Photovoltaics Report

Fraunhofer Institute for Solar Energy Systems ISE
with the support of PSE Projects GmbH

Freiburg, 29 May 2025
www.ise.fraunhofer.de

CONTENT

Introduction

Preliminary Remarks

- The intention of this presentation is to provide up-to-date information. However, facts and figures change rapidly, and the given information may soon be outdated again.
- This work has been carried out under the responsibility of Dr. Simon Philipps (Fraunhofer ISE) and Werner Warmuth (PSE Projects GmbH).
- Price indications are always to be understood as nominal, unless stated explicitly. For example, prices in the learning curves are inflation adjusted.
- The slides have been made as accurate as possible. Please send any comments or suggestions for improvement to both simon.philipps@ise.fraunhofer.de and warmuth@pse-projects.de
- Please cite the information presented in these slides as follows:
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Quick Facts

Parameter	Value	Status	Reference	Date of data
Germany / EU27 / Worldwide				
PV installation market [GW]	15.3 / 55.9 / 456 GW 16.9 / 76.4 / 602	End of 2023 End of 2024	BNA / SPE / IEA BNA / SPE / IEA	04/2025; 12/2023; 04/2025 04/2025; 04/2025; 04/2025
Cumulative installation [GW]	83.1_{net} / 211.6_{net} / 1,555 GW 100.0_{net} / 251.1_{net} / 2,156.5 GW	End of 2023 End of 2024	ISE / ISE / IEA ISE / ISE / IEA	04/2025; 04/2025; 04/2025 04/2025; 04/2025; 04/2025
PV power generation [TWh]	53.9_{net} / 246.8_{gross} / 1641.6_{gross} 59.7_{net}	2023 2024	ISE / EI / EI ISE	06/2024; 06/2024; 06/2024 05/2025
PV electricity share	$12.5\%_{net}$ / $9.0\%_{gross}$ / $5.5\%_{gross}$ $14.5\%_{net}$	2023 2024	ISE / EI / EI ISE / EI / EI	06/2024; 06/2024; 06/2024 05/2025
Worldwide				
c-Si share of production	98%	2024	ITRPV	03/2025
Record solar cell efficiency: III-V MJ (conc.) /mono-Si /CIGS /multi-Si /CdTe	47.6 / 27.4 / 23.4 / 24.4 / 21.0%	10/2024	Green et al.	10/2024
Germany				
Price PV rooftop system (3 to 10 kWp)	900 to 1,300 €/kWp	2024	gruenes.haus	12/2024
LCOE PV power plant	4.1 to 5.0 ct€ / kWh	2024	ISE	08/2024
Lowest/Latest PV-tender price (average, volume-weighted value)	4.33/4.66 ct€ / kWh	02/2018; 03/2025	BNA	04/2025

Executive Summary

PV Market: Global

- Photovoltaics is a fast-growing market: The Compound Annual Growth Rate (CAGR) of cumulative PV installations was about 27% between the years 2014 and 2024.
- Wafer size increased. Keeping the same number of cells, larger PV module sizes are realized, allowing a power range of over 700 W per module.
- In 2024, Europe's contribution to the total cumulative PV installations amounted to 23%. In contrast, installations in China accounted for 49% (in 2023 43%) and in North America for 5% respectively.
- Silicon wafer-based technology accounted for about 98% of total production in 2024 with a 70% share of n-type wafers according to ITRPV. Monocrystalline technology became the dominant technology in c-Si production.
- Market shifts from subsidy-driven to a competitive pricing model (Power Purchase Agreements PPA).
- In addition to building-integrated (roof or building facades) and ground-mounted systems, more and more PV systems are being installed on agricultural land (agrivoltaics) and bodies of water (floating PV). Furthermore, vehicle-integrated PV enters the market.
- With increasing share of power generated by renewables, the integration of batteries with energy management systems is becoming increasingly important.

Executive Summary

PV Market: Focus Germany

- In 2024, PV installations in Germany (approximately 4.8 million PV systems with a capacity of over 800 W) accounted for about 4.6% (100 GWp) of the cumulative PV capacity installed worldwide (2156.5 GWp). According to the BNA, newly installed capacity in Germany amounted to approximately 16.9 GWp in 2024, compared to 15.3 GWp in 2023.
- In 2024, PV accounted for 14.5% of net electricity generation and all renewable energies for around 62%.
- In 2024 GHG emissions of about 51 million tons CO2 equivalents were avoided due to 74 TWh PV electricity consumed in Germany.
- PV system performance has strongly improved. Before 2000 the typical Performance Ratio was about 70%, while today it is around 80% to 90%.
- Today residential and small commercial PV systems are often installed together with battery storage and a charging station for electric vehicles. Due to relative high electricity tariffs in Germany, self consumption is the prevailing business model. The installation of balcony solar systems is another growing trend.
- With increasing generation capacity from solar and wind, the flexible integration of volatile electricity into the grid becomes more important. Grid expansion, load management, smart grids, bidirectional charging of vehicle batteries, etc. must be promoted in order to avoid curtailment of renewable power plants.

Executive Summary

Solar Cell / Module Efficiencies

- The record lab cell efficiency* is 27.4% for monocrystalline and 24.4% for multicrystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 23.4% for CIGS and 21.0% for CdTe solar cells. Record lab cell efficiency for perovskite solar cells is 25.2%.
- In the last 10 years, the efficiency of commercial monocrystalline wafer-based silicon modules increased from about 16% to values over 22%. At the same time, the CdTe module efficiency increased from 9% to 19%.
- In the laboratory, the best performing modules are based on monocrystalline silicon with 25.4% efficiency. Record efficiencies demonstrate the potential for further efficiency increases at the production level.
- In the laboratory, high concentration multi-junction solar cells achieve an efficiency of up to 47.6% today. With concentrator technology, module efficiencies of up to 38.9% have been reached.

* Only official lab record efficiencies with minimum cell area of 1 cm^2 are listed. Latest reference: Solar Cell Efficiency Tables (Version 65), Progress in Photovoltaics: Research and Applications, 10/2024

Executive Summary

Energy Payback Time

- Silicon usage for silicon cells has been reduced significantly during the last 20 years from around 16 g/Wp (in 2004) to about 2.0 g/Wp in 2024 due to increased efficiencies, thinner wafers (140 µm) using diamond wire saws, and larger ingots.
- The Energy Payback Time of PV systems is dependent on the geographical location: PV systems manufactured in Europe and installed in Northern Europe require approximately 1.1 years to pay back the energy input, while PV systems installed in the South require 0.9 years to pay back the energy input, depending on the technology installed and the grid efficiency.
- A PV system located in Sicily using wafer-based silicon modules has an Energy Payback Time of about one year. Assuming a 20-year lifetime, this type of system can produce twenty times the energy invested in it.
- PV modules can be recycled, recovering rare and valuable materials. Further research and development is needed to make these recycling processes more in-depth and cost-effective.

Executive Summary

Price Development

- Due to the coronavirus crisis and the associated disruptions to supply and trade chains, market prices rose noticeably in 2022 and at times some products were not available in sufficient quantities. In 2023 prices fell again and have continued to fall in 2024.
- In Germany, a typical 10 to 100 kWp PV rooftop-system cost around 14,000 €/kWp in 1990. At the end of 2024, such systems cost less than 9% of that in 1990. Over the last 34 years, the compound annual growth rate (CAGR) of net prices was -6.9%.
- The Experience Curve (also called Learning Curve) shows that in the last 44 years the module price decreased by 25.7% with each doubling of the cumulated global module production. Cost reductions result from economies of scale and technological improvements. The global average selling price (ASP) was about 0.13 US$/Wp in 2024.

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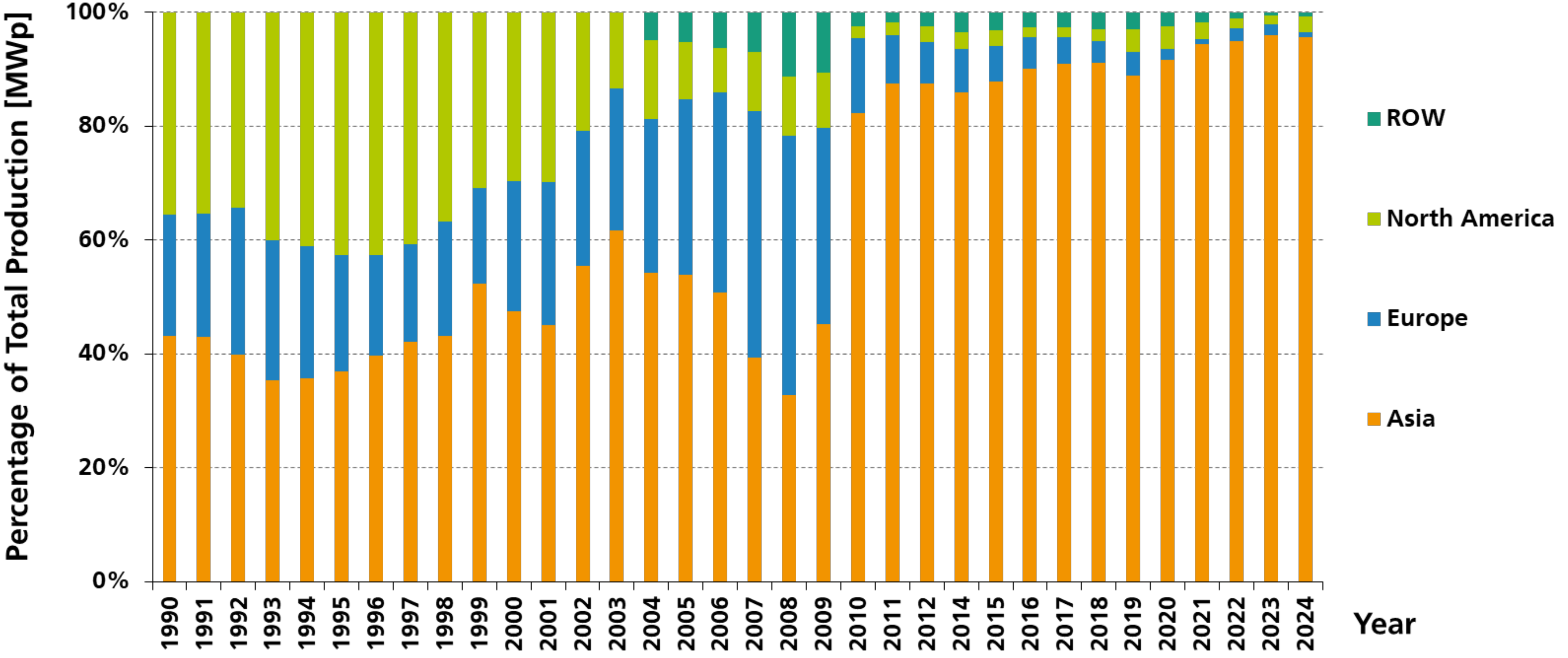
1. PV Market

- By region
- By technology

PV Module Production by Region 1990-2024

Percentage of Total MWp Produced



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 2025 . Date of data: 05/2025

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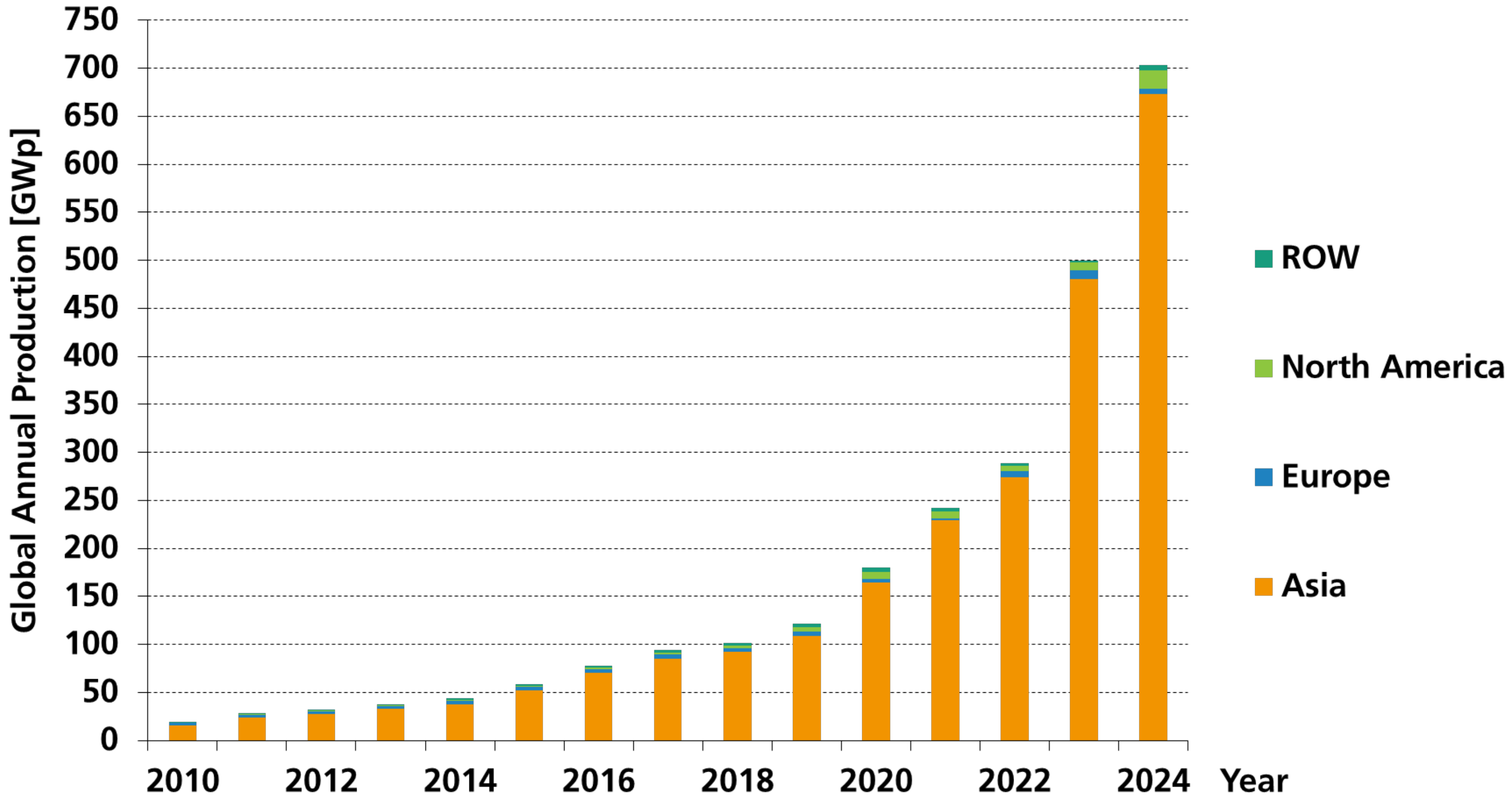
PV Module Production by Region

Global Annual Production



Annual Production Today

Annual production has increased 14-fold over the past decade. In 2024, approximately 96% of solar modules and their components came from Asia, primarily from China with a module production share of about 80%, which also controls more than 95% of the market for certain components, such as ingots and wafers.

Data from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 estimates basaed on IEA and other sources. Graph: PSE Projects GmbH 2025. Date of data 05/2025

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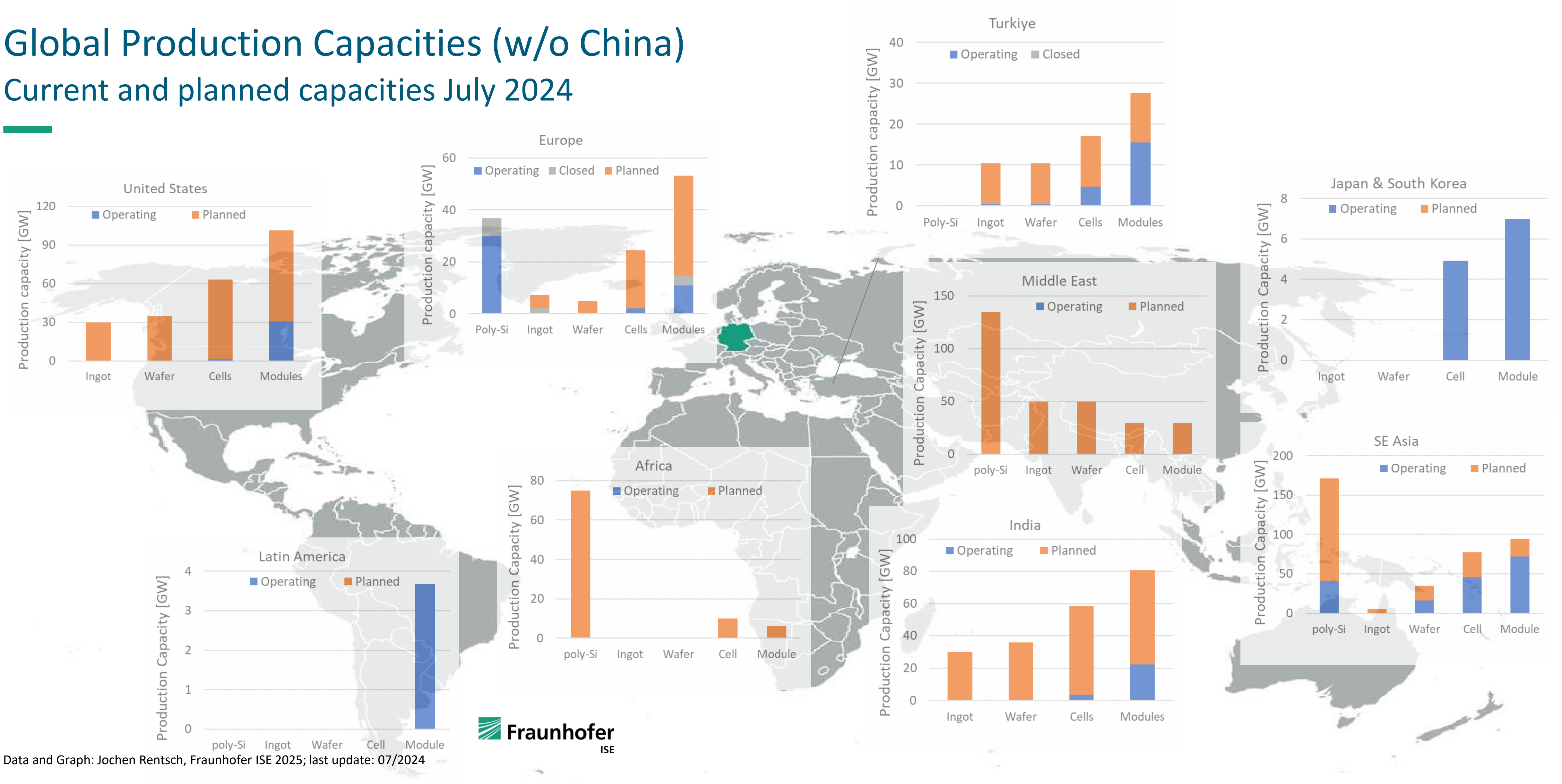
Global Production Capacities (w/o China)

Current and planned capacities July 2024



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Data and Graph: Jochen Rentsch, Fraunhofer ISE 2025; last update: 07/2024

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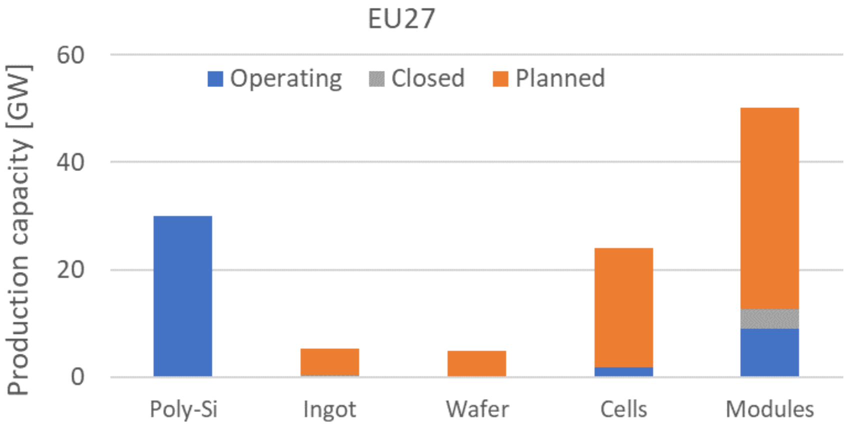
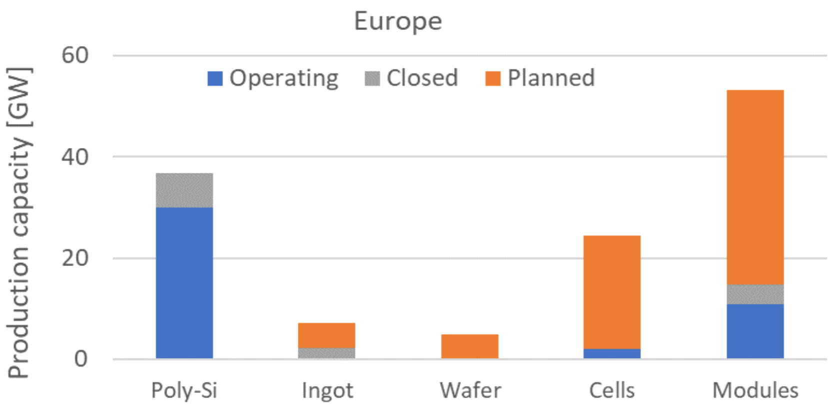
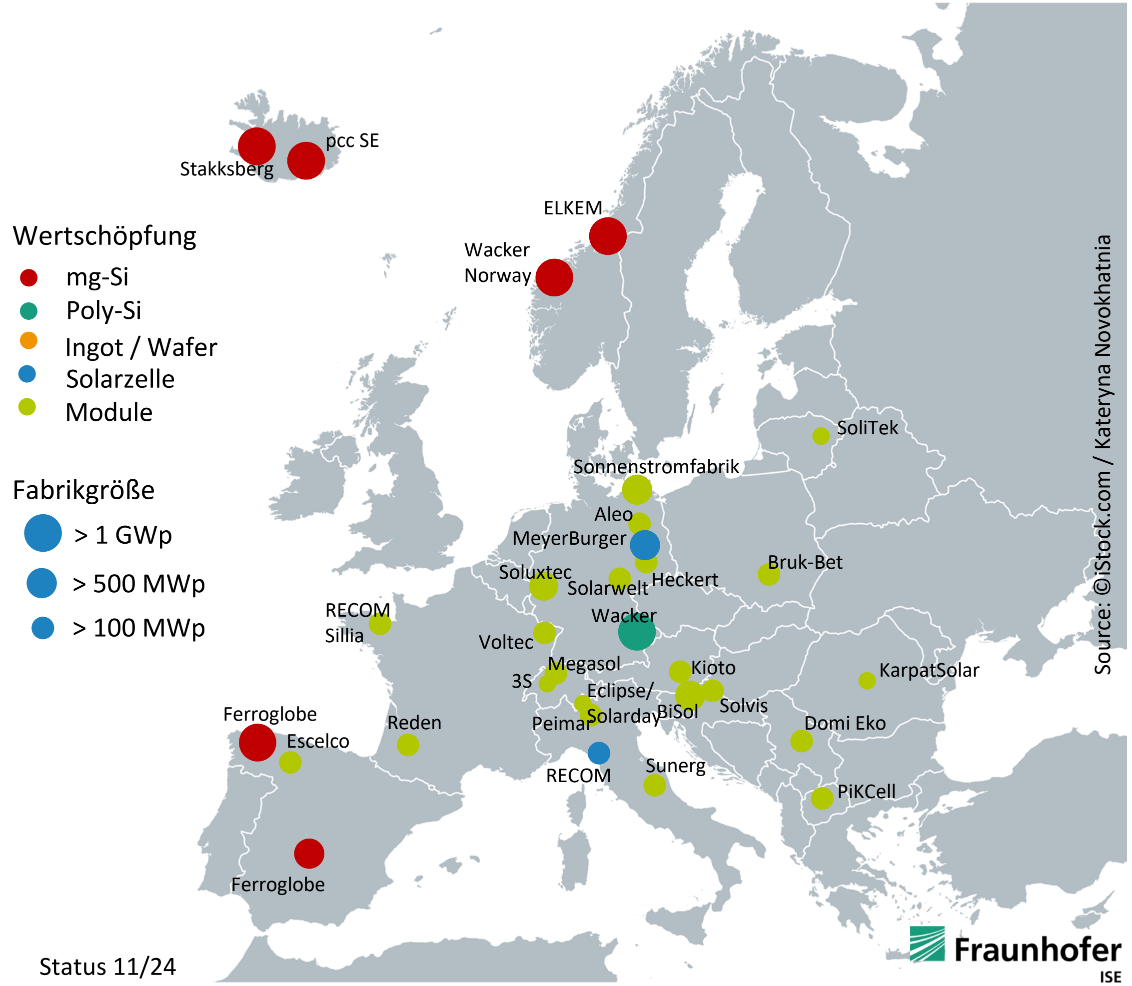
EU PV Manufacturing Landscape – Status Quo

November 2024







* currently 2,100 kg/MWp poly-Si necessary for Ingot production
** majority of EU produced poly-Si is sold into the semiconductor industry
*** currently 3.150 kg/MWp mg-Si necessary for Ingot production

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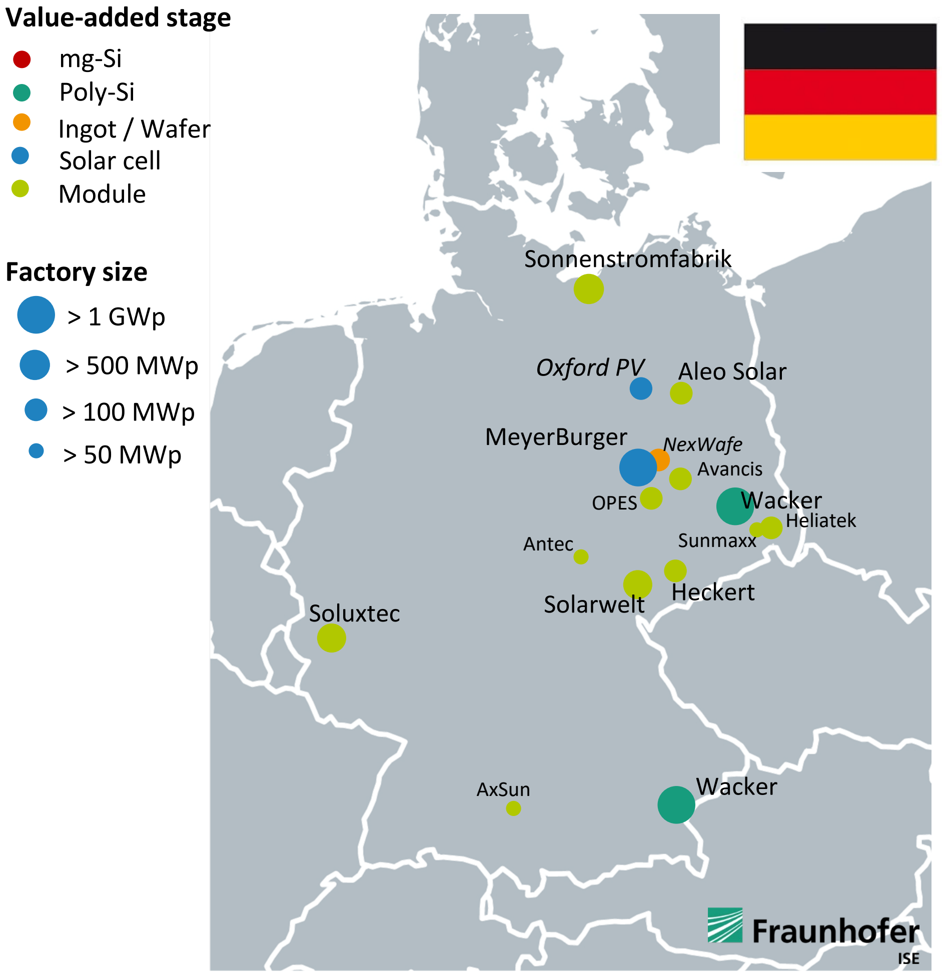
PV Production in Germany - Status Quo

PV Module Suppliers – November 2024

Company	Location	Capacity [MW]	Website
Soluxtec	Bitburg	1200	https://www.soluxtec.de/
Sonnenstromfabrik	Wismar	525	https://www.sonnenstromfabrik.com/de/
Solarwelt (Heckert)	Langenwetzendorf	400	https://www.heckertsolar.com/standort-lwd/
Heckert Solar	Chemnitz	400	https://www.heckertsolar.com
Aleo Solar	Berlin	300	https://www.aleo-solar.de/
Heliatek	Dresden	250	https://www.heliatek.com/de/
OPES	Zwenkau	200	https://www.opes-solutions.com/de/
Avancis	Torgau	100	https://www.avancis.de/
AxSun	Laupheim	50	https://www.axsun.de/
Sunmaxx	Ottendorf-Okrilla	50	https://sunmaxx-pvt.com/de
Antec Solar	Arnstadt	50	https://www.antec.solar/

Data and Graph: Jochen Rentsch, Fraunhofer ISE 2025; last update: 11/2024



Source: ©iStock.com / Kateryna Novokhatnia

Status 11/24

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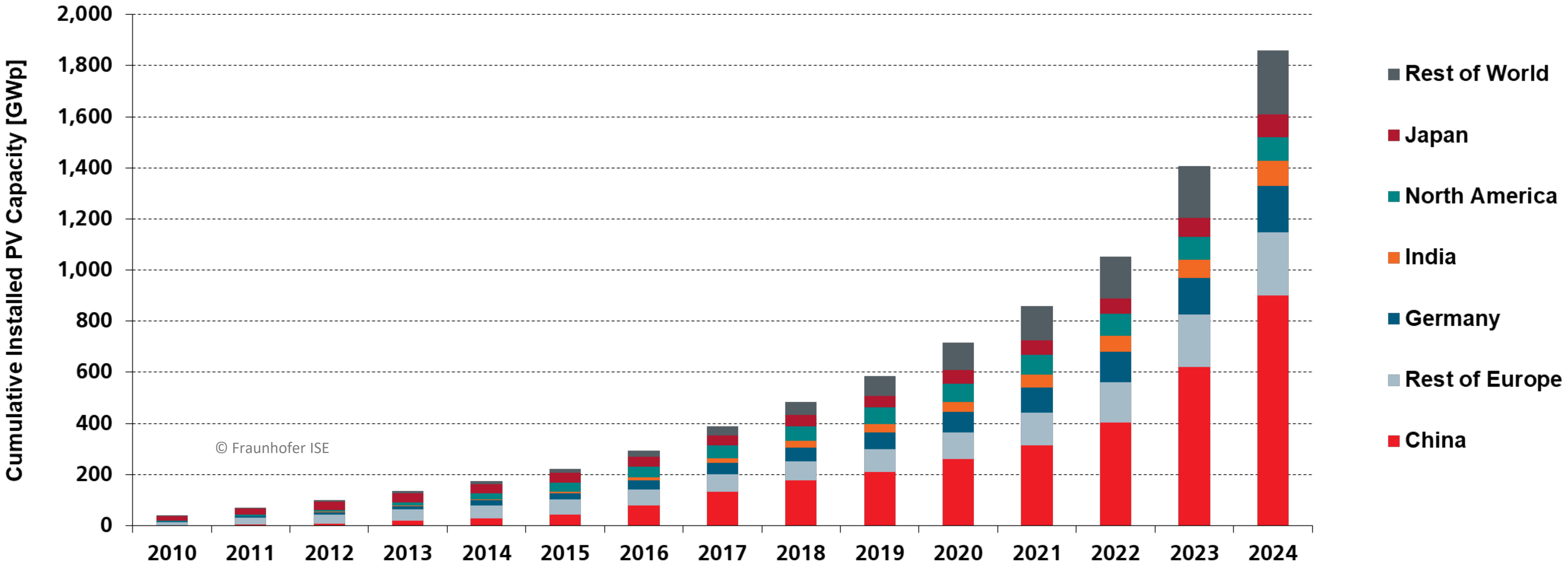
Global Cumulative PV Installation
By Region



Note: Cumulative installed capacity is considered here as ‘aggregate annual additions.’

Data: IRENA 2025. Graph: PSE Projects GmbH 2025. Date of data: 24.03.2025

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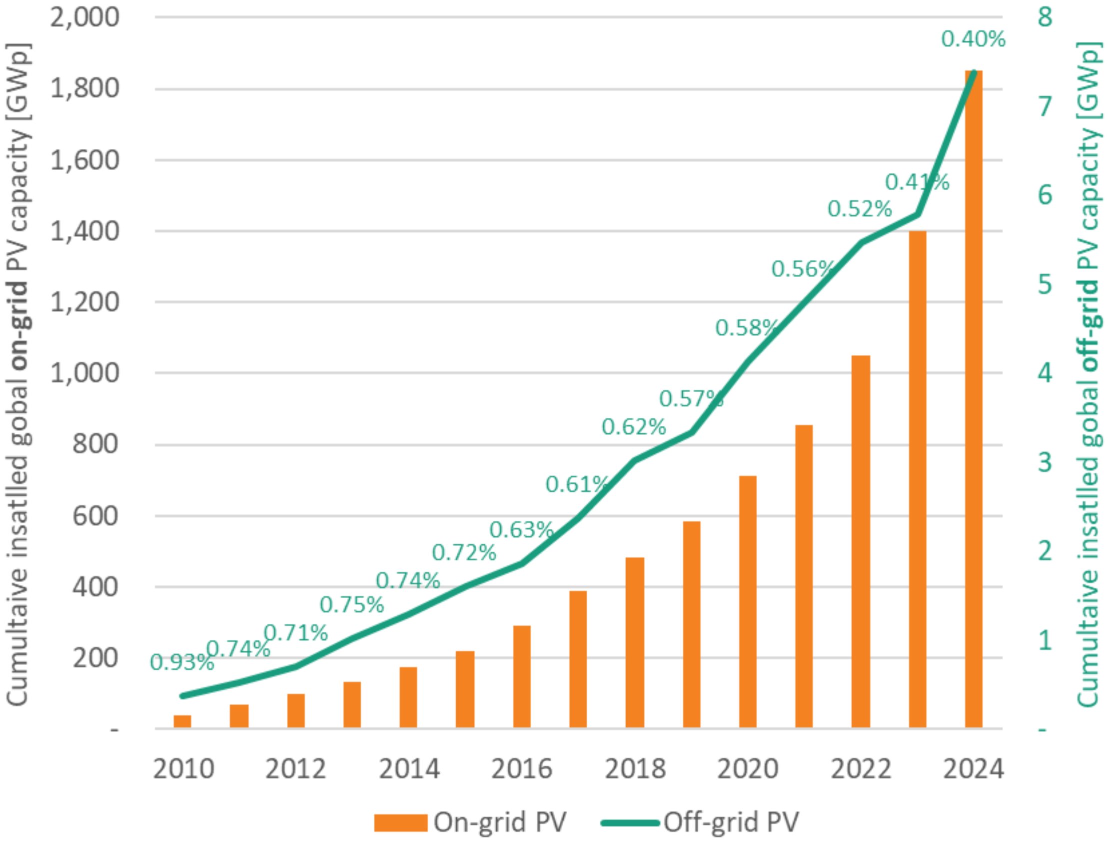
Global Cumulative PV Installation

Cumulative Installed On-Grid and Off-Grid Capacity (2010-2024)



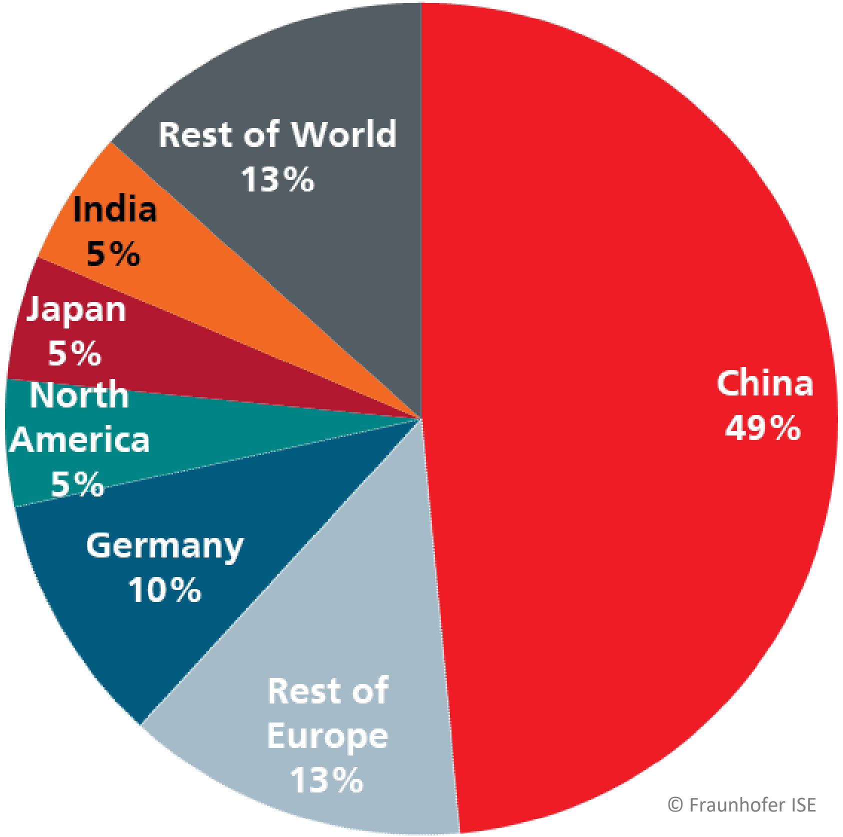
Data: IRENA 2025. Graph: PSE Projects GmbH 2025. Date of data: 04/2025

Percentages show share of cumulative off-grid PV installations in relation to total cumulative PV installations. Approximately 99.6% of today’s installed PV capacity is connected to the grid.

The proportion of off-grid systems compared to the total cumulative systems has roughly halved over time from just under 1 % in 2010 to 0.40 % in 2024.

Global Cumulative PV Installation by Region

Status 2024



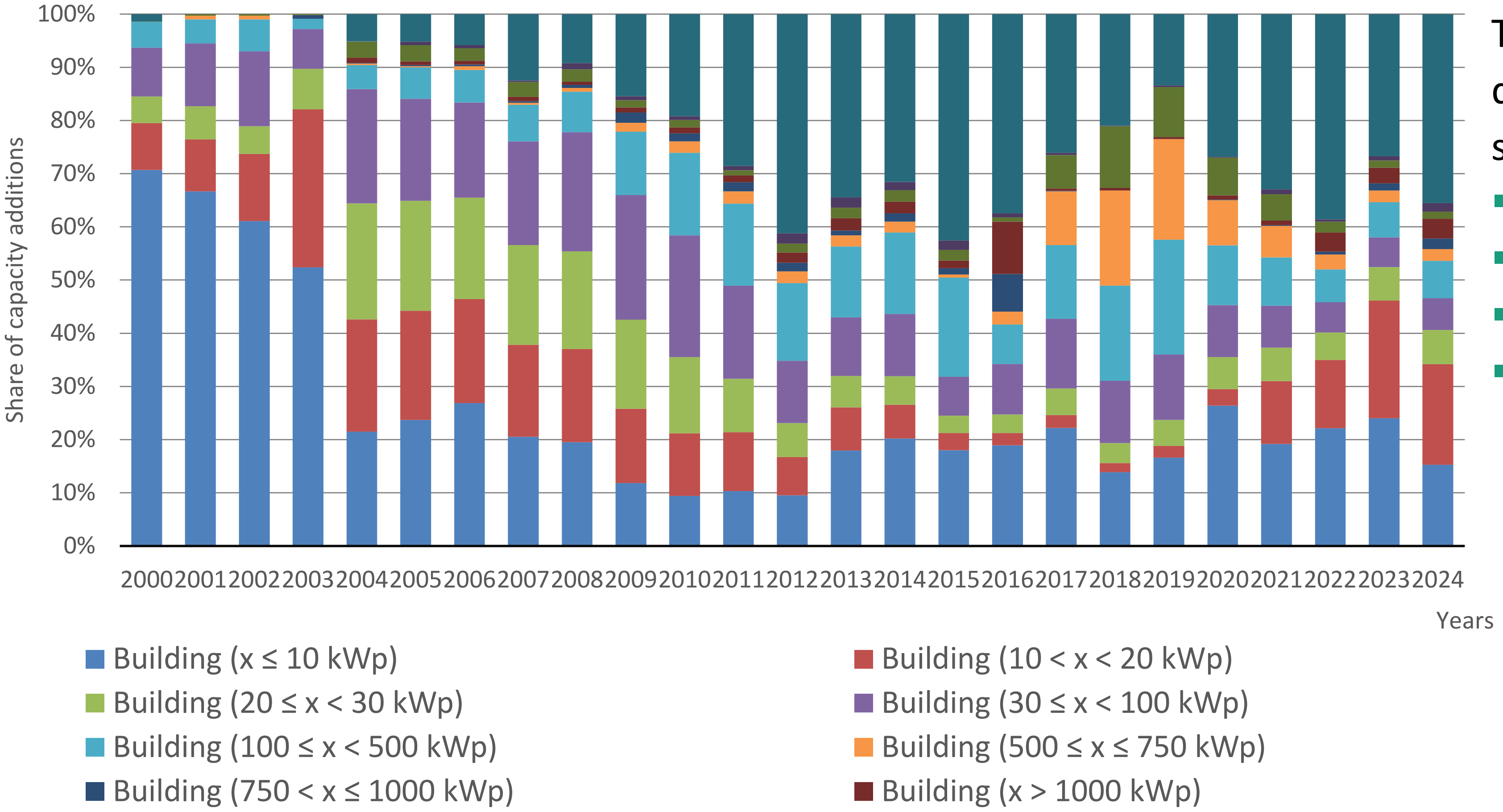
The total cumulative installations amounted to about 2,156.5 GWp according to IEA-PVPS at the end of year 2024; IRENA reports 1,858.6 GWp.

All percentages are related to global installed PV capacity, including off-grid systems.

Source: IEA-PVPS Snapshot of Global Market; Data: IRENA 2025. Graph: PSE Projects GmbH 2025. Date of data: 24.03.2025

Annually Installed PV System Capacity in Germany

Percentage of Annual Capacity by System Size



The annual distribution of the different system size categories strongly depends on current:

- regulations
- market incentives (like EEG)
- tender procedures
- bankability (trust of investors)

Note:

“Building” includes roofs, facades and plug-in systems.

“Ground-mounted” includes bodies of water, parking lots and other structures.

Source until year 2020: Fraunhofer ISE, own calculations based on EEG-master and -flow data (netztransparenz.de, Sept. 2021)
Source since 2021: Fraunhofer ISE, own calculations based on MaStR (Date: 05.05.2025) and data validation algorithm

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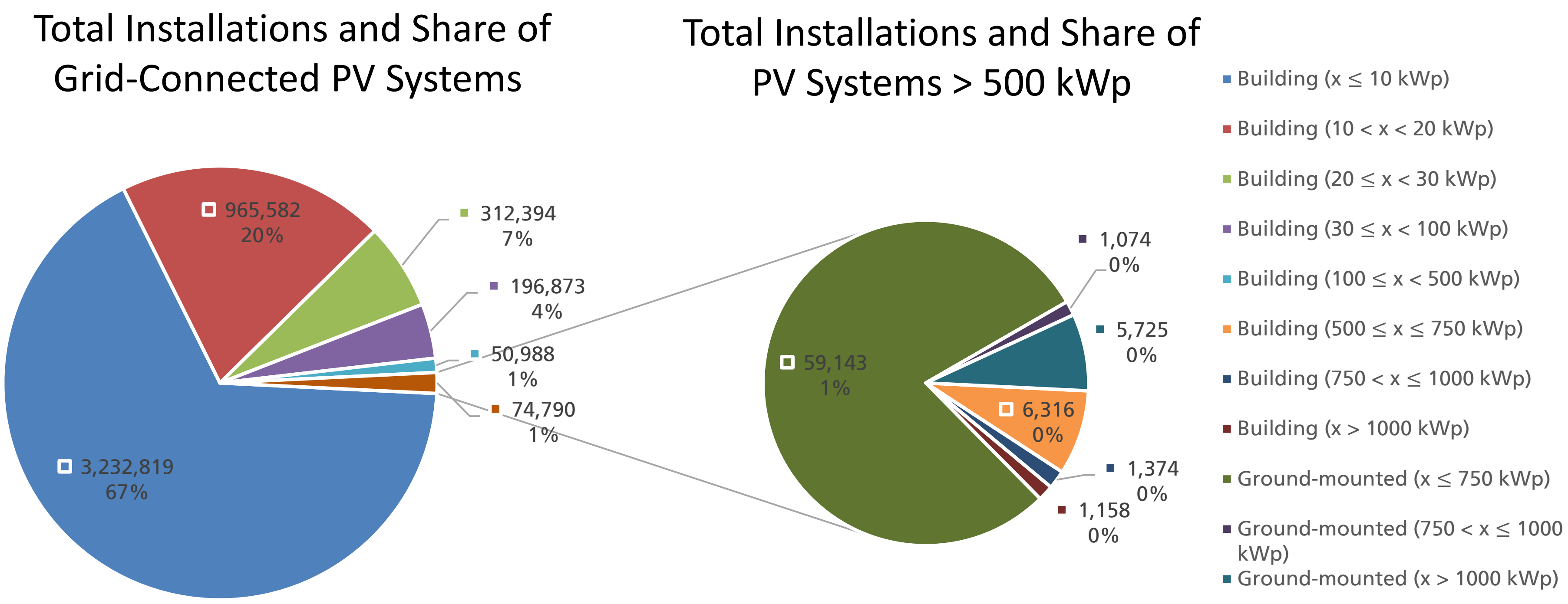
Number of Total Cumulative PV Installations by System Size in 2024

Germany



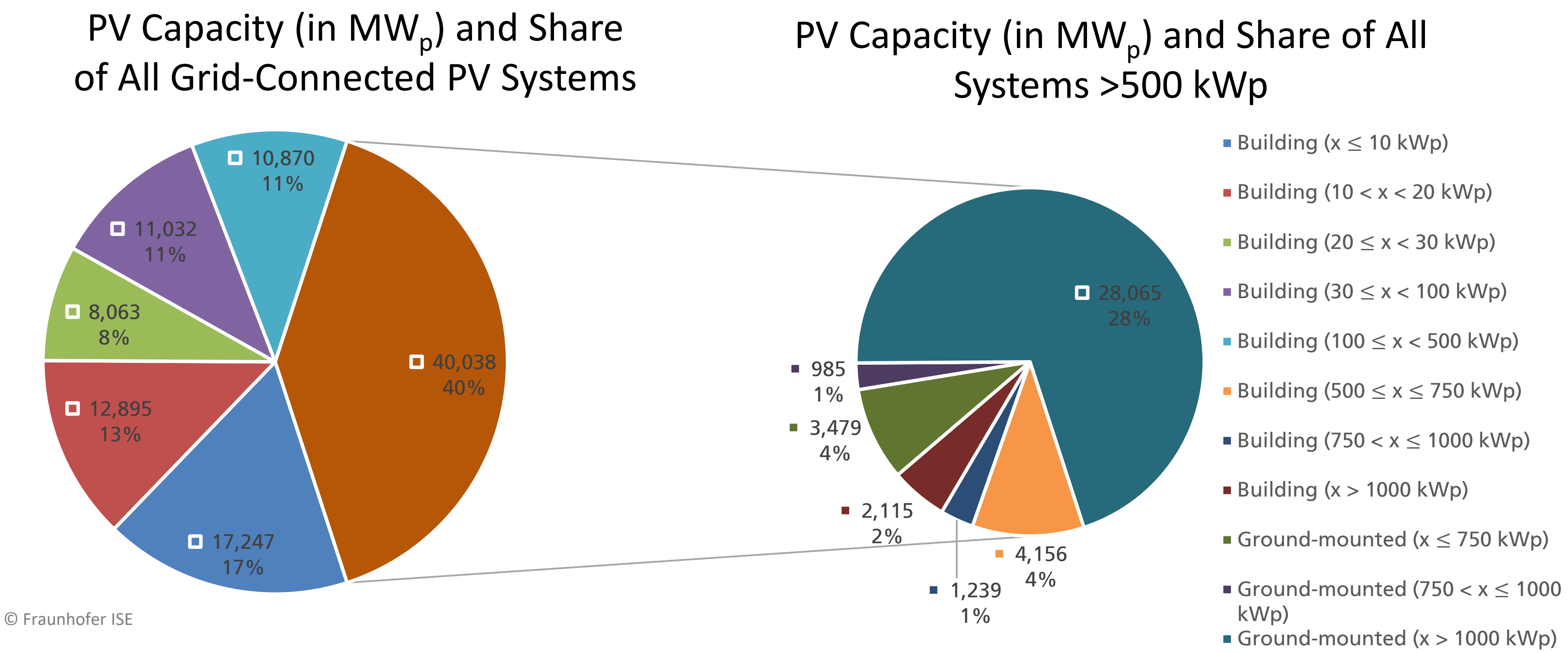
At the end of 2024, about 4.8 million grid-connected PV systems were installed in Germany.

Note:
In 2024, around 800,000 plug-in systems (up to 800 W feed-in power from so-called balcony PV systems), were registered in Germany.
Due to underreporting, the actual number is estimated to be around 3 million installed systems. [1]

Source: Fraunhofer ISE, own calculations based on MaStR (Date: 05.05.2025) and data validation algorithm
[1] Includes reported plug-in systems and systems assigned to this category according to MaStR (Date: 05.05.2025) and additional estimates by Fraunhofer ISE

Total Cumulative Capacity of PV Installations by System Size in 2024

Germany



At the end of 2024, total cumulative PV capacity in Germany amounted to around 100.1 GWp.

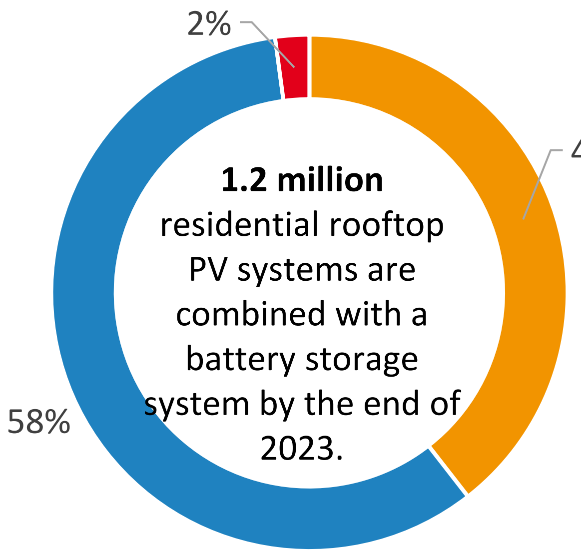
Note:
Balcony solar systems (up to 800 W feed-in power) accounted for 720 MW_p in 2024. These were mostly within the building PV system class ($x \leq 10\ kW_p$), [1].

Source: Fraunhofer ISE, own calculations based on MaStR (Date: 05.05.2025) and data validation algorithm
[1] Includes reported plug-in systems and systems assigned to this category according to MaStR (Date: 05.05.2025) and additional estimates by Fraunhofer ISE

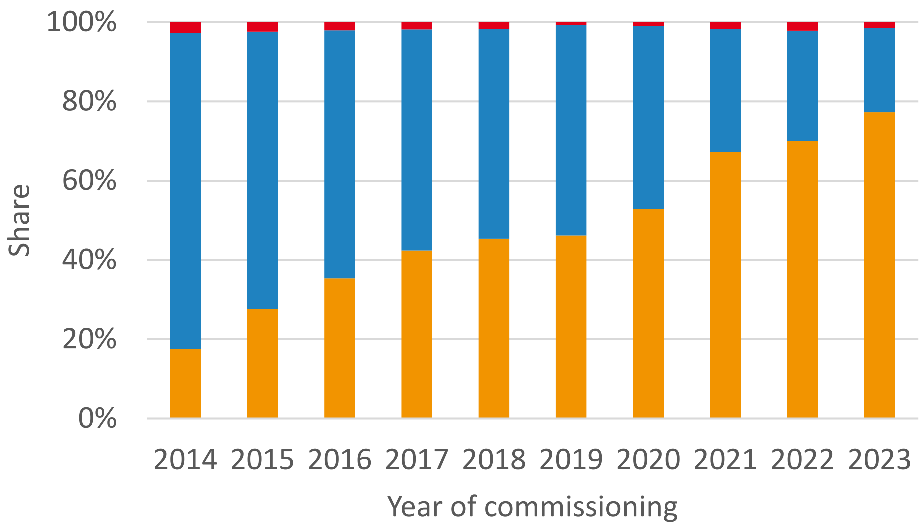
Share of Residential Rooftop Systems with and without Battery Storage

Germany

Share at the End of 2023



Share in Year of Commissioning



■ PV systems with battery storage ■ PV system without battery storage ■ Unknown

By the end of 2023, over 1.2 million units, or 40 percent of all residential PV systems have a battery energy storage system (BESS).

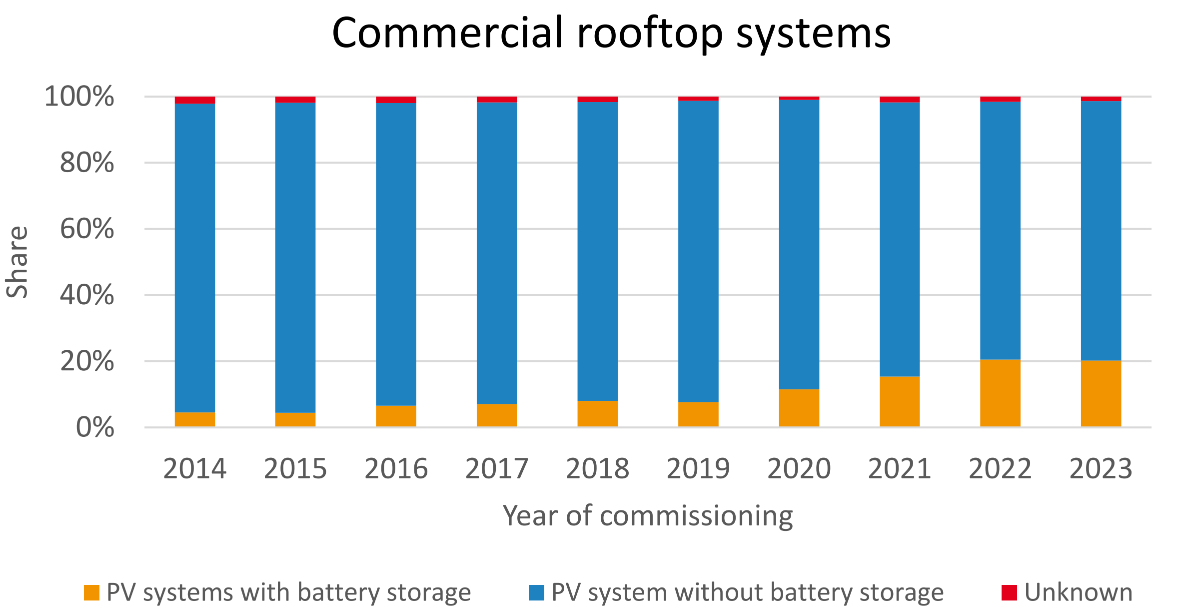
The share of commissions for residential rooftop PV systems with BESS increased from <20% in 2014 to nearly 80% in 2023.

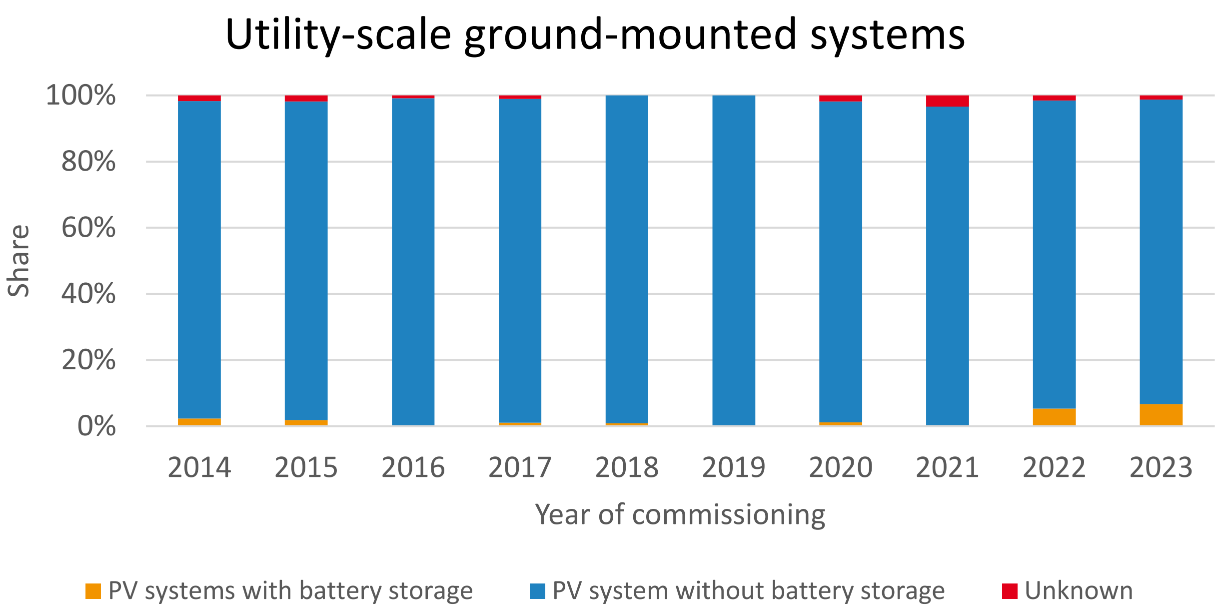
Note:
Residential rooftop PV systems are defined as all systems on buildings with a maximum capacity of 30 kWp according to MaStR-Data.

Source: Marktstammdatenregister - MaStR (Date: 01.04.2024)

Share of PV Installations with and without Battery Storage, BESS

Commercial Rooftop and Utility-Scale Systems in Germany





The share of commissions for PV installations with BESS increased from 5% in 2014 to 20% in 2023 in the com-mercial rooftop sector.

In 2022 and 2023 there was a significant increase in commissions for PV with BESS, reaching a share of around 7% in the utility-scale PV power plant sector.

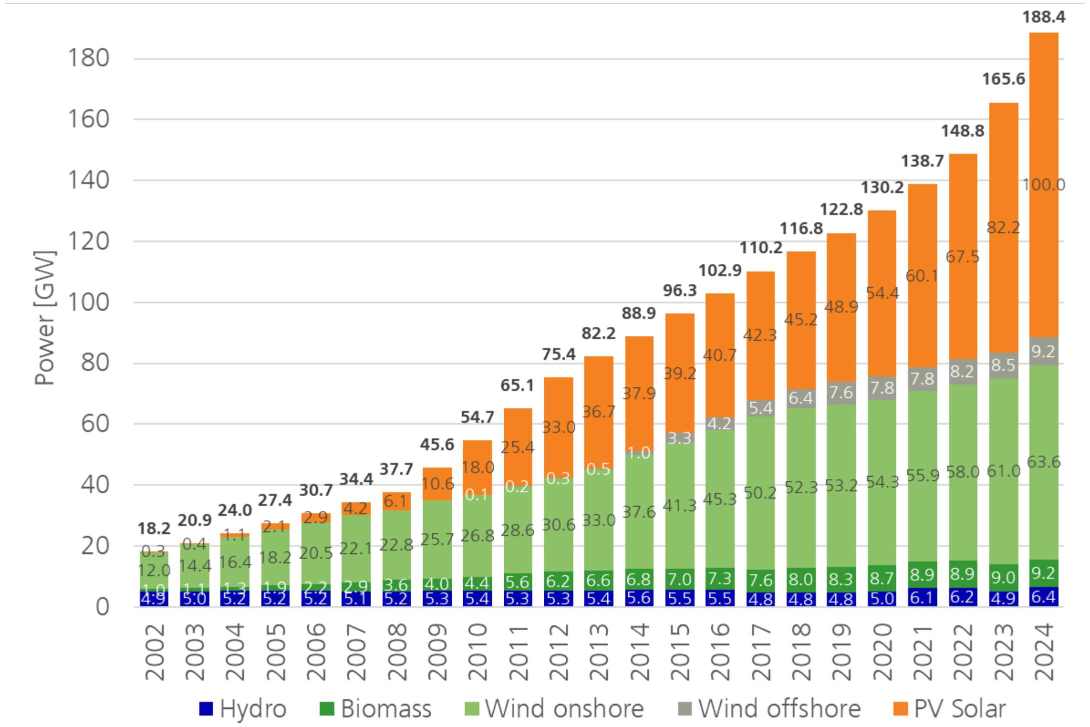
Note: Commercial rooftop PV systems are defined as all systems on buildings with a capacity greater than 30 kWp according to MaStR-Data.

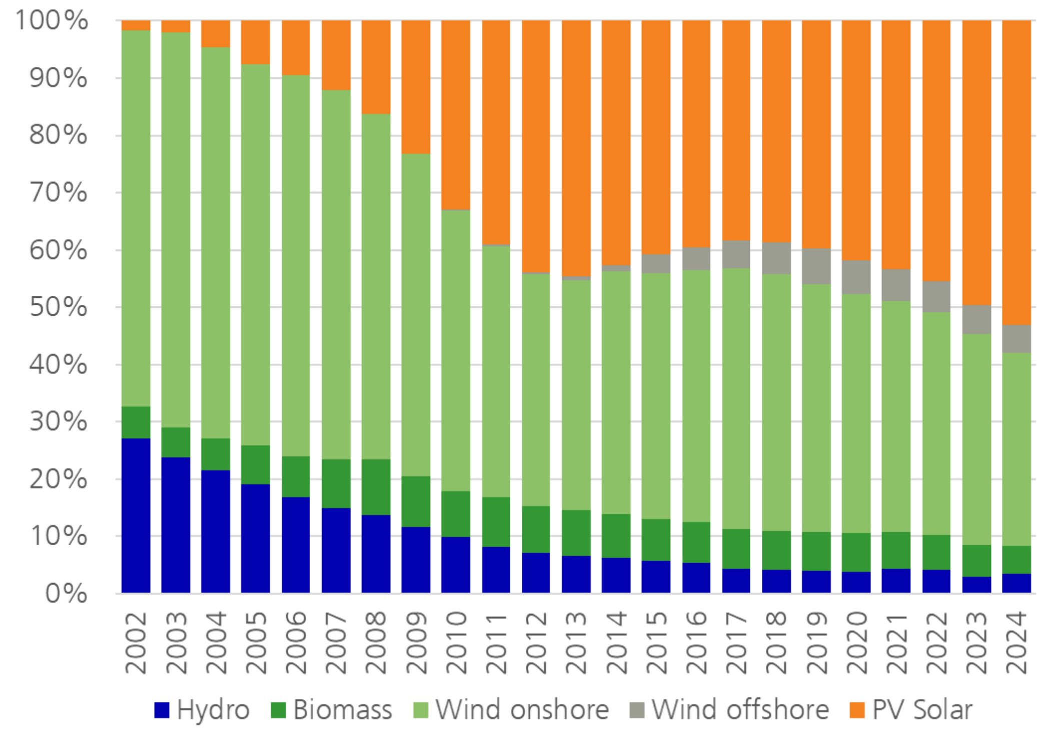
Note: Utility-scale ground-mounted PV systems are defined as all ground-mounted systems with a capacity greater than 1 MWp according to MaStR-Data.

Source: Marktstammdatenregister - MaStR (Date: 05.05.2025)

Electrical Capacity of Renewable Energy Sources (RES)

Germany





Renewable energy sources accounted for 188.4 GW of the total 263.9 GW net installed electricity generation capacity in Germany in 2024, resulting in a RE share of 71.4% of total capacity.

Data:: Energy Charts by Prof. Dr. Bruno Burger. Date of data: 03/2025

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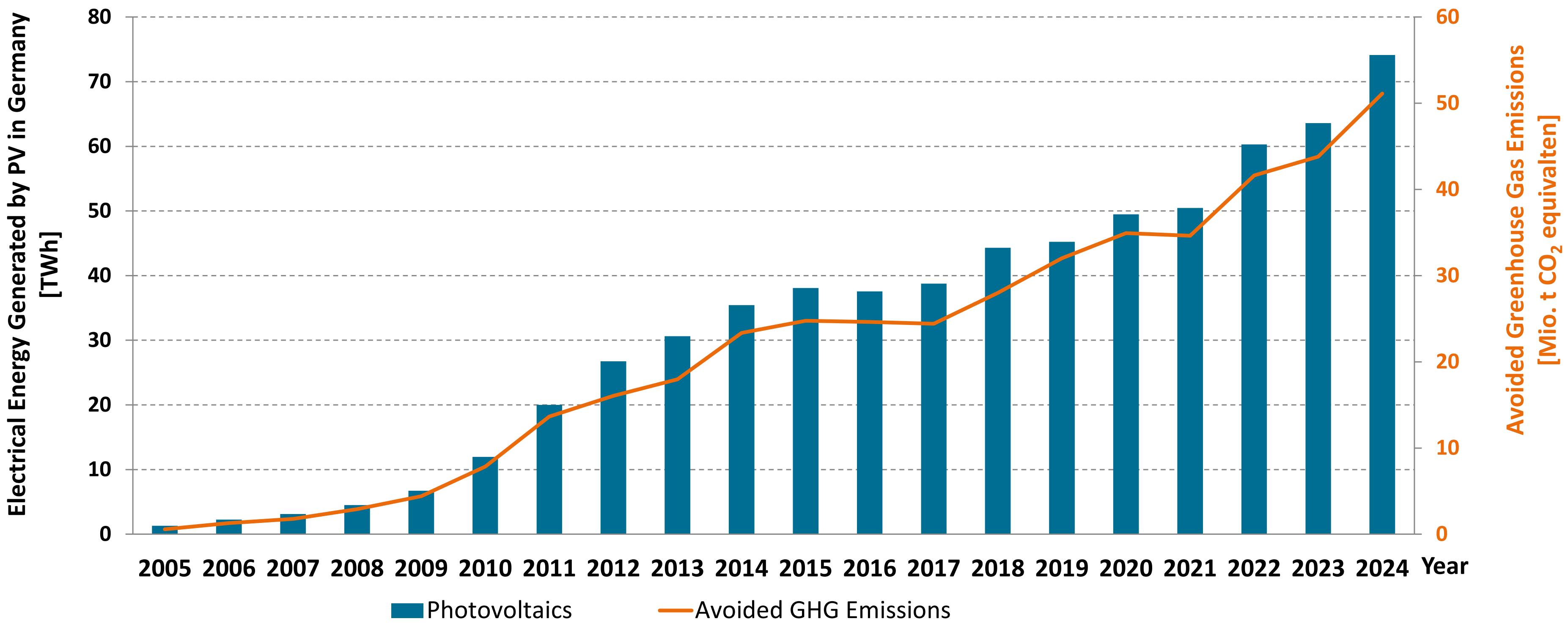
PV Energy Generated and Resulting GHG Emissions Avoided

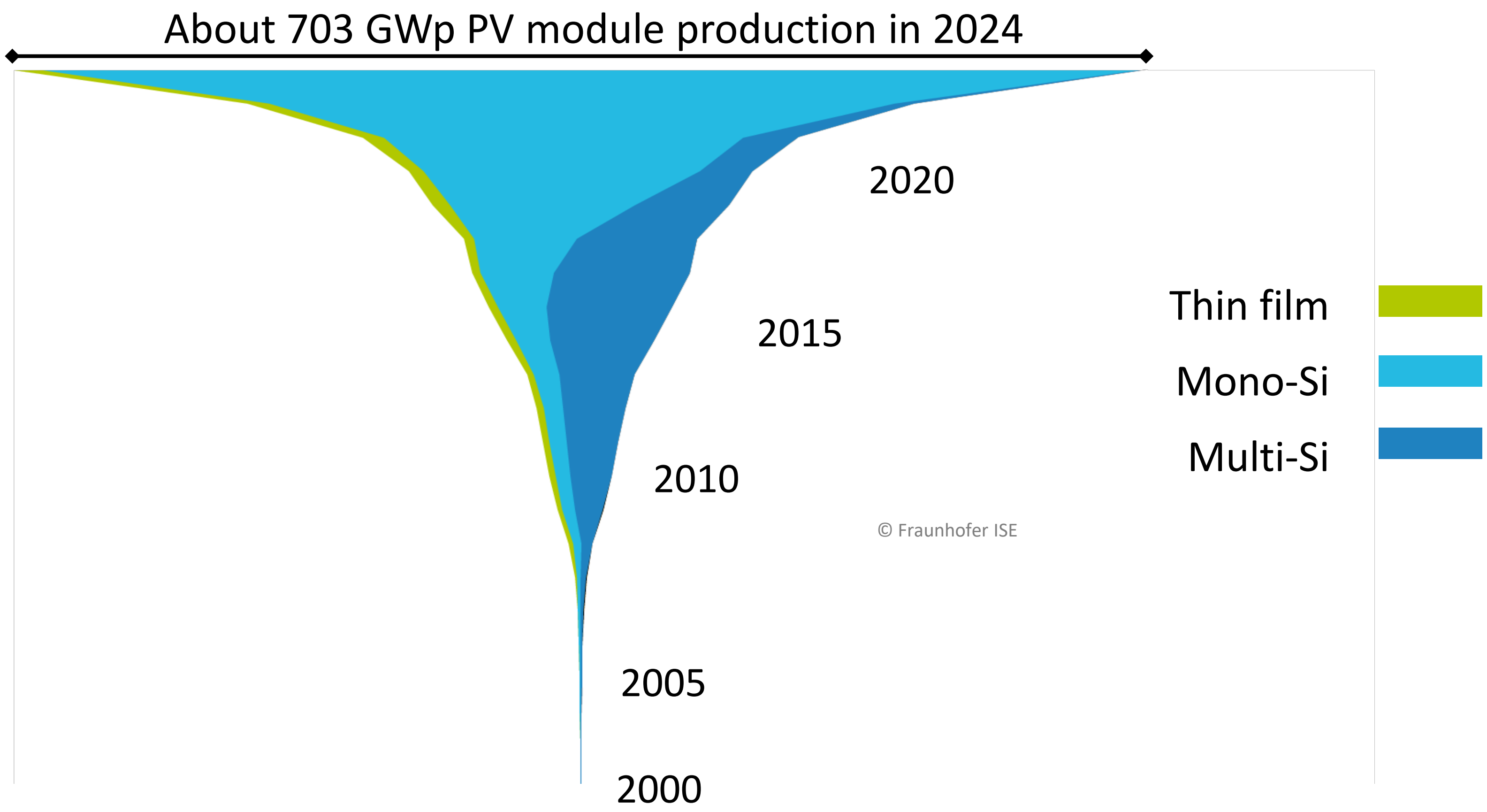
Germany



In 2024, greenhouse gas emissions of about 51 Mio. t CO_2-equivalent were avoided due to 74 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 04/2024. Graph: PSE Projects GmbH 2025

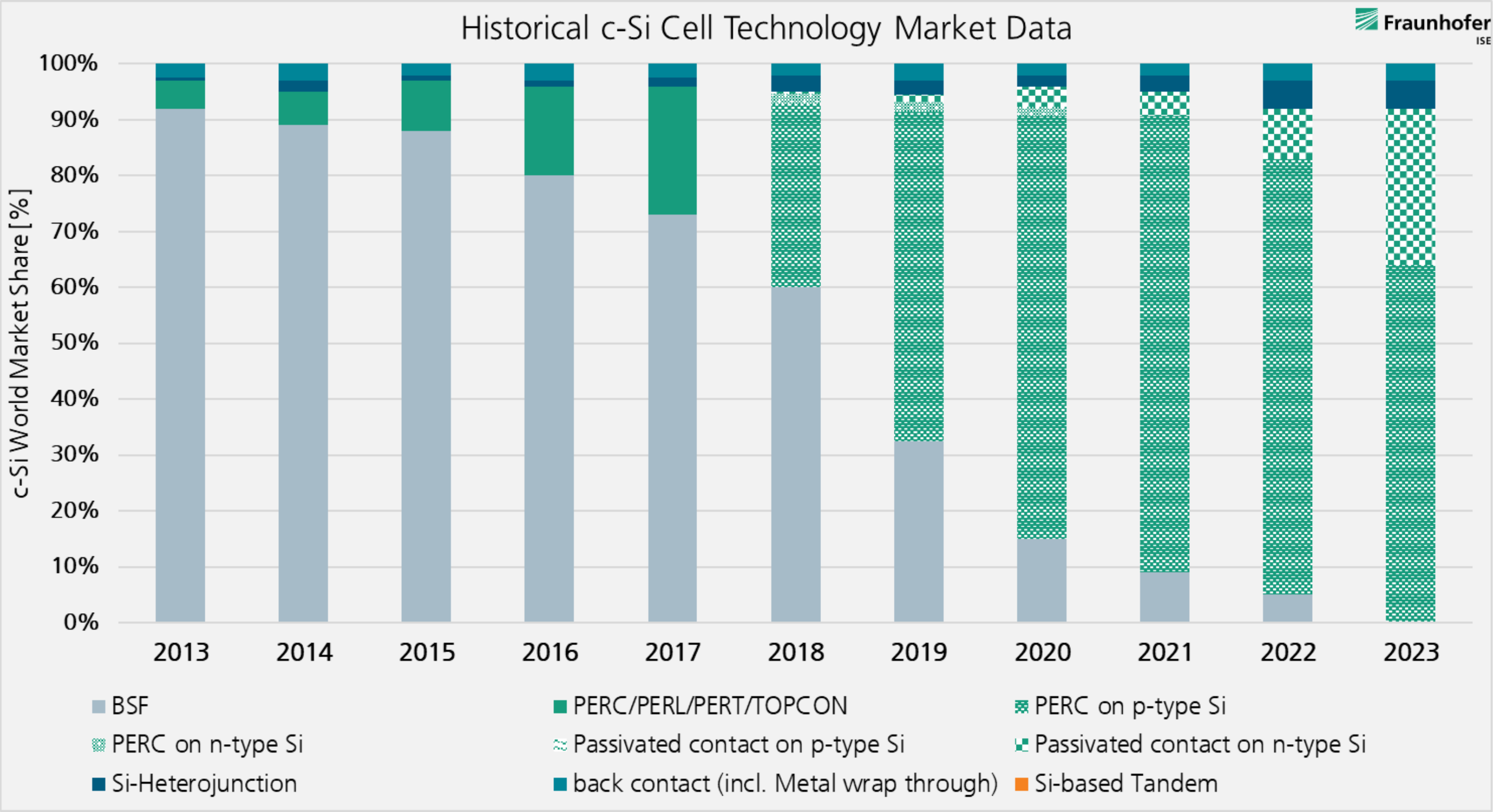
Annual PV Production by Technology
Worldwide (in GWp)



Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; from 2022; VDMA for 2024: ISE; Graph: PSE Projects GmbH 2025

Technology Overview

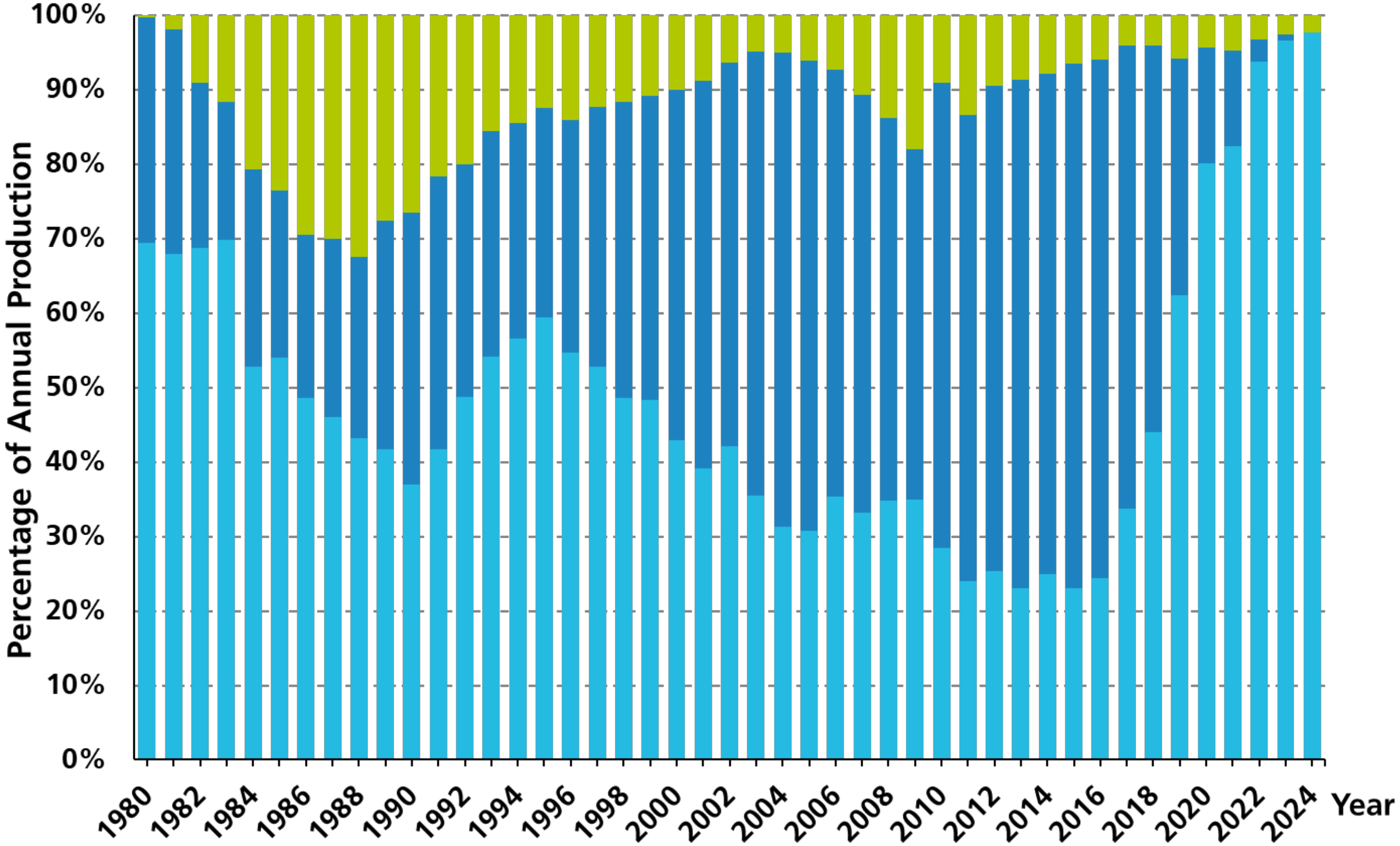
Different crystalline-Silicon Cell Technology Market Shares



Source: based on ITRPV 2013-2024

PV Production by Technology

Percentage of Global Annual Production



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 2025 . Date of data: 05/2025

Production 2024 (GWp)

Thin film*	16	
Multi-Si	0	
Mono-Si	687	
Total	703	(ITRPV)

*only First Solar and Avancis were considered in totaling the thin film technology.

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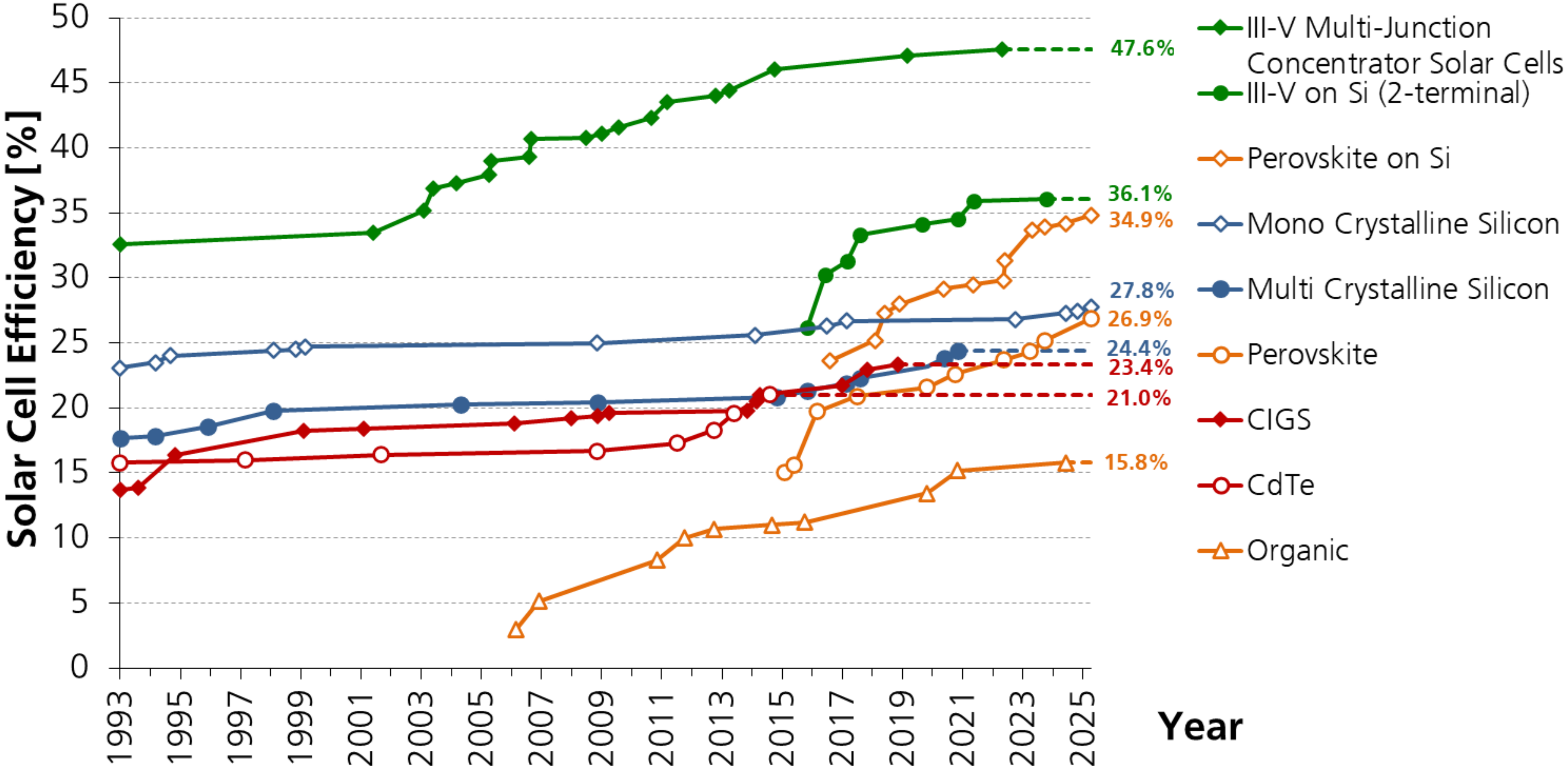
2. Solar Cells / Modules / System Efficiency

- Development in the Laboratories
- Development in the PV Industry
- Performance Ratio (PR)

Development of Laboratory Solar Cell Efficiencies

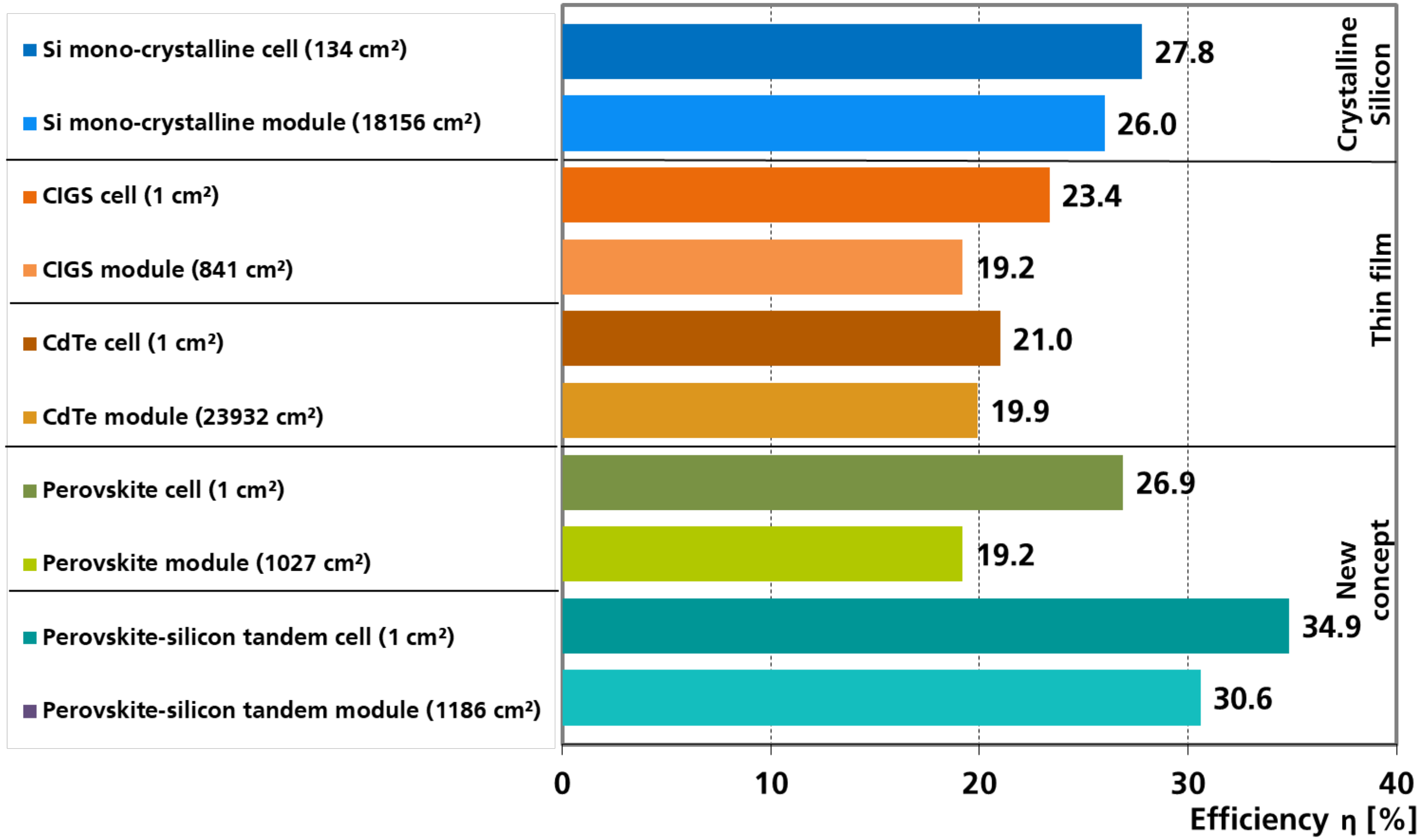


Data: Solar Cell Efficiency Tables (Versions 1 to 66), Progress in Photovoltaics: Research and Applications, 1993-2025. Graph: Fraunhofer ISE 2025. Date of data: 04/2025

Only official lab record efficiencies published in the Solar Cell Efficiency Tables, Progress in Photovoltaics: Research and Applications are included in the graph.

Efficiency Comparison of Technologies

Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables (Version 66), Progress in PV: Research and Applications 2025. Graph: PSE Projects GmbH 2025. Date of data: 04/2025

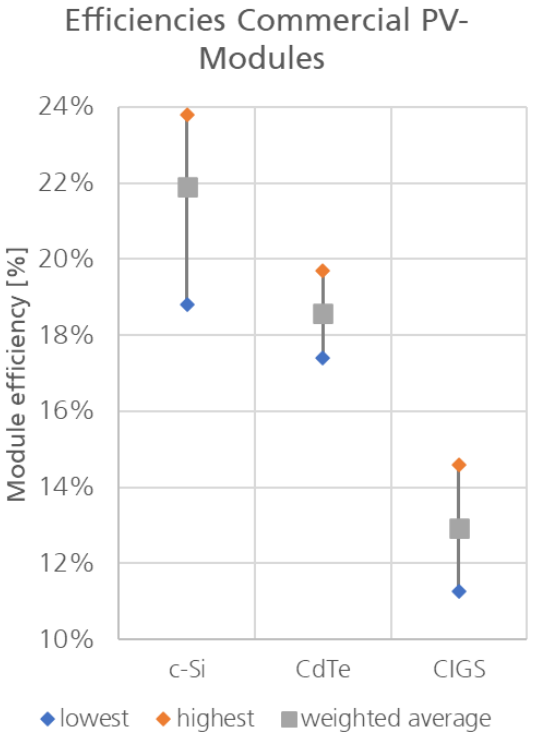
Note: In mass production, the cell-to-module ratio (CTM) improved in past years by reducing losses and using possible gains when integrating solar cells in modules.

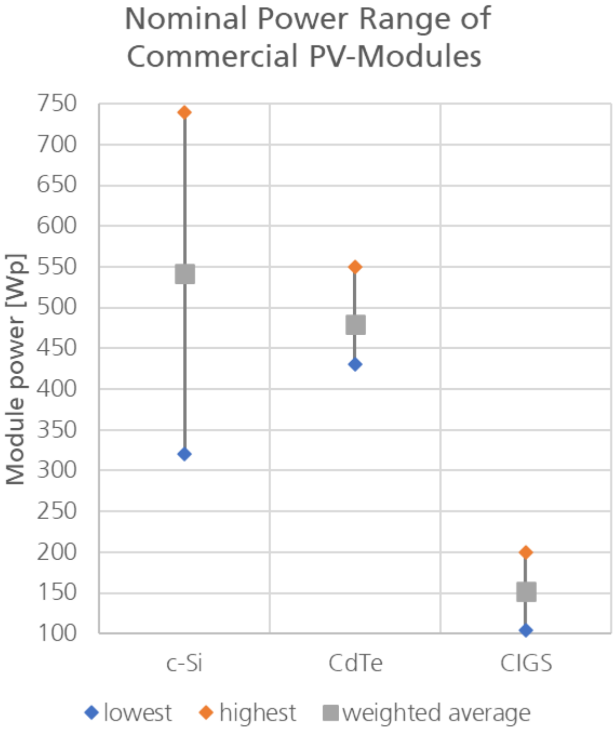
Fraunhofer ISE provides the software suite SmartCalc.CTM for determining precise Cell-to-Module (CTM) power loss analyses. Geometrical losses, optical losses and gains as well as electrical losses are considered in the analysis.

www.cell-to-module.com

Current Efficiencies and Power of Commercial PV Modules

Sorted by Technology





- Total weighted average efficiency of crystalline Silicon (c-Si) wafer-based modules is 22.0% in Q4-2024 (21.6% in Q4-2023); weighting factor is total shipments in year 2023. Lowest module efficiency in this group is 18.8% (17.4% one year before) and highest value is 23.8% (23.3% in 2023).
- Top 10 manufacturers represent about 85% of total shipment volume in 2023 and origin mainly in Asia.
- n-type TopCon and Heterojunction replaces p-type PERC technology.

Note: The selection is based on modules from the top 10 manufacturers in 2024, with module data sheets available worldwide at the end of October 2024. For CdTe, only data from First Solar and for CIGS technology, only modules from Avancis have been considered due to limited number of suppliers. Some products for Building-Integrated PV (BIPV) have not been considered.

Data Source: company product data sheets; Graph: PSE Projects GmbH 2025; Date of data: 10/2024

3. Life Cycle Assessment (LCA) and Sustainability Aspects

- Silicon usage, wafer thickness and kerf loss for c-Si
- Energy Payback Time EPBT: Development and comparison

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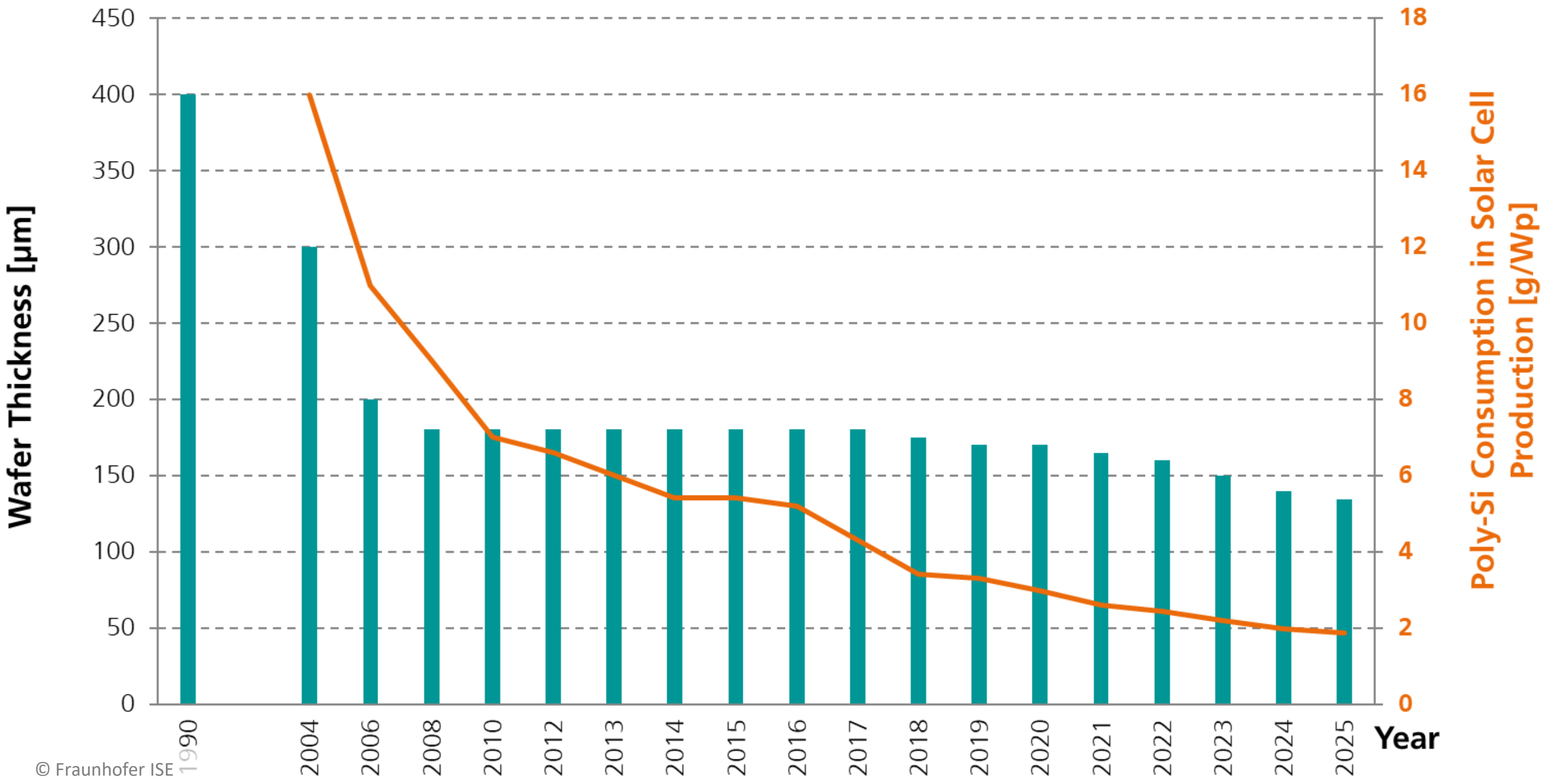
c-Si Solar Cell Development

Wafer Thickness [µm] & Silicon Usage [g/Wp]



Polysilicon consumption in solar cell production (in grams per watt-peak) has decreased by almost 10% year-on-year since 2004 due to:

- reductions in wafer thickness
- kerf loss, and
- by process optimizations such as recycling silicon from kerf loss
- Progress in cell efficiency also has impacted the specific silicon usage.

Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV; ; from 2016 ISE without recycling of Si; from 2017 ongoing with recycling of Si. Graph: PSE Projects GmbH 2025

Energy Payback Time: Historical Trend

Harmonized Study Data for Monocrystalline Silicon Rooftop PV Systems

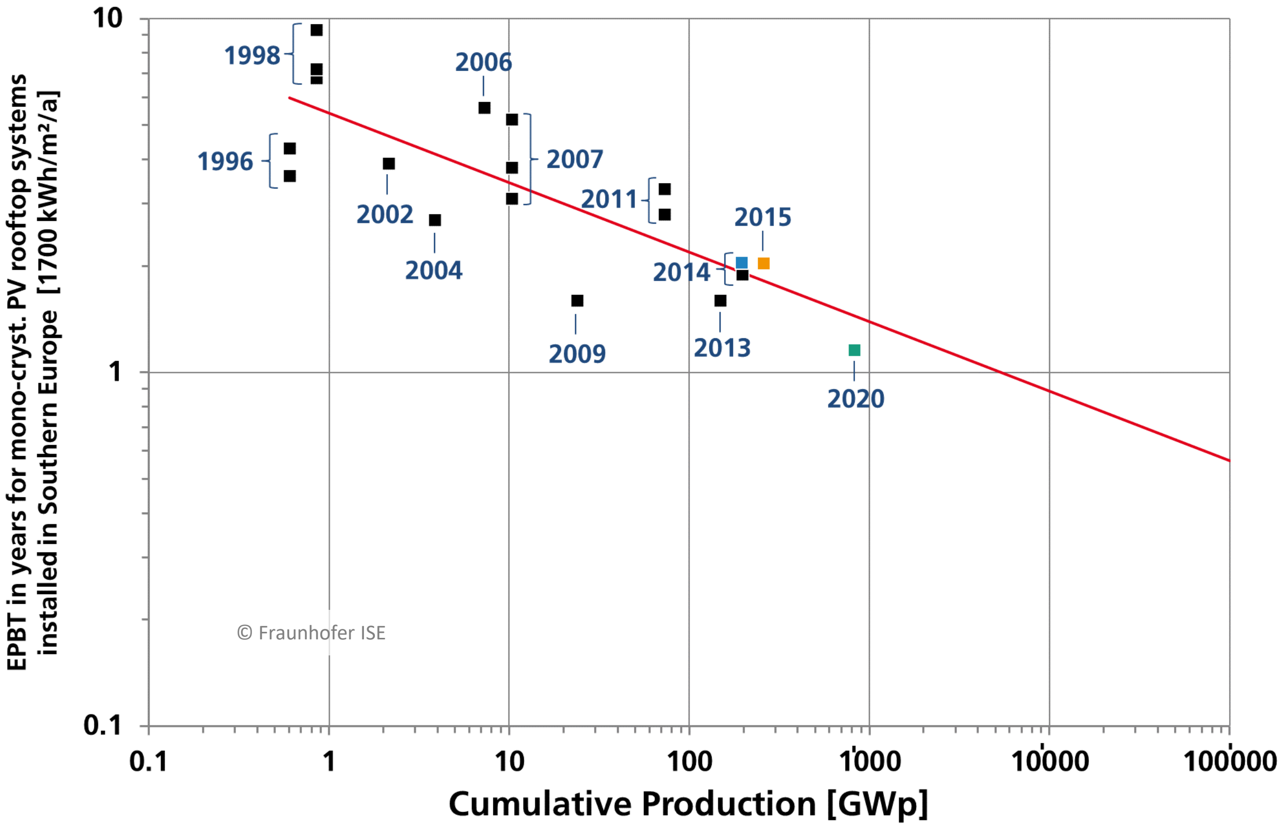
Learning Rate:

Each time the cumulative production doubled, the EPBT went down by 12.8 % over the last 24 years.

Harmonization methodology
based on Koppelaar (2016) harmonized results and harmonization parameters

1) Performance Ratio	
based on average annual PV yield during lifetime	
PV system lifetime	25
Degradation	0.70%
PR (initial)	80%
PR (incl. average degradation during lifetime)	**73.6%**
2) Grid efficiency	
for converting PV yield in primary energy equivalents	
grid efficiency	**35%**

EPBT of Leccisi (2016), Louwen (2014) and Friedrich (2020) were harmonized with 1) PR (incl. average degradation) and 2) grid efficiency to results of Koppelaar (2016)*



Data: Fraunhofer ISE. Graph: PSE Projects GmbH 2021

Irradiation: 1700 kWh/m²/a at an optimized tilt angle; **Years:** Estimated average year of original data

* Koppelaar (2016) - Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization, Renewable and Sustainable Energy Reviews
Leccidi et al. (2016) - The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update, Energies
Louwen et al. (2014) - Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs, Progress in Photovoltaics
Friedrich et al. (2020) - Global Warming Potential and Energy Payback Time Analysis of Photovoltaic Electricity by Passivated Emitter and Rear Cell (PERC) Solar Modules, submitted JPV

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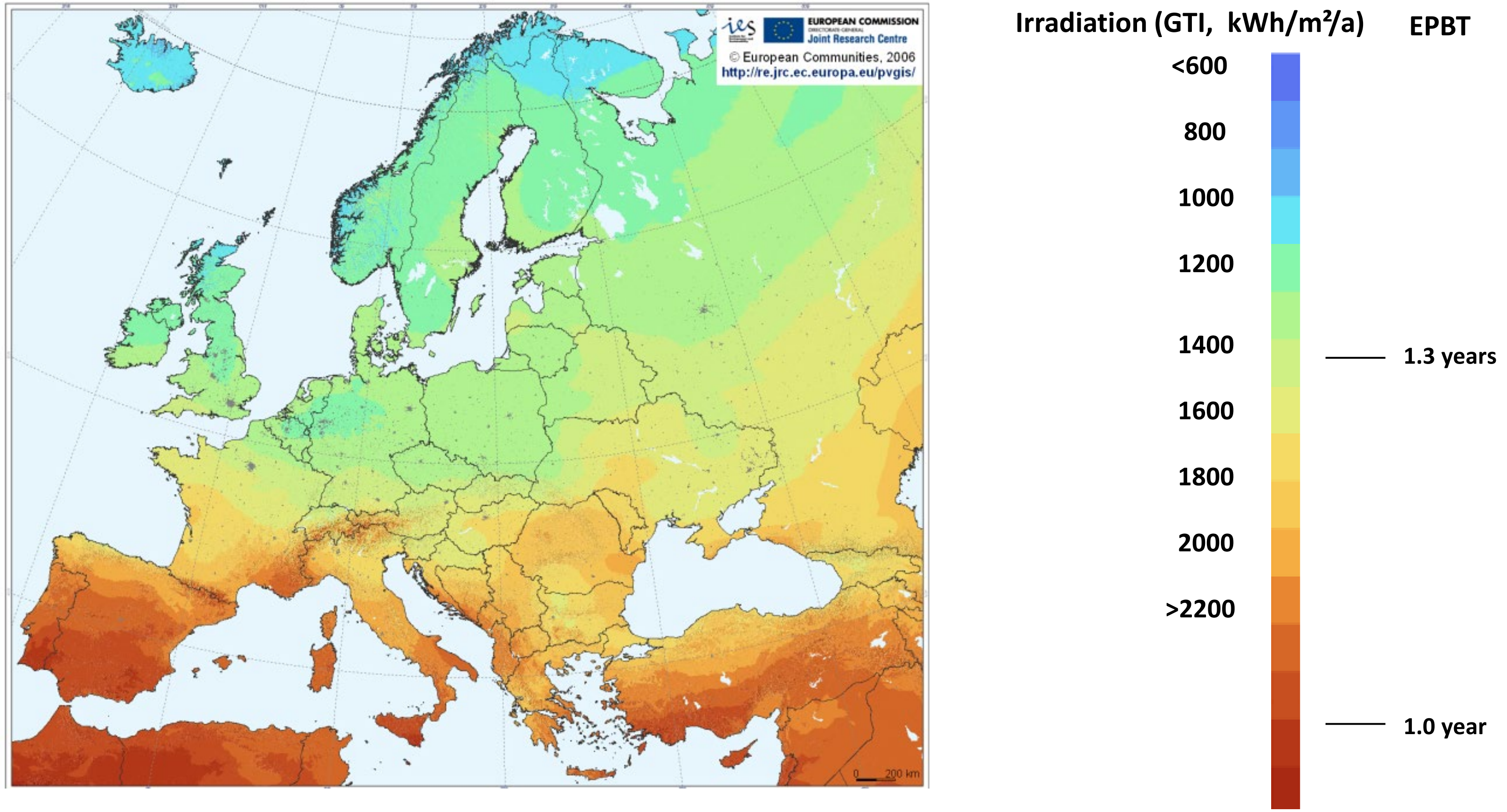
Energy Pay-Back Time of Silicon PV Rooftop Systems

Geographical Comparison

- 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.



Data source: Fraunhofer ISE. Image: JRC European Commission. Graph: PSE Projects GmbH 2020 (Modified scale with updated data from Fraunhofer ISE)

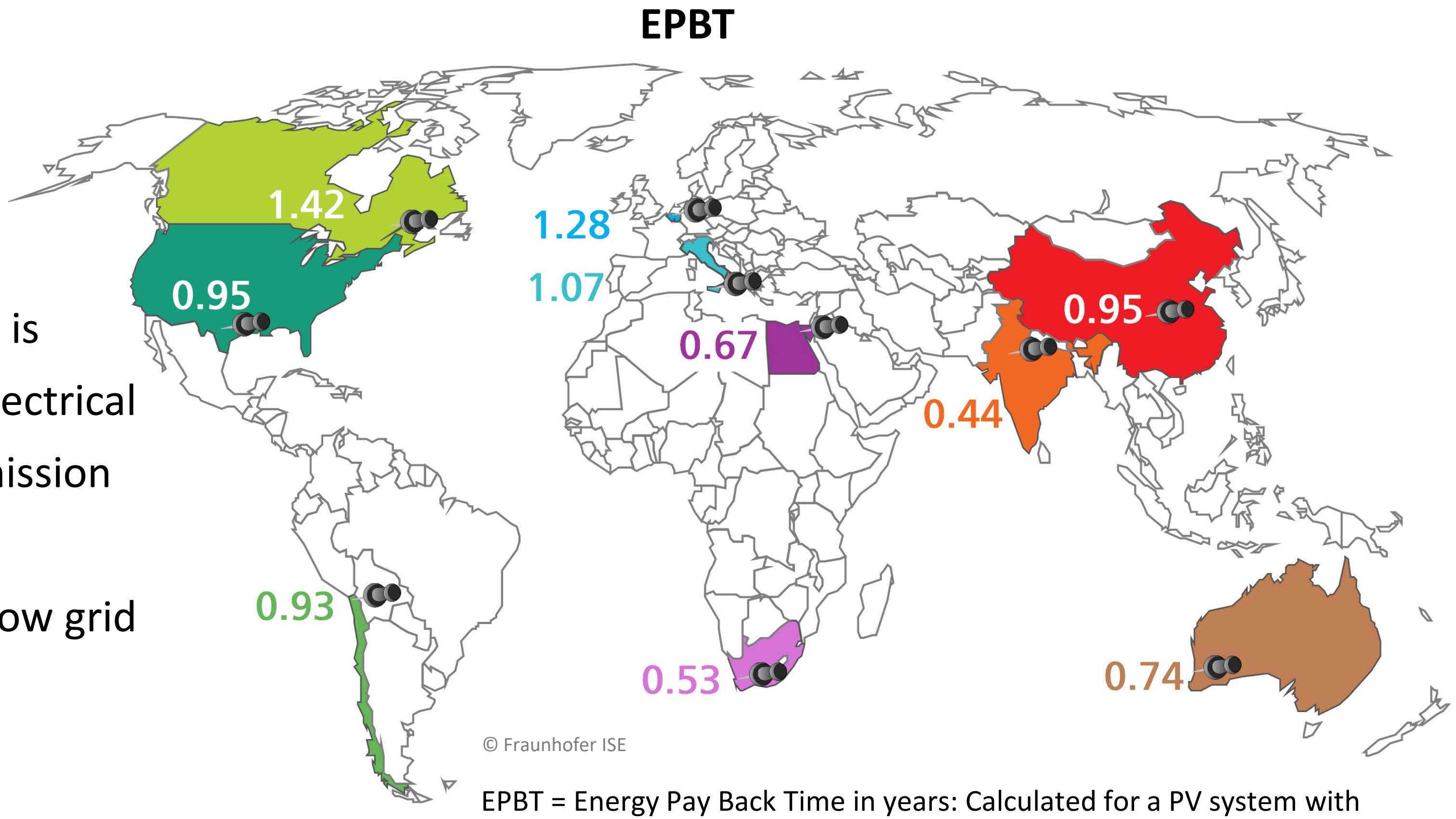
*Cz PERC cells module with 19.9% efficiency
**relation between primary energy to produced electricity in the grid used for manufacturing of the PV system

World Map EPBT of Silicon PV Rooftop Systems

Comparison of EPBT China

Influencing Factors and Interpretation

- **EPBT:** the lower, the better
- **Irradiation:** the higher, the better
- **Grid efficiency:** the higher, the better
  - in countries where upstream production is located (better energy mix to generate electrical power, less losses in the electrical transmission network), and
  - at downstream (where PV is installed) a low grid efficiency reduces the EPBT.

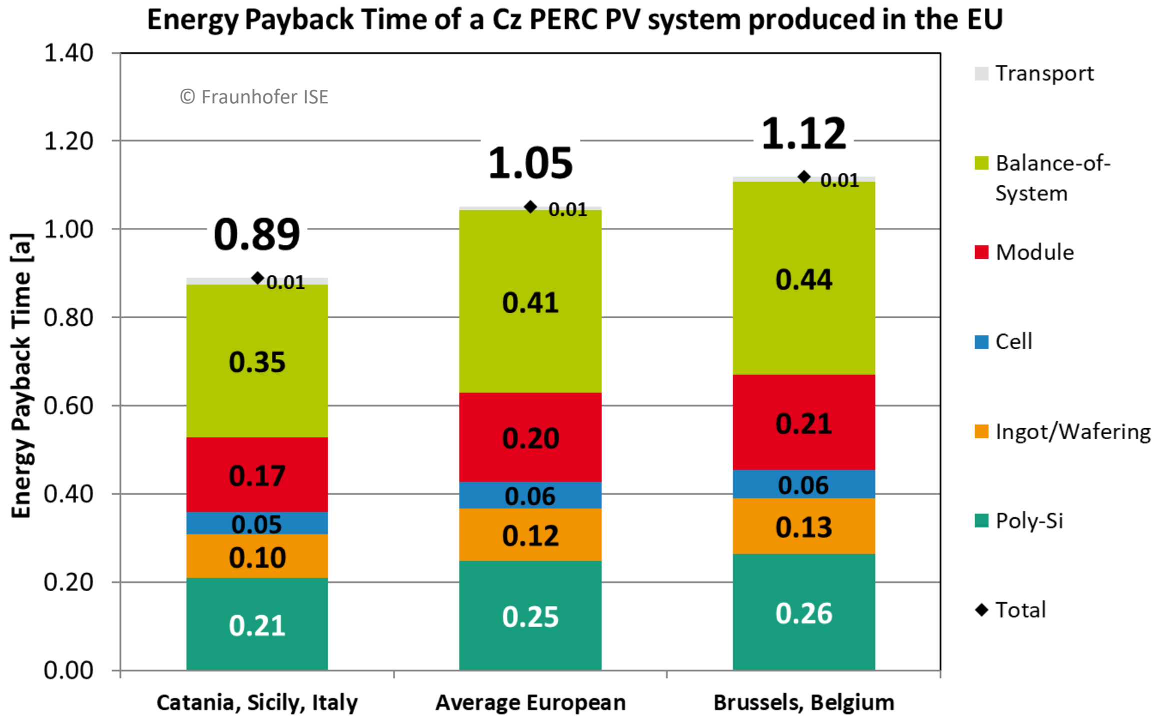


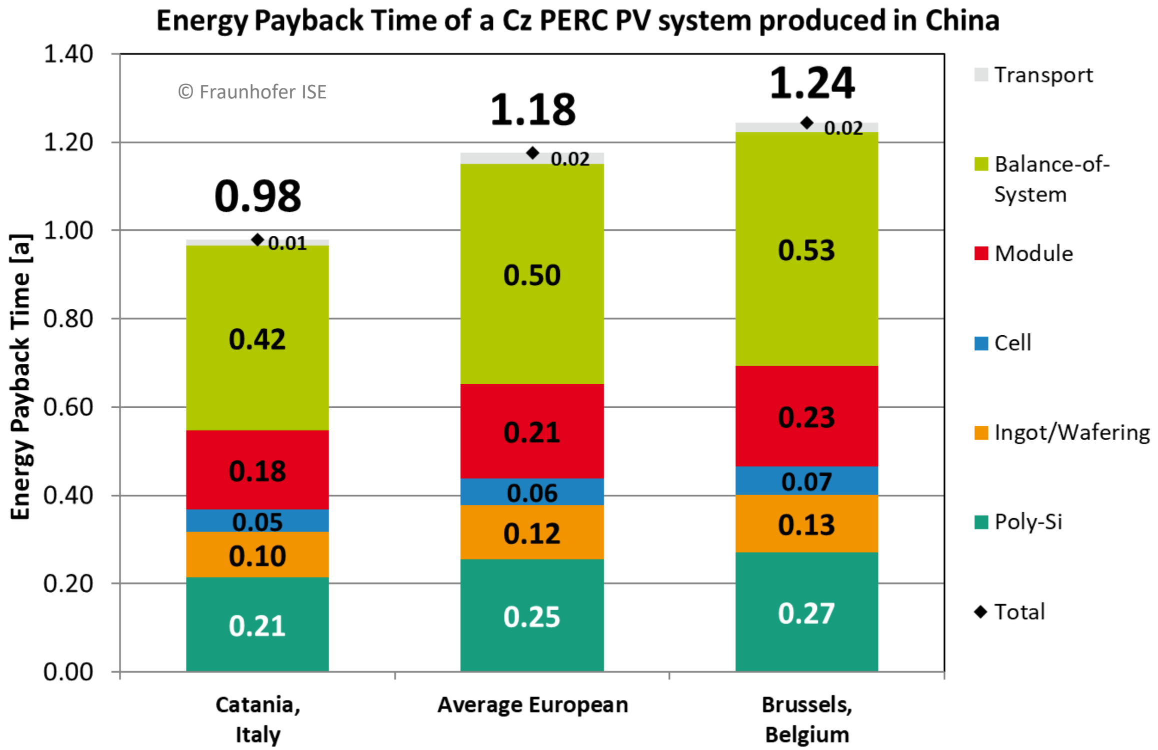
EPBT = Energy Pay Back Time in years: Calculated for a PV system with Cz PERC 60-cell modules with 19.9 % efficiency, produced in China

Data source: Fraunhofer ISE.

Energy Payback Time of Silicon PV Rooftop Systems

Comparison of EPBT China / EU, Local Irradiation and Grid Efficiency in 2021

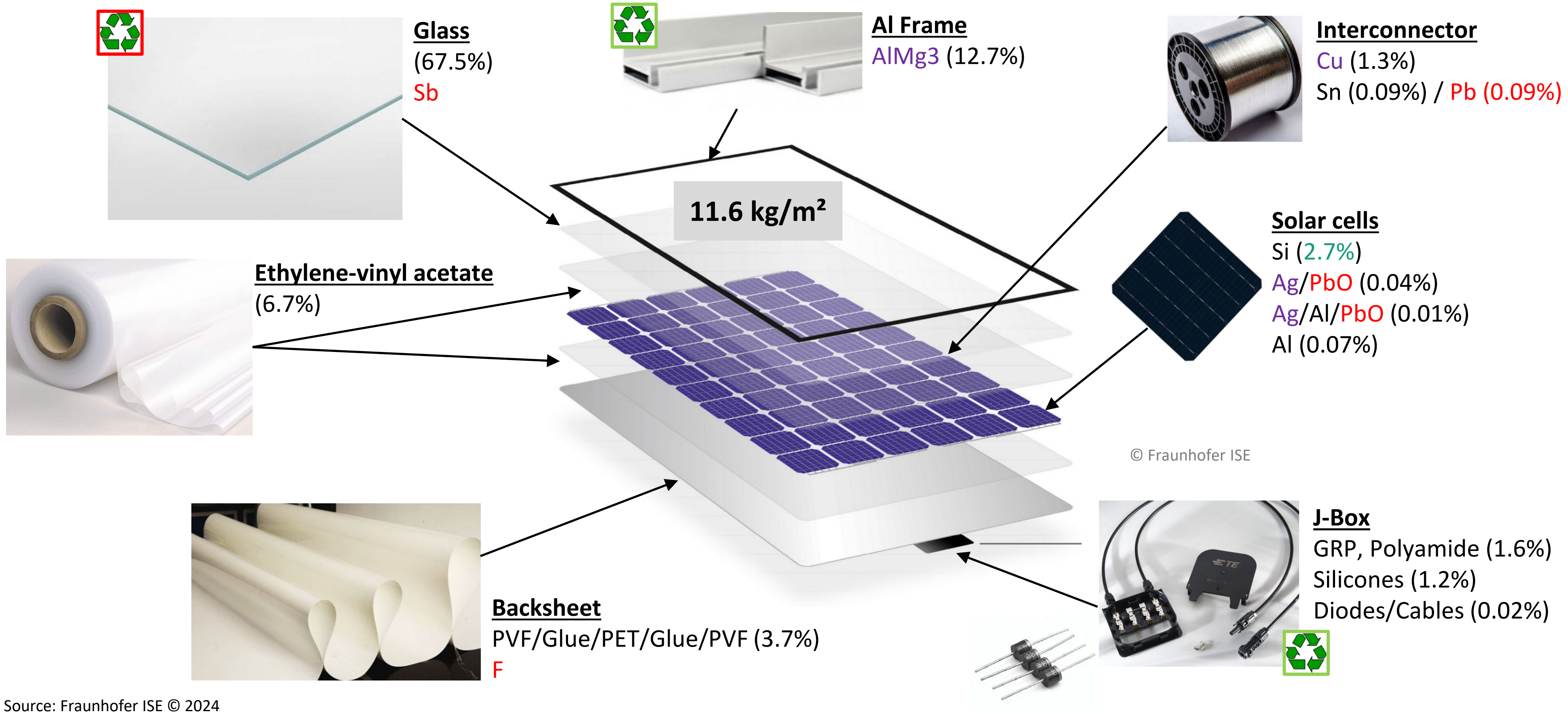




EPBT for PV systems produced in Europe is shorter than for those produced in China because of better grid efficiency in Europe.

Data source: Fraunhofer ISE. Calculations for year 2021 made at 22-July 2022

PV Module
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

Mass fraction of substance in relation to total module mass of 11.6 kg/m² (100%) given in brackets; Date of data: 2021

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PV Module

Measures to Improve the Life Cycle

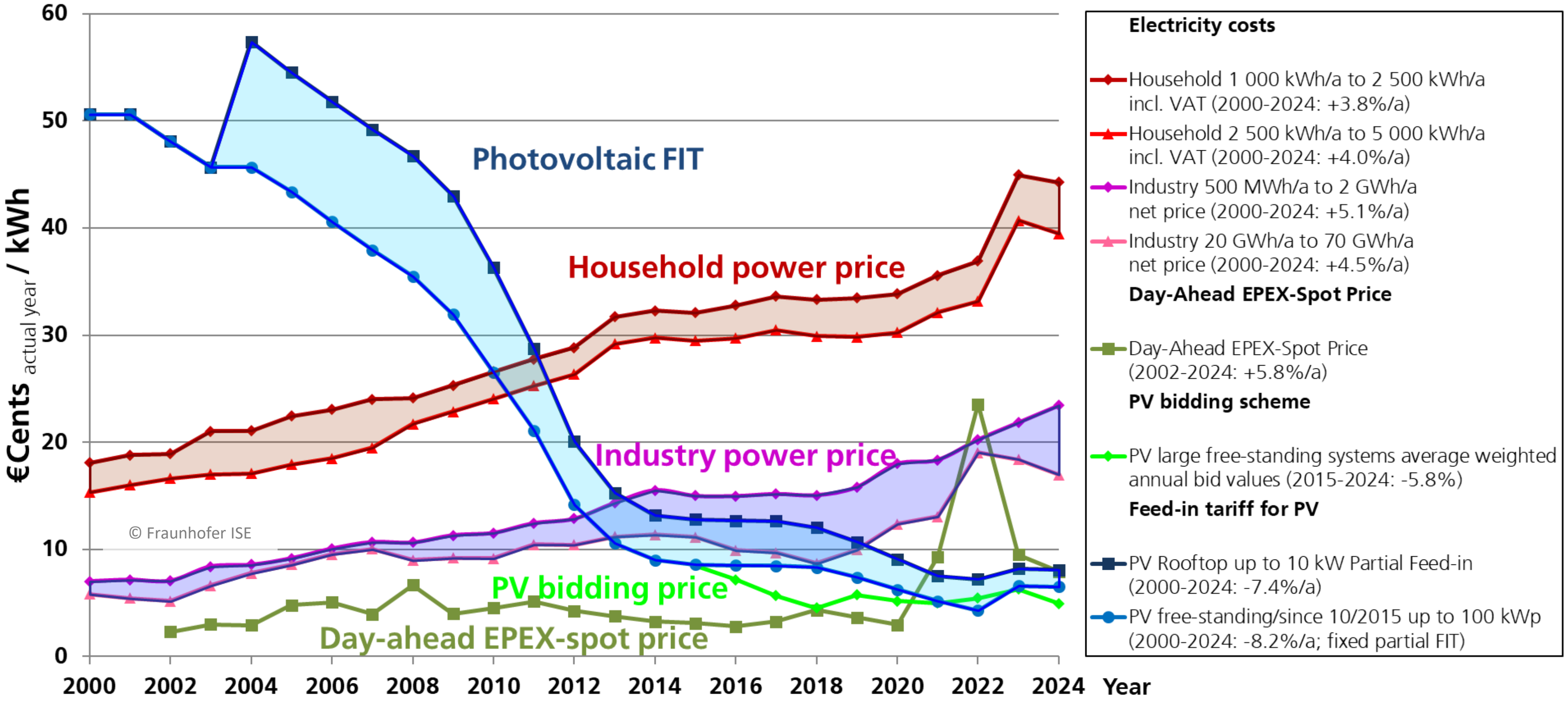
What to reduce or avoid?	What solutions are available?
Material consumption (general)	Higher efficiency PV modules; longer lifetime; better recyclability; bio-based polymers
Silicon	Thinner wafer
Silver (Ag)	Multi-busbars with more precise application of the silver paste; busbar-less cells; Replacing silver (Ag) by copper (Cu) or aluminium (Al)
Antimony (Sb) in glass	Sb-free solar glass
Fluorinated backsheets	Double-glass modules; alternative backsheets without fluorine compounds
Glass consumption	Thinner glass, reuse or recycling of solar glass instead of downcycling
Lead (heavy metal issues)	Lead-free solders or alternative contacting; alternative interconnection using electrically conductive adhesive (ECA)
Aluminium frame	Frameless modules; steel or plastic frame
Module failure due to faulty bypass diode	Install replaceable bypass diode

Data source: Fraunhofer ISE

4. Price Development

- Electricity costs
- Market incentives in Germany
- Costs for PV systems
- Price Learning Curve

Electricity Prices, PV Feed-In Tariffs (FIT) and Bidding Scheme in Germany
With Photovoltaic Rooftop Systems Partial Feed-In Tariff



Data: BNA; energy-charts.info; Design: B. Burger - Fraunhofer ISE. Graph: PSE Projects GmbH 2025; Date of data: 05/2025

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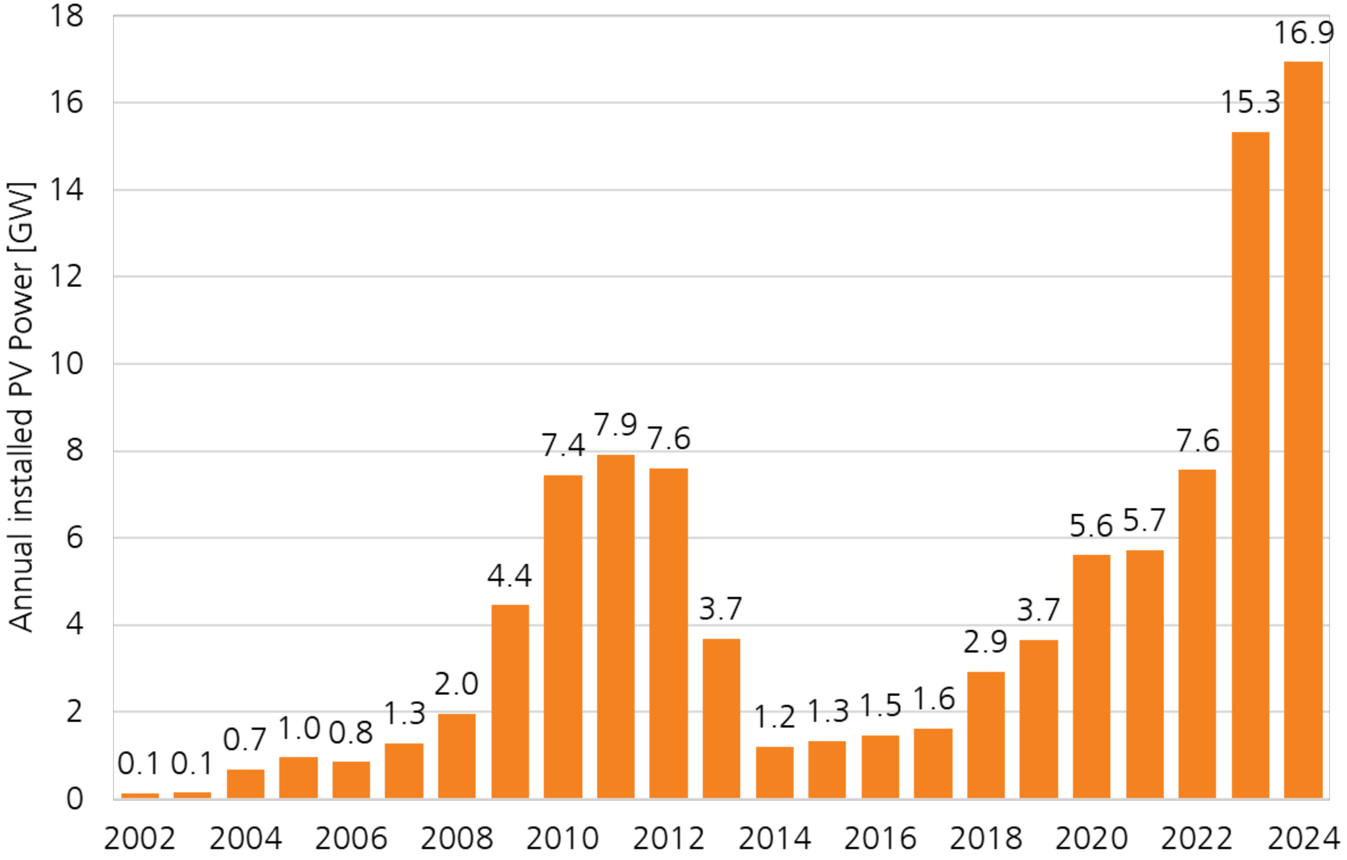
PV Market Development and Incentive Schemes in Germany



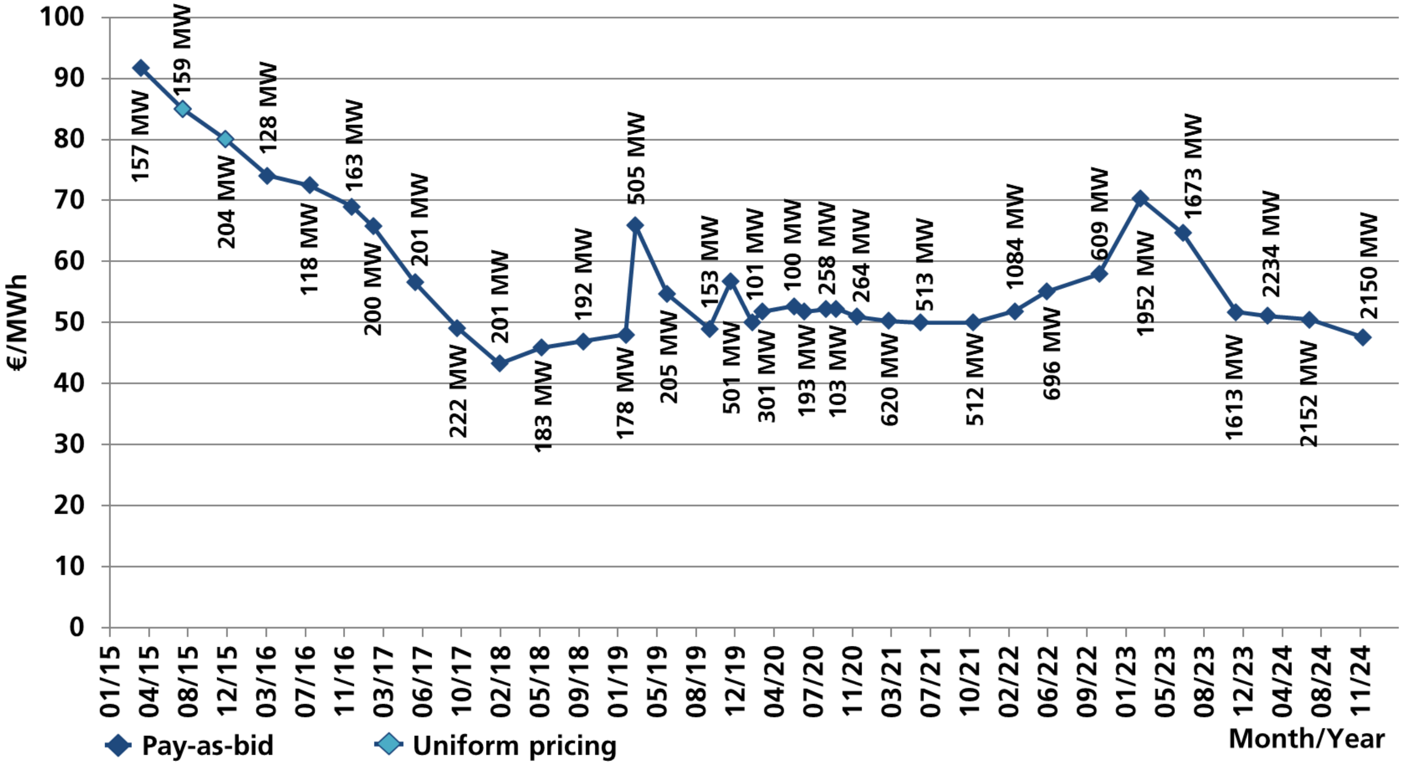
Data: BNA. Graph: B. Burger, Fraunhofer ISE Energy-Charts. Date of Data: 09.04.2025

Market Incentive	Start	End
1‘000 Roofs Program	1990	1995
Cost-covering remuneration	1993	1999
100‘000 Roofs-Program	1999	2003
EEG	2000	ongoing
PV Tendering scheme	2015	ongoing

The EEG 2023 law relies on a massive expansion of renewable energies with total installed PV capacity targets of 215 GW in 2030 and 400 GW in 2040. In 2024, new PV systems totaling around 16 GW capacity have been connected to the grid. From 2026 on, the expansion target is 22 GW of new installations on an annual basis.

PV Tender Scheme in Germany for Free-Standing Systems

Average, quantity weighted award value

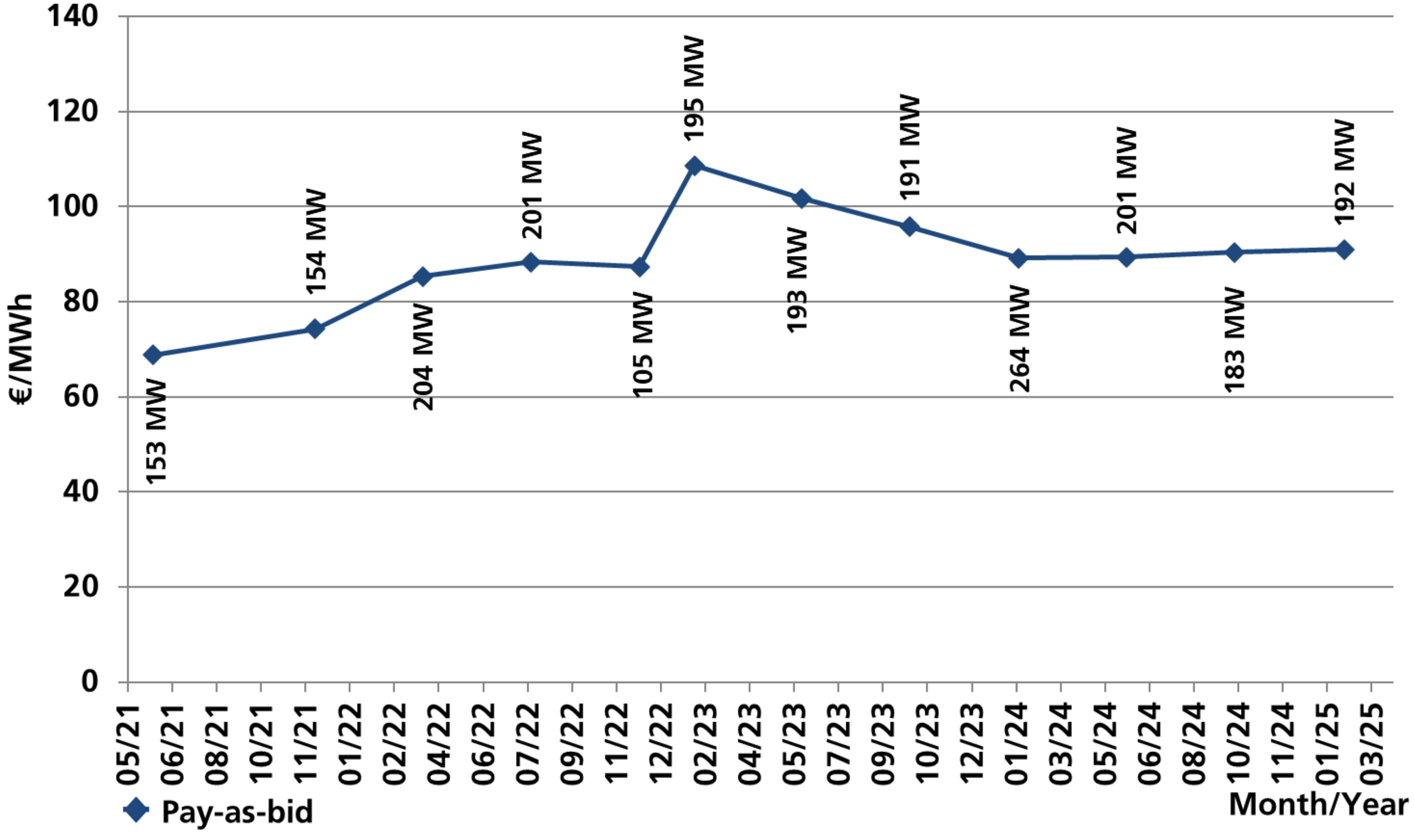


- The PV tender scheme for large ground-mounted systems started in April 2015. The total capacity of this scheme amounted to 21.8 GW in December 2024 with 4.76 ct€ / kWh as latest average quantity weighted award price.
- PV-rooftop and special tenders are not displayed in the graph.

Data: BNA. Graph: PSE Projects GmbH 2025 – Date of data: 04/2025

PV-Tender in Germany for Large Rooftop-Systems

Average, quantity weighted award value



- PV tender scheme for large rooftop systems (>750 kW) started in June 2021 and total capacity of this scheme accumulates to 2.2 GW by October 2024 with 10.5 ct€ / kWh as latest average quantity weighted award price.
- Lowest PV tender round was in June 2021 with 6.88 ct€ / kWh as average quantity weighted award price.

Data: BNA. Graph: PSE Projects GmbH 2025 – Date of data: 05/2025

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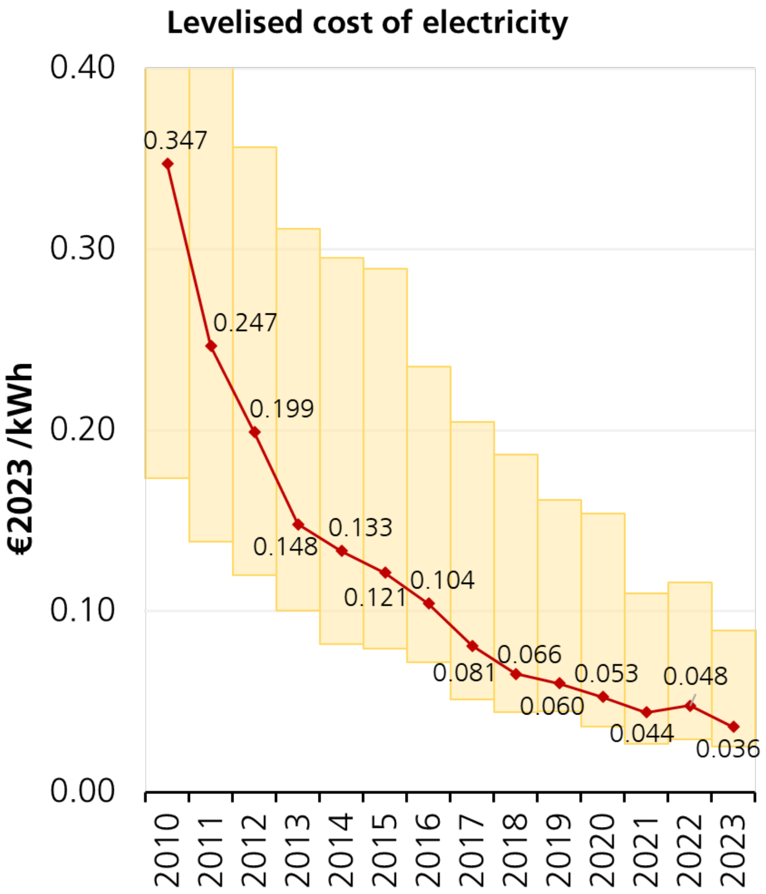
Global Weighted Average Levelized Costs of Electricity for Large PV Systems

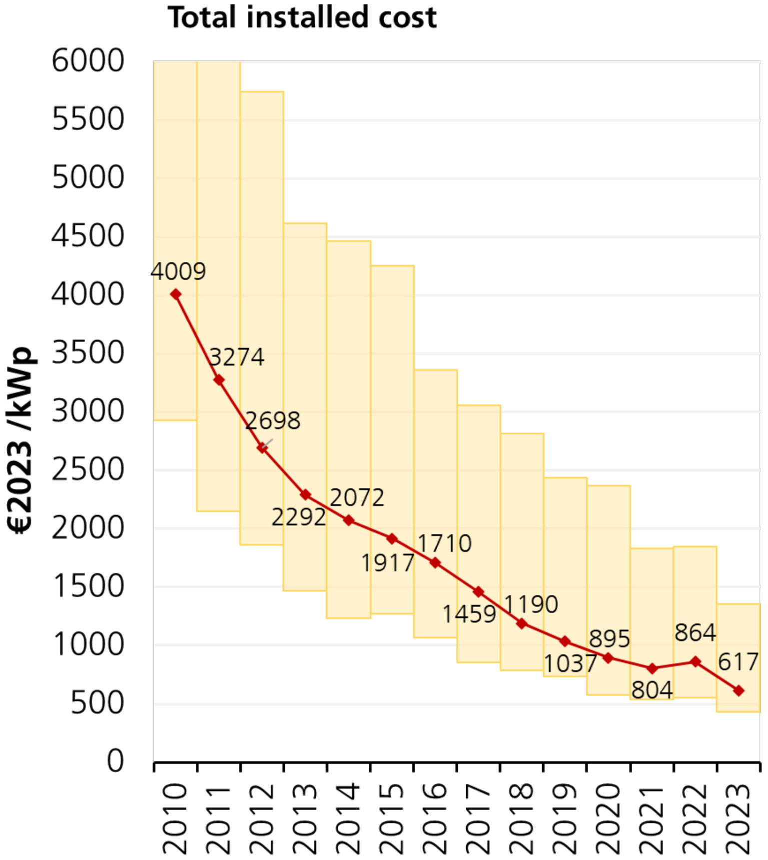
(with 5th percentile and 95th percentile)



- The global weighted average LCoE for 2023 for large PV systems is 0.036 €/kWh (= 36 €/MWh).
- The 5th percentile is a value associated with the location within the data where 5% of the data is below that value. For 2023, the 5th percentile is 0.025 €/kWh (= 25 €/MWh).
- The 95th percentile is the value where 5% of the data has a higher value. For 2023 the 95th percentile is 0.089 €/kWh (= 89 €/MWh).
- The LCoE has decreased by 16% year-on-year over the last 13 years.

Data: IRENA (2024), Renewable Power Generation Costs in 2023, International Renewable Energy Agency, Abu Dhabi.
Currency converted from USD to EUR. Date of data: Sep-2024

Global Weighted Average Total Installed Costs For Large PV Systems
(with 5th percentile and 95th percentile)

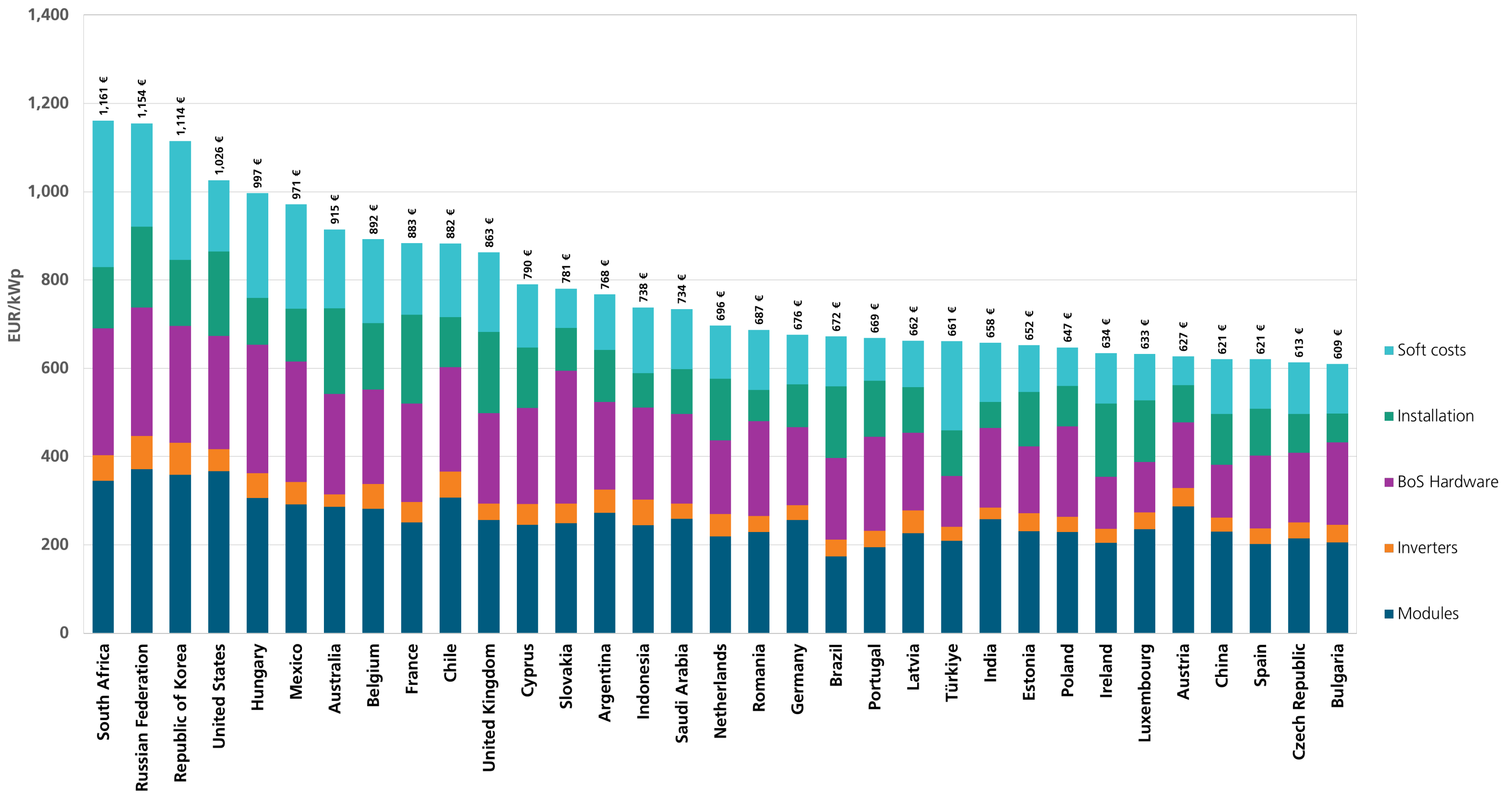


- The global weighted average total cost for large PV systems was 617 €/kWp in 2023.
- The 5th percentile is a value associated with the location within the data where 5% of the data is below this value. For 2023 the 5th percentile is 429 €/kWp.
- The 95th percentile is the value where 5% of the data has a higher value. For 2023, the 95th percentile is 1355 €/kWp.
- Total installed cost for large PV systems decreased by about 13% on year-to-year basis in the last 13 years.

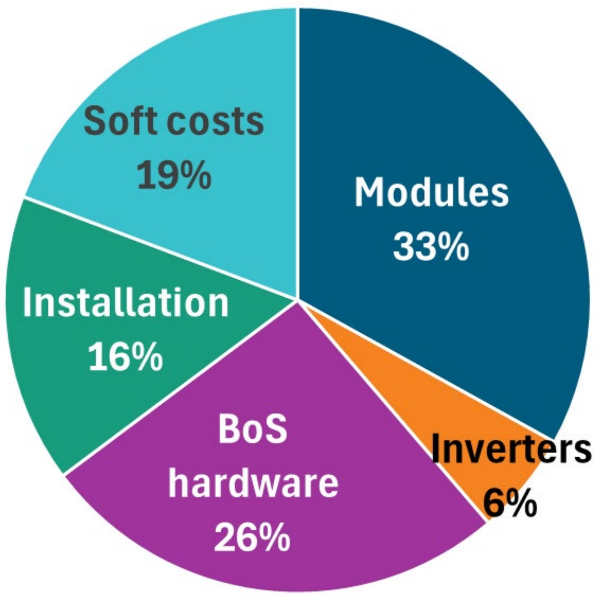
Data: IRENA (2024), Renewable Power Generation Costs in 2023, International Renewable Energy Agency, Abu Dhabi.
Currency converted from USD to EUR. Date of data: Sep-2024

Breakdown of Utility-Scale PV Total Installed Costs

By Country in 2023



Breakdown of Cost Components
(average of available country data):



Data: IRENA (2024), Renewable Power Generation Costs in 2023, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: Sep-2024

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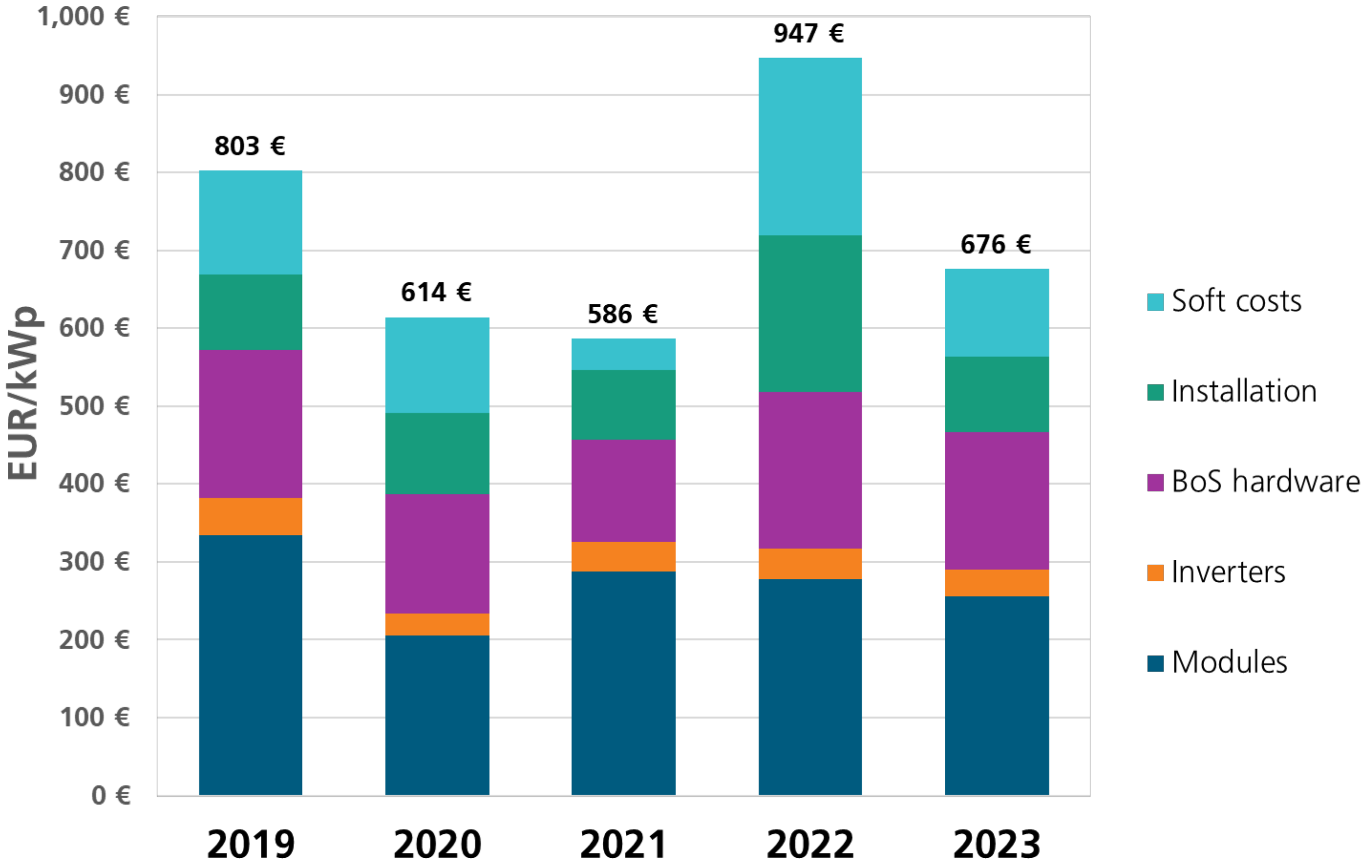
Breakdown of Total Installation Costs of Utility-Scale PV

Germany 2019 to 2023



Supply shortages due to the coronavirus crisis led to price turbulence in 2022. Prices are returning to pre-crisis levels.

Data: IRENA (2024), Renewable Power Generation Costs in 2023, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: Sep-2024

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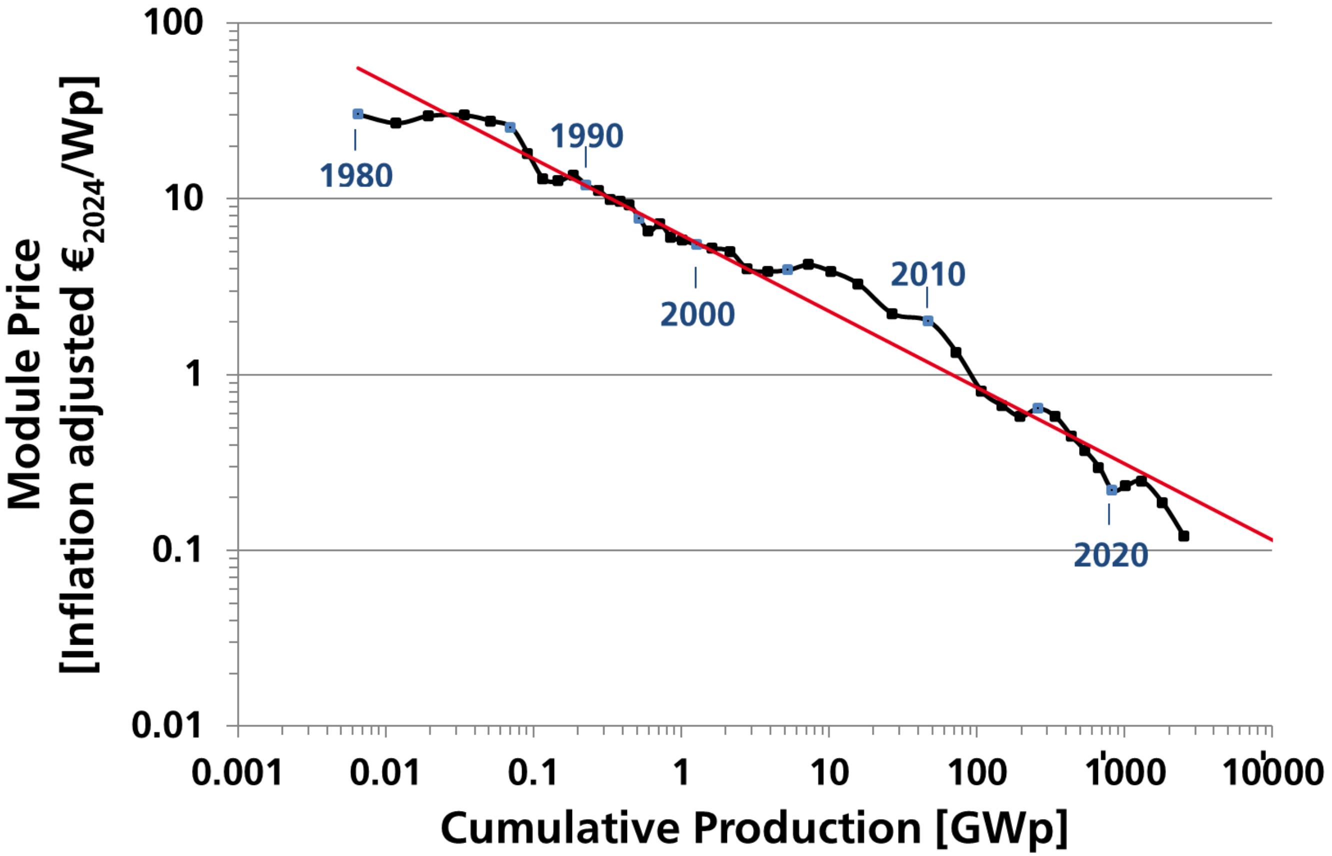
Price Experience Curve

Includes all Commercially Available PV Technologies

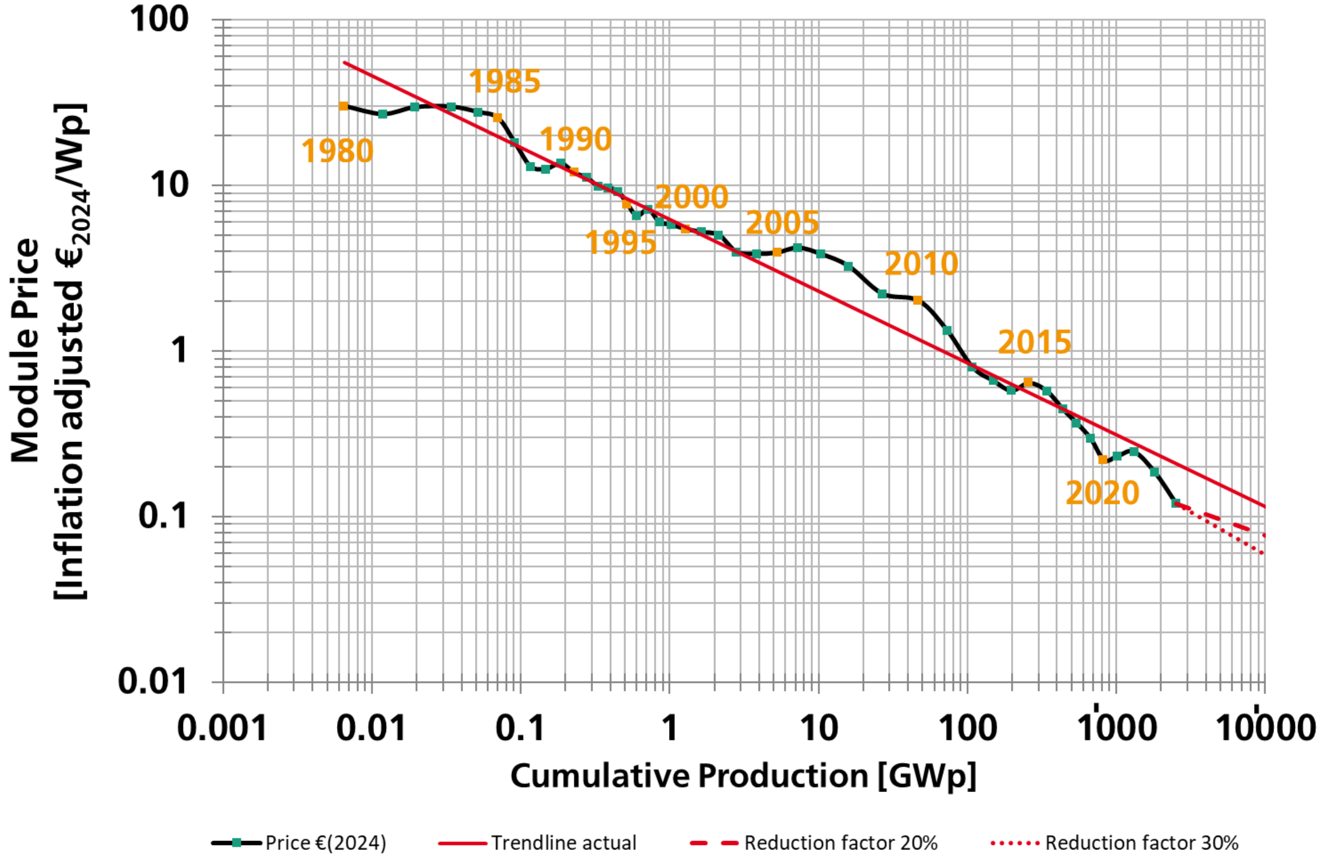


Learning Rate:
Each time the cumulative PV module production doubled, the module price dropped about 25.7% over the past 44 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit from 2022; VDMA for 2024: ISE; Graph: PSE Projects GmbH 2025.

Price Experience Curve

Includes all Commercially Available PV Technologies



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Further Reading

Selected studies and analyses

Fraunhofer-ISE Energy Charts

Study: Levelized Cost of Electricity - Renewable Energy Technologies

Recent facts about photovoltaics in Germany

Power Generation from Renewable Energy in Germany

What will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050

Sustainable PV Manufacturing in Europe – An Initiative for a 10 GW Green Fab

Meta Study: Future Crosssectoral Decarbonization Target Systems in Comparison to Current Status of Technologies

Abbreviations

Abbreviation	Explanation	Abbreviation	Explanation
AC	Alternating Current	**HCPV**	High Concentrator Photovoltaic
Al-BSF	Aluminum Back Surface Field	**HJT (also HIT)**	Heterojunction with Intrinsic Thin-Layer
BESS	Battery Energy Storage Systems	**IBC**	Interdigitated Back Contact (solar cells)
BIPV	Building Integrated PV	**LCOE**	Levelized Cost of Energy
BOS	Balance of System	**LCPV**	Low Concentrator Photovoltaic
CdTe	Cadmium-Telluride	**MJ**	Multi Junction
CI(G)S	Copper Indium (Gallium)Diselenide	**MPP**	Maximum Power Point
CPV	Concentrating Photovoltaic	**n-type**	Negatively doped wafer (with phosphorous)
c-SI	Crystalline Silicon	**PERX**	Passivated emitter and rear cell
CTM	Cell-to-Module	**PR**	Performance Ratio
Cz	Czochralski Method	**p-type**	Positively doped wafer (with boron or gallium)
DC	Direct current	**PV**	Photovoltaic
EEG	Renewable Energy Source Act (Erneuerbare-Energien-Gesetz, EEG)	**RE**	Renewable Energies
EI	The Energy Institute	**ROI**	Return on Investment
EPBT	Energy Payback Time	**SI**	Silicon
EROI	Energy Return of Invest	**SIC**	Silicon carbide
FZ	Floating Zone	**TOPCon**	Tunnel Oxide Passivated Contact
GaAs	Gallium Arsenide	**VAT**	Value Added Tax
GaN	Gallium nitride		

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Ralf Preu	ISE
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Jochen Rentsch	ISE
Gerhard Stryi-Hipp	ISE
Tobias Reuter	ISE
Harry Wirth	ISE
Werner Warmuth	PSE Projects GmbH

The information provided in this Photovoltaics Report is very concise by its nature . Its principal purpose is to provide a rough overview about the current solar PV market, the technologies and the environmental impact.

However, there are many more aspects. These and further details can be provided by Fraunhofer ISE upon request. Please contact us if you are interested in receiving a tailor-made offer.

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Thank You
for Your Interest

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