Photovoltaics – Current Status, Technologies, and Market Outlook

Graphic: Primolo

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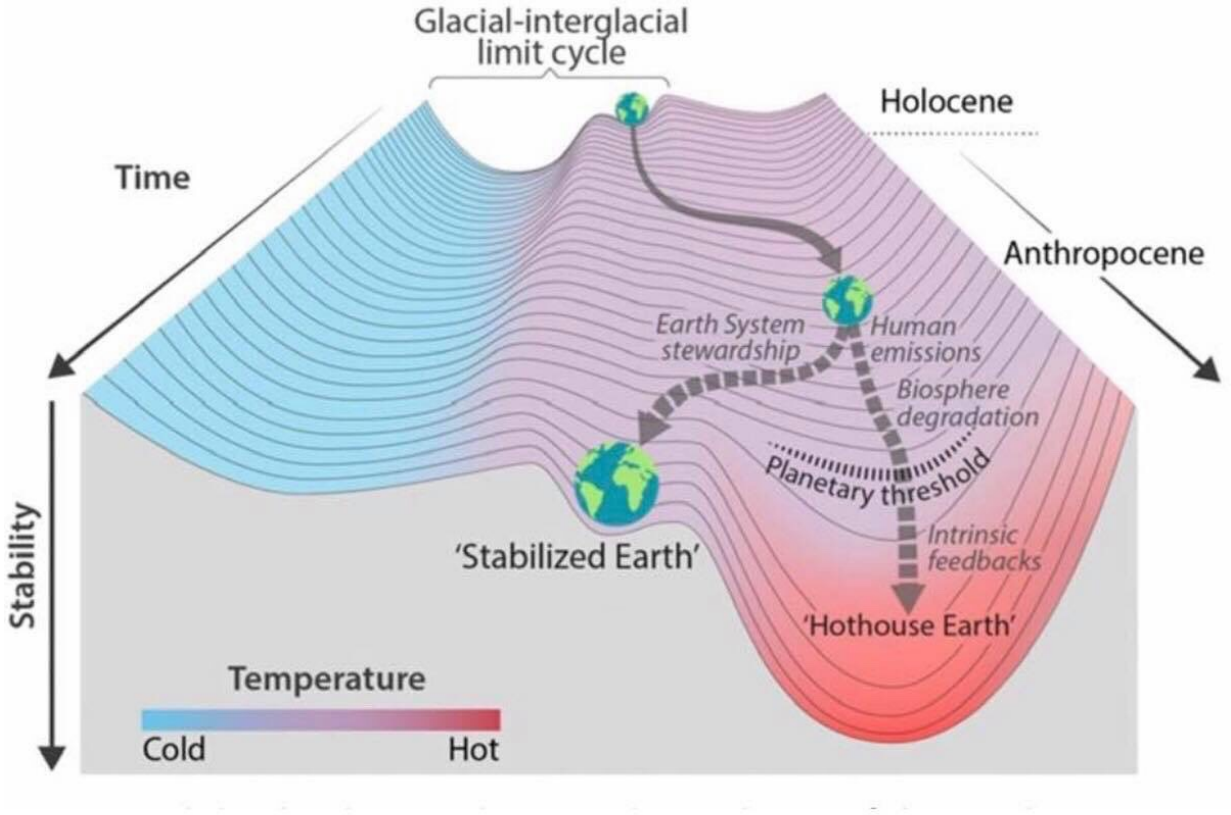
Colloquium, Department of Physics
Warsaw University
April 28, 2025

Hothouse Earth: The Danger of Catastrophic Climate Change



Source: W. Shell and other IPCC Authors, incl. J. Schellnhuber, PNAS 8/2018

Global Climate Change:
Destructive wild fires, extreme weather conditions like hurricanes, draughts, downpours, melting glaciers, disappearing coral reefs……

National Geographic, October 10th 2020:
"Climate change is contributing to California's fires"

CNN, November 16th 2019:
„Venice sees worst floods in 50 years"

CBS News, January 3rd 2020:
„How climate change has intensified the deadly fires in Australia"

The Guardian, March 11th 2020:
"Polar ice caps melting six times faster than in 1990s"

Time, May 22nd 2020:
"The Taste of Bordeaux Is Going to Change"

BBC, May, 22nd 2020:
"Cyclone Amphan batters India and Bangladesh"

Slide courtesy Hans-Martin Henning, Fraunhofer ISE 2020

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National Geographic, October 10th 2020:
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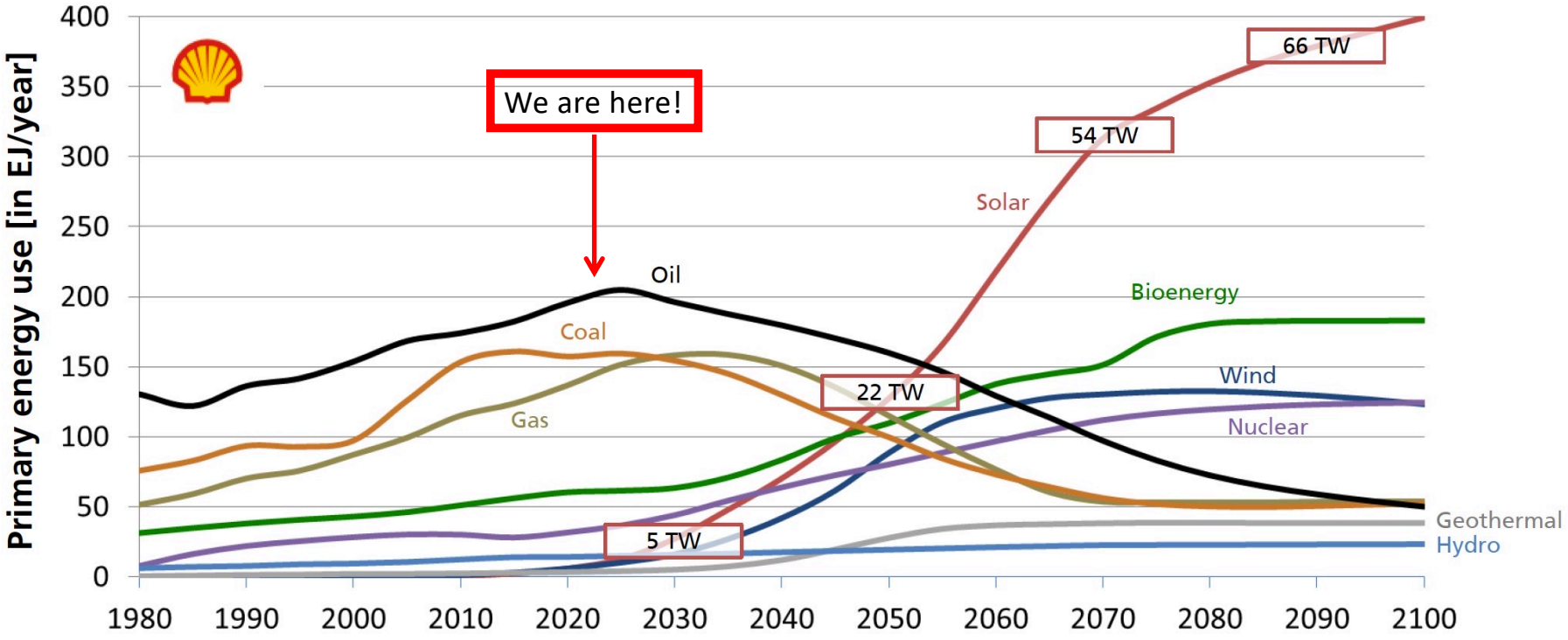
The Guardian, March 11th 2020:
"Polar ice caps melting six times faster than in 1990s"

Tagesschau (Germany) October 30th 2024:
500 mm rain , ½ m in 24hrs, in Valencia (Spain)

Slide courtesy Hans-Martin Henning, Fraunhofer ISE 2020

Global energy scenario of Shell

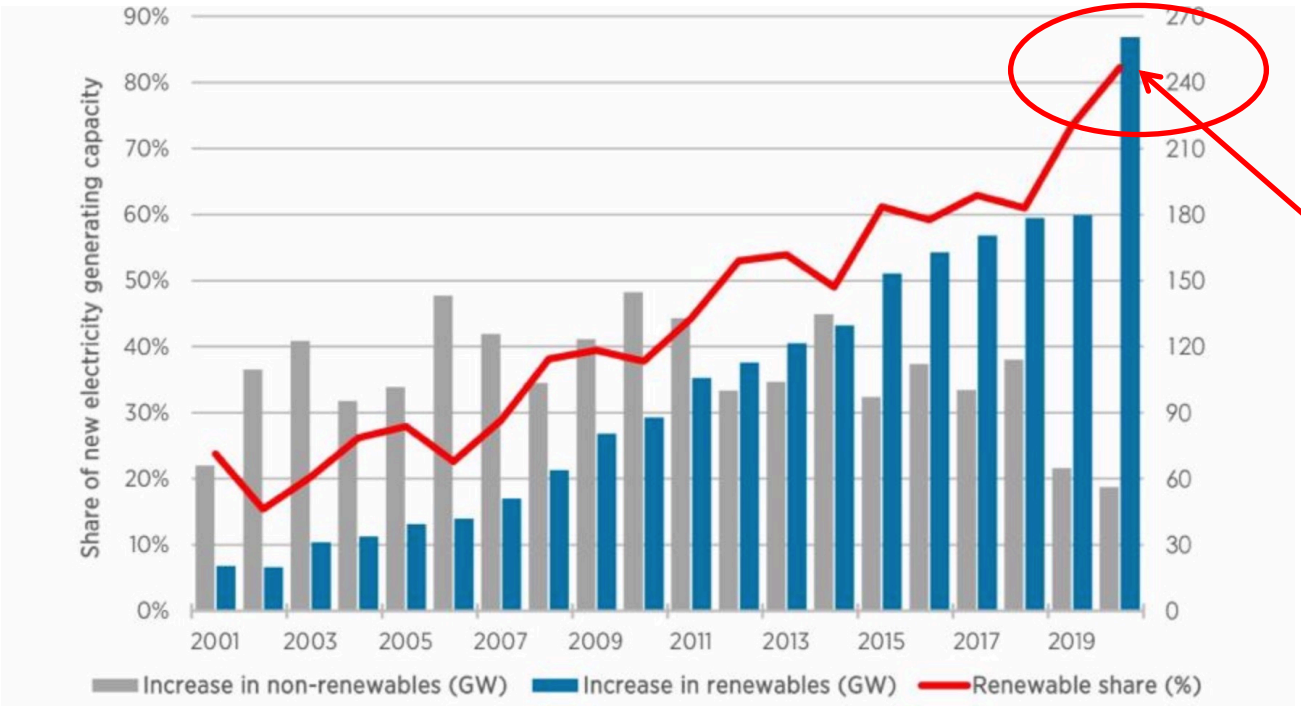
Dominating role of photovoltaic in the future



Slide courtesy Hans-Martin Henning, Fraunhofer ISE

https://www.carbonbrief.org/in-depth-is-shells-new-climate-scenario-as-radical-as-it-says

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

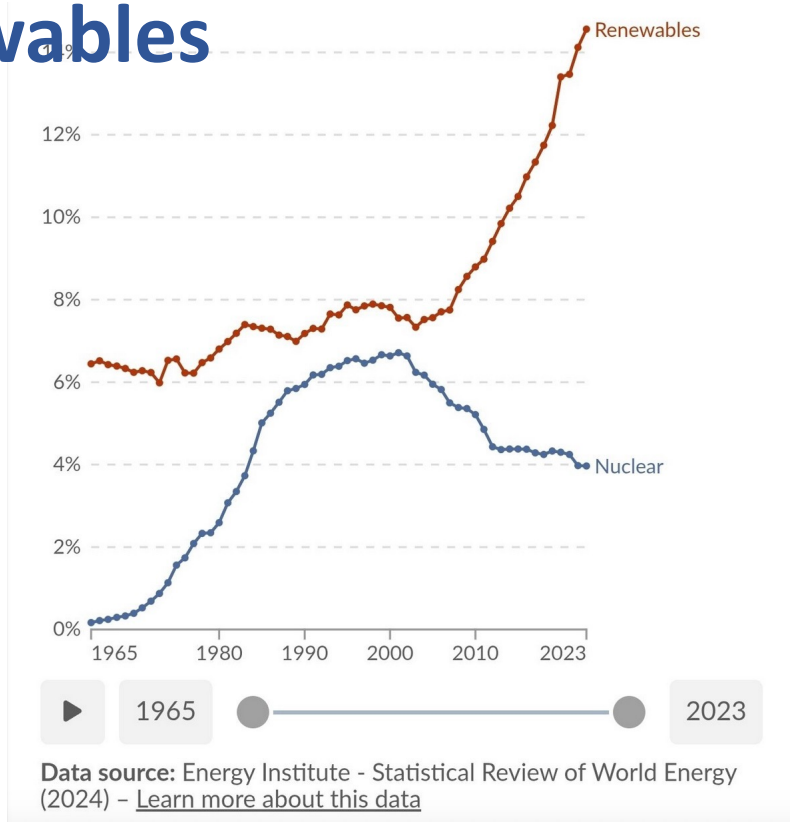


New global power generation capacity in 2020 was 80% in renewables, mainly PV and wind!

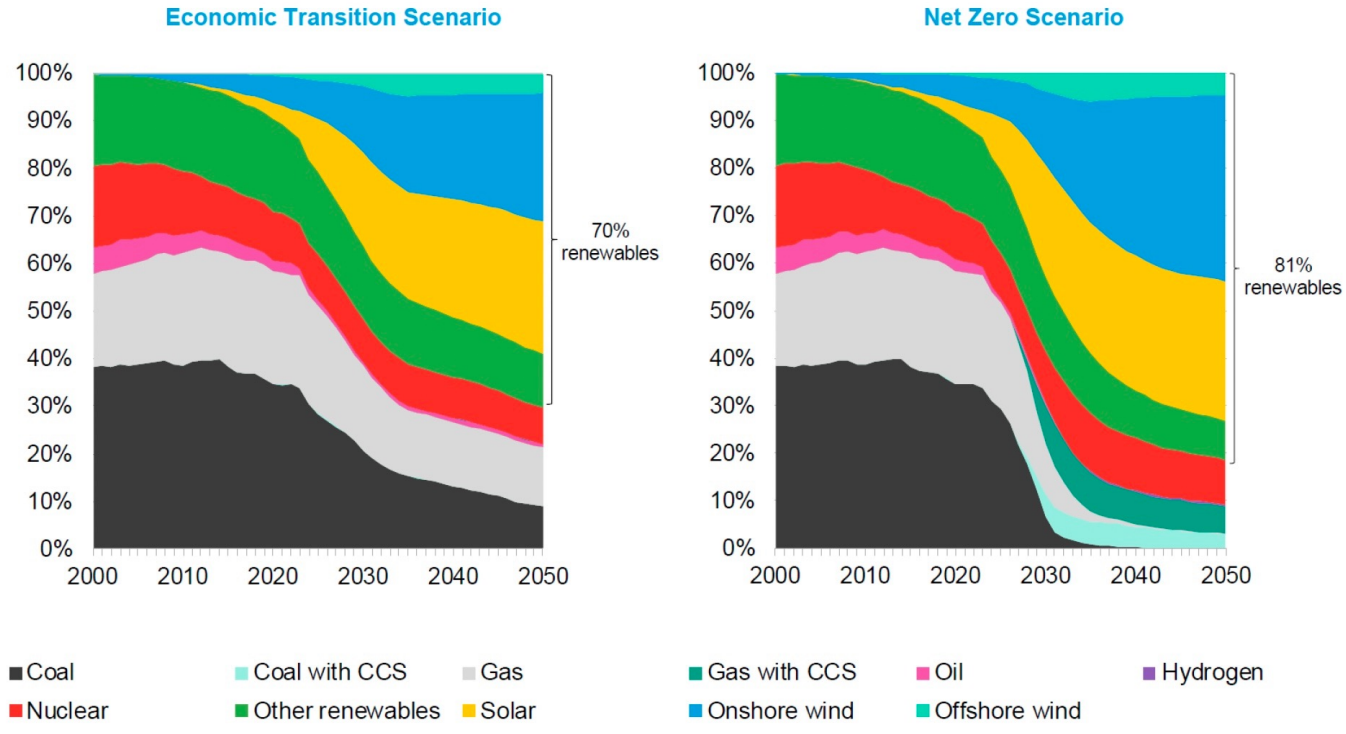
Source: Bloomberg 2021

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

Shares of Primary Energy Consumption fromNuclear and Renewables



The Global Energy Transformation
Renewable Energy increasingly dominates electricity production



Note: Includes electricity generation for hydrogen production under the Net Zero Scenario. 'Other renewables' includes all other non-combustible renewable energy, including hydro, bioenergy, geothermal and solar thermal. CCS is carbon capture and storage.

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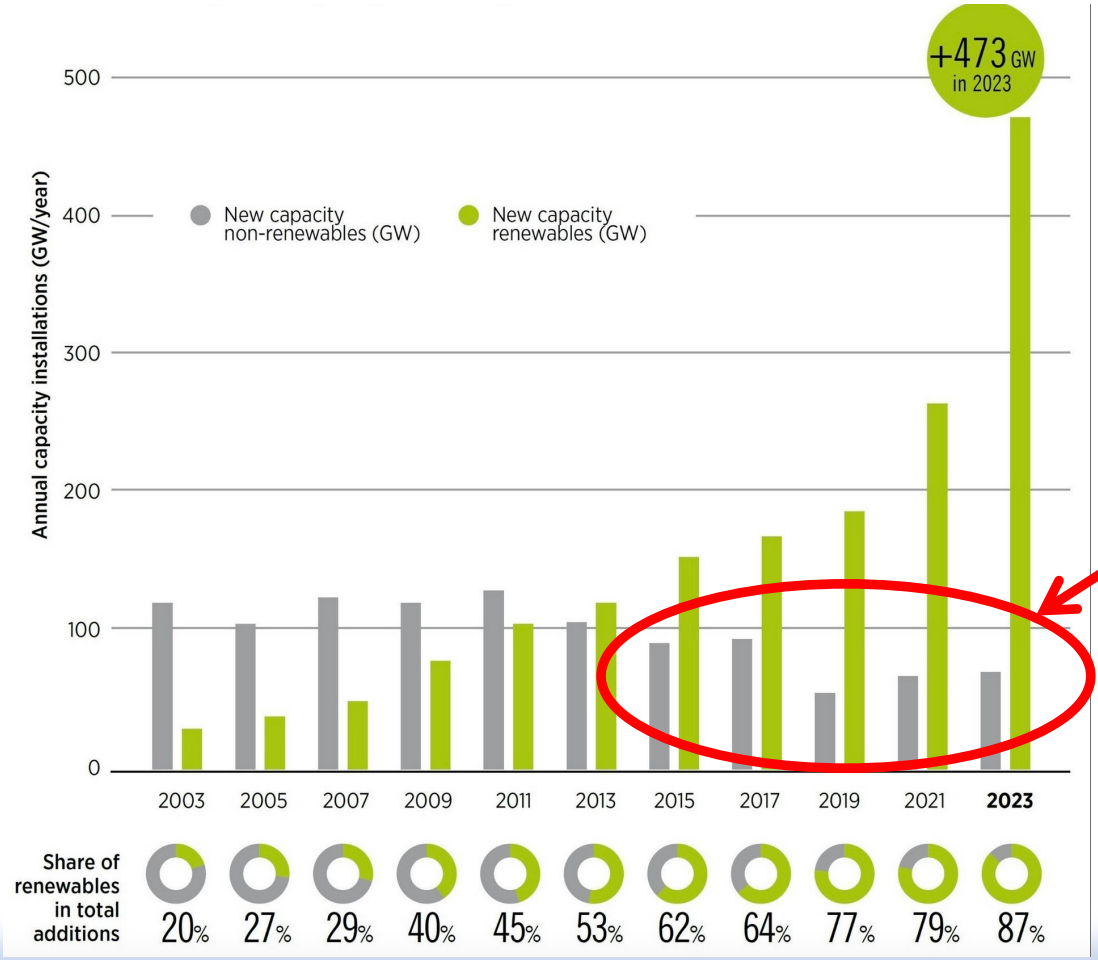
Source: New Energy Outlook 2024, Bloomberg New Energy Finance, May 2024

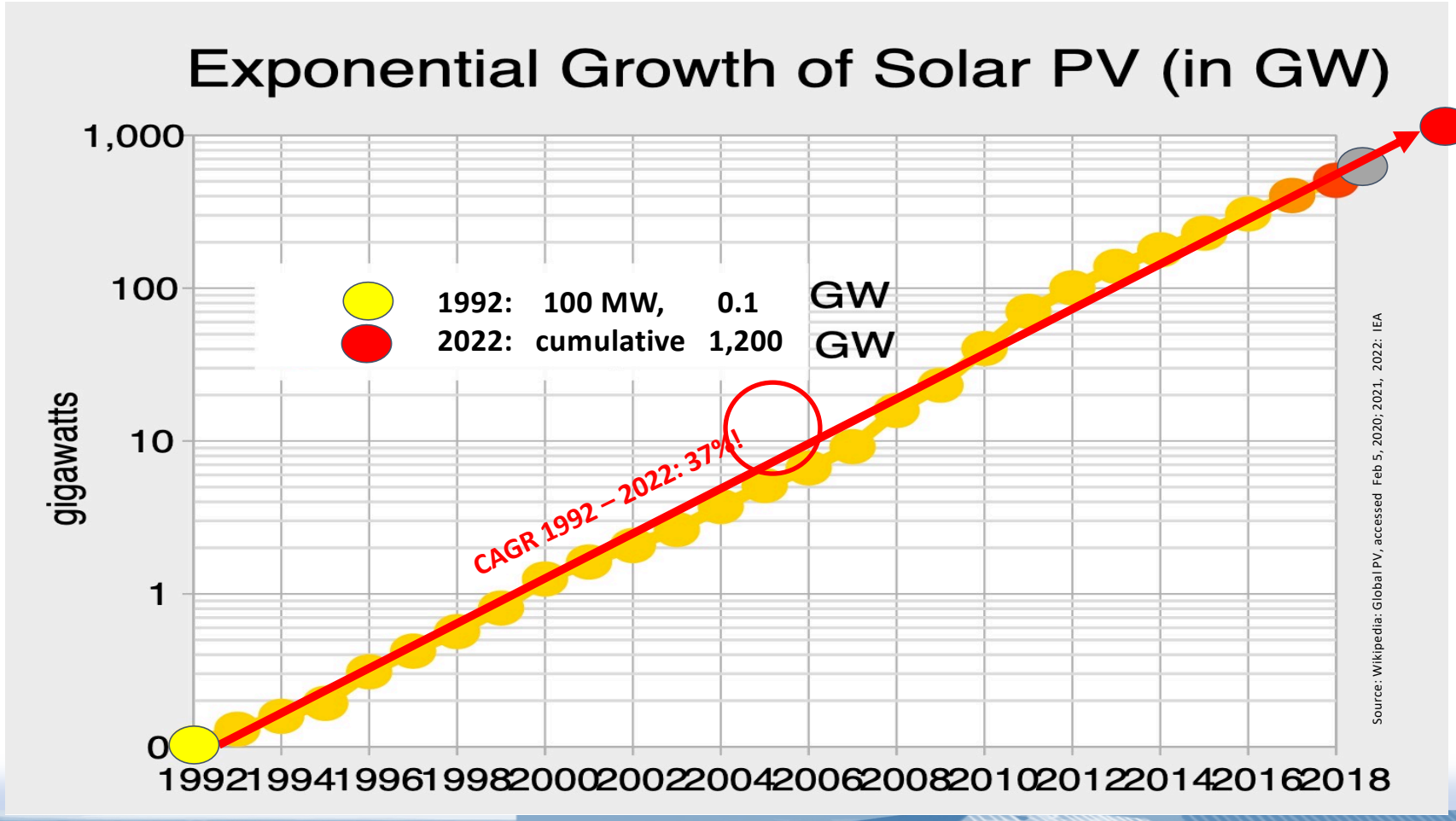
Fraunhofer ISE

Annual Installed Electric Power additions 2003-2023

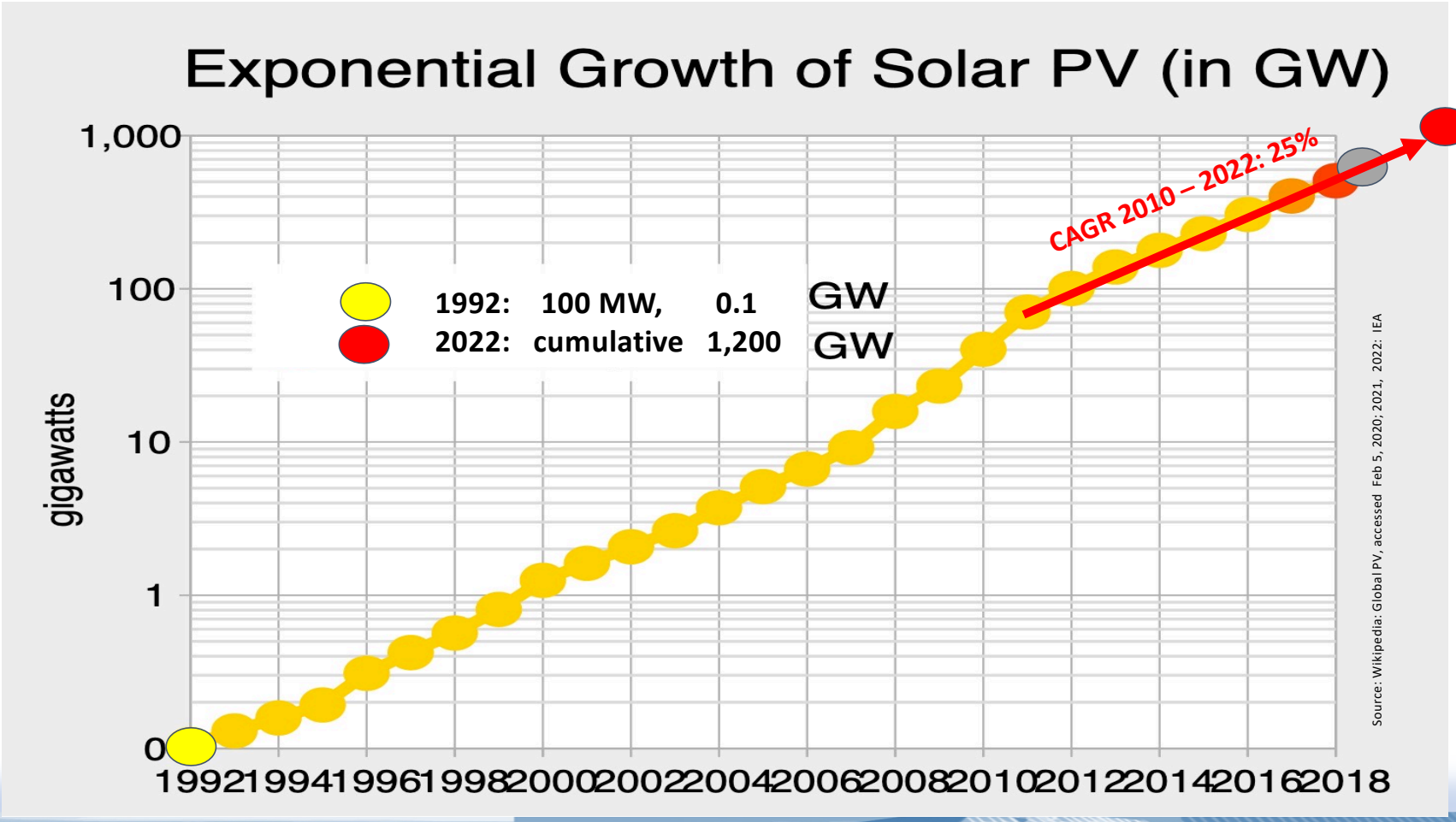


Since 2013:
Annual new non-renewable power installations below 100GW/yr!

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



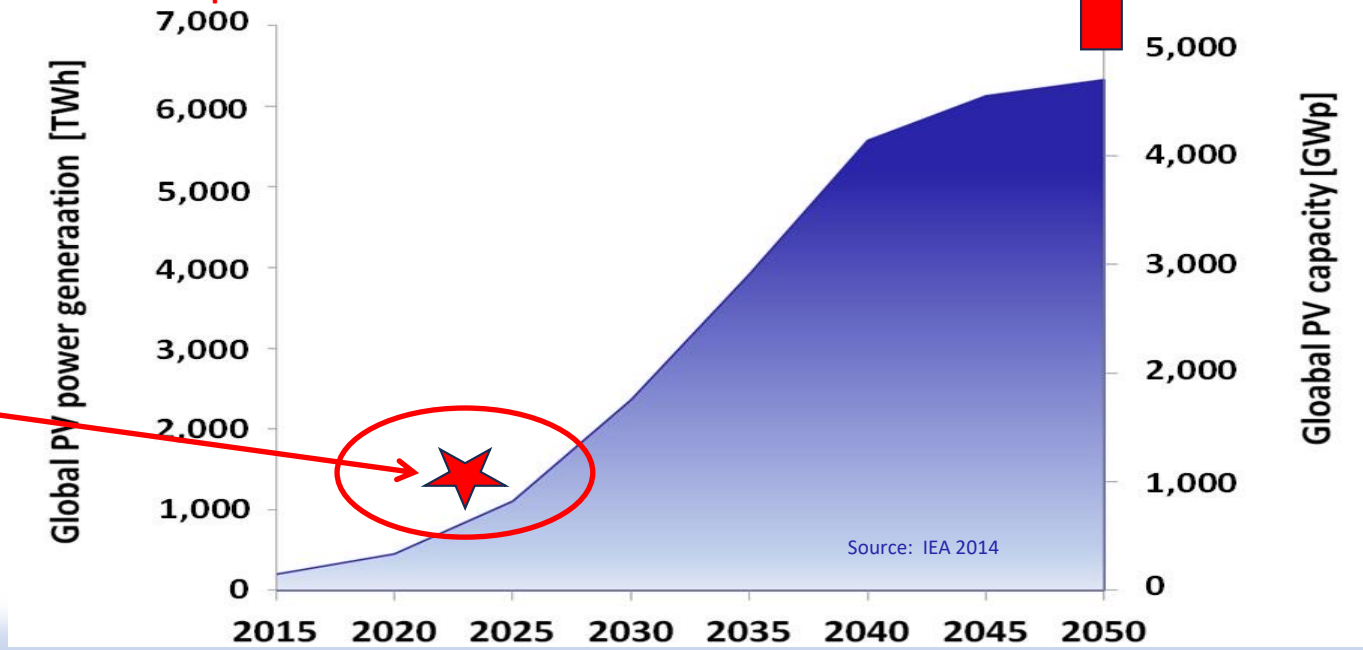
Global Growth of PV Installations 2010 – 2022 CAGR: 25%!



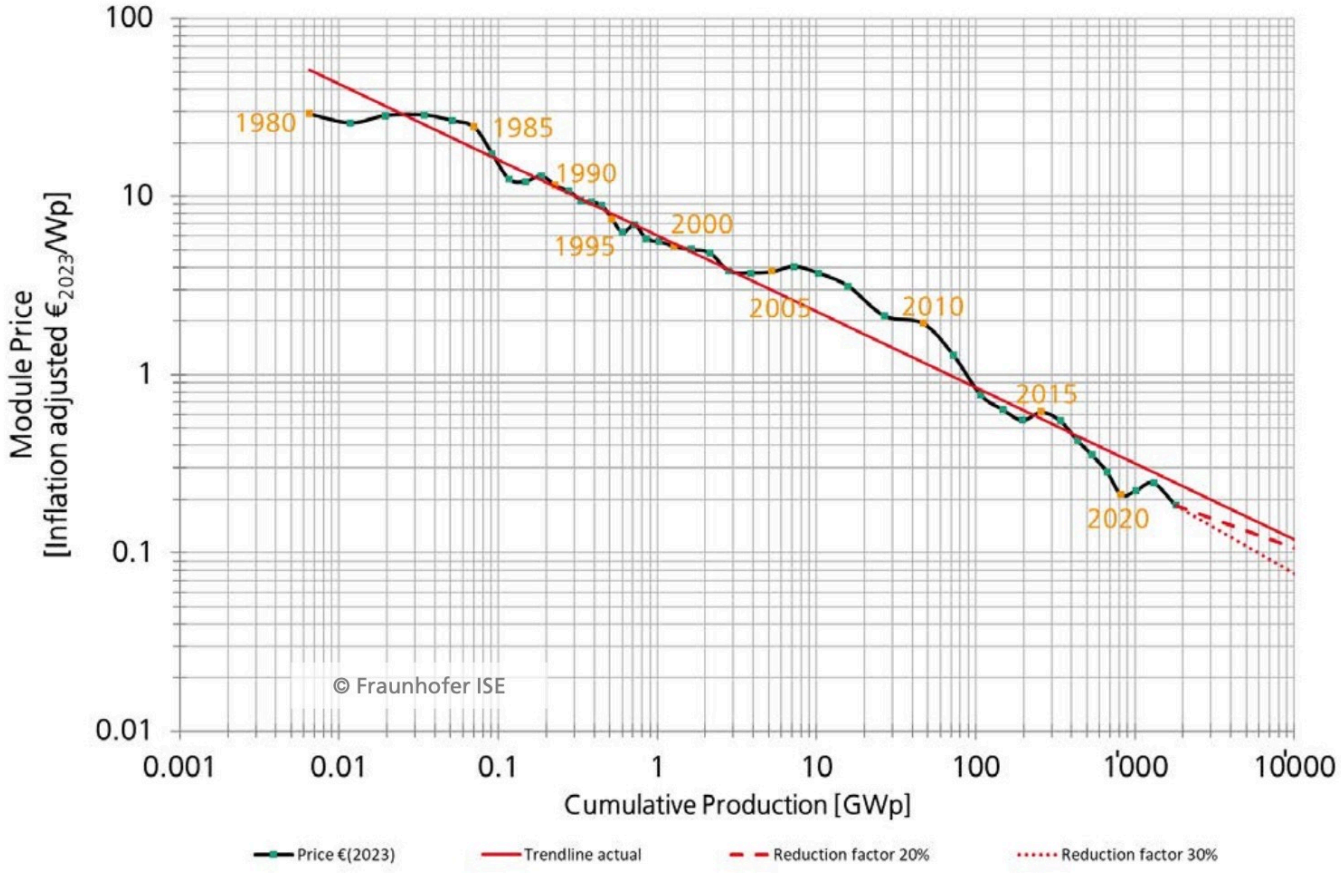
PV Heading into the Terawatt Range – this is a Disruption!

- 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, may be 50 TW** of PV will be installed!
- **Today, 1,500 GW_p or 1.5 TW_p have been installed!**

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



PV Price-Learning Curve 1980 - 2023:



1976: $100/$W_p$
2024: below $0.10/$W_p$
13% Annual Price Reduction!

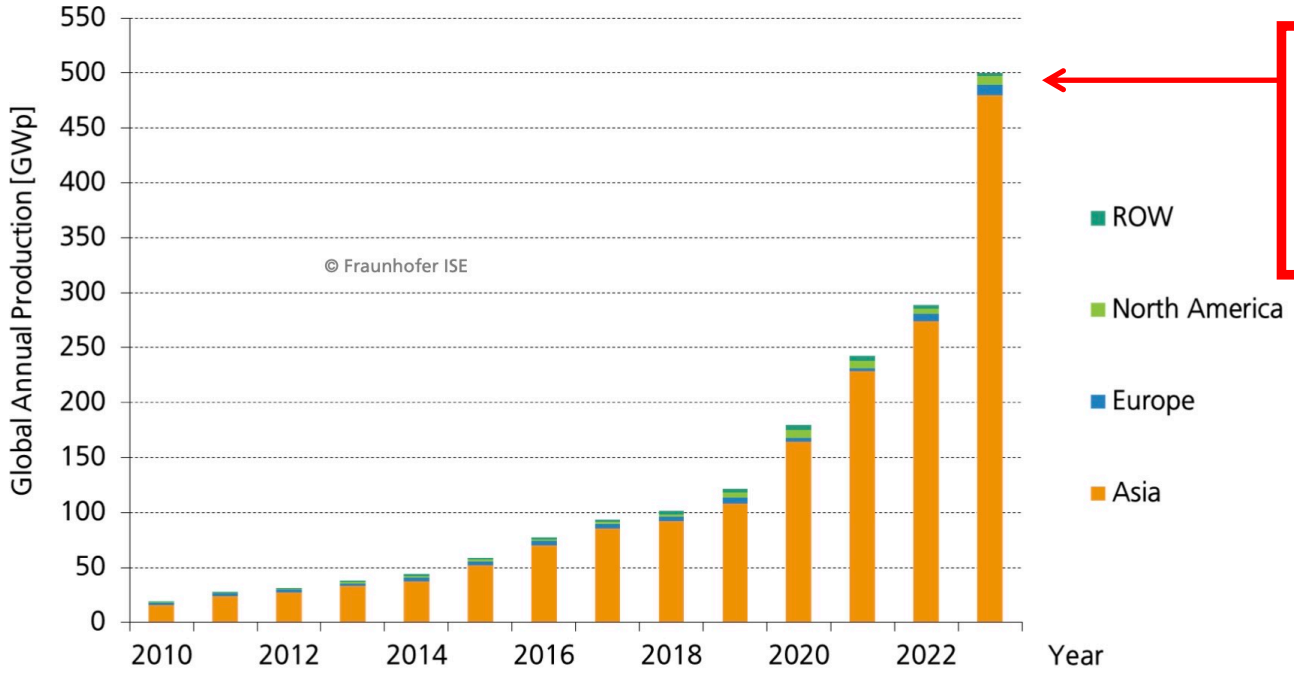
Since 1980:
24% Price reduction for each doubling of globally installed volume!

2024: PV electricity is available at close to 1 ct/kWh in sun-rich regions!

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; from 2022: ISE; Graph: PSE Projects GmbH 2024

PV Module Production by Region 1990-2023

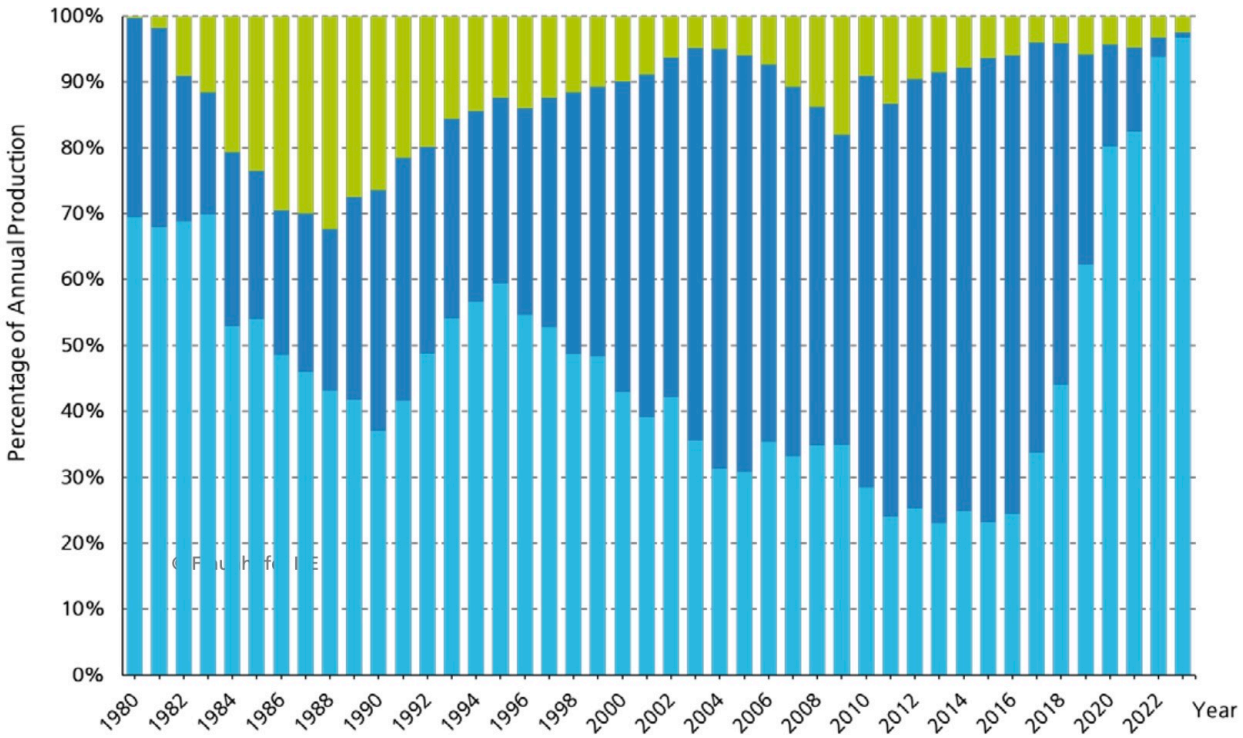
Total GWp Produced Crystalline Si Wafer-based Solar Modules



2023:
0.5 TW newly installed!
2022/23:
+ 70% market volume,

Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 estimates based on IEA and other sources. Graph: PSE Projects GmbH 2024 . Date of data: 04/2024

PV Production by Technology:
Percentage of Global Annual Production

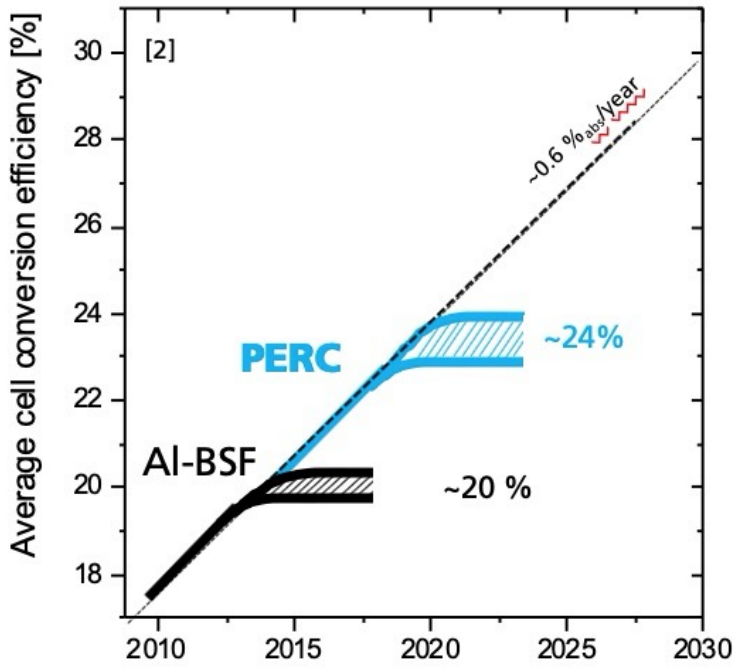


Production 2023* (GWp)		
Thin film	13	
Multi-Si	4	
Mono-Si	485	
Total	502	(ITRPV)

*estimated numbers

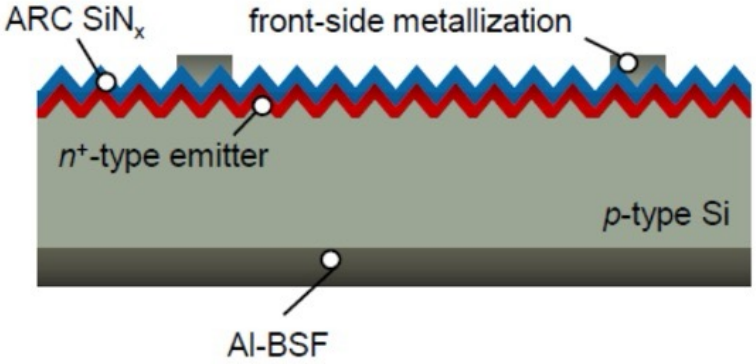
Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 estimates based on IEA and other sources. Graph: PSE Projects GmbH 2024 . Date of data: 04/2024

Increasing the Efficiency
Industrial Realisation



- **Now for many years:**
  Increase of efficiency in industrial production
  ~ 0,6 $\%_{abs}$/year [1]

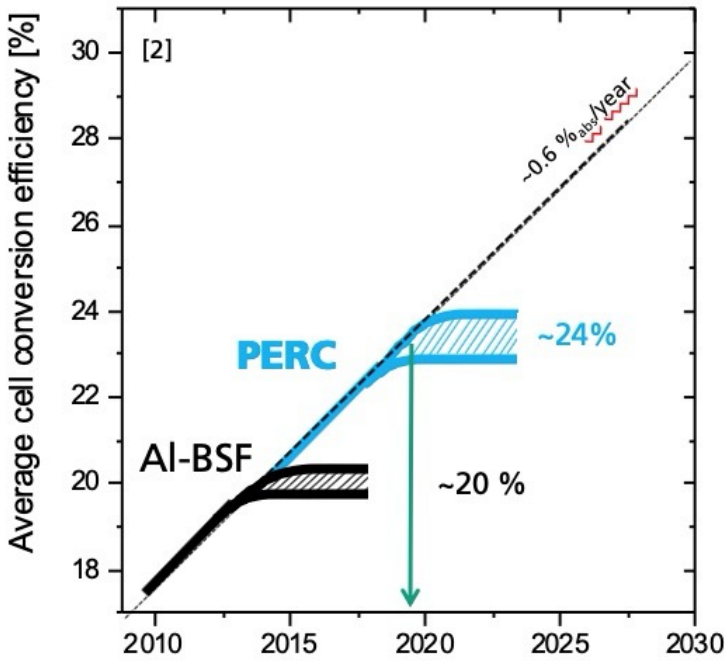
- Efficiency limitation due to full area Al-BSF (back surface field) rear side



Slide courtesy A. Bett, Fraunhofer ISE 2020

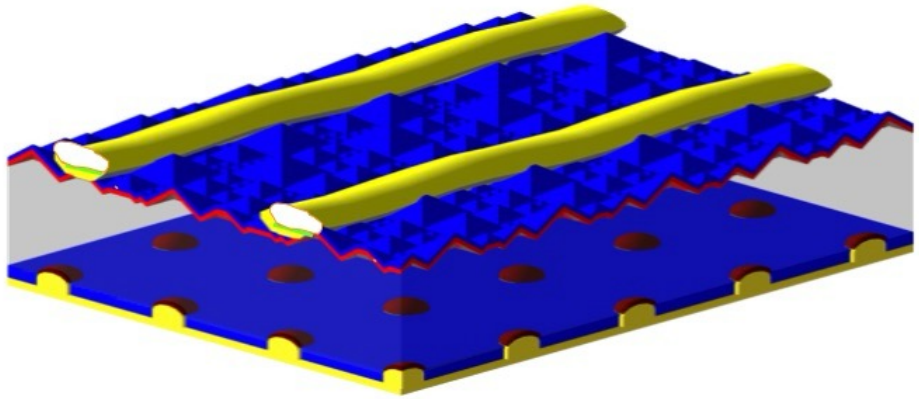
[1] F.Fertig et al. Silicon PV 2019 and 2017
[2] M. Hermle, ETIP PV, PV Manufacturing in Europe, 2017, Brussels

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)**



Slide courtesy A. Bett, Fraunhofer ISE 2020

[1] F.Fertig et al. Silicon PV 2019 and 2017
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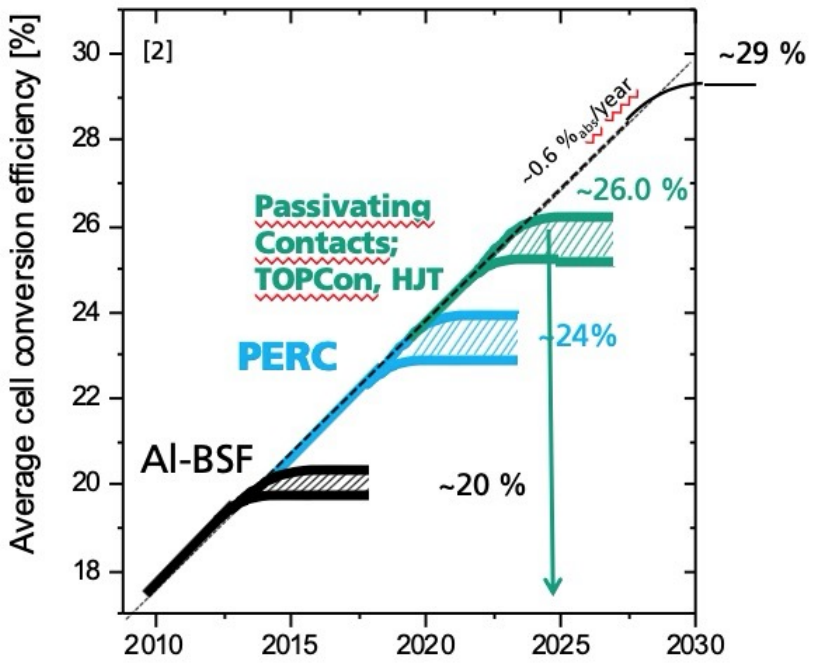
Innovations with Respect to Efficiency
Industrial Realisation – A View Into the Coming Years



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

Slide courtesy A. Bett, Fraunhofer ISE 2020

[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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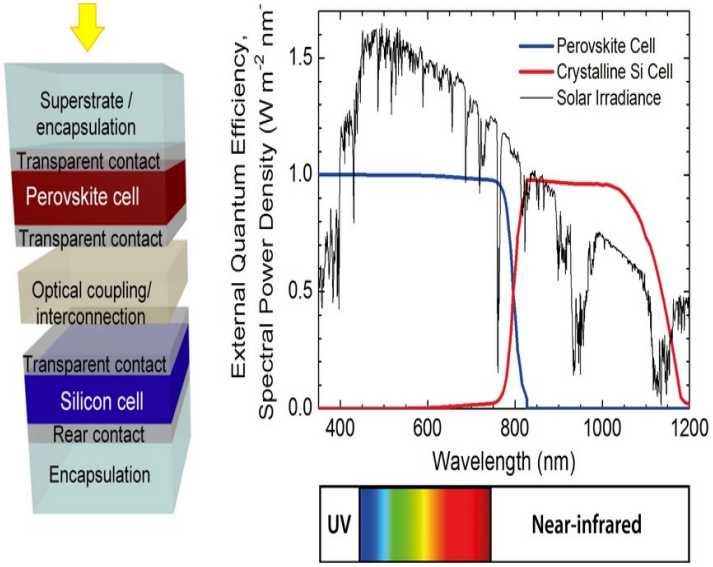
Perovskites-on-Silicon Tandem Cells



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.

J. Phys. Chem. Lett. 2016, 7, 161−166
http://pvlab.epfl.ch/page-124775-en.html

Slide courtesy N. Mathews, ERI@N, NTU 2017

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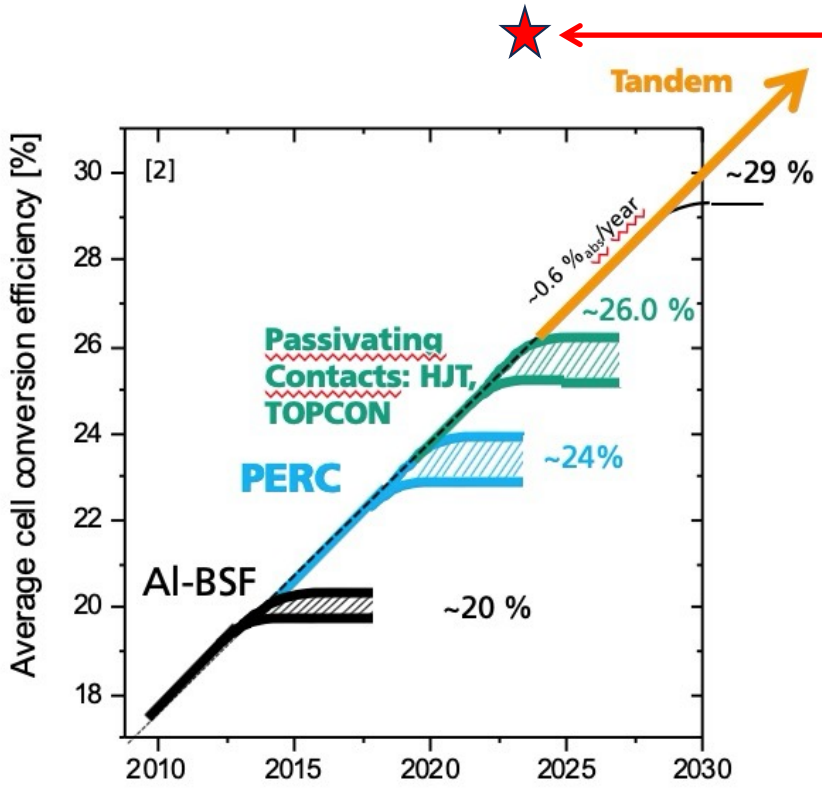
Beyond the Shockley-Queisser Limit: Further Innovations in PV Cell Technology!

Tandem Solar Cells on Silicon

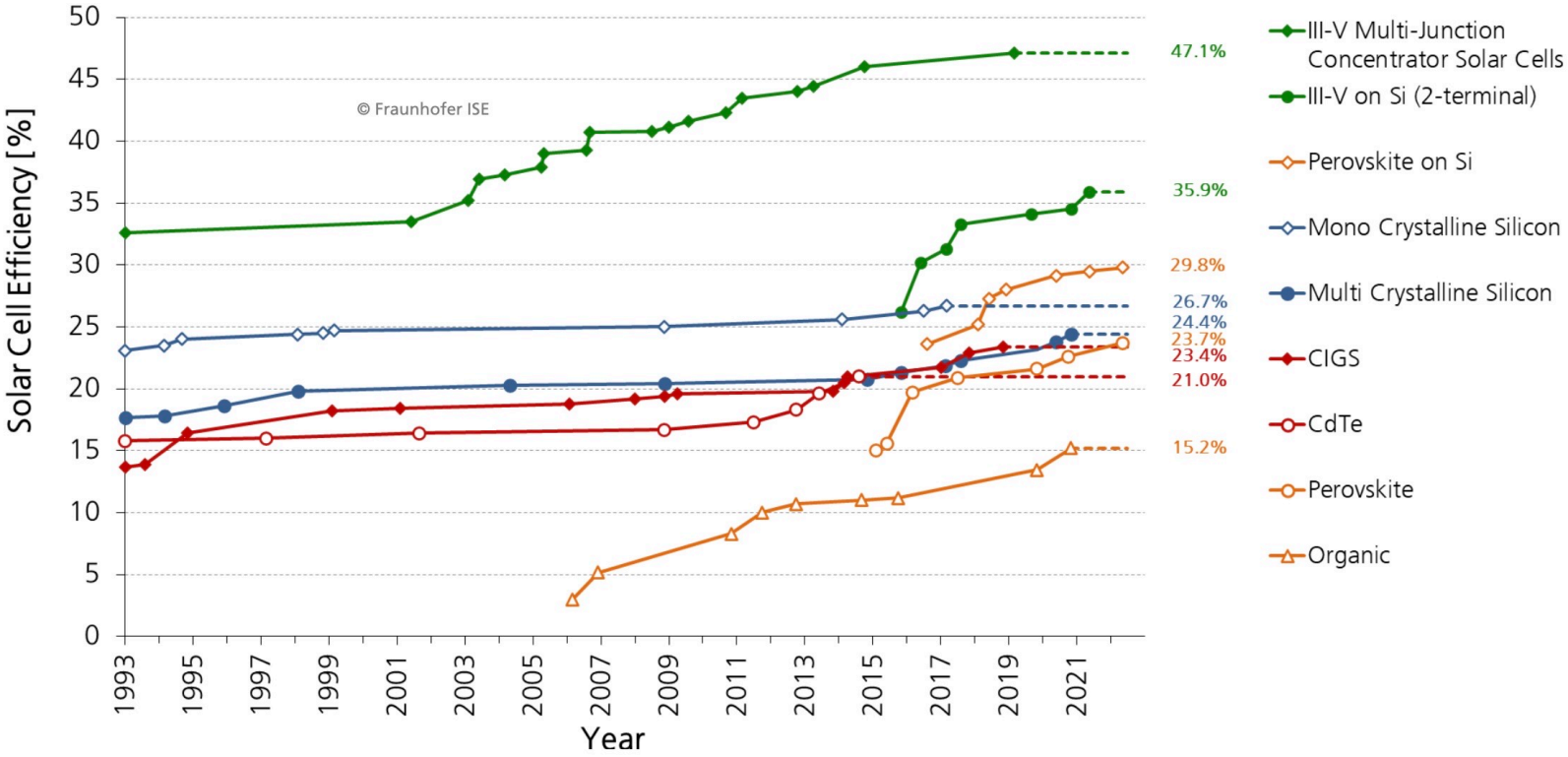


On November 3, 2023, LONGi announced a world record of 33.9% efficiency of crystalline silicon-perovskite tandem solar cells at 19th CSPV.

Slide courtesy A. Bett, Fraunhofer ISE 2020

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

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 60), Progress in Photovoltaics: Research and Applications, 1993-2022. Graph: Fraunhofer ISE 2022. Date of data: May 2022

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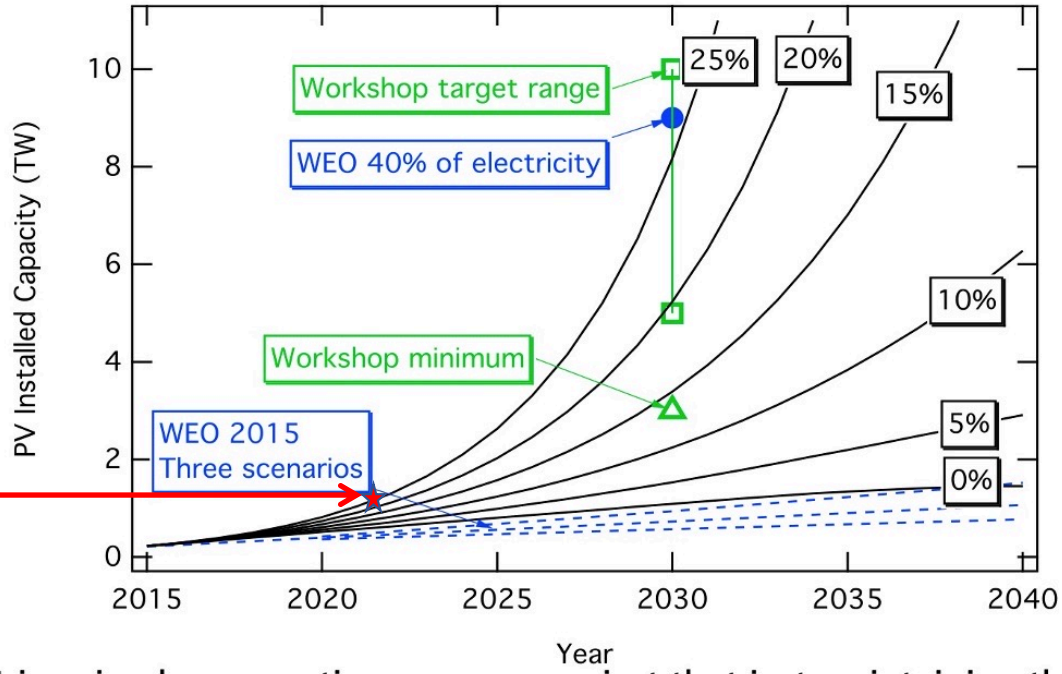
Only official lab record efficiencies published in the Solar Cell Efficiency Tables, Progress in Photovoltaics: Research and Applications are included in the graph. The following novel results will be included as soon as they are published in the tables:
III-V multi-junction solar cell, 47.6% by Fraunhofer ISE; Perovskite on Si, 31.25% by CSEM / EPFL

Projections to TW-scale PV from 1st TW workshop 2016

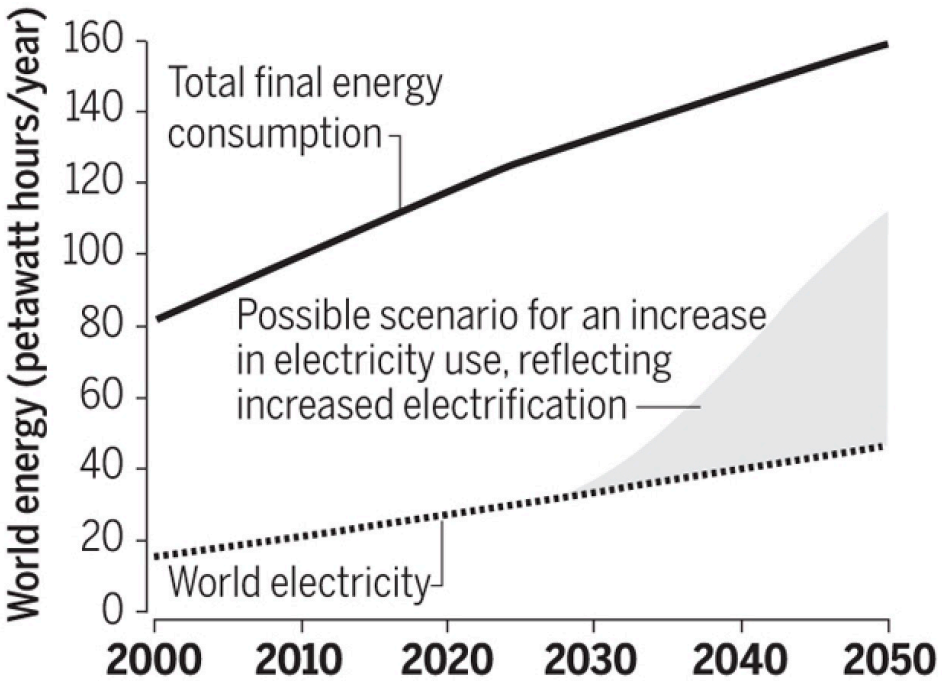


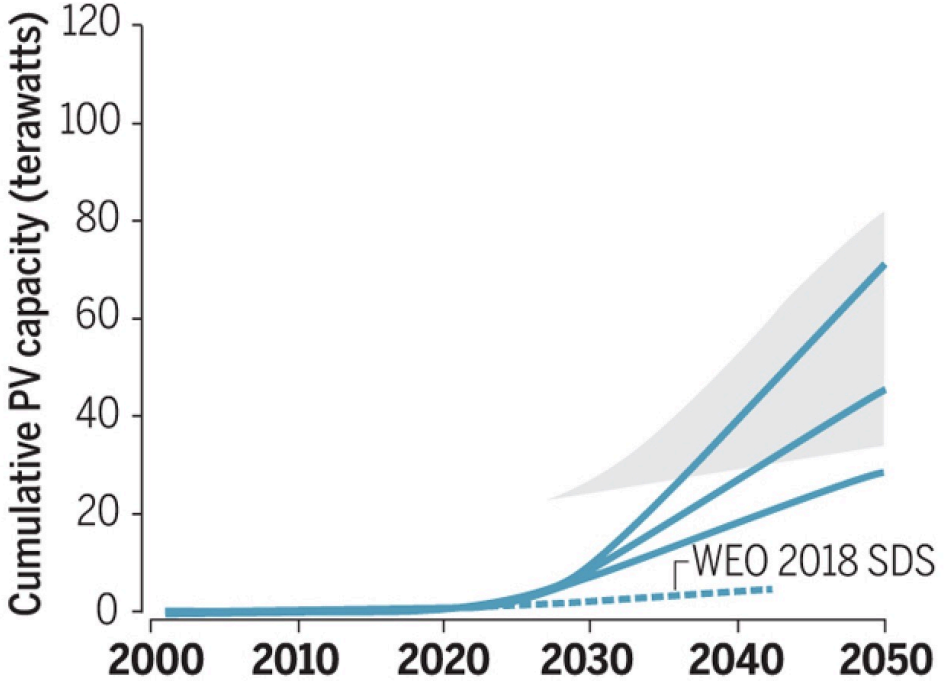
6 years later:
1 TW installed in March 2022:
We follow the most optimistic growth curve!

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)

POLICY FORUM

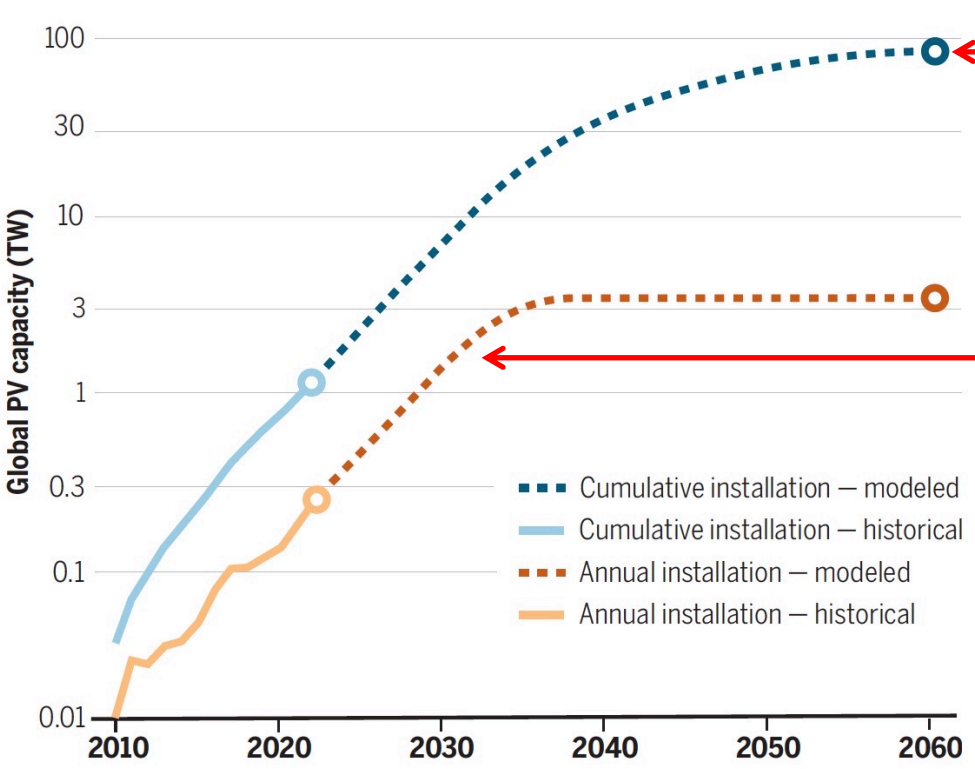
RENEWABLE ENERGY

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 Dharmrin, 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



100% RE requires ca. 75 TW of PV!

2030: More than 1 TW/yr projected!

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

Agro-PV, APV: Combining Solar Energy and Food Harvesting

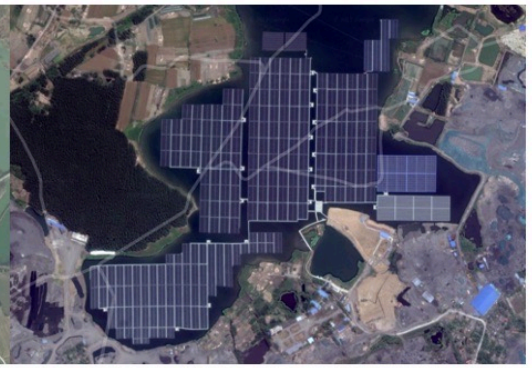
- (A) Bavaria, Hochschule Weihenstephan, 30 kWp, 2013
- (B) Italy, R.E.M. Spa, 3x 3 MWp each, 2011
- (C) France, University of Montpellier, 50 kWp, 2010
- (D) Japan, Solar Sharing, Ministry of Agriculture, Forest and Fishery, Akira Nagashima, 2013
- (E) Italy, Corditec, Ahlers, 800 kWp, 2012
- (F) Egypt, SEKEM, Almaden, Kairo, 90 kWp, 2017

Slide courtesy S. Schindele, Fh-ISE

Floating PV: Harvesting Solar Energy on Water reduces evaporation, provides cooling, dams: grid connected!

8MW, Lingxi lake, Lingxi, Hebei

8.5MW, Sanshan, Wuhu, Anhui



Coal mining subsidence area, Huainan, Anhui

Image sources: Google Map and Sungrow press release.

Slide courtesy S. Schindele, Fraunhofer ISE

Photovoltaics – Current Status, Technologies, and Market Outlook

- PV has become the **lowest-cost way to produce electricity** in many countries, a rapidly growing element of the electricity supply, driven by Multi-Gigawatt-scale production, smart incentives and technical innovations!
- We expect the global PV market to continue its rapid growth, from the current 500 GW/yr towards 1,000GW (1 TW)/yr before 2030, possibly till it reaches 3 TW/yr, 6x 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 heterostructuctures (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**!
- **Nuclear power,** like all other baseload-power options, has no place in our future electricity supply, as solar and wind can easily cover 100% of the daytime power needs!