinsch

Fraunhofer Institute for Solar Energy Systems ISE

Samstags Forum Regio Freiburg

8-12-2018

www.ise.fraunhofer.de

Fraunhofer ISE

AGENDA

- New trends for Integrated Photovoltaics (Agrophotovoltaics / BIPV)
- Photovoltaics in general
- Some words on sustainability
- Perovskite solar cells
- Up-scaling issues (in-situ concept)
- Conclusions

Integrated Photovoltaics

- Ökostation Freiburg, the role model from 1986 (91)

Fraunhofer ISE

Integrated Photovoltaics / Agrophotovoltaics

Photo: Fraunhofer ISE

- Free-standing standard Si-PV modules in agriculture (south-orientation)

Fraunhofer ISE

Integrated Photovoltaics / Agrophotovoltaics

- Free-standing bifacial Si-PV modules in agriculture (east-west orientation)

Fraunhofer ISE

Integrated Photovoltaics / Agrophotovoltaics

- Preventing overheating in glass houses by partially shading PV modules

Building Integrated Photovoltaics (BIPV)

- Mounting of Si-PV modules <u>onto</u> the building façade as architectural elements

Fraunhofer ISE

Building Integrated Photovoltaics (BIPV)

Photo: Sunovation

- Integration of Si-PV into decorative glass facade

Fraunhofer ISE

Building Integrated Photovoltaics (BIPV)

Photo: Schüko

- Integration of Si-PV as thermally isolating glass façade (house of glass)

Fraunhofer ISE

Building Integrated Photovoltaics (BIPV)

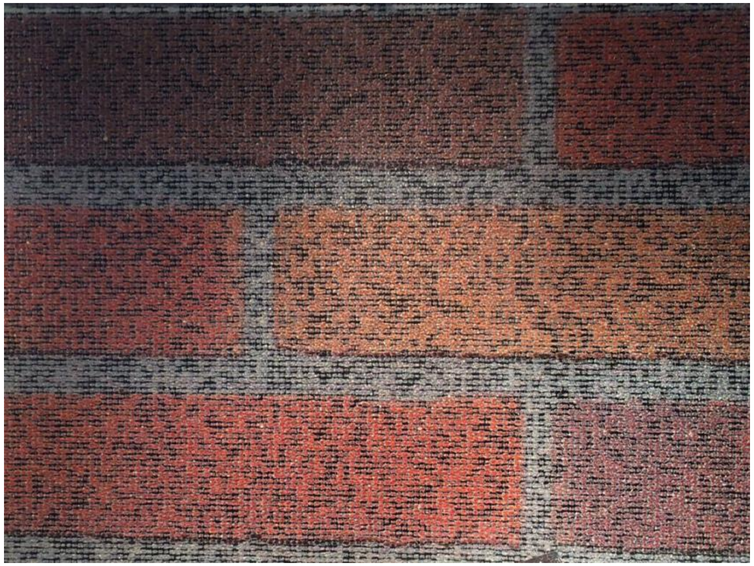


Photo: ECN, NL

- Integration of Si-PV modules optically fitting to traditional brick walls and roofs

Fraunhofer ISE

Building Integrated Photovoltaics (BIPV)

Photo: Fraunhofer ISE

- Demonstration of dye solar modules as transparent decorative glass elements

Fraunhofer ISE

Building Integrated Photovoltaics (BIPV)

Photo: EPFL Lausanne

- Integration of dye solar modules as transparent decorative glass façade elements

Building Integrated Photovoltaics (BIPV)

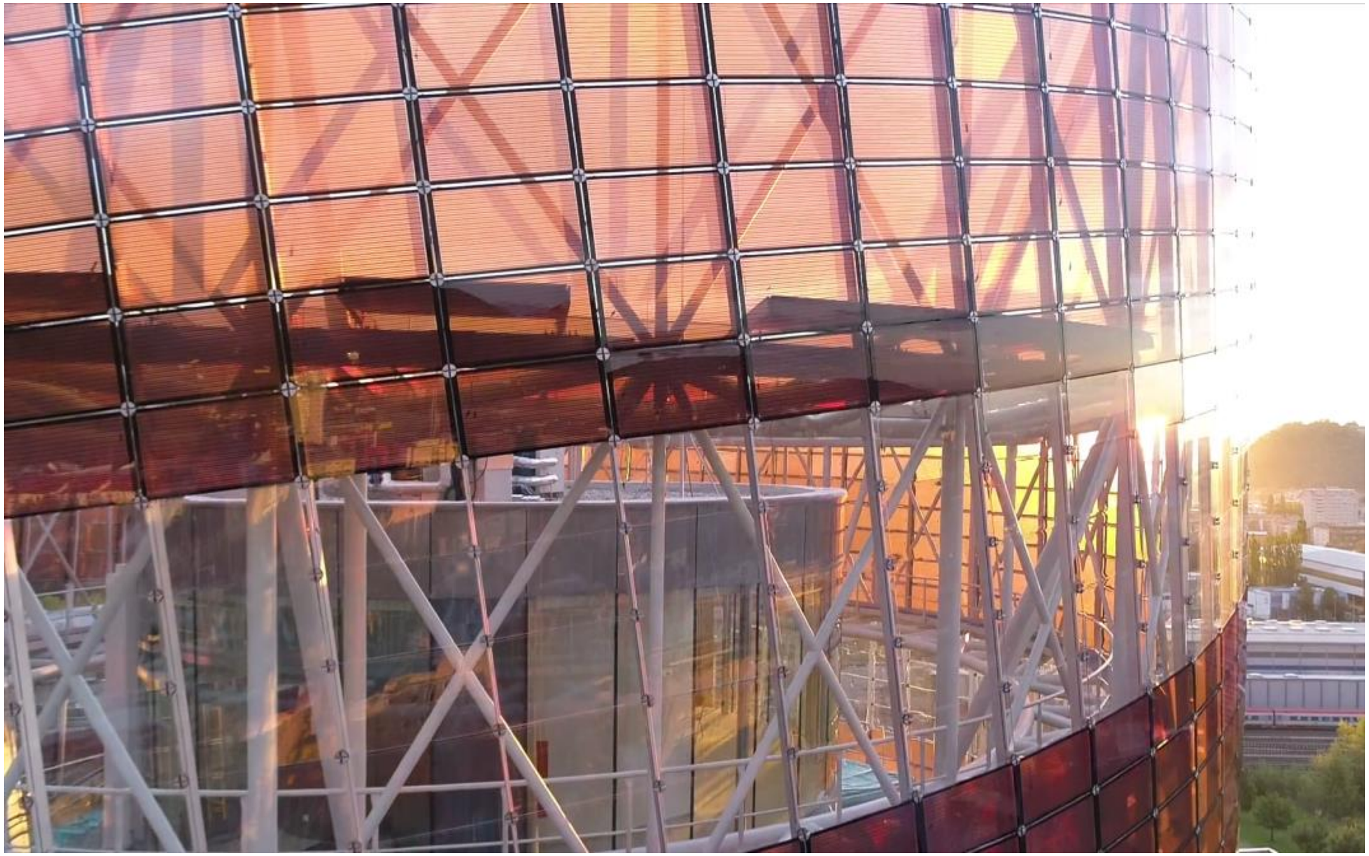


Photo: h.glass

- Integration of dye solar modules as transparent decorative glass façade elements

Building Integrated Photovoltaics (BIPV)

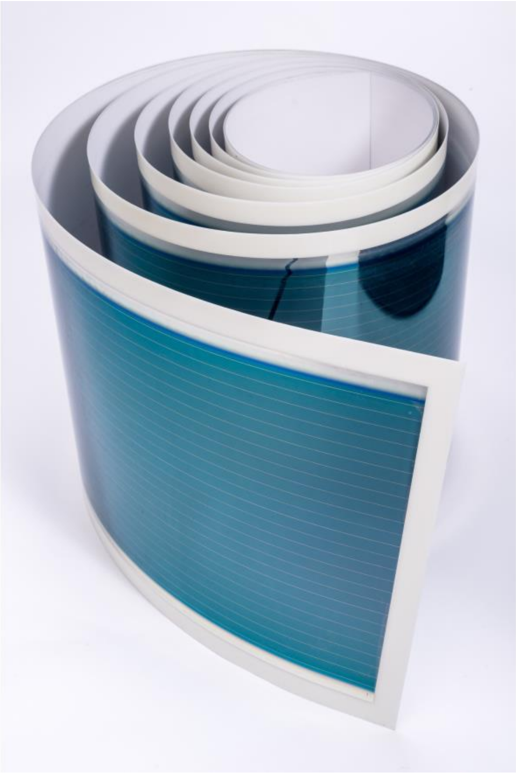


Photo: Heliatek

- Organic solar cells on foils
- E.g. integration on steel facades

Fraunhofer ISE

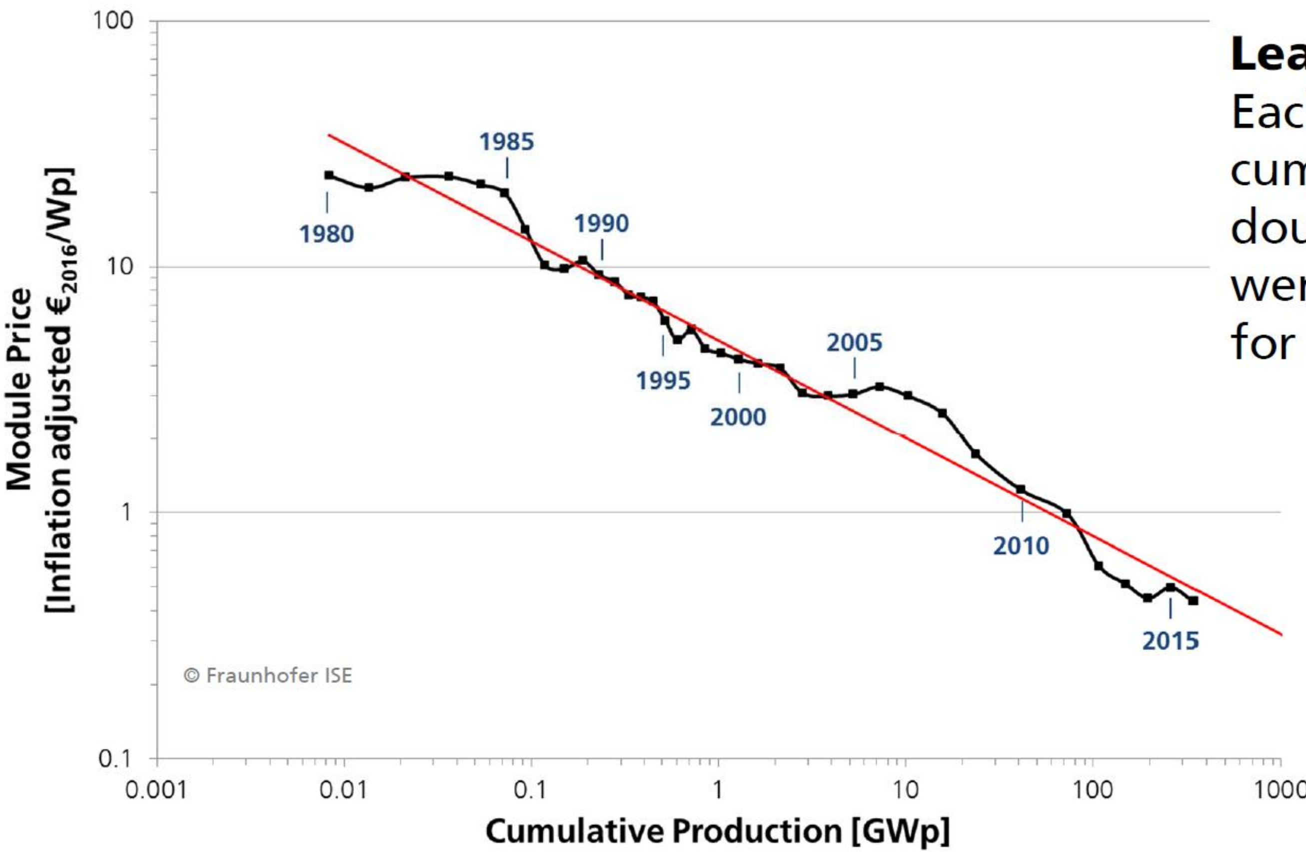
Building Integrated Photovoltaics (BIPV)

Photo: OPVIUS

- Printed organic solar cells integrated into decorative foils

Fraunhofer ISE

Price learning curve of standard PV



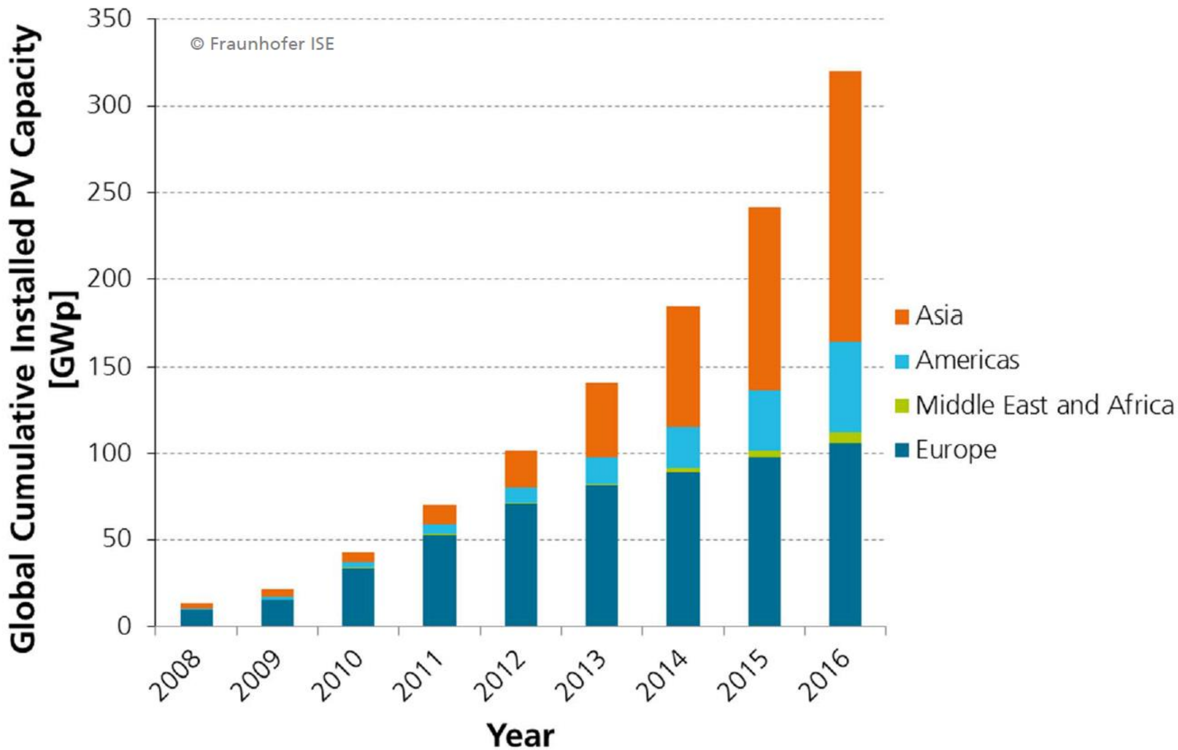
Learning Rate:
Each time the cumulative production doubled, the price went down by 24 % for the last 36 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2016: IHS. Graph: PSE AG 2017

- PV module will become lowest cost electricity generator

Fraunhofer ISE

Global Cumulative PV Installations until 2016



Data: IHS. Graph: PSE AG 2017

- Generated > 500.000 Mio € of turnovers so far
- In 10 years status changed from “pioneer” to “business dominated”
- Contribution to electricity production worldwide: 1.3%

Investor driven PV

- Extensive use of extra land

1 GW_p ground mounted PV plant, China, www.huawei.com

Private owner driven PV

- Stimulation of energy saving

Israel's 'green house' entry in the 2013 Solar Decathlon

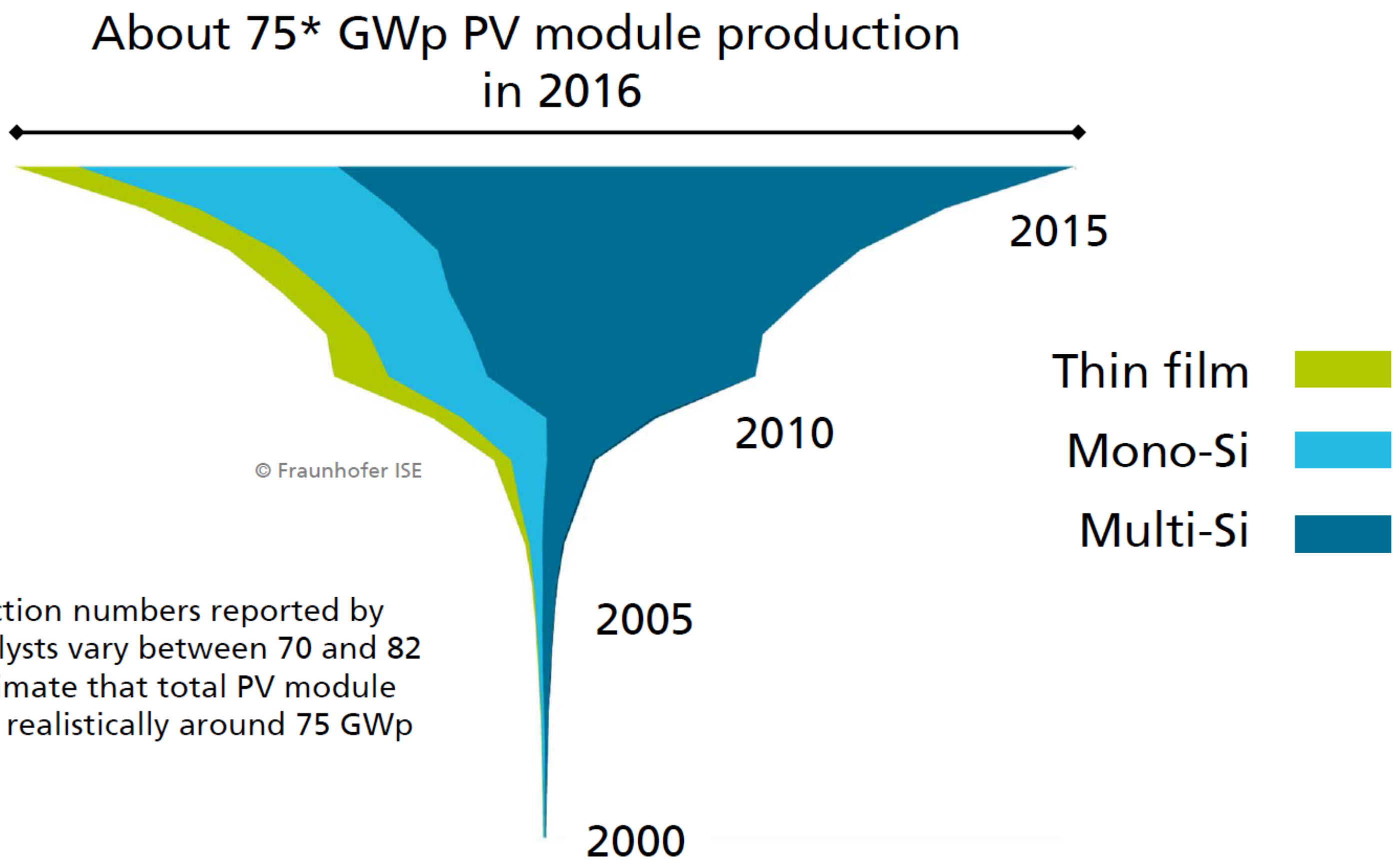
Fraunhofer ISE

Architectural driven PV

- Ideal for urban areas

Fraunhofer ISE

Annual PV Production by Technology Worldwide (in GW_p)



*2016 production numbers reported by different analysts vary between 70 and 82 GWp. We estimate that total PV module production is realistically around 75 GWp for 2016.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017

Silicon Ingots for wafer based PV

- 7 kg of silicon / kW_p to be cut into 180 µm thick wafers
- 99.999% silicon

Source: Solarworld

Fraunhofer ISE

Refinery of Silicon Feedstock for PV

- 500.000 tons per year worldwide

Wacker Burghausen, Germany

Fraunhofer ISE

Integrating silicon refinery and PV polysilicon production

- Cost reduction by economy of scale

LDK Polysilicon manufacturing facility, China, www.fluor.com

Fraunhofer ISE

Silicon PV Module manufacturing

- Complex process from the wafer to the complete module

Source: Solarworld

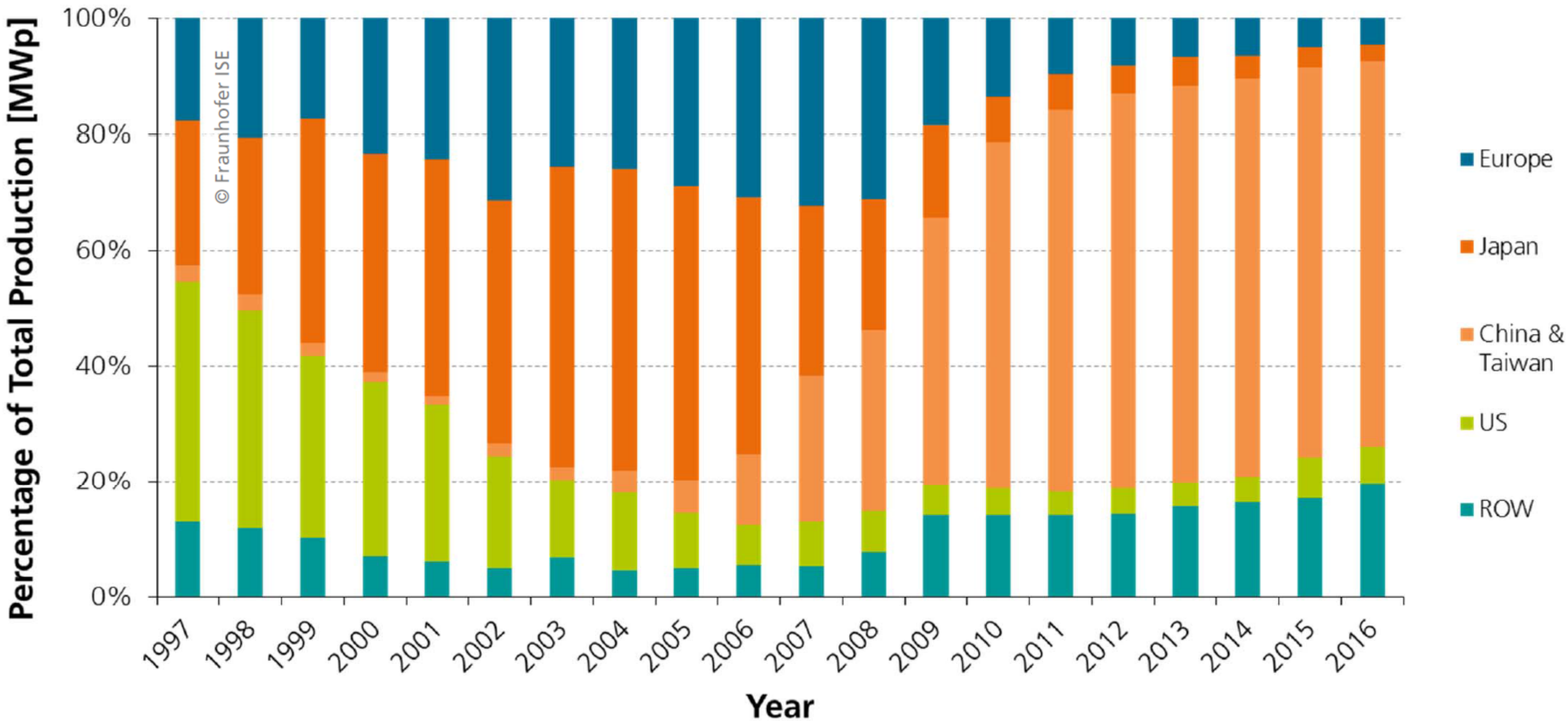
Floatglass Production Worldwide

- 370 lines, 65 Mio. tons / year
- Equivalent to 1000 GW_p (!) of PV per year

NSG Weiherhammer, Germany

Fraunhofer ISE

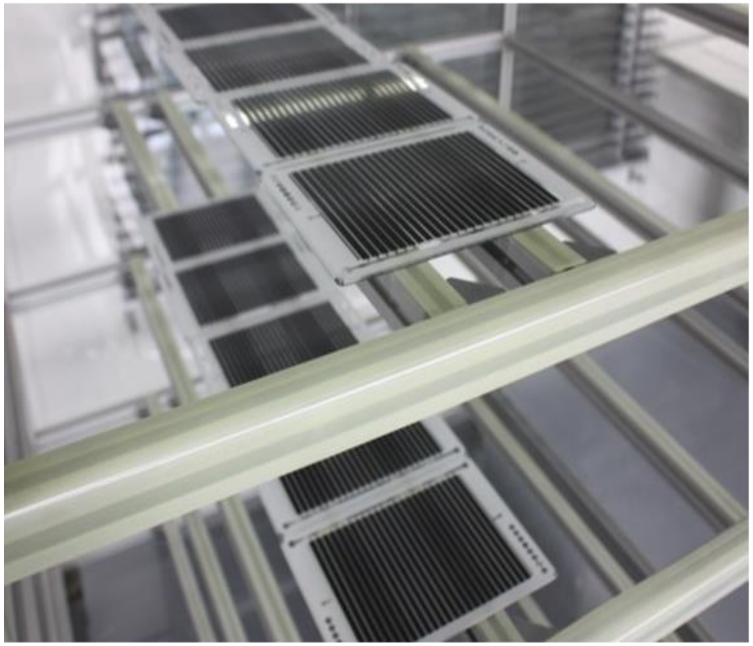
PV Module Production by Region 1997 - 2016

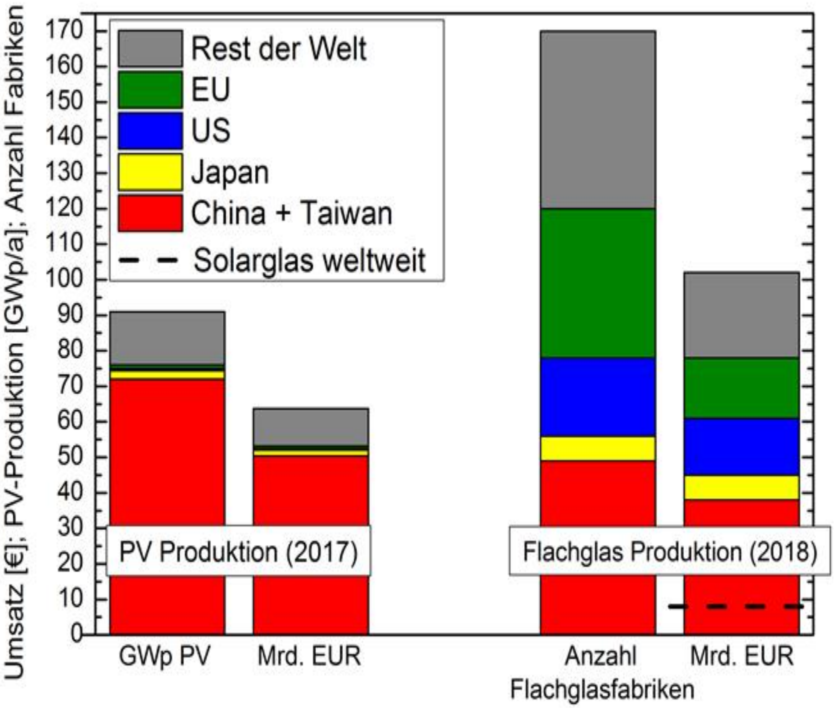


- Strong price competition drives production to China
- Local production like in flat glass industry still not favorable

Fraunhofer ISE

Alternative Thinking in Photovoltaics
e.g. by adopting the business model of the glass industry

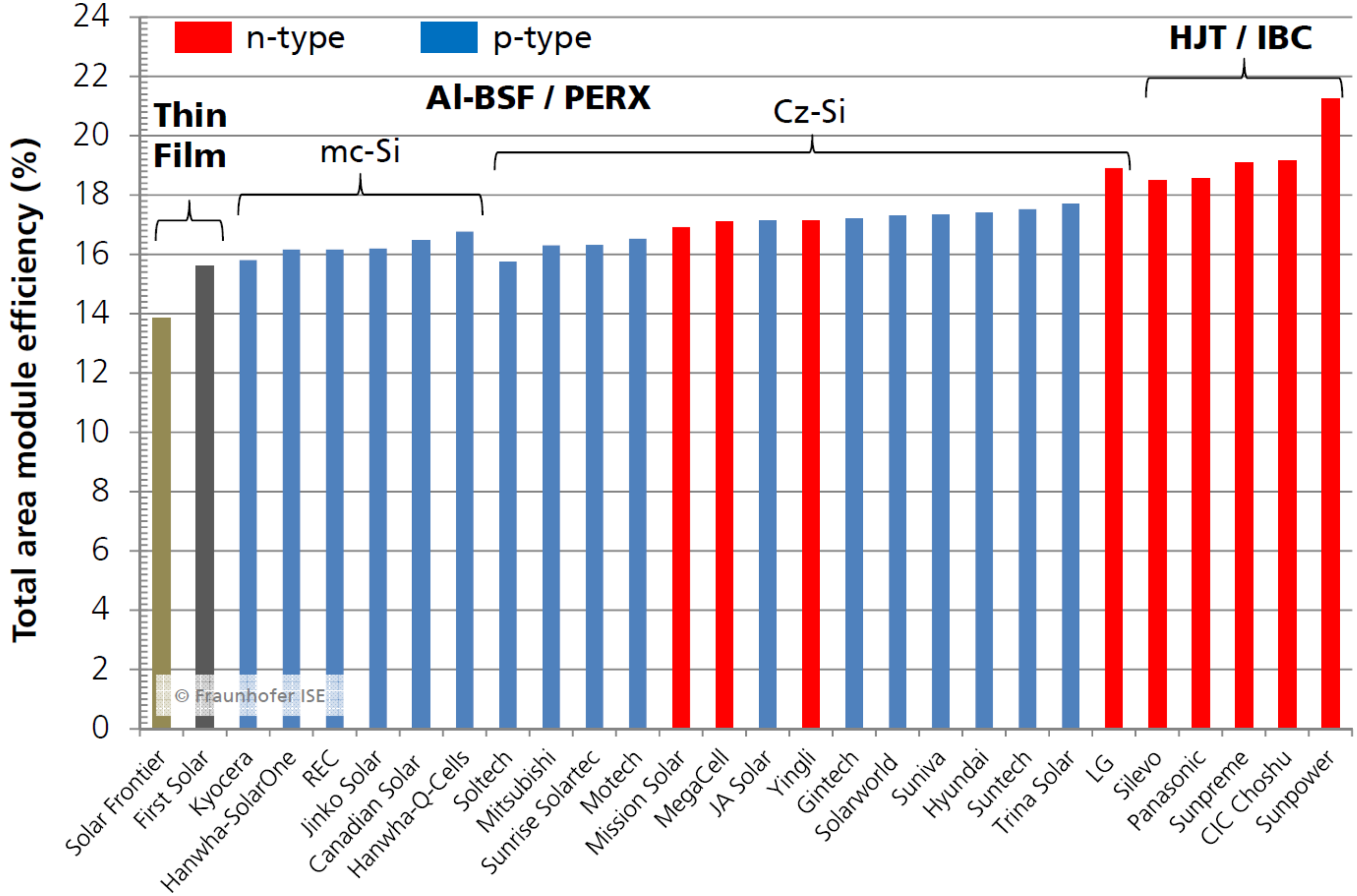




- Centralized production of Photovoltaics (2018)
- Global decentralized production of glass based printed photovoltaics (future)

Fraunhofer ISE

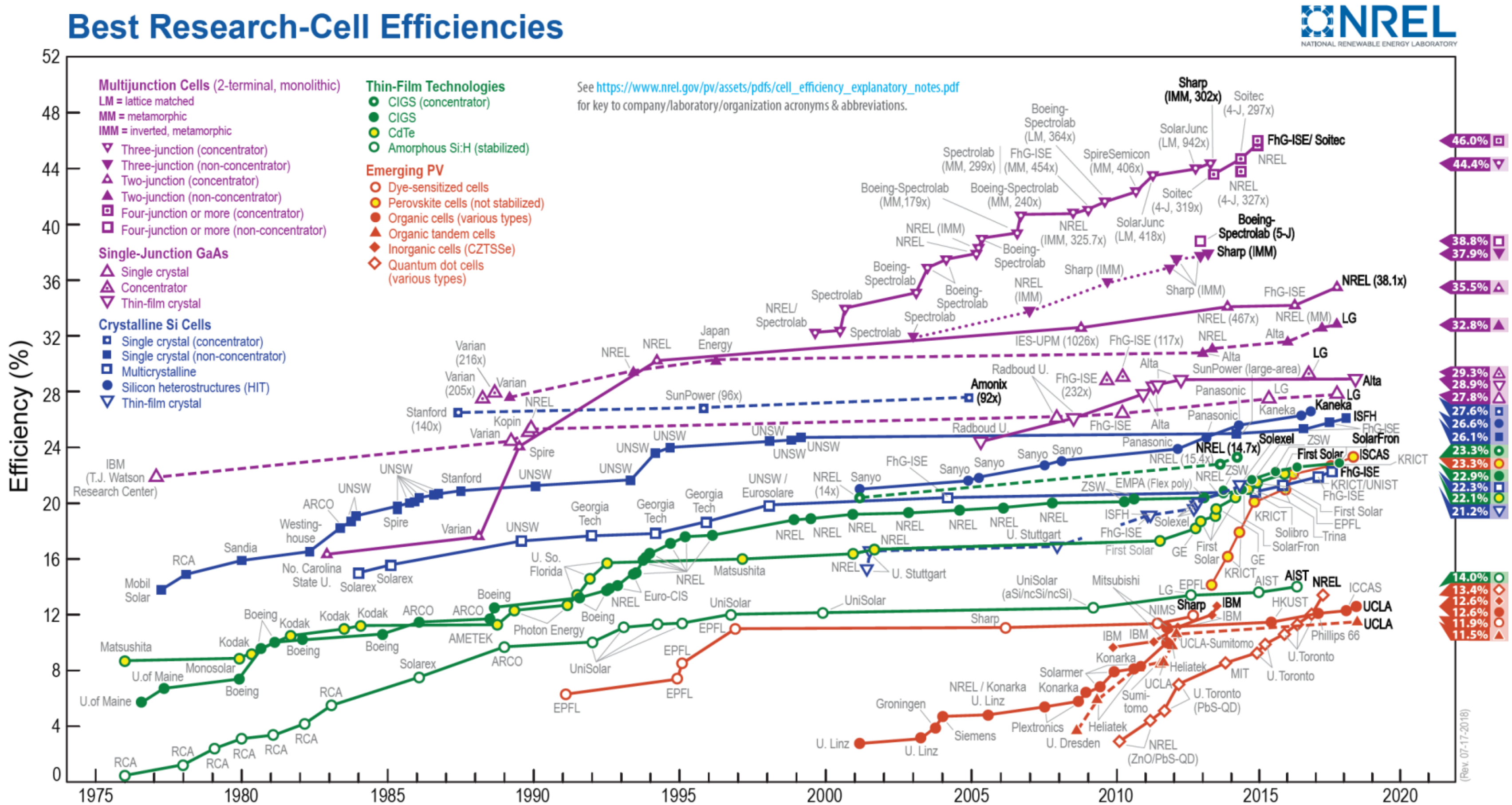
Efficiencies of Selected Commercial PV Modules



Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2015.

- > 18% module efficiency is a competitive target

World-record efficiencies of PV technologies



■ Perovskite solar cells are “the” new research topic in PV

Fraunhofer ISE

A brief look at the carbon footprint (in g CO_2 / kWh_{el})
Existing and potential energy technologies

Carbon Foot Print:	mono-Si multi-Si a-Si	CdTe CIGS	OSC DSC PSC	Hydro Wind	Gas Brown coal Nuclear
g CO_2 / kWh_{el}	38 27 33	16 21	> 15 > 15 > 10	10 – 40 10 – 40	400 – 550 850 – 1200 10 – 30

literature numbers, for PSC own estimation based on in-situ concept

PV: numbers are for installation in Southern Europe and manufacturing in Europe

- For Middle Europe a factor of 1.5 – 1.7 is necessary
- For BIPV a factor of 0.5 – 4 (depending on integration type) can be assumed
- Not included: mounting structure, energy storage and replacement after 25 years

Fraunhofer ISE

Strategies for enhancing PV for 50% contribution in worldwide (growing) electricity production

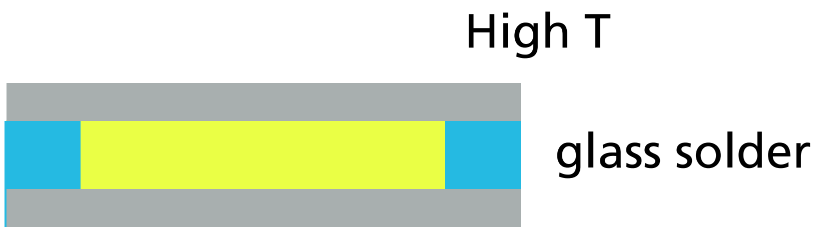
- Straight forward approach:
  Ramping up production facilities by a factor of 7 and produce state-of-the-art PV technology for the next 20 years. As a result > 8 billion tons of extra CO_2 will be emitted.

- Replace to save approach:
  Avoid growing electricity demand, shut-down 1 KWh non-renewable for 1 KWh renewable

- Research driven approach:
  Promote research on new PV technologies with lowest carbon dioxide footprint and highest sustainability

Worldwide electricity consumption: 22000 TWh (2014)
Current PV production rate: 100 GWp/a PV = 100 TWh/a
Worldwide CO_2 emissions: 35 billion (10^9) tons / year

Motivation for in-situ solar cell concept (Fraunhofer ISE)
- Making sensitive PV technologies sustainable -



1. Encapsulating „inorganic part“ by thermal glass fusing

2. Applying „organic part“ and formation of complete cell (from solution or gas phase)

- material, cell and module development is integrated research (from the start on)
- > 25 years stability goal for PV seems reachable in this case
- low-cost and mass producible („just glass“)

Fraunhofer ISE

Perovskite minerals

An old class of materials for young solar cell researchers

Lev Alekseevich Perovski

(1792 - 1856)

AMX_3

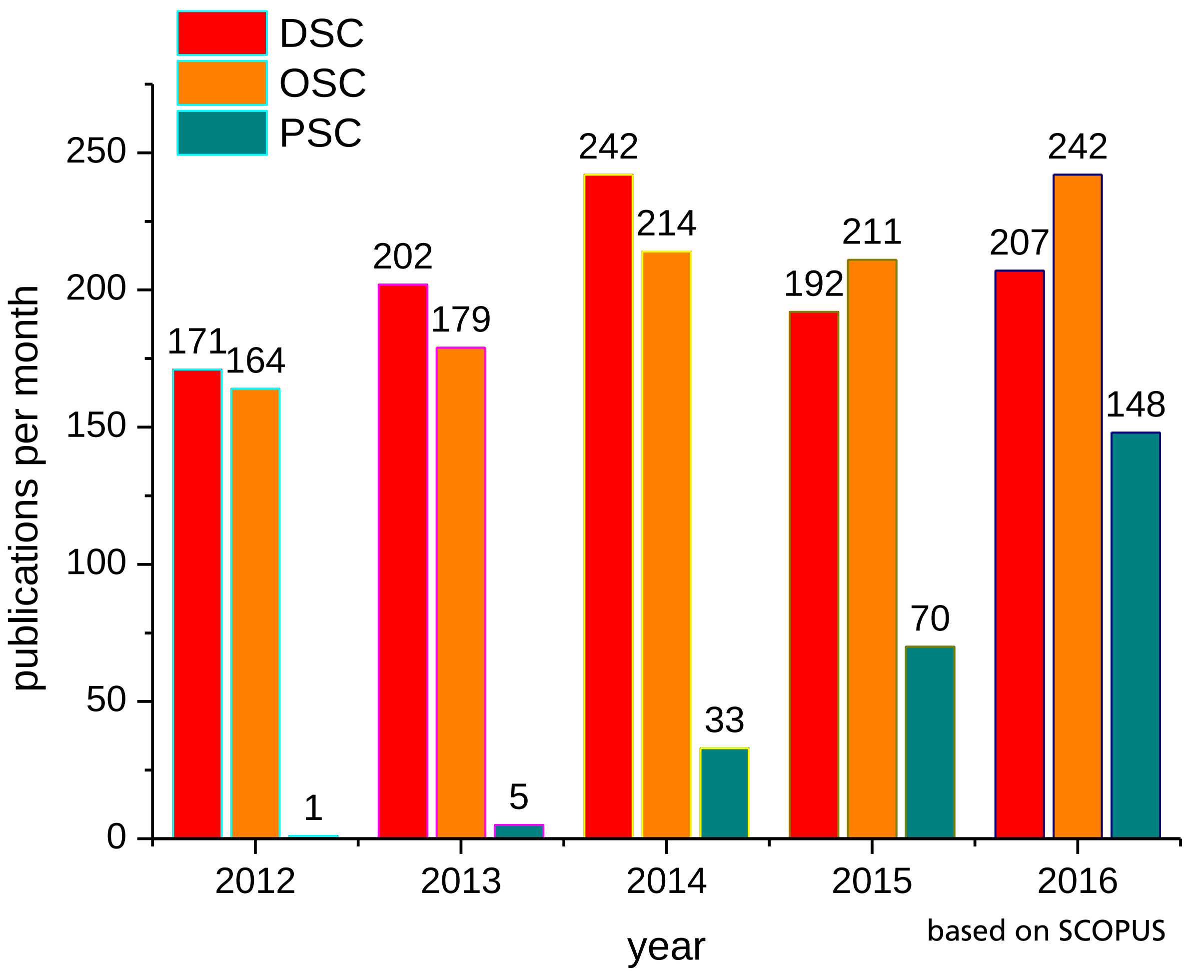
e.g. $CaTiO_3$ or $CH_3NH_3PbI_3$

Henry Snaith

(Science paper 2012)

Fraunhofer ISE

Research on dye-, organic-, and perovskite solar cells
Development of monthly publications

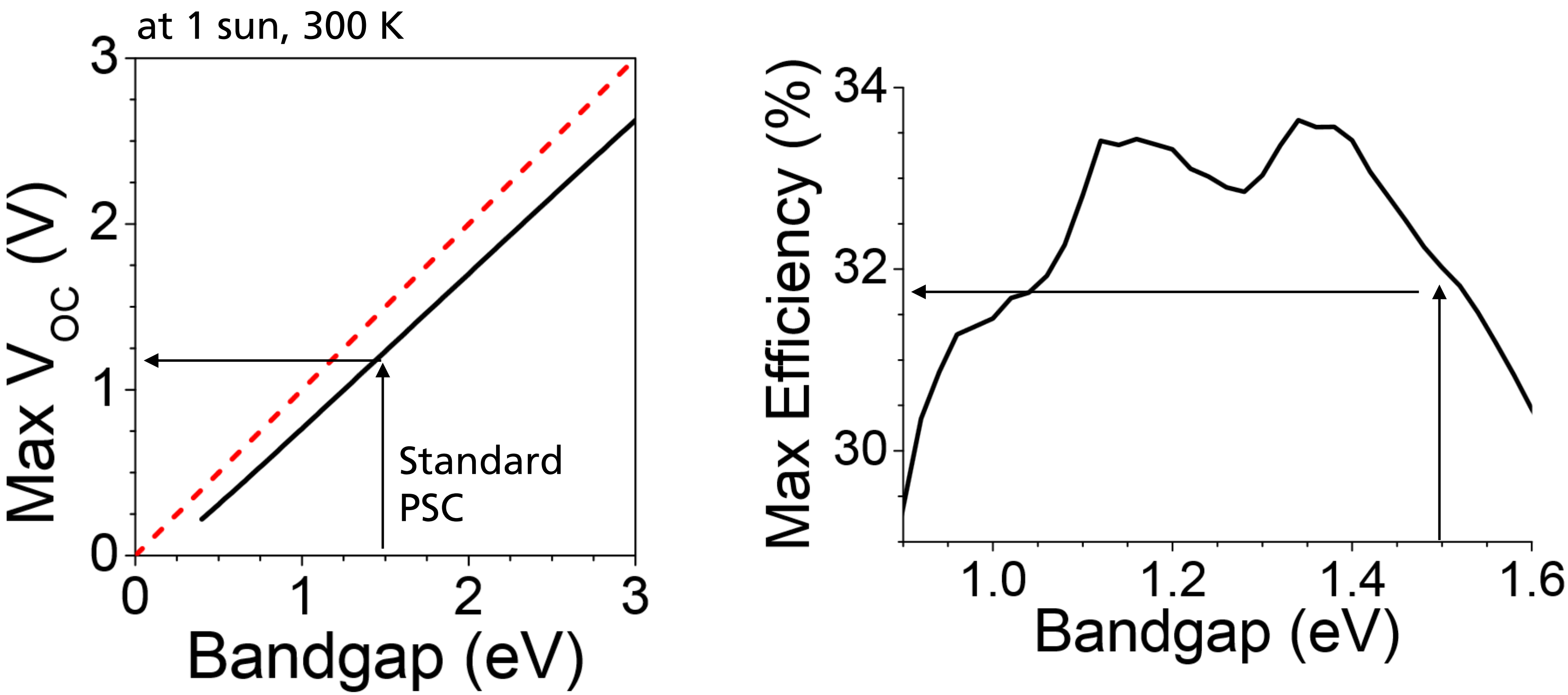


based on SCOPUS

Fraunhofer ISE

Shockley Queisser Limit for single junction solar cells

<u>Ideal</u> charge transport and <u>only</u> radiative recombination

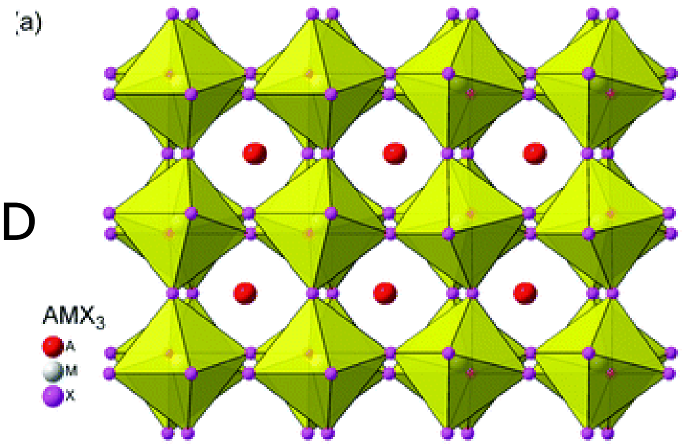


- Perovskite solar cells (laboratory) today, V_{oc} = 1.0 – 1.2 V, eta = 20 - 22%

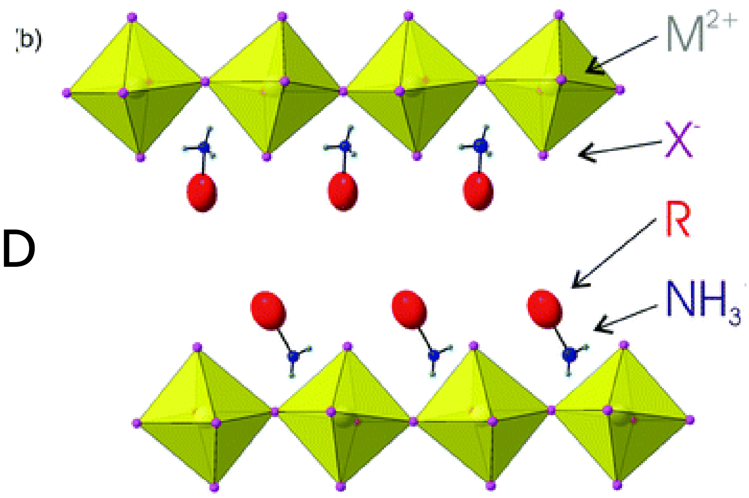
Fraunhofer ISE

Organic-inorganic metal perovskite crystals as photoactive material (double salt)

3 D



2 D



Simple solution based process:

$MX_2 + RNH_3X \rightarrow RNH_3MX_3$

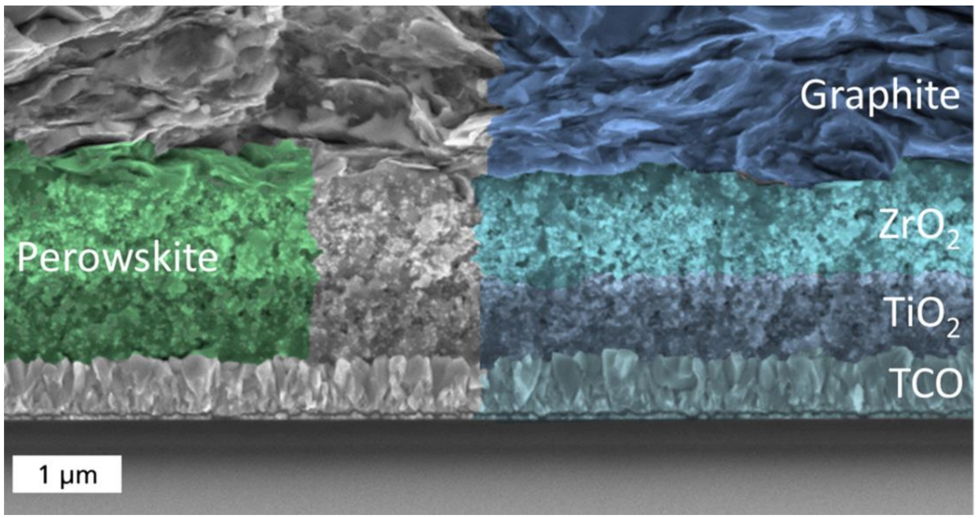
$M^{2+}X_3^-$ is stabilized by RNH_3^+

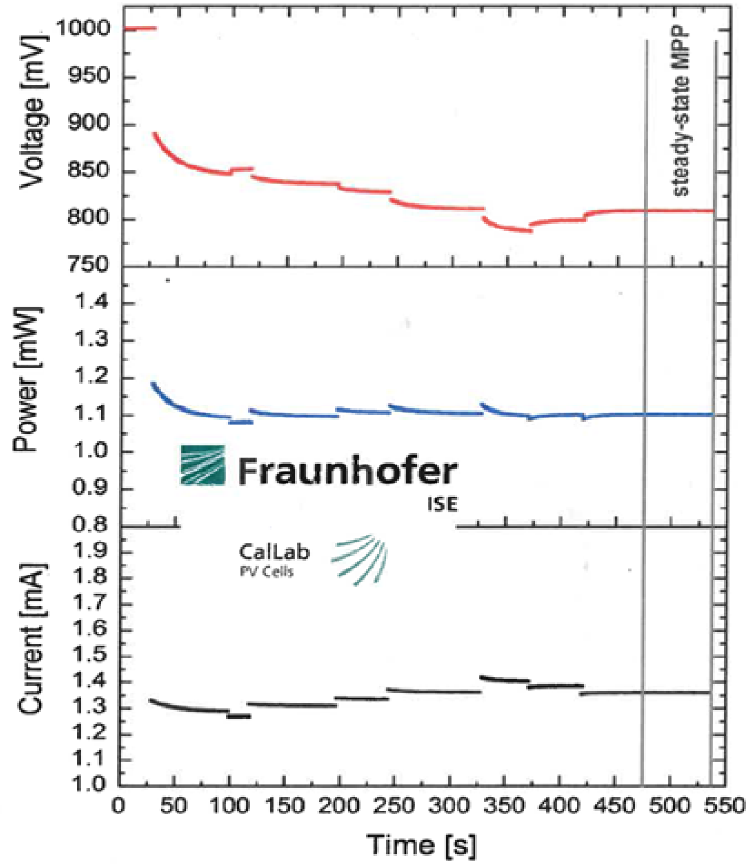
Semiconducting and ionic properties

Ion migration and redox chemistry

23% cell certified in 2018

Solution processed printed perovskite solar cells at ISE
Mesoporous HTL-free concept:





- V_{oc} = 1.0 V (<u>without</u> critical HTL)
- Worldrecord certified stabilized efficiency (12.6 %) for screen-printed PSC

L. Wagner, S. Chacko, G. Mathiazhagan, S. Mastroianni, A. Hinsch, High Photovoltage of 1 V on a steady-state certified HTL-free perovskite solar cell by a molten-salt approach, *ACS Energy Letters*, available online (2018)

Degradation mechanism in standard perovskite PSC

Recent results from literature*)

Redox reaction under light + (dry) air:

$$CH_3NH_3PbI_3 + O_2 \downarrow + h\nu \rightarrow CH_3NH_2 \uparrow + \underline{PbI_2} + \tfrac{1}{2} I_2 \uparrow + H_2O \uparrow$$

$O_2 + e^- \rightarrow O_2^-$ radical, $I^- - e^- \rightarrow \tfrac{1}{2} I_2$

Inorganic perovskite like $CsPbI_3$ more redox stable? But higher E_g and lower eta …

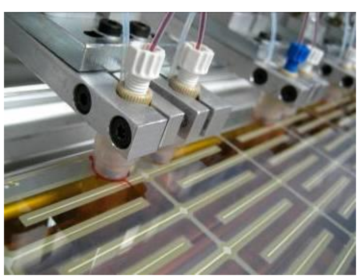
*) Saif Haque et al. (Imperial College), presented at EMRS Warsaw and PSCO Genua 2016

Learning from the past: In-situ fabrication of glass frit sealed (dye solar cell) DSC module, Fraunhofer ISE 2011

- pilot-type manufacturing of large area DSC modules on single substrates shown

main advantage:

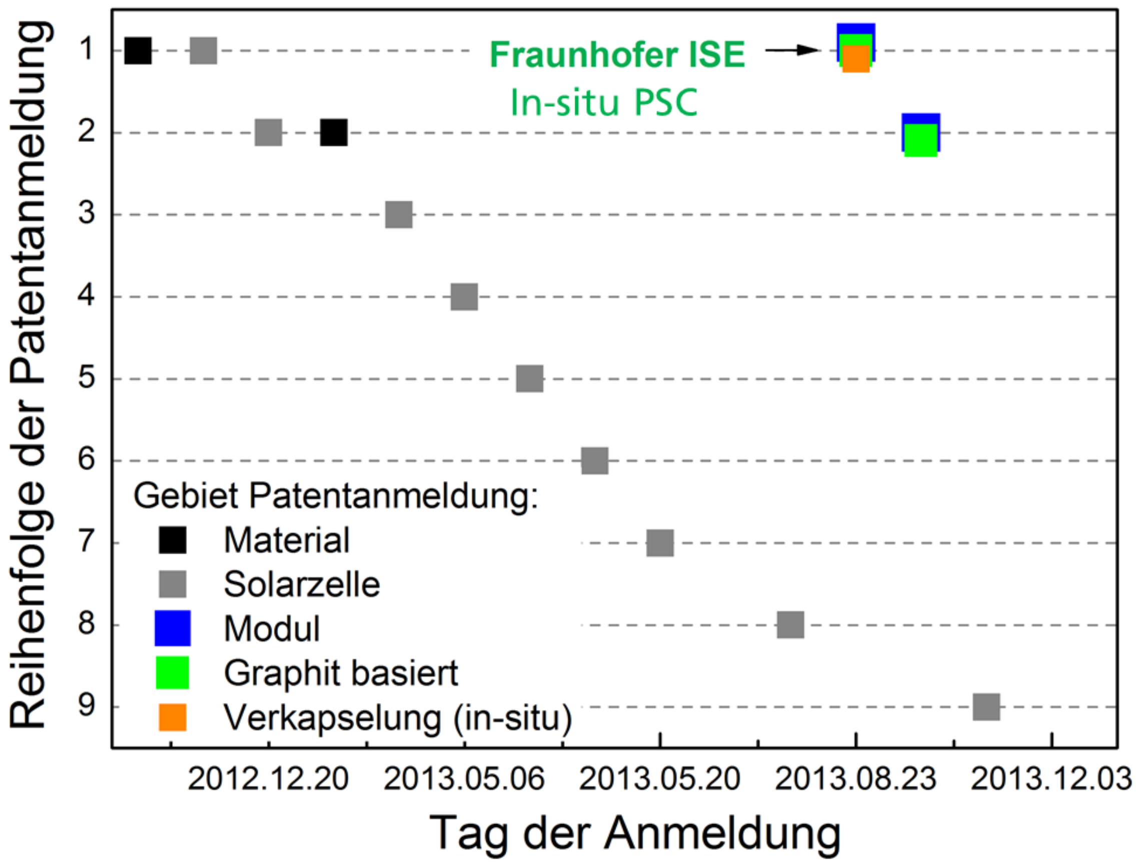
- handling of chemistry (dye solution and electrolyte filling) is carried out in closed tube system



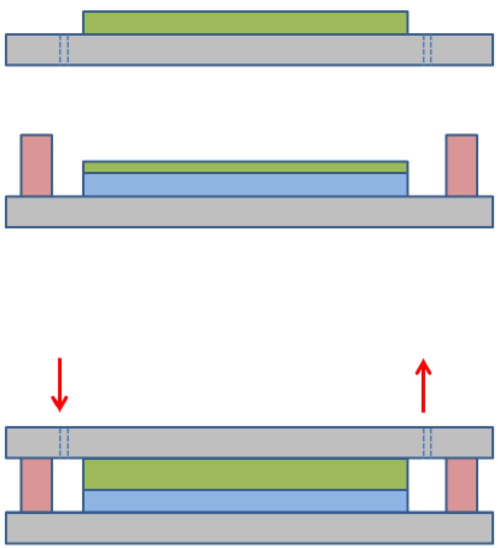
Andreas Hinsch, Welmoed Veurman, Henning Brandt, Katrine Flarup Jensen, Simone Mastroianni, **Status of Dye Solar Cell Technology as a Guideline for Further Research**, ChemPhysChem. Volume 15, Issue 6, pages 1076–1087, April 14, **2014**

Base Patents Perovskite Solar Cells in 2013
Position Fraunhofer ISE

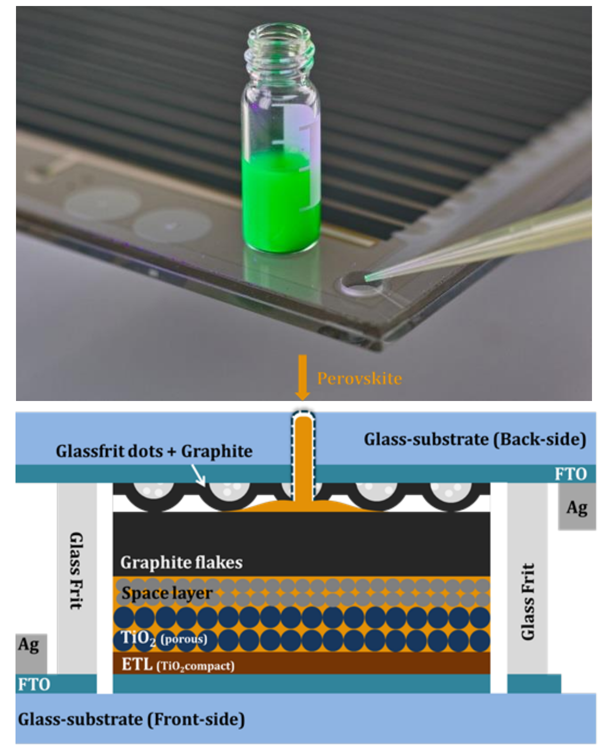
7.2018 in China zum Patent erteilt !



The concept of in-situ Perovskite Solar Cells: Advantage: High T sealing and low T crystallization



1. TCO glass structuring (holes)
2. printing (screen or ink-jet)
   - micronized graphite
   - nano-porous TiO_2
   - low melting glass solder
3. sintering
4. glass fusing above T_g
5. in-situ deposition of perovskite from solution or gas phase

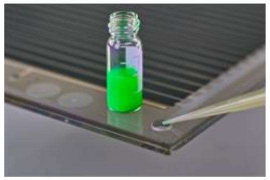


- Manufacturing of a glass solder sealed module pre-fab
- Crystallization of absorber from a perovskite solution / melt (in-situ)

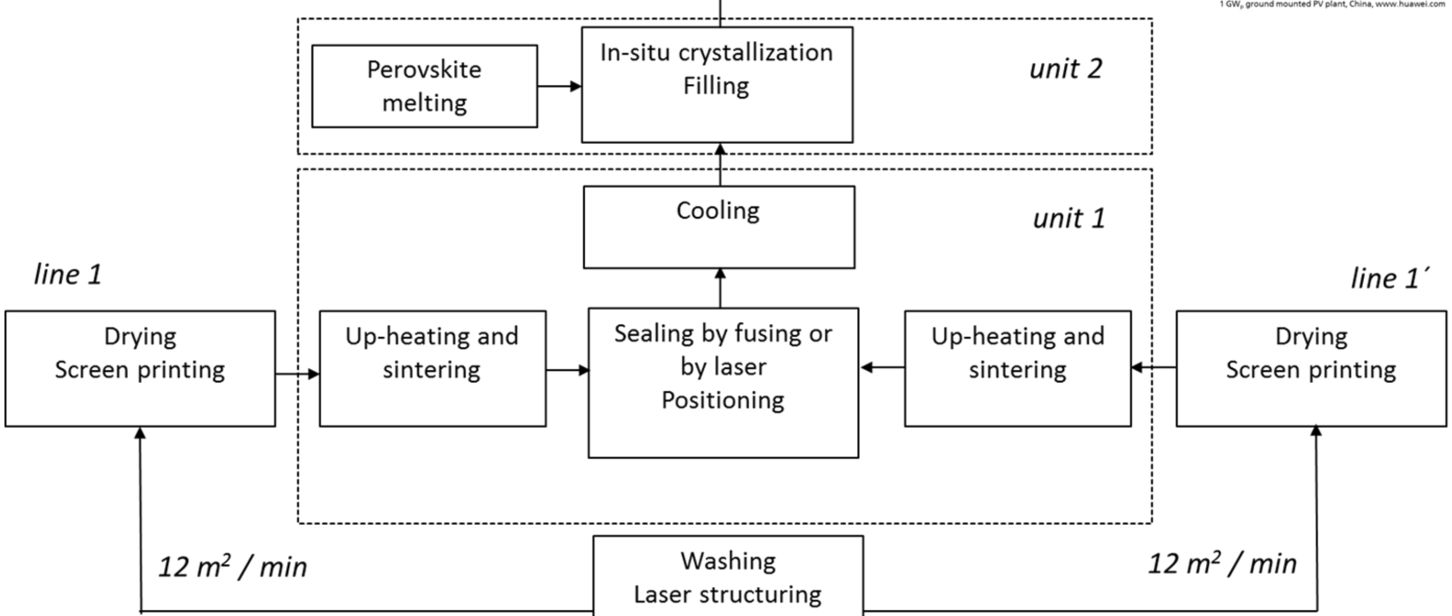
Fraunhofer ISE

Manufacturing Scenario for *in-situ* PSC (1 GW_p/a)

Scenario 1
PSC on glass

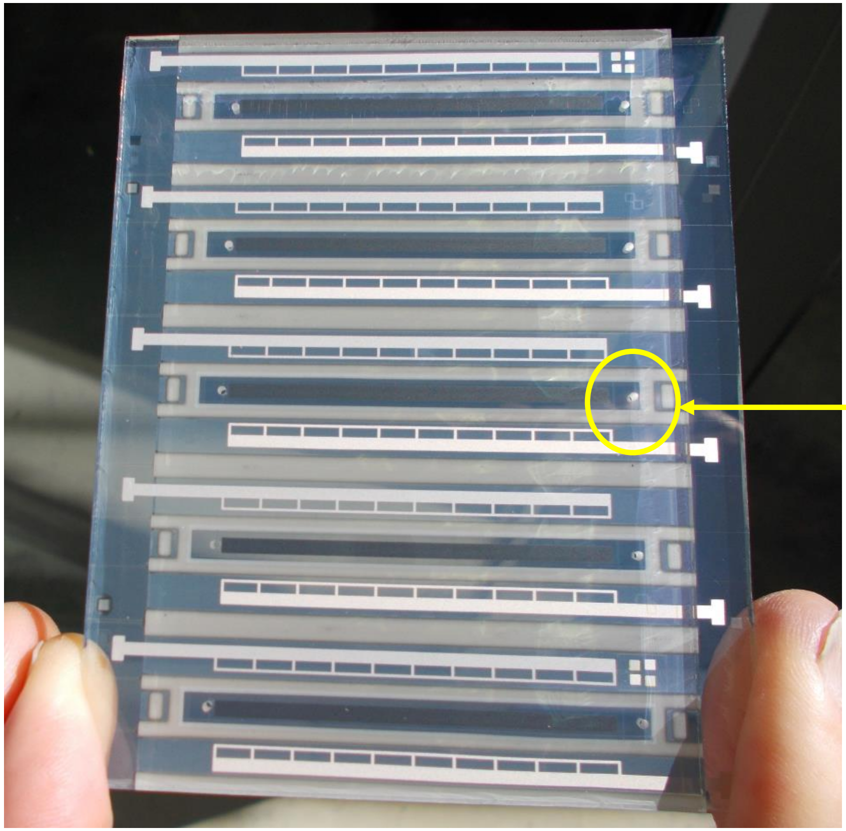


1 GW_p ground mounted PV plant, China, www.huawei.com



Fraunhofer ISE

Manufacturing of in-situ PSC test cells
Fusing and conversion



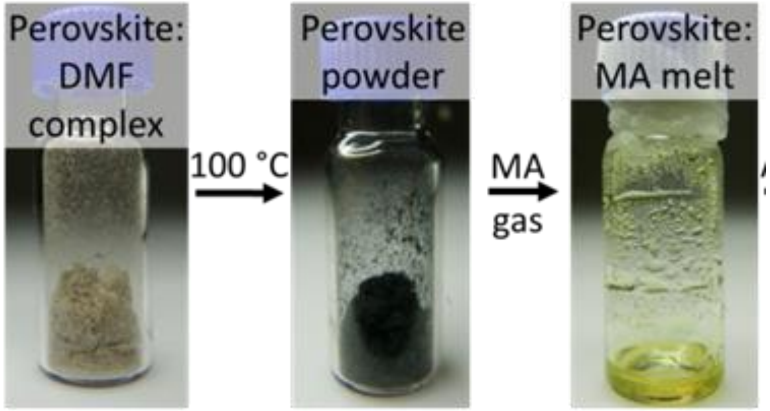
1 µl/cm² solution

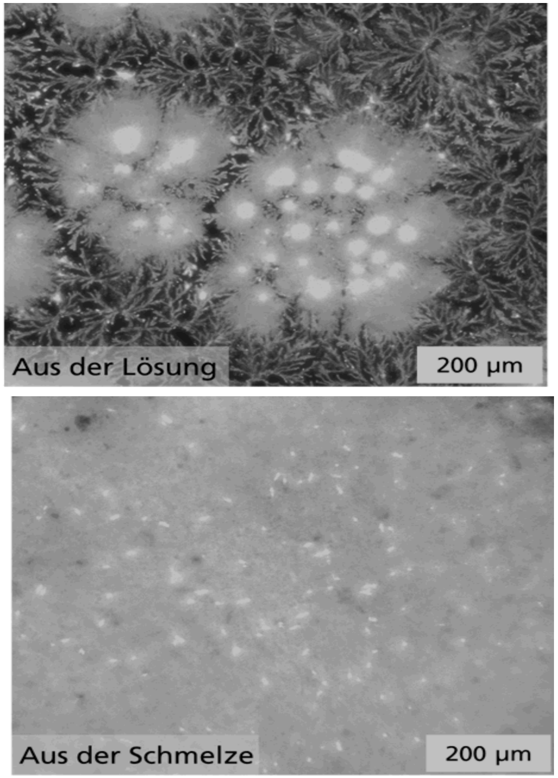
- after fusing, before filling with perovskite
1 step solution

- complete cells after annealing under low pressure

Homogenous Crystallization in-situ PSC
Bottleneck precipitation finally solved:

- melting of perovskite with a polar gas (MA) at room temperature



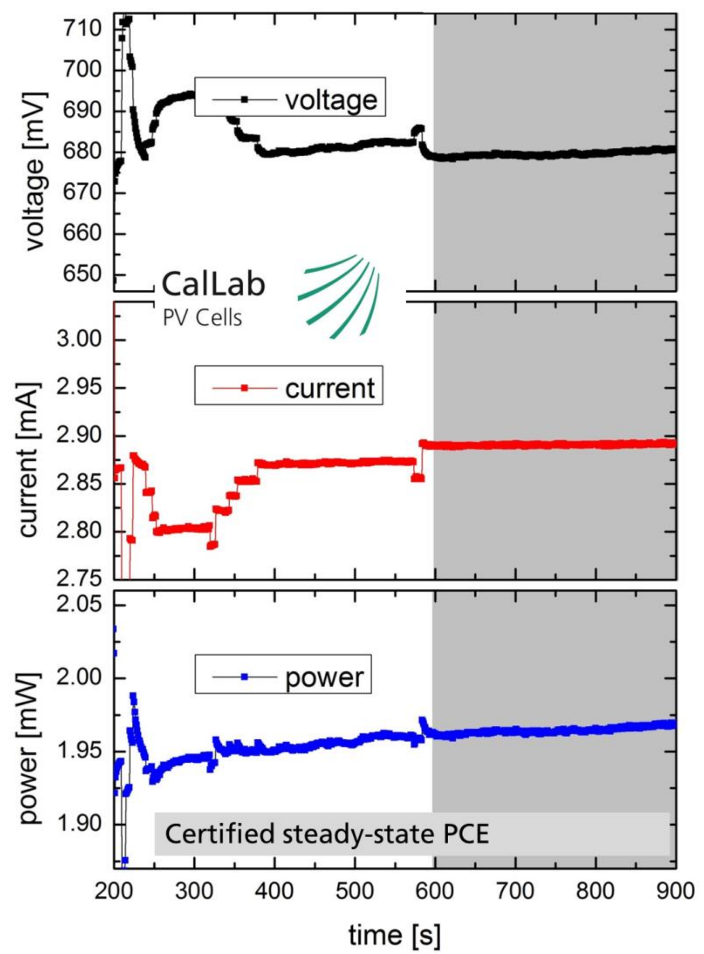


Microscopic photoluminescence of photoelectrode layer

- recrystallization by gas desorption prevents precipitation

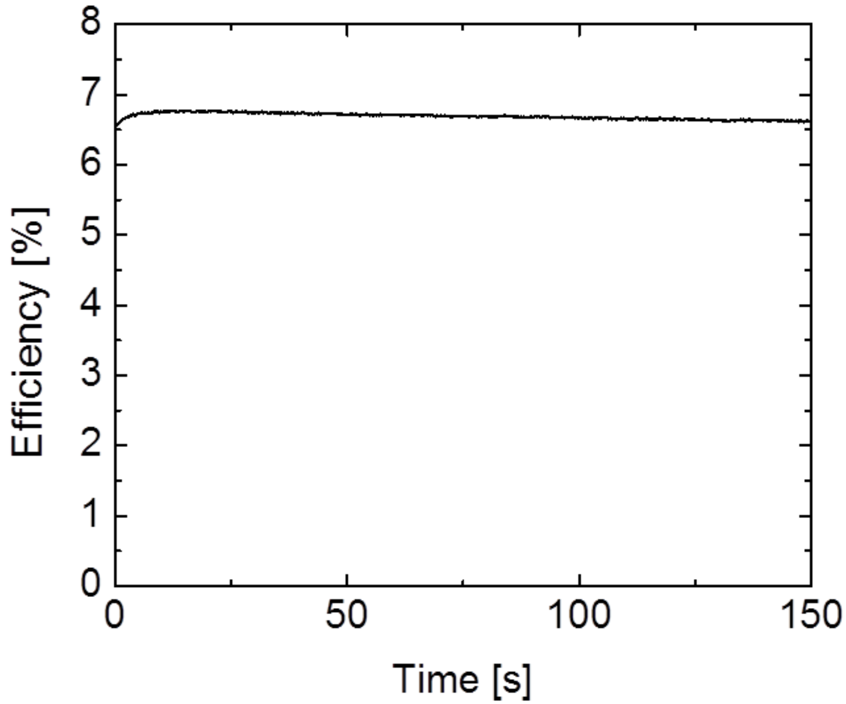
Certified efficiency of in-situ Perovskite Solar Cells
Stabilized at maximum power point MPP

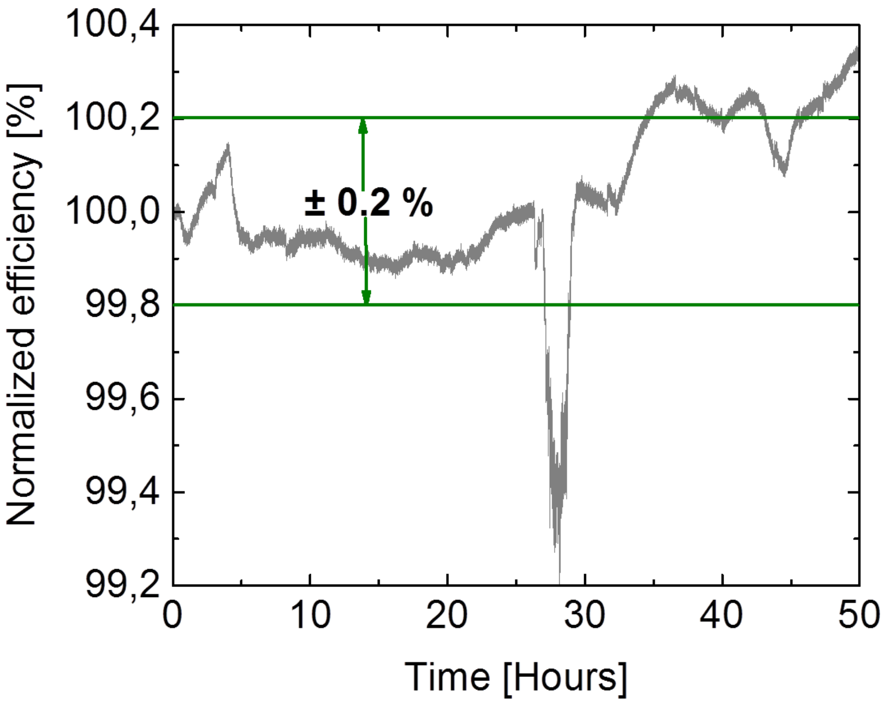
- V_{oc} = 0.98 V (HTL –free)
- Worldwide first certified stabilized efficiency (9.3 %) for in-situ PSC
- Proof-of-concept for up-scaling achieved



Fraunhofer ISE

Stability measurements of in-situ Perovskite Solar Cells
Short- and long-time stabilization at maximum power point MPP

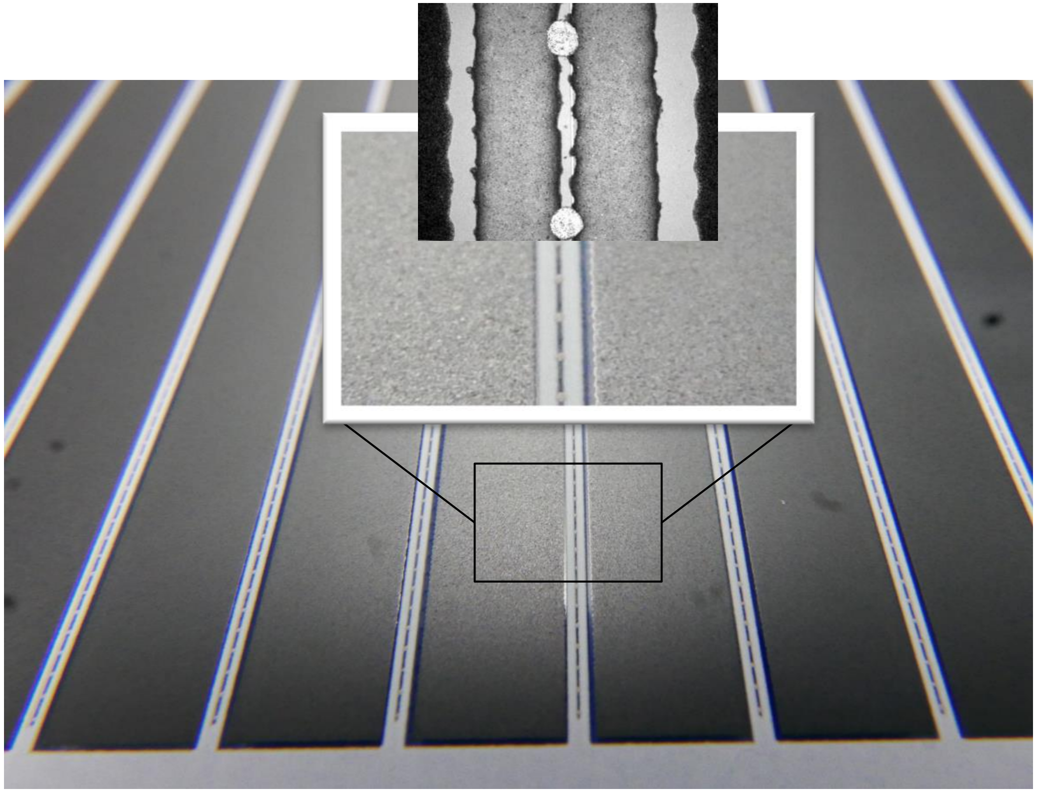




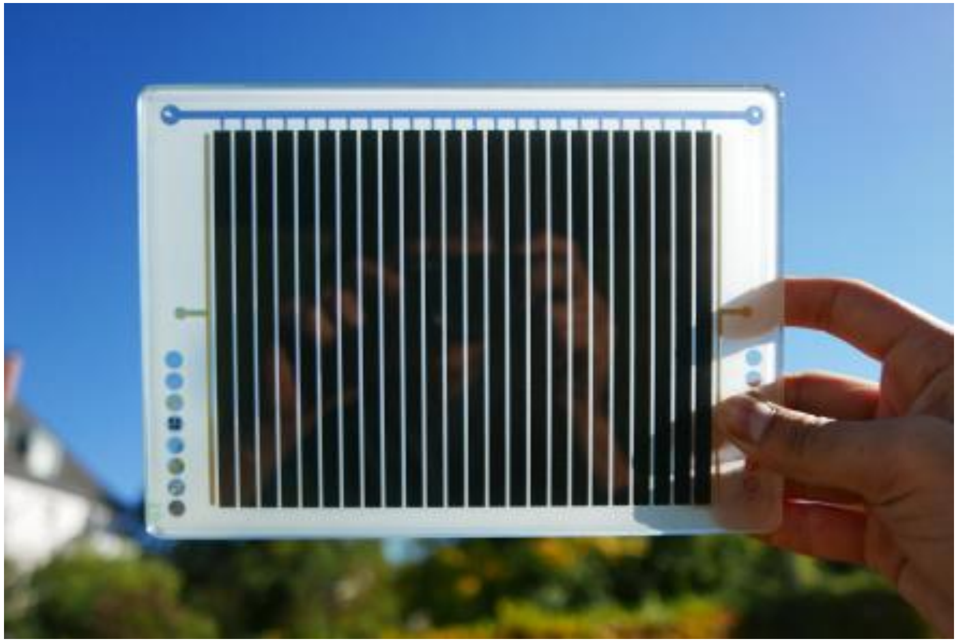
- short-time stabilization of MPP at full sun AM1.5
- long-time stabilization with MPP load resistor at 1/10 sun intensity

Fraunhofer ISE

High precision screen-printing of in-situ PSC modules
Alignment of interconnect points and glass solder lines



Status: Prototyping in-situ Perovskite Solar modules
Glass solder sealed Pre-Fab for final filling and crystallization



- Photovoltage V_{oc} of 20 V reached so far

Fraunhofer ISE

Conclusion & Outlook
Printed in-situ Perovskite Solar Modules

Conclusion

- Proof-of-principle with certified stabilized efficiency (9.3 %)
- Up-scaling demonstrated for screen-printing and thermal fusing
- Patented technology for long-term stable perovskite PV

Outlook / Planning

- Concept and realization of perovskite “filling-station”
- Set-up for automated active crystallization control
- Pilot-type module manufacturing with partners from glass industry

Acknowledgement

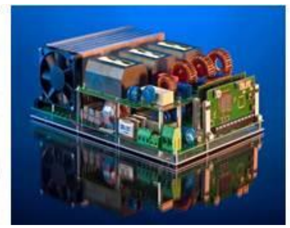
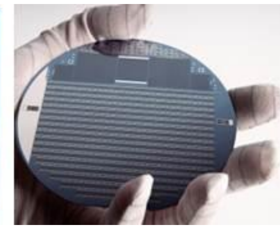
Bundesministerium
für Bildung
und Forschung

MesoPIN: 03SF048A 4A

Fraunhofer
MAVO PeroTec

Thank you for your Attention!




Fraunhofer Institute for Solar Energy Systems ISE

Dr. Andreas Hinsch

www.ise.fraunhofer.de

andreas.hinsch@ise.fraunhofer.de

Fraunhofer ISE