Part 1.2 PV modules, systems & economics

- PV modules
- PV systems
- PV economics

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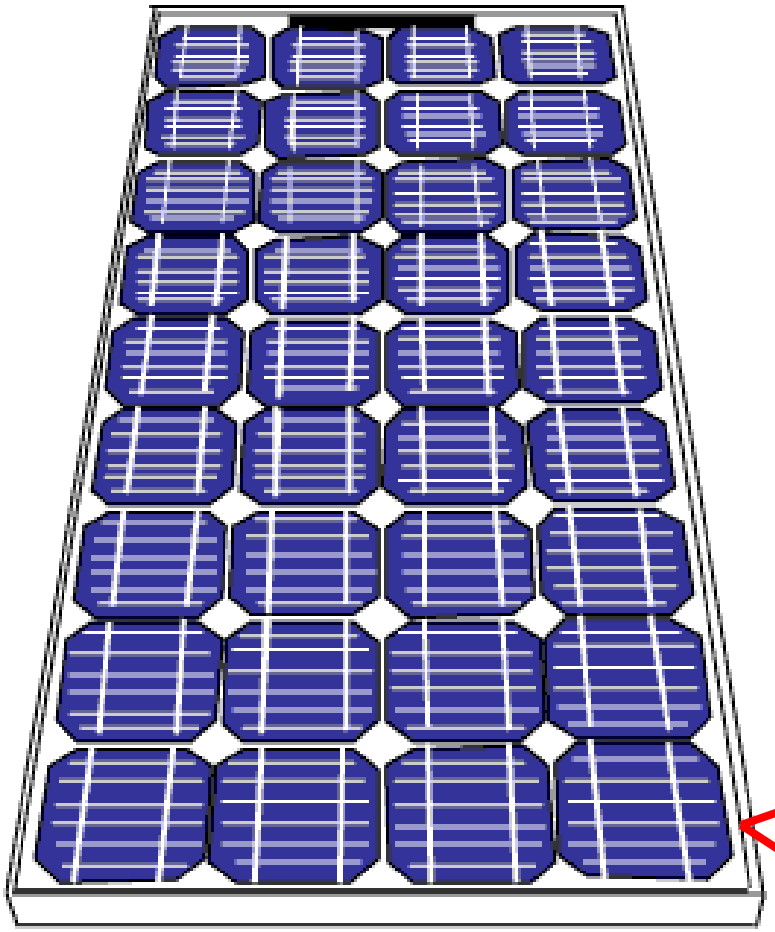
Empa
Materials Science and Technology

PV modules

PV modules (example c-Si)



www.pveducation.org

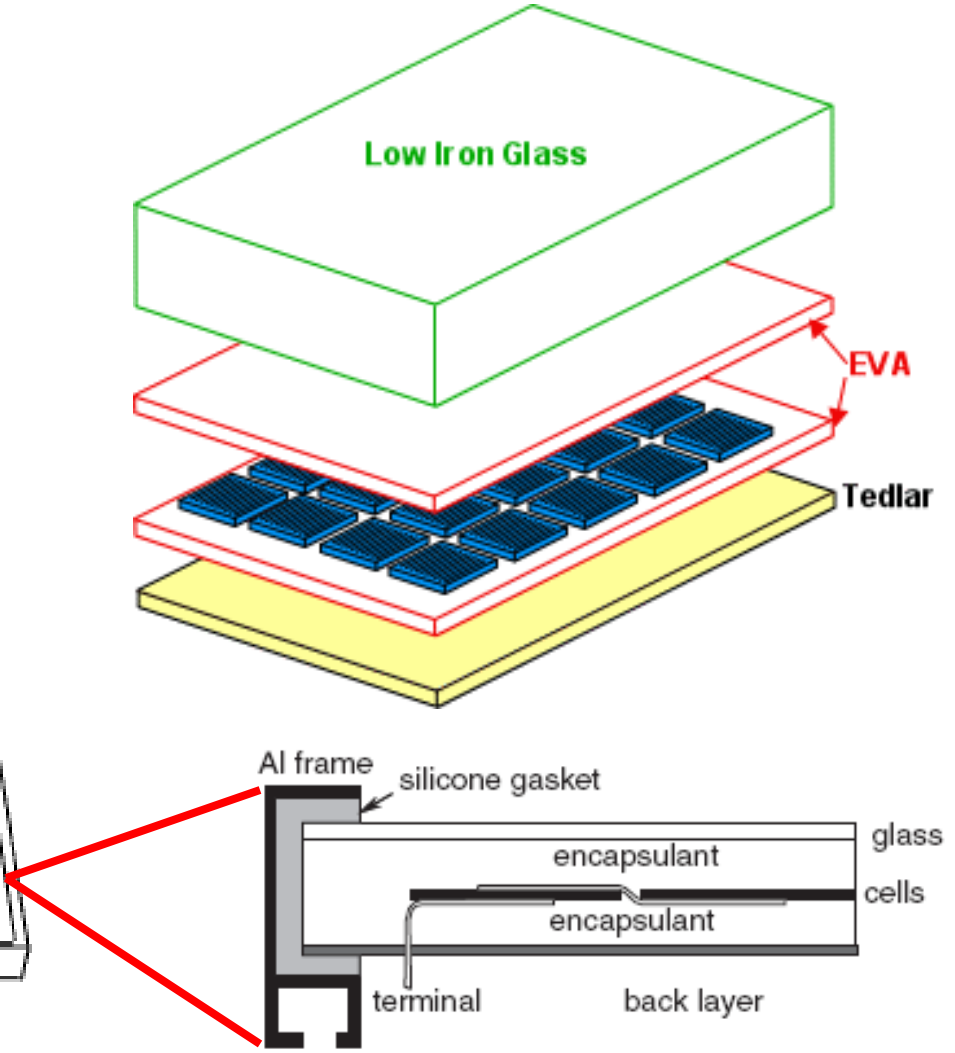
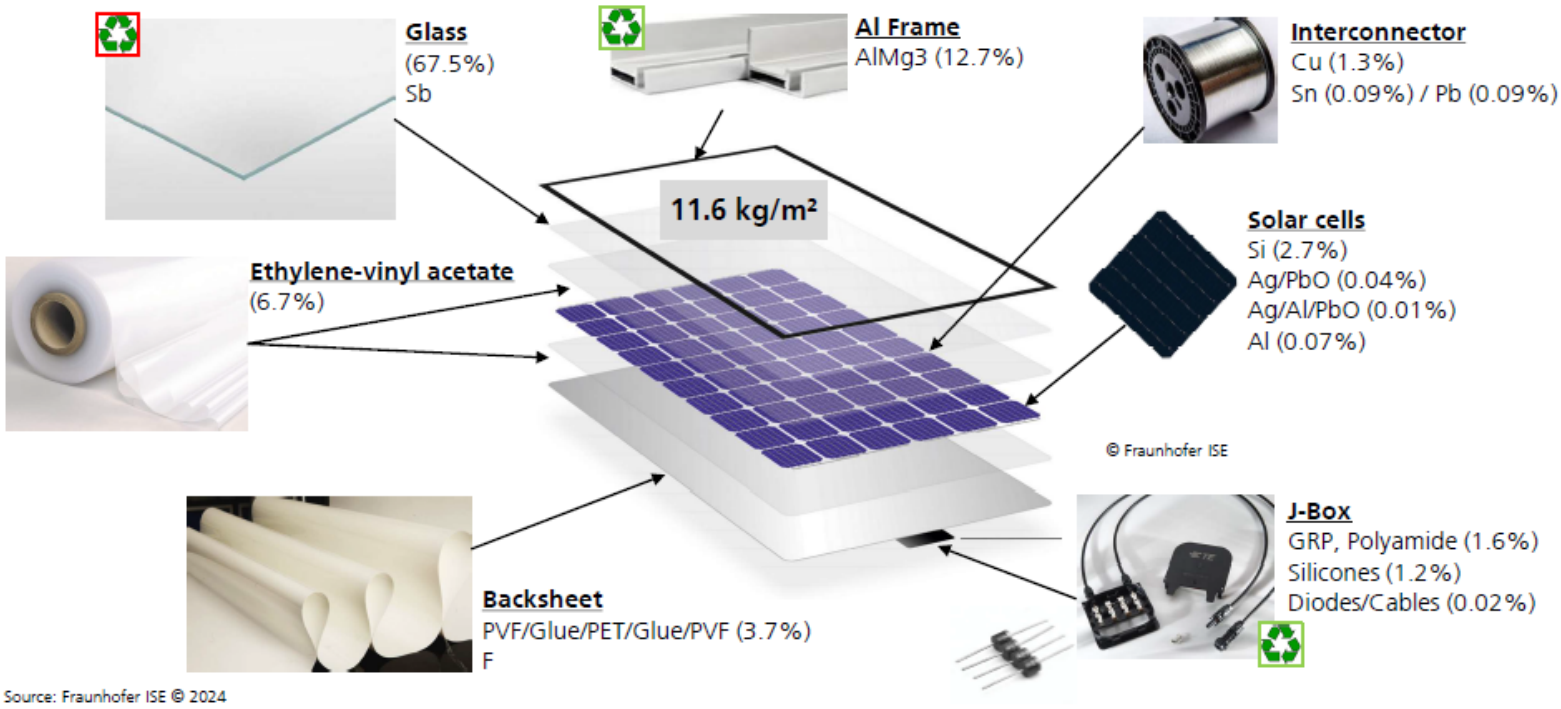


Figure 7.19 Cross- section of a standard module

Handbook of Photovoltaic Science and Engineering, 2011

PV module materials

Materials and Components



Please note: Highly transparent glass can also be produced without antimony (Sb), and some European suppliers are doing so. It is technically feasible to recycle and reuse almost 100% of the materials used in PV modules. The European WEEE Directive stipulates that at least 80% of the module mass of old modules must be processed and recycled for reuse. For economic reasons, however, only the glass, frame and junction box (J-Box) are recycled today.

Color legend:

Available/harmless materials
Rare/valuable materials
Hazardous substances

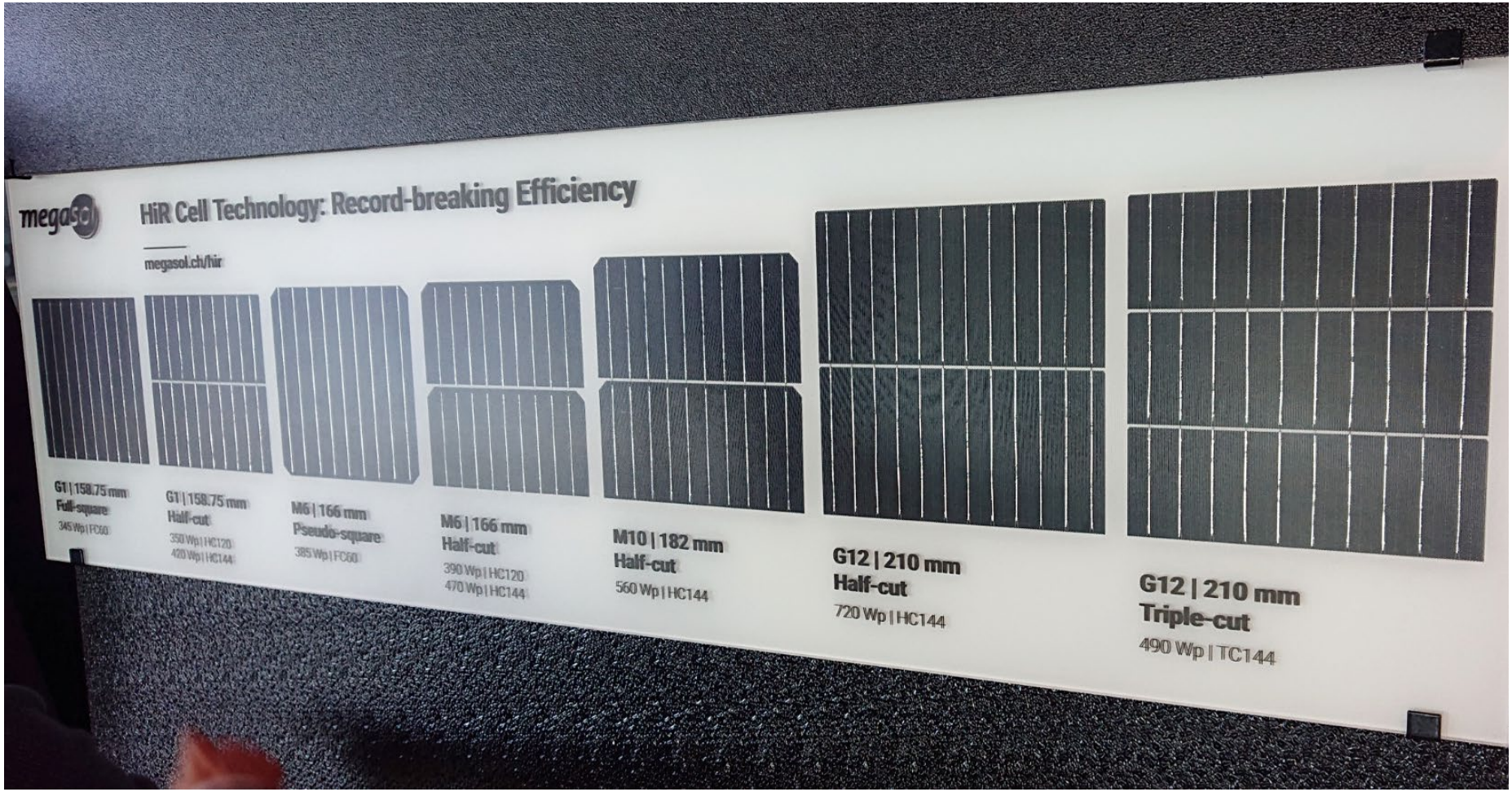
Recycling takes place

Downcycling takes place

Source: Fraunhofer ISE © 2024

Photovoltaics report, Fraunhofer ISE, 2025

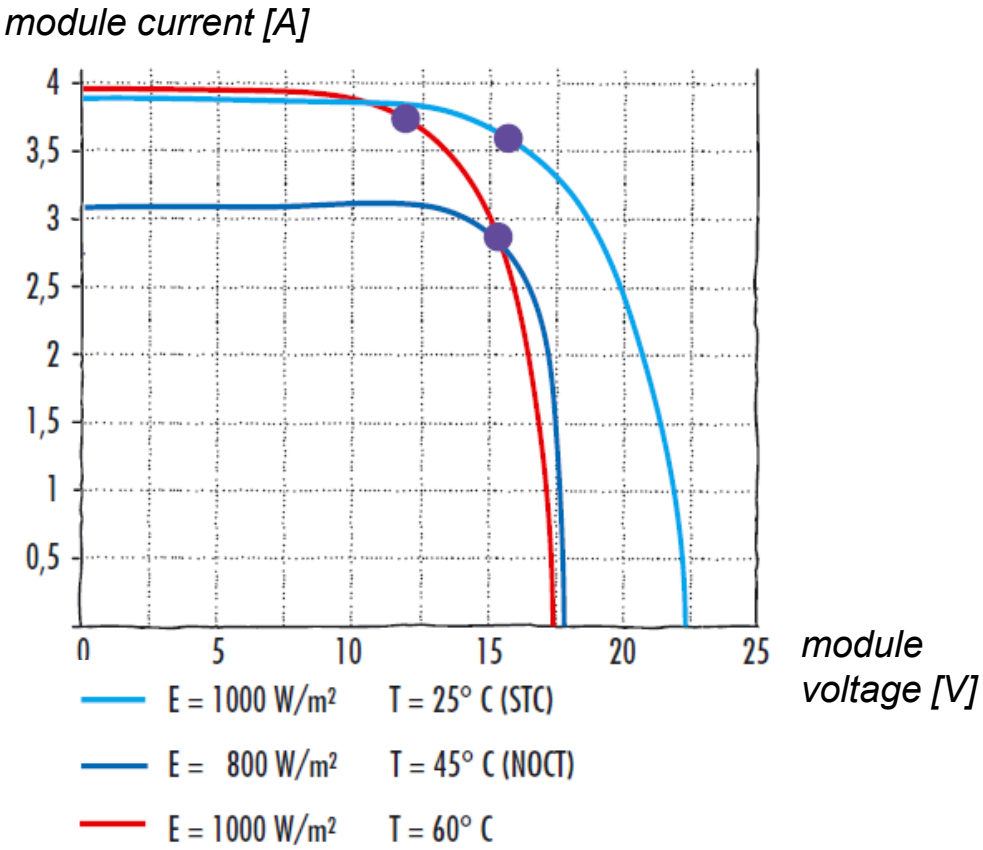
Half-cut and triple-cut cells



Exhibition of Swiss PV Tagung 2021

- From 2015, half-cut and triple-cut modules became dominant because of 1-2% higher power (due to lower resistive losses)

Module characteristics



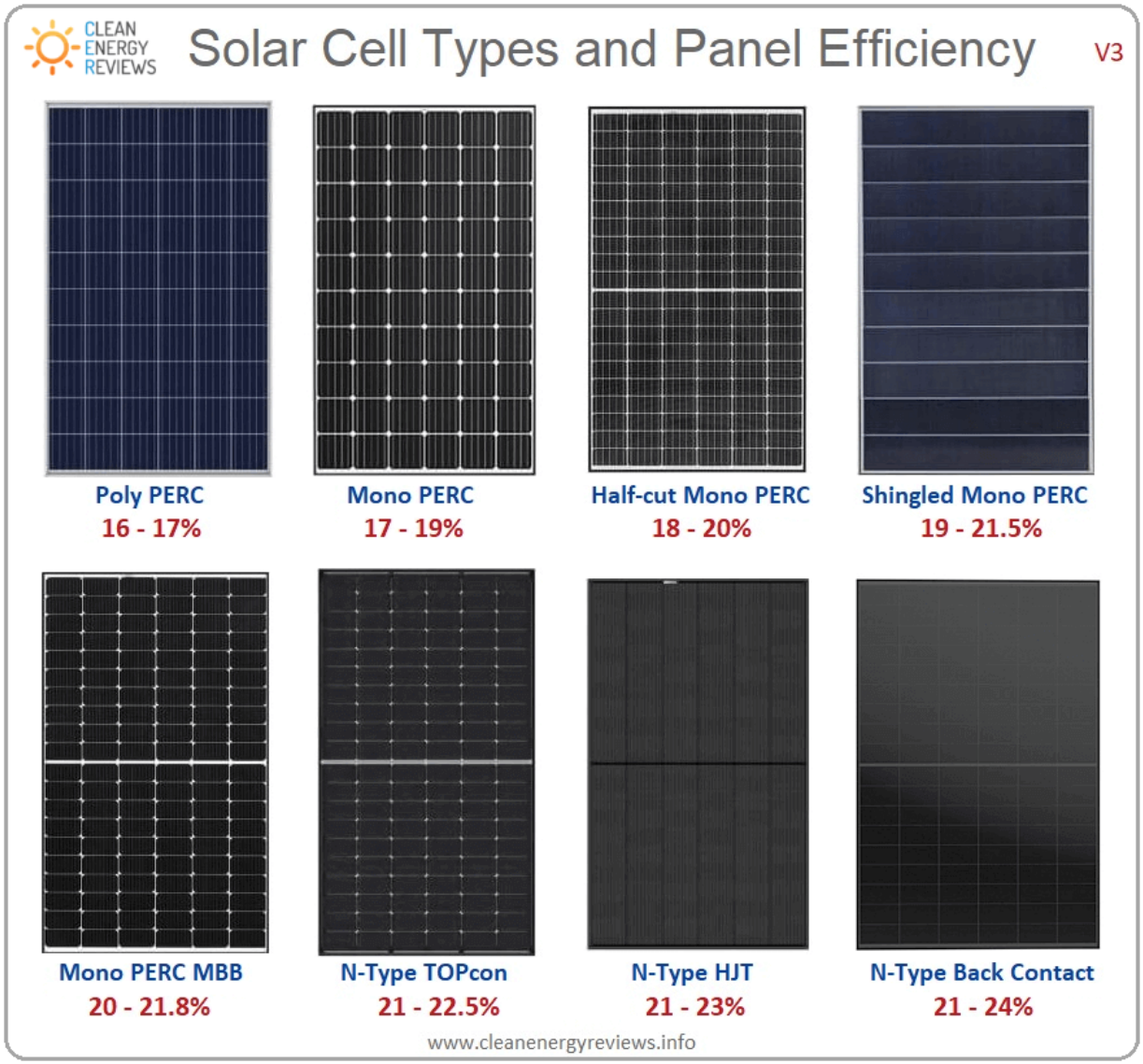
I-V curve influenced by:

- irradiation intensity

- module temperature

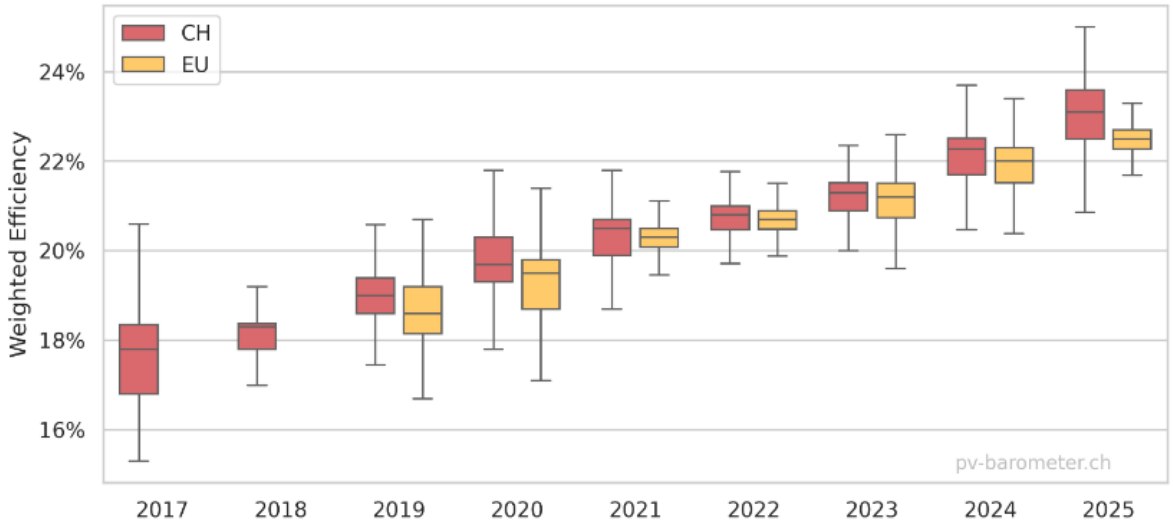
- STC (Standard Test Conditions): 25°C, AM1.5 G, 1000 W/m^2
- NOCT (Nominal Operating Cell Temperature):
  Temperature of cells within module reached at following conditions:
  Voc, 20°C ambient air temperature, 1 m/s wind speed, AM1.5, 800 W/m^2

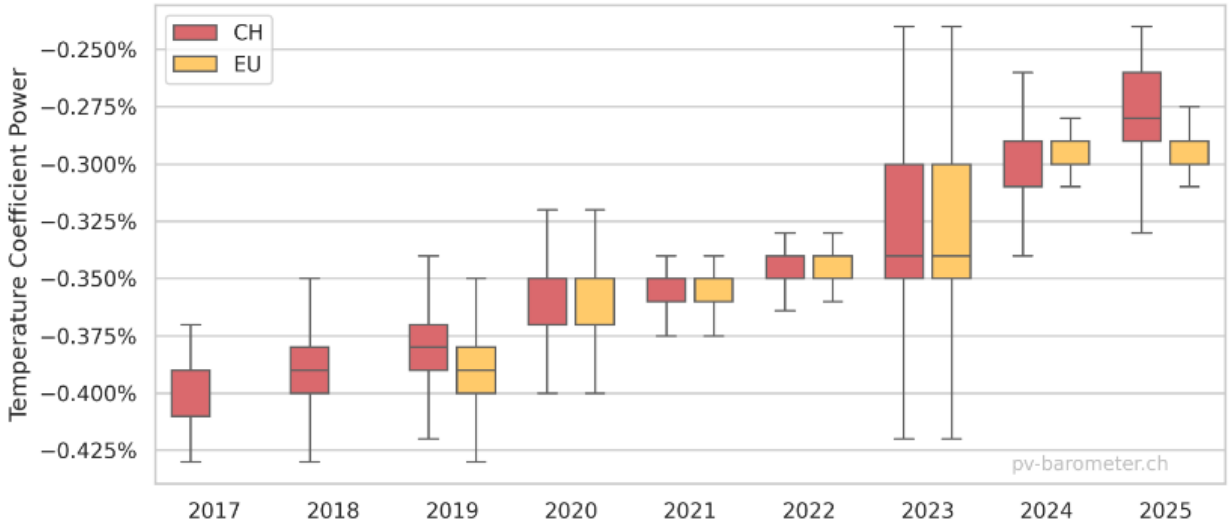
PV module by technology



2023 data from www.cleanenergyreviews.info

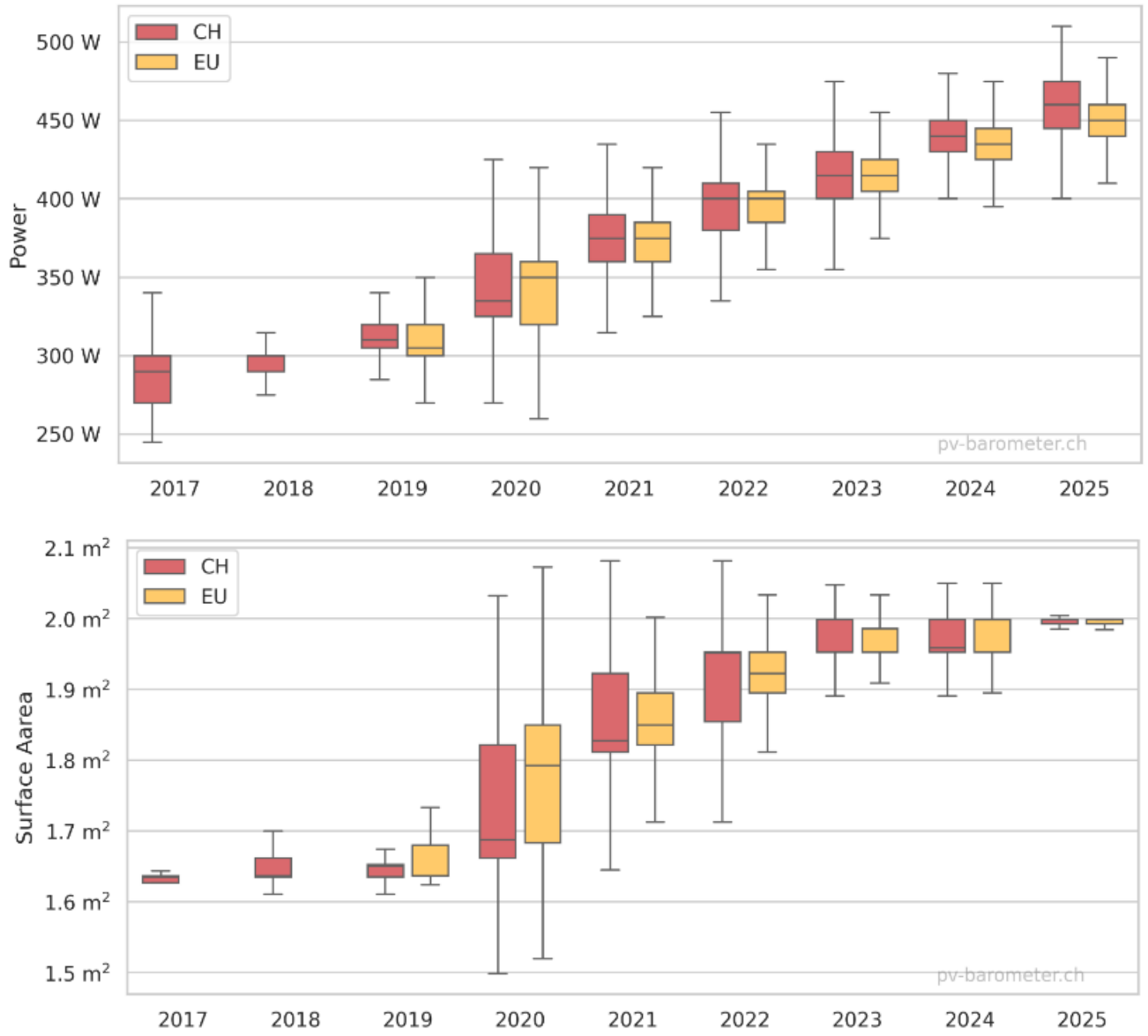
PV modules: efficiency & temp. coeff.



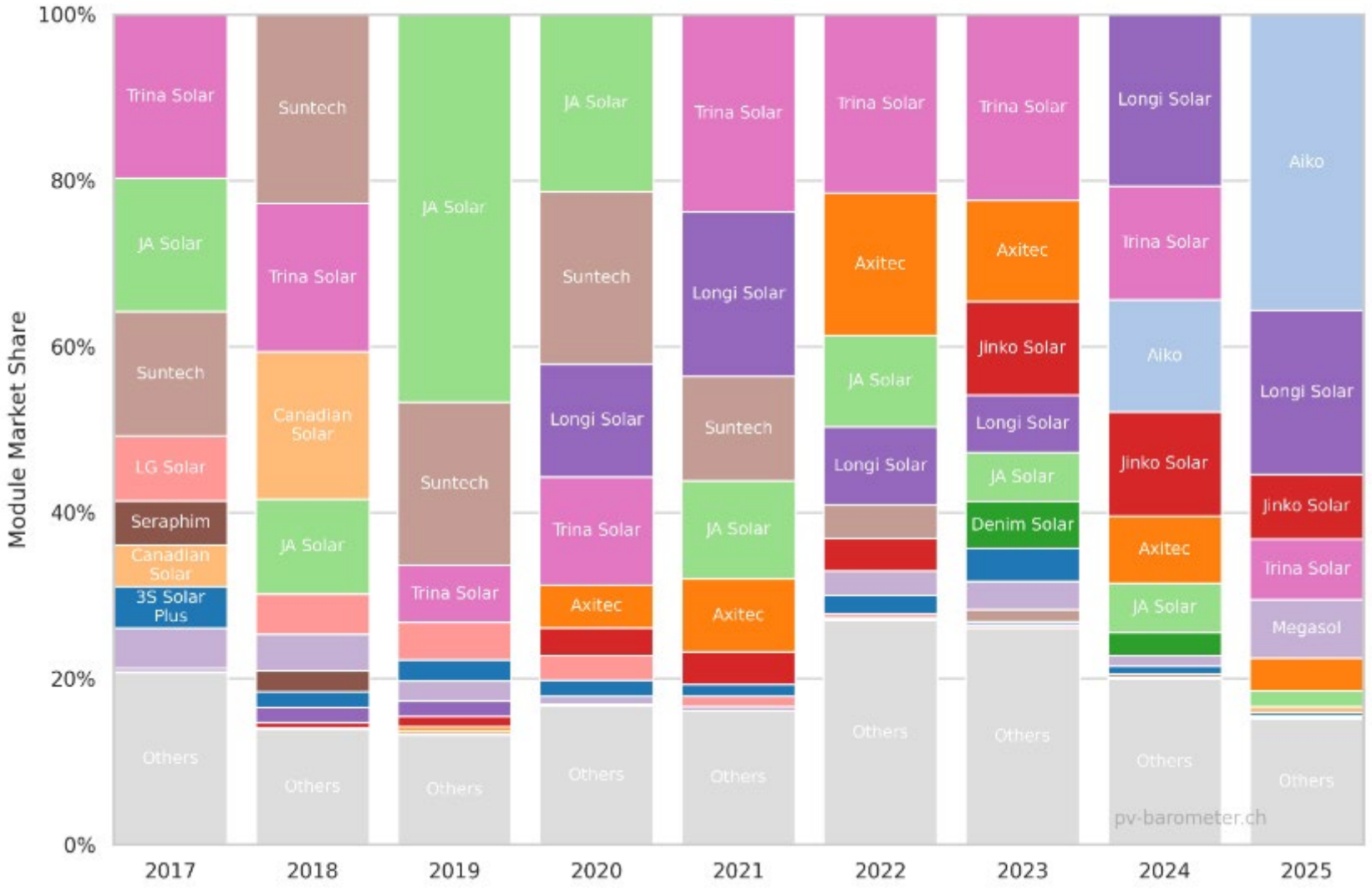


Photovoltaik Barometer 2026, Berner Fachhochschule, 31 March 2026

PV Modules: power & size



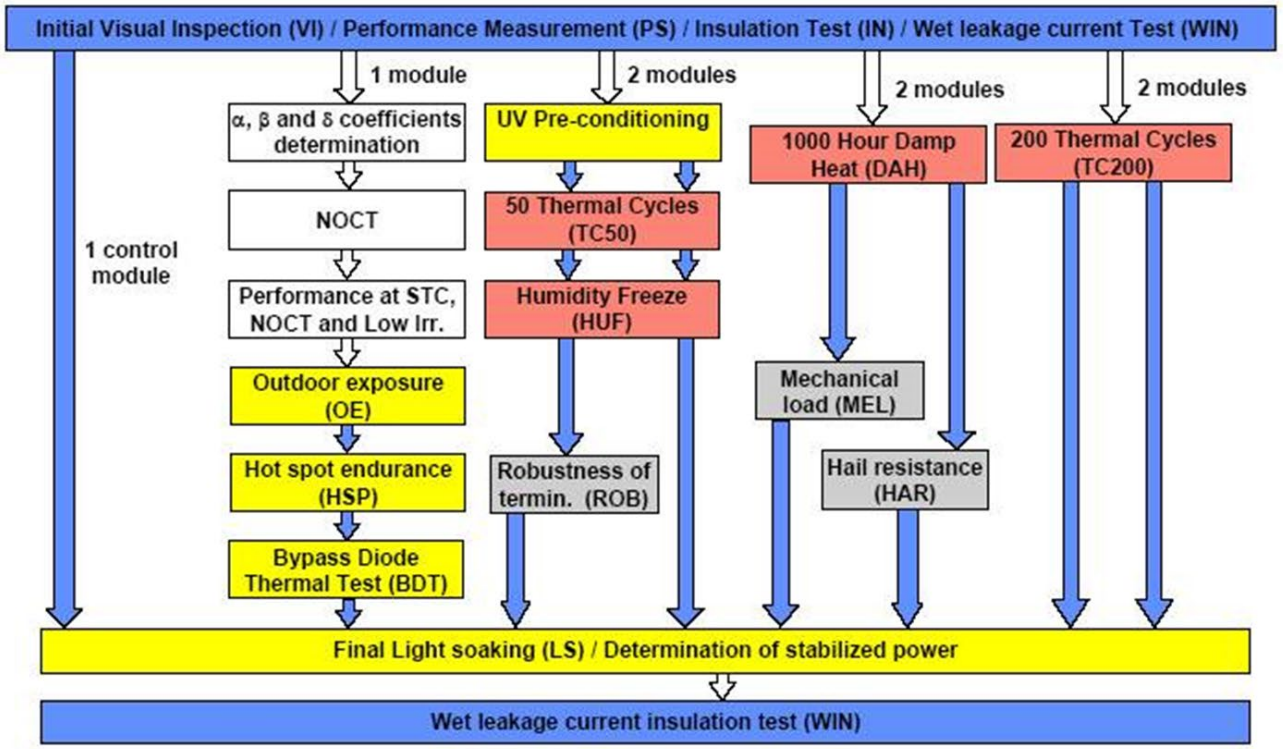
PV Modules: producers



Photovoltaik Barometer 2026

PV module certification

- IEC 61215: life-time testing for crystalline silicon PV
- IEC 61646: life-time testing for thin-film PV



Courtesy: A. Virtuani, SUPSI

- Accelerated life-time testing corresponds to ~20 years outdoor
- Typical warranty: 30 years for power, >20 years for product (as of 2025)
- Warranty ≠ Lifetime (PV module can serve for 30…40 years and more…)

PV systems

Ground mounted
- Utility scale

BAPV : Roof top (commercial, industrial, residential

BIPV: Roof & facade

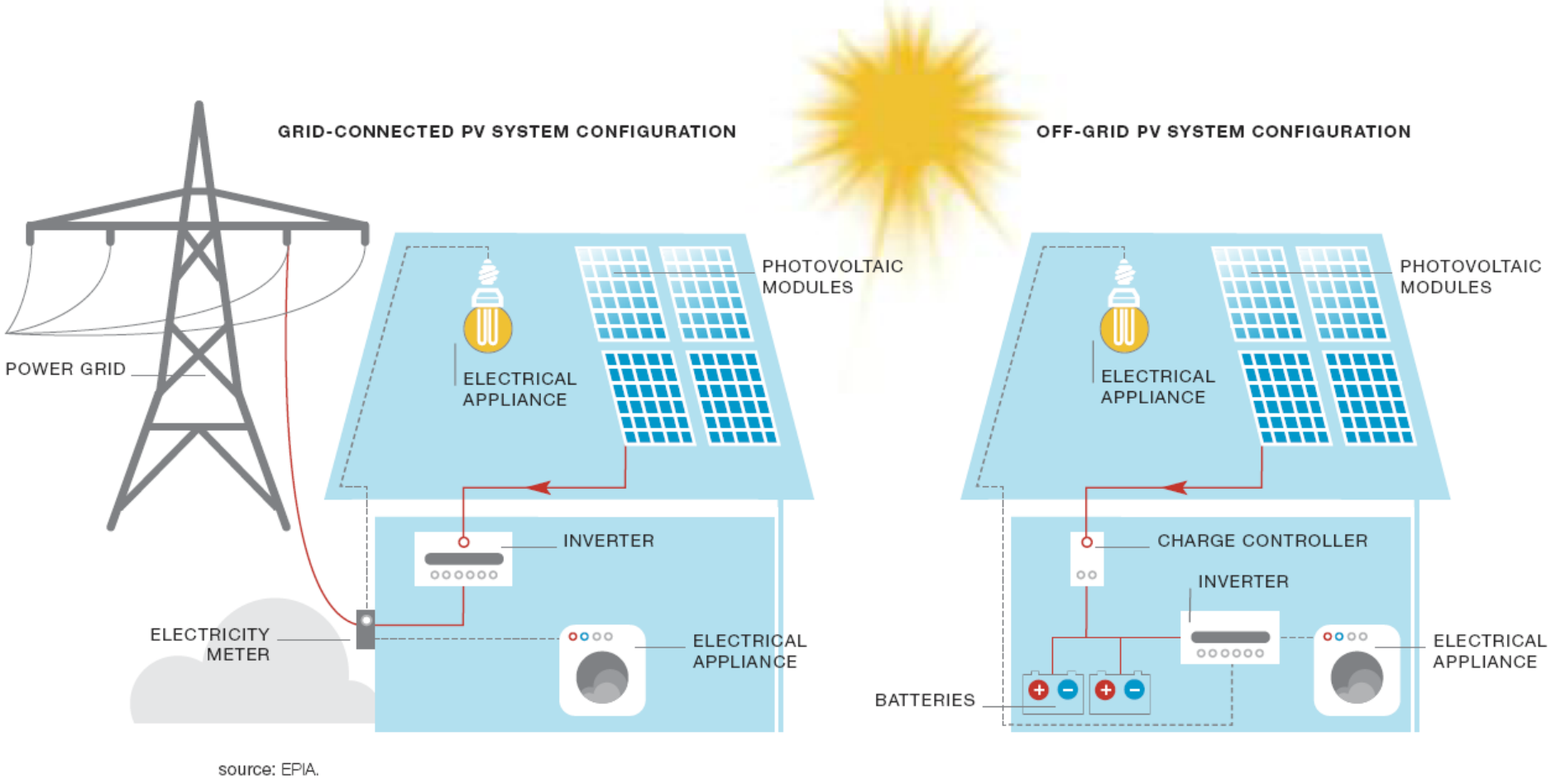
Agrivolatics

Floating

on vehicles, airships, space power,…

Pictures: from various web sites

PV systems



- PV systems components: PV modules, electricity meter; AC isolator, fusebox, inverter, charge controller, generation meter, DC isolator, cabling, mounting, etc….

Performance ratio (PR)

$$PR = \frac{Produced\ energy\ [kWh]}{Expected\ energy\ [kWh]} \times 100\%$$

$$PR = \frac{Actual\ energy\ [kWh]}{A\ [m^2] \times Eff\,[\%] \times Insolation\ [kWh/m^2]}$$

Depends on:

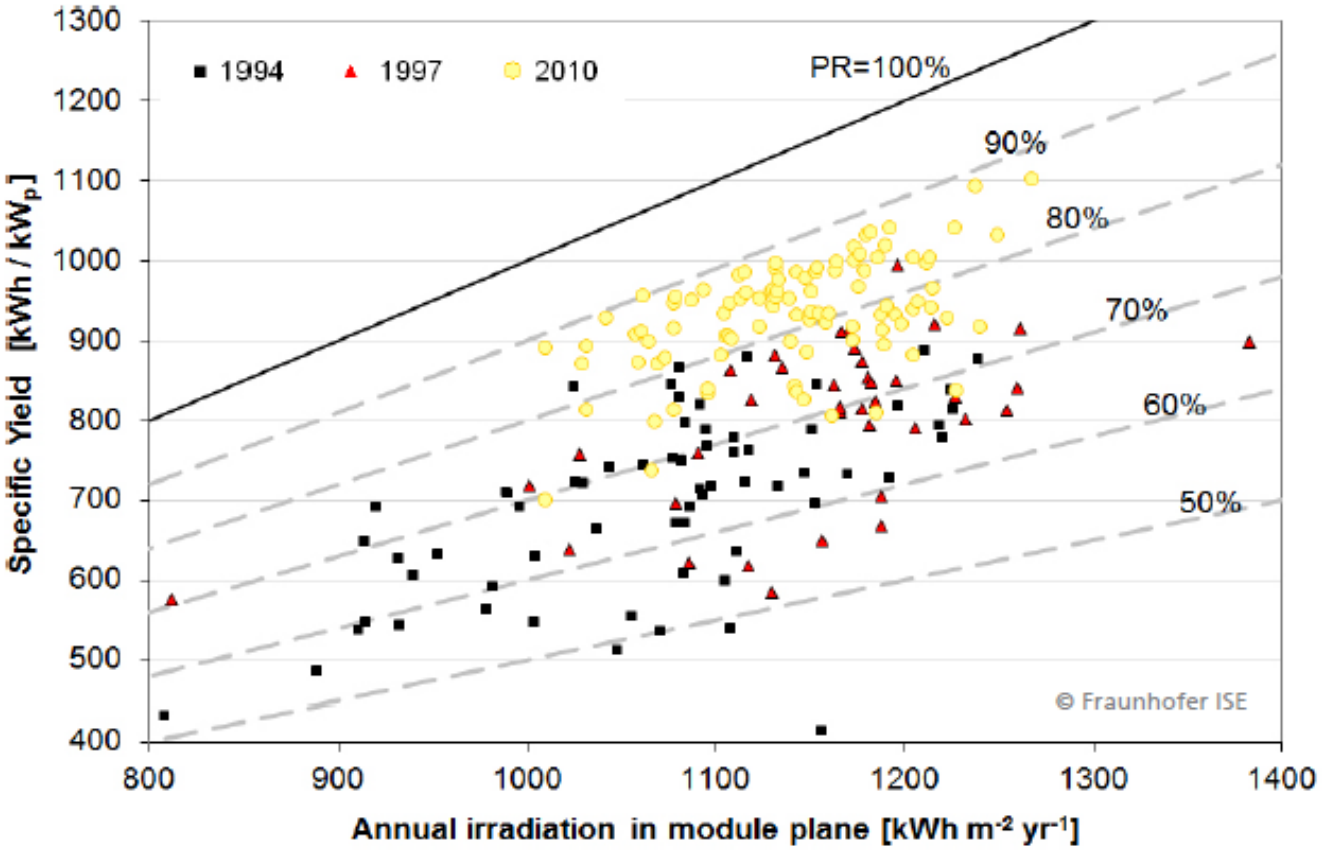
- Temperature of modules
- Shading of modules
- Shading of measurement unit
- Performances losses
- Efficiency of modules and inverters
- Wiring losses
- Mismatch

Does not depend on location, orientation or meteorological parameters

- => Quality measure for PV systems and PV plants

Performance Ratio Development for PV Systems

Germany



In the 1990's

- Typical PR ~70 %
- Widely ranging PR values

Today

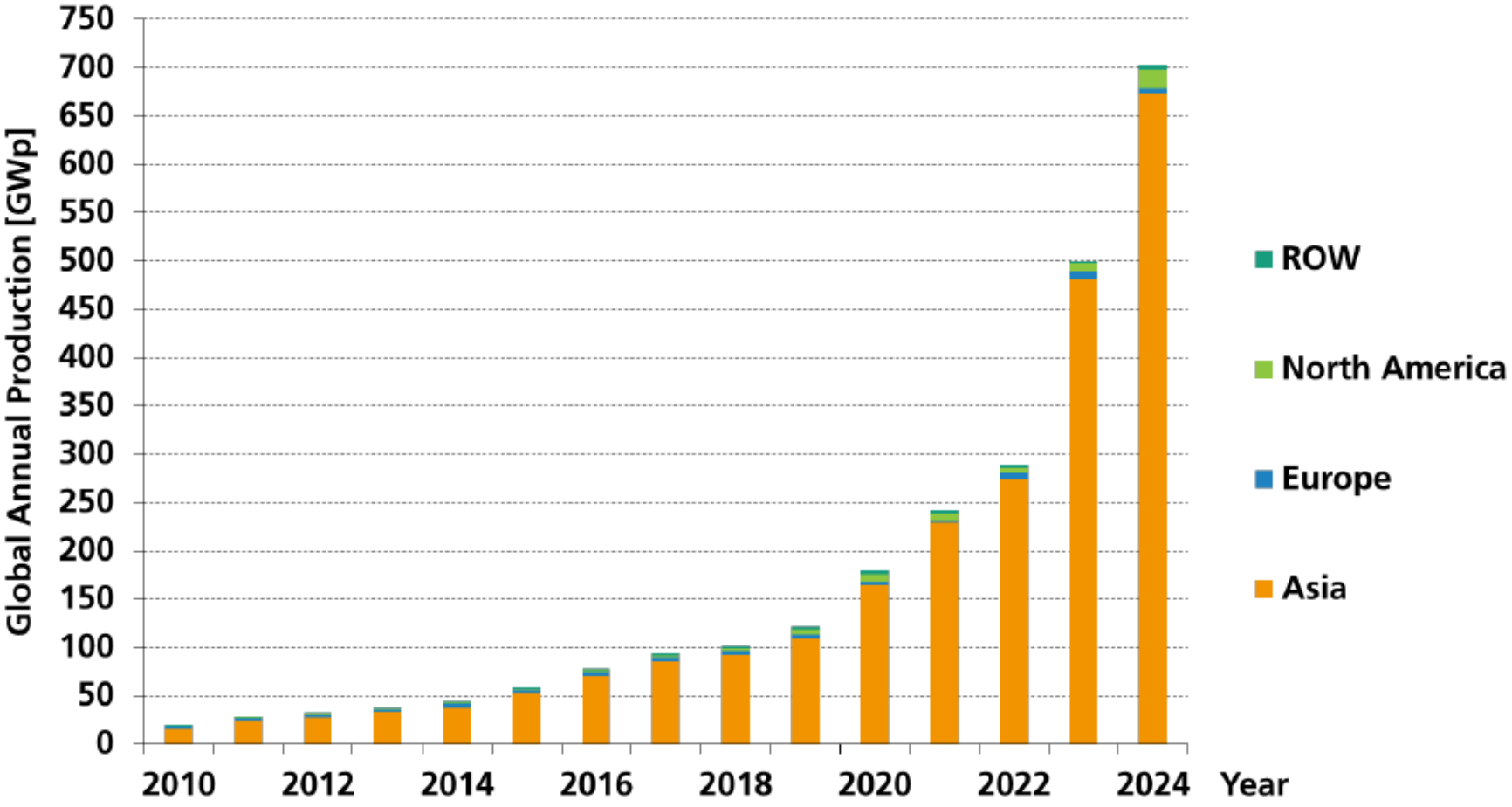
- Typical PR ~83 %
- Less variance in PR as compared to 1990's

Source: Photovoltaics report, ISE Fraunhofer, May 2024

PV economics

PV Module Production by Region

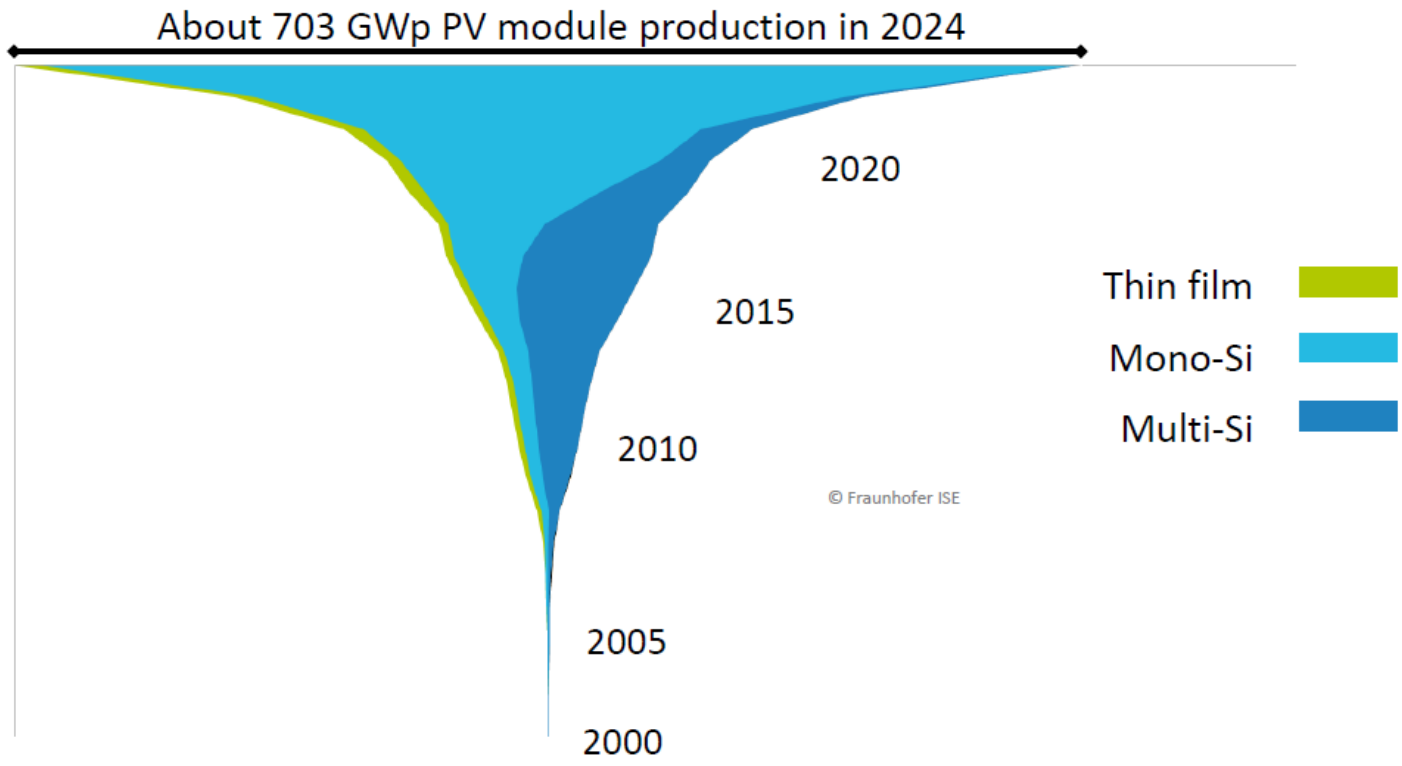
Global Annual Production



Source: Photovoltaics report, Fraunhofer Institute ISE, May 2025

Annual PV Production by Technology

Worldwide (in GWp)

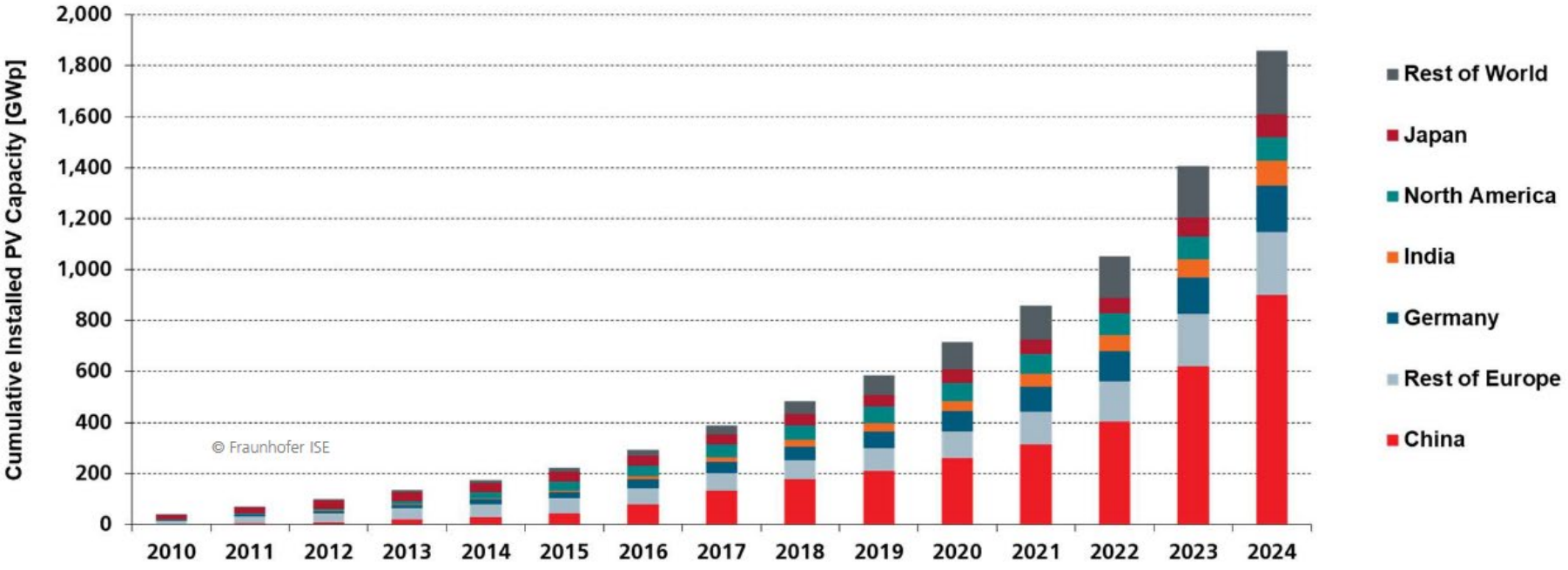


Source: Photovoltaics report, ISE Fraunhofer, May 2025

Global PV installations

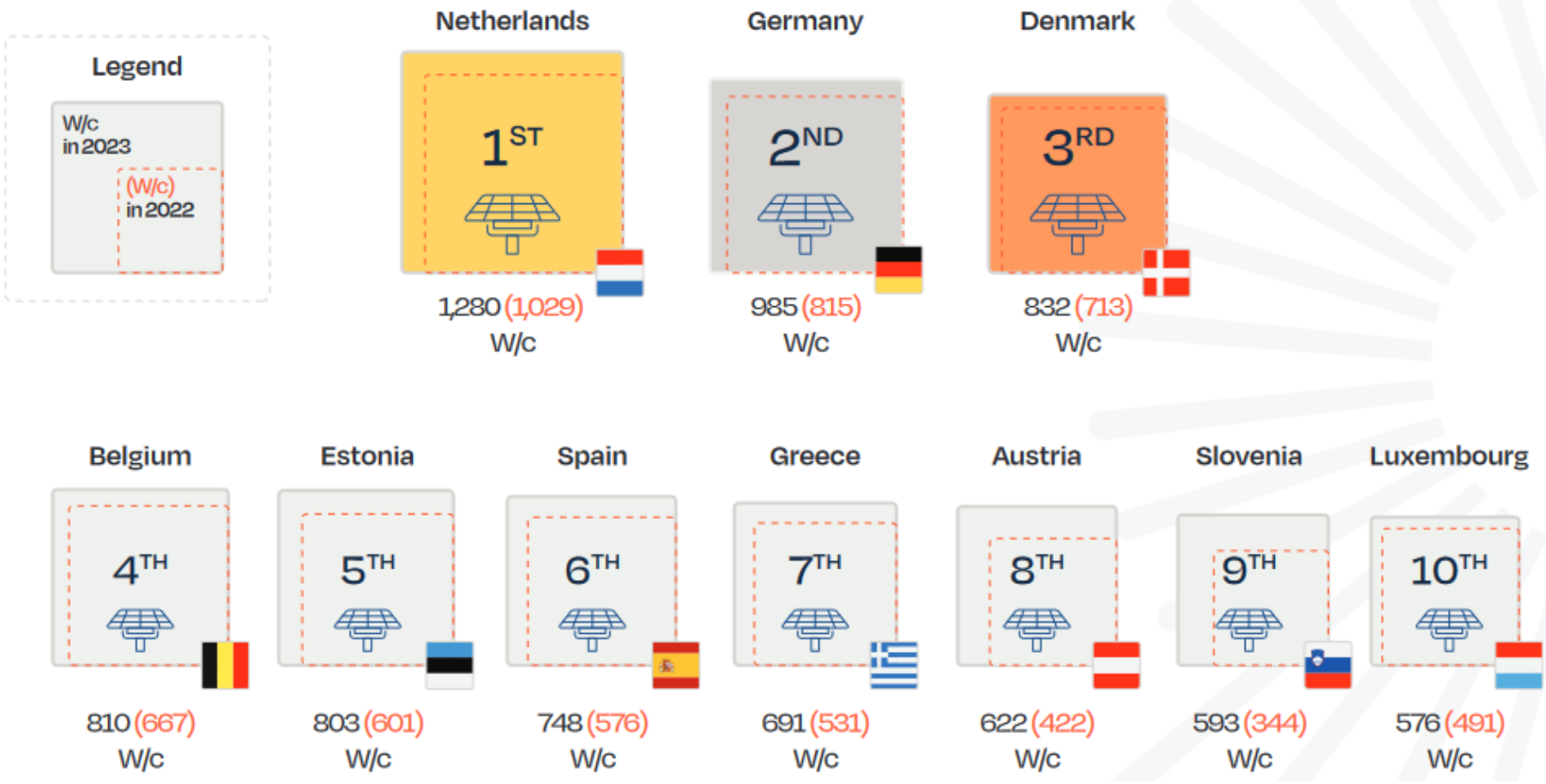
Global Cumulative PV Installation

By Region



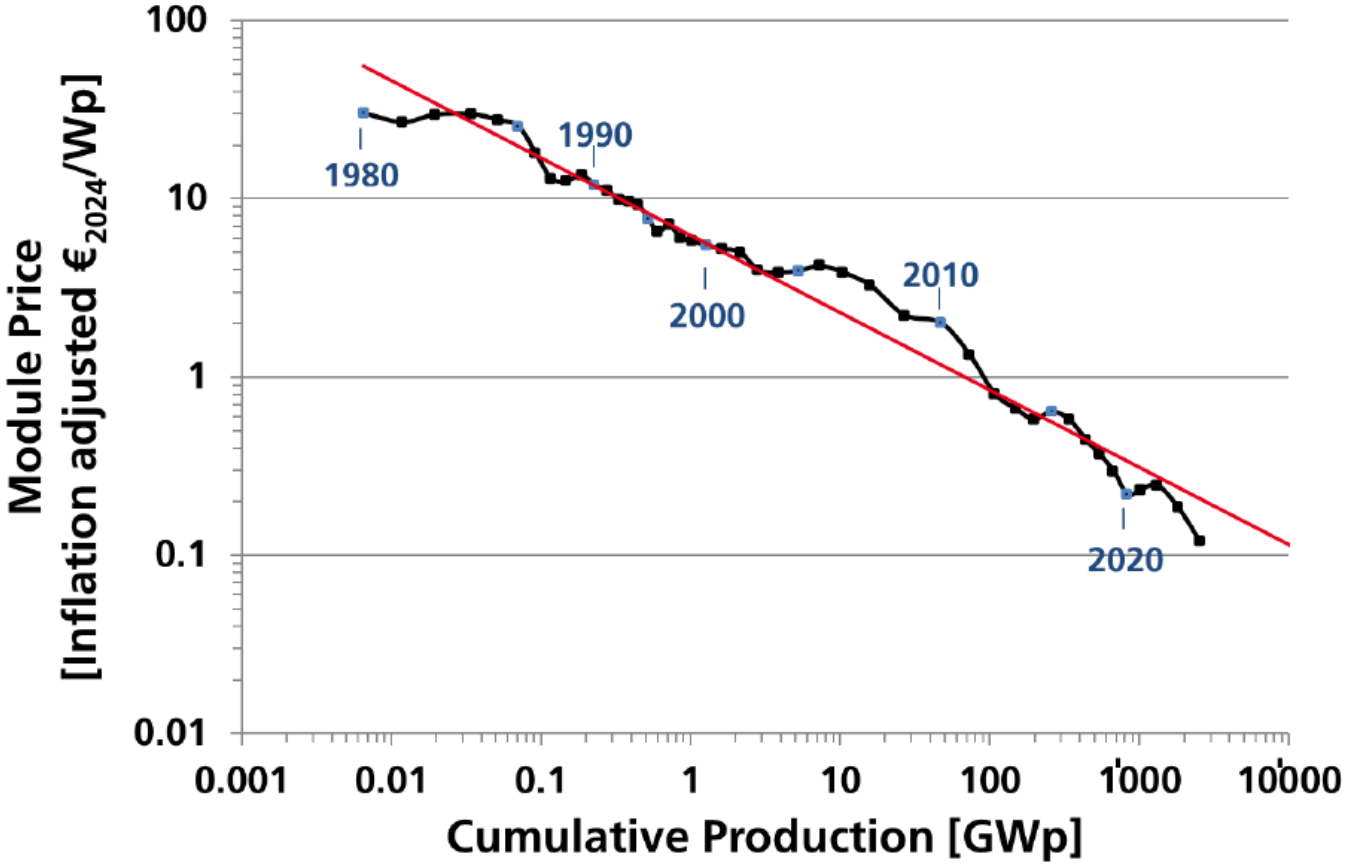
Source: Photovoltaics report, Fraunhofer Institute ISE, Oct 2025

Top 10 countries by PV per capita



Source: SolarPower Europe 2023

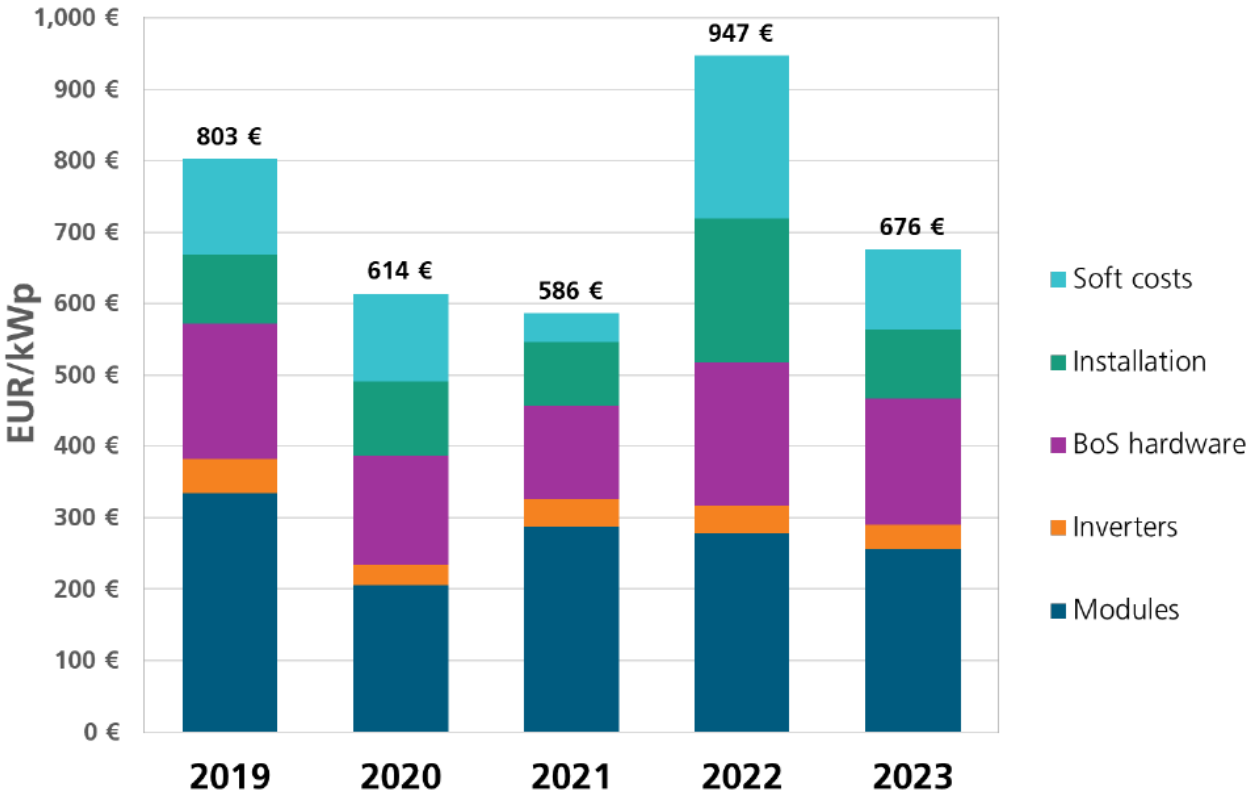
PV module price (all techs)

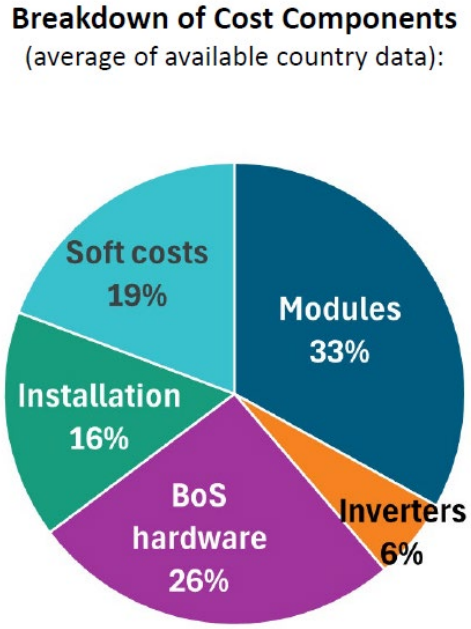


Source: Photovoltaics report, Fraunhofer ISE, May 2025

- Price of PV modules falls by ~25% upon doubling capacity (last 44 years)

PV system cost structure
(Utility-scale PV systems in Germany, 2019-2023)





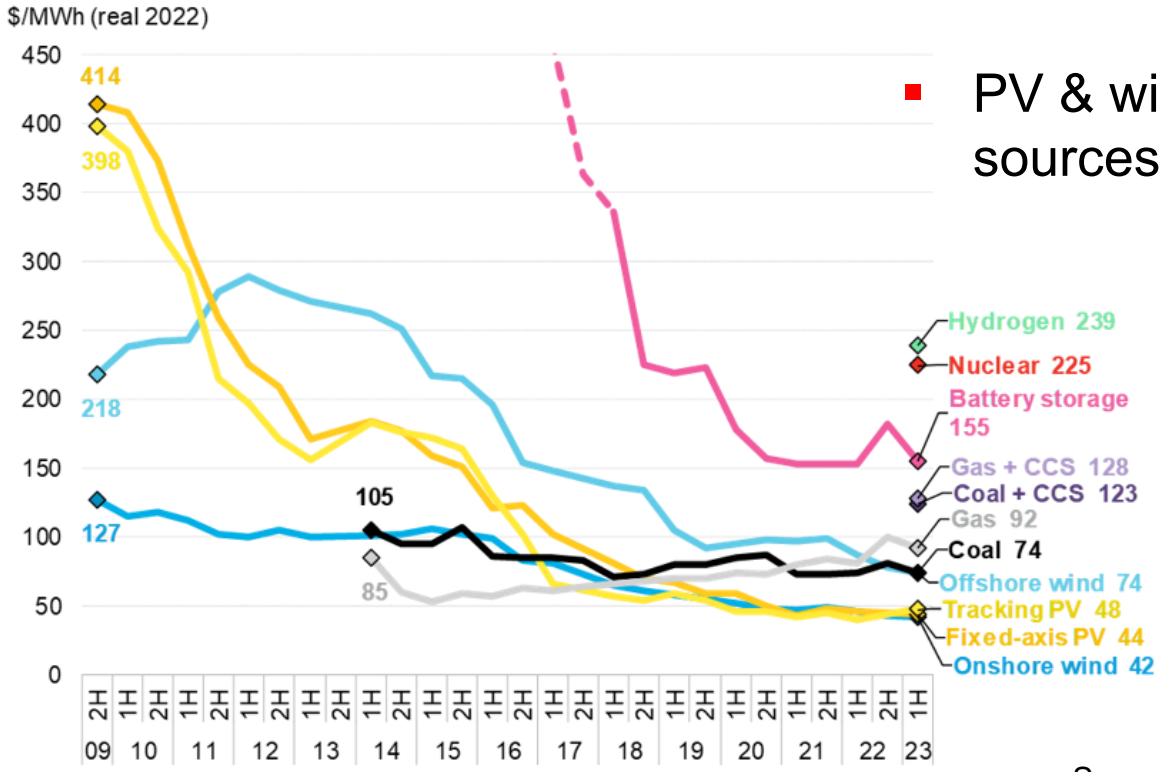
Photovoltaics report, Fraunhofer ISE, May 2025

- PV modules = 33% of the total PV system cost!

Levelized cost of electricity (LCOE)

LCOE - average net cost of electricity generation for a generator over its lifetime (incl. system costs, installation, maintenance, degradation, financing, subventions,..)

Figure 1: Global levelized cost of electricity benchmarks, 2009-2023

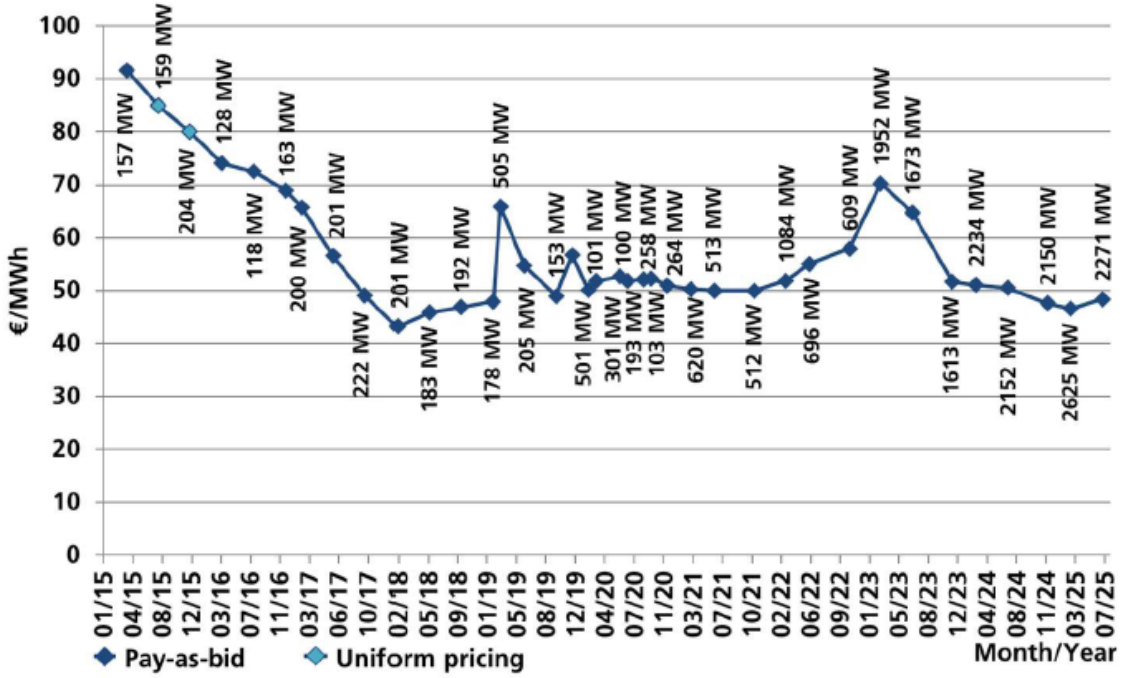


- PV & wind became the cheapest sources of electricity since 2020

Source: BloombergNEF, June 2023

PV Tender Scheme in Germany for Free-Standing Systems

Average, quantity weighted award value



Data: BNA. Graph: PSE Projects GmbH 2025 – Date of data: 08/2025

- The PV tender scheme for large ground-mounted systems started in April 2015. The total capacity of this scheme amounted to 21.8 GW in December 2024 with 4.76 ct€ / kWh as latest average quantity weighted award price.
- PV-rooftop and special tenders are not displayed in the graph.

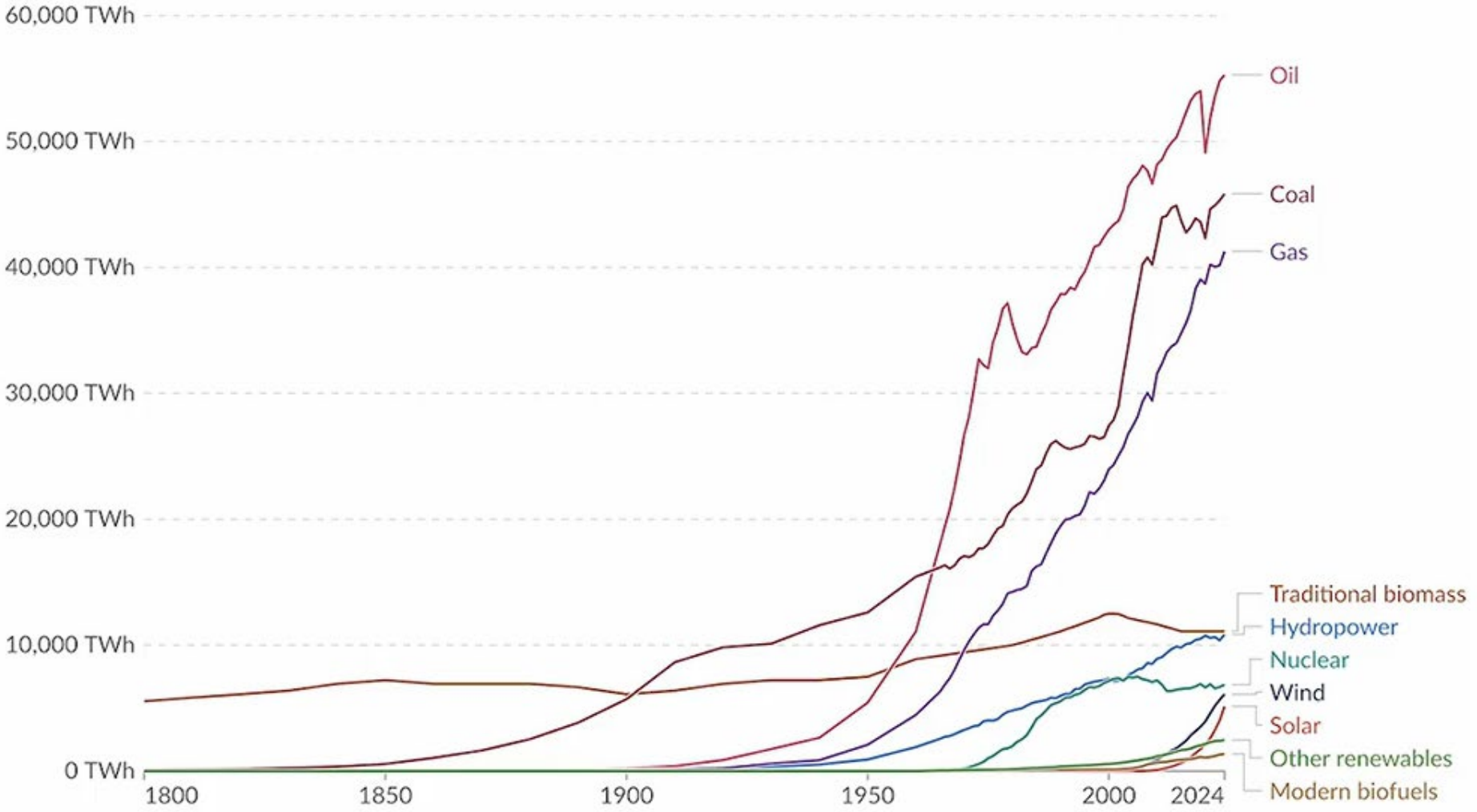
Source: Photovoltaics report, Fraunhofer ISE, 2025

- PV tender price is **5 ct€ / kWh** (Germany, 2025)

Global primary energy consumption by source

Our World in Data

Primary energy[1] consumption is measured in terawatt-hours[2], using the substitution method[3].



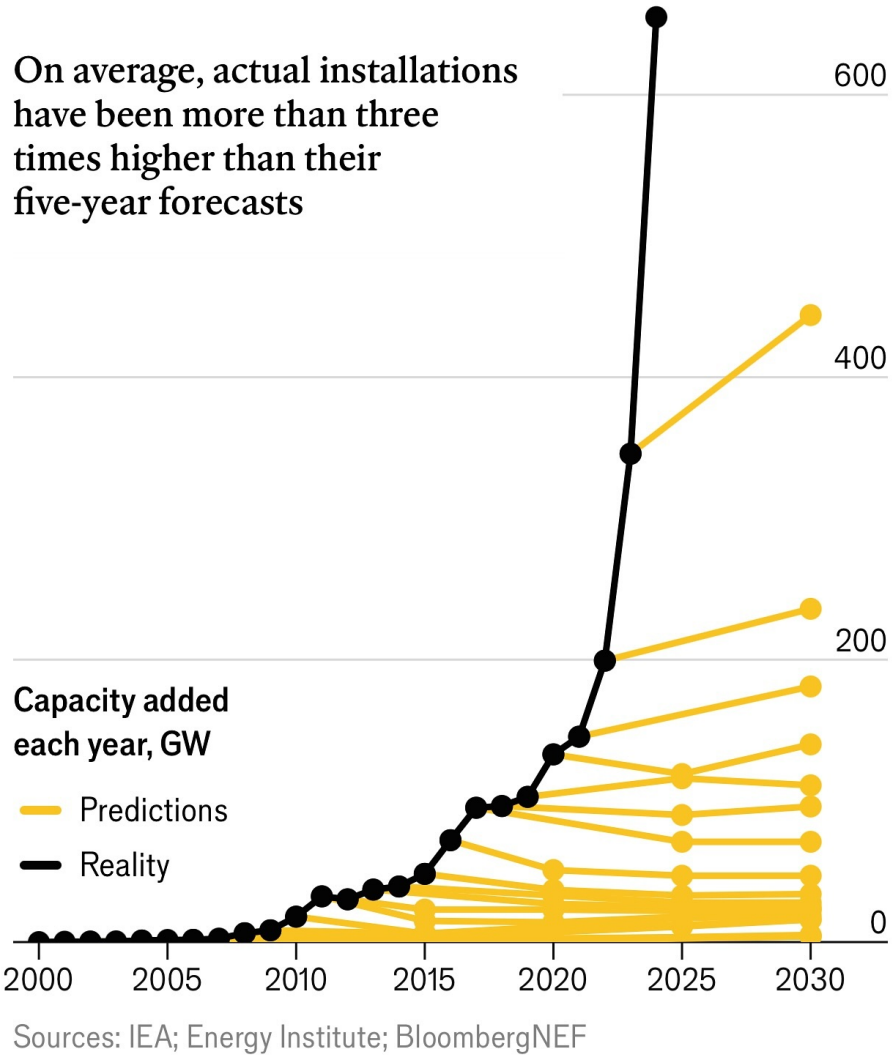
Data source: Energy Institute - Statistical Review of World Energy (2025); Smil (2017)

OurWorldinData.org/energy | CC BY

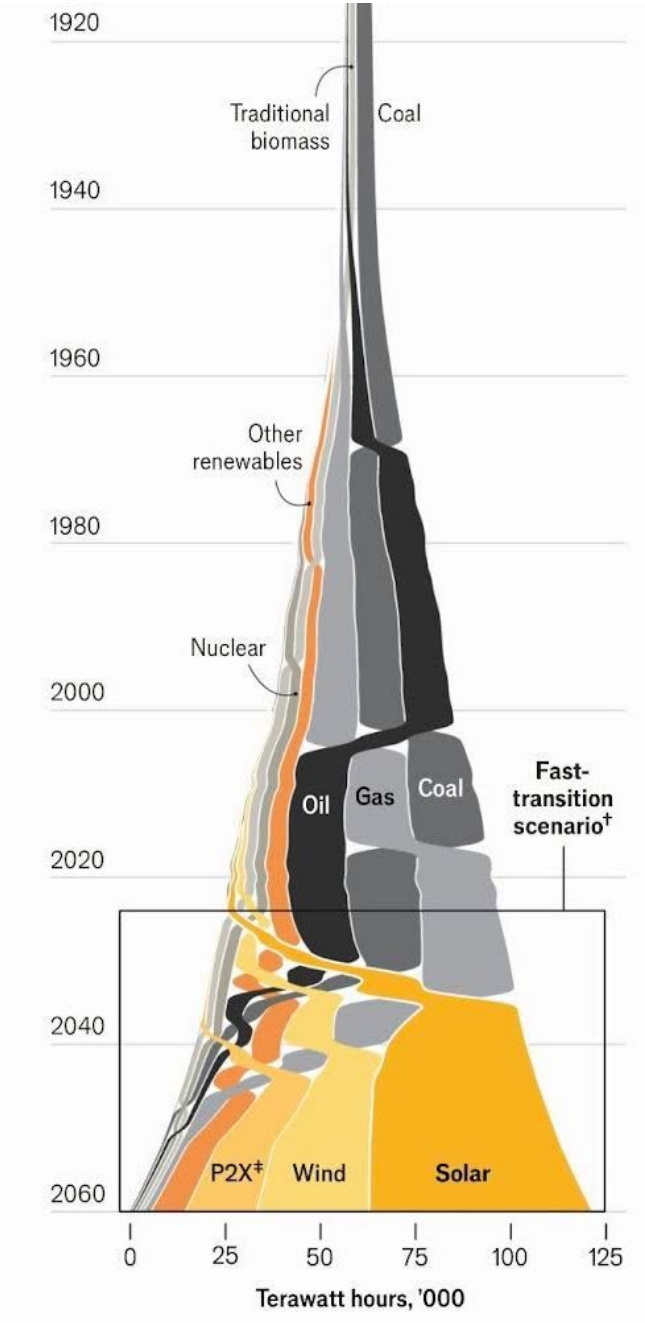
Note: In the absence of more recent data, traditional biomass is assumed constant since 2015.

↓ EASY PV

how solar outgrew expectations



Sources: IEA; Energy Institute; BloombergNEF

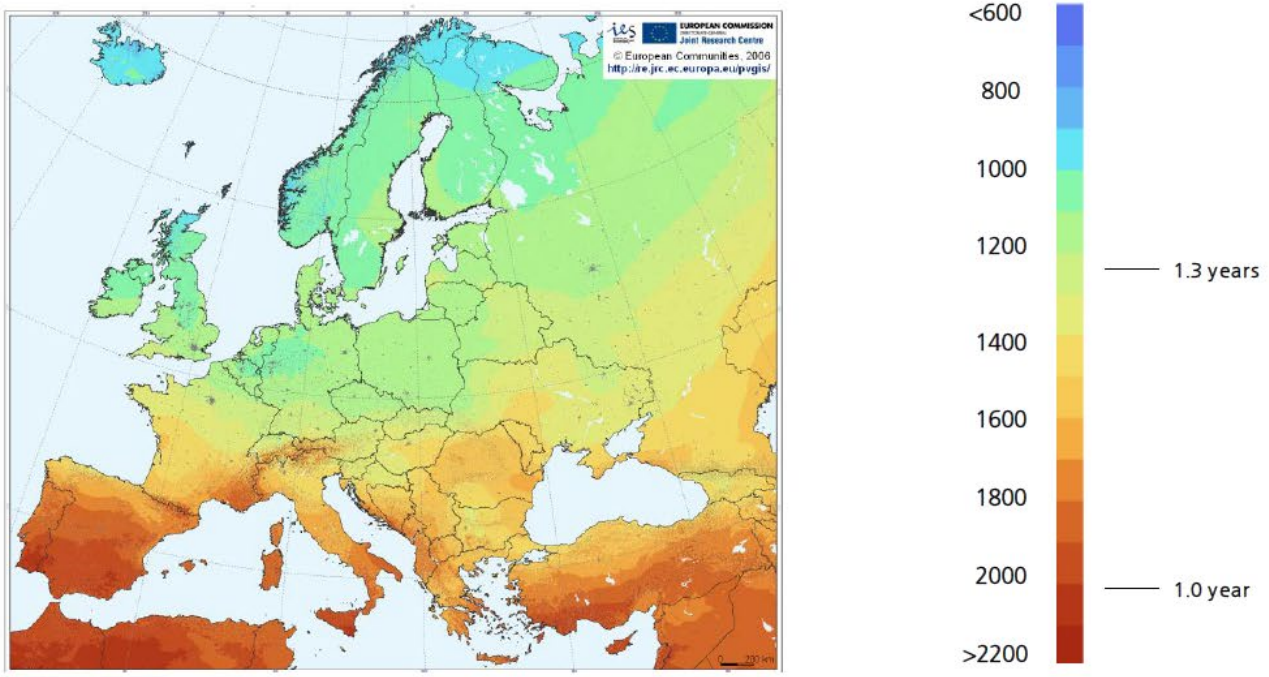


«Sun Machines», The Economist, 2024

Energy payback time (EPBT)

$$EPBT = \frac{E_{input}}{E_{output}/year}$$

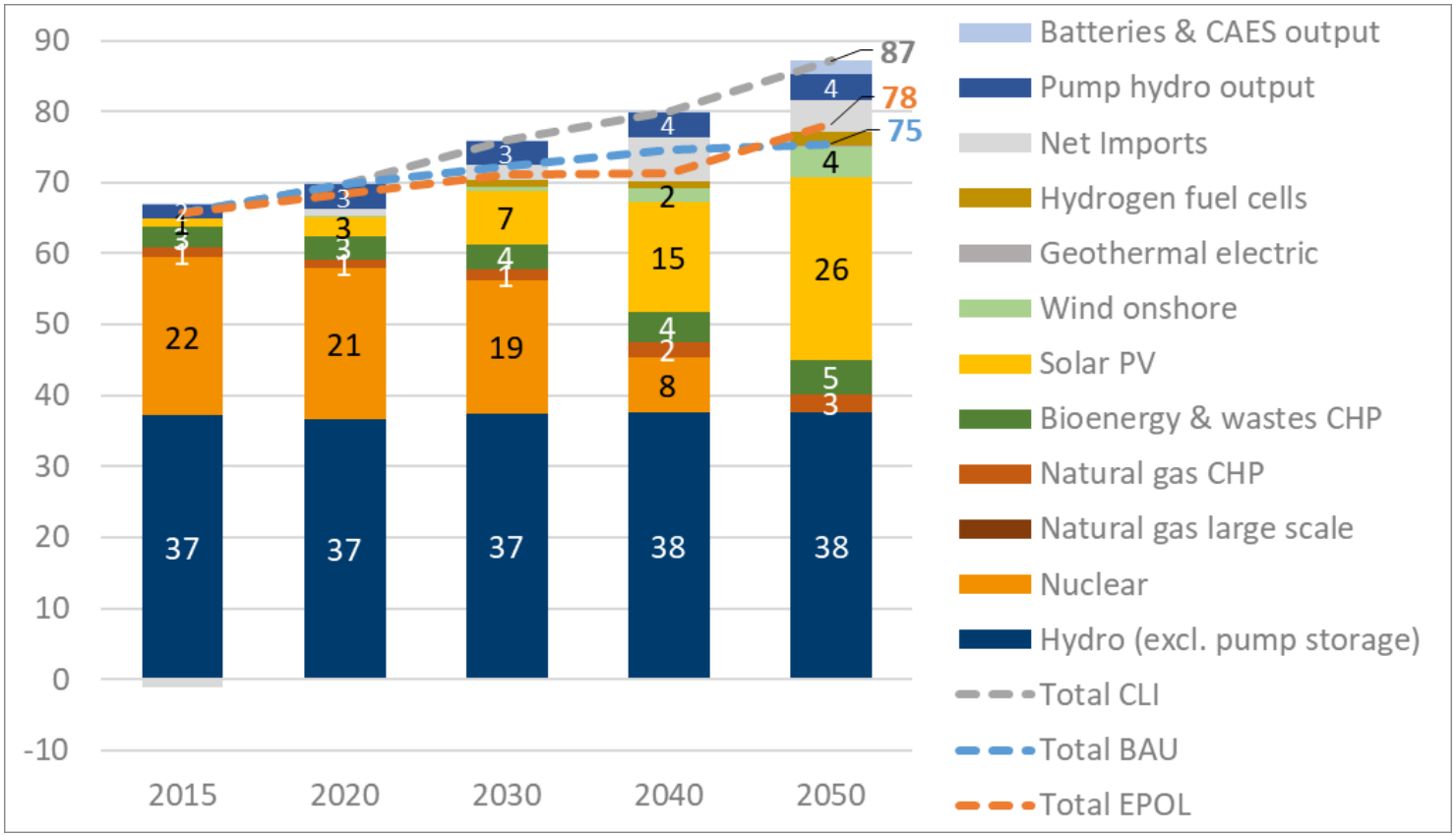
- Rooftop PV-system using mono-crystalline Silicon cells* produced in China
- EPBT is dependent on irradiation, but also on other factors like grid efficiency**.
- Better grid efficiency in Europe may decrease the EPBT by typically 9.5 % compared to PV modules produced in China.



Photovoltaics report, ISE Fraunhofer, may 2024

- 1 year to generate equivalent amount of energy that was used for manufacturing PV modules (depends on technology and location)

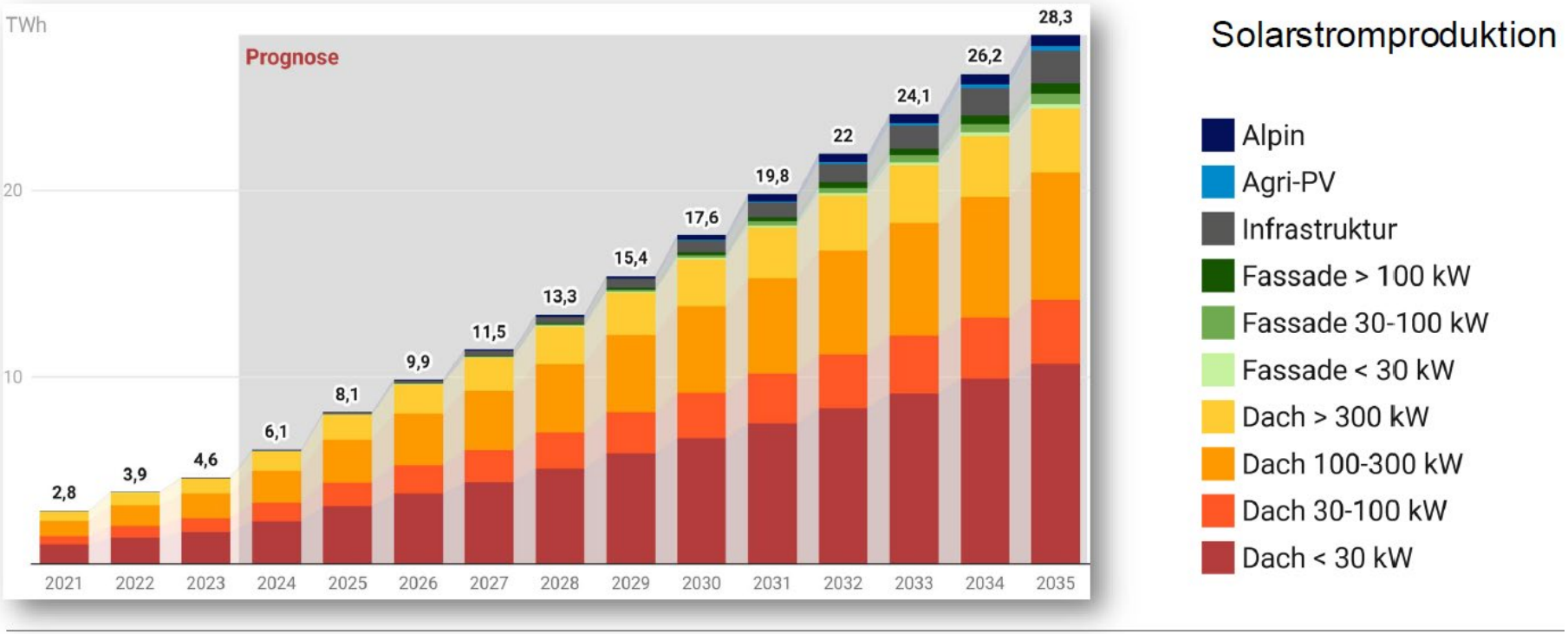
Swiss Energy Strategy 2050



Electricity supply mix in the CLI scenario, TWh/a
Source: “Transformation of the Swiss Energy System for a Net-Zero Greenhouse Gas Emission Society”, ETH Zürich, 2021

- PV is predicted to become the 2nd pillar for energy production in CH by 2050

PV in Switzerland



10 TWh
will be produced by PV in 2026

17%
of electricity consumption in 2026 come from PV