Part 1.2 PV modules, systems & economics

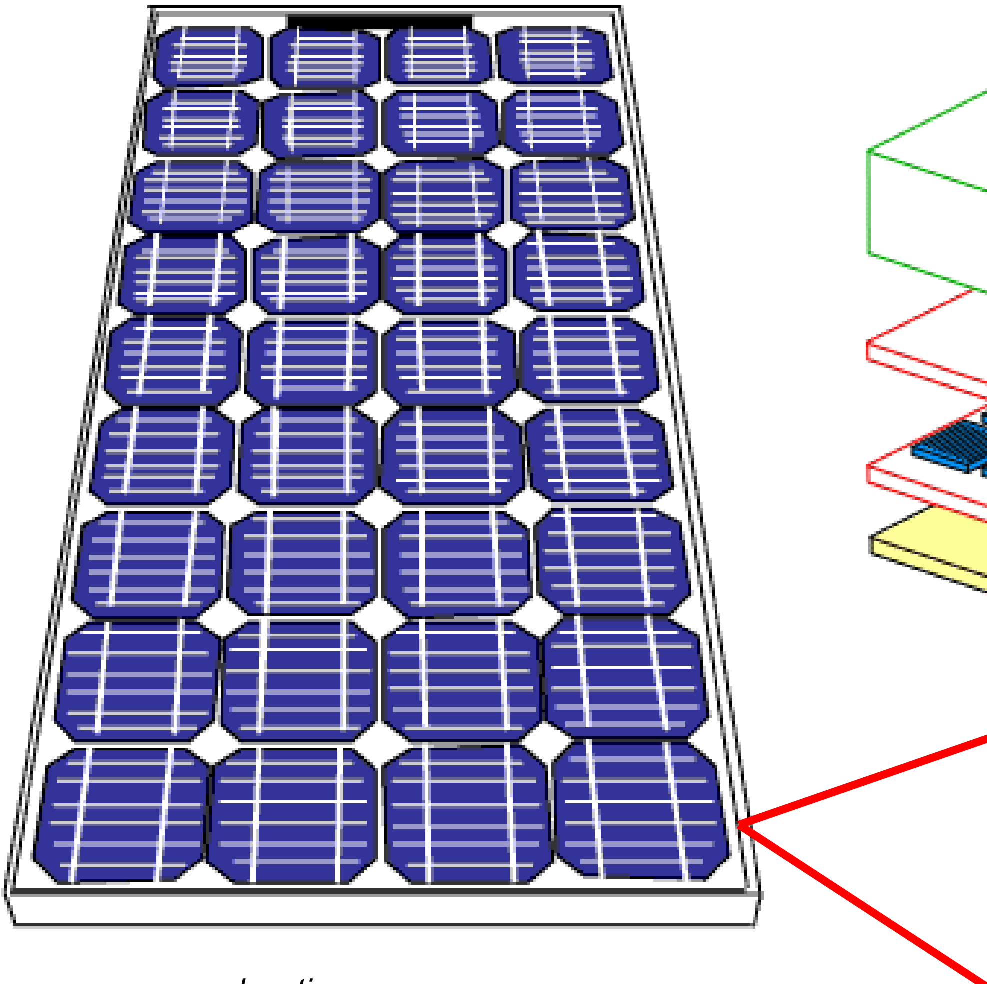
- PV modules
- PV systems
- PV economics

Dr. Yaroslav Romanyuk
Laboratory for Thin films and Photovoltaics
Empa – Swiss Federal Laboratories for Materials Science and Technology
yaroslav.romanyuk@empa.ch

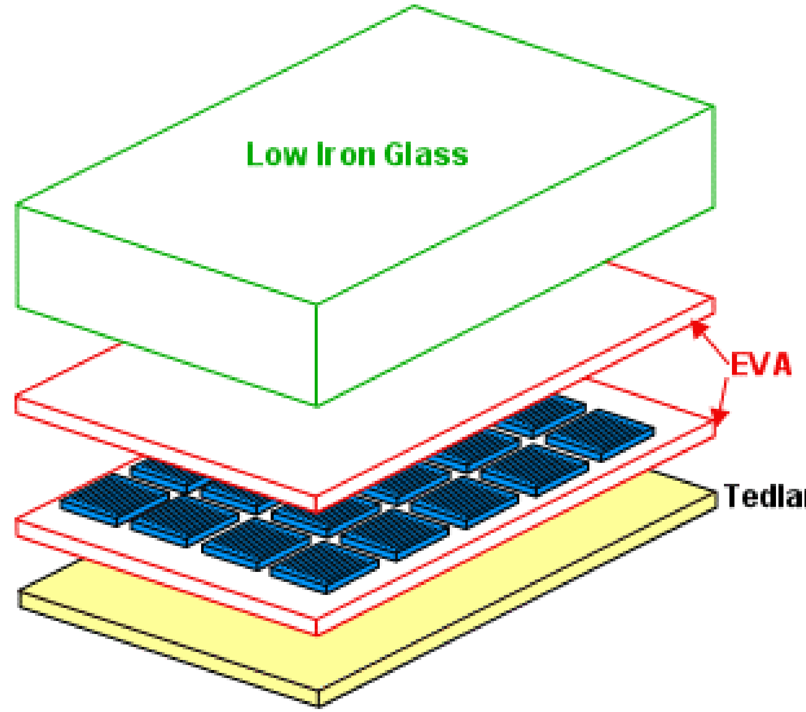
Empa
Materials Science and Technology

PV modules

PV modules (example c-Si)



www.pveducation.org



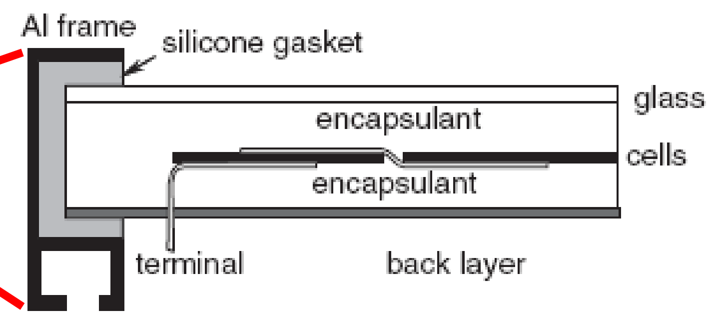
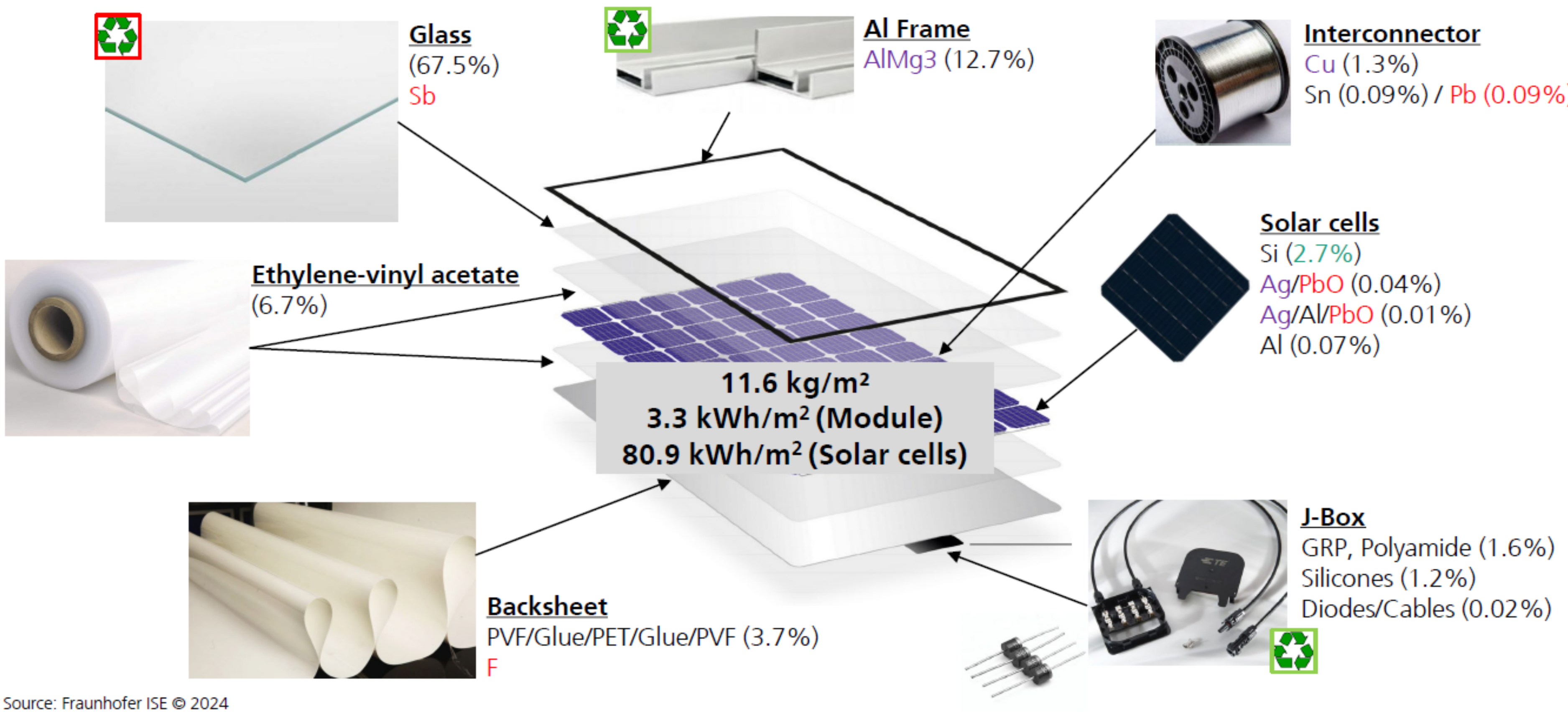


Figure 7.19 Cross- section of a standard module

Handbook of Photovoltaic Science and Engineering, 2011

PV module materials

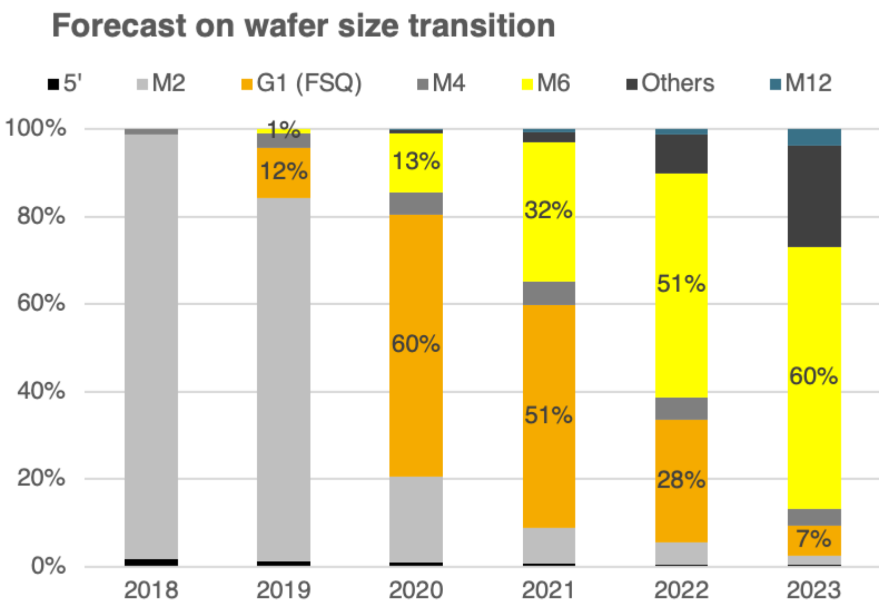


Source: Fraunhofer ISE © 2024

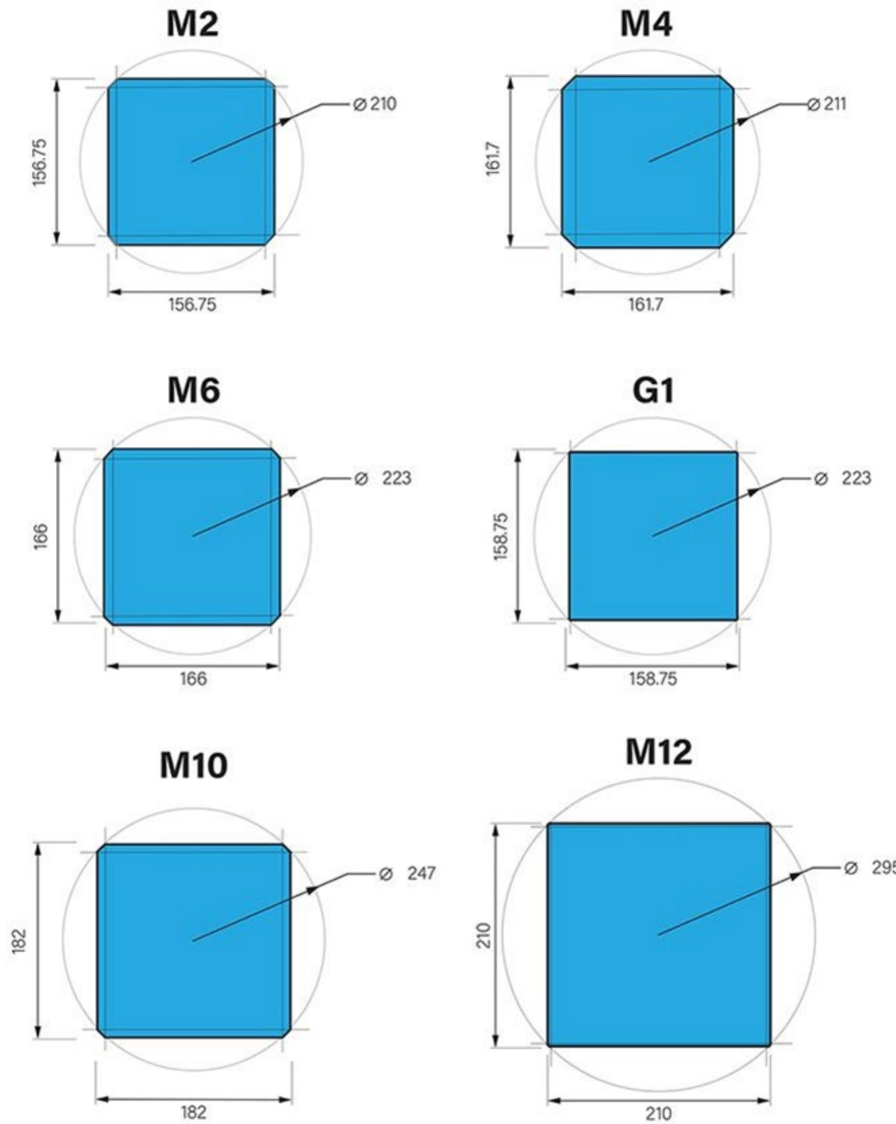
Color legend:
Available/harmless materials
Rare/valuable materials
Hazardous substances
Recycling takes place
Downcycling takes place

Si wafer generations

- ~2020: Rapid transition
  - Larger wafer sizes

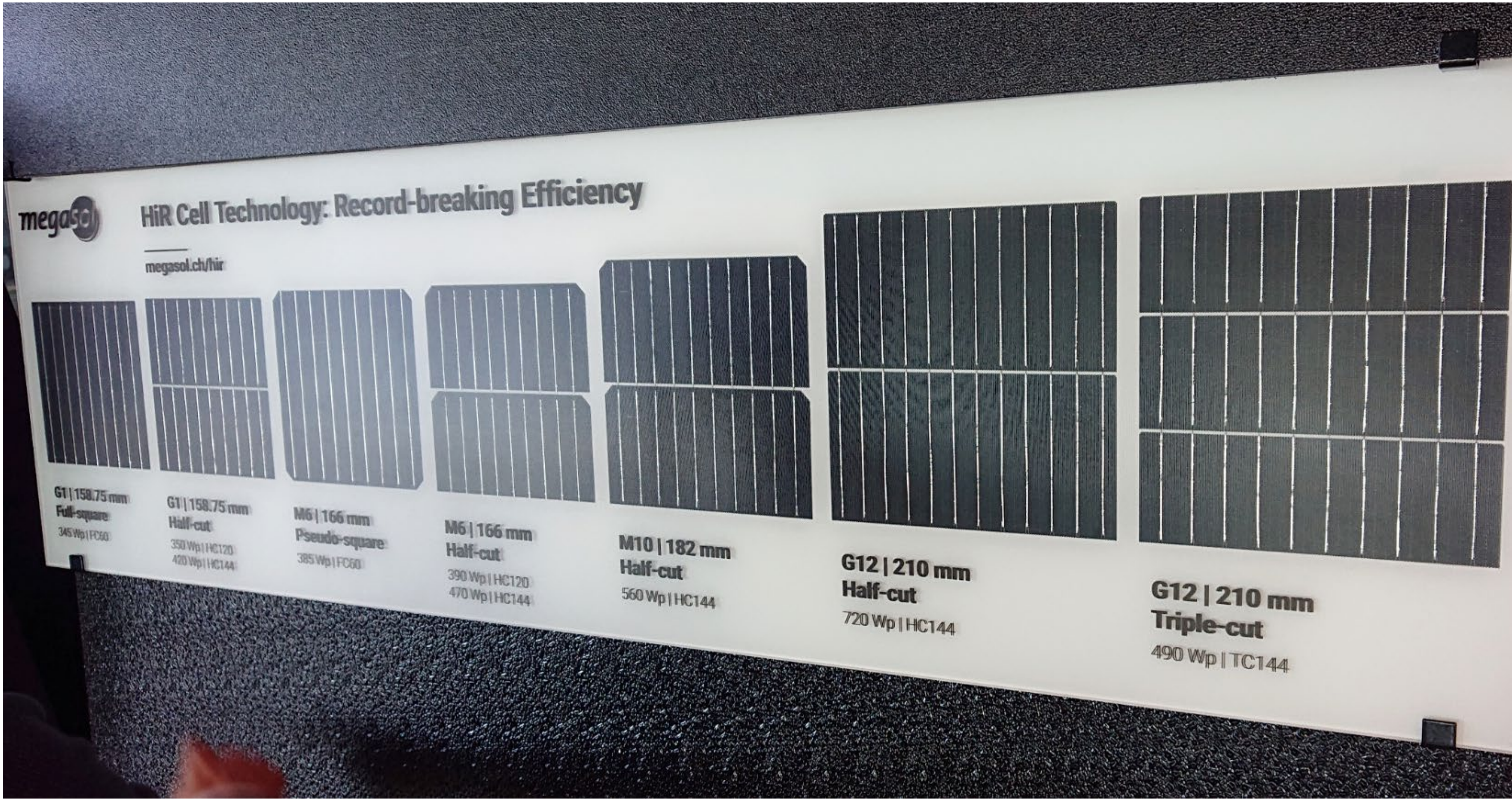


Forecast PV Infolink
https://www.infolink-group.com/en/solar/analysis-trends/Wafer-trends-for-2020-Transitioning-to-larger-size



https://www.dsneg.com/info/bigger-wafers-half-cut-technology-multi-bus-62643057.html

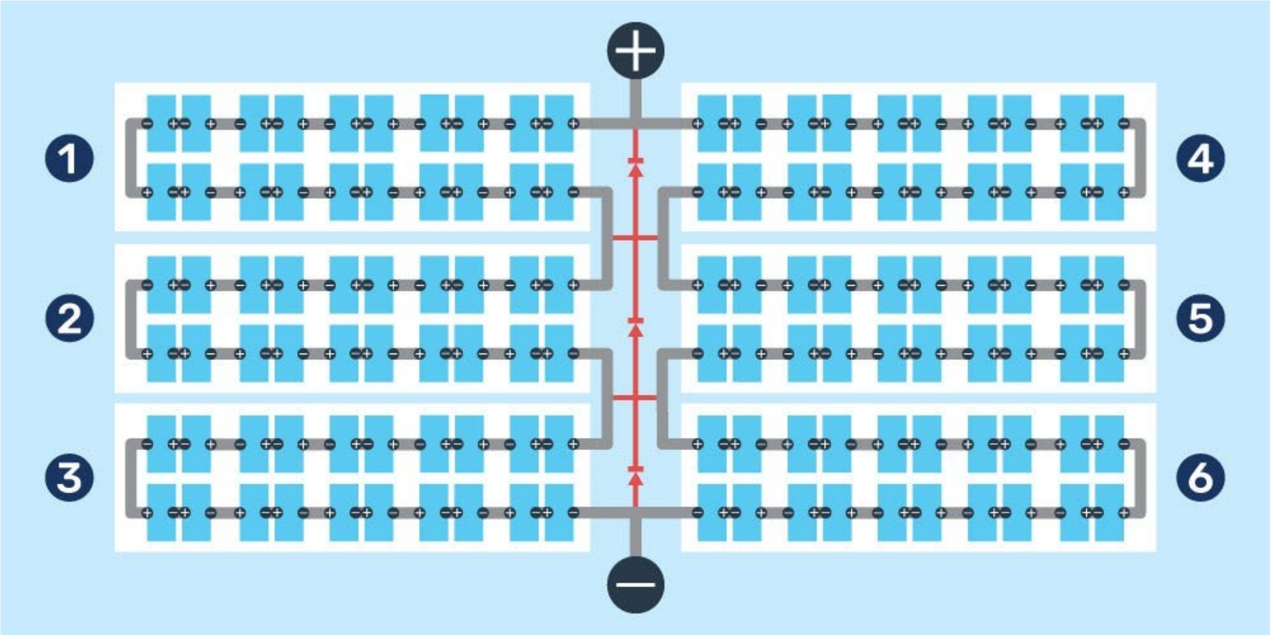
Half-cut and triple-cut cells



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)

Half-cell modules



https://www.solarreviews.com/blog/half-cut-solar-cell-technology-explained

- 120 or 144 half-cells
- 6 strings of cells
- 3 bypass diodes
- Power > 250…380 W

Advantages:

- higher shade tolerance & reduced hot spot effects
- reduced power loss by reducing internal resistance
- offer a higher wattage than old 250 W panels

- BUT more expensive because require more soldering steps and laser cutting

PV modules with monolithic interconnection

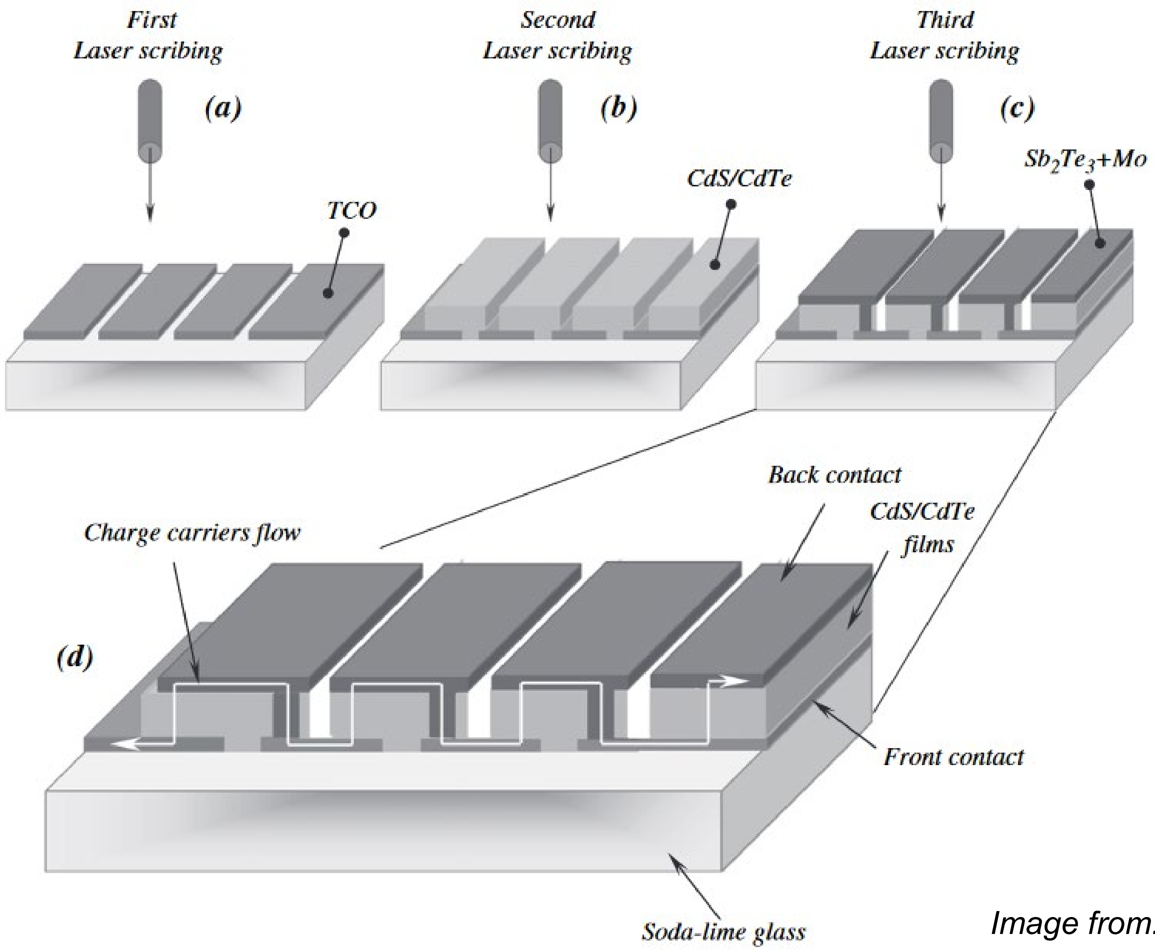
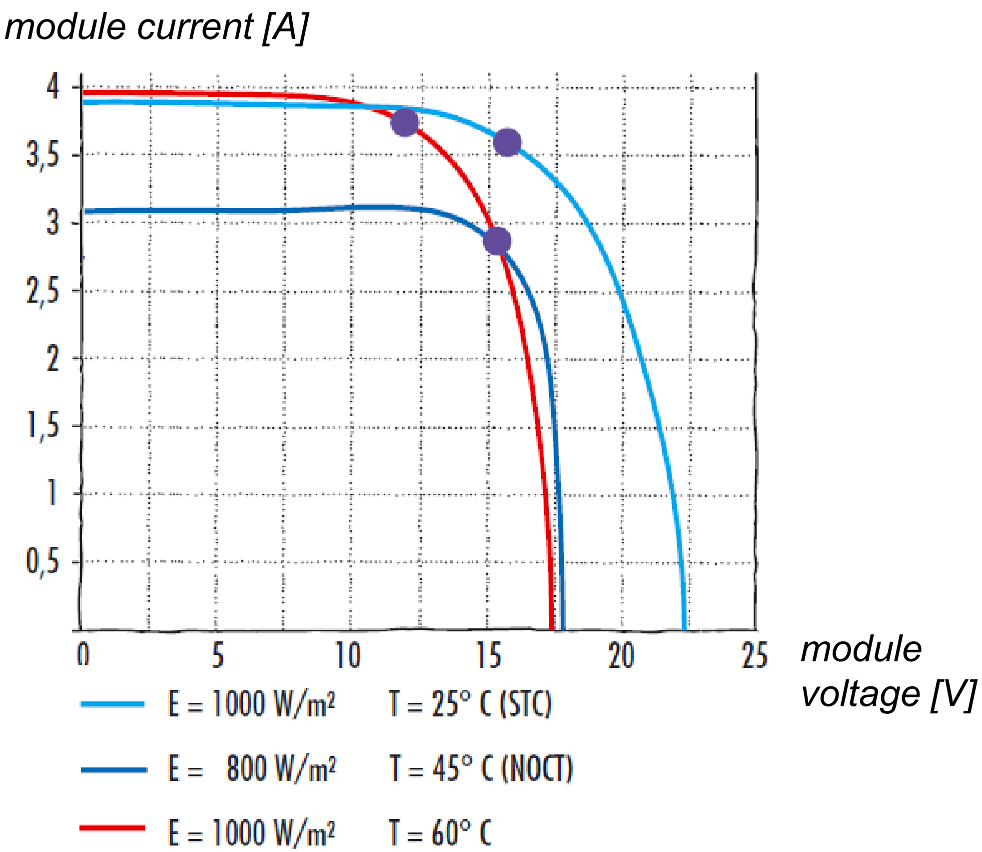


Image from: A. Bosio et al., PIP 2006

- Typical for thin-film techs on insulating substrates: CdTe, CIGS, a-Si, perovskites
- Patterning is performed by mechanical or laser scribing between deposition steps

Module characteristics



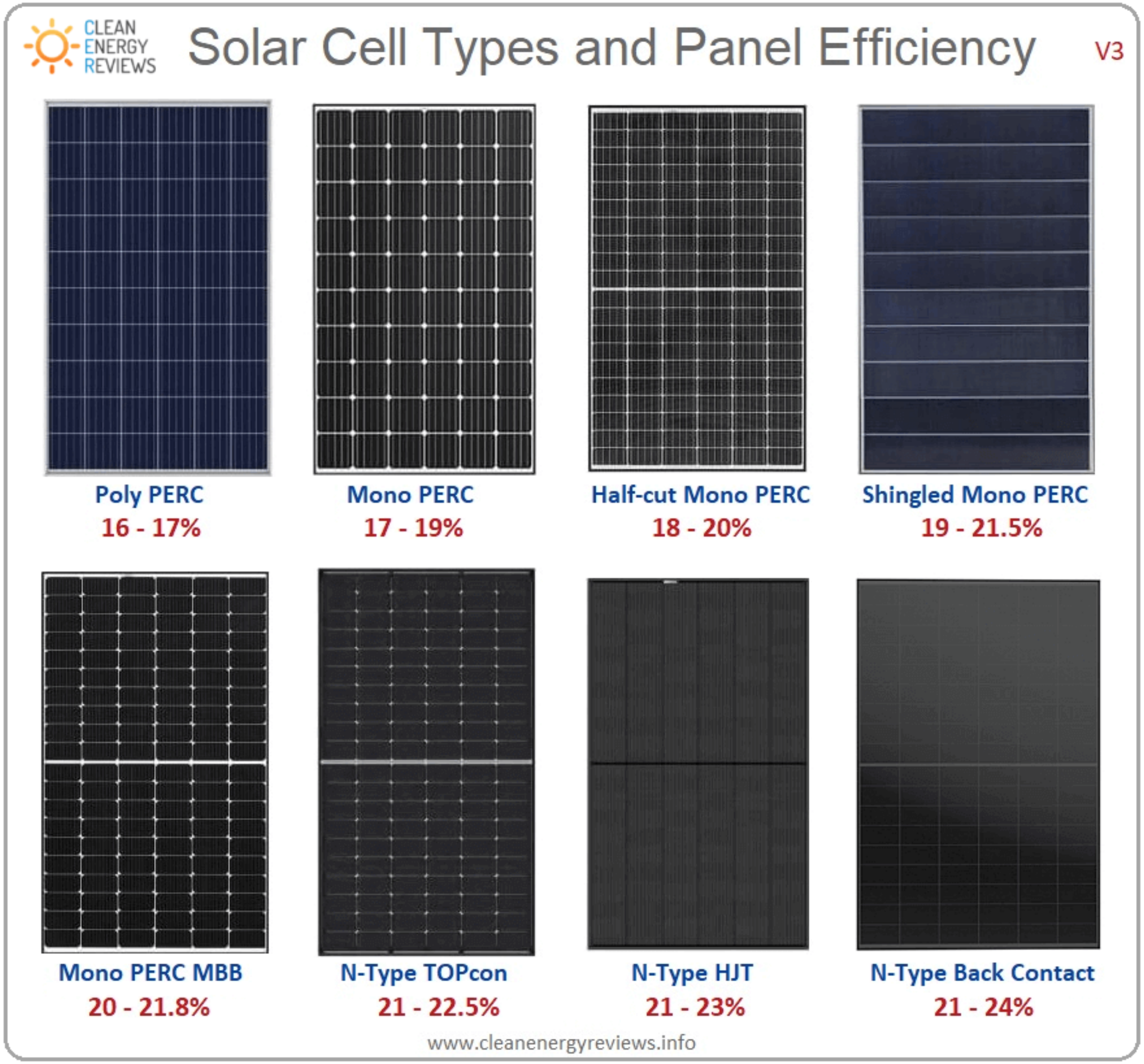
I-V curve influenced by:

- 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 efficiency

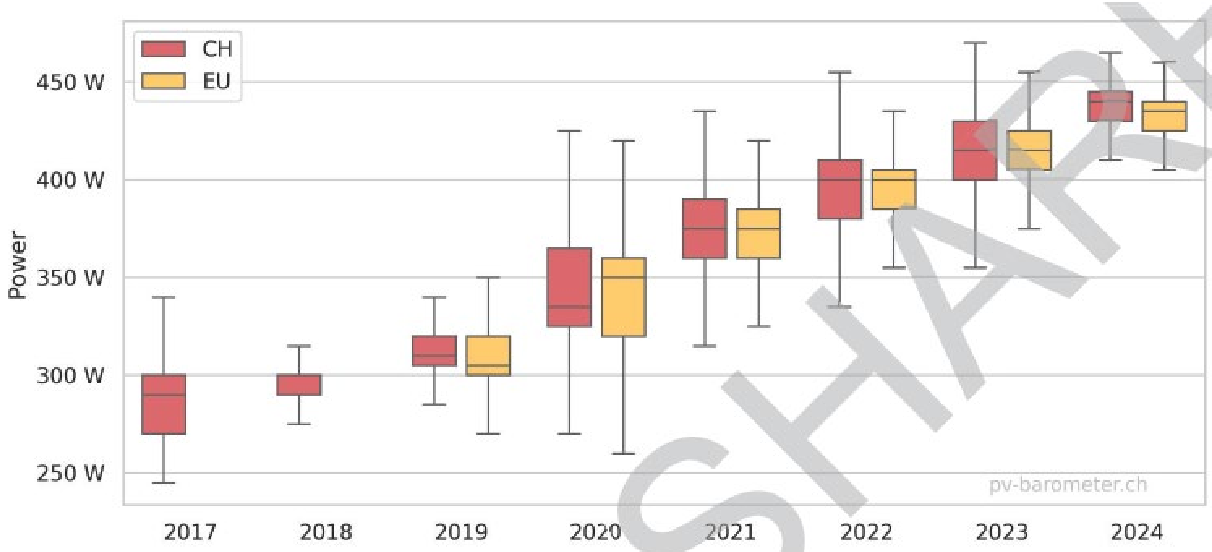


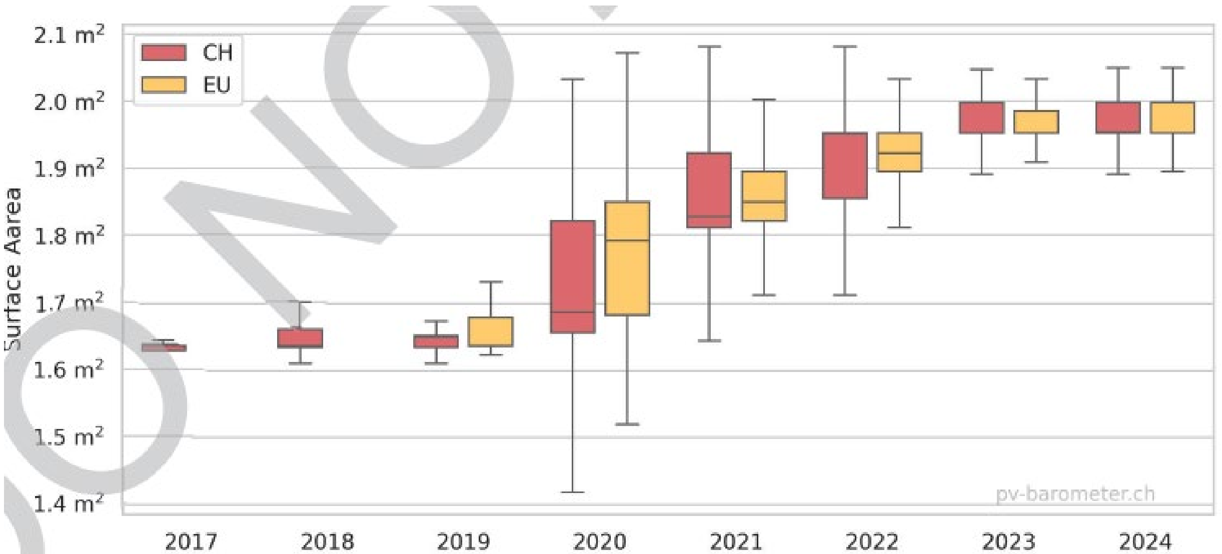
2023 data from www.cleanenergyreviews.info

PV modules: efficiency & temp. coeff.

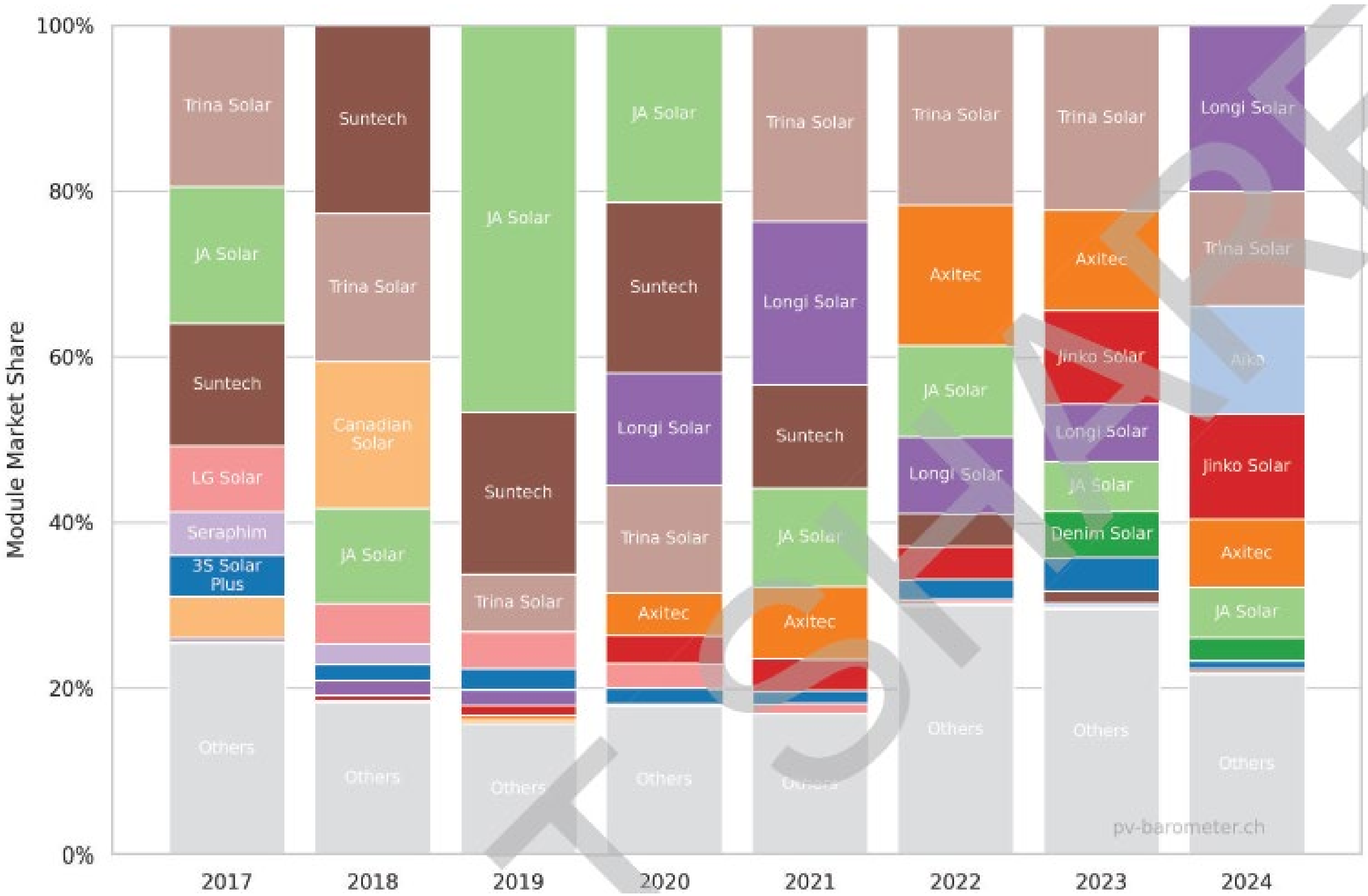
Photovoltaik Barometer 2025, Berner Fachhochschule, 31 March 2025

PV Modules: power & size





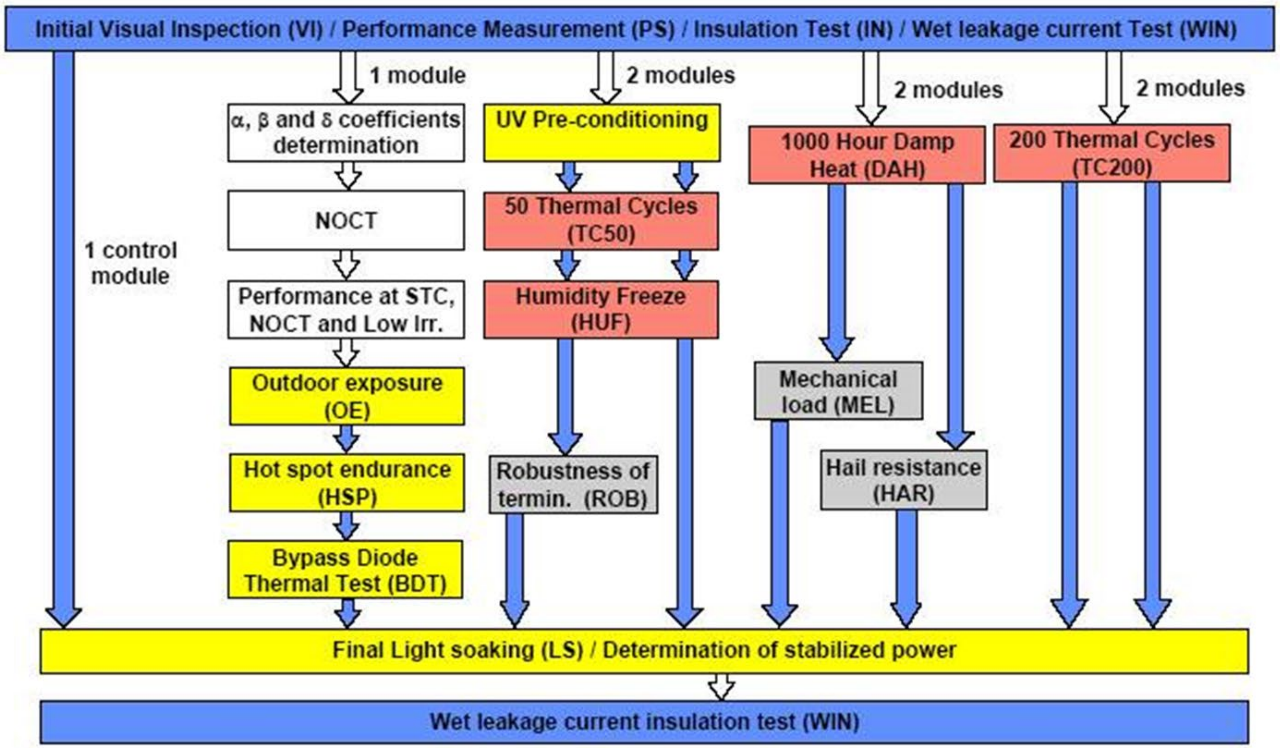
PV Modules: producers



Photovoltaik Barometer 2025, Berner Fachhochschule, 31 March 2025

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: > 90% power 20 years, > 80% power after 30 years
- Warranty ≠ Lifetime (PV module can serve for 30…40 years and more…)

Module degradation

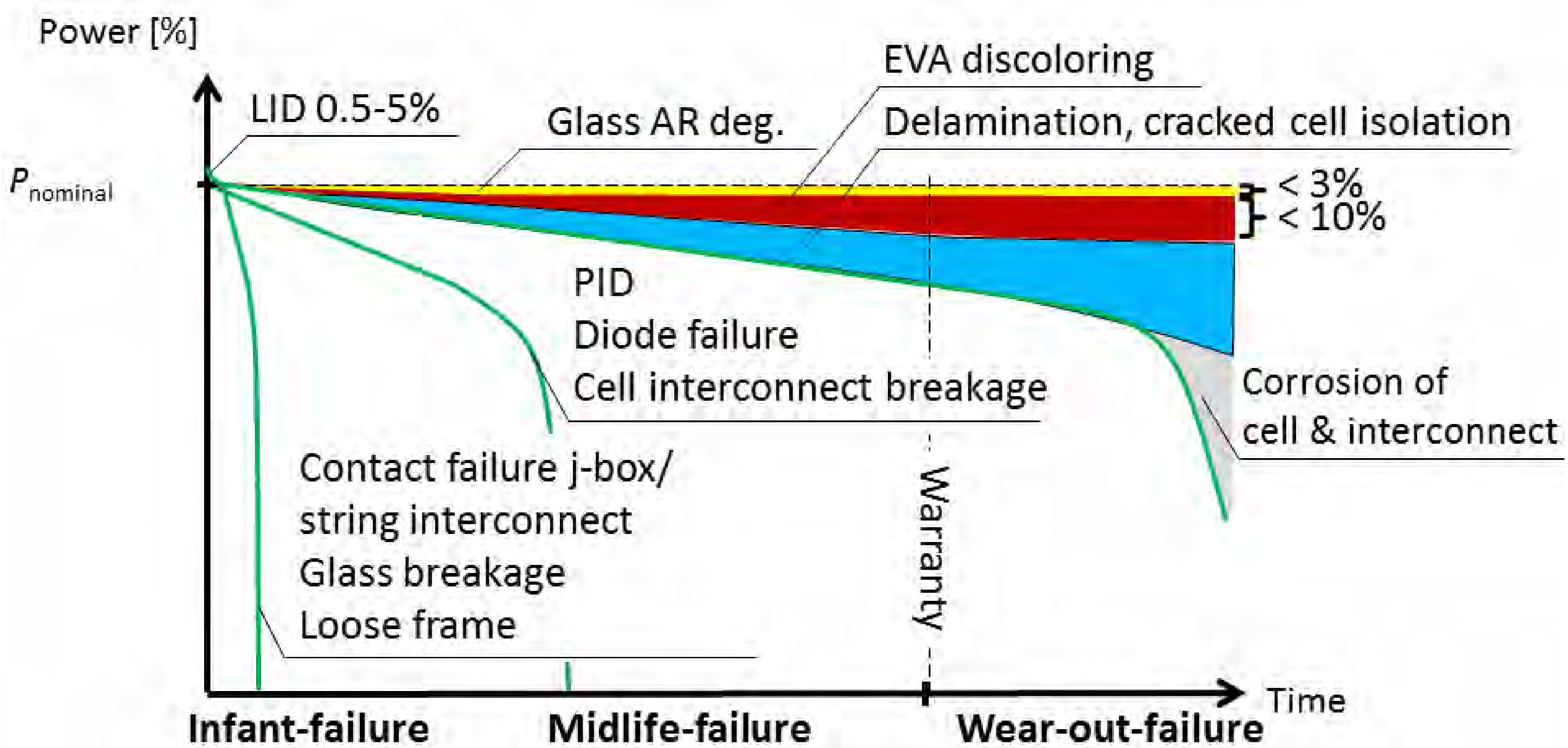


Fig. 3.1: Three typical failure scenarios for wafer-based crystalline photovoltaic modules are shown. Definition of the used abbreviations: LID – light-induced degradation, PID – potential induced degradation, EVA – ethylene vinyl acetate, j-box – junction box.

Report IEA-PVPS T13-01:2014

PV systems

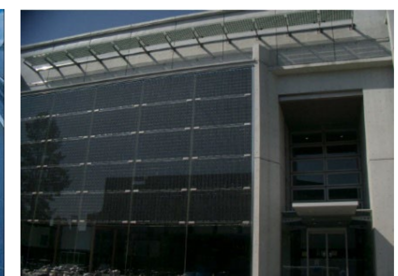
Ground mounted
- Utility scale


BAPV : Roof top (commercial, industrial, residential




BIPV: Roof & facade



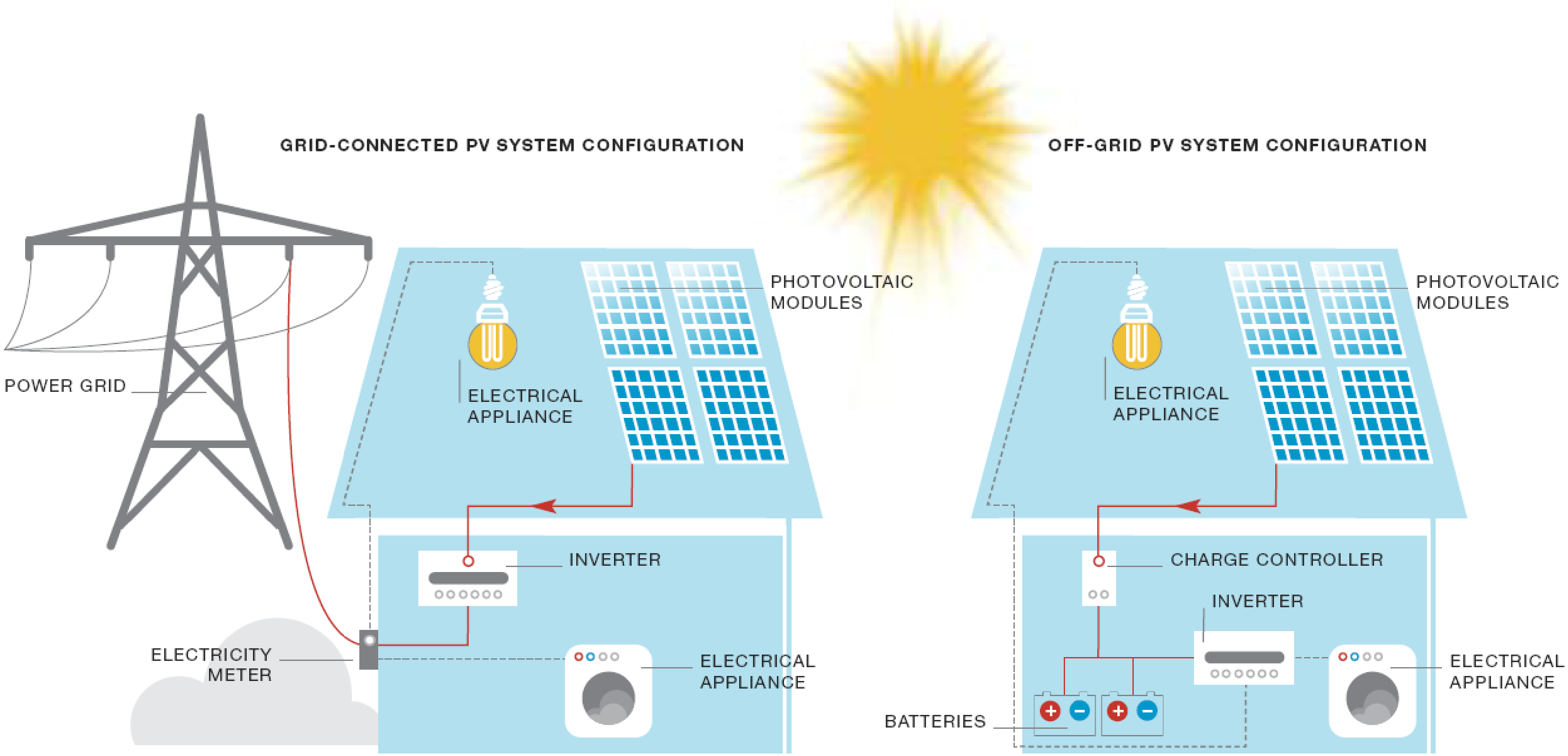
Agrivolatics

Floating

on vehicles, airships,
space power,…

Pictures: from various web sites

PV systems



source: EPIA.

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

Performance ratio (PR)

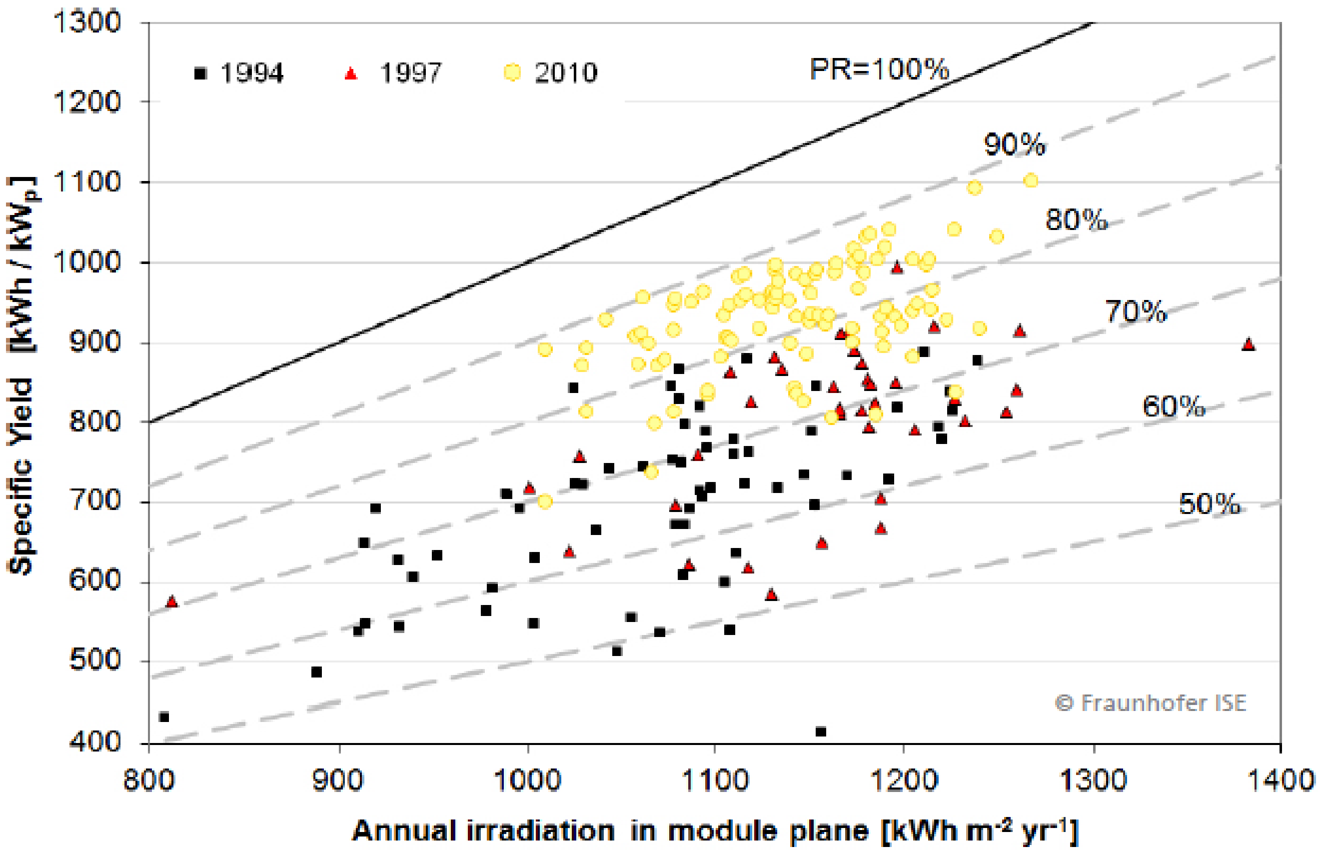
$$PR = \frac{Produced\ energy\ [kWh]}{Expected\ energy\ [kWh]} \times 100\%$$

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

- **Quality factor for PV systems and PV plants**
  - Does not depend on location, orientation or meteorological parameters

- **Depends on external parameters:**
  - Temperature of modules
  - Shading of modules
  - Shading of measurement unit
  - Performances losses
  - Efficiency of modules and inverters
  - Wiring losses
  - Mismatch

Performance Ratio Development for PV Systems
Germany



In the 1990's

- Typical PR ~70 %
- Widely ranging PR values

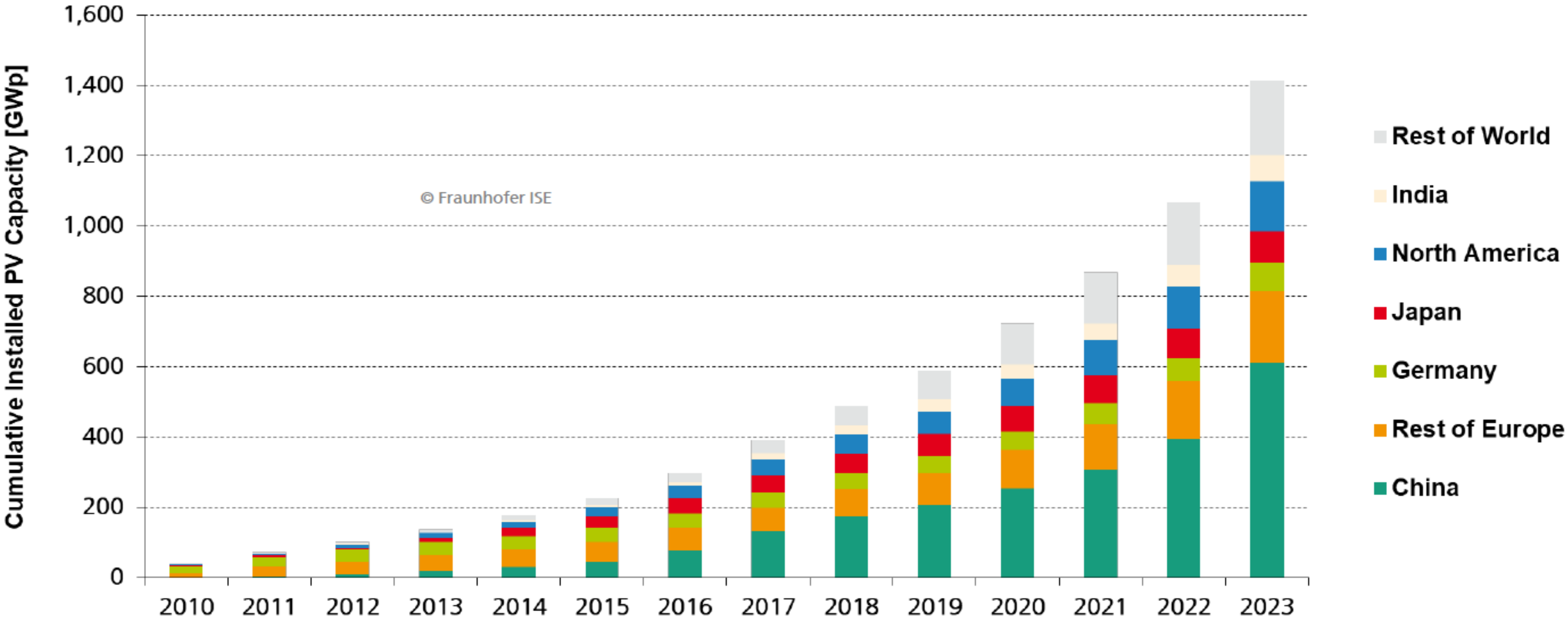
Today

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

Source: Photovoltaics report, ISE Fraunhofer, May 2024

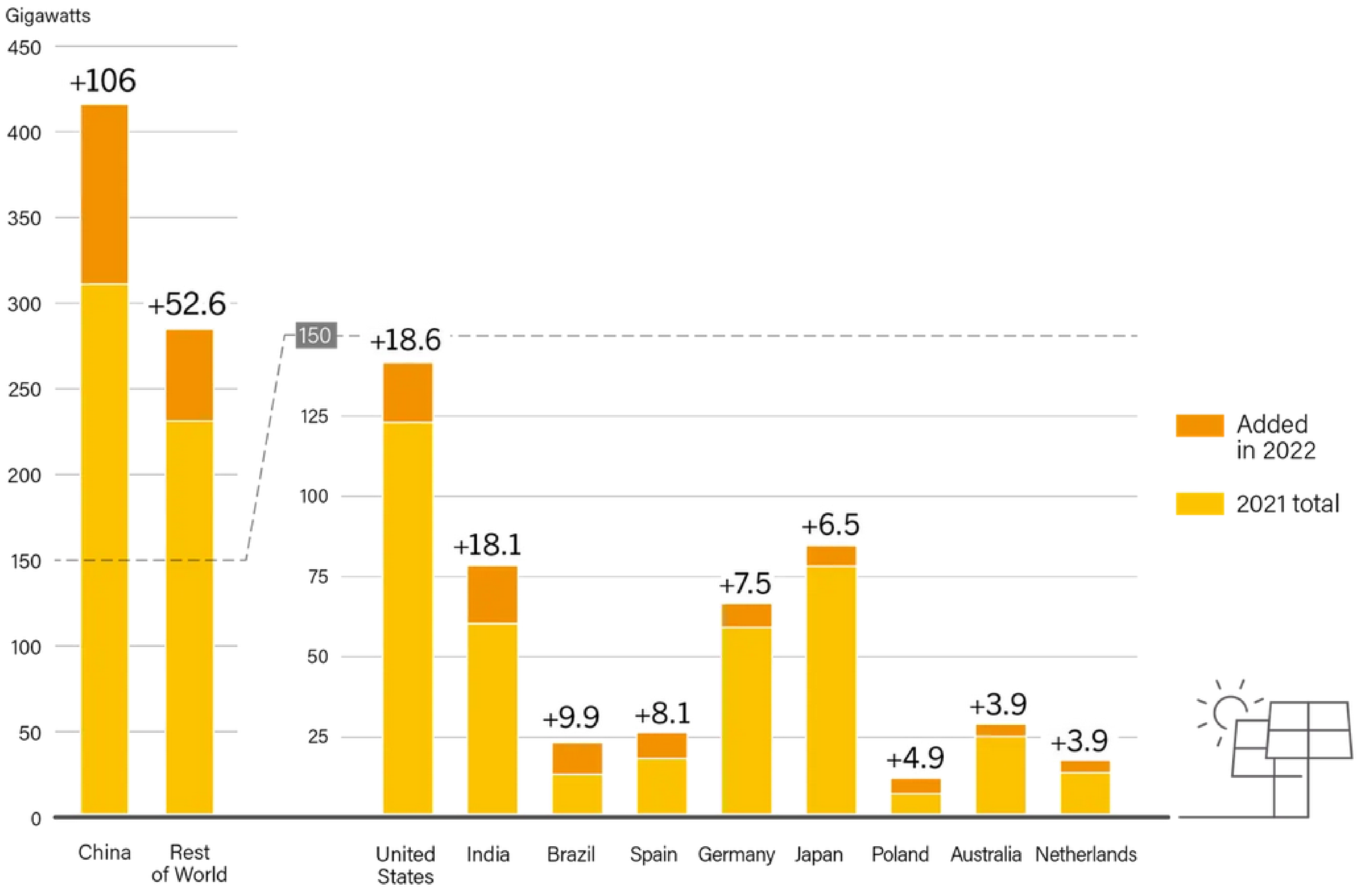
PV economics

Global PV installations



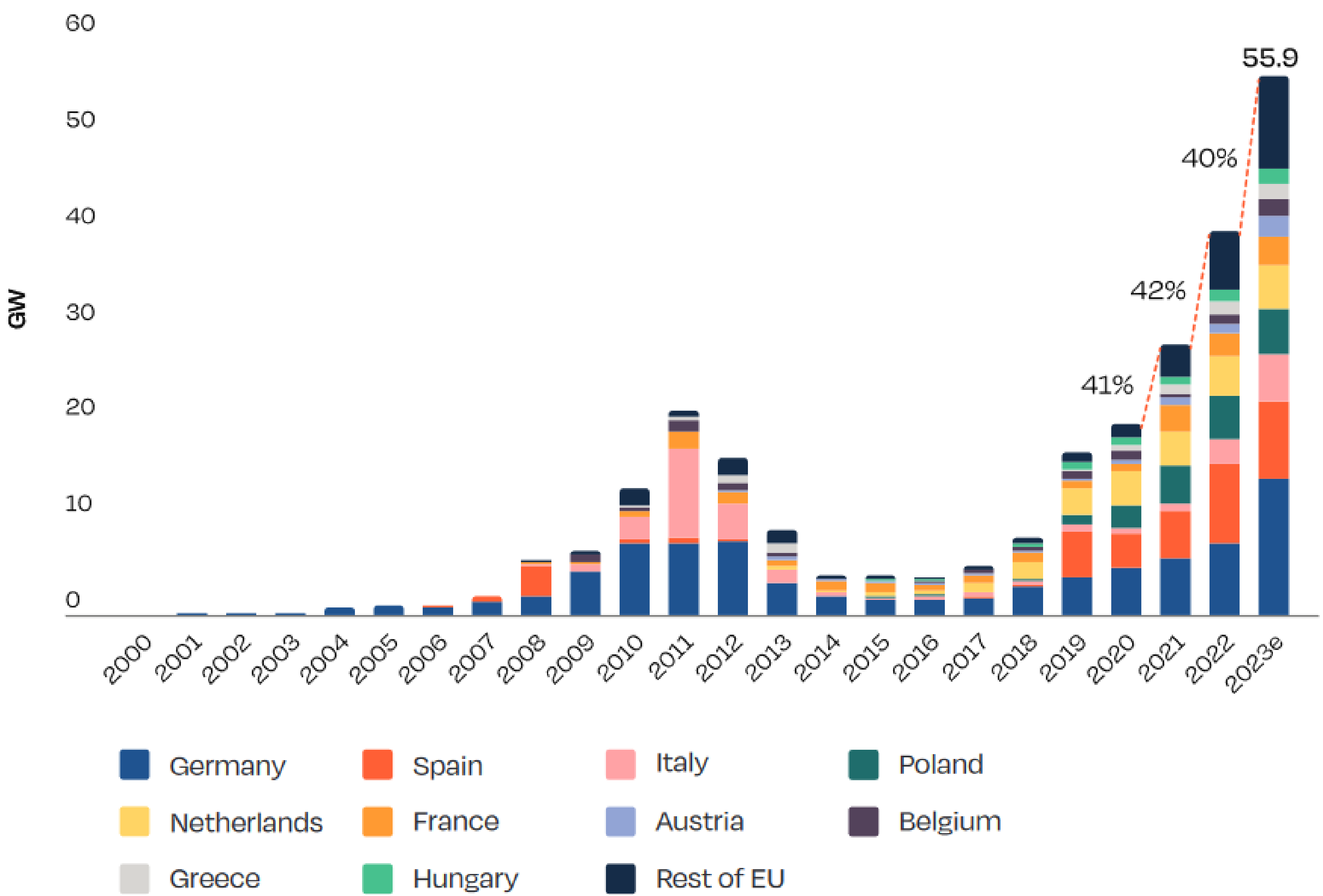
Source: Photovoltaics report, Fraunhofer Institute ISE, May 2024

Solar PV Capacity and Additions, Top 10 Countries for Capacity Added, 2022



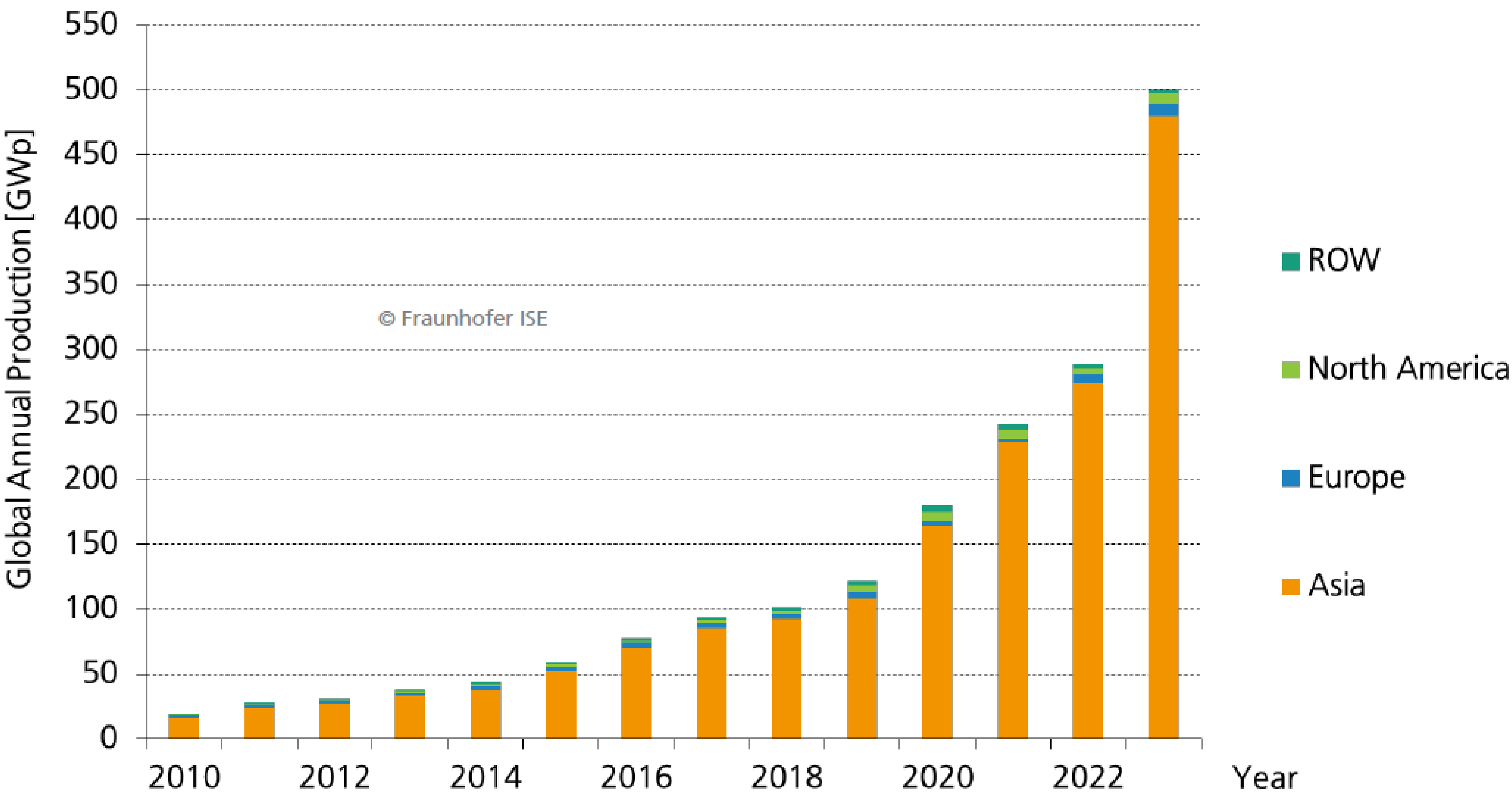
RENEWABLES 2023 GLOBAL STATUS REPORT

Annual PV installations in Europe 2000-2023



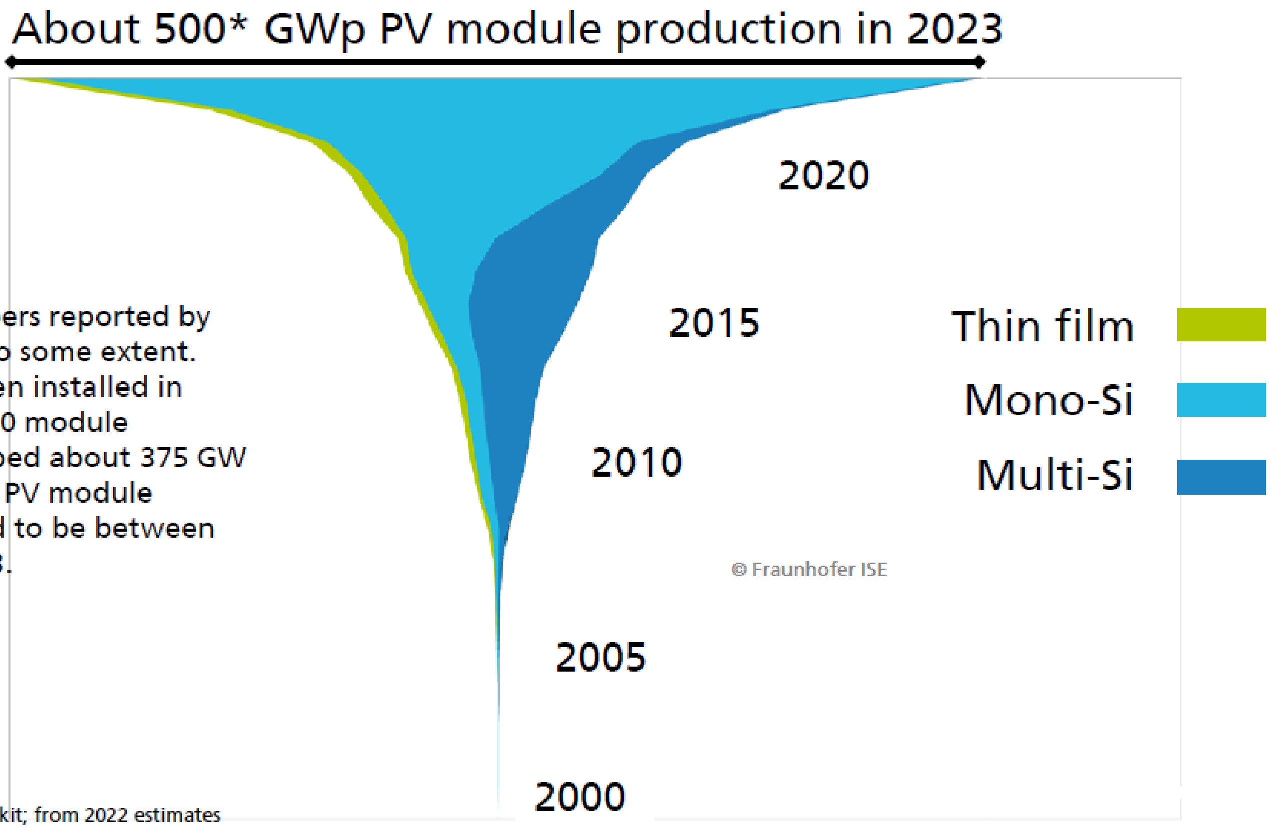
Source: SolarPower Europe 2023

PV module production by region



Source: Photovoltaics report, Fraunhofer Institute ISE, July 2024

Annual PV Production by Technology
Worldwide (in GWp)



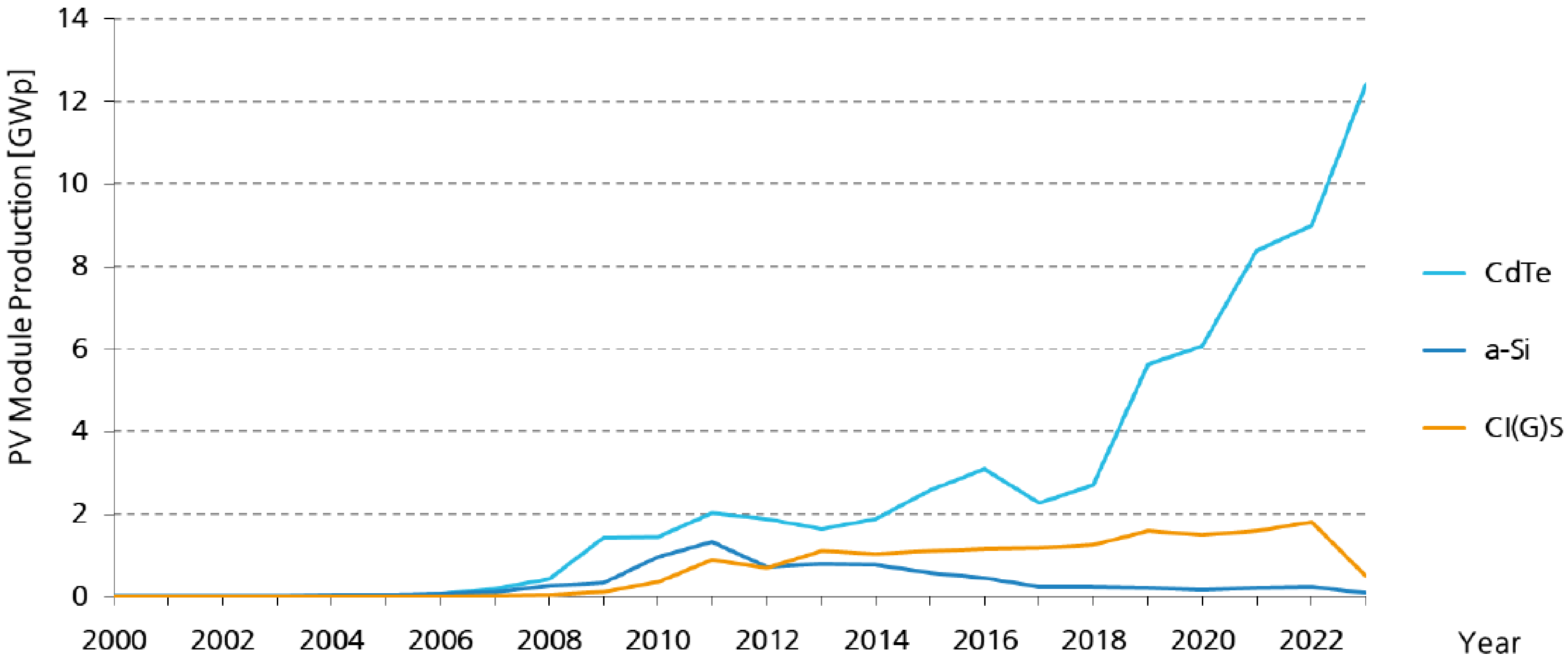
*2023 production numbers reported by different analysts vary to some extent. About 410 GW have been installed in 2023 globally. The TOP10 module producer together shipped about 375 GW PV panels in 2023. Total PV module shipments are estimated to be between 460 and 502 GW in 2023.

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

Source: Photovoltaics report, ISE Fraunhofer, July 2024

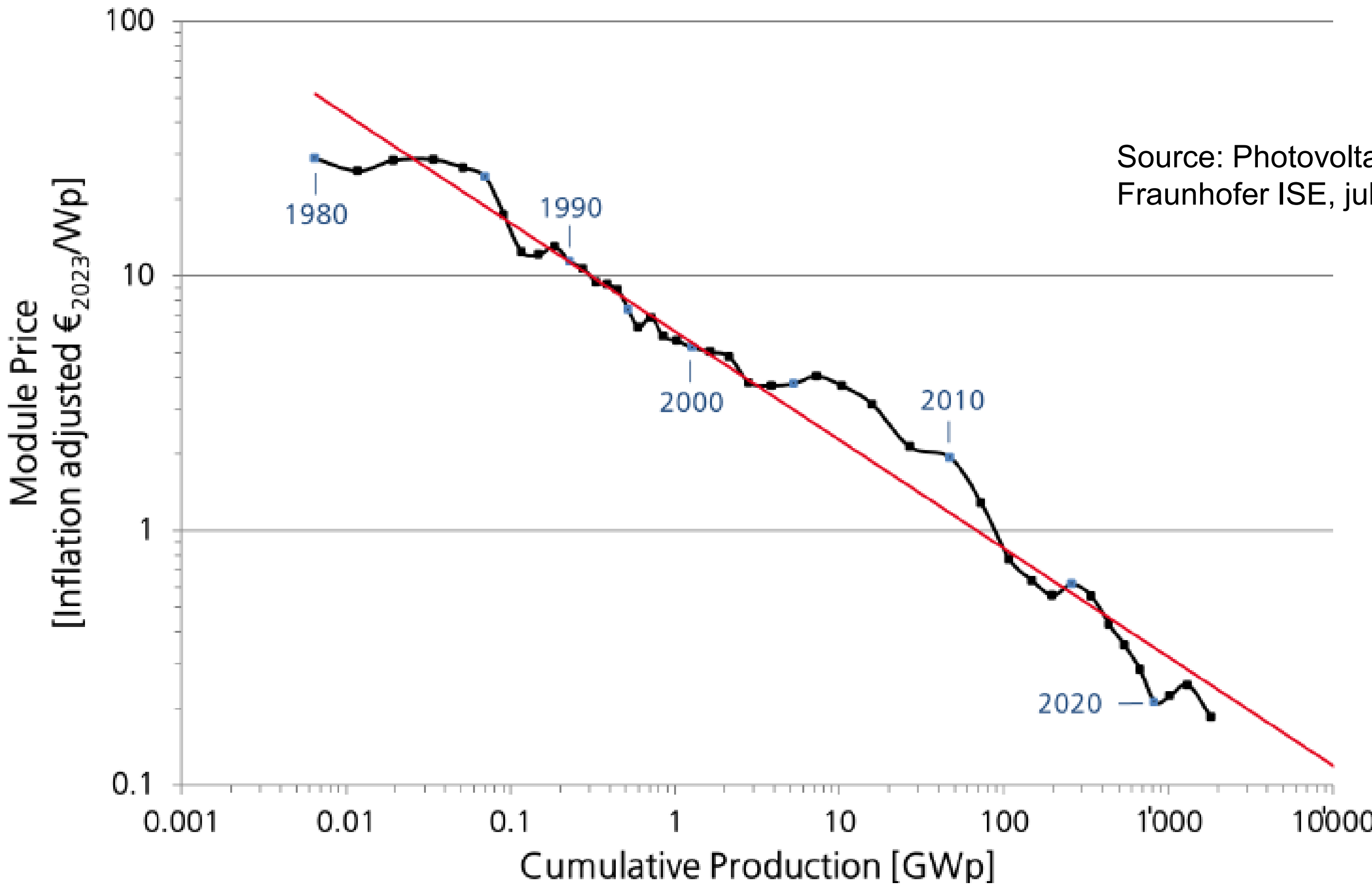
Thin-Film Technologies

Annual Global PV Module Production



Source: Photovoltaics report, Fraunhofer Institute ISE, May 2024

PV module price (all techs)

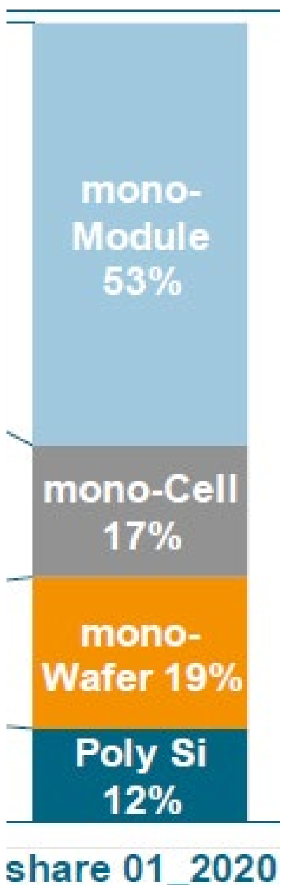


Source: Photovoltaics report, Fraunhofer ISE, july 2024

- Price of PV modules falls by ~24% upon doubling capacity (last 43 years)

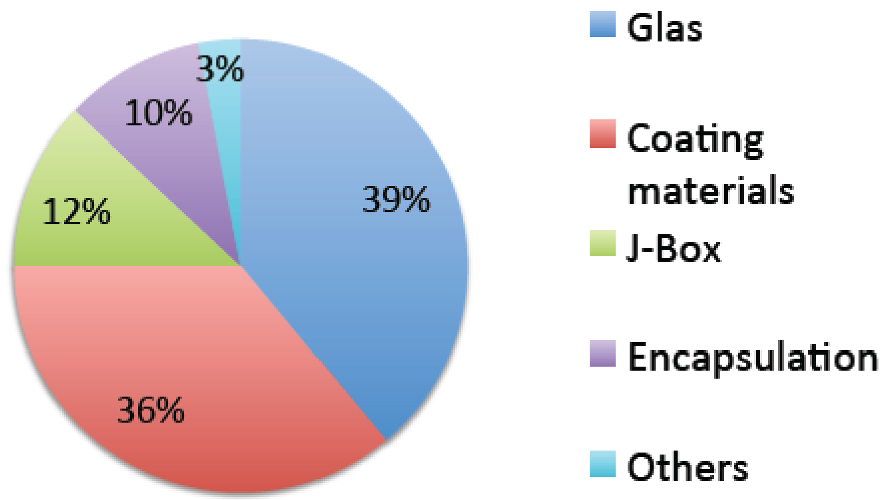
PV module cost structure

Crystalline Si module



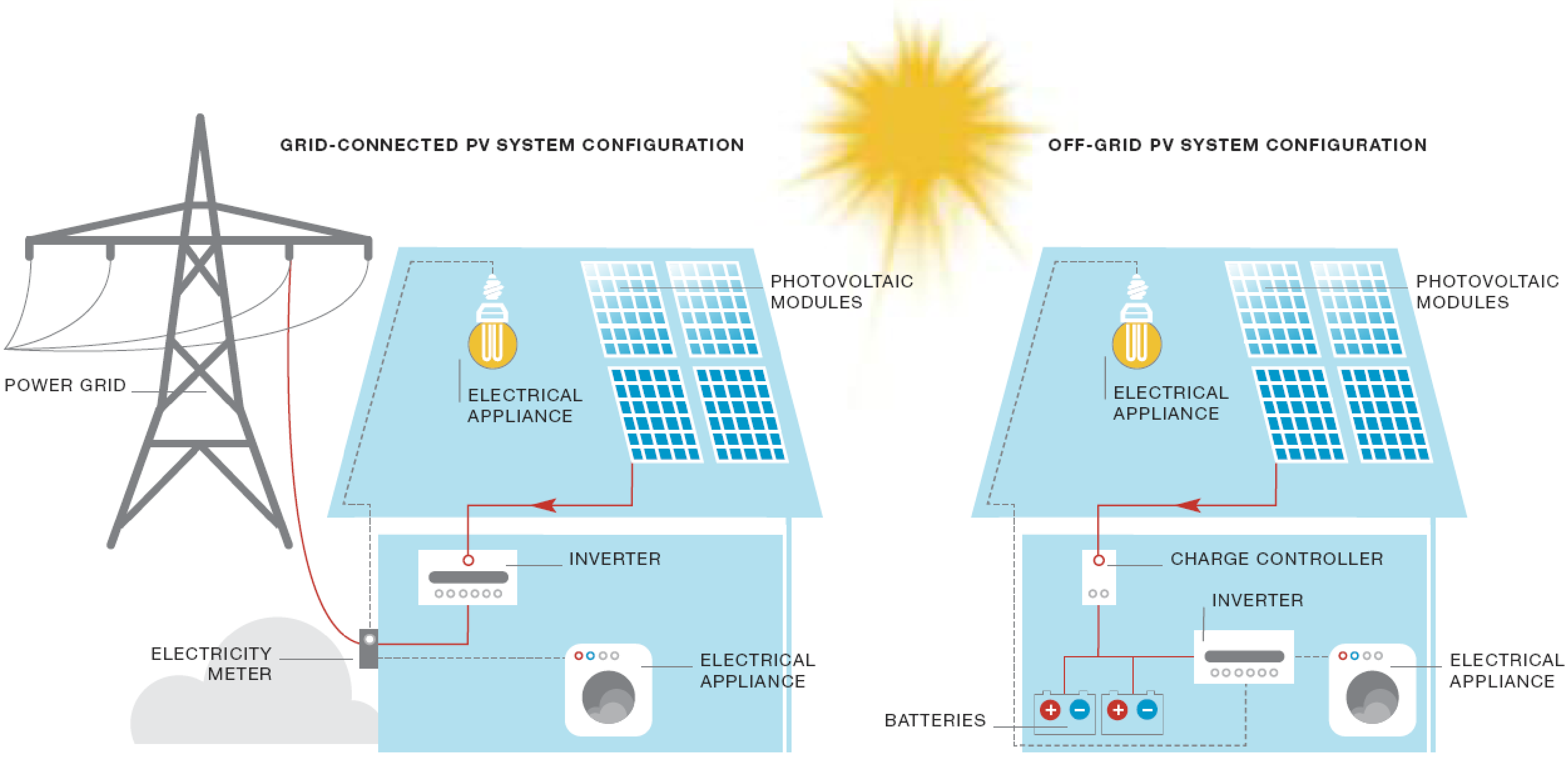
International Technology Roadmap for Photovoltaic, April 2020

Thin film module (CIGS)



PICON Solar, 2011

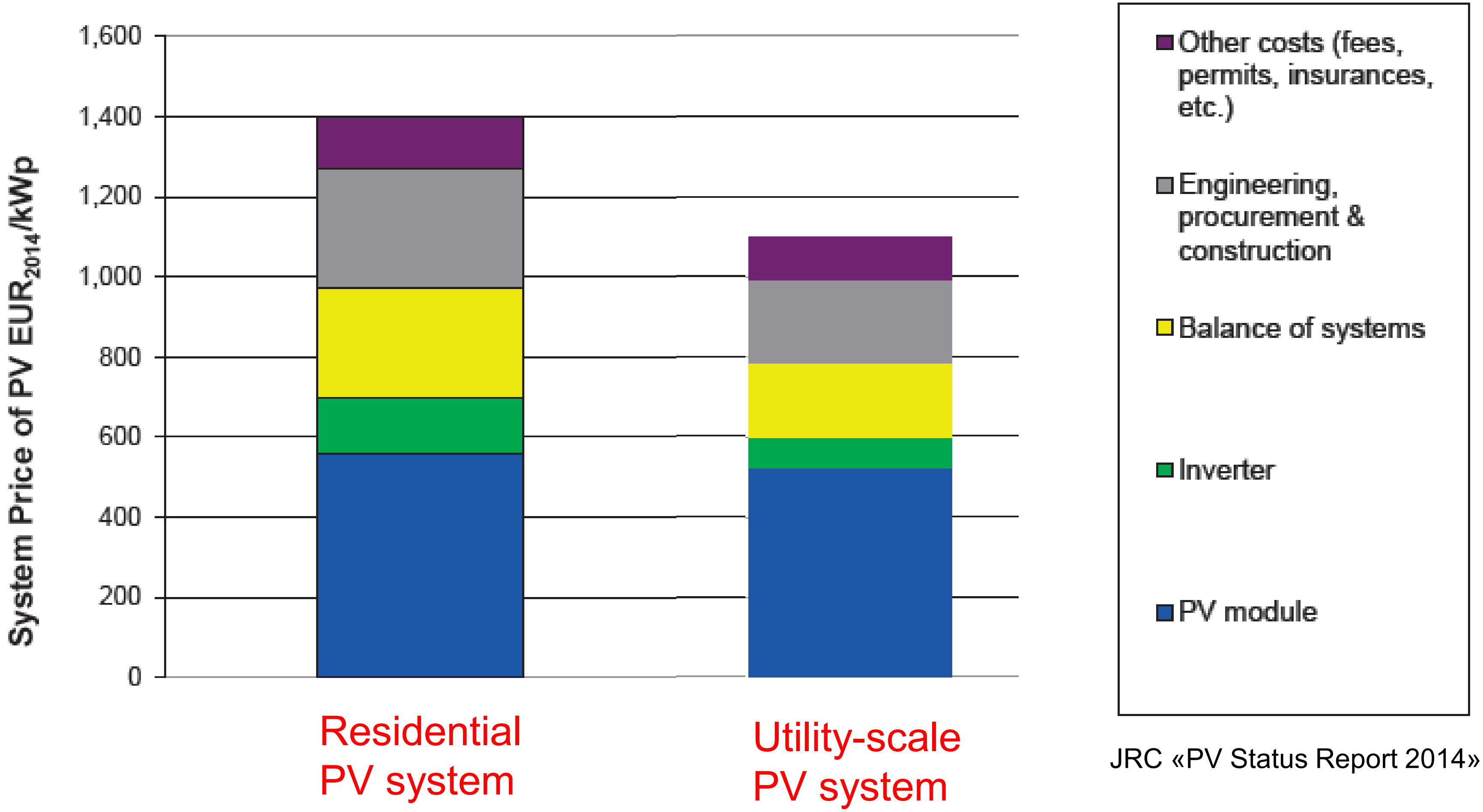
PV systems



source: EPIA.

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

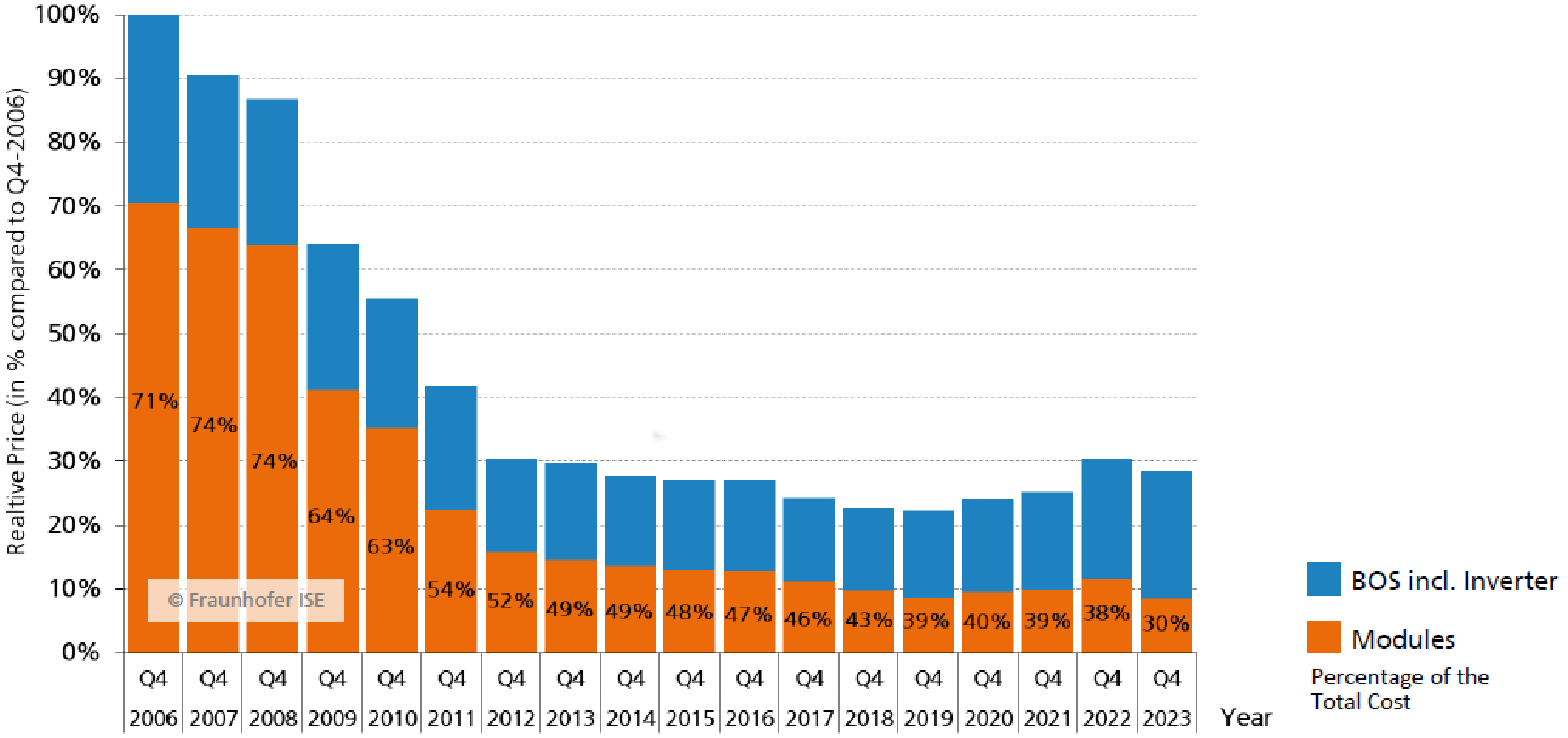
PV system costs



JRC «PV Status Report 2014»

- Module cost < 50% of the total PV system cost!

Price Development for PV Rooftop Systems in Germany (10kWp - 100kWp)

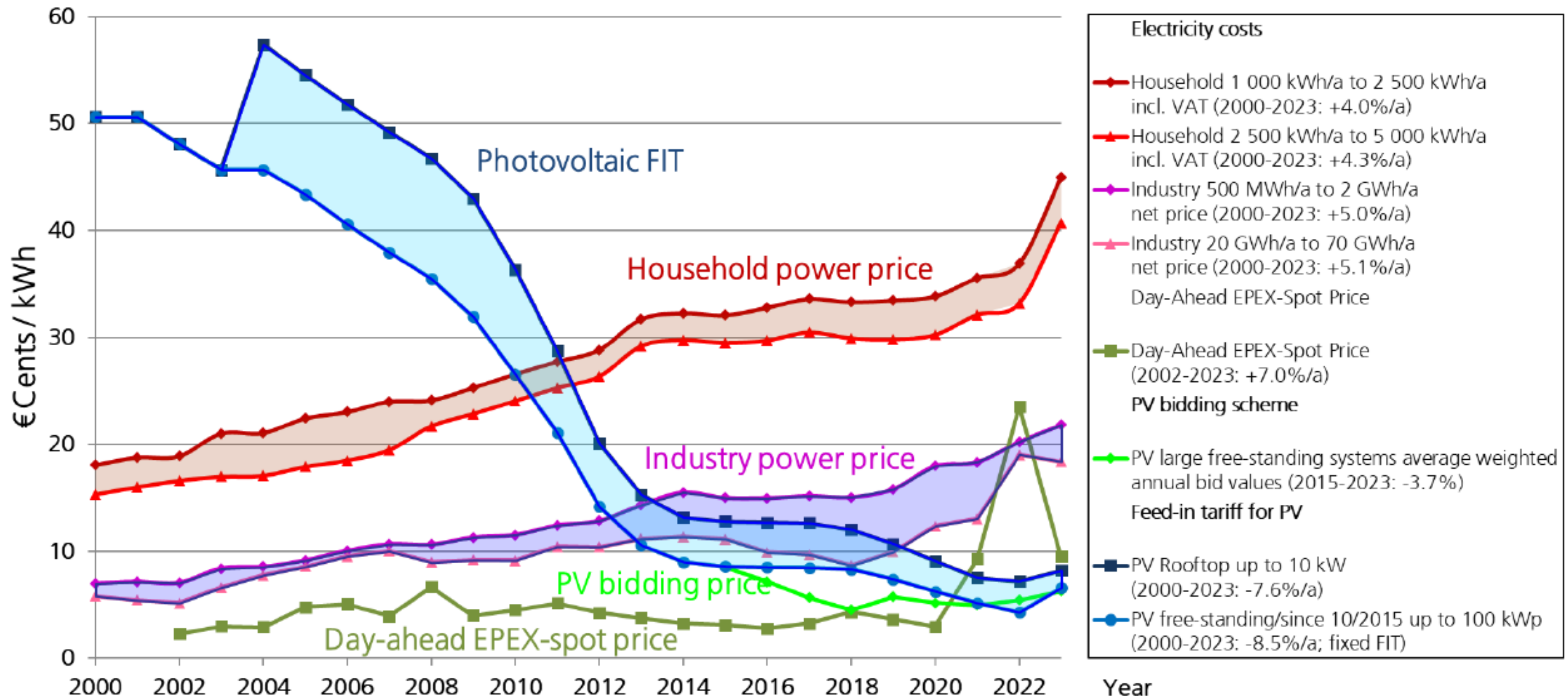


Data: BSW-Solar. Graph: PSE Projects GmbH 2024. Date of data: 11/2023

- Modules represent a smaller part of the overall system cost – that is why module efficiency matters

Source: Photovoltaics report, Fraunhofer Institute ISE, May 2024

Electricity Prices, PV Feed-In Tariffs (FIT) and bidding scheme in Germany

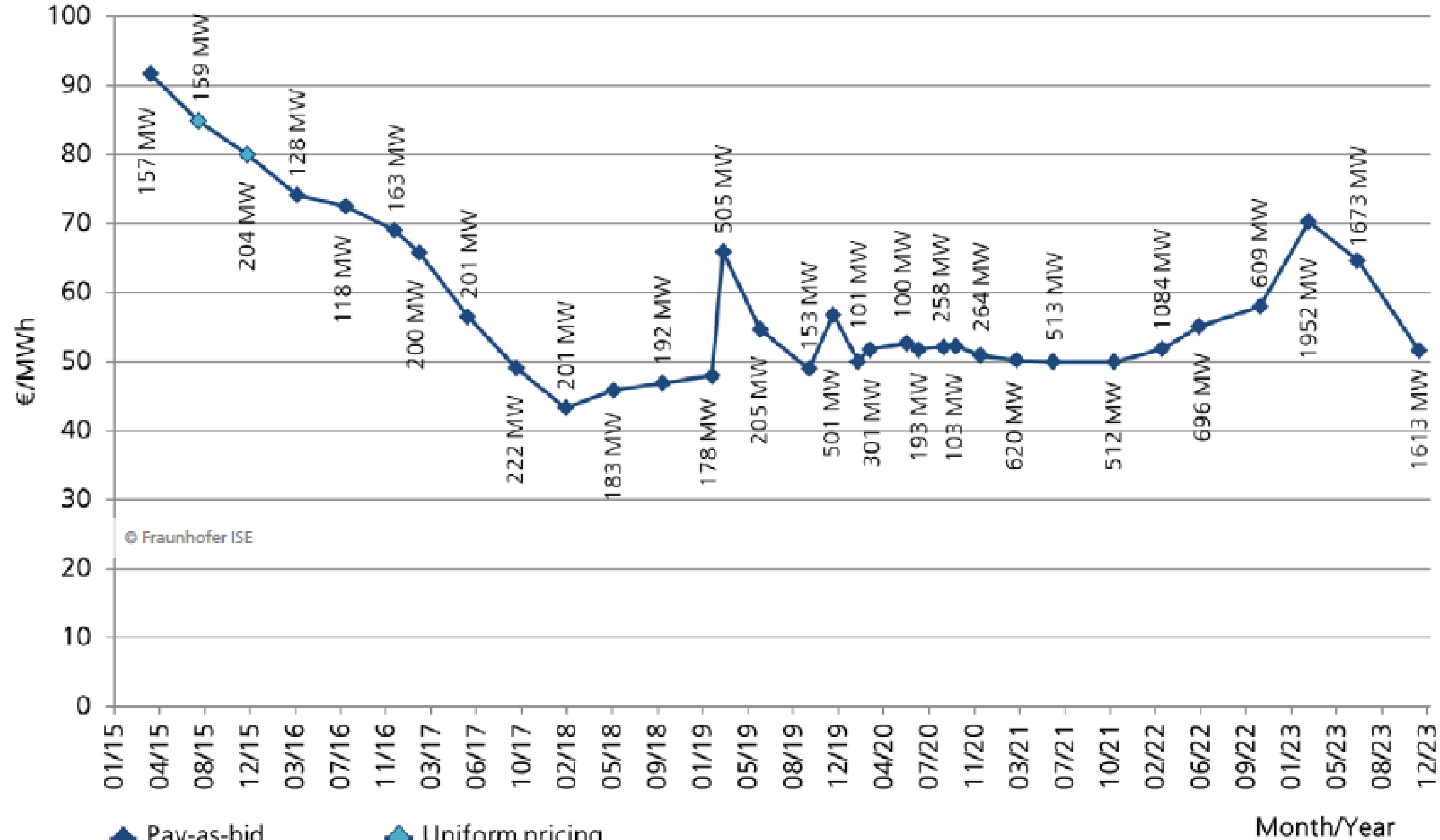


Data: BNA; energy-charts.info; Design: B. Burger - Fraunhofer ISE. Graph: PSE Projects GmbH 2024; Date of data: 04/2024

Source: Photovoltaics report, Fraunhofer Institute ISE, May 2024

PV-Tender in Germany for Free-standing Systems

Average, quantity weighted Award Value

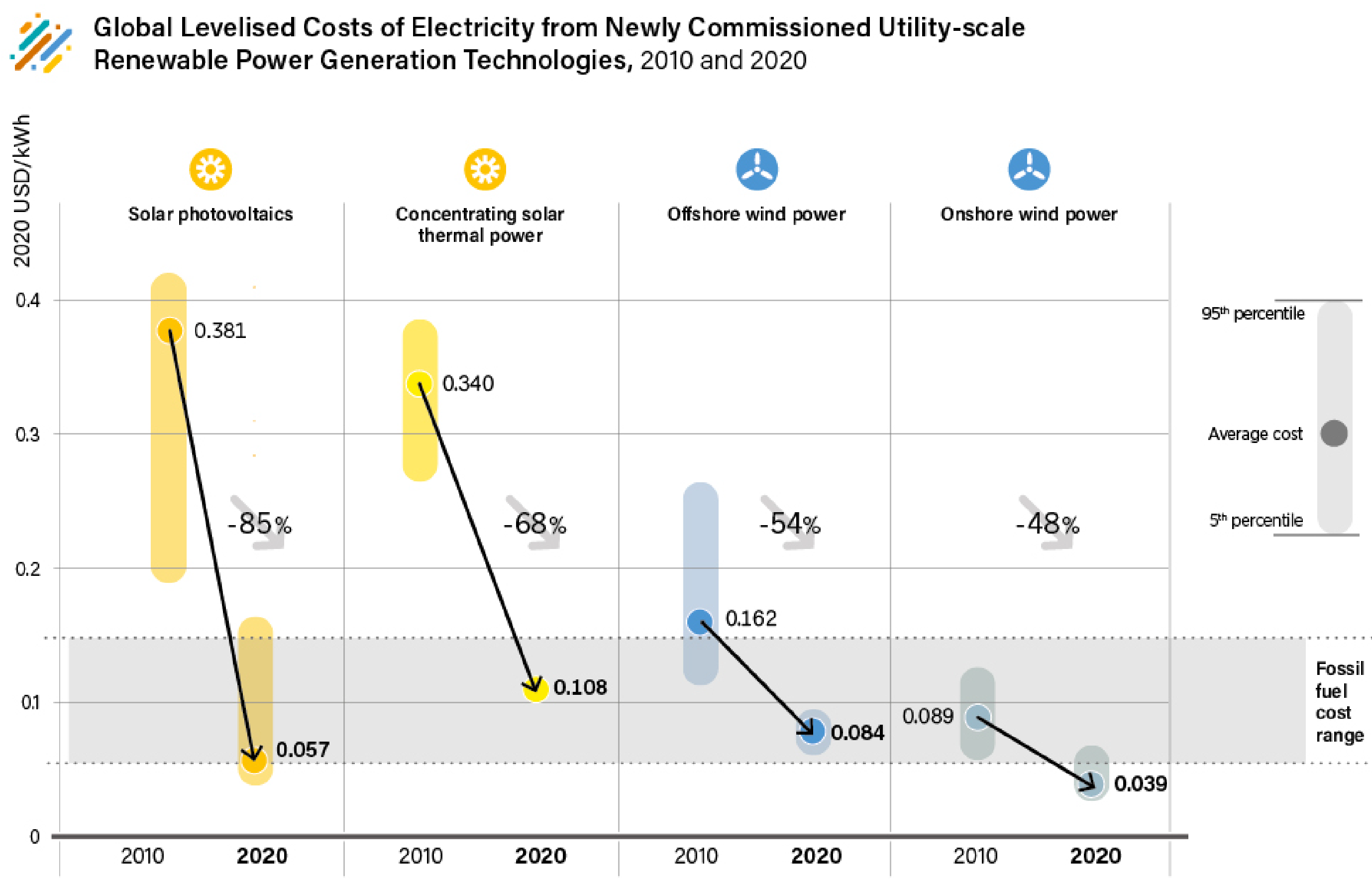


Source: Photovoltaics report, Fraunhofer Institute ISE, Feb 2023

- PV tender price is **5 ct€ / kWh** (Germany, 2023)

Levelized cost of energy (LCOE)

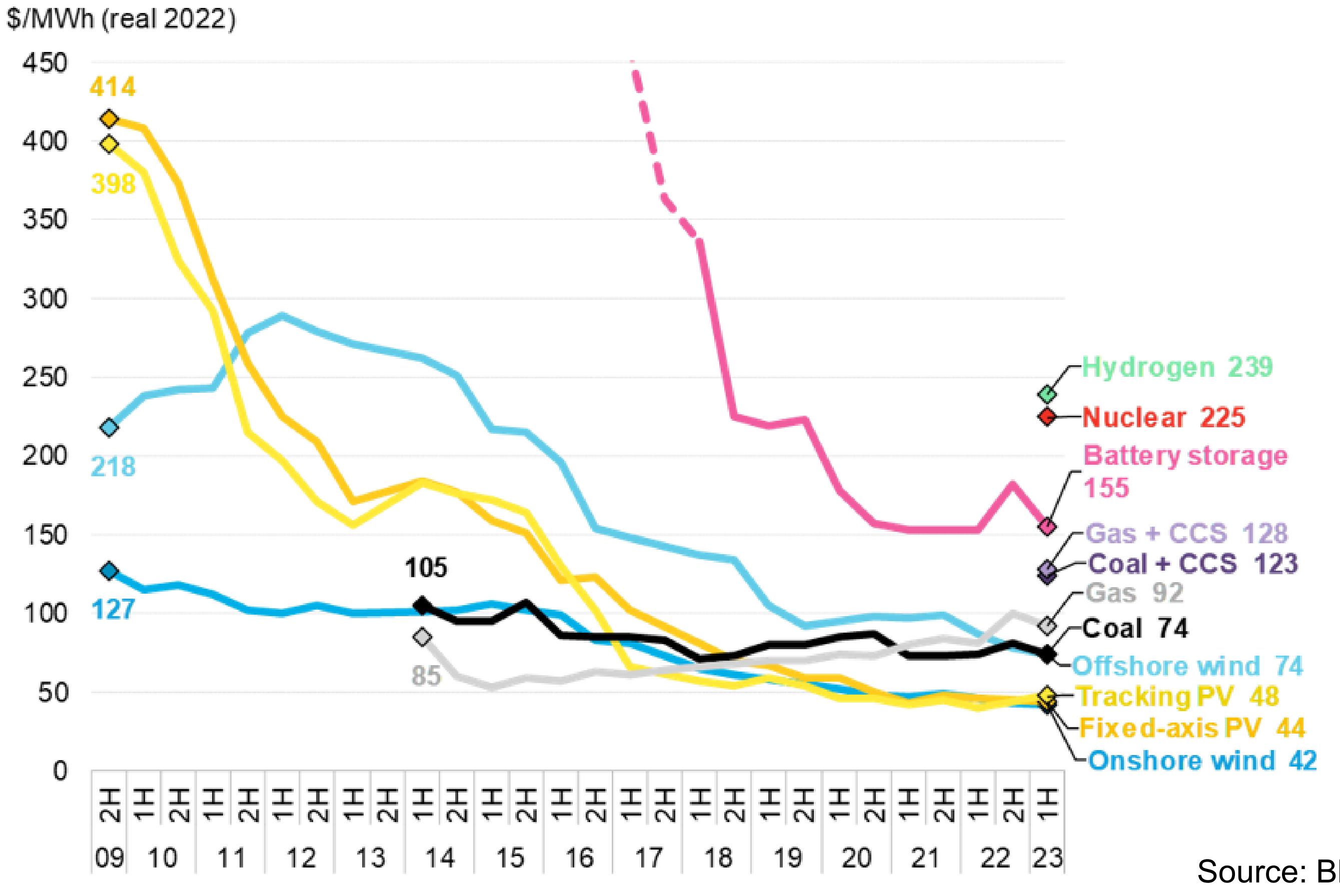
LCOE - average net cost of electricity generation for a generator over its lifetime (incl. system costs, installation, maintenance, degradation, financing, subventions,..)



RENEWABLES 2021 GLOBAL STATUS REPORT
http://www.ren21.net/status-of-renewables/global-status-report/

Levelized cost of energy (LCOE)

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



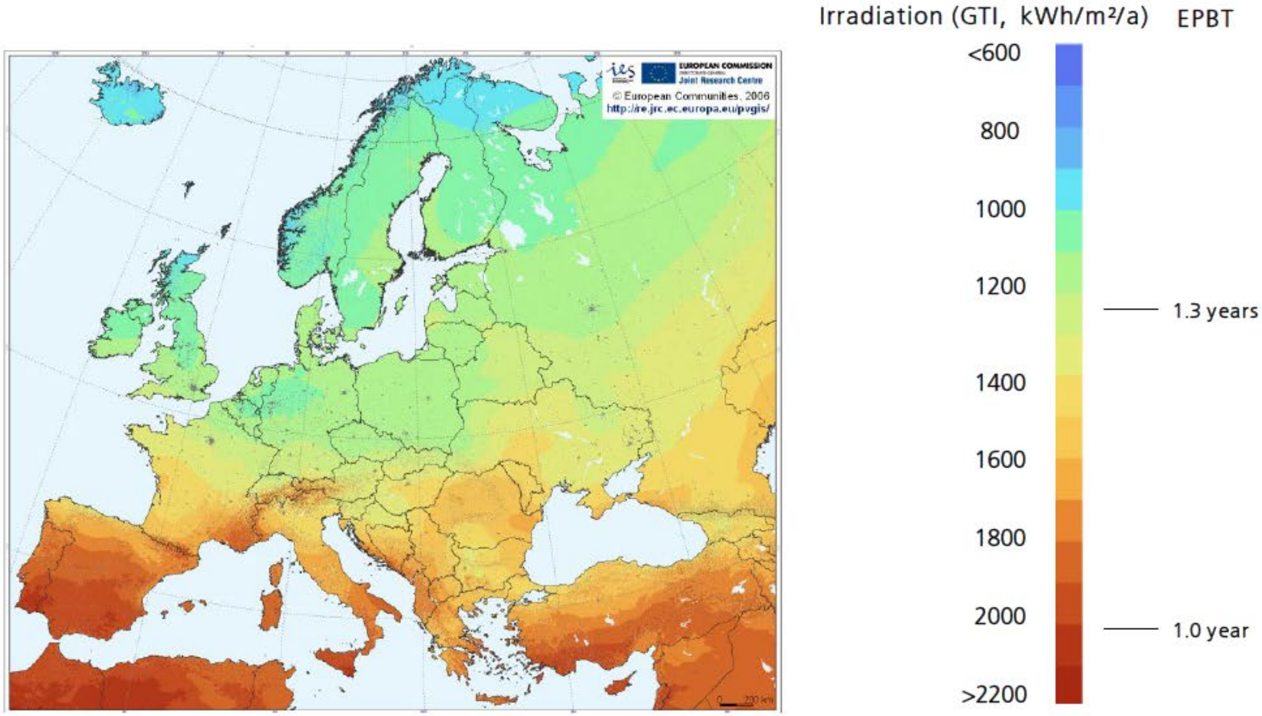
Source: BloombergNEF, June 2023

- PV & wind became the cheapest sources of electricity!

Energy payback time (EPBT)

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

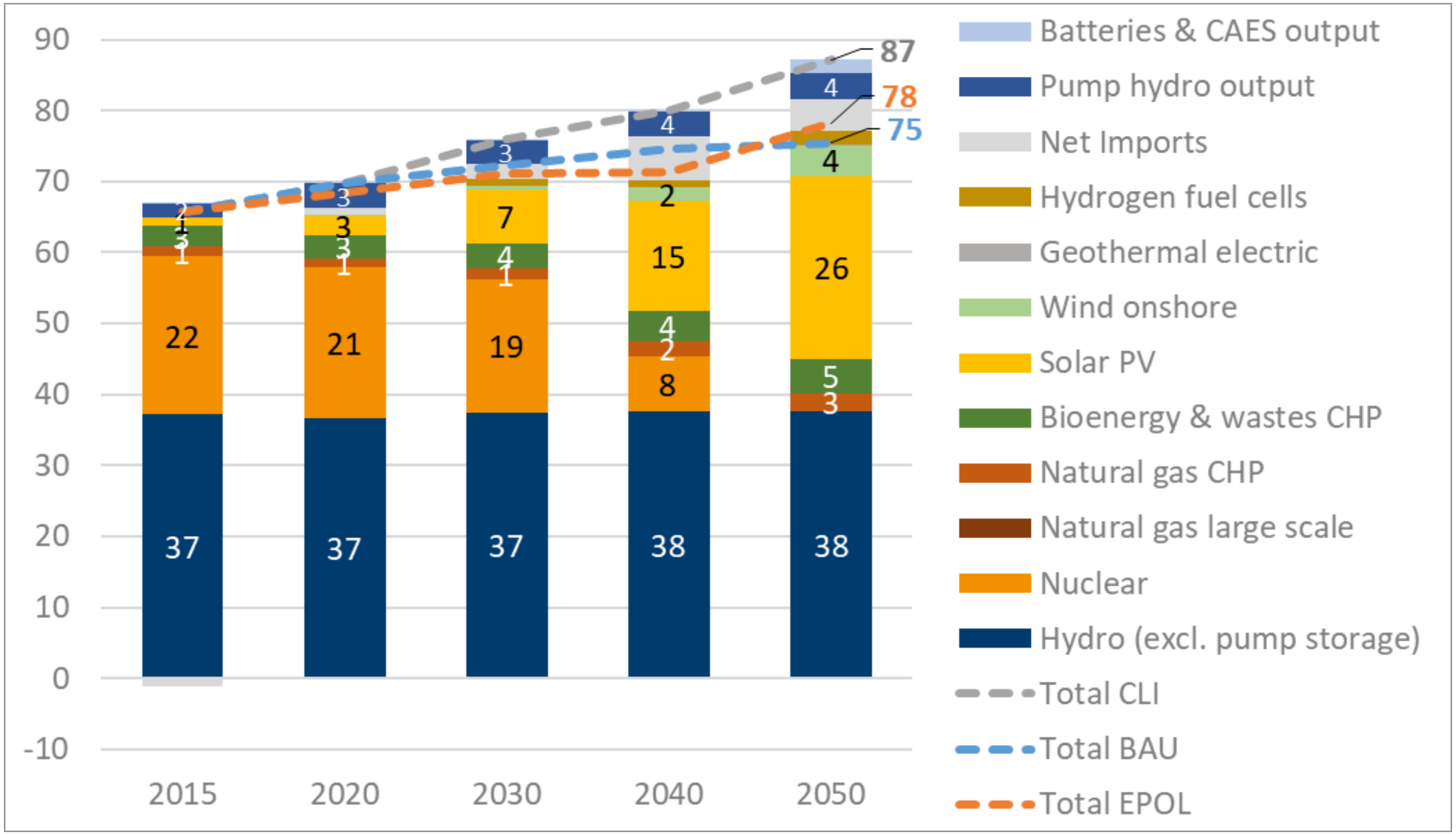
- Rooftop PV-system using mono-crystalline Silicon cells* produced in China
- EPBT is dependent on irradiation, but also on other factors like grid efficiency**.
- Better grid efficiency in Europe may decrease the EPBT by typically 9.5 % compared to PV modules produced in China.



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)

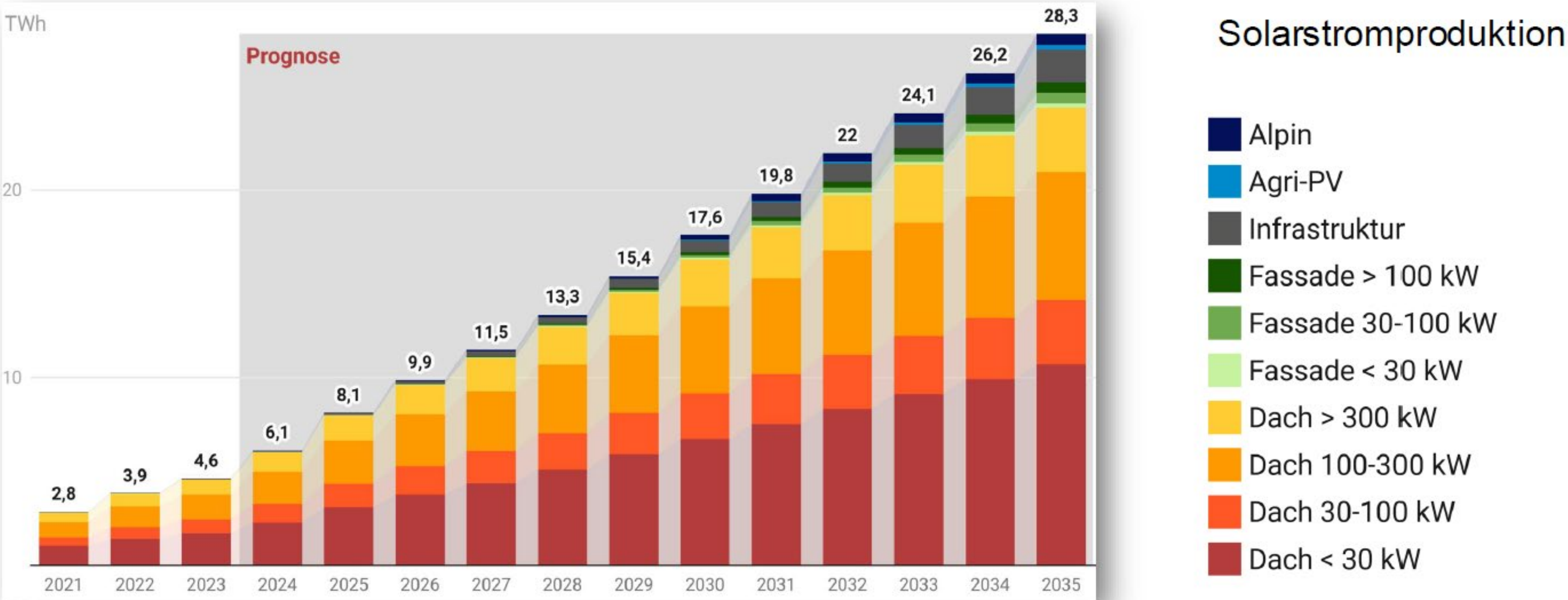
Swiss Energy Strategy 2050



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



>8 TWh
will be produced by PV in 2025

14%
of total electricity consumption in 2025 will come from PV