PHOTOVOLTAICS REPORT

Prepared by

Fraunhofer Institute for Solar Energy Systems, ISE

with support of PSE Projects GmbH

Freiburg, 16 September 2020

www.ise.fraunhofer.de

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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 However, facts and figures change rapidly and the given information may soon be outdated again.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 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: ©Fraunhofer ISE: Photovoltaics Report, updated: 16 September 2020

Quick Facts

Parameter	Value	Status	Reference
	Germany / EU28 / Worldwide		
PV market*	4 / 16.7 / 131 GW	2019	SPE / SPE / JRC
Cumulative installation	49 / 132 / 635 GW	End of 2019	SPE / SPE / JRC
PV power generation	46 / 127 / 585 TWh	2018	ISE / BP / BP
PV electricity share	8.7% (net) / gross: 3.9% / 2.2%	2018	ISE / BP / BP
	Worldwide		
c-Si share of production	95%	2019	IHS Markit
Record solar cell efficiency: III-V MJ (conc.) / mono-Si / CIGS / multi-Si / CdTe	47.1 / 26.7 / 23.4 / 23.2 / 21.0%	Dez. 2019	Green et al.
	Germany		
Price PV rooftop system	~ 1300 €/kWp	End of 2019	BSW
LCOE PV power plant	3.7 to 6.8 ct€ / kWh	End of 2018	ISE
PV-Tender Price	4.33 ct€ / kWh	Feb. 2018	BNA

* Not yet confirmed

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 35% between year 2010 to 2019.
- Concerning PV module production in 2019, China (mainland) hold the lead with a share of 66%, followed by Rest of Asia-Pacific & Central Asia (ROAP/CA) with 18%. Europe contributed with a share of 3%; USA/CAN contributed 4%.
- In 2019, Europe's contribution to the total cumulative PV installations amounted to 24% (compared to 25% in 2018). In contrast, installations in China accounted for 36% (same value as the year before).
- Si-wafer based PV technology accounted for about 95% of the total production in 2019. The share of mono-crystalline technology is now about 66% (compared to 45% in 2018) of total production.
- Market shifts from subsidy driven to competitive pricing model (Power Purchase Agreements PPA).
- Batteries and storage solutions get increasing importance e.g. to achieve higher self-consumption rates.

Executive Summary
PV Market: Focus Germany

- In 2019, Germany accounted for about 8% (49 GWp) of the cumulative PV capacity installed worldwide (635 GWp) with about 1.7 million PV systems installed in Germany. In 2019 the newly installed capacity in Germany was about 4 GWp; in 2018 it was 2.8 GWp.
- PV covered 8.2% of Germany's gross electricity demand in 2019. Renewable sources delivered about 43% of the total net power consumption in 2018 in Germany.
- In 2019 about 29 Mio. t CO_2 equivalent GHG emissions have been avoided due to 47.5 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 22.3% 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 21.6%.
- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17% (Super-mono 21%). 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 13 years from around 16 g/Wp to less than 4 g/Wp due to increased efficiencies, thinner wafers and wires 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 1.5 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 98% and higher.
- The market share of string inverters is estimated to be 52%. 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 44%.
  A small proportion of the market (about 1%) belongs to micro-inverters (used on the module level). The market for DC / DC converters, also called “power optimizers”, is estimated to be in the same range.
- The specific net retail price of all inverters in Germany is about 12 €-cents /Wp. Costs for central inverters for large freestanding PV-power plants were in the range between 7 to 9 €-cents /Wp in Germany in 2019.
- 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

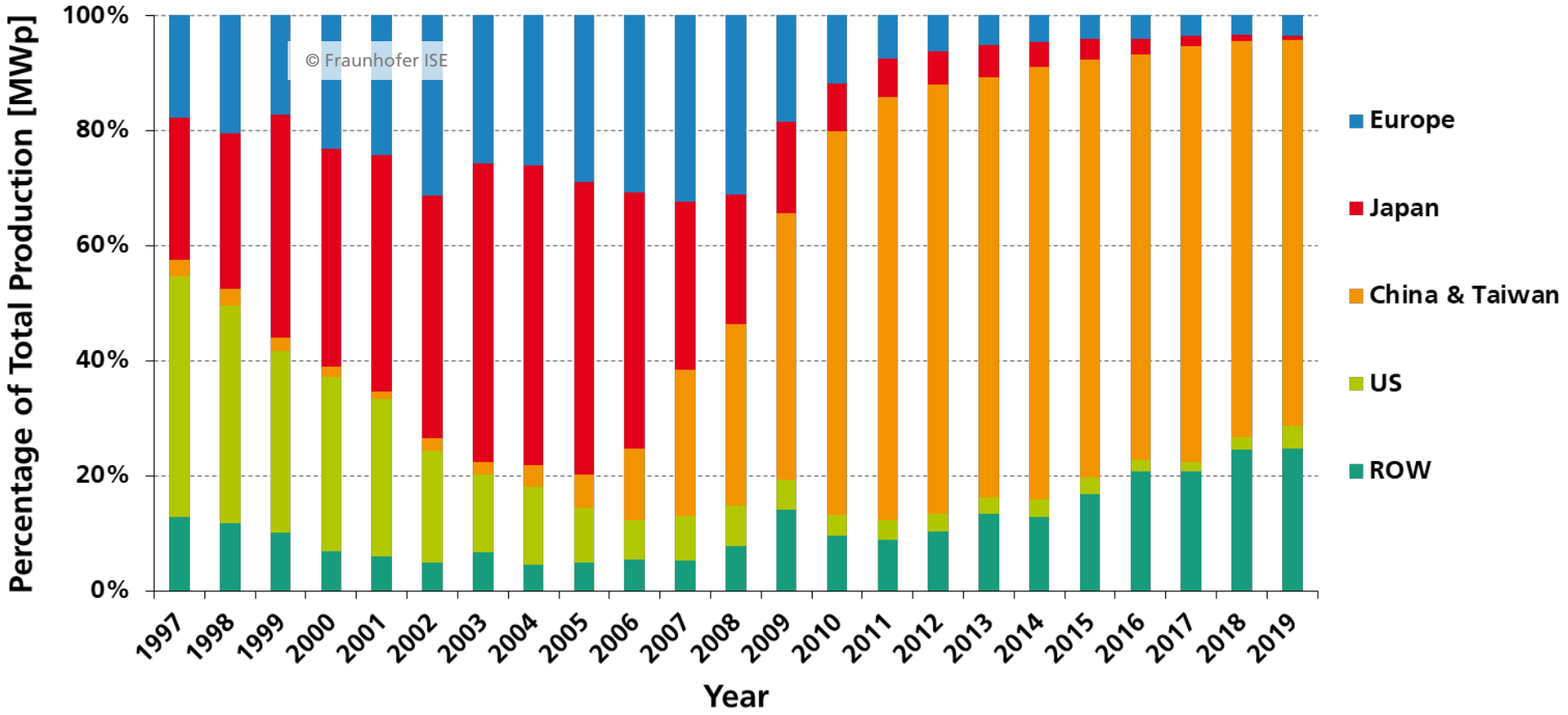
- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2019, such systems cost about 1,050 €/kWp in average. This is a net-price regression of about 92% over a period of 29 years and is equivalent to an annual compound average price reduction rate of 8.5%.
- The Experience Curve – also called Learning Curve - shows that in the last 39 years the module price decreased by 24% with each doubling of the cumulated module production. Cost reductions result from economies of scale and technological improvements.

1. PV Market

- By region
- By technology

PV Module Production by Region 1997-2019

Percentage of Total MWp Produced



Data: Up to 2009: Navigant Consulting; since 2010: IHS Markit. Graph: PSE Projects GmbH 2020

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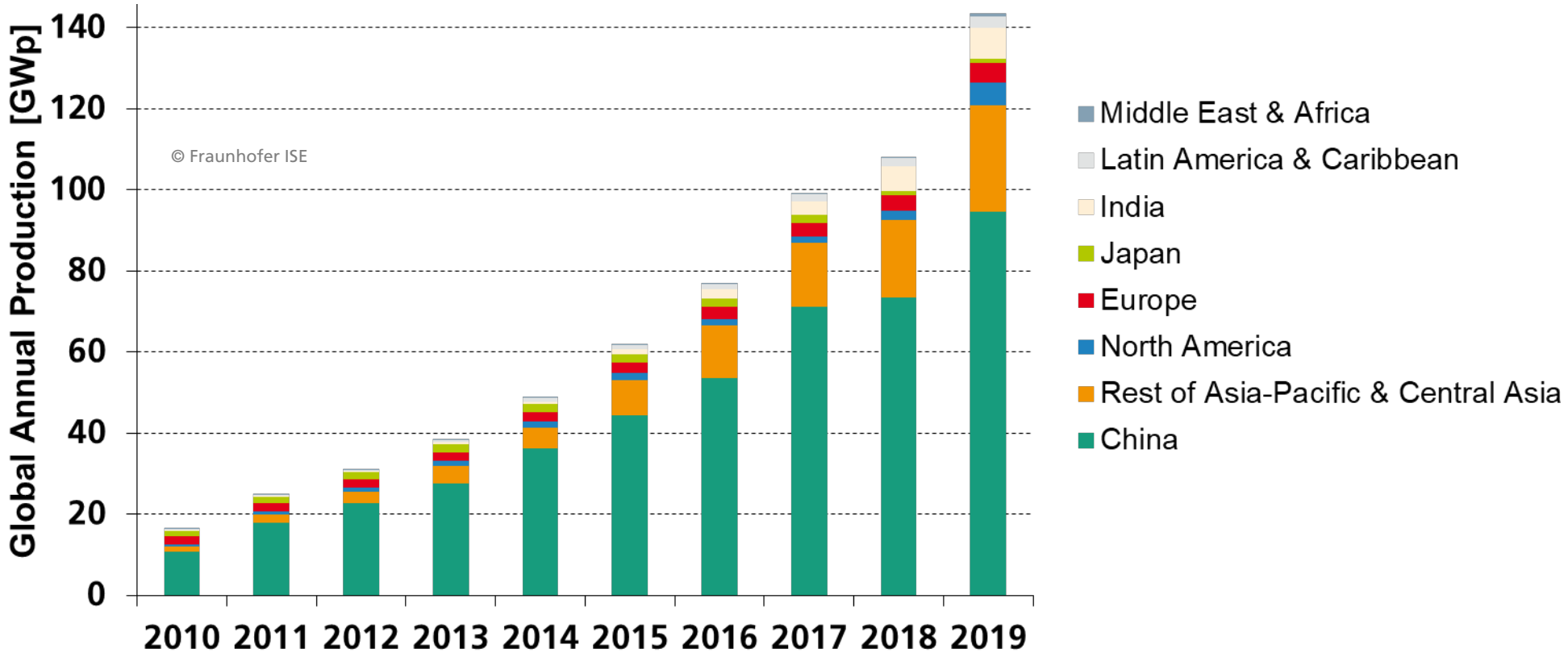
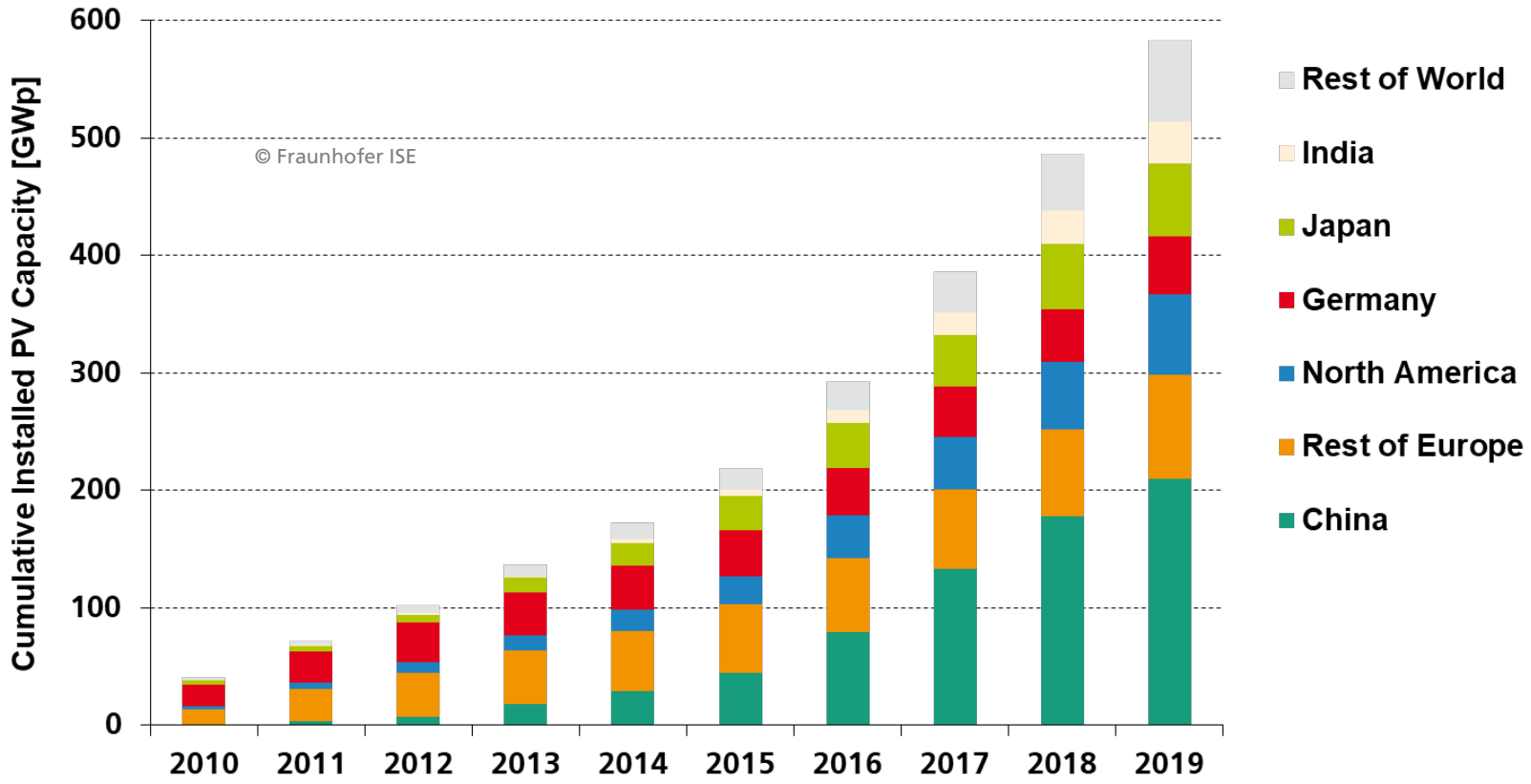
PV Module Production by Region

Global Annual Production



Data: IHS Markit 2020. Graph: PSE Projects GmbH 2020

Global Cumulative PV Installation
On- and Off-Grid

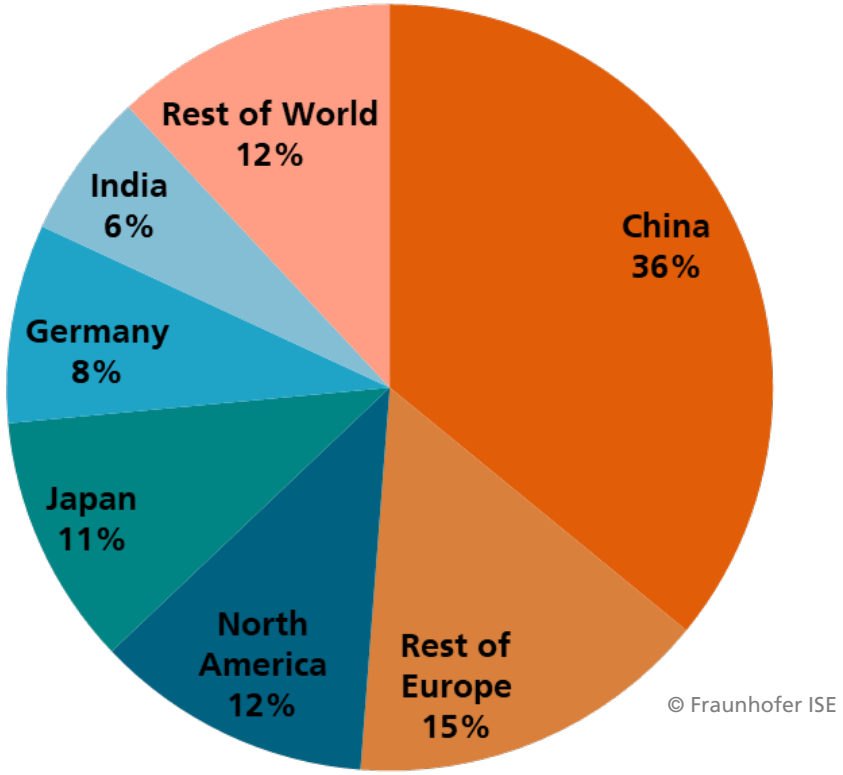


The share of off-grid installations decreased by time; from about 1% in year 2010 to about 0.6% in year 2019.

Data: IRENA 2020. Graph: PSE Projects GmbH 2020

Global Cumulative PV Installation by Region

Status 2019



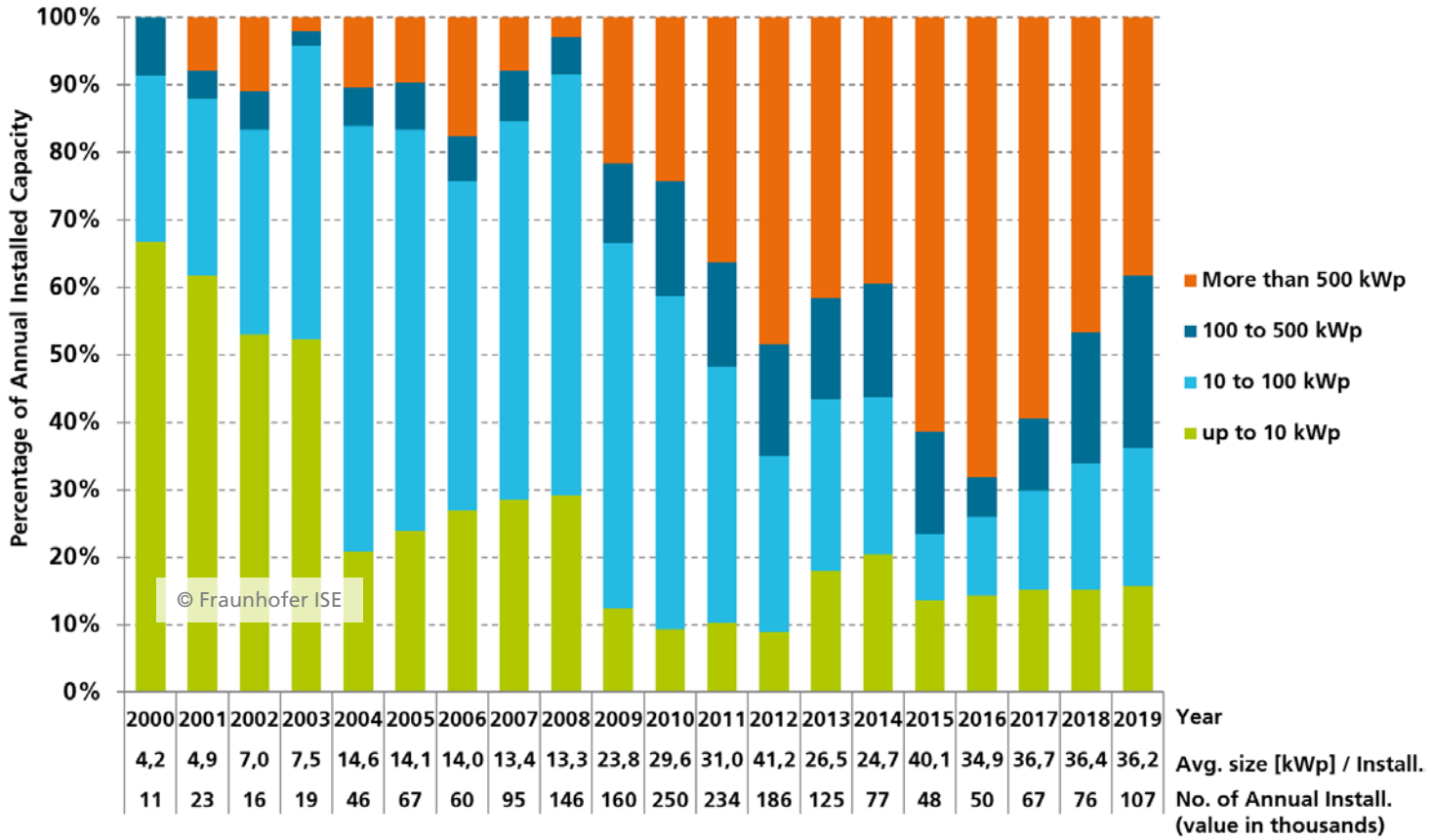
The total cumulative installations amounted to 584 GWp at the end of year 2019.

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

Data: IRENA 2020. Graph: PSE Projects GmbH 2020

Number of PV Systems Annually Installed in Germany

Percentage of Annual Capacity by System Size



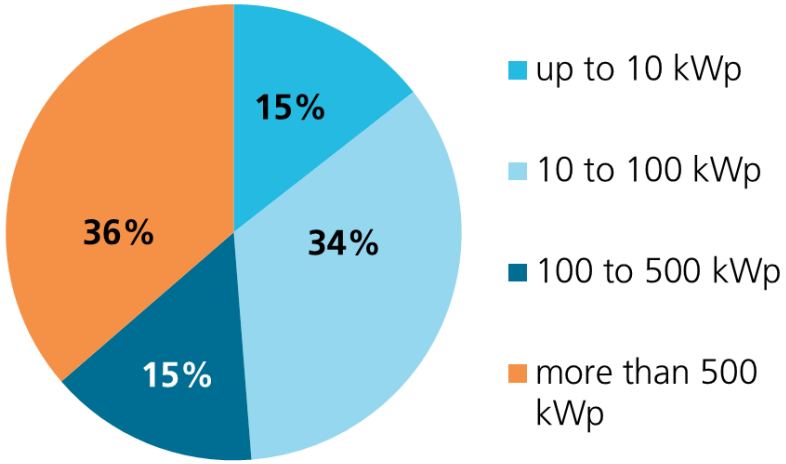
According to BNA at end of year 2019 in Germany a total cumulated PV capacity of 49.9 GW was installed.

Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur (BNA); values for 2019 may not be final. Graph: PSE Projects GmbH 2020

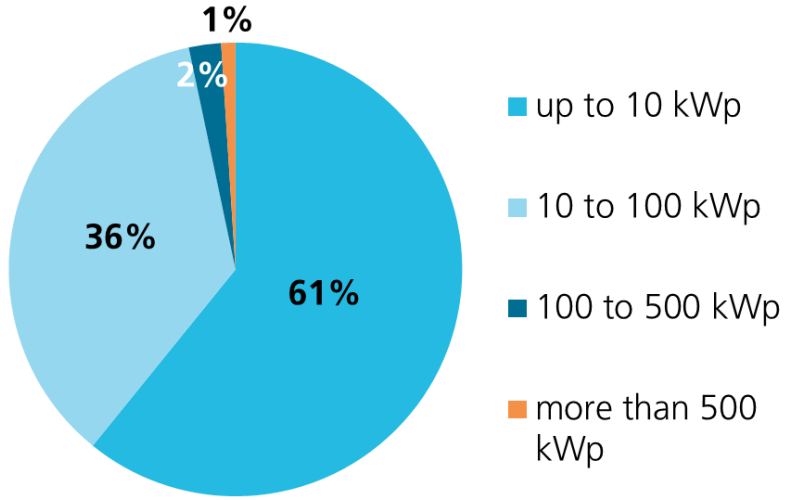
Share of Capacity and Number of PV-Systems Installed

Percentage of Cumulative Installations in Germany

Share of PV-Systems in Germany by cumulatice capacity (2019)



Share of PV-Systems in Germany by cumulative numbers (2019)



While the larger PV-systems account for about a third of the total installed capacity, the number of large-scale systems with more than 500 kWp is only about 1% of the total installed systems.

Data: Bundesnetzagentur 2020. Graph: PSE Projects GmbH 2020

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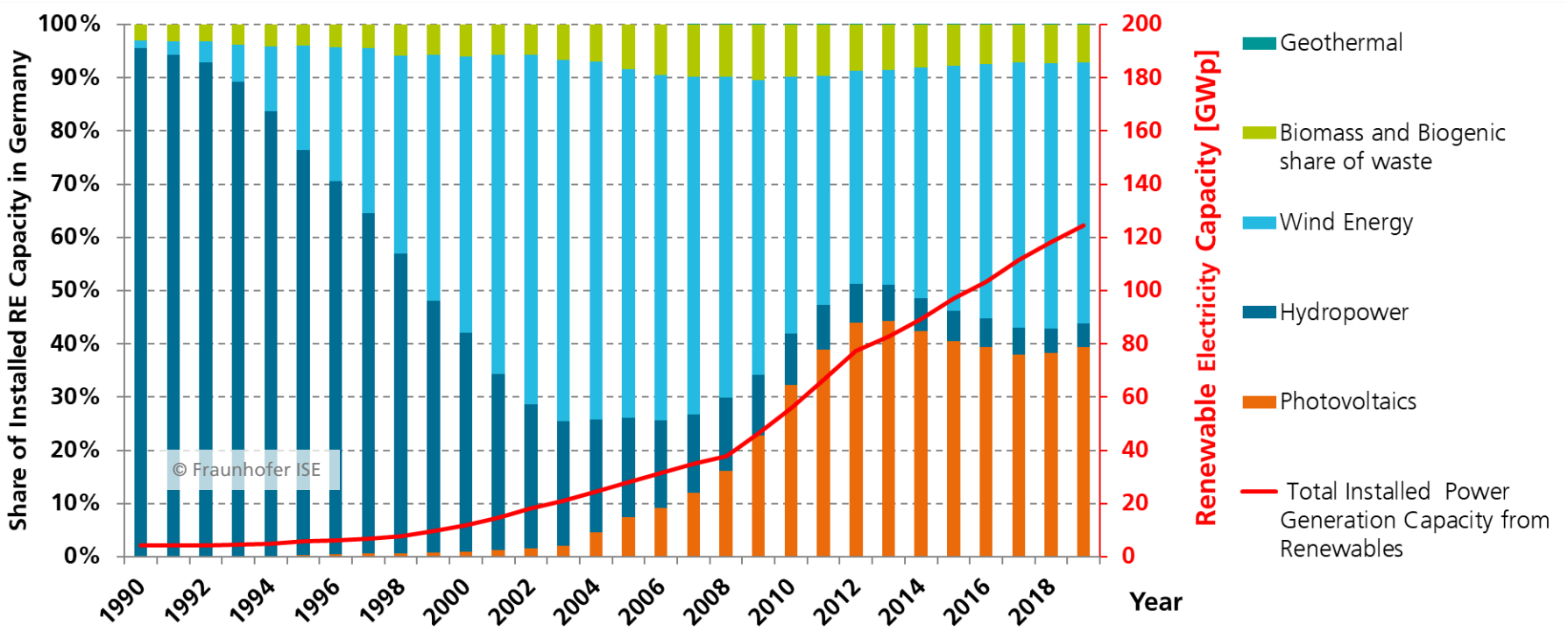
Electrical Capacity of Renewable Energy Sources

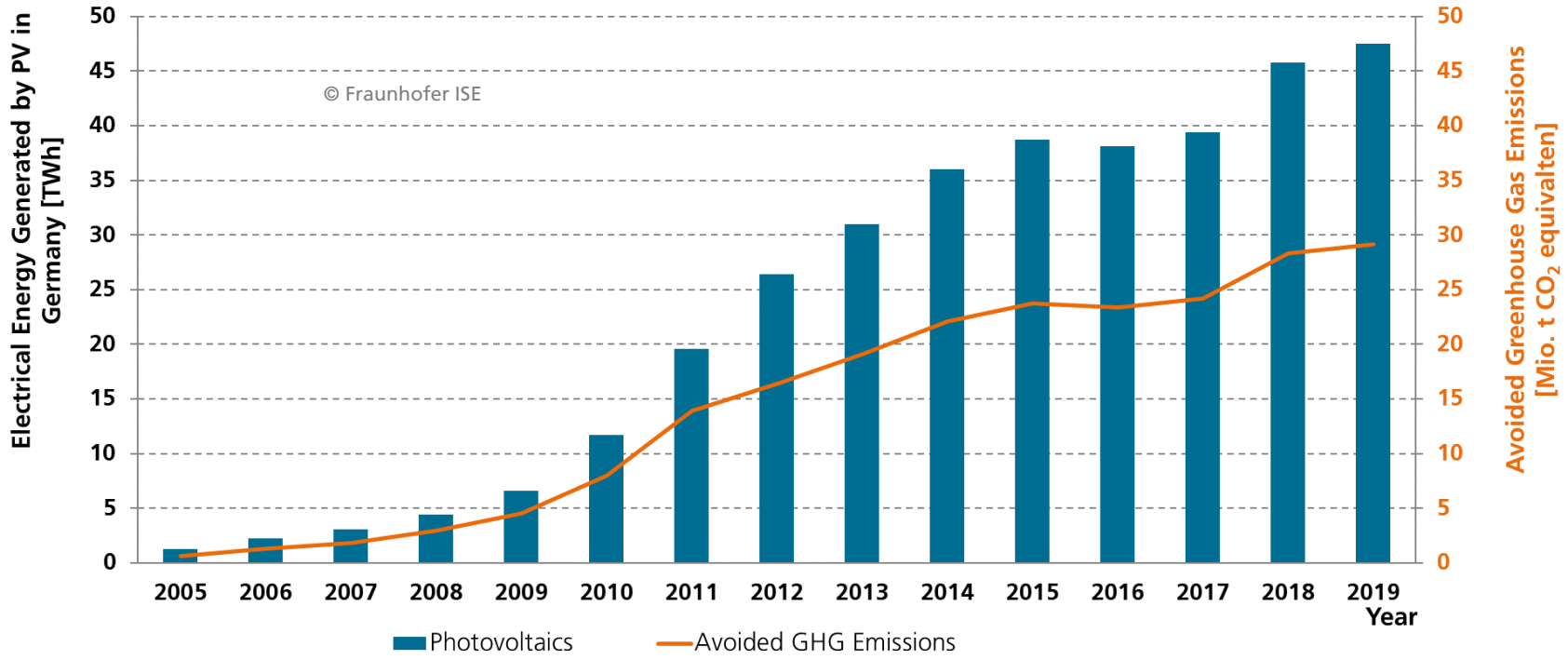
Germany



In 2019 about 42.1% (244 TWh) of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.

Data: BMWi / AGEE-Stat.; Data up to 2012: BMU, BDEW; Data electricity generation: energy Charts by Prof. Dr. Bruno Burger. Graph: PSE Projects GmbH 2020

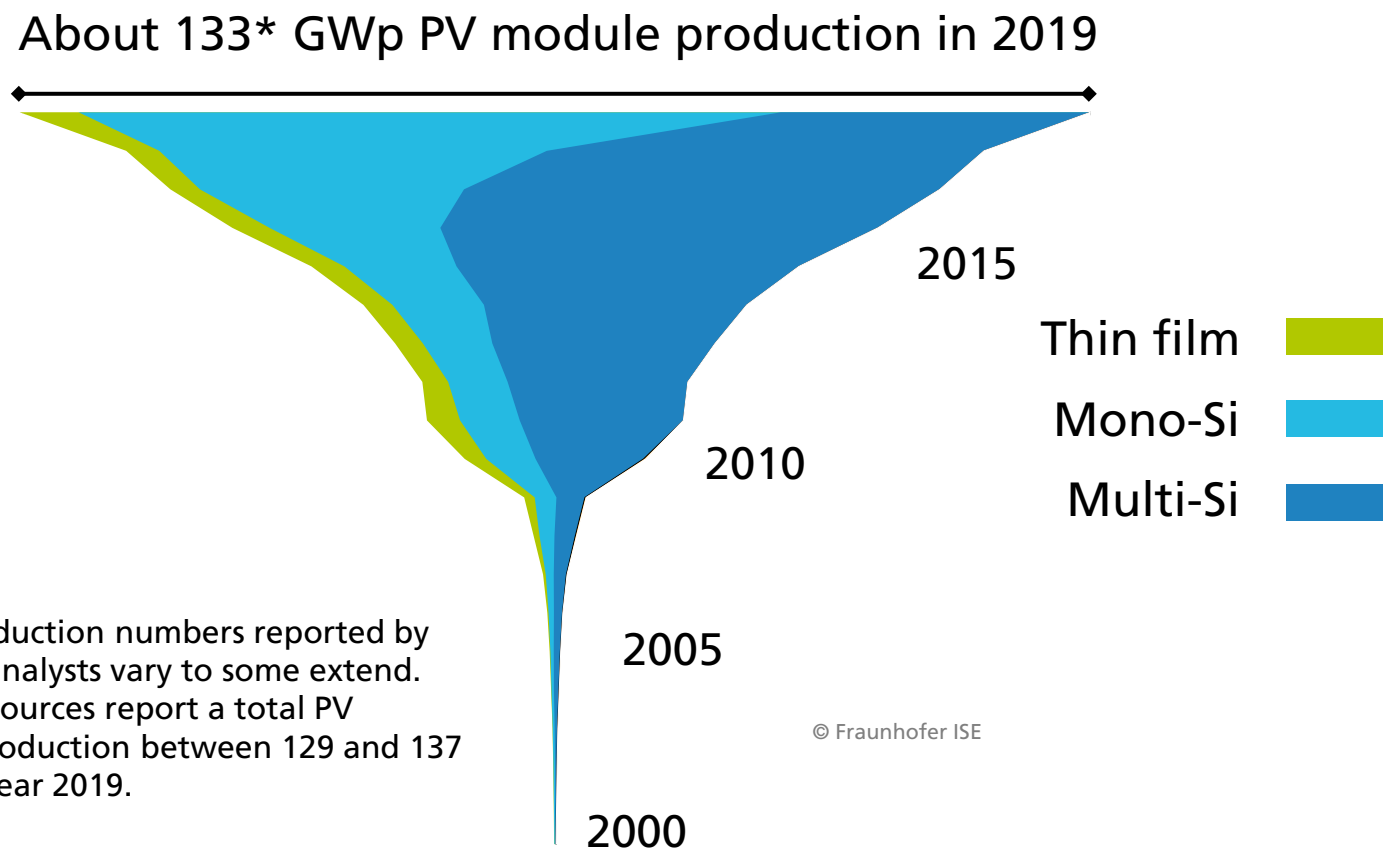
PV Energy Generated **and Resulting GHG Avoided Emissions**
Germany



- In 2019 Greenhouse Gas emissions of about 29 Mio. t CO_2-equivalent were avoided due to 47.5 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2020. Graph: PSE Projects GmbH 2020

Annual PV Production by Technology
Worldwide (in GWp)

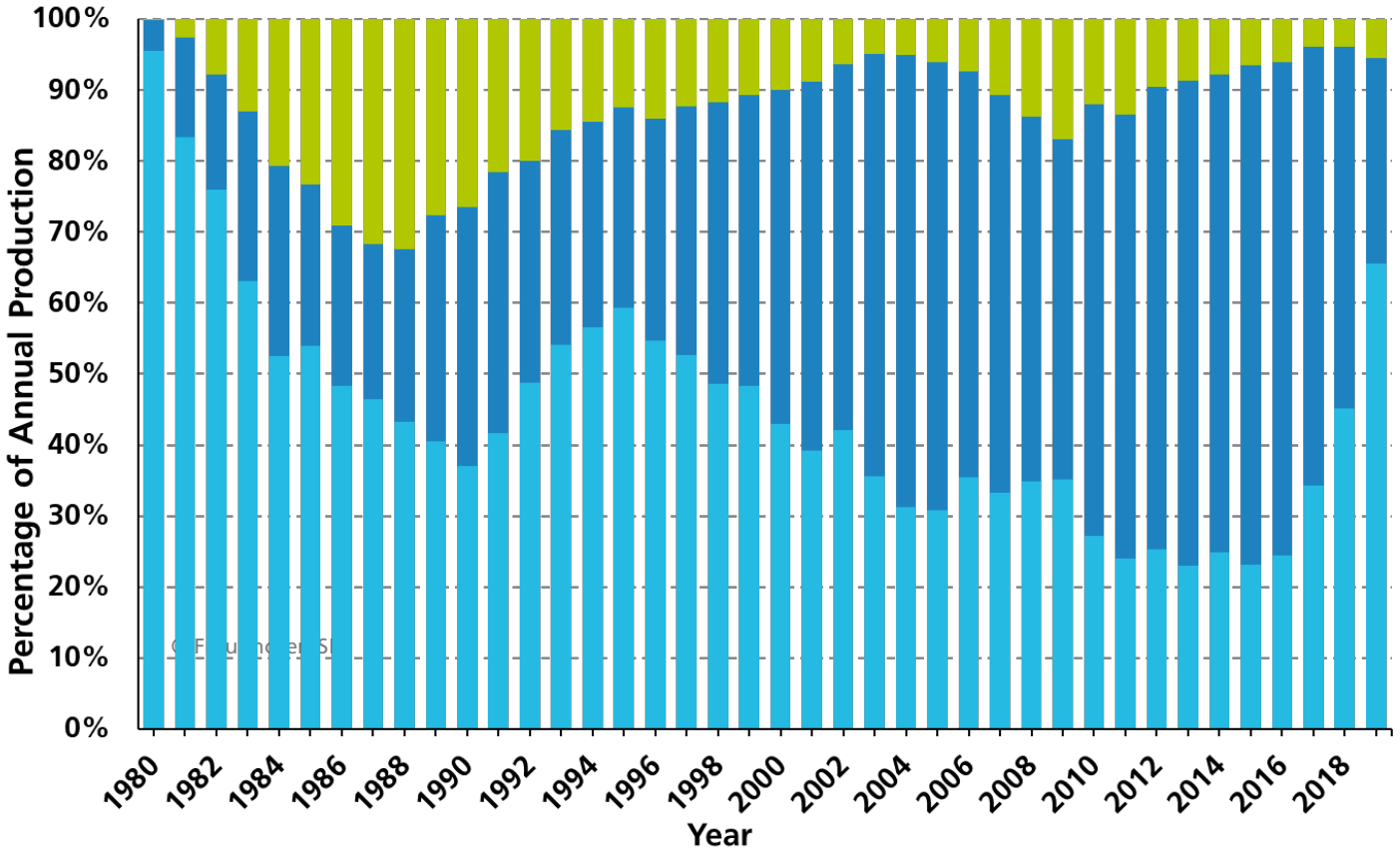


*2019 production numbers reported by different analysts vary to some extend. Different sources report a total PV module production between 129 and 137 GWp for year 2019.

Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2020

PV Production by Technology

Percentage of Global Annual Production



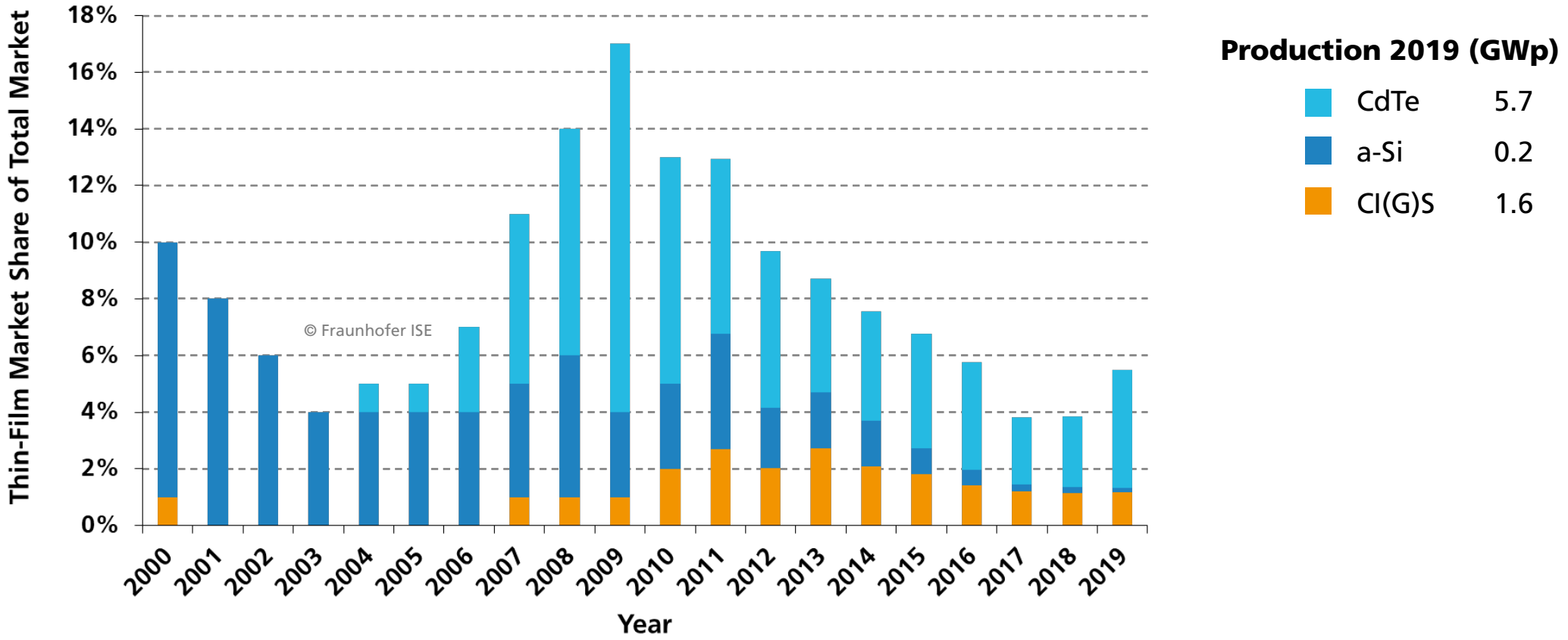
Production 2019 (GWp)

Thin film	7.5
Multi-Si	39.6
Mono-Si	89.7

Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2020

Market Share of Thin-Film Technologies

Percentage of Total Global PV Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2020

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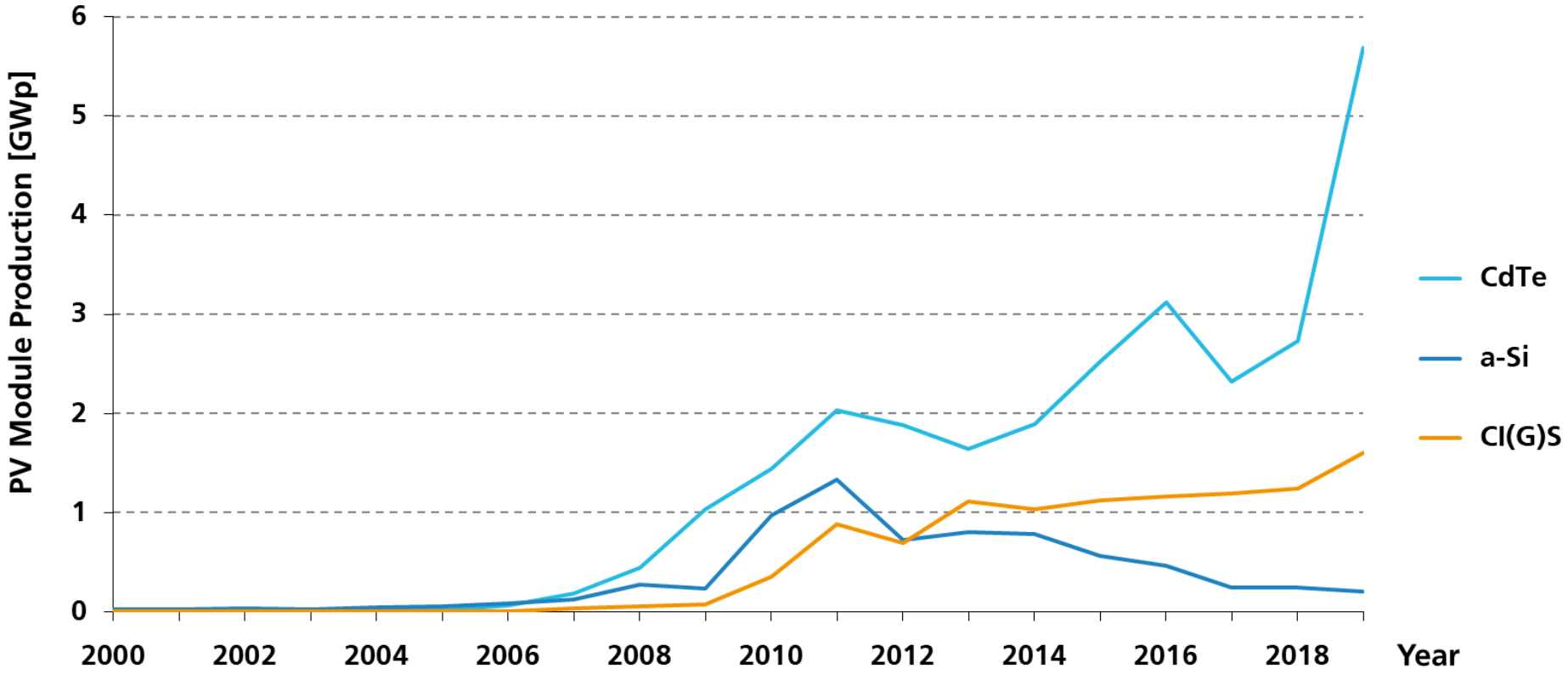
Thin-Film Technologies

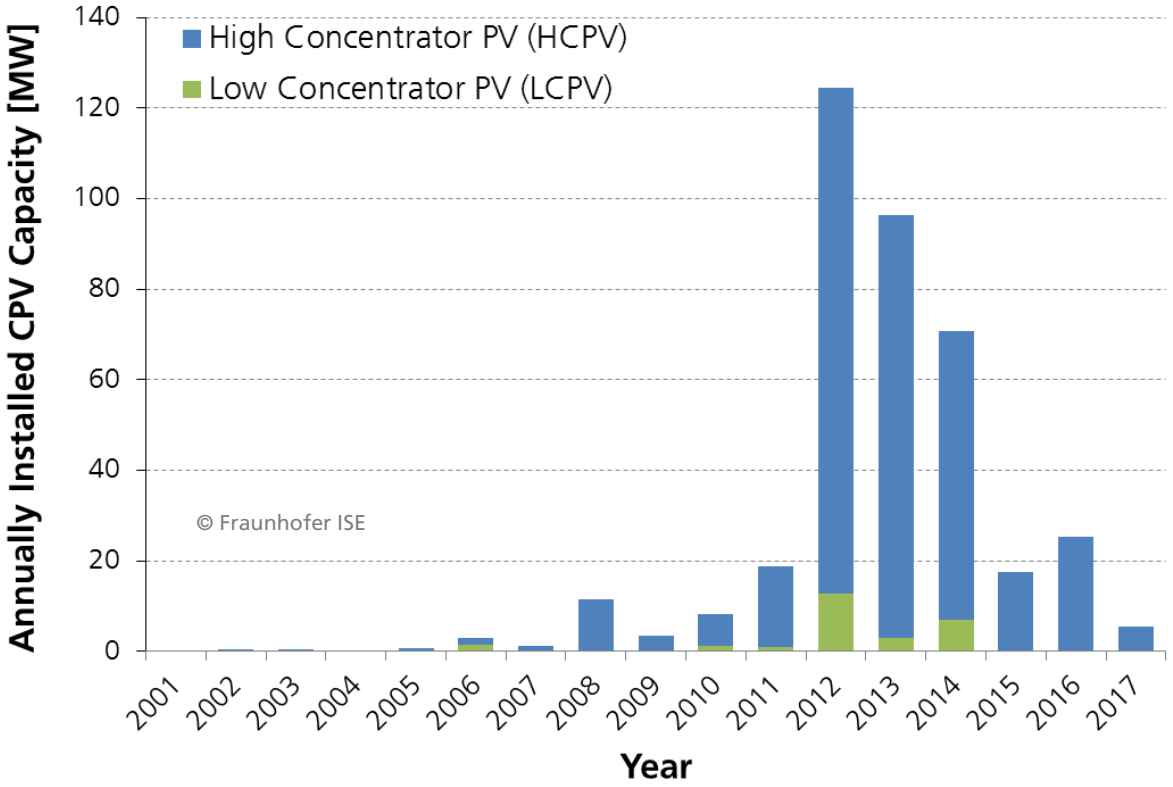
Annual Global PV Module Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2020

Low and High Concentrator PV Systems (LCPV/HCPV)

Annually Installed Capacity



LCPV and HCPV have concentration factors below 100 suns and from 300 up to 1000 suns, respectively.

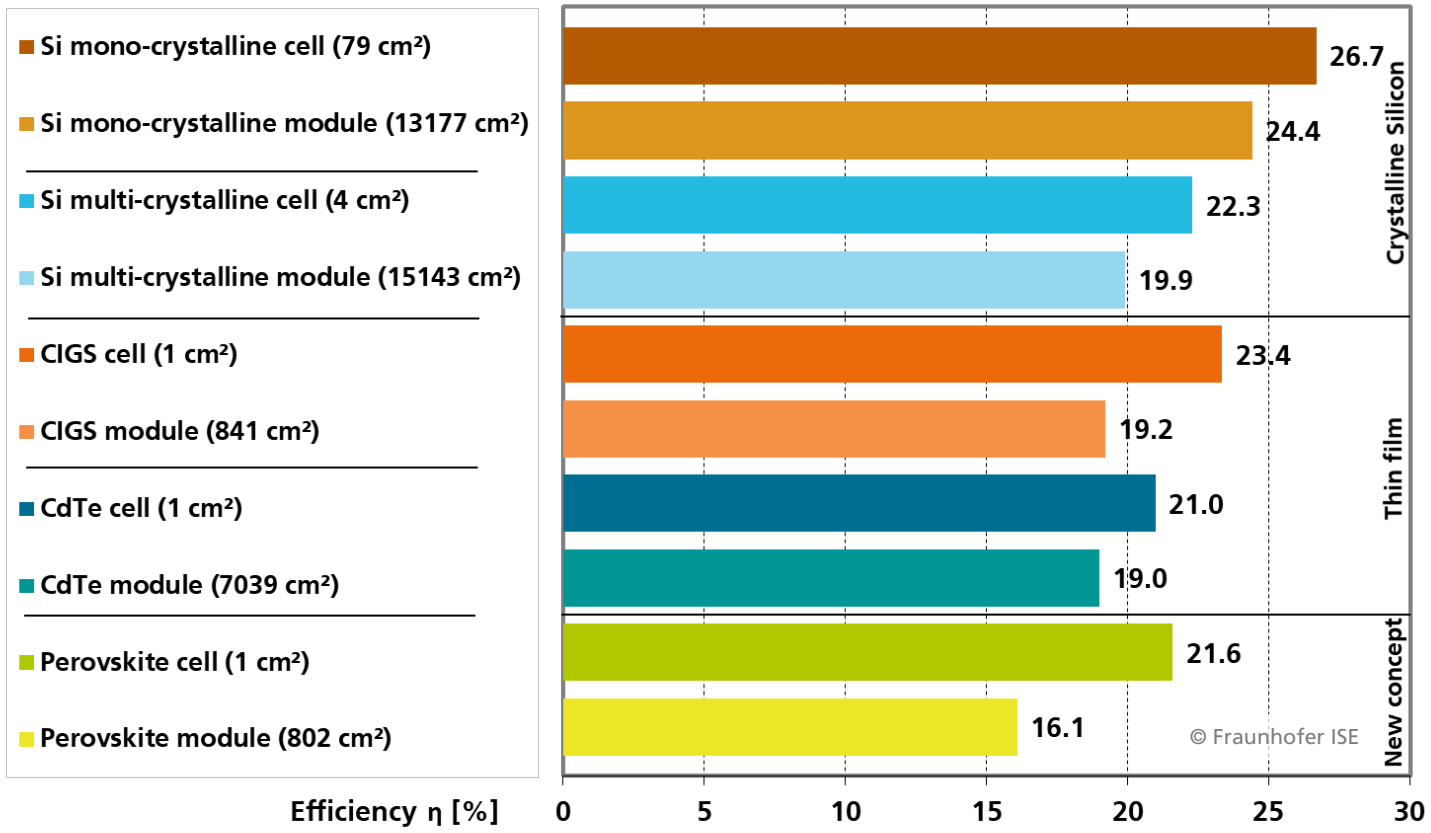
Data: ISE 2018

For more details on CPV see ISE/NREL Report: Current Status of Concentrator Photovoltaics (CPV) Technology

2. Solar Cells / Modules / System Efficiency

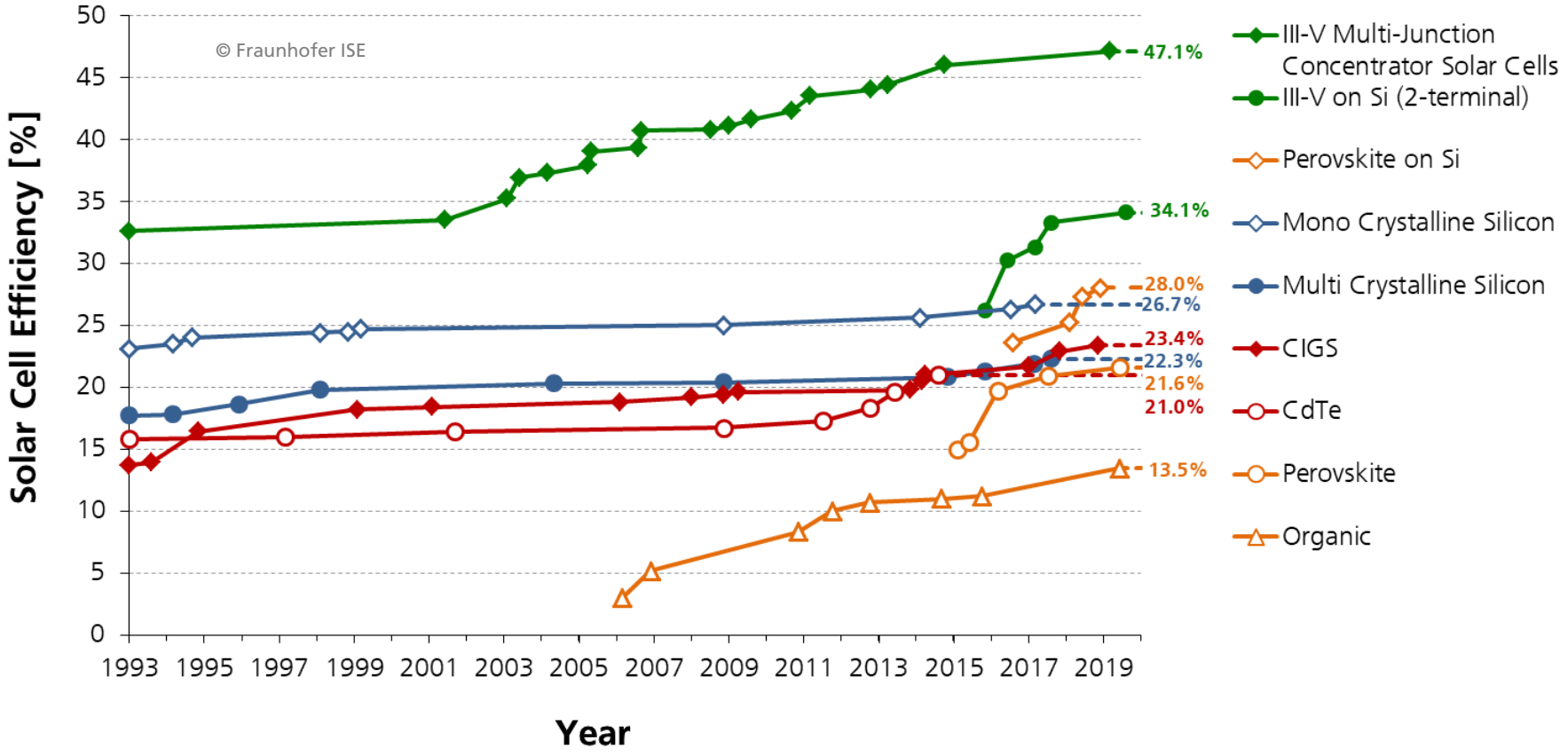
- Development in the PV Industry
- Development in the Laboratories
- High Concentration Photovoltaics (HCPV)
- Performance Ratio (PR)

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



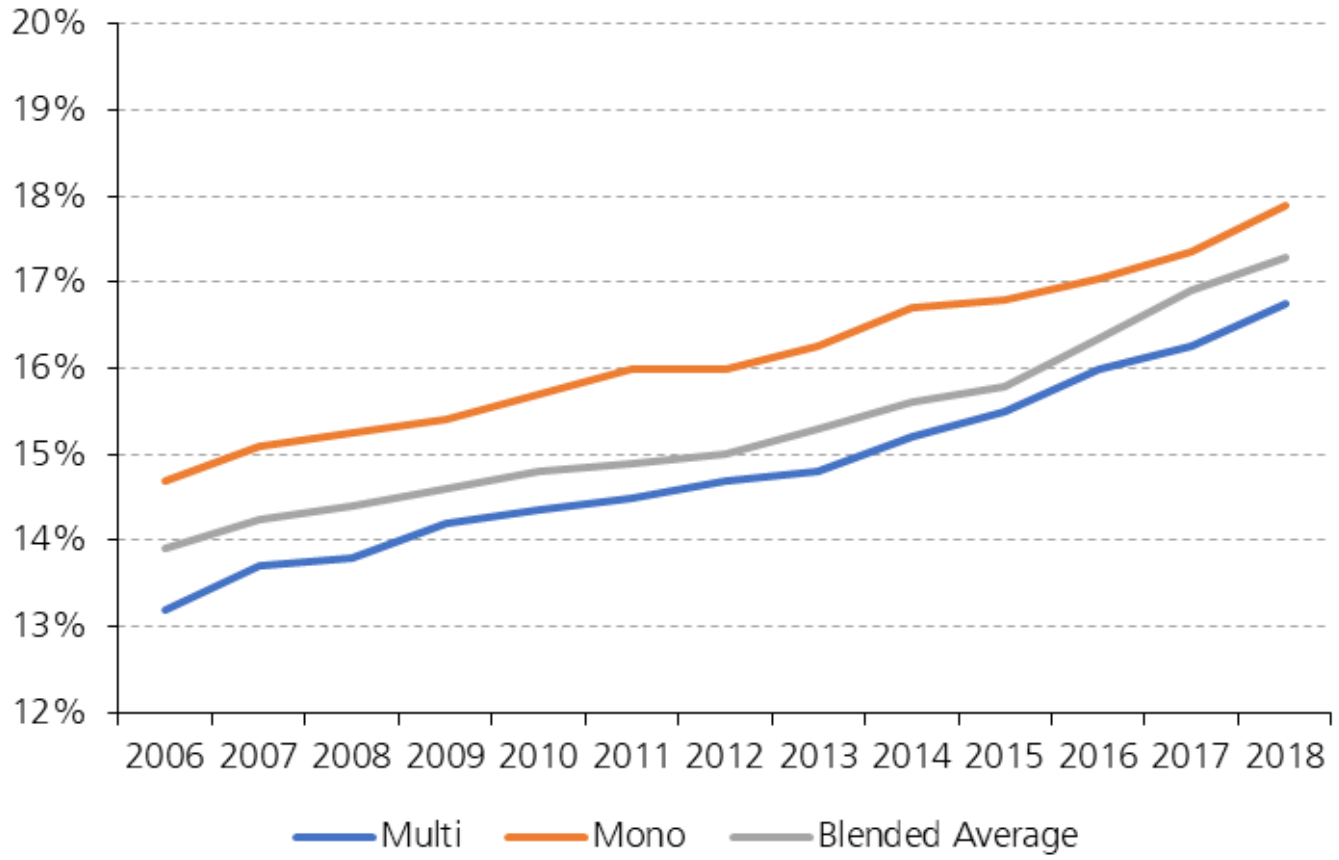
Data: Green et al.: Solar Cell Efficiency Tables (Version 55), Progress in PV: Research and Applications 2019. Graph: PSE Projects GmbH 2020

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 55), Progress in Photovoltaics: Research and Applications, 1993-2019. Graph: Fraunhofer ISE 2020

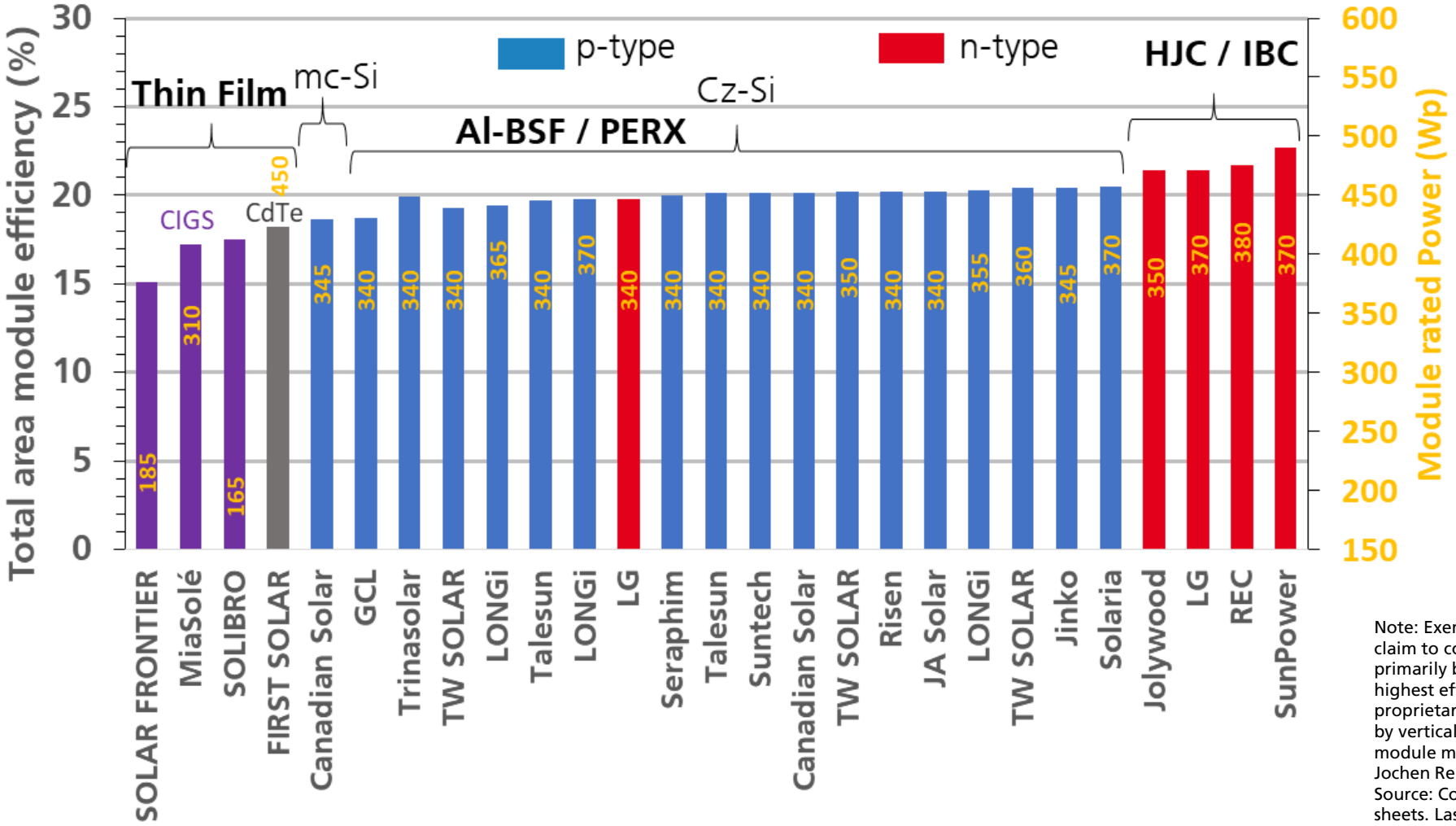
Average Crystalline-Silicon PV Module Efficiency



Data source: IHS Markit 2019

Current Efficiencies and Power of Selected Commercial PV Modules

Sorted by Bulk Material, Cell Concept and Efficiency



Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2019.

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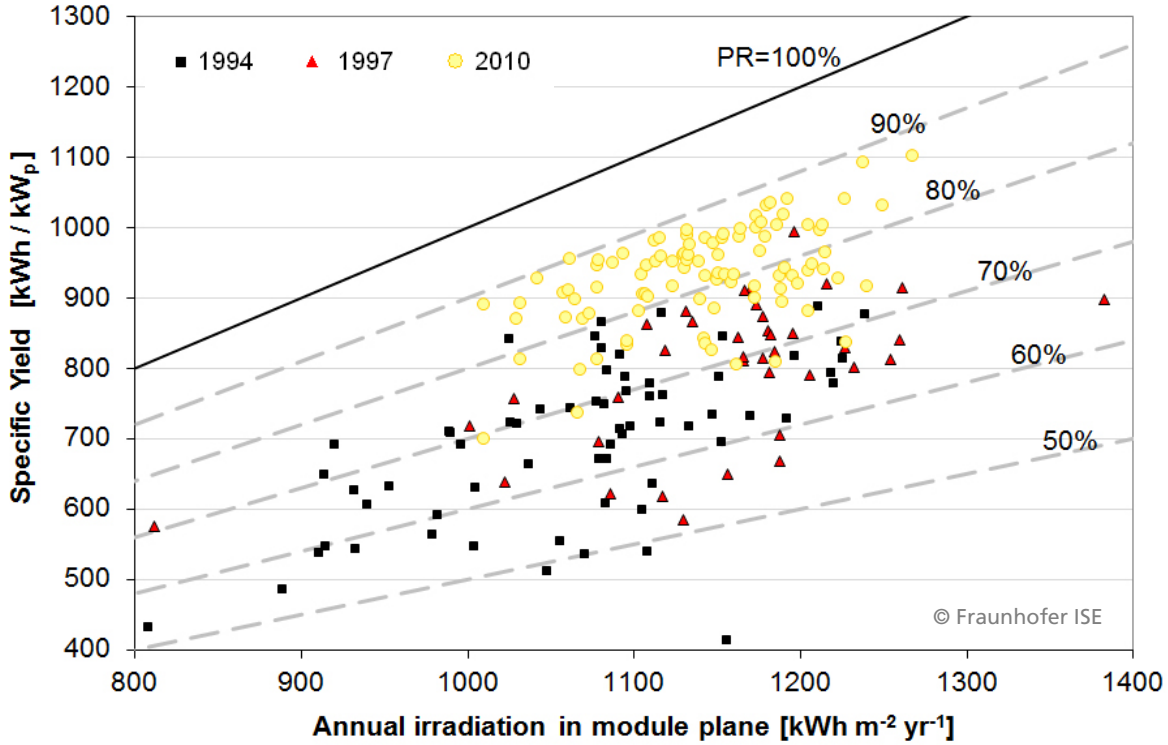
Performance Ratio Development for PV Systems
Germany



In the 1990's

- Typical PR ~70 %
- Widely ranging PR values

Today

- Typical PR ~80-90 %
- Less variance in PR as compared to 1990's

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

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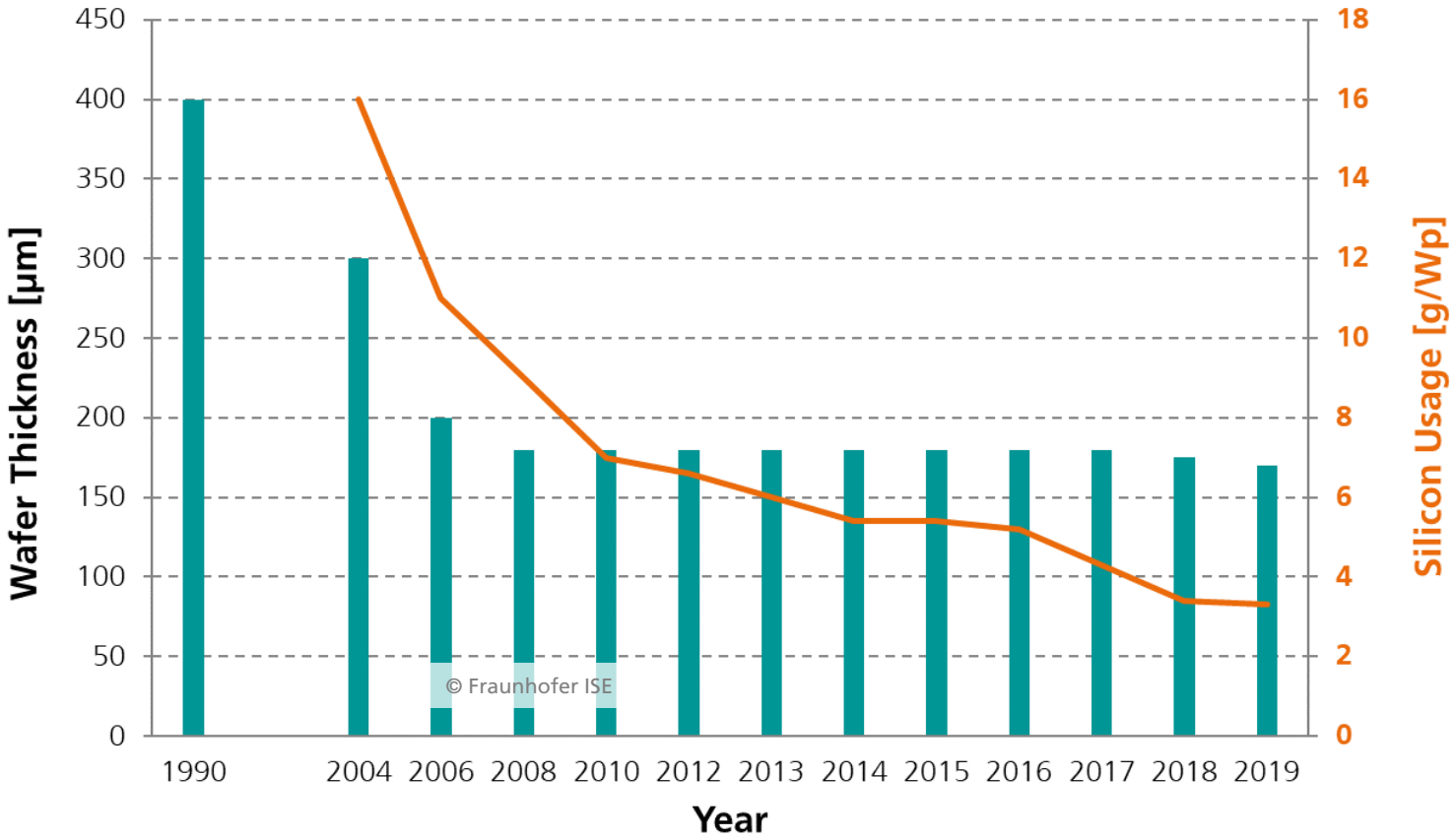
3. Energy Return of Invest (EROI) & Energy Payback Time (EPBT)

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

c-Si Solar Cell Development

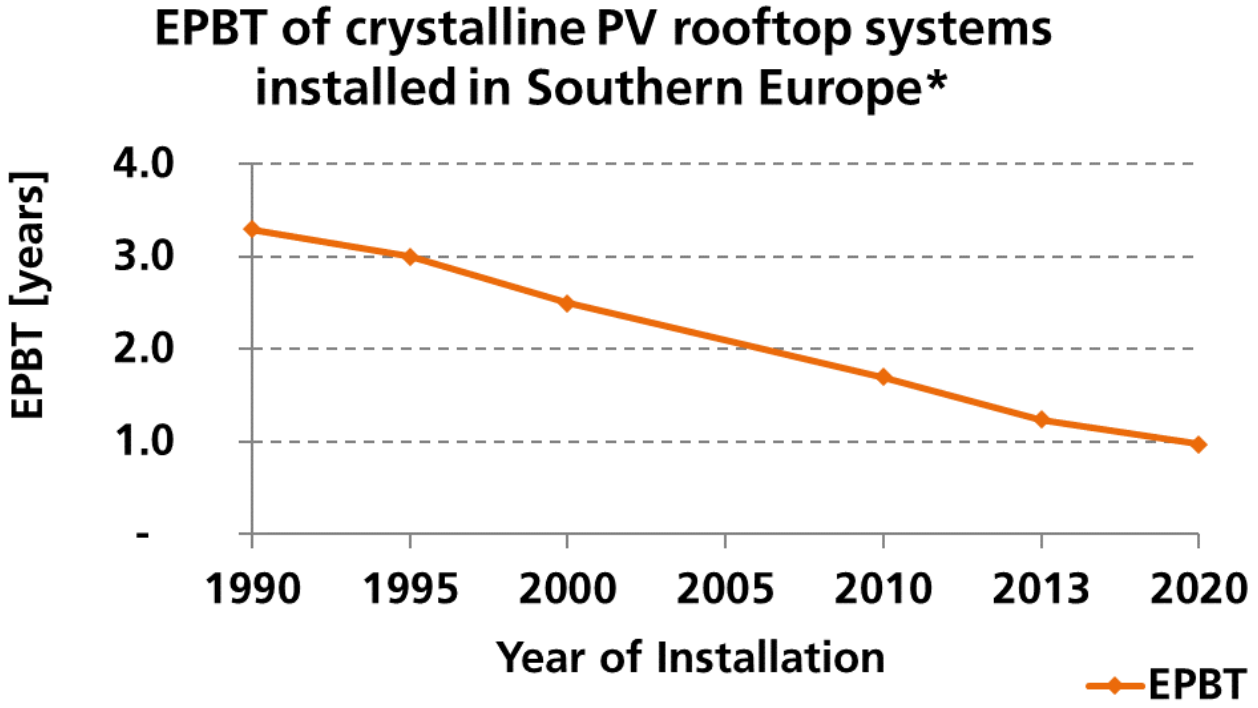
Wafer Thickness [µm] & Silicon Usage [g/Wp]



Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV 2015; ISE 2016 without; 2017 to 2019 with recycling of Si. Graph: PSE Projects GmbH 2020

Historic Trend in Energy Payback Time of Crystalline Silicon PV Modules

- Depending on the technology and location of the PV system, the EPBT today ranges from 0.4 to 1.5 years.
- Rooftop PV systems produce net clean electricity for approx. 97 % of their lifetime, assuming a life span of 30 years or more.

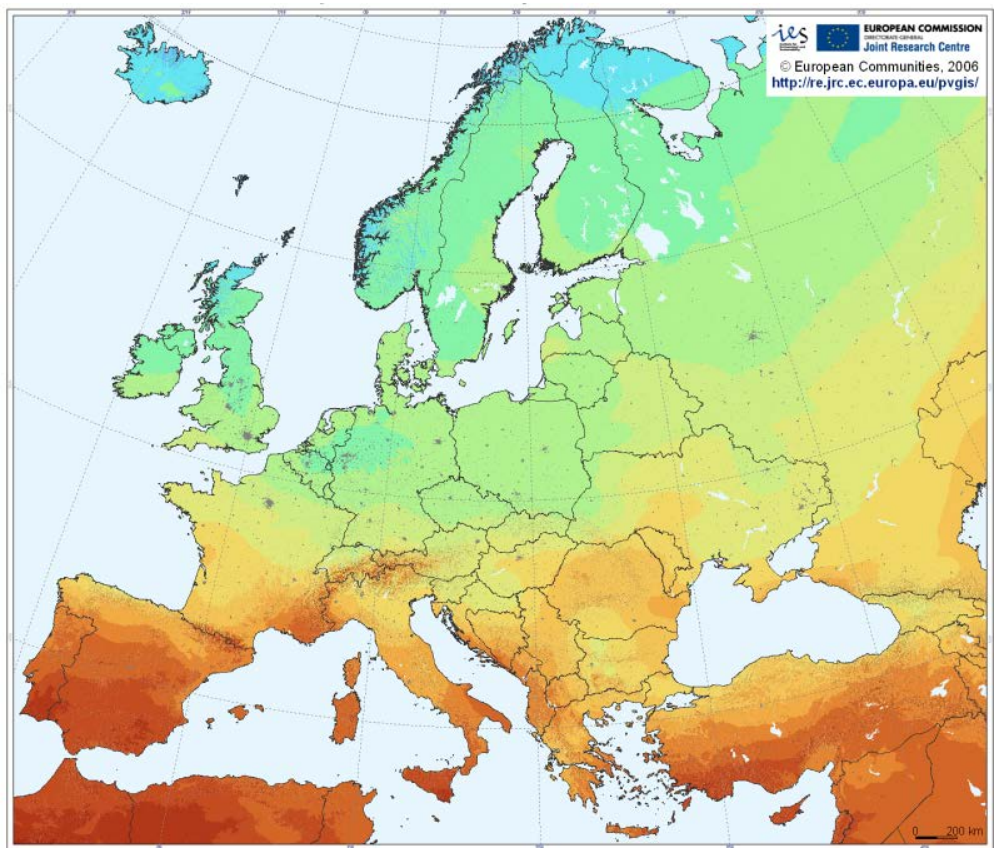


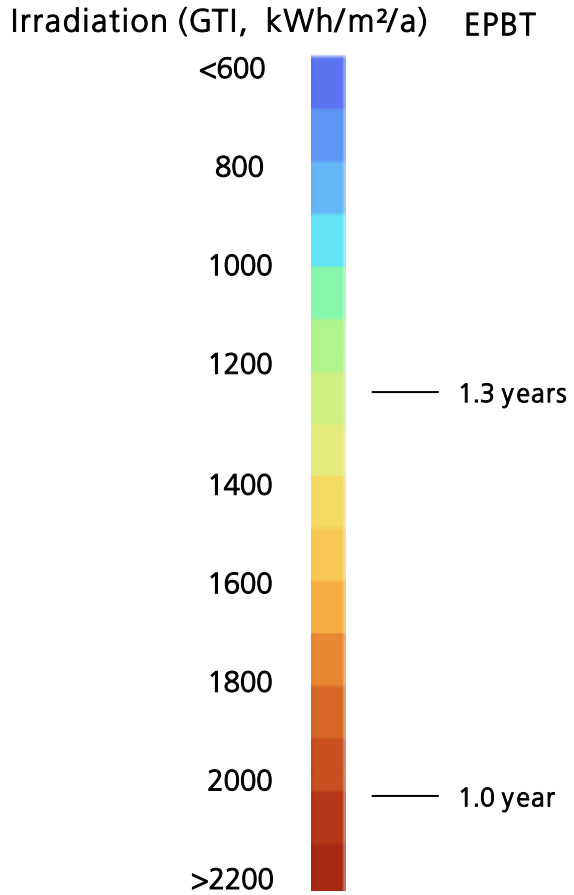
*Irradiation: 1700 kWh/m²/a at an optimized tilt angle

Data: EPIA Sustainability Working Group Fact Sheet 2011; 2010 and 2013: M.J. de Wild-Scholten; 2020: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2020

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)

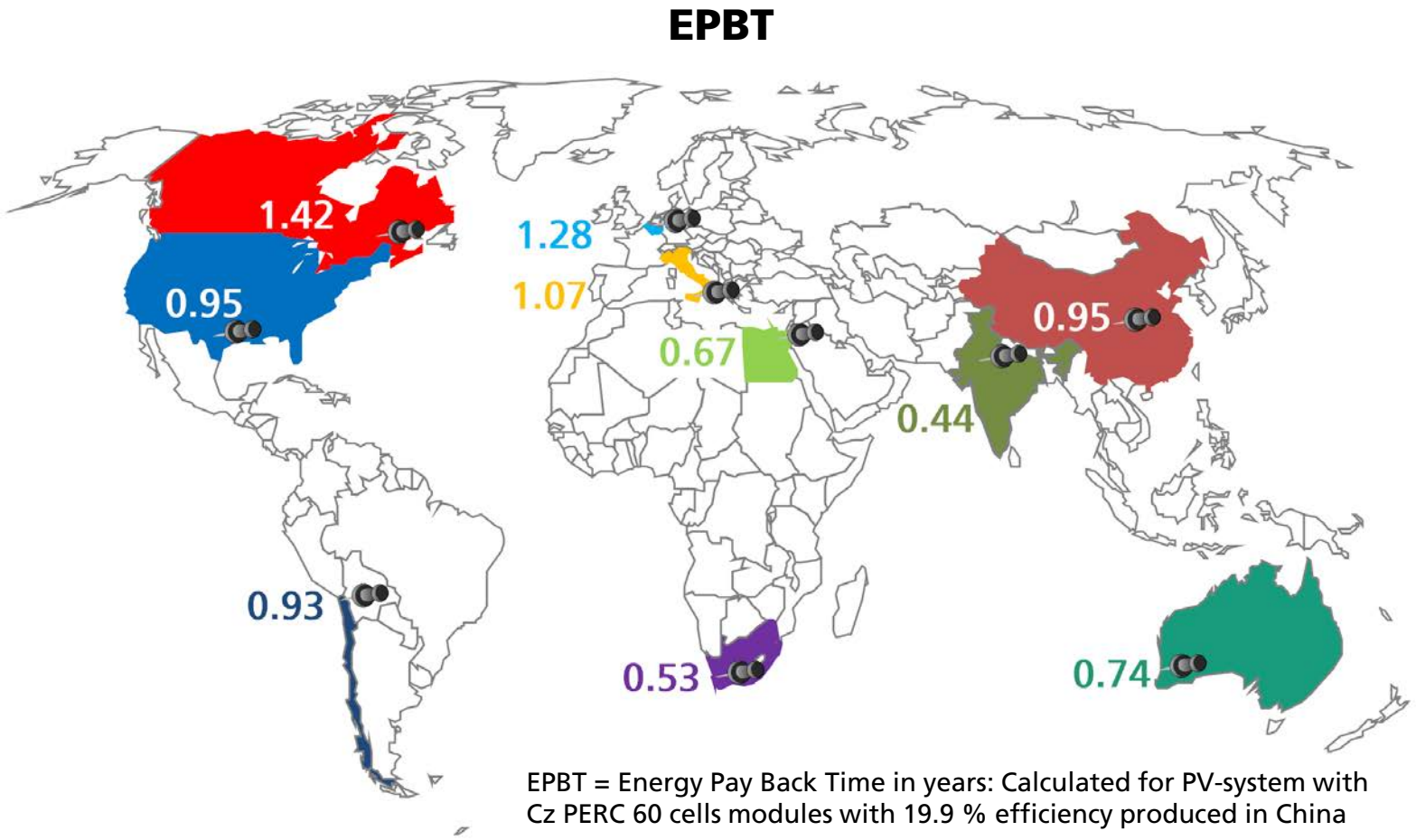
*Cz PERC cells module with 19.9% efficiency

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



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

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

Silicon PV Rooftop Systems –
Comparison of EPBT China / EU, local Irradiation and Grid Efficiency

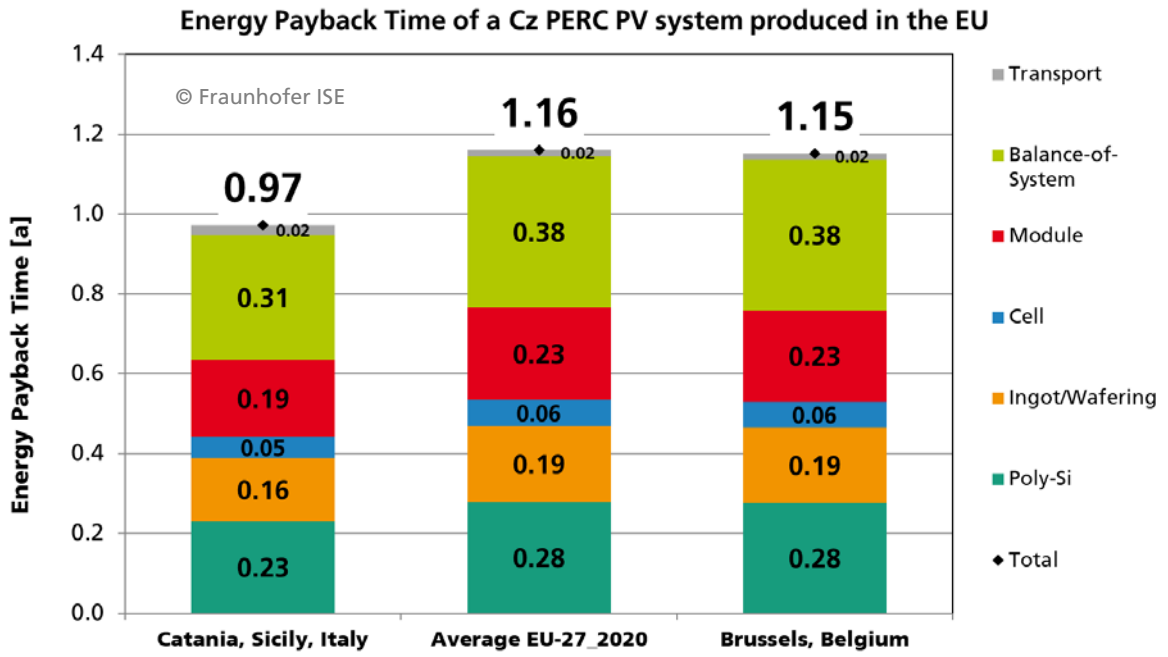
The following data are provided for the selected locations:

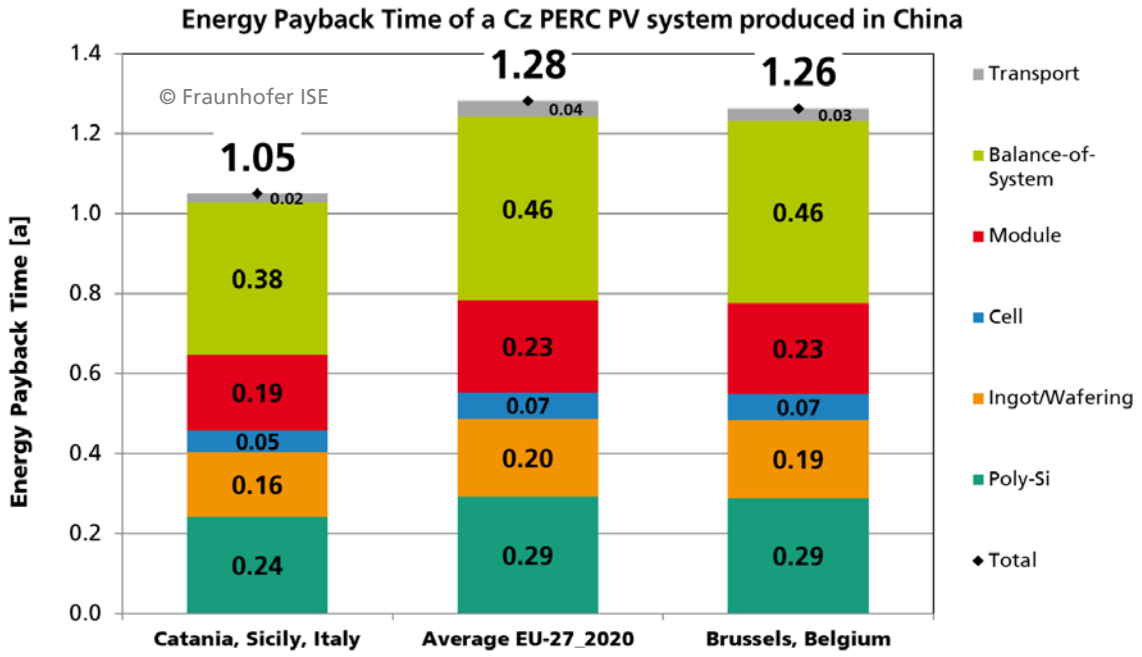
- EPBT CN = Energy Pay Back Time in years: PV-system with Cz PERC cells modules with 19.9 % efficiency produced in China, BoS components produced in the EU
- Irradiation measured at module level (= Global Tilted Irradiation GTI) in kWh/m²/year
- Grid Efficiency = Electric to primary energy conversion ratio in percent as kWh_{Grid} /MJ_{eq}

Location	**Houston**, TX	**Arica**, Arica y Parinacota	**Ottawa**	**Brussels**	**Catania**, Sicily	**Cape Town**	**Cairo**	**Jaipur**, Rajasthan	**Lanzhou**, Gansu	**Perth**, Western Australia
Country	USA	Chile	Canada	Belgium	Italy	South Africa	Egypt	India	China	Australia
Grid	US American	Canadian	Canadian					Indian	Chinese	
EPBT EU (a)	0.86	0.86	1.28	1.15	0.97	0.48	0.61	0.40	0.89	0.69
EPBT CN (a)	0.95	0.93	1.46	1.26	1.05	0.52	0.66	0.44	0.94	0.74
Irradiation	1913	2279	1566	1249	2048	2163	2416	2242	1799	2166
Grid Efficiency	9.2%	11.0%	11.9%	8.5%	11.2%	6.1%	8.2%	4.9%	8.9%	8.4%

Data: Lorenz Friedrich, Fraunhofer ISE. Design: 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 Price
- Inverter Concept Comparison

Inverter/Converter Market 2019

Inverter / Converter	Power	Efficiency	Market Share (Estimated)*	Remarks
String Inverters	up to 150 kWp	up to 98%	61.6%	• 5 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	36.7%	• ~ 4 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-97%	1.7%	• ~ 29 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 99.5%	5.1%	• ~ 8 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed

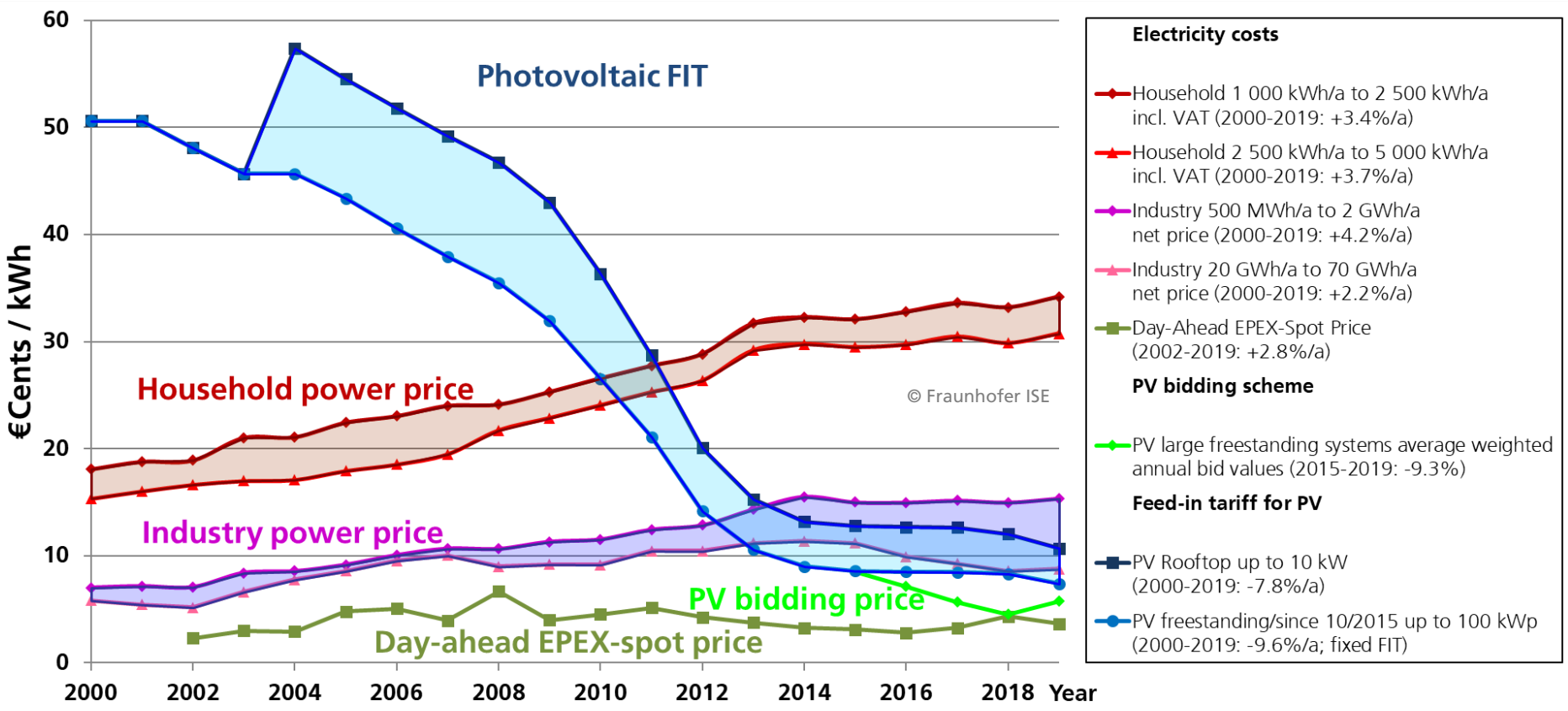
Data: IHS Markit 2020. Remarks: Fraunhofer ISE 2020. Design: PSE 2020

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

5. Price Development

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

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



Data: BMU, EEG 2019 and BMWi Energiedaten. Design: B. Burger - Fraunhofer ISE , Update: 03 April 2020

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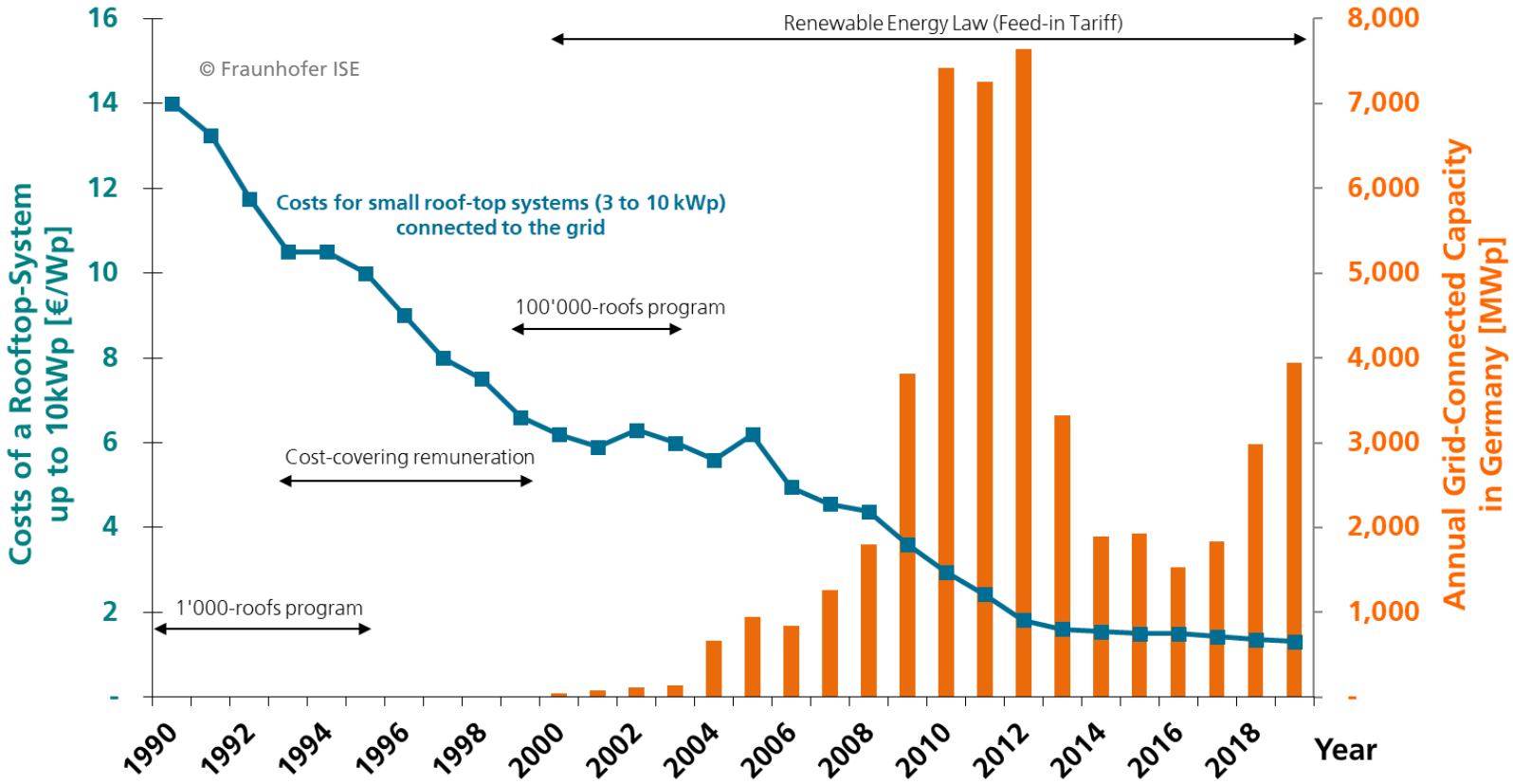
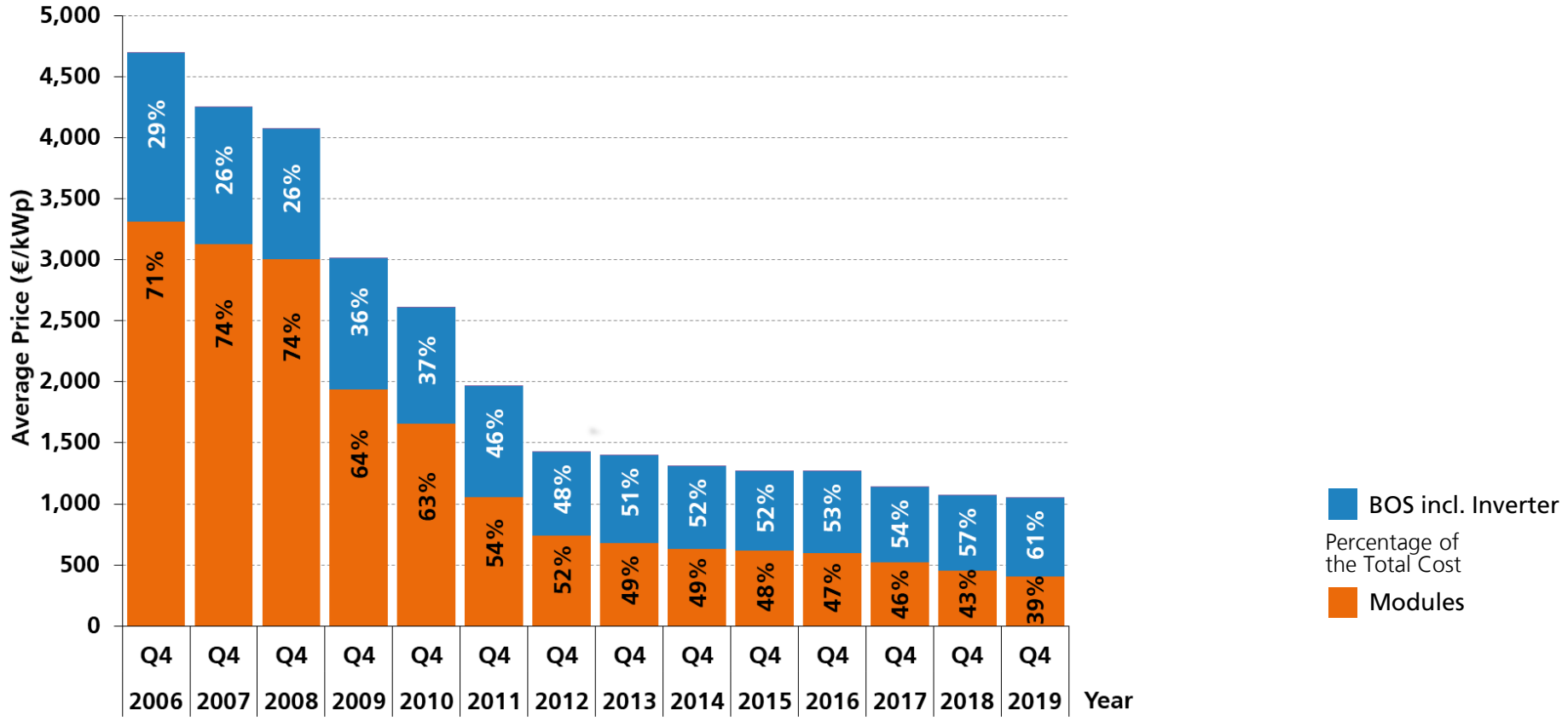
Investment for Small Rooftop PV Systems in Relation to Market Development and Subsidy Schemes in Germany



Data: BSW-Solar, BNA. Graph: PSE Projects GmbH 2020

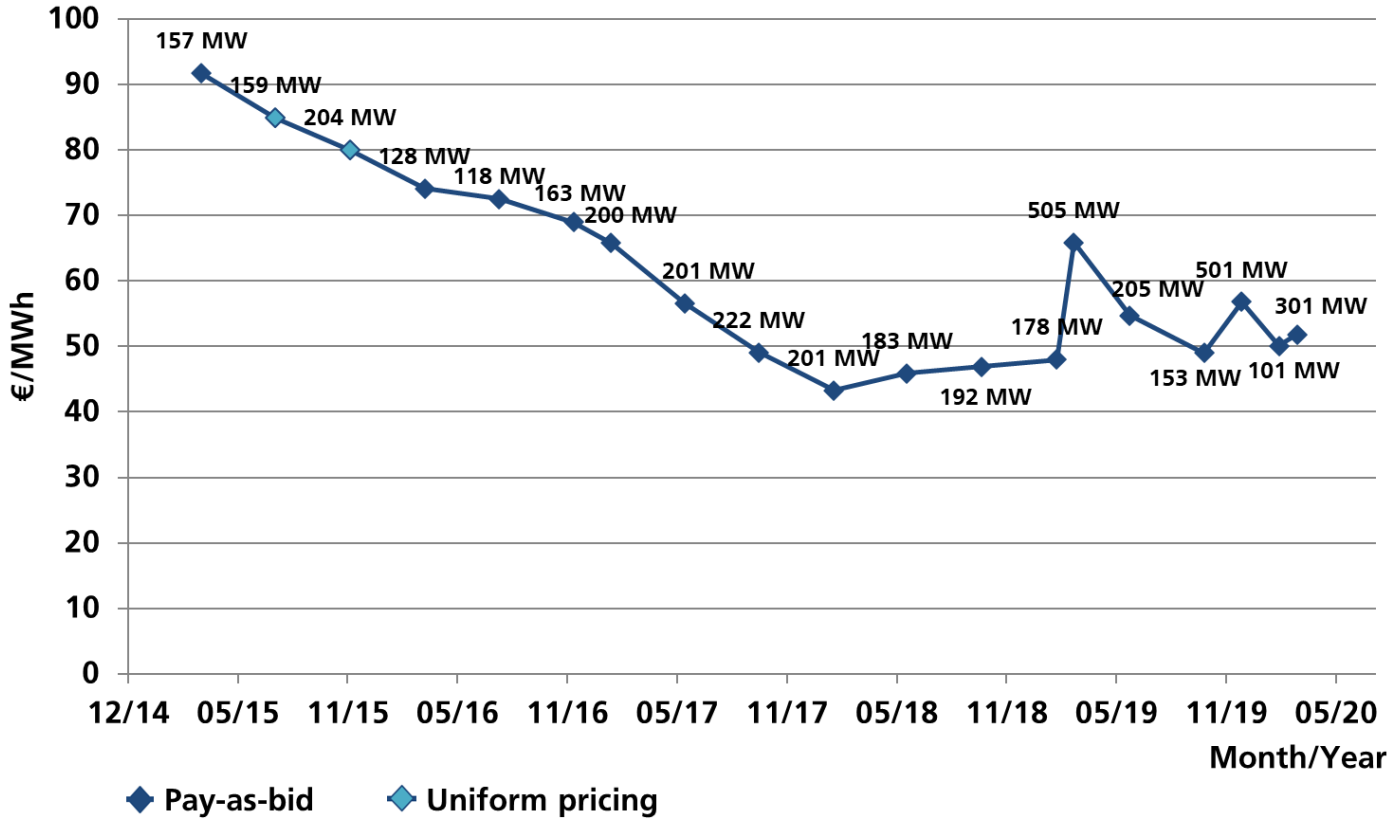
Average Price for PV Rooftop Systems in Germany
(10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE 2020

PV-Tender in Germany

Average, quantity weighted Award Value



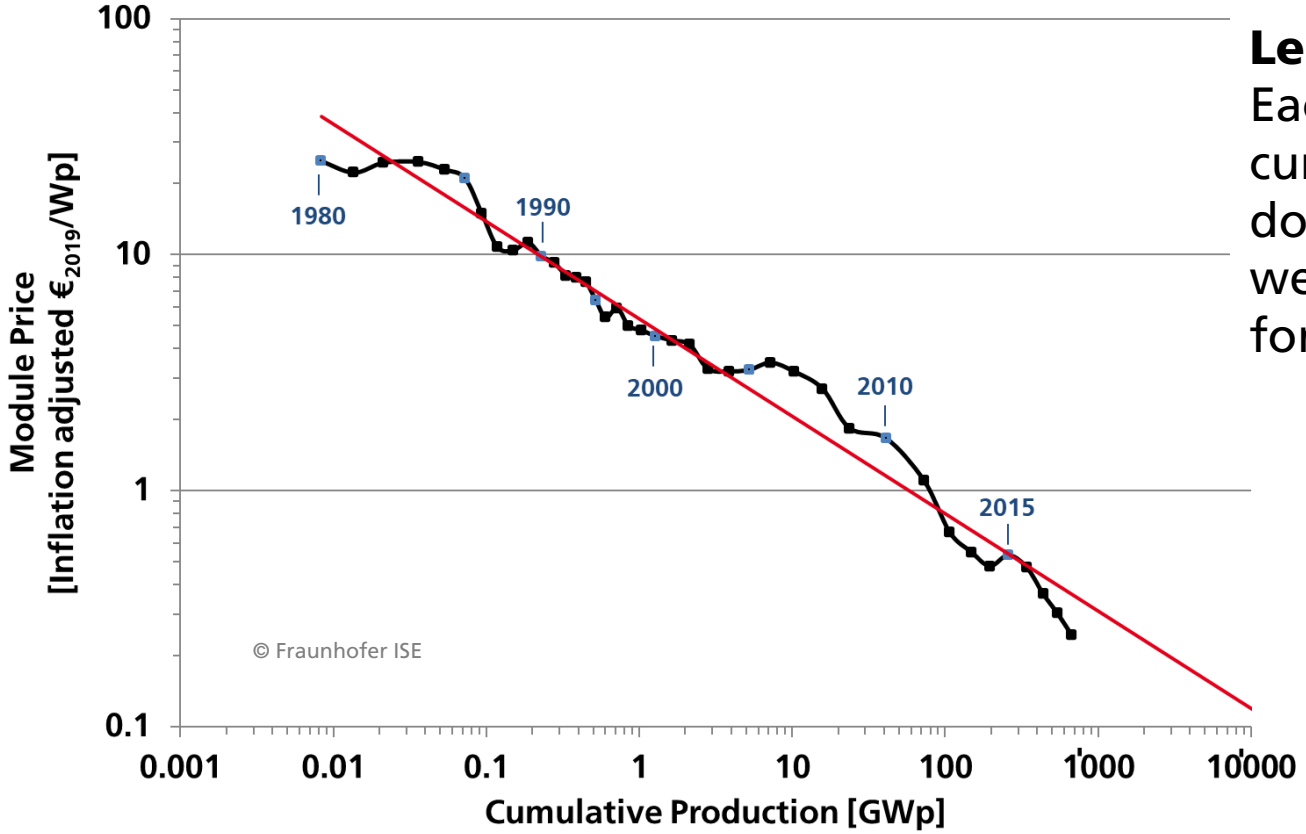
Lowest PV-Tender Round in Feb. 2018:
4.33 ct€ / kWh as average quantity weighted award price

PV-Tender scheme started in April 2015 and total capacity of this scheme accumulates to 4 GWp

Data: BNA. Graph: PSE 2020

Price Learning Curve

Includes all Commercially Available PV Technologies

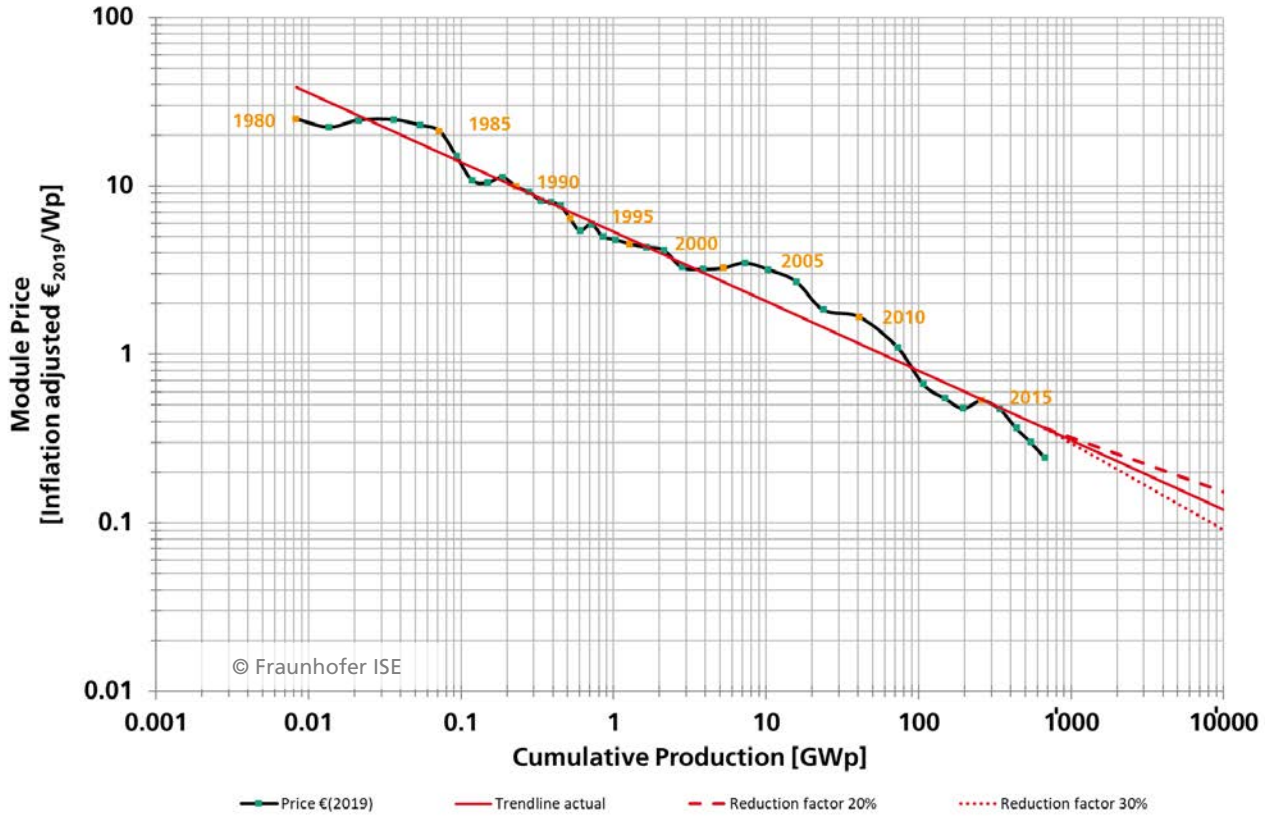


Learning Rate:
Each time the cumulative production doubled, the price went down by 25 % for the last 39 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; for 2019 estimation from different sources. Graph: PSE 2020

Price Learning Curve

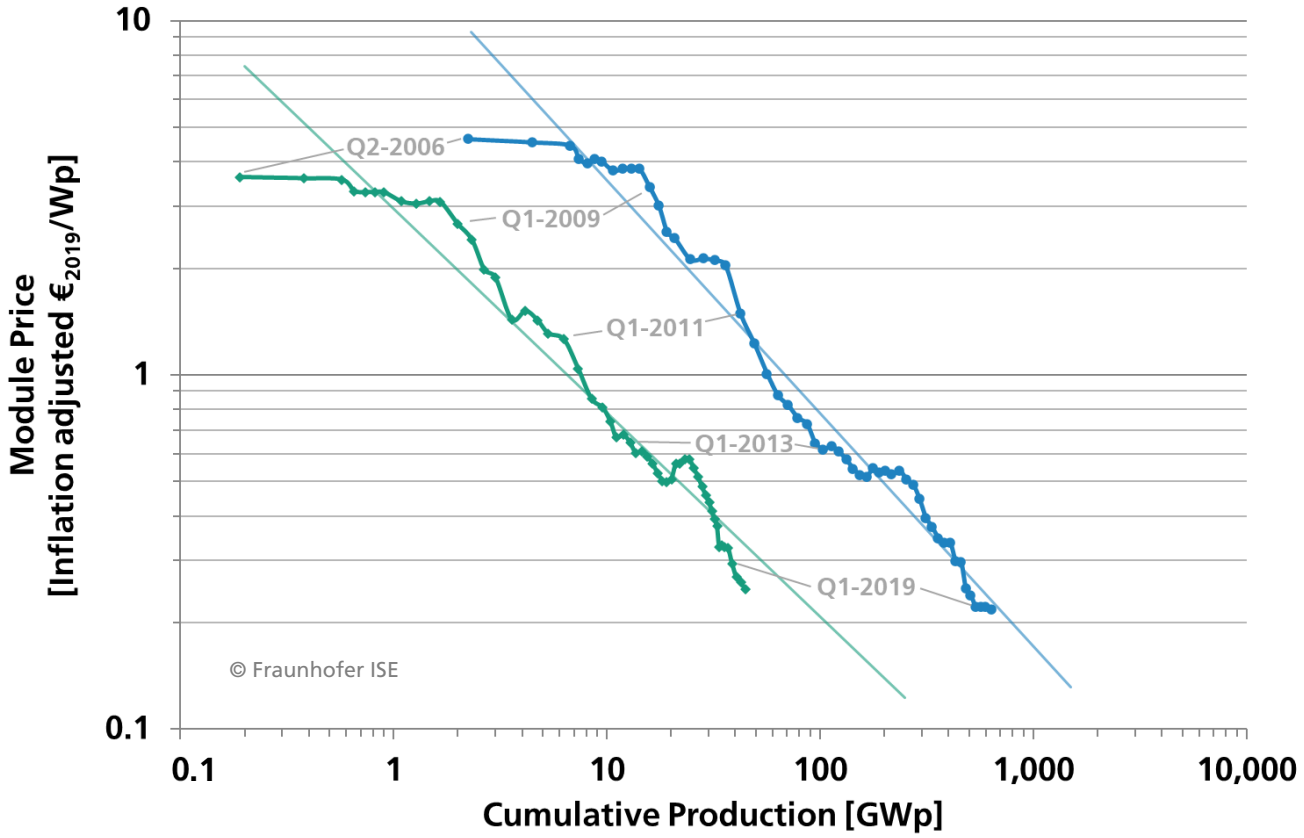
Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative production doubled, the price went down by 25 % for the last 39 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; for 2019 estimation from different sources. Graph: PSE 2020

Price Learning Curve by Technology
Cumulative Production up to Q4-2019



Estimated cumulative production up to Q4-2019:

c-Si	636 GWp
Thin Film	45 GWp

Crystalline Technology
(from Q2-2006 to Q4-2019) LR 31
Thin Film Technology
(from Q2-2006 to Q4-2019) LR 29

Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit. Graph: PSE 2020

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
- Study: Current Status of Concentrator Photovoltaic (CPV) Technology

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	PERX	Passivated emitter and rear cell
Cz	Czochralski Method	PR	Performance Ratio
DC	Direct current	p-type	Positively doped wafer (with boron)
EEG	Renewable Energy Law (Erneuerbare Energie 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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Harry Wirth	ISE
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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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