

# Competitive Photovoltaic Manufacturing



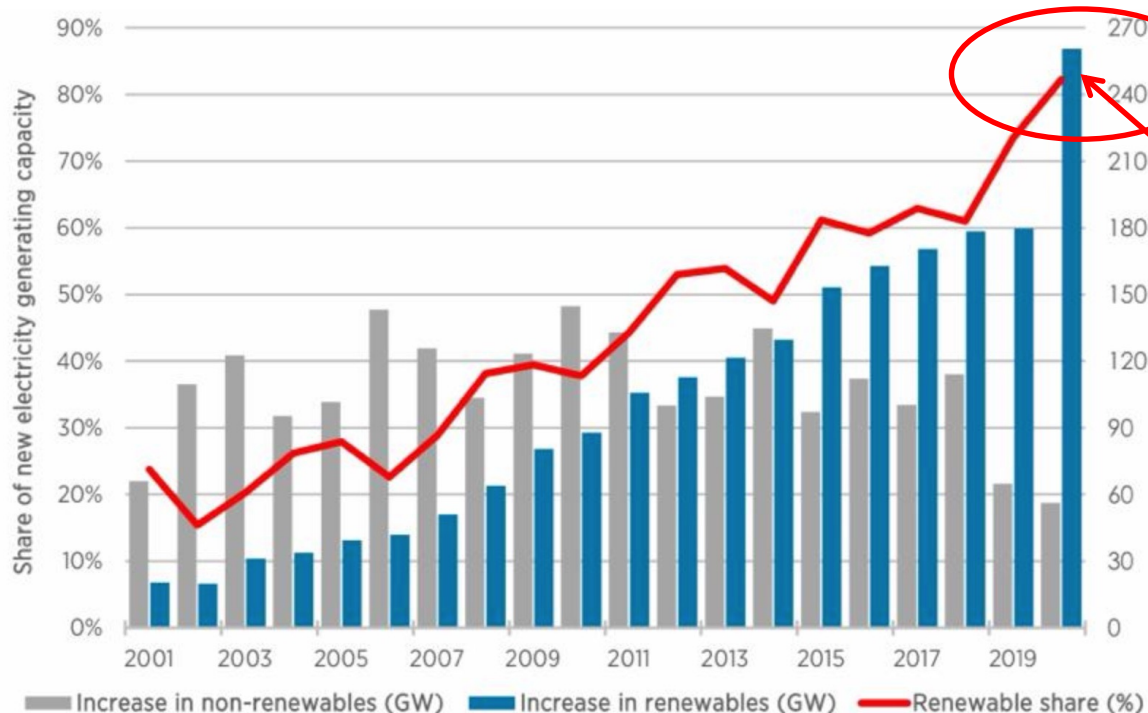
Eicke R. Weber

European Solar Manufacturing Council ESMC  
Prof. emer., Dept. of Materials Science, UC Berkeley  
Director emer., Fraunhofer Institute for  
Solar Energy Systems ISE, Freiburg

EPIC Summit 2024  
Juan-les-Pins April 16, 2024

Graphic: Primolo

# Fraction of Renewable Energy in the Growth of Global Energy Capacities 2001-2020



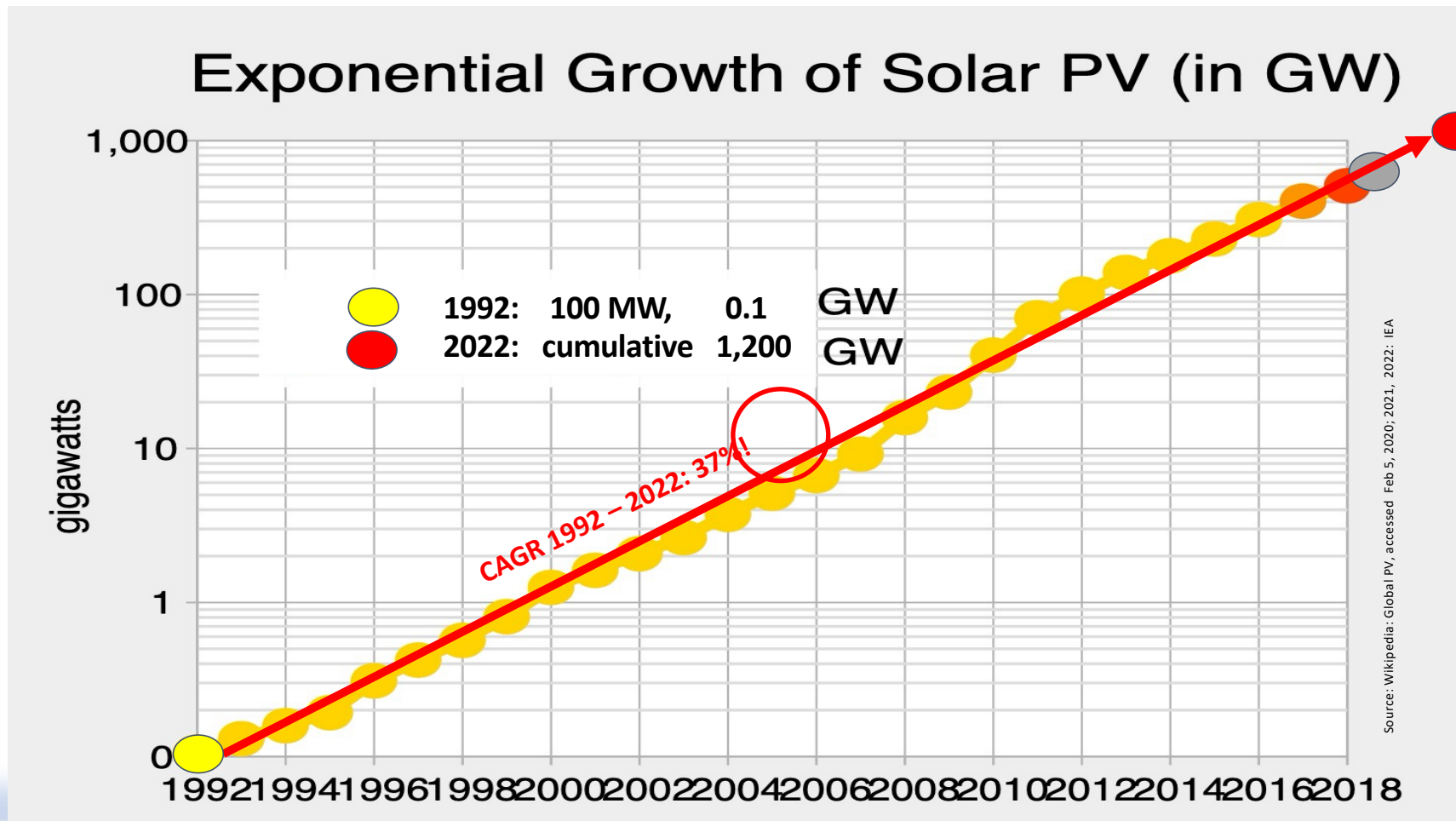
Today:  
More than 80% of all newly installed power generation is based on renewable energy!

8:20 PM Thanks, Marc, for the IRENA data: IRENA/Agency/Publications/2021/IRENA-Global-Energy-Transformation-Outlook-2021.pdf?utm\_source=twitter&utm\_medium=organic

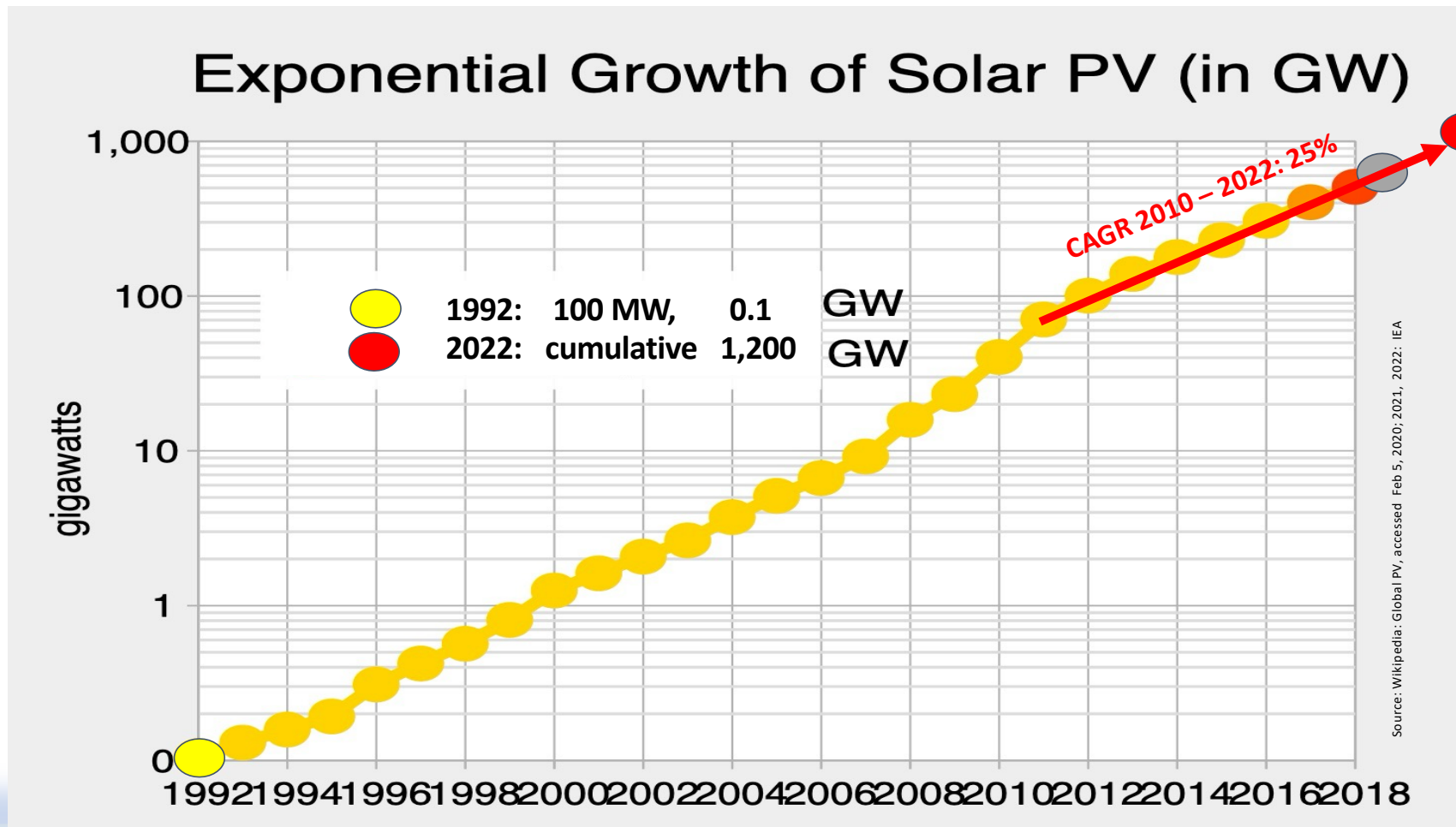
New global power generation capacity in 2020 was 80% in renewables, mainly PV and wind!

Source: Bloomberg 2021

# 30 Years of Global Growth of PV Installations 1992 – 2022 CAGR: 37%!



# Global Growth of PV Installations 2010 – 2022 CAGR: 25%!



21.05.2023

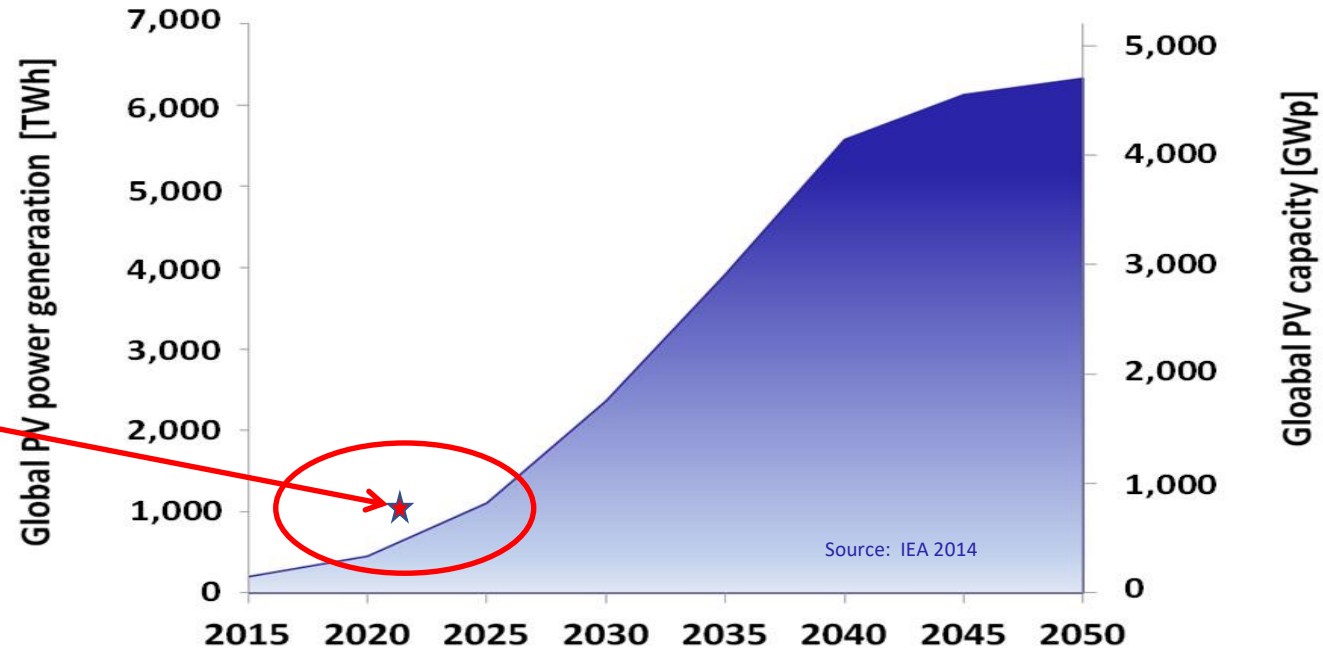
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## PV Heading into the Terawatt Range – this is a Disruption!

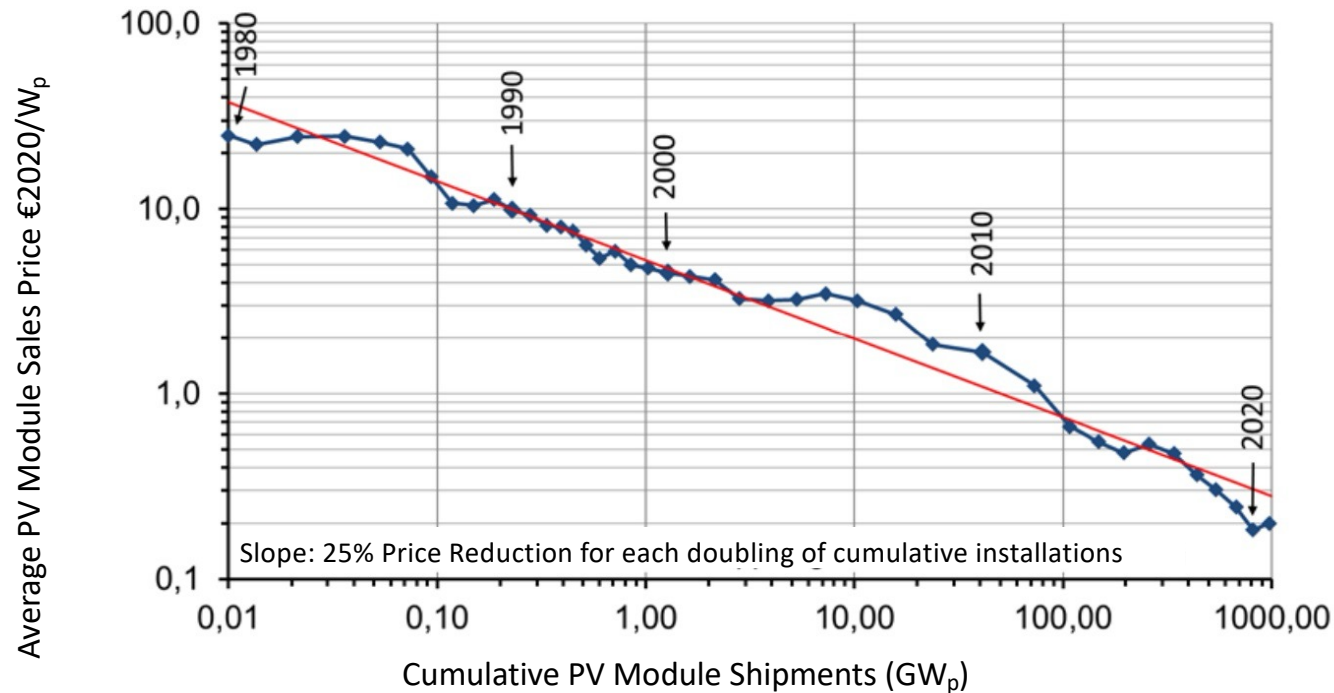


- Rapid introduction of PV globally is fueled by the availability of cost-competitive, distributed energy and the danger of catastrophic climate changes
- In 2050 or before, **much more than 5TW** of PV PV will be installed!
- **By March 15, 2022, the first 1,000 GW<sub>p</sub> have been installed!**

We are just at the beginning of the global growth curve!



## PV Learning Curve 1980 - 2022:

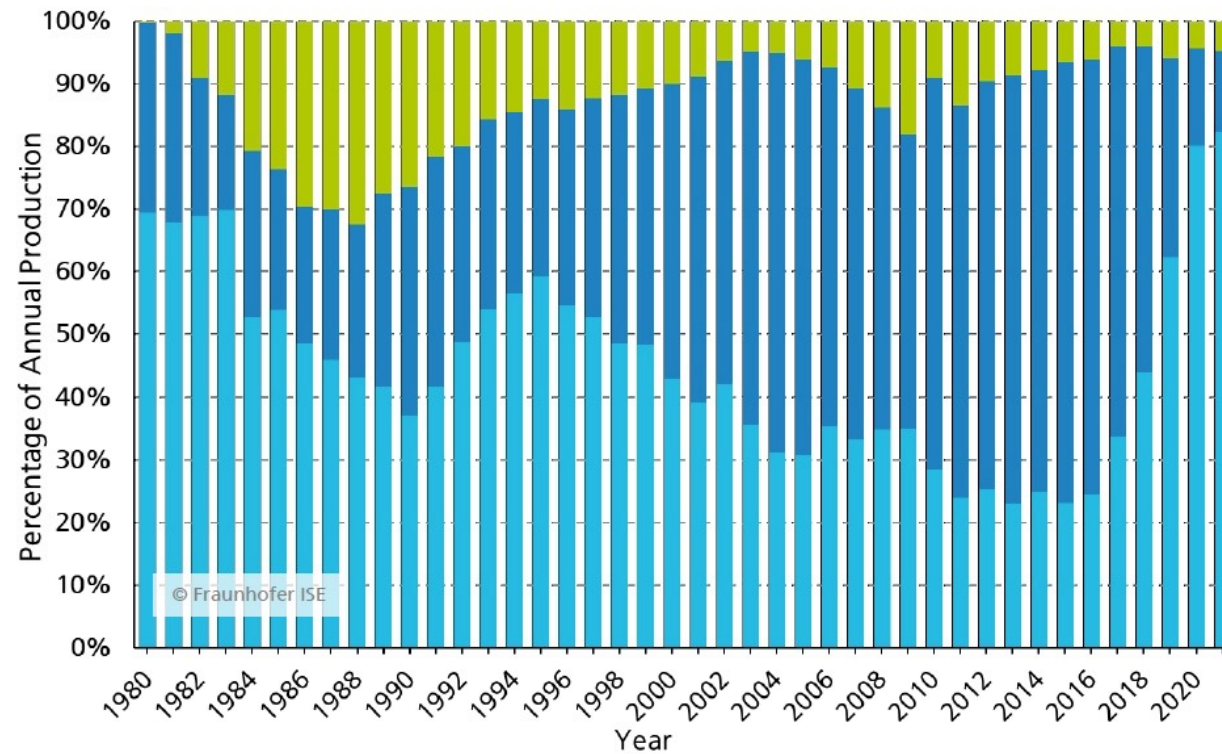


**1976: \$100/W<sub>p</sub>**  
**2020: \$0.20/W<sub>p</sub>**  
**13% Annual Price Reduction!**

**2022: PV electricity is available at less than 2ct/kWh!**

Source: PSE AG/Fraunhofer ISE, Data: Strategies Unlimited/Navigant Consulting/EuPD

# PV Production by Technology: Percentage of Global Annual Production



Production 2021\* (GWp)

Thin film	10
Multi-Si	20
Mono-Si	160

\*estimated numbers

Fh-ISE PV Report 2022, Data from 2000 to 2009: Navigant; since 2010: IHS Markit. Graph: PSE 2020 Date of data: July 2022

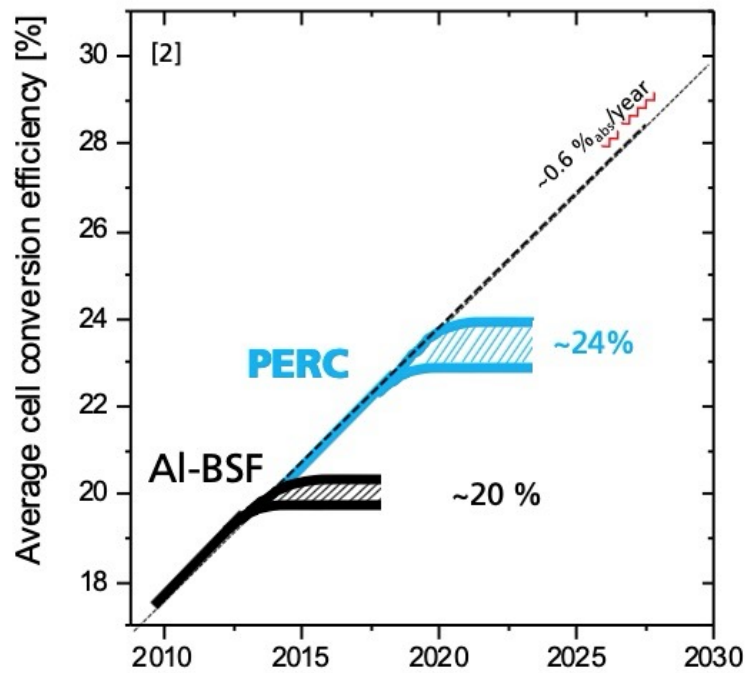
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7

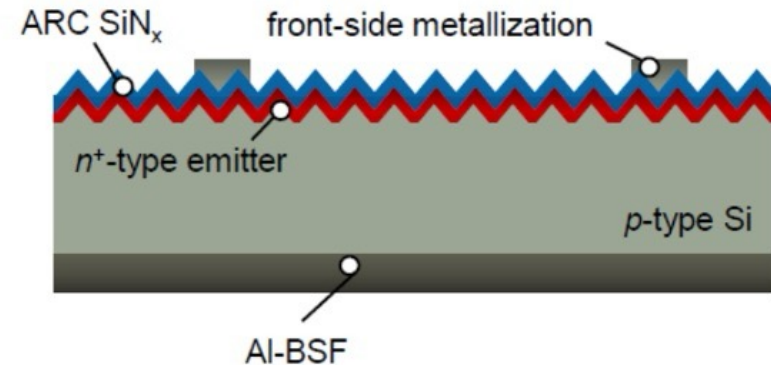
# Increasing the Efficiency

## Industrial Realisation



Slide courtesy A. Bett, Fraunhofer ISE 2020

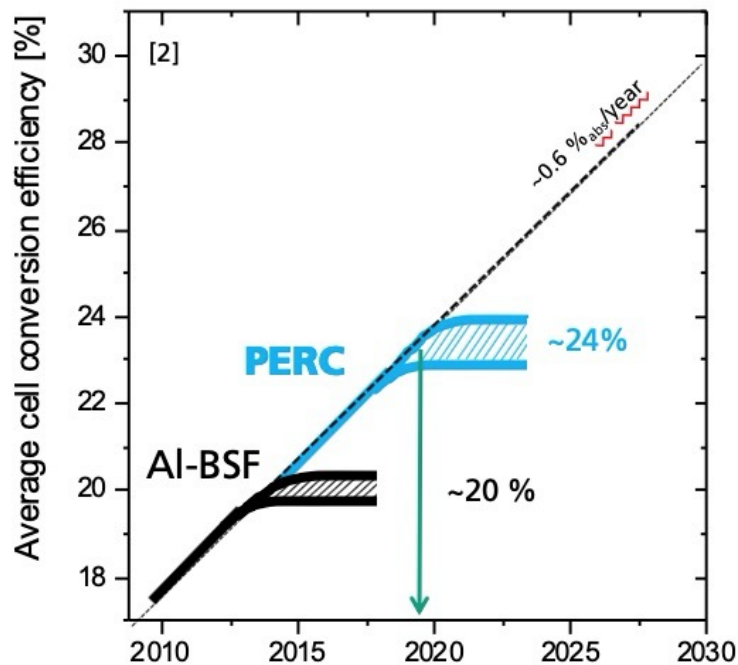
- **Now for many years:**  
Increase of efficiency in industrial production  
~ 0,6 %<sub>abs</sub>/year [1]
- Efficiency limitation due to full area Al-BSF (back surface field) rear side



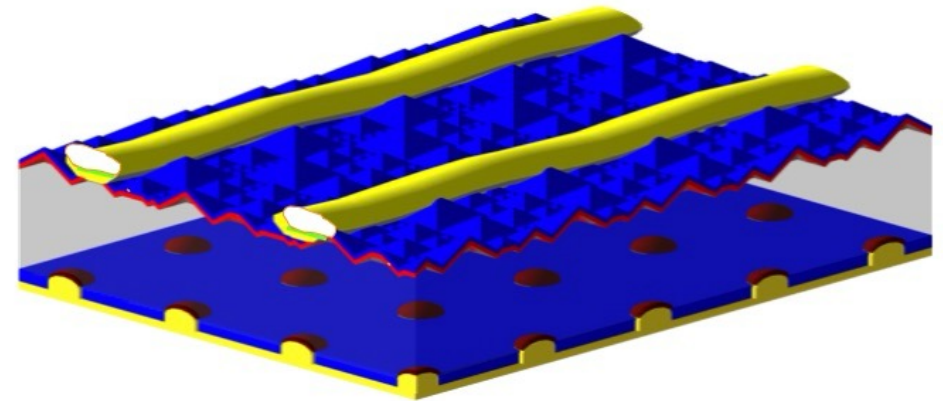


# Increasing the Efficiency

## Industrial Realisation

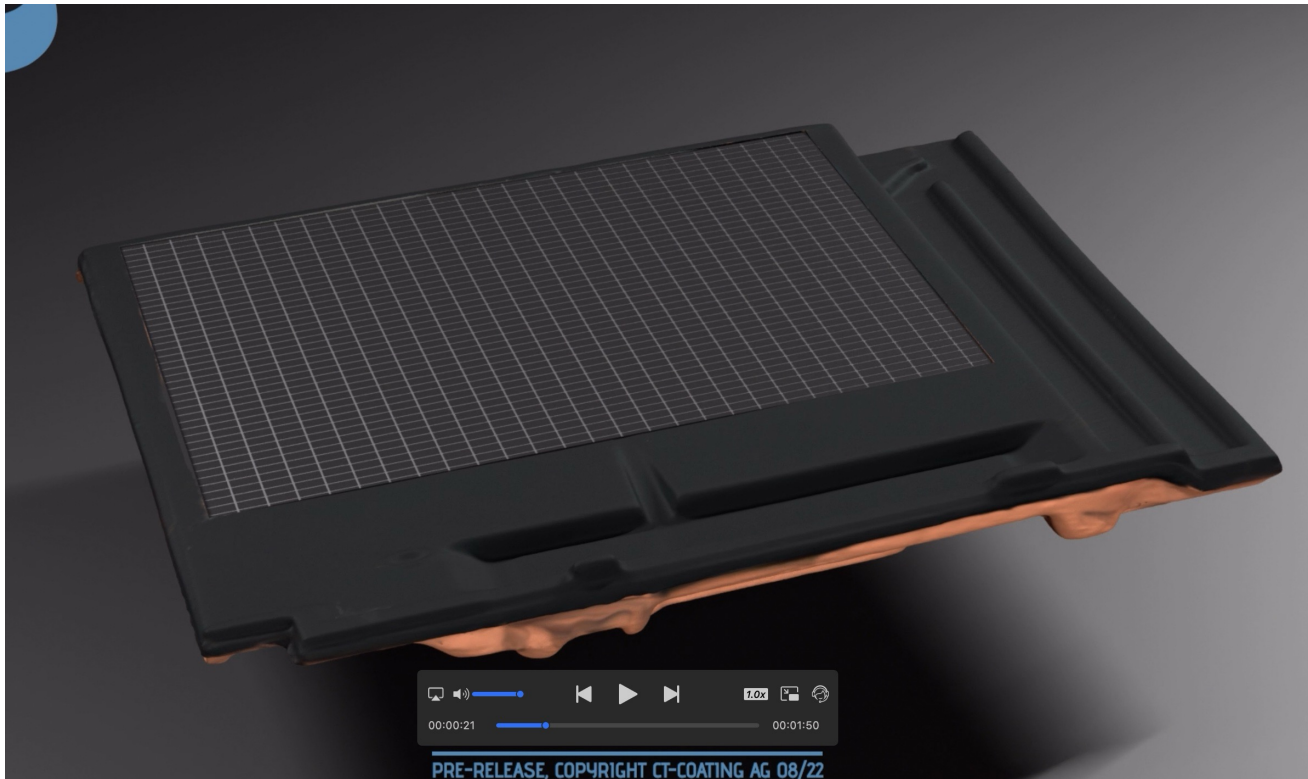


- **Now for many years:** Increase of efficiency in industrial production  $\sim 0,6\%_{\text{abs}}/\text{year}$  <sup>[1]</sup>
- Replacement of the full area Al-BSF with a **partial rear contact (PRC)**



Slide courtesy A. Bett, Fraunhofer ISE 2020

# Innovative New Approaches: Foil-Based Solar Tiles



Slide Copyright CT-Coating AG

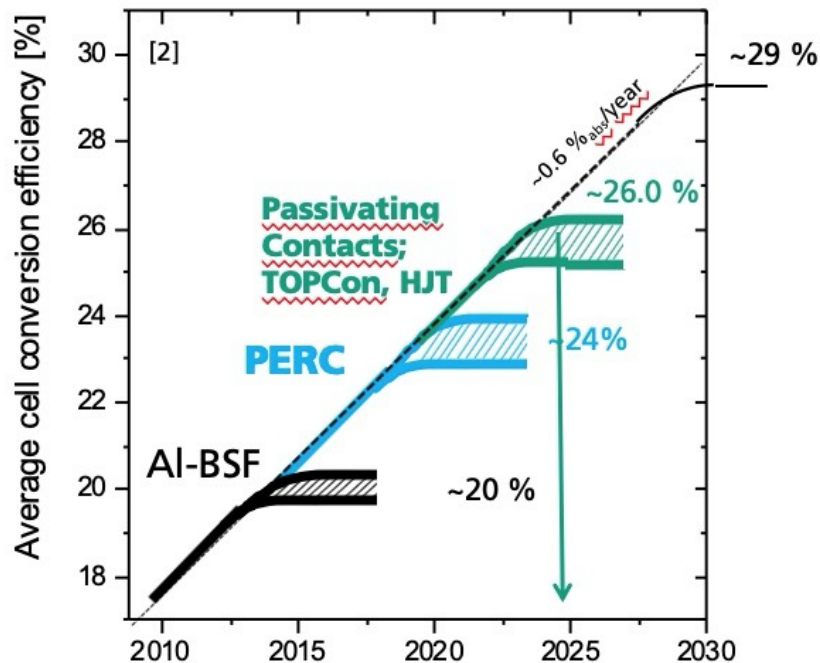
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10

# Innovations with Respect to Efficiency

## Industrial Realisation – A View Into the Coming Years



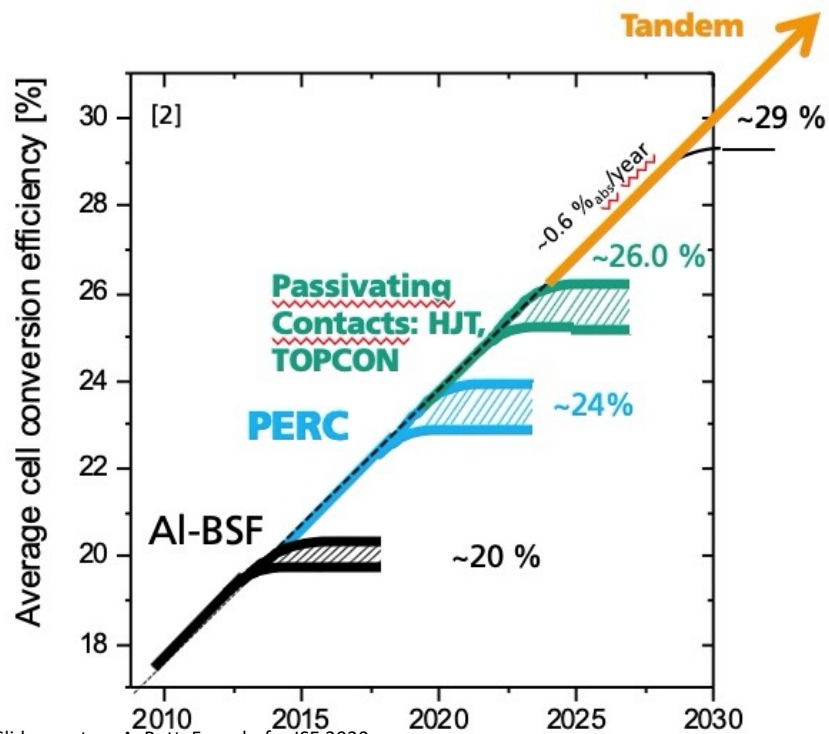
- **Now for many years:** increase of efficiency in industrial production  $\sim 0,6\%_{\text{abs}}/\text{year}$  <sup>[1]</sup>
- Industrial production with 26% seems possible
- The theoretical efficiency limit for **Si solar cells** is **limited to  $\sim 29\%$**

**What will we see after 2025 in industrial production?**

Slide courtesy A. Bett, Fraunhofer ISE 2020

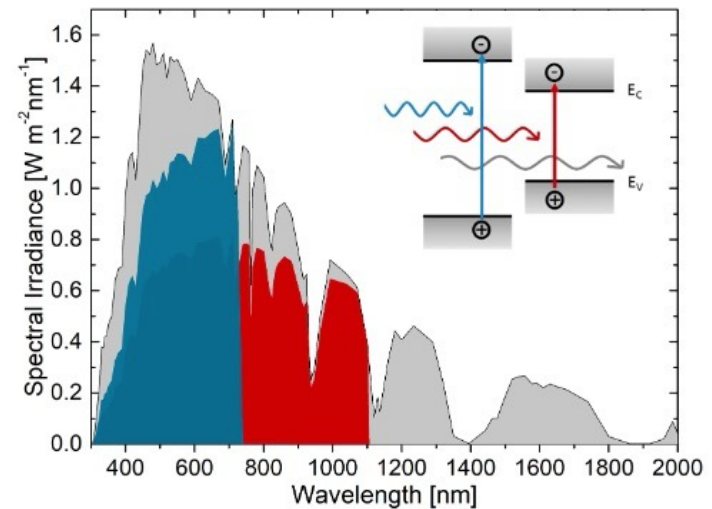
# Beyond the Shockley-Queisser Limit: Further Innovations in PV Cell Technology!

## Tandem Solar Cells on Silicon

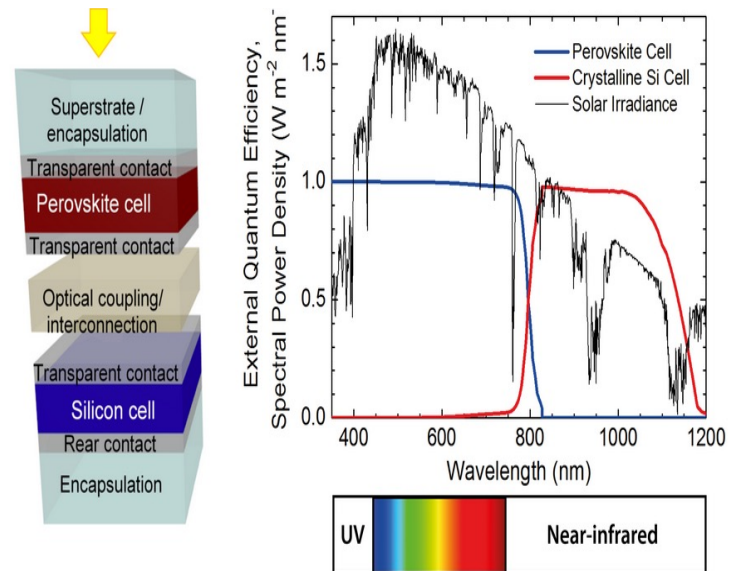


Slide courtesy A. Bett, Fraunhofer ISE 2020

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



# Perovskites-on-Silicon Tandem Cells

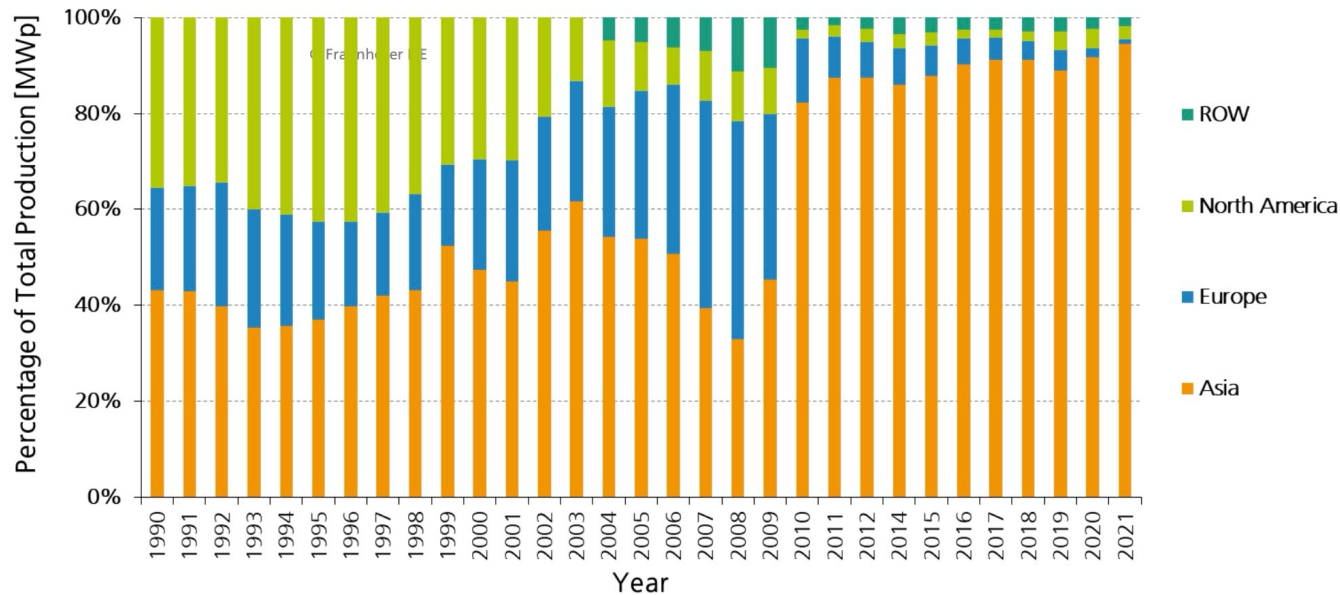


Left: Schematic illustration of a perovskite/silicon tandem cell. Right: Light enters through the perovskite cell, where mostly the visible part of the solar spectrum is absorbed. Near-infrared light is transmitted to the silicon cell where it is absorbed

Perovskite solar cells having high efficiency with **tunable bandgap** have great potential for tandem application with silicon solar cells.

# PV Module Production by Region 1990-2021

## Percentage of Total MWp Produced Crystalline Wafer-based Solar Modules



Data: Up to 2004 Strategies Unlimited; 2005 to 2009: Navigant Consulting; 2010 to 2019: IHS Markit; since 2020 IEA PVPS. Graph: PSE 2022; Date of data: 26-April 2022

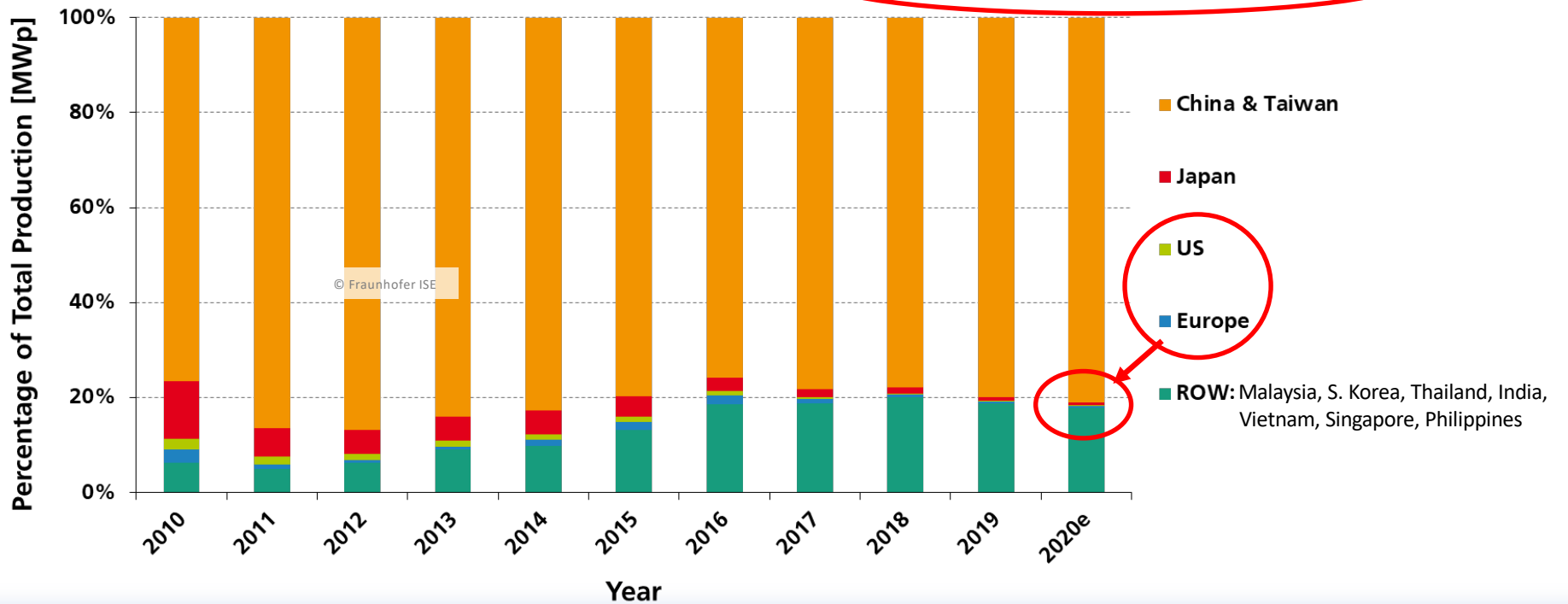
Source: Fraunhofer ISE PV Report 2023



# PV Cell Production by Region 2010-2020e

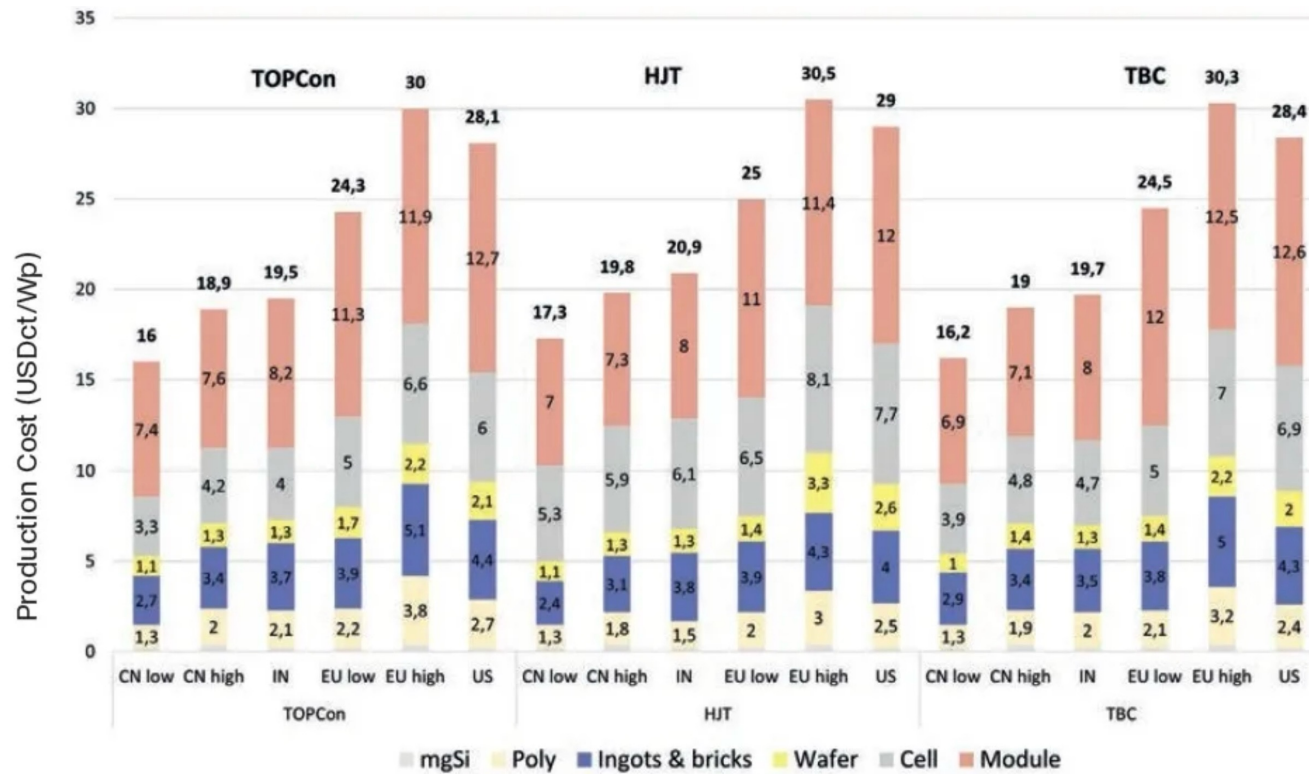
## Percentage of Total MWp Produced Crystalline Wafer-based Solar Cells

In 2020, about 99% of c-Si solar cell production was in Asia, 0.4% in Europa and 0.3% in the USA



Source: Fraunhofer ISE 2021

# PV Production Cost Comparison



Source: [Yury Erofeev](#) based on ETIP PV Report 2023



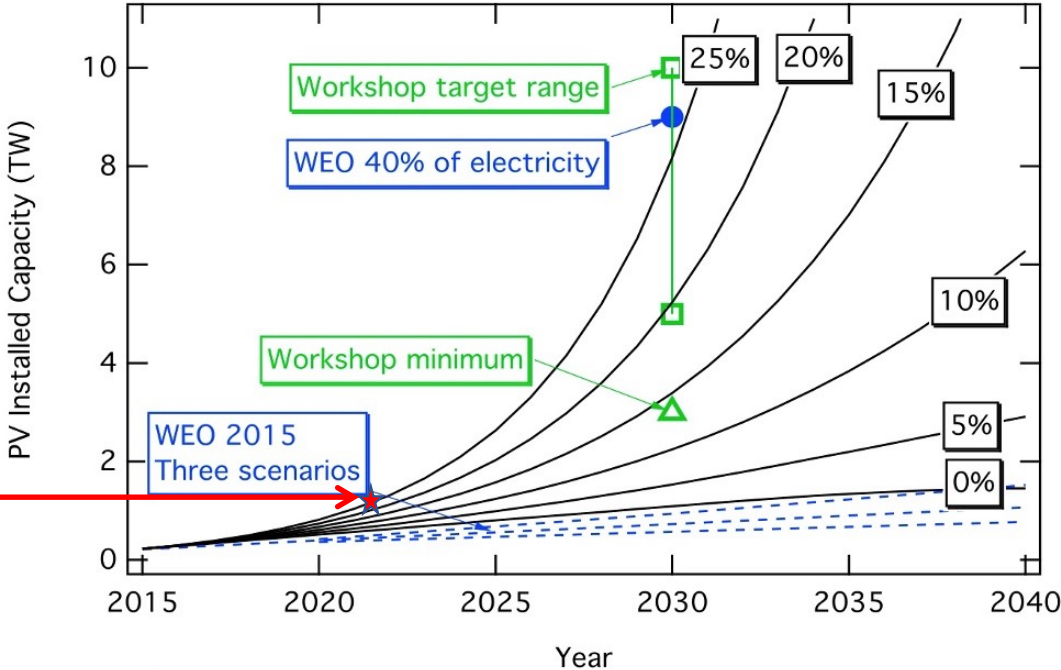




# Projections to TW-scale PV from 1<sup>st</sup> TW workshop 2016



6 years later:  
1 TW installed in March 2022:  
We follow the most optimistic growth curve!

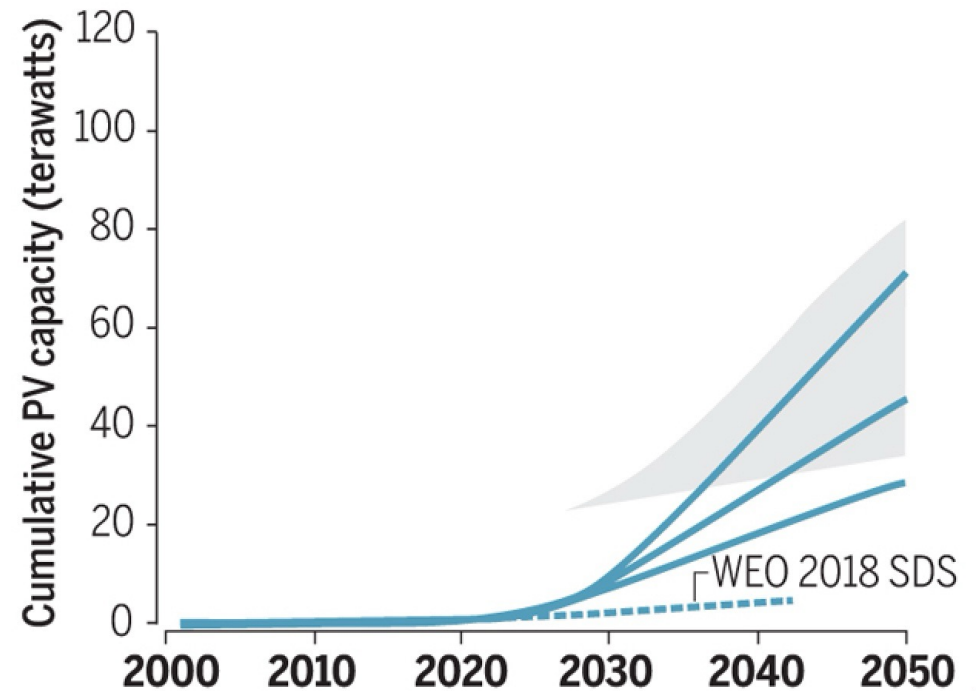
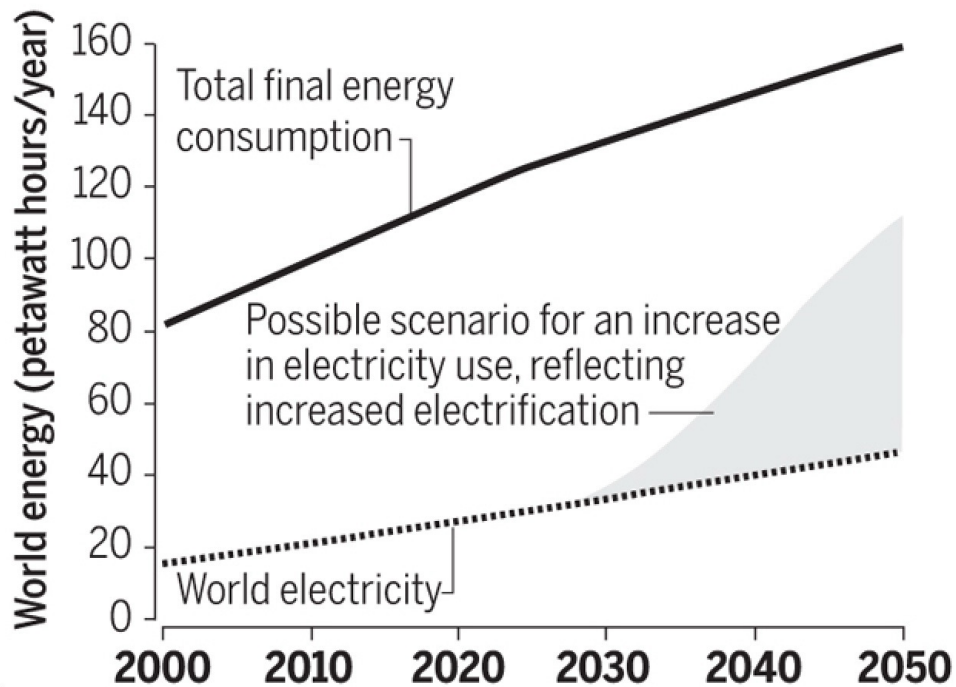


Using simple assumptions, we can project that just maintaining the 2015 deployment rate would reach 1-TW deployment before 2030.

**A 25% annual growth rate would reach 5-10 TW by 2030!**

Source: Nancy M. Haegel et al, *Science* 356, 141 (2017)

## 2019: Scenarios for Growth of PV till 2050: 10 Terawatt by 2030, 30-70 Terawatt by 2050!



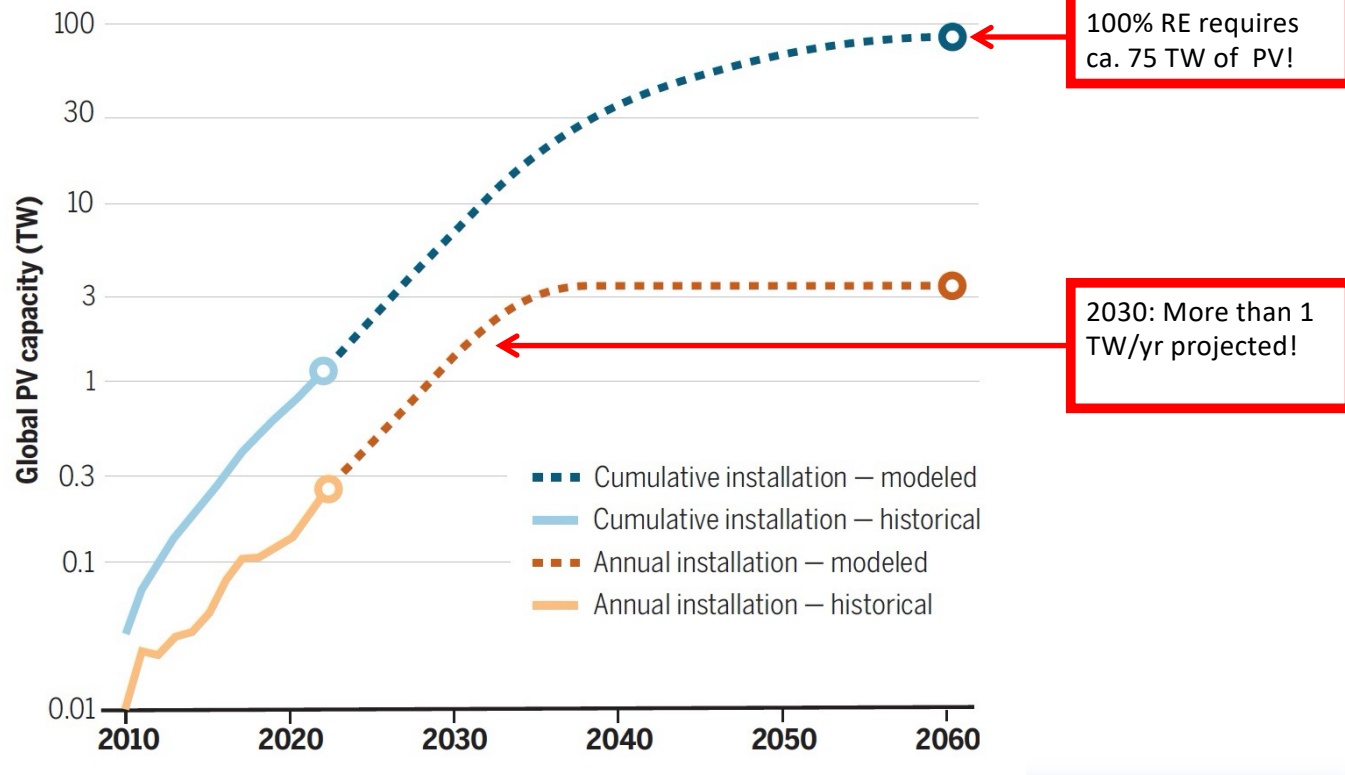
Source: Nancy M. Haegel, Harry Atwater Jr., Teresa Barnes, Christian Breyer, Anthony Burrell, et al, 'Terawatt-scale photovoltaics: Transform global energy', Science 364, 836-838 (2019)

# Photovoltaics at multi-terawatt scale: Waiting is not an option

25% annual PV growth is possible over the next decade

By Nancy M. Haegel, Pierre Verlinden, Marta Victoria, Pietro Altermatt, Harry Atwater, Teresa Barnes, Christian Breyer, Chris Case, Stefaan De Wolf, Chris Deline, Marwan Dharmin, Bernhard Dimmler, Markus Gloeckler, Jan Christoph Goldschmidt, Brett Hallam, Sophia Haussener, Burkhard Holder, Ulrich Jaeger, Arnulf Jaeger-Waldau, Izumi Kaizuka, Hiroshi Kikusato, Benjamin Kroposki, Sarah Kurtz, Koji Matsubara, Stefan Nowak, Kazuhiko Ogimoto, Christian Peter, Ian Marius Peters, Simon Philipps, Michael Powalla, Uwe Rau, Thomas Reindl, Maria Roumpani, Keiichiro Sakurai, Christian Schorn, Peter Schossig, Rutger Schlatmann, Ron Sinton, Abdelilah Slaoui, Brittany L. Smith, Peter Schneidewind, BJ Stanbery, Marko Topic, William Tumas, Juzer Vasi, Matthias Vetter, Eicke Weber, A. W. Weeber, Anke Weidlich, Dirk Weiss, Andreas W. Bett

## 2022: PV Installations and Growth Towards 75TW by 2050



Source: Nancy M. Haegel et al, *Science* 380, 6640 (April7, 2023)



PreNDA Presentation

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**Next Generation Manufacturing**

**Heterojunction PV Cells & Modules**

March, 2022

15.04.24

Eicke R. Weber

20

# Competitive Photovoltaic Manufacturing



- PV has become the **lowest-cost way to produce electricity** in many countries, a rapidly growing element of the electricity supply, driven by Gigawatt-scale production, smart incentives and technical innovations!
- We expect the global PV market to continue its rapid growth, from the current 320 GW/yr towards 1,000GW (1 TW)/yr before 2030, possibly till it reaches 3 TW/yr, 10x today's production capacity!
- **For 2040 and beyond, we expect global PV installations of 75 TW!**
- **Si-wafer based PV technologies**, currently more than 95% of the total PV production, are experiencing **exciting technology improvements**, transitioning from PERC to TOPCON, HJT, then to tandem structures exceeding the 30% efficiency limit. **Exciting innovations are still to come!**
- These innovations are based on **novel materials systems and nanostructures**, such as ultrathin oxide tunnel barriers (TOPCON), aSi - cSi - aSi heterostructures (HJT), or novel tandem structures with IV/IV, III/V, II/VI, or Perovskite on Si!
- **Competition in PV Manufacturing is fierce**, driven by low prices of multi-GW scale production in China, partly below production cost! To re-establish PV production in other parts of the world - Europe, US, India, GCC requires intelligent support mechanisms or powerful voluntary support for **Domestic Production Portfolios!**

