

PHOTOVOLTAICS REPORT



Prepared by

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

Freiburg, 24 February 2022

www.ise.fraunhofer.de

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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 However, facts and figures change rapidly, and the given information may soon be outdated again.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 this is stated explicitly. For example, prices in the learning curves are inflation adjusted.
- The slides have been made as accurate as possible and we would be grateful to receive any comments or suggestions for improvement.
Please send your feedback to simon.philipps@ise.fraunhofer.de and also to warmuth@pse-projects.de
- Please quote the information presented in these slides as follows:
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Quick Facts

Parameter	Value	Status	Reference	Date of data
<i>Germany / EU27 / Worldwide</i>				
PV market	4.9 / 18.2 / 144 GW 5.3 / 26 / 183 GW	End of 2020 End of 2021*	BNA / SPE / BNEF BNA / SPE / BNEF	11/2021; 12/2020; 02/2022 02/2022; 02/2022; 02/2022
Cumulative installation	54.0 / 138.2 / 710 GW	End of 2020	ISE / SPE / IRENA	11/2021; 07/2021; 09/2021
PV power generation	47.7 _{net} / 145.9 _{gross} / 855.7 _{gross} TWh	2020	ISE / BP / BP	10/2021; 07/2021; 07/2021
PV electricity share	9.9% _{net} / 5.3% _{gross} / 3.2% _{gross}	2020	ISE / BP / BP	12/2021; 07/2021; 07/2021
<i>Worldwide</i>				
c-Si share of production	95%	2020	IHS Markit	05/2021
Record solar cell efficiency: III-V MJ (conc.) / mono-Si / CIGS / multi-Si / CdTe	47.1 / 26.7 / 23.4 / 24.4 / 21.0%	06/2021	Green et al.	06/2021
<i>Germany</i>				
Price PV rooftop system	1,050 to 1,850 €/kWp	End of 2021	BSW	11/2021
LCOE PV power plant	3.1 to 5.7 ct€/ kWh	2021	ISE	
Lowest/Latest PV-Tender Price	4.33/5.00 ct€/ kWh	02/2018; 11/2021	BNA	11/2021

Executive Summary

PV Market: Global

- Photovoltaics is a fast-growing market: The Compound Annual Growth Rate (CAGR) of cumulative PV installations including off-grid was 34% between year 2010 to 2020.
- In 2020 producers from Asia count for 95% of total c-Si PV module production. China (mainland) holds the lead with a share of 67%. Europe contributed with a share of 3%; USA/CAN with 2%.
- Wafer size increased and by keeping the number of cells larger PV module sizes are realized allowing a power range beyond 600 W per module.
- In 2020, Europe's contribution to the total cumulative PV installations amounted to 22% (compared to 24% in 2019). In contrast, installations in China accounted for 33% (same value as the year before).
- Si-wafer based PV technology accounted for about 95% of the total production in 2020. The share of mono-crystalline technology is now about 84% (compared to 66% in 2019) of total c-Si production.
- Market shifts from subsidy driven to competitive pricing model (Power Purchase Agreements PPA).

Executive Summary

PV Market: Focus Germany

- In year 2020, Germany accounted for about 7.6% (53.6 GWp) of the cumulative PV capacity installed worldwide (707.5 GWp) with about 2 million PV systems installed in Germany. In 2021 the newly installed capacity in Germany was 5.3 GWp; in 2020 it was 4.6 GWp.
- PV covered 9.9% of Germany's net electricity generation in 2021 while all Renewable sources delivered about 45.9%.
- In 2020 about 35 Mio. t CO₂ equivalent GHG emissions have been avoided due to 50.6 TWh electrical energy generated by PV in Germany.
- PV system performance has strongly improved. Before 2000 the typical Performance Ratio was about 70%, while today it is in the range of 80% to 90%.

Executive Summary

Solar Cell / Module Efficiencies

- The record lab cell efficiency is 26.7% for mono-crystalline and 24.4% for multi-crystalline 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 is 25.5%.
- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 15% to 20% and more. At the same time, CdTe module efficiency increased from 9% to 19%.
- In the laboratory, best performing modules are based on mono-crystalline silicon with 24.4% 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 47.1% today. With concentrator technology, module efficiencies of up to 38.9% have been reached.

Executive Summary

Energy Payback Time

- Material usage for silicon cells has been reduced significantly during the last 16 years from around 16 g/Wp to about 3 g/Wp due to increased efficiencies, thinner wafers and diamond wire sawing as well as larger ingots.
- The Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 1.2 years to balance the input energy, while PV systems in the South equal their energy input after 1 year and less, depending on the technology installed and the grid efficiency.
- A PV system located in Sicily with wafer-based Silicon modules has an Energy Payback Time of around one year. Assuming 20 years lifespan, this kind of system can produce twenty times the energy needed to produce it.

Executive Summary

Inverters

- Inverter efficiency for state-of-the art brand products is 98% and higher.
- The market share of string inverters is estimated to be 64%. These inverters are mostly used in residential, small and medium commercial applications in PV systems up to 150 kWp. The market share of central inverters, with applications mostly in large commercial and utility-scale systems, is about 34%.
A small proportion of the market (about 1%) belongs to micro-inverters (used on the module level). The market share for DC / DC converters, also called “power optimizers”, is estimated to be 5% of the total inverter market.
- Trends: Digitalisation, Repowering, new features for grid stabilization and optimization of self-consumption; storage; utilization of innovative semiconductors (SiC or GaN) which allow very high efficiencies and compact designs; 1500 V maximum DC string voltage.

Executive Summary

Price Development

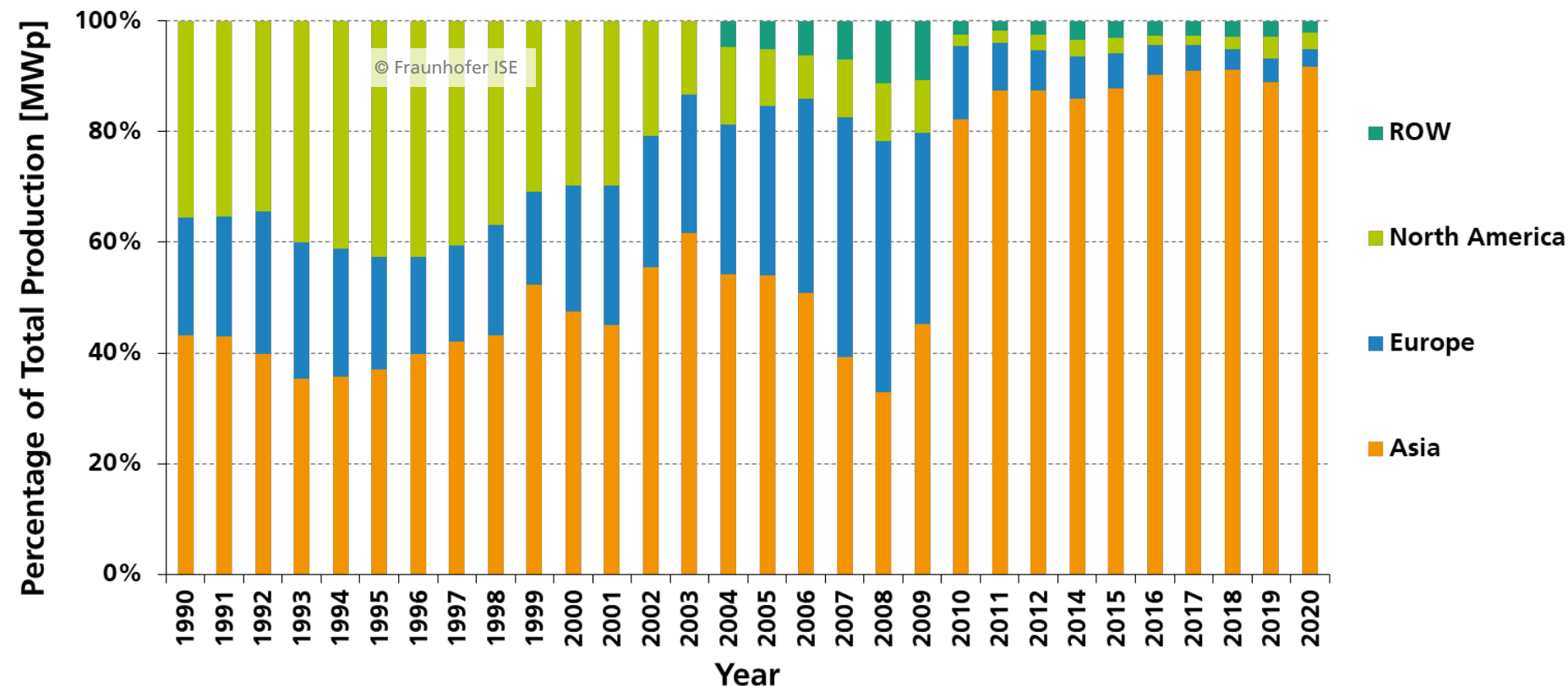
- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2020, such systems cost only 7.4% of the price in 1990. This is a net-price regression of about 92% over a period of 30 years.
- The Experience Curve – also called Learning Curve - shows that in the last 40 years the module price decreased by 26% with each doubling of the cumulated global module production. Cost reduction results from economies of scale and technological improvements.

1. PV Market

- By region
- By technology

PV Module Production by Region 1990-2020

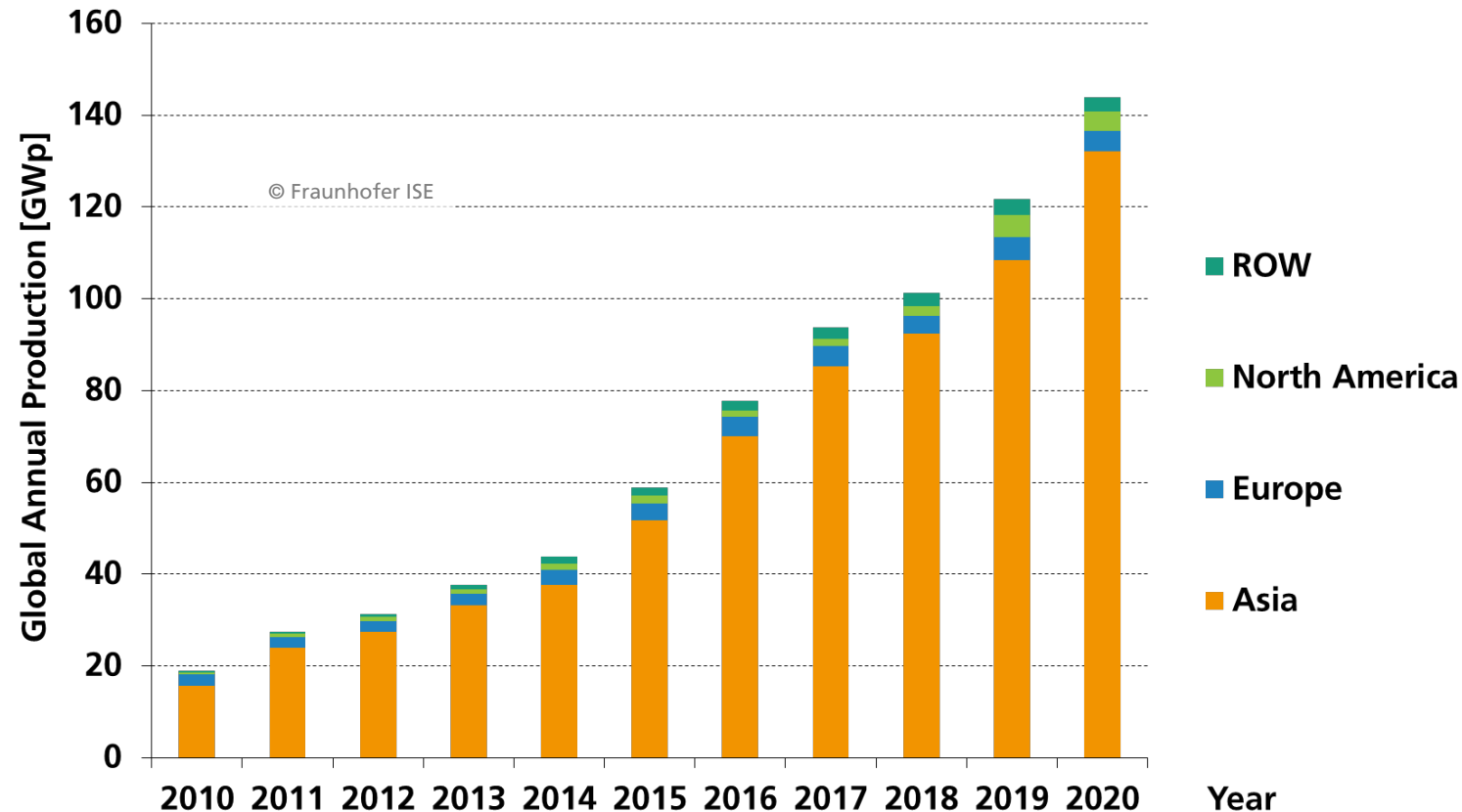
Percentage of Total MWp Produced



Data: Up to 2004 Strategies Unlimited; 2005 to 2009: Navigant Consulting; since 2010: IHS Markit. Graph: PSE 2021

PV Module Production by Region

Global Annual Production

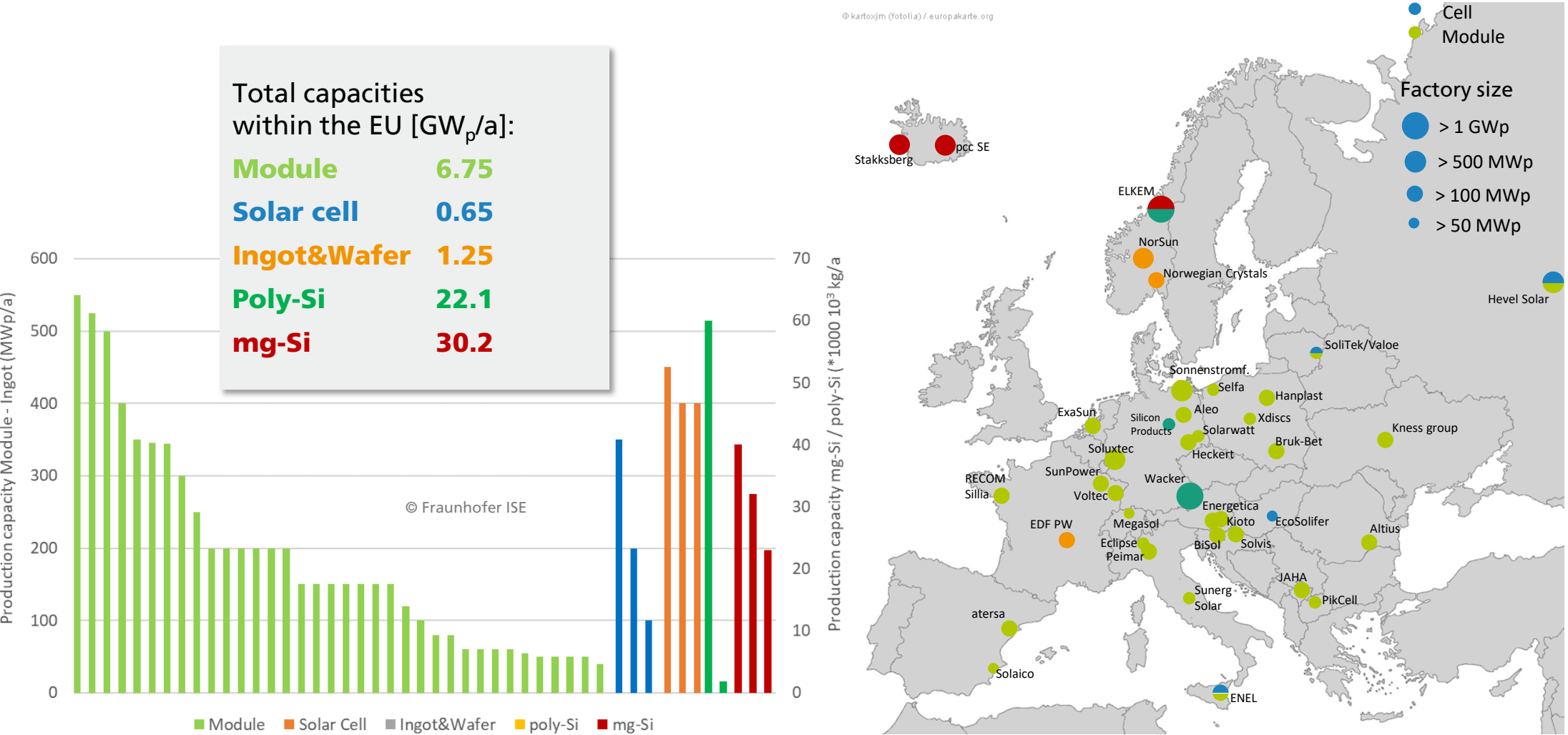


About 82% of the global PV module has been produced in Asia in year 2010. It increased to about 92% of total global production in year 2020. China (mainland) accounted with about 97 GW for 67% of the global module production in year 2020. The annual production has increased by a factor of 7 in this decade.

Data: IHS Markit 2021. Graph: PSE 2021; Date of data: 19-May 2021

Current European c-Si PV Manufacturing Landscape

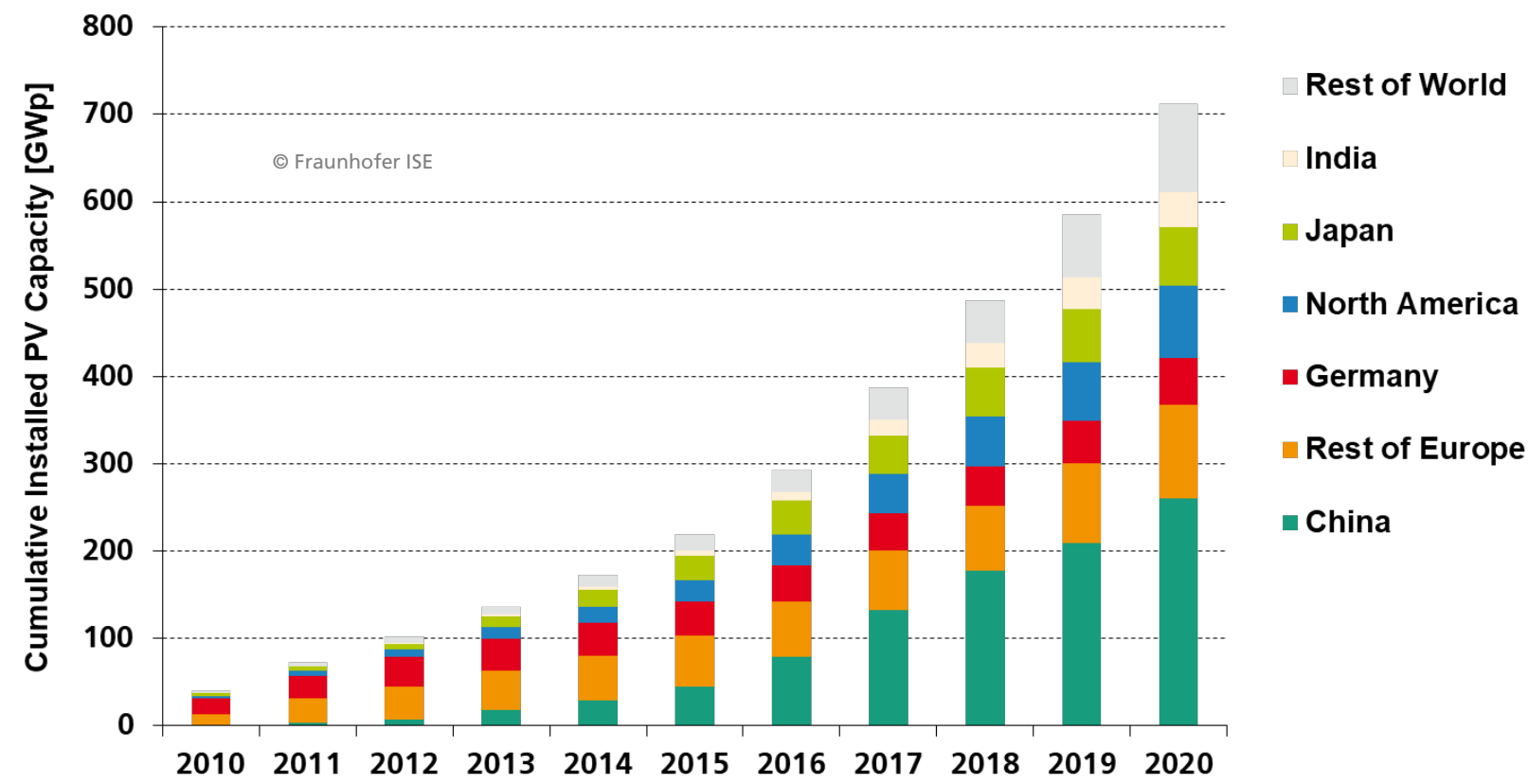
Status Quo, End of 2020



Data and Graph: Jochen Rentsch, Fraunhofer ISE 2021

Global Cumulative PV Installation

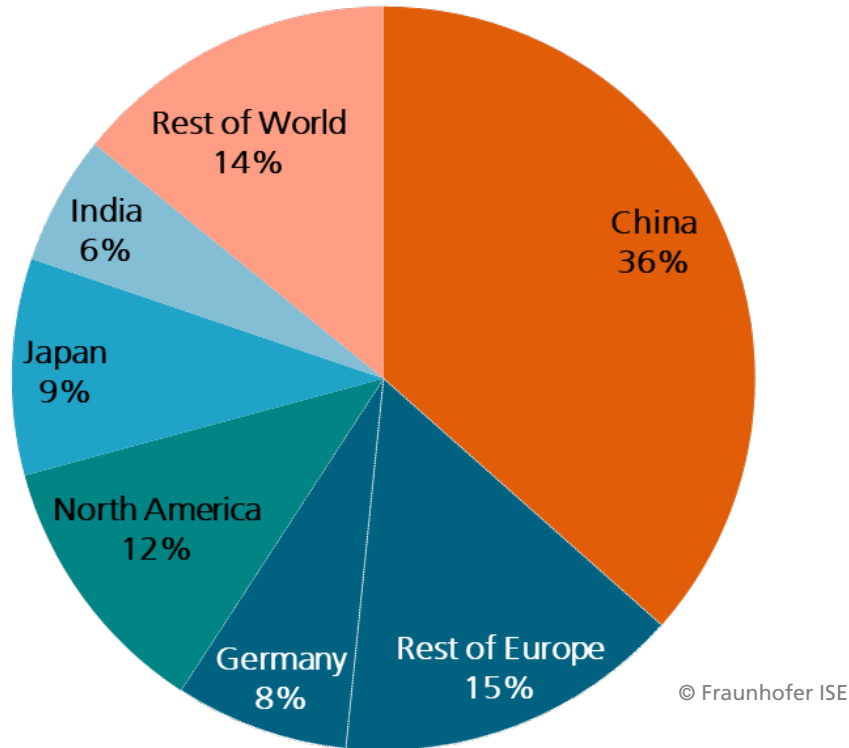
From 2010 to 2020



Data: IRENA 2021. Graph: PSE 2021. Date of data: Apr-2021

Global Cumulative PV Installation by Region

Status 2020



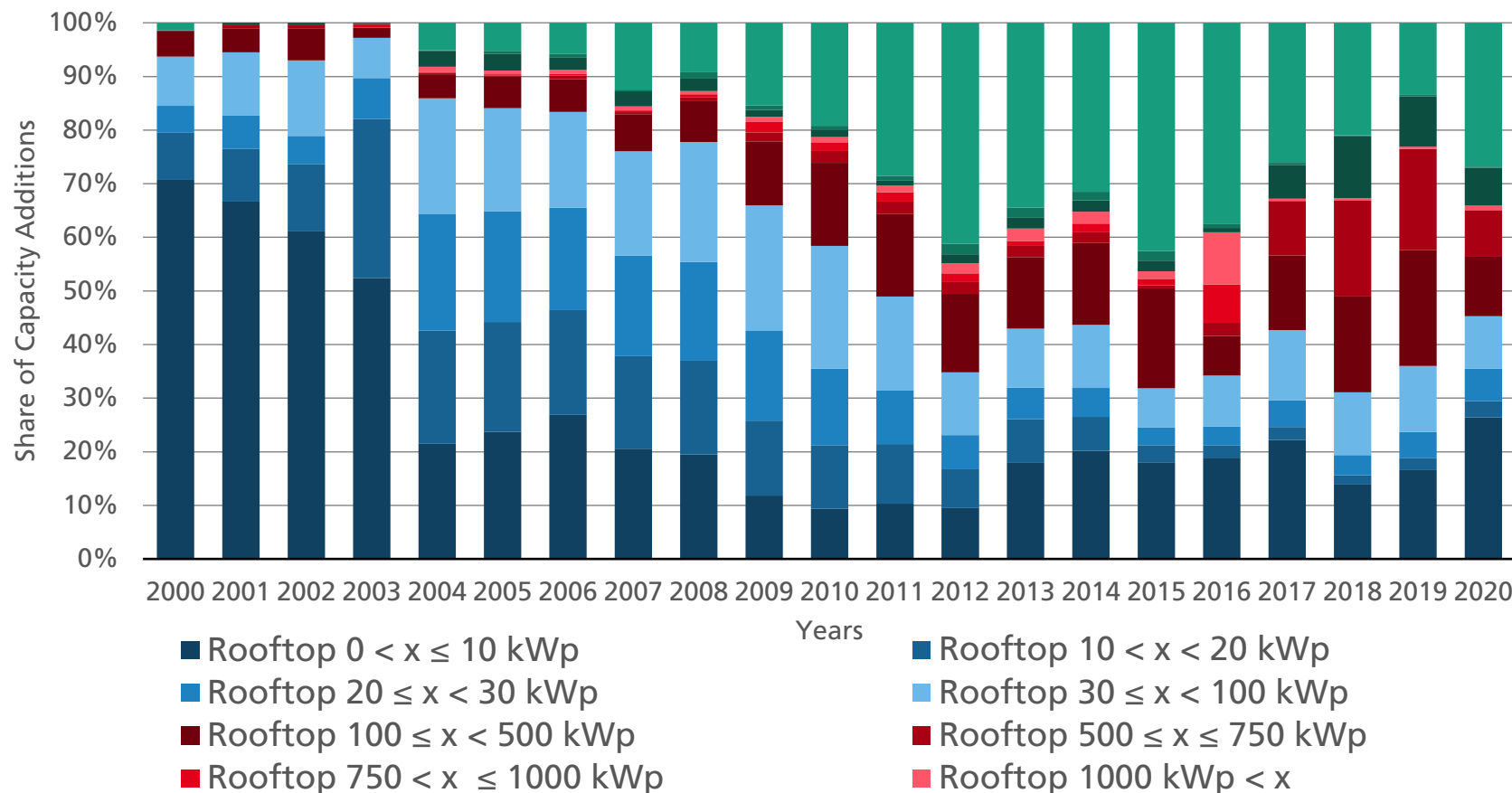
The total cumulative installations amounted to about 710 GWp at the end of year 2020.

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

Data: IRENA 2021. Graph: PSE 2021; Date of data: Aug-2021

Annually Installed PV System Capacity in Germany

Percentage of Annual Capacity by System Size



The annual distribution of PV System size classes strongly depend on:

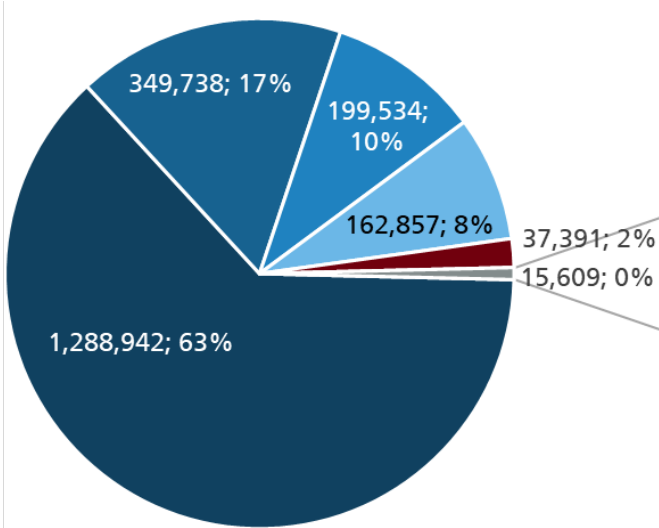
- Regulations
- Market incentives (like EEG)
- Tender procedures
- Bankability (trust of investors)

Source: Fraunhofer ISE, own calculations based on EEG-master and -flow data (netztransparenz.de, Sept. 2021)

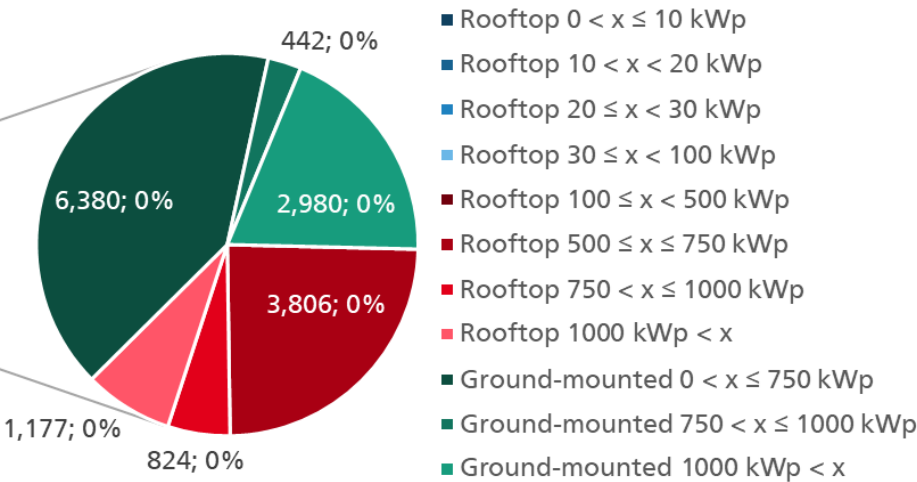
Share of Number of PV-Systems Installed

Percentage of Cumulative Installations by System Size in Germany in 2020

Total number of all grid-connected PV-Systems



Number of PV-Systems larger than 500 kWp



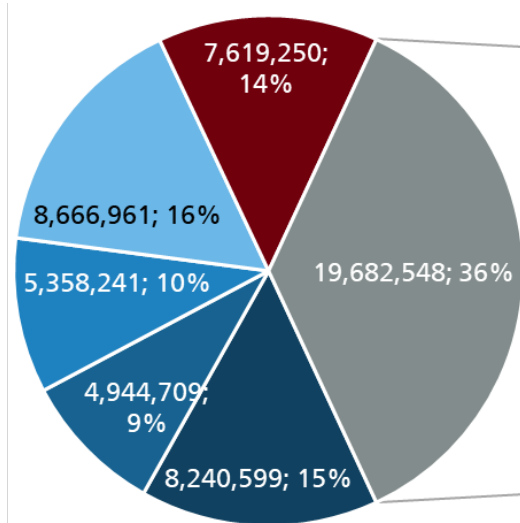
End of 2020 about 2 million grid-connected PV-Systems were installed in Germany.

Source: Fraunhofer ISE, own calculations based on Markstammdatenregister (BNetzA; Sept. 2021)

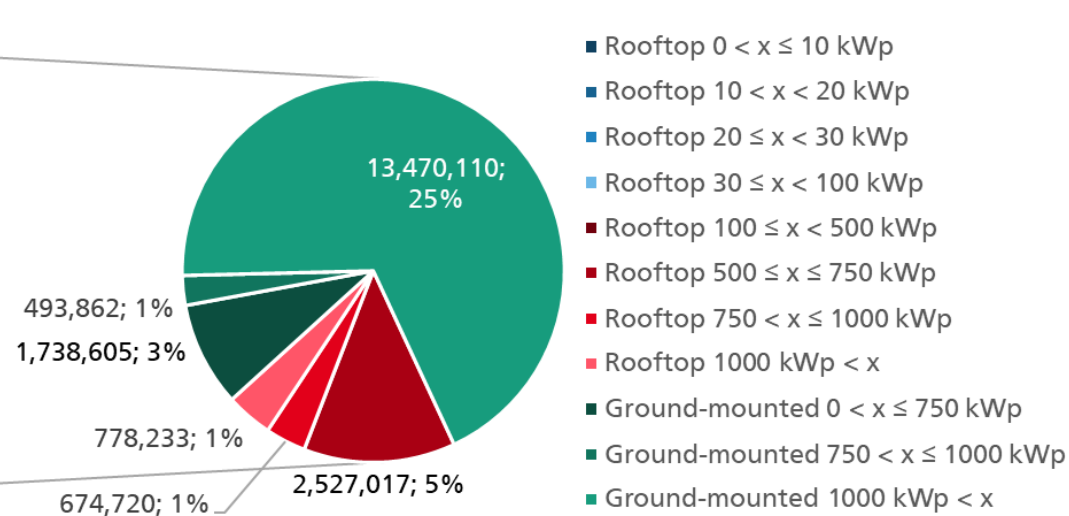
Share of Capacity of PV-Systems Installed

Percentage of Cumulative Installations by System Size in Germany in 2020

PV Capacity in kWp and percentage of all grid-connected PV-Systems



PV Capacity in kWp and percentage of Systems larger than 500 kWp

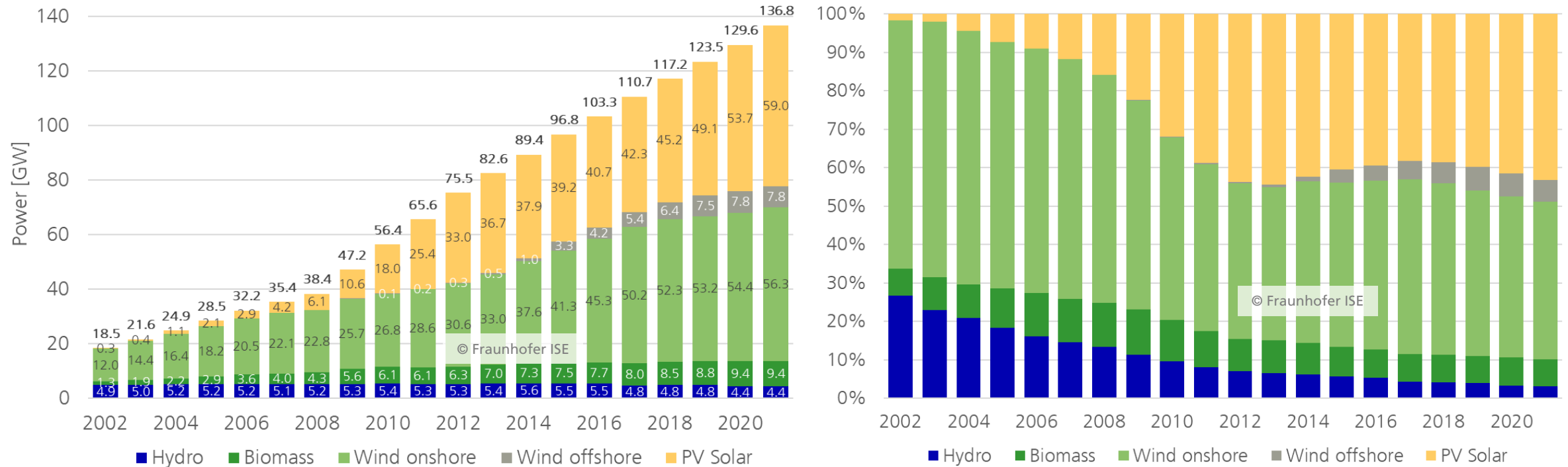


At the end of 2020 a total cumulated PV capacity of about 54 GW was installed in Germany.

Source: Fraunhofer ISE, own calculation based on Marktstammdatenregister and EEG-master data (netztransparenz.de, September 2021; BNetzA; September 2021)

Electrical Capacity of Renewable Energy Sources

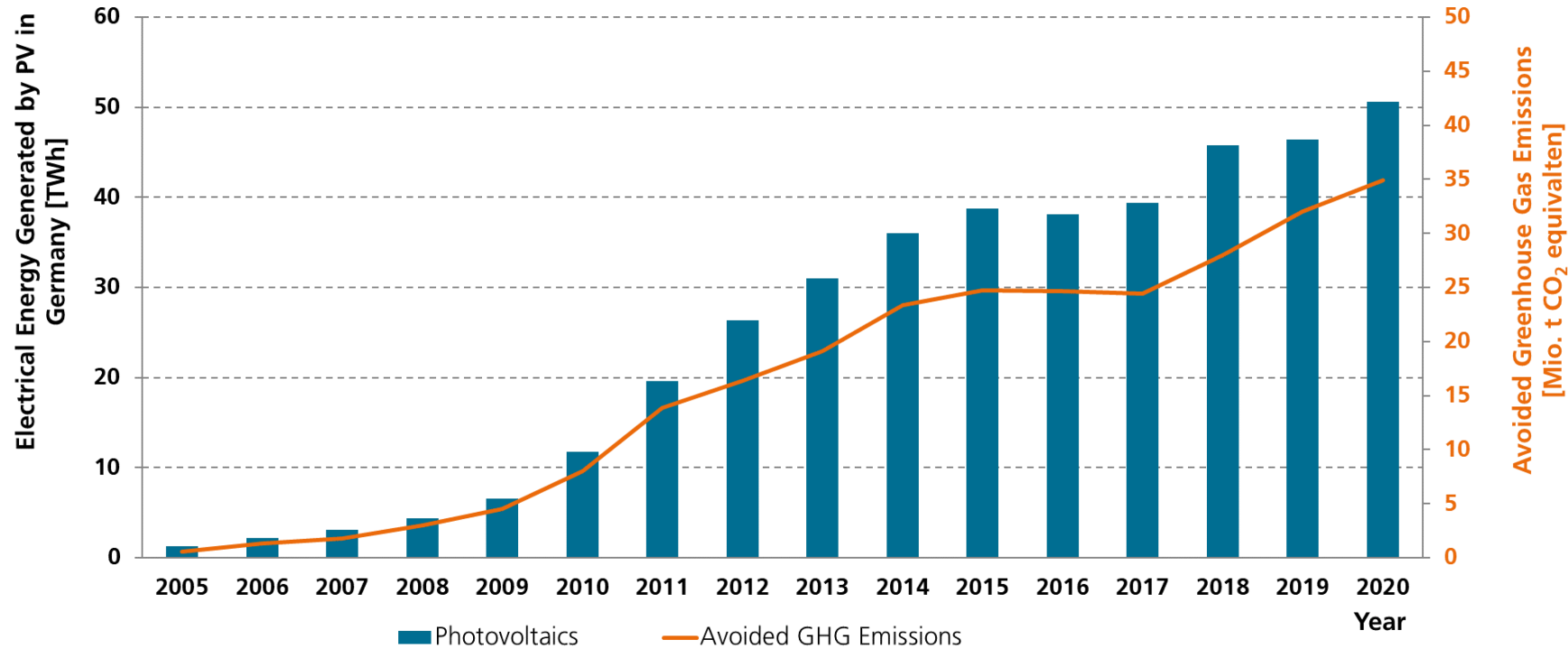
Germany



136.8 GW of total 234.2 GW net installed electricity generation capacity in Germany were from renewable energy (RE) sources in Germany in year 2021. This results in a RE share of 58.4% of total capacity.

Data: Energy Charts by Prof. Dr. Bruno Burger. Date of data: Jan-2022

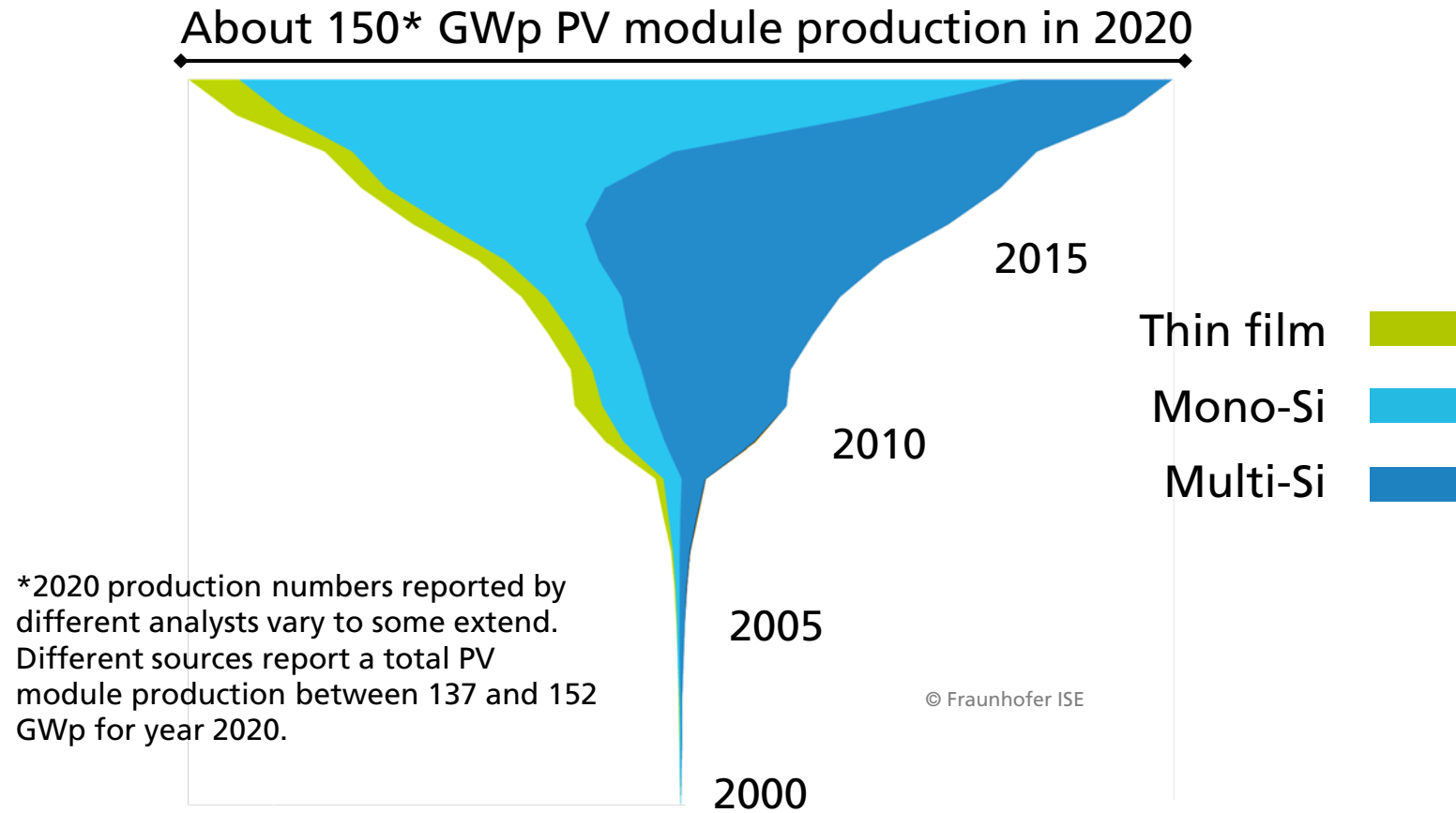
PV Energy Generated and Resulting GHG Avoided Emissions Germany



- In 2020 Greenhouse Gas emissions of about 35 Mio. t CO₂-equivalent were avoided due to 50.6 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2021. Graph: PSE 2021

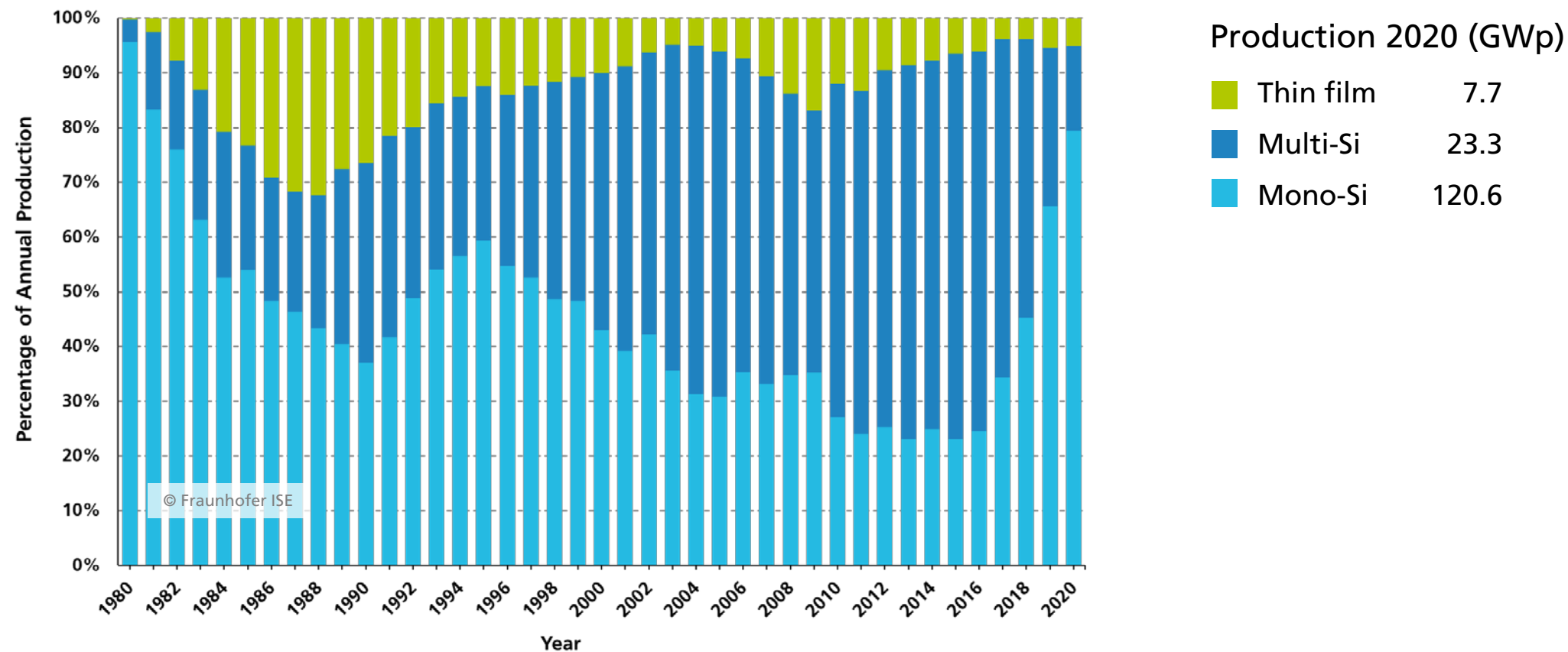
Annual PV Production by Technology Worldwide (in GWp)



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2021. Date of data: Jun-2021

PV Production by Technology

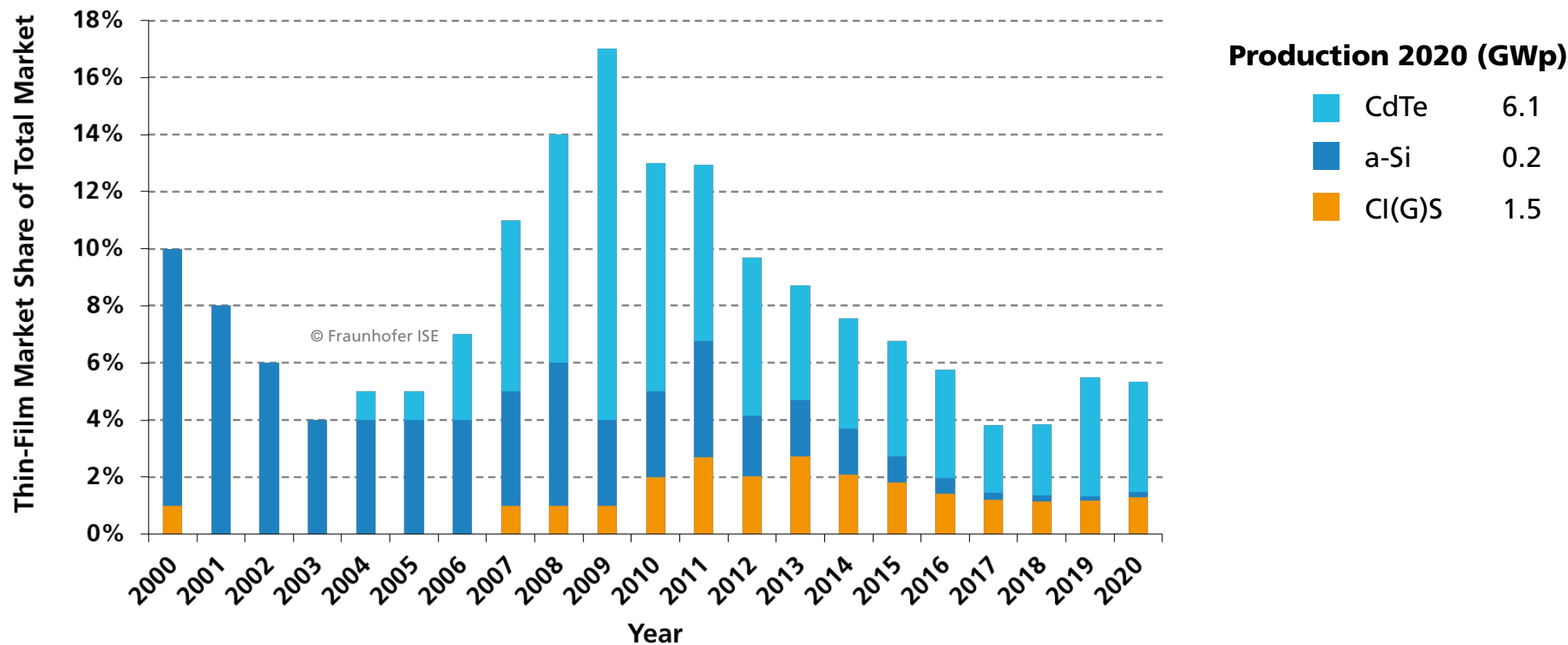
Percentage of Global Annual Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2021. Date of data: May-2021

Market Share of Thin-Film Technologies

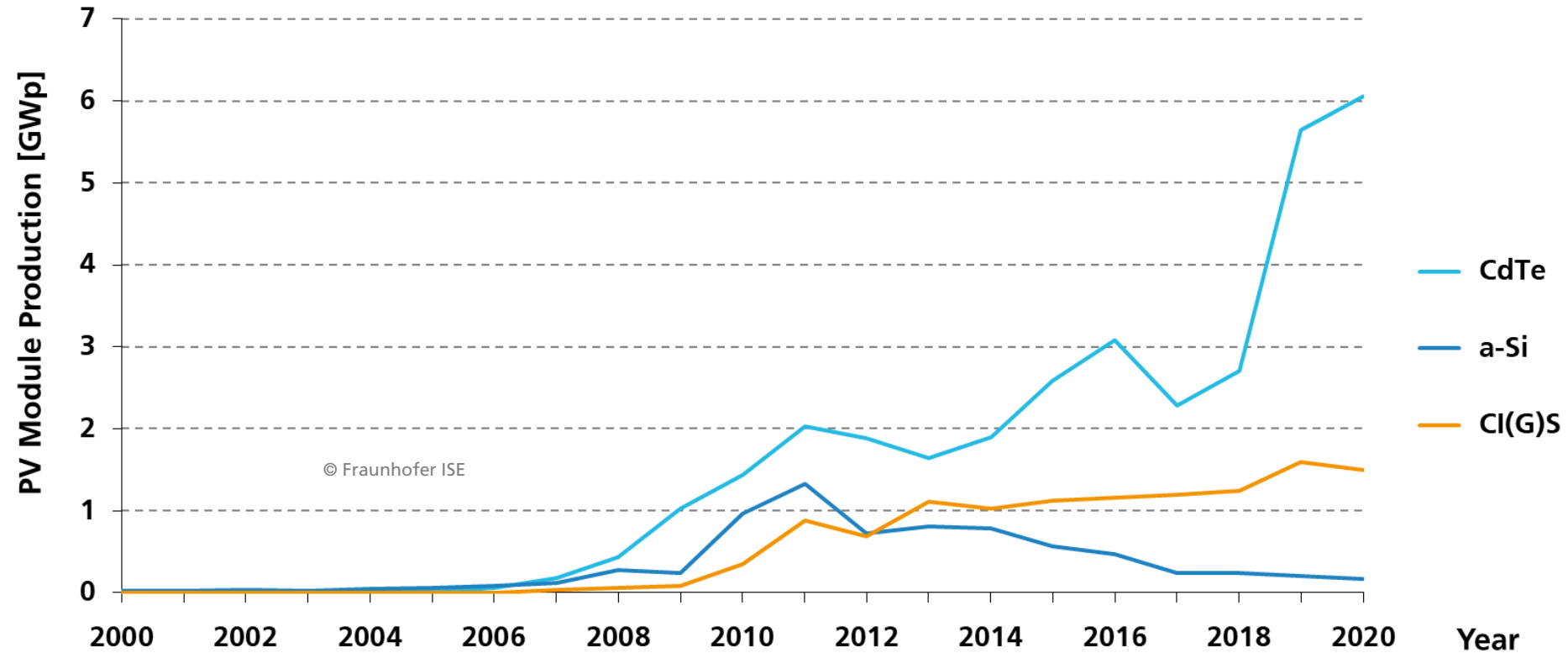
Percentage of Total Global PV Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2021 . Date of data: May-2021

Thin-Film Technologies

Annual Global PV Module Production

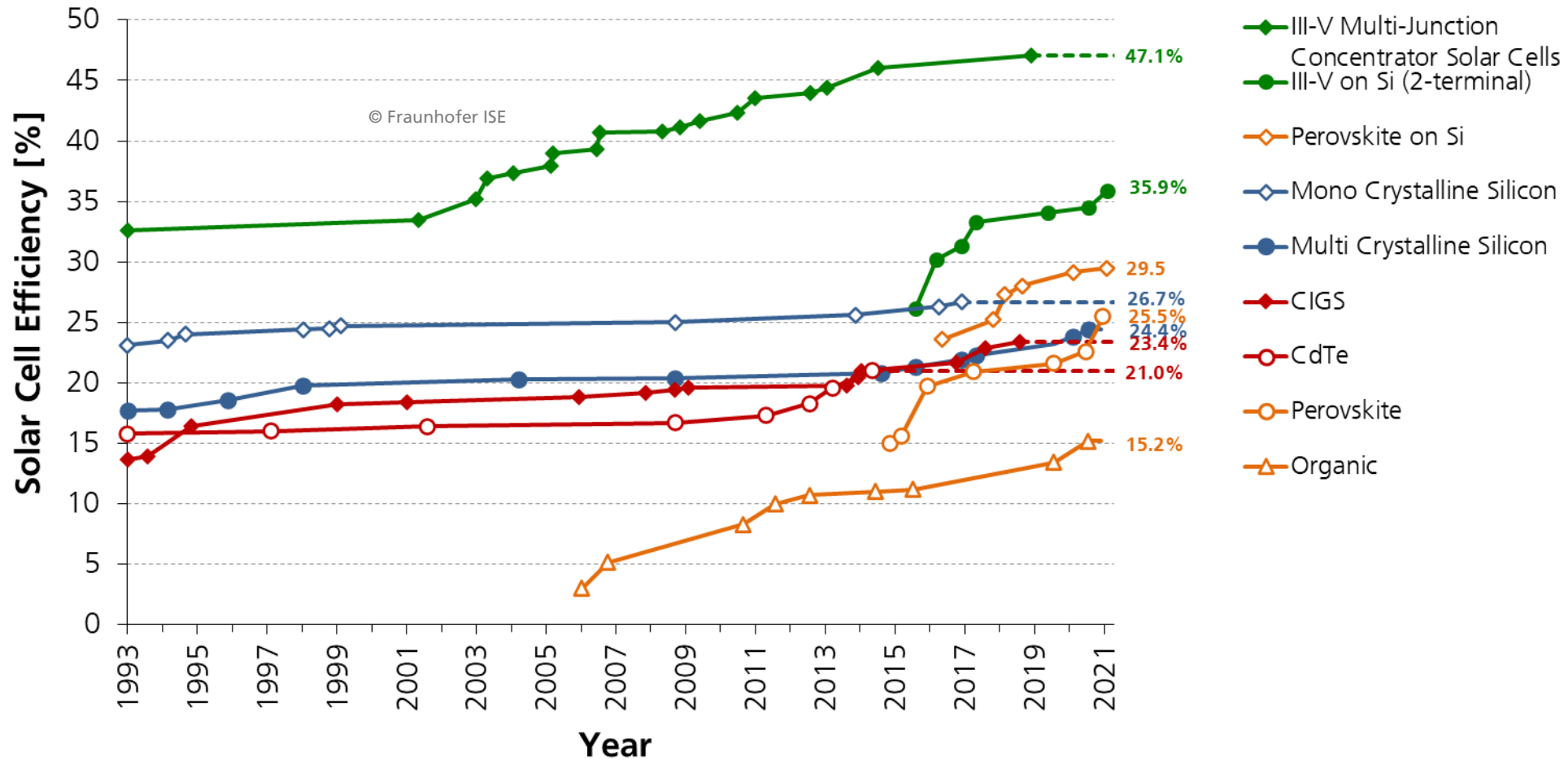


Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2021 . Date of data: May-2021

2. Solar Cells / Modules / System Efficiency

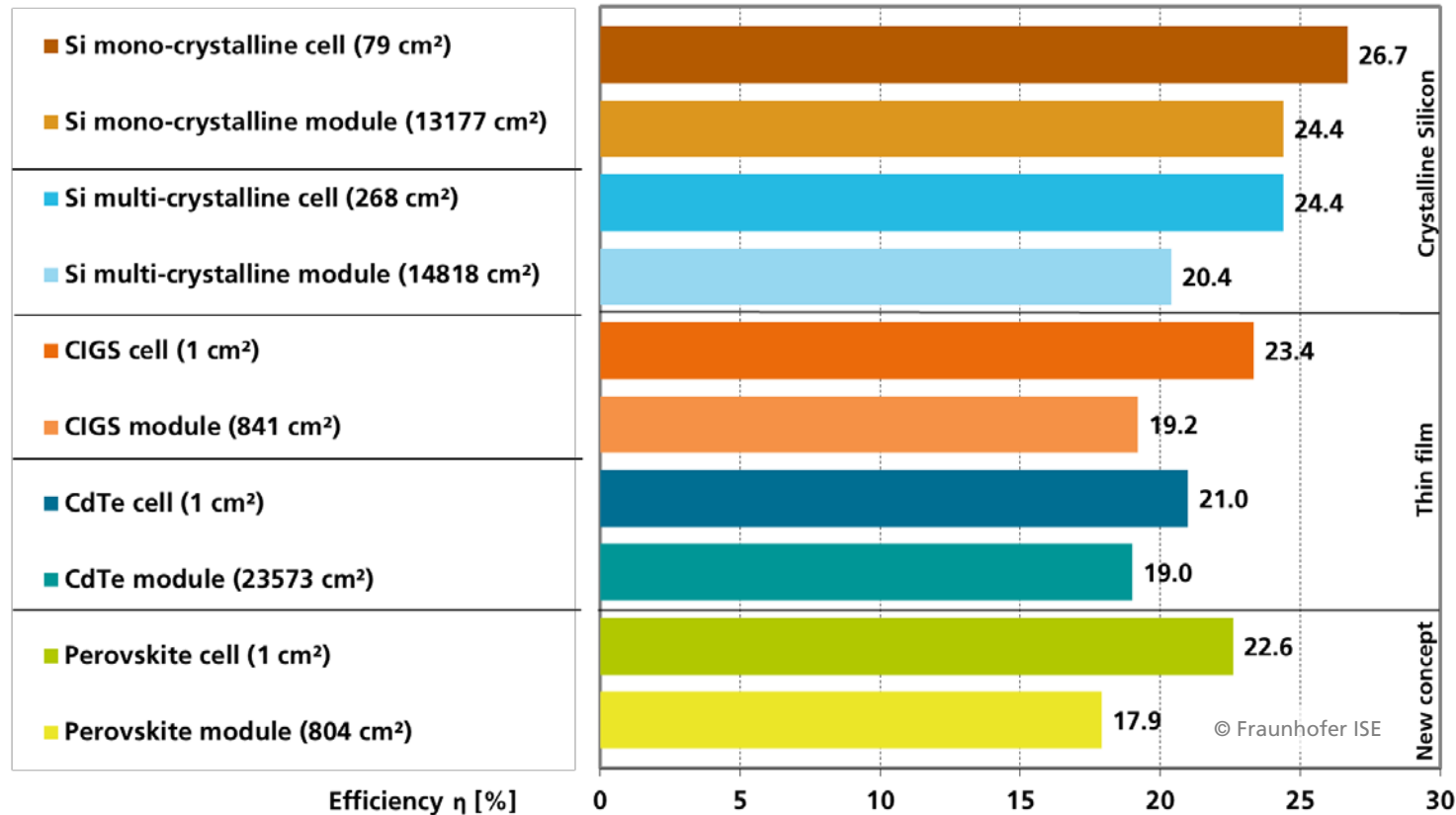
- Development in the Laboratories
- Development in the PV Industry
- Performance Ratio (PR)

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 59), Progress in Photovoltaics: Research and Applications, 1993-2021. Graph: Fraunhofer ISE 2021 . Date of data: Nov. 2021

Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules



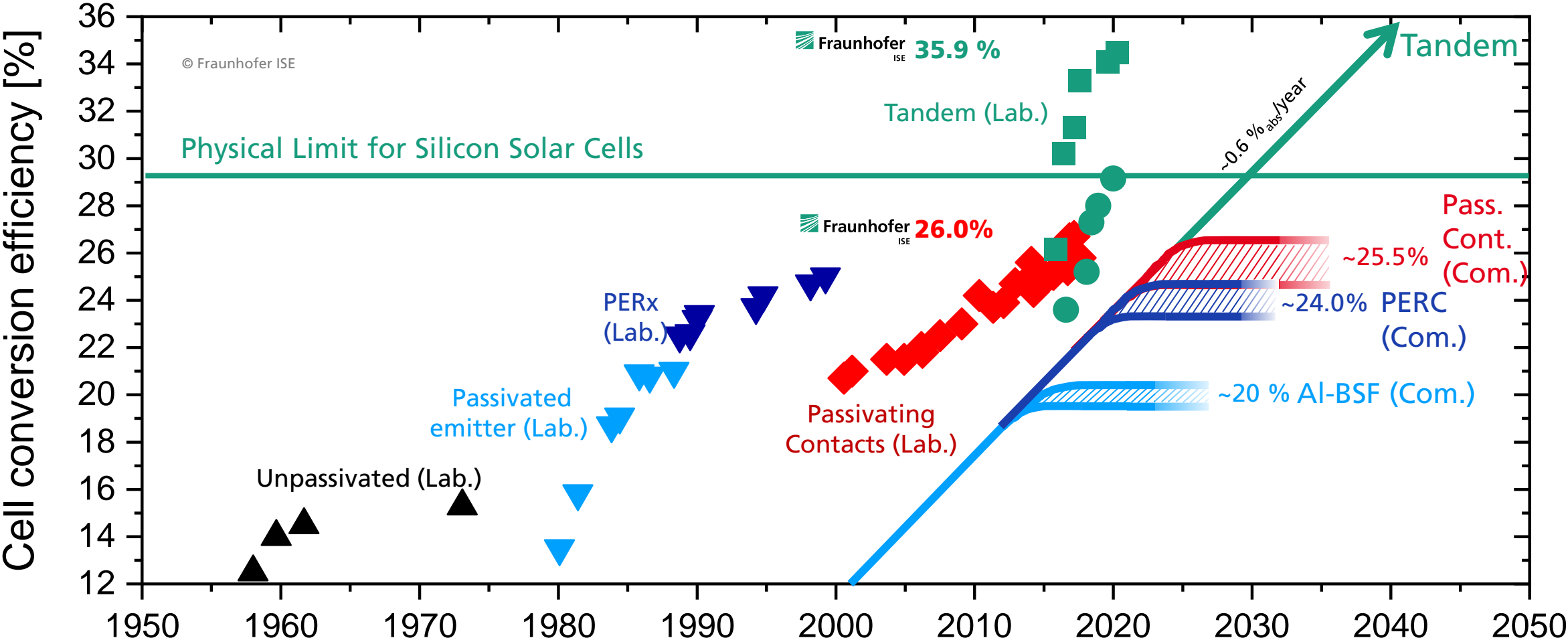
Note: In mass production Cell-to-Module ratio (CTM) improved in past years by reducing losses and using possible gains when integrating solar cells in modules. Fraunhofer ISE provides SmartCalc.CTM software suite for the precise CTM power loss analysis. It considers geometrical losses, optical losses & gains as well as electrical losses.

www.cell-to-module.com

Data: Green et al.: Solar Cell Efficiency Tables (Version 59), Progress in PV: Research and Applications 2021. Graph: PSE 2021. Date of data: Nov. 2021

Development of Laboratory and Commercial Solar Cell Efficiencies

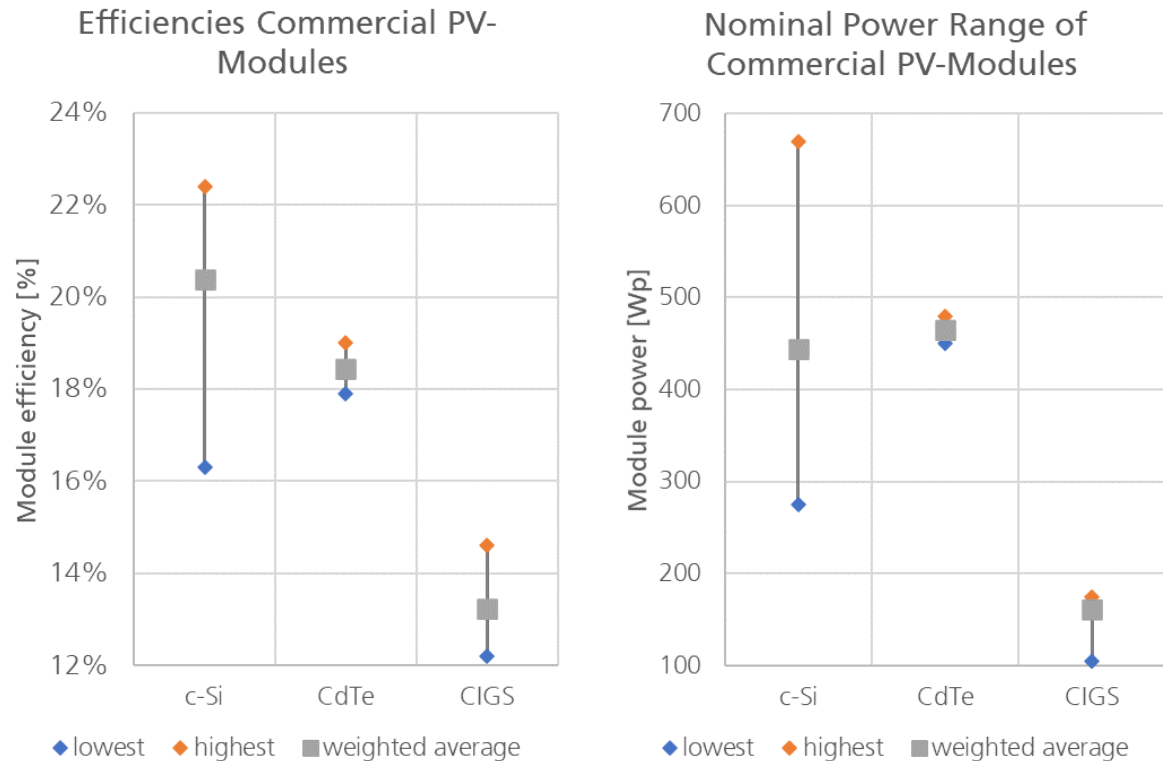
What's Next?



Graph: Fraunhofer ISE 2021

Current Efficiencies and Power of Commercial PV Modules

Sorted by technology



Total weighted average efficiency of crystalline Silicon(c-Si) wafer-based modules is **20.4%** in Q4-2021 (weighting factor is total shipments in year 2020). Lowest module efficiency in this group is 16.3% and highest value is 22.4%.

Top 10 manufacturers represent about 78% of total shipment volume and origin mainly in Asia.

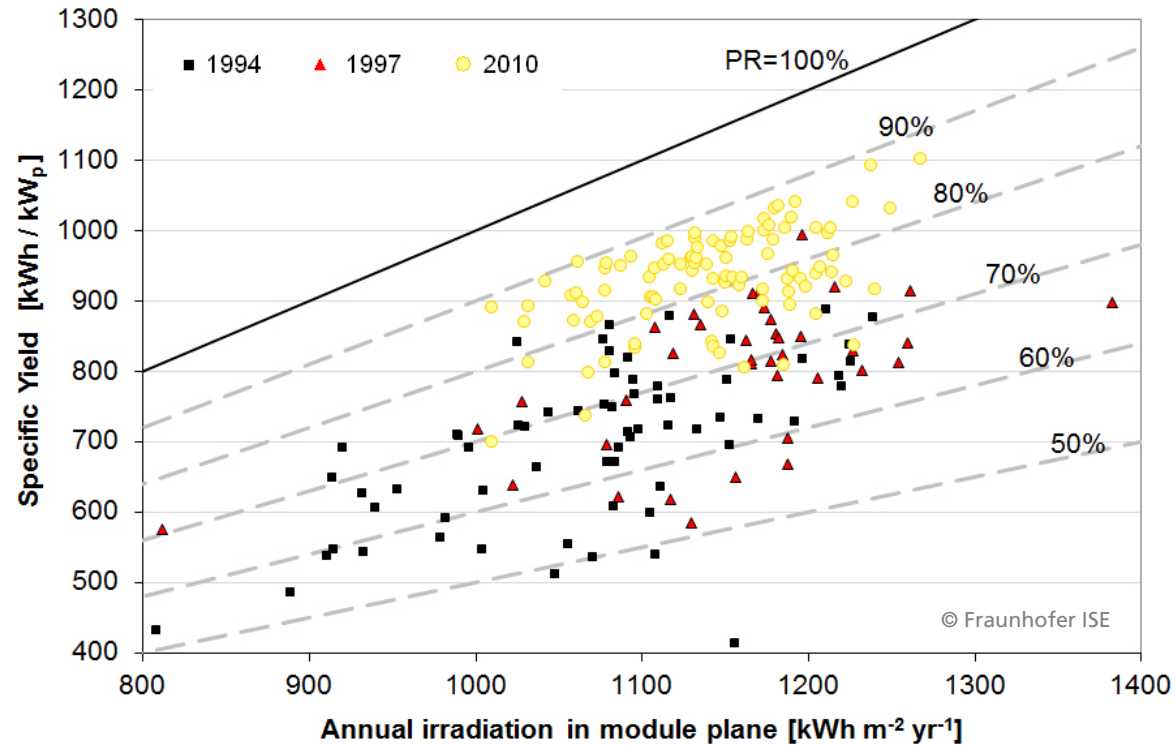
Predominant c-Si technology is mono-PERC with half-cut cells and Multi-Busbar.

Note: Selection based on modules of Top10 manufacturers in year 2020 (exception CIGS) with global available module data sheets at end of Oct-2021.

Data Source: Company product data sheets; Date of data: 04-Nov. 2021 Fraunhofer ISE

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

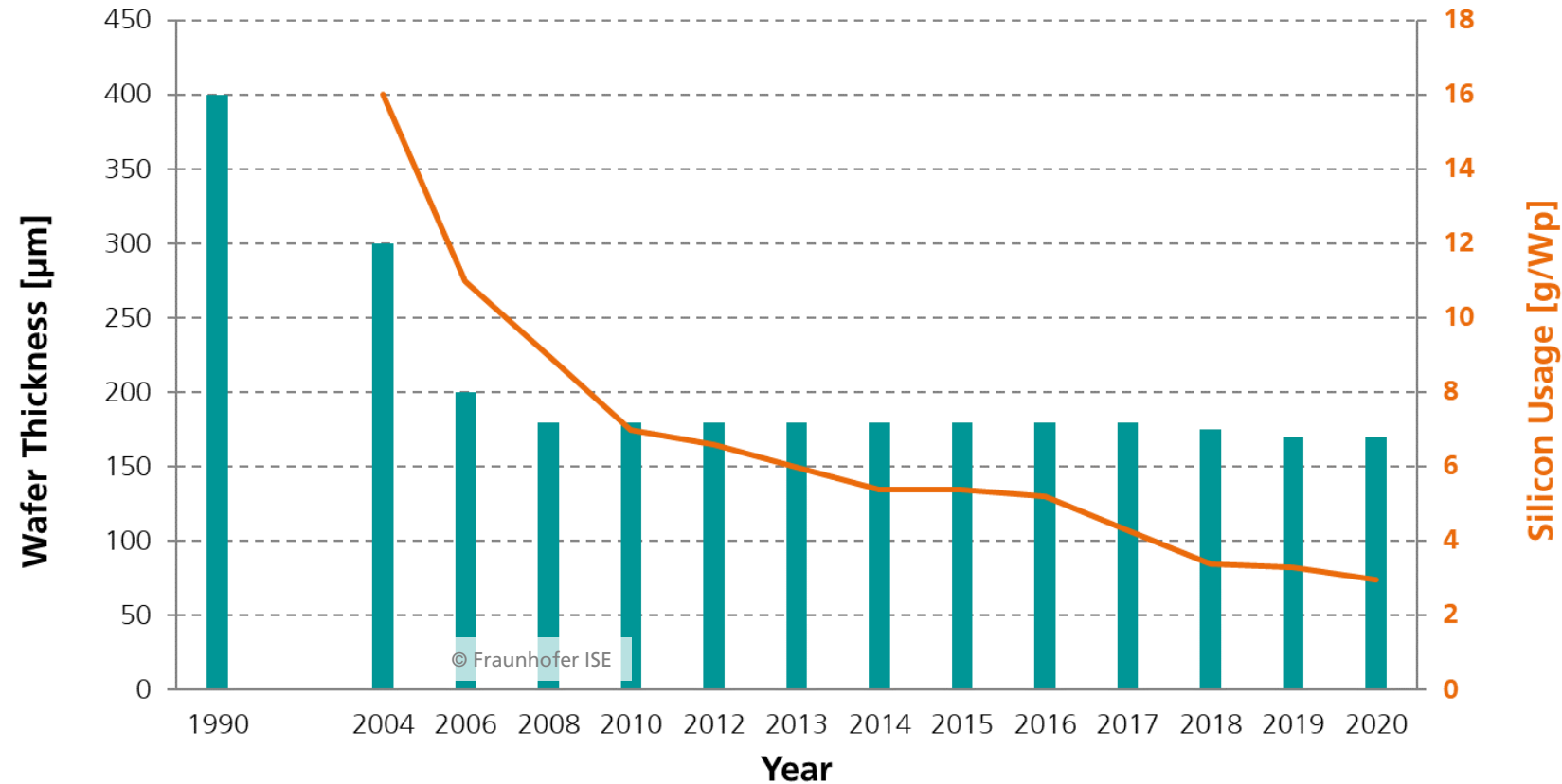
Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation, CPIA 2021

3. Energy Return of Invest (EROI) & Energy Payback Time (EPBT)

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

c-Si Solar Cell Development

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



Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV 2015; ISE 2016 without; 2017 to 2020 with recycling of Si. Graph: PSE Projects GmbH 2021

Historic Trend in Energy Payback Time

Harmonized Study data for mono-crystalline Silicon Rooftop PV-Systems

- **Learning Rate:**
Each time the cumulative production doubled, the EPBT went down by 12.8 % for 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%

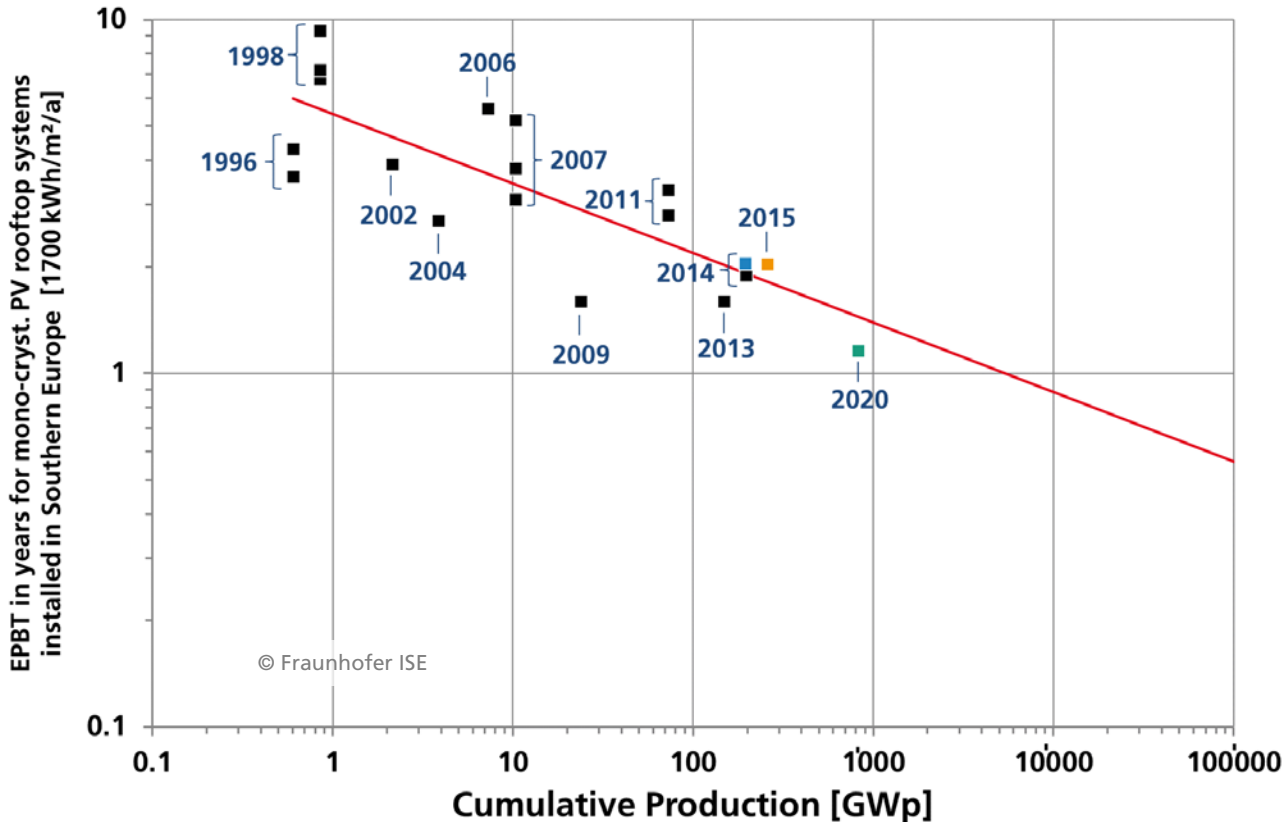
PR (incl. average degradation during lifetime) 73.6%

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: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2021

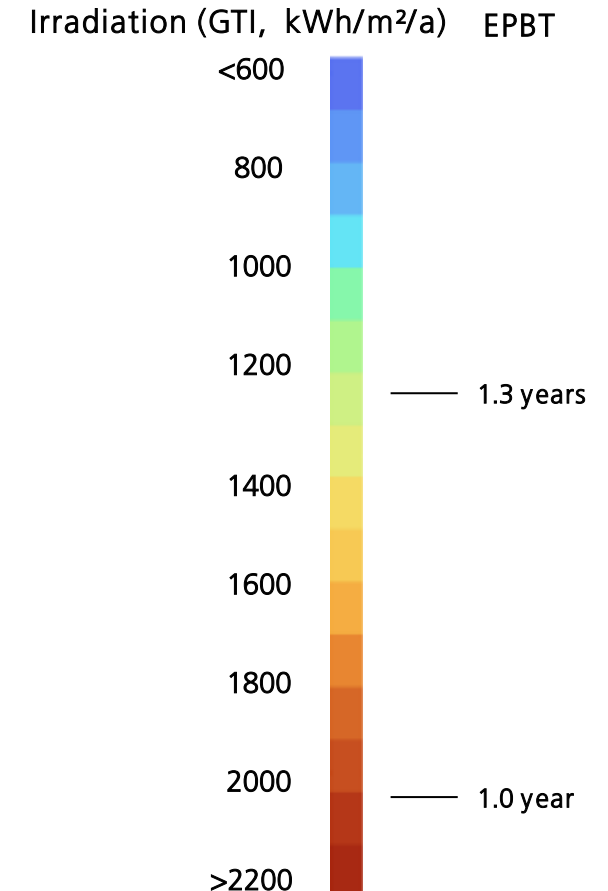
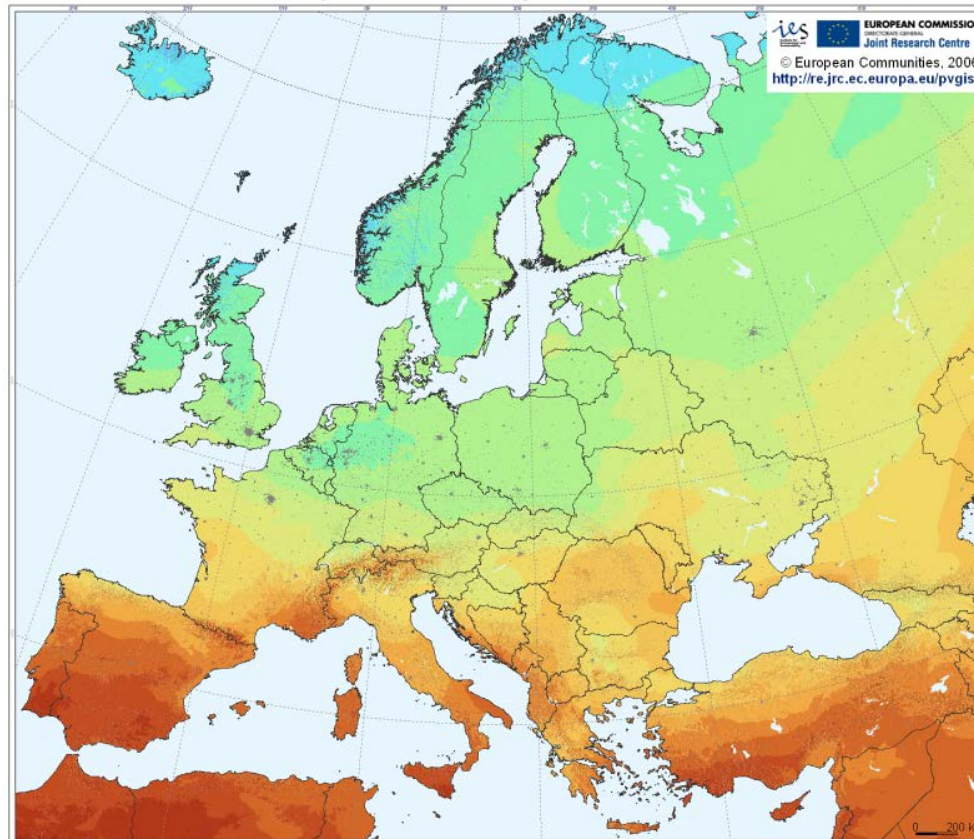
Irradiation: 1700 kWh/m²/a at an optimized tilt angle; **Years:** Estimated average year of original data

* ■ 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

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.

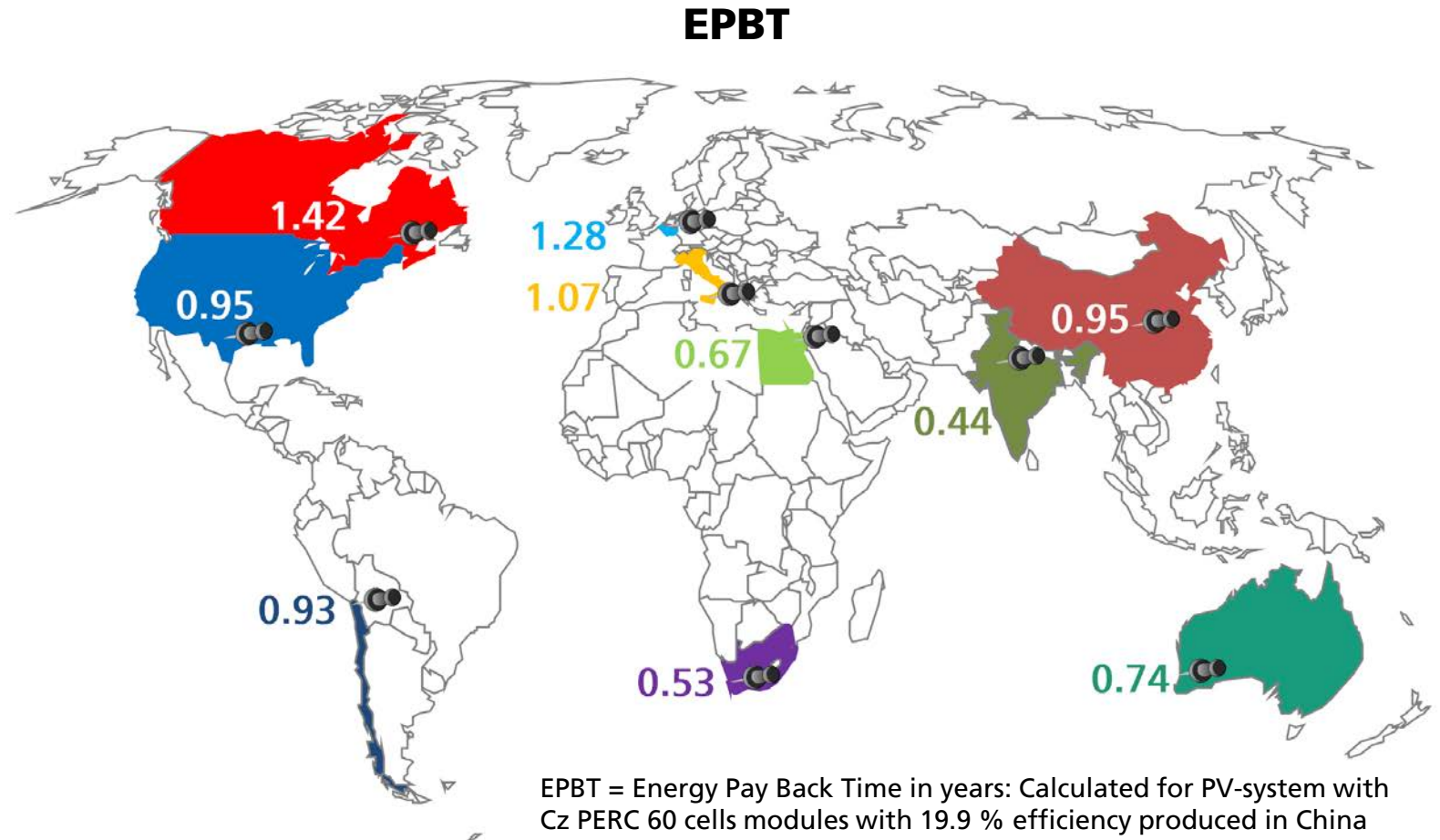


Data: Lorenz Friedrich, Fraunhofer ISE. Image: JRC European Commission. Graph: PSE 2020 (Modified scale with updated data from Fraunhofer ISE)

World Map EPBT of Silicon PV Rooftop Systems – Comparison of EPBT China

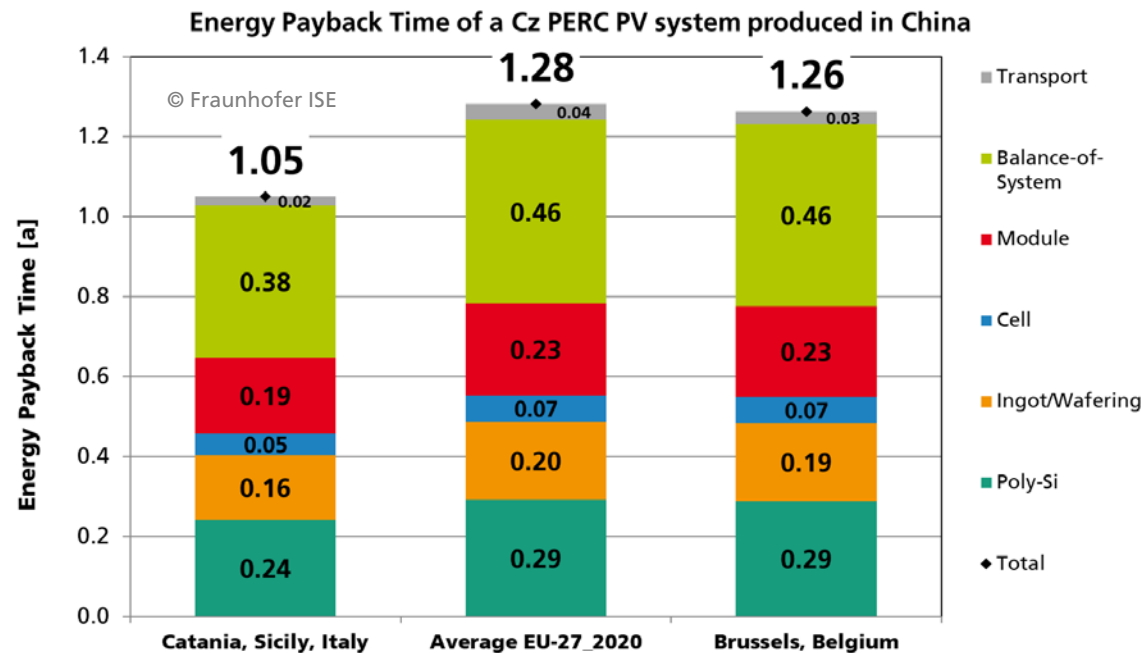
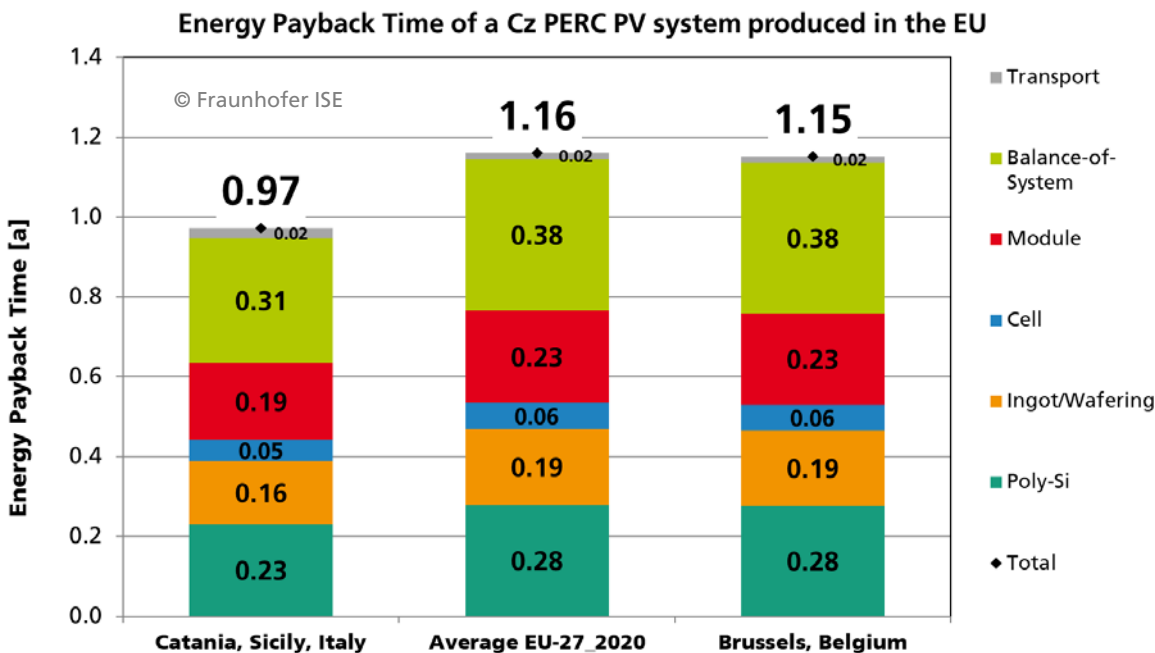
Influencing factors and interpretation:

- 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). At downstream (where PV is installed) a low grid efficiency reduces the EPBT.



Data: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2020

Energy Pay-Back Time of Silicon PV Rooftop Systems – Comparison of EPBT China / EU, local Irradiation and Grid Efficiency



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

Data: Lorenz Friedrich, Fraunhofer ISE. Design: PSE 2020

4. Inverters

■ Inverter/Converter Market

Inverter/Converter Market 2020

Inverter / Converter	Power	Efficiency	Market Share (Estimated)*	Remarks
String Inverters	up to 150 kWp	up to 98% (DC/AC)	64.4%	<ul style="list-style-type: none"> • 3 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5% (DC/AC)	33.7%	<ul style="list-style-type: none"> • 3 - 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-97% (DC/AC)	1.4%	<ul style="list-style-type: none"> • ~ 25 €-cents /Wp • Ease-of-replacement concerns
Power Optimizer	Module Power Range	up to 99.5% (DC/DC)	5.1%	<ul style="list-style-type: none"> • ~ 8 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed

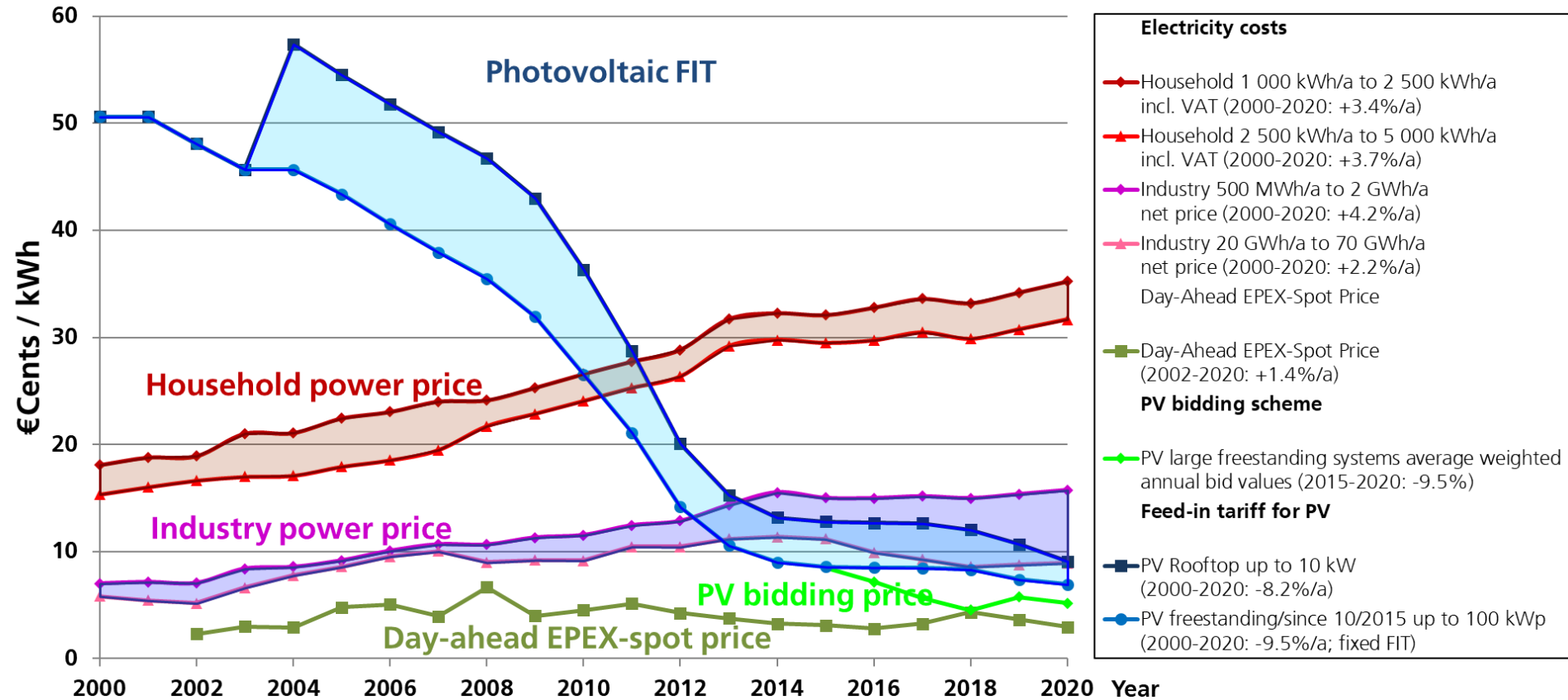
Data: IHS Markit 2021; IRENA 2021. Remarks: Fraunhofer ISE 2021. Date of data: Jun-2021

*Total Market Share related to shipment in MWac is greater than 100% because DC/DC converters are required to be paired with string inverters

5. Price Development

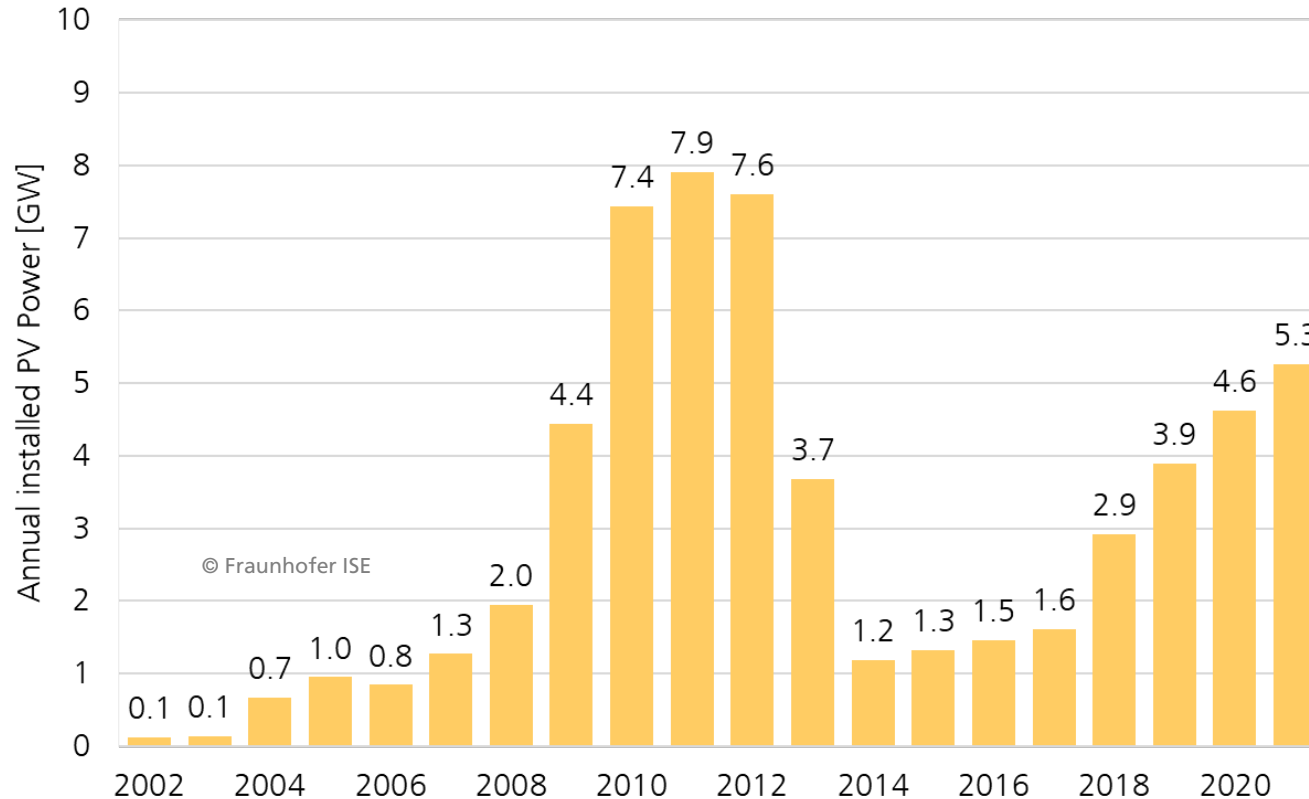
- Electricity costs
- Market incentives in Germany
- Costs for PV systems
- Price Learning Curve

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



Data: BMU and BMWi Energiedaten 2020. Design: B. Burger - Fraunhofer ISE. Date of data: Feb.2021

PV Market Development and Incentive Schemes in Germany

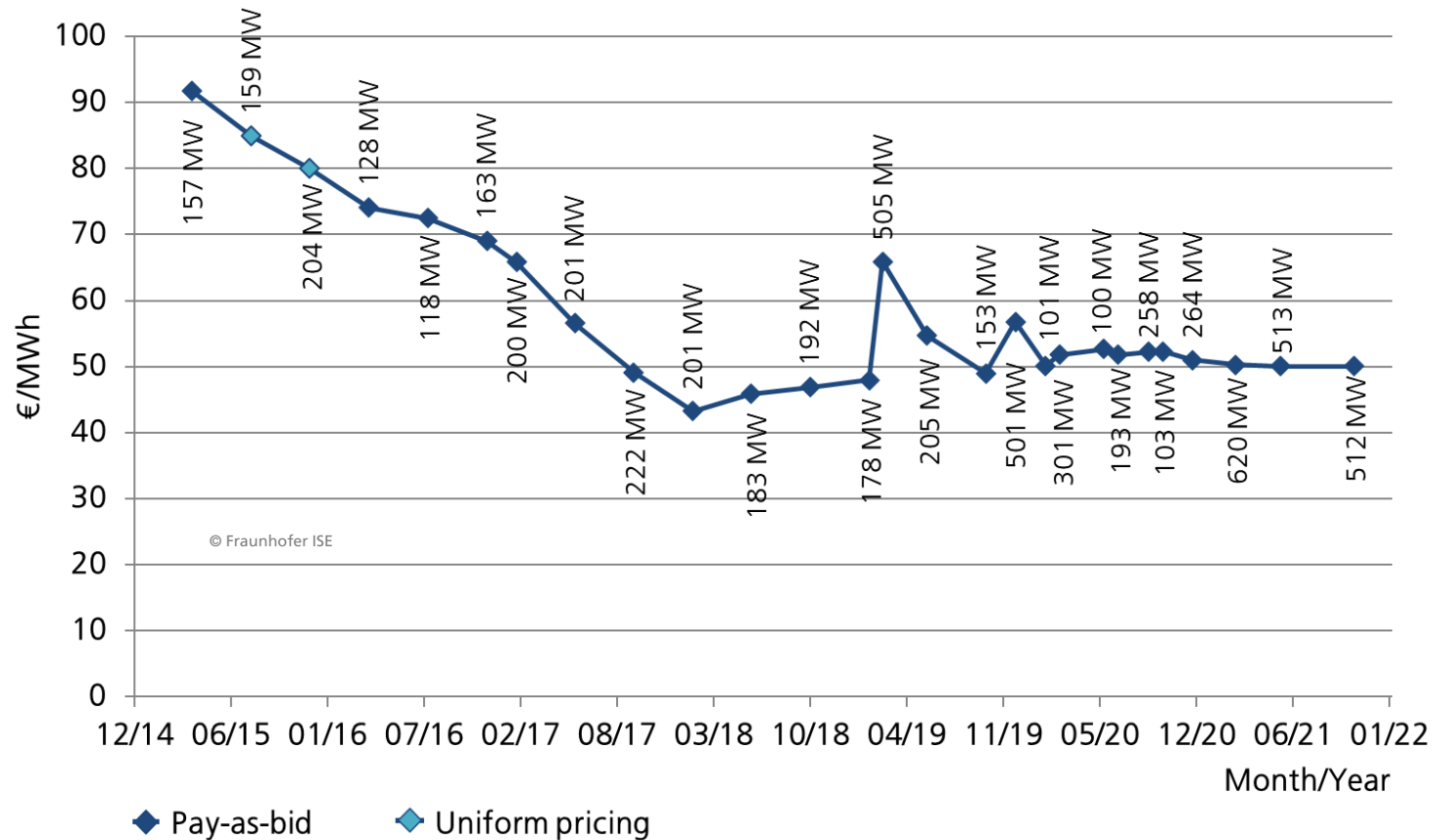


Data: BNA. Graph: B. Burger, Fraunhofer ISE Energy-Charts. Date of Data: 31-Jan-2022

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

PV-Tender in Germany

Average, quantity weighted Award Value



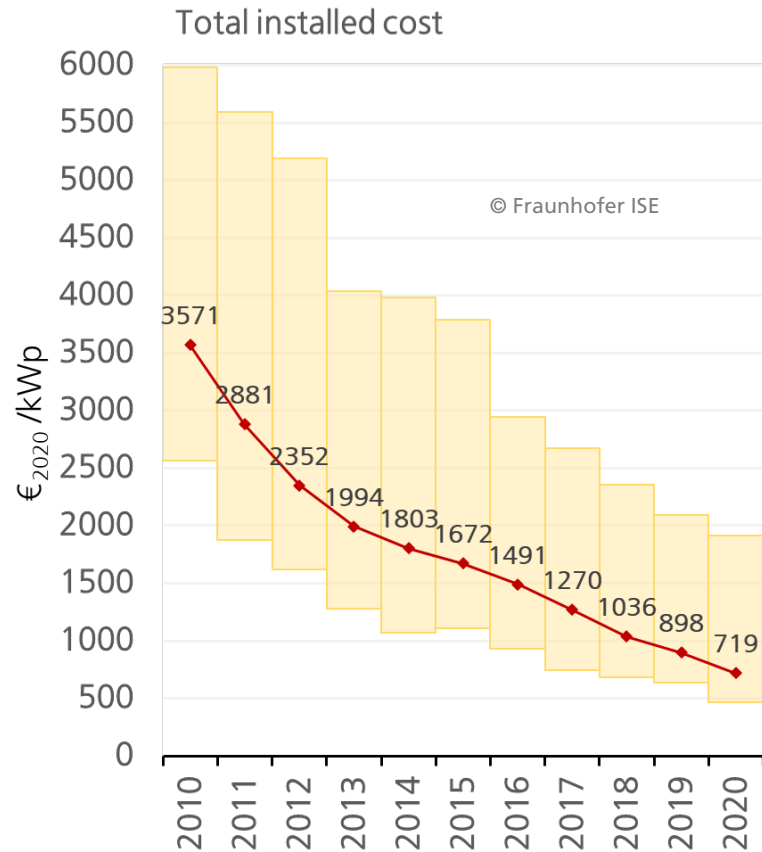
Data: BNA. Graph: PSE 2021 – Date of data: Nov-2021

Lowest PV-Tender Round was in Feb. 2018 with 4.33 ct€ / kWh as average quantity weighted award price.

PV-Tender scheme started in April 2015 and total capacity of this scheme accumulates to 5.8 GW by Nov-2021 with 5.00 ct€ / kWh as latest average quantity weighted award price.

Special tenders are not displayed in the graph.

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



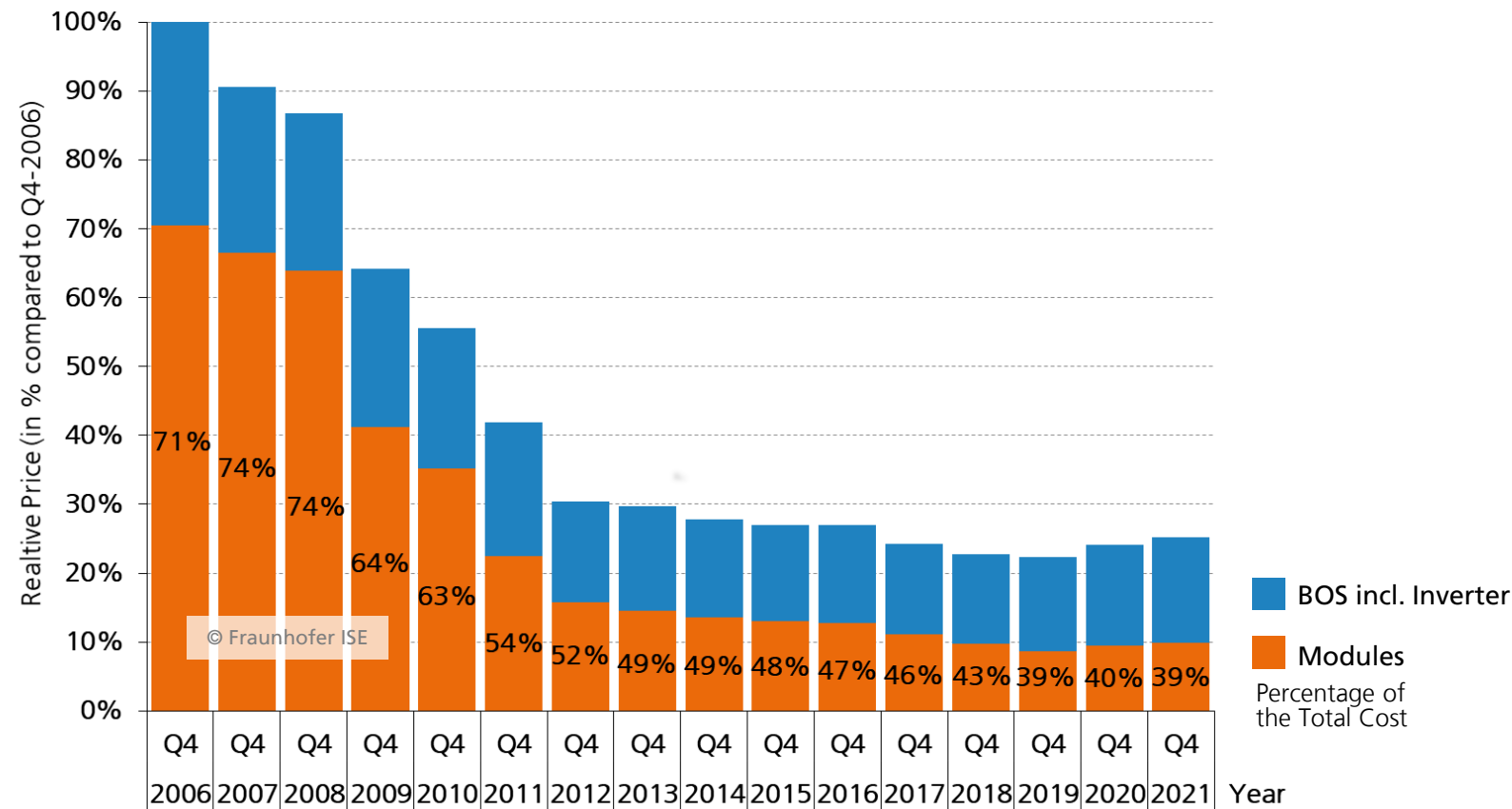
Total installed cost for large PV systems decreased by about 15% on year-to-year basis in the last decade.

The 5th percentile is a value associated with the location within the data where 5% of data is below that value. In year 2020 the 5th percentile was 466 €/kWp.

The 95th percentile is the value where 5% of the data has a larger value. In year 2020 the 95th percentile was 1912 €/kWp.

Data: IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: June 2021

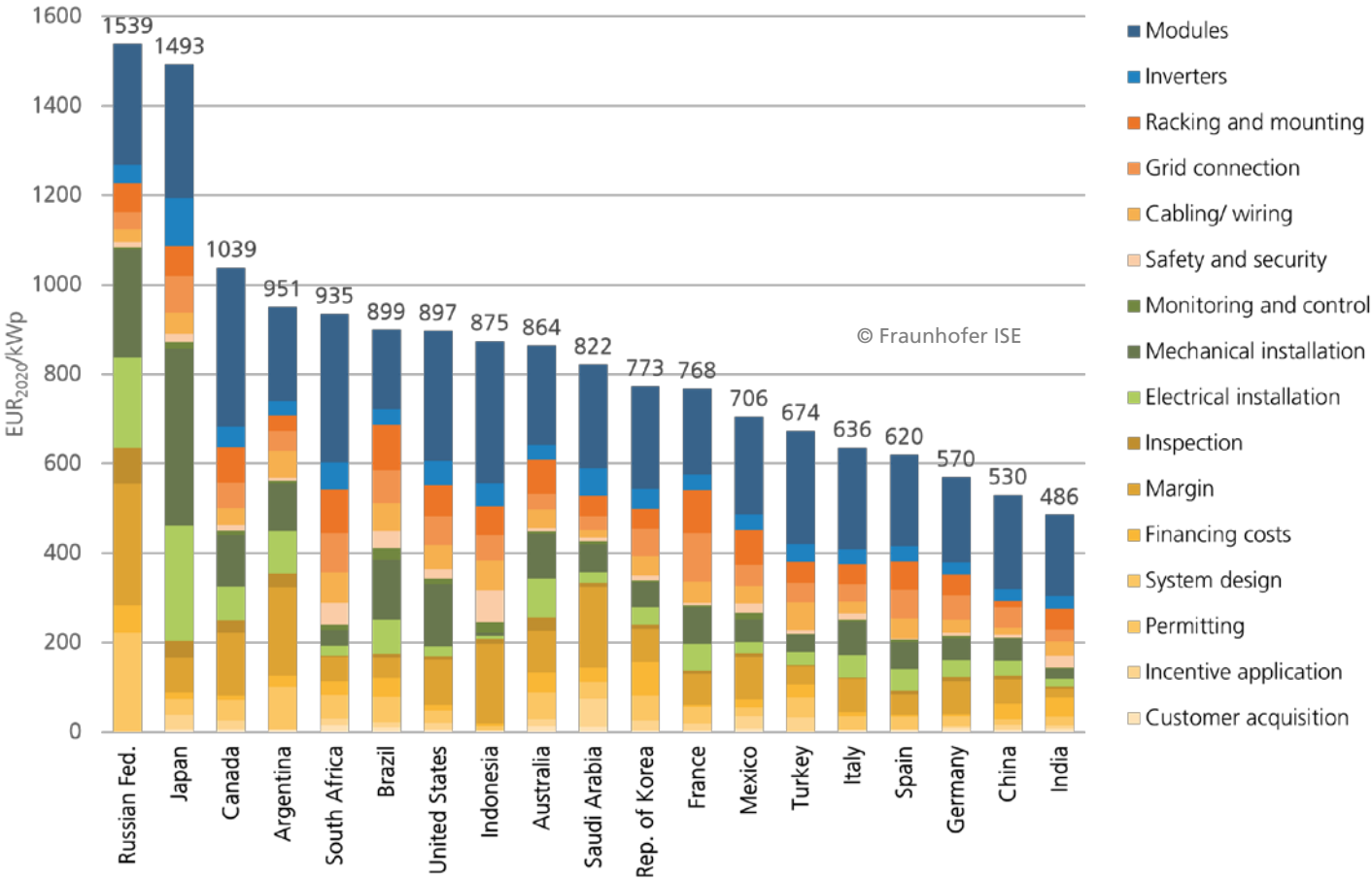
Price Development for PV Rooftop Systems in Germany (10kWp - 100kWp)



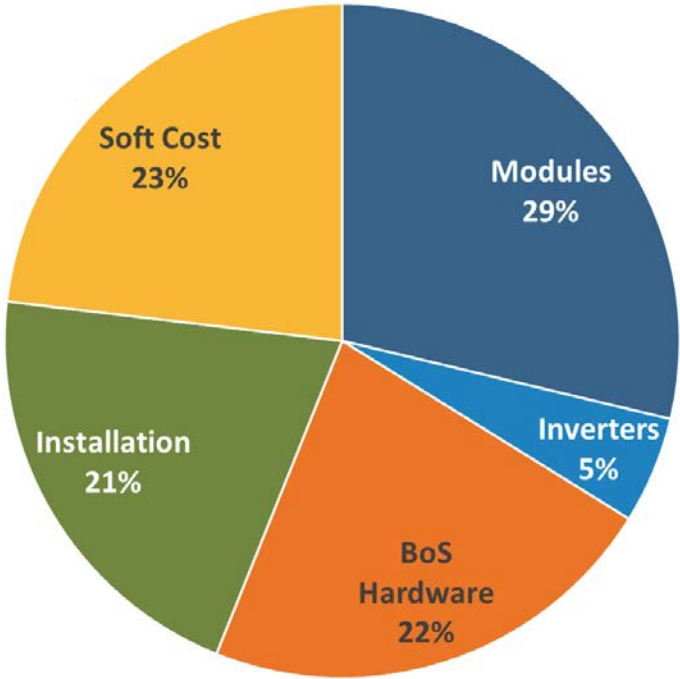
Balance of System (BOS) encompasses all components of a PV system other than the PV modules; like inverter, mounting system, switches, wiring and installation work. Annual average BOS cost increased by 10.8% on y-to-y basis in 2021 and annual average PV module cost increased by 20.0% due to COVID-19 market disturbances.

Data: BSW-Solar. Graph: PSE 2021. Date of data: Nov-2021

Breakdown of Utility-scale PV Total Installed Costs By Country in 2020



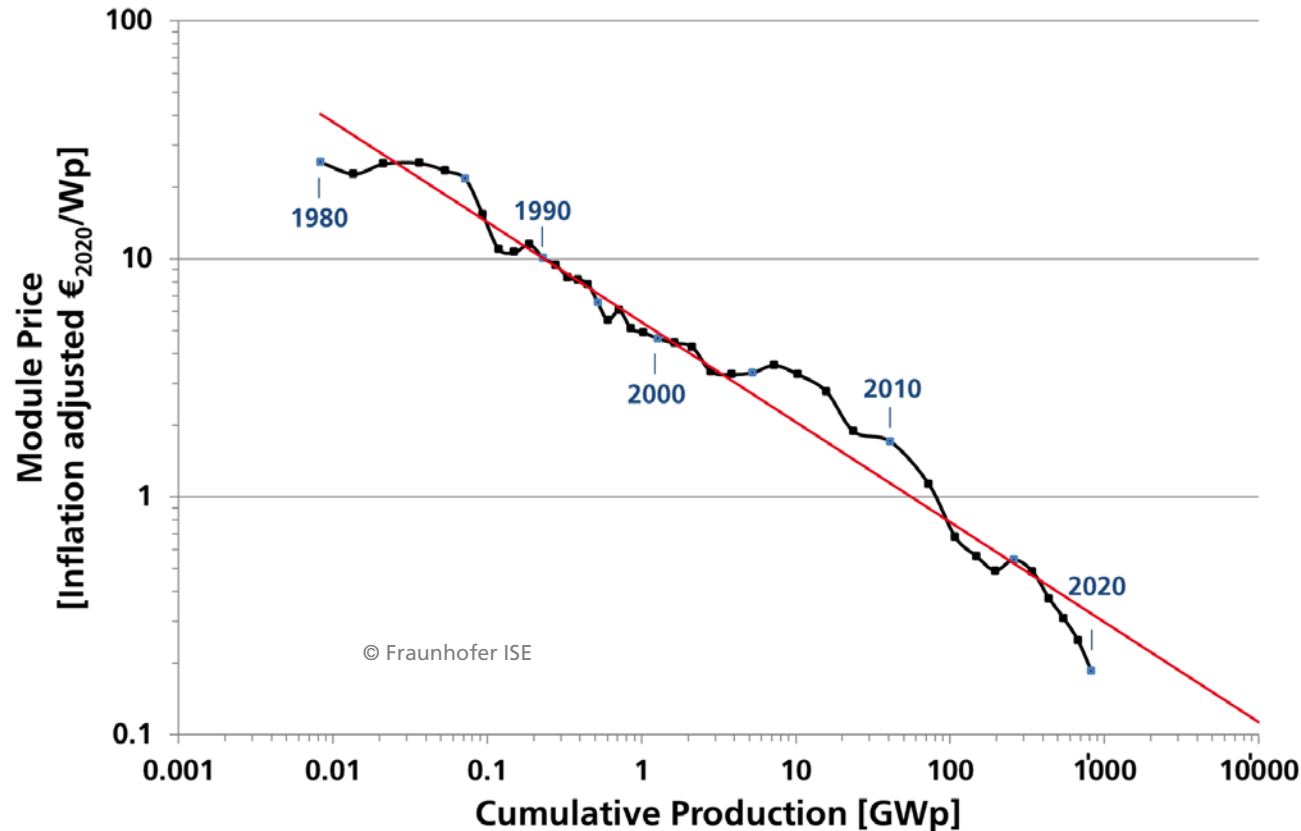
Breakdown of cost components
(average of available country data):



Data: IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: Jun-2021

Price Learning Curve

Includes all Commercially Available PV Technologies

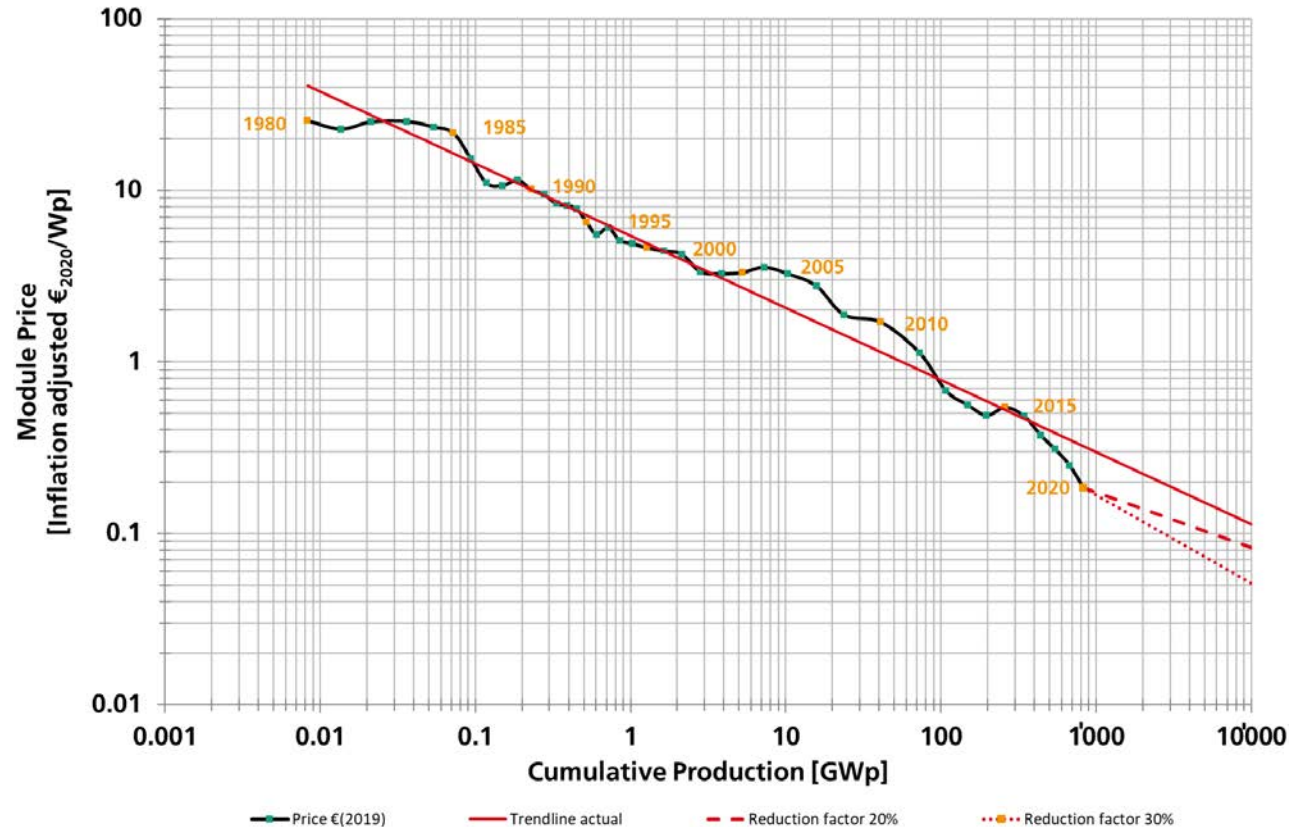


Learning Rate:
Each time the cumulative PV module production doubled; the price went down by 25% for the last 40 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2021

Price Learning Curve

Includes all Commercially Available PV Technologies

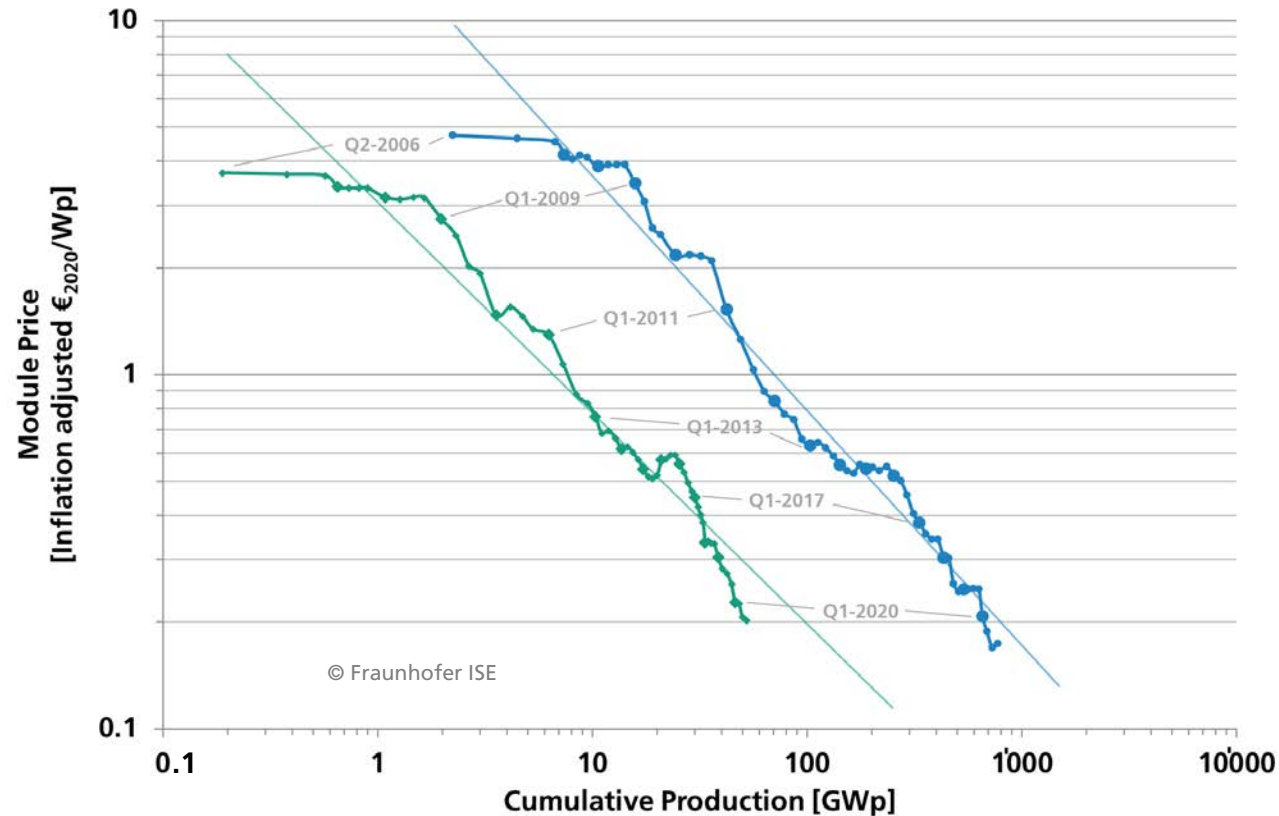


Learning Rate:
Each time the cumulative PV module production doubled the price went down by 25% for the last 40 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2021

Price Learning Curve by Technology

Cumulative Production up to Q4-2020



Estimated cumulative PV module production up to Q4-2020:

● c-Si	773 GWp
◆ Thin Film	52 GWp

Crystalline Technology
(from Q2-2006 to Q4-2020) LR 32
Thin Film Technology
(from Q2-2006 to Q4-2020) LR 30

Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit. Graph: PSE 2021

Further Reading

Selected studies and analyses

- [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](#)

Please click on the link to find the respective information.

Abbreviations

Abbr.	Explanation	Abbr.	Explanation
AC	Alternating Current	HCPV	High Concentrator Photovoltaic
Al-BSF	Aluminum Back Surface Field	HJT (also HIT)	Heterojunction with Intrinsic Thin-Layer
BIPV	Building Integrated PV	IBC	Interdigitated Back Contact (solar cells)
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	PERC	Passivated emitter and rear cell
Cz	Czochralski Method	PR	Performance Ratio
DC	Direct current	p-type	Positively doped wafer (with boron)
EEG	Renewable Energy Source Act (Erneuerbare-Energien-Gesetz)	PV	Photovoltaic
EPBT	Energy PayBack Time	RE	Renewable Energies
EROI	Energy Return of Invest	ROI	Return on Investment
FZ	Floating Zone	SI	Silicon
GaAs	Gallium Arsenide	SIC	Silicon carbide
GaN	Gallium nitride	VAT	Value Added Tax

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The information provided in this ‚Photovoltaics Report‘ is very concise by its nature and the purpose is to provide a rough overview about the Solar PV market, the technology and environmental impact.

There are many more aspects and further details can be provided by Fraunhofer ISE. Upon request, you are welcome to receive a tailor-made offer.

Please contact us if you are interested in ordering this service.

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