PHOTOVOLTAICS REPORT

Prepared by

Fraunhofer Institute for Solar Energy Systems, ISE

with support of

PSE Conferences & Consulting GmbH

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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 However, facts and figures change rapidly and the given information may soon be outdated again.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 Conferences & Consulting GmbH).
- 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-co.de
- Please quote the information presented in these slides as follows: ©Fraunhofer ISE: Photovoltaics Report, updated: 14 March 2019

Quick Facts

Parameter	Value	Status	Reference
Germany / EU28 / Worldwide			
PV market*	3 / 8 / 100 GW	2018	BNA / SPE / IHS
Cumulative installation*	45.4 / 122.6 / 515 GW	End of 2018	BNA / SPE / IHS
PV power generation	38 / 120 / 443 TWh	2017	ISE / BP / BP
PV electricity share	7.2% (net) / gross: 3.6% / 1.7%	2017	ISE / BP / BP
Worldwide			
c-Si share of production	95%	2017	IHS
Record solar cell efficiency: III-V MJ (conc.) / mono-Si / multi-Si / CIGS / CdTe	46.0 / 26.7 / 22.3 / 21.7 / 21.0%	Dez. 2018	Green et al.
Germany			
Price PV rooftop system	~ 1400 €/kWp	End of 2018	BSW
LCOE PV power plant	4 to 7 ct€ / kWh	End of 2017	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 PV installations was 24% between year 2010 to 2017.
- Concerning PV module production in 2017, China&Taiwan hold the lead with a share of 70%, followed by Rest of Asia-Pacific & Central Asia (ROAP/CA) with 14.8%. Europe contributed with a share of 3.1% (compared to 4% in 2016); USA/CAN contributed 3.7%.
- In 2017, Europe's contribution to the total cumulative PV installations amounted to 28% (compared to 33% in 2016). In contrast, installations in China accounted for 32% (compared to 26% in 2016).
- Si-wafer based PV technology accounted for about 95% of the total production in 2017. The share of multi-crystalline technology is now about 62% of total production.
- In 2017, the market share of all thin film technologies amounted to about 5% of the total annual production.

Will be updated in late spring 2019 as soon as market and production values of 2018 are confirmed.

Executive Summary
PV Market: Focus Germany

- In 2018, Germany accounted for about 9% (45.4 GWp) of the cumulative PV capacity installed worldwide (515 GWp) with about 1.7 million PV systems installed in Germany. In 2018 the newly installed capacity in Germany was about 3.0 GWp; in 2017 it was 1.7 GWp.
- PV covered about 7% of Germany's electricity demand in 2017. Renewable sources delivered about 38% of the total net power consumption in 2017 in Germany.
- In 2017 about 19 Mio. t CO_2 emissions have been avoided due to 38.4 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 22.9% for CIGS and 21.0% for CdTe solar cells.
- 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 16%.
- 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 46.0% 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 about 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 2.5 years to balance the input energy, while PV systems in the South equal their energy input after 1.5 years and less, depending on the technology installed.
- A PV system located in Sicily with multi-Si 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.
- The Energy Payback Time for CPV-Systems in Southern Europe is less than 1 year.

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). It is estimated that 3 GWp of DC / DC converters, also called “power optimizers”, have been installed in 2017.
- The specific net retail price of all inverters in Germany is about 12 €-cents /Wp. Central inverters tend to be cheaper than string inverters.
- Trends: New features for grid stabilization and optimization of self-consumption; storage unit included in the inverter; utilization of innovative semiconductors (SiC or GaN) which allow very high efficiencies and compact designs.

Executive Summary
Price Development

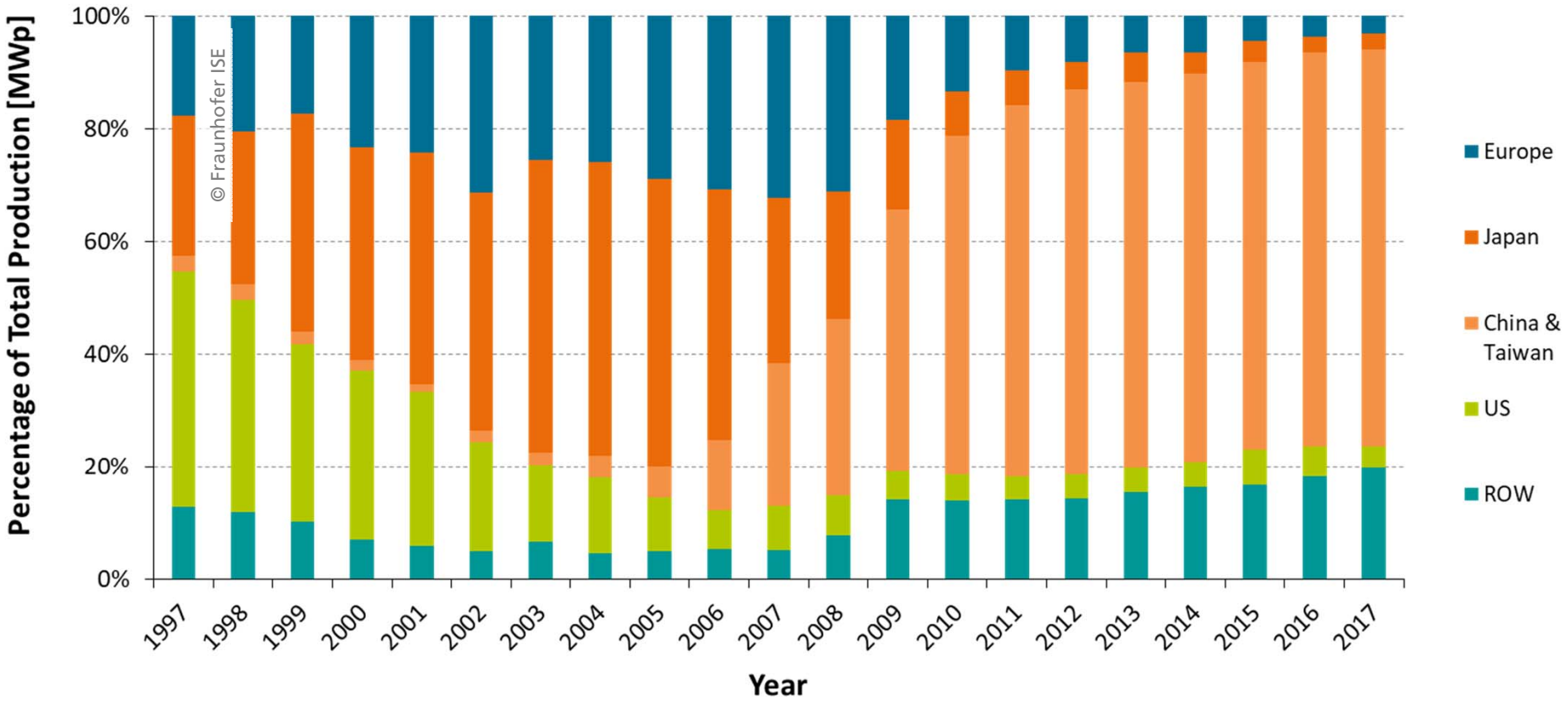
- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2018, such systems cost about 1,070 €/kWp in average. This is a net-price regression of about 92% over a period of 28 years and is equivalent to an annual compound average price reduction rate of 8%.
- The Experience Curve – also called Learning Curve - shows that in the last 38 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 1997-2017

Percentage of Total MWp Produced



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE GmbH 2018

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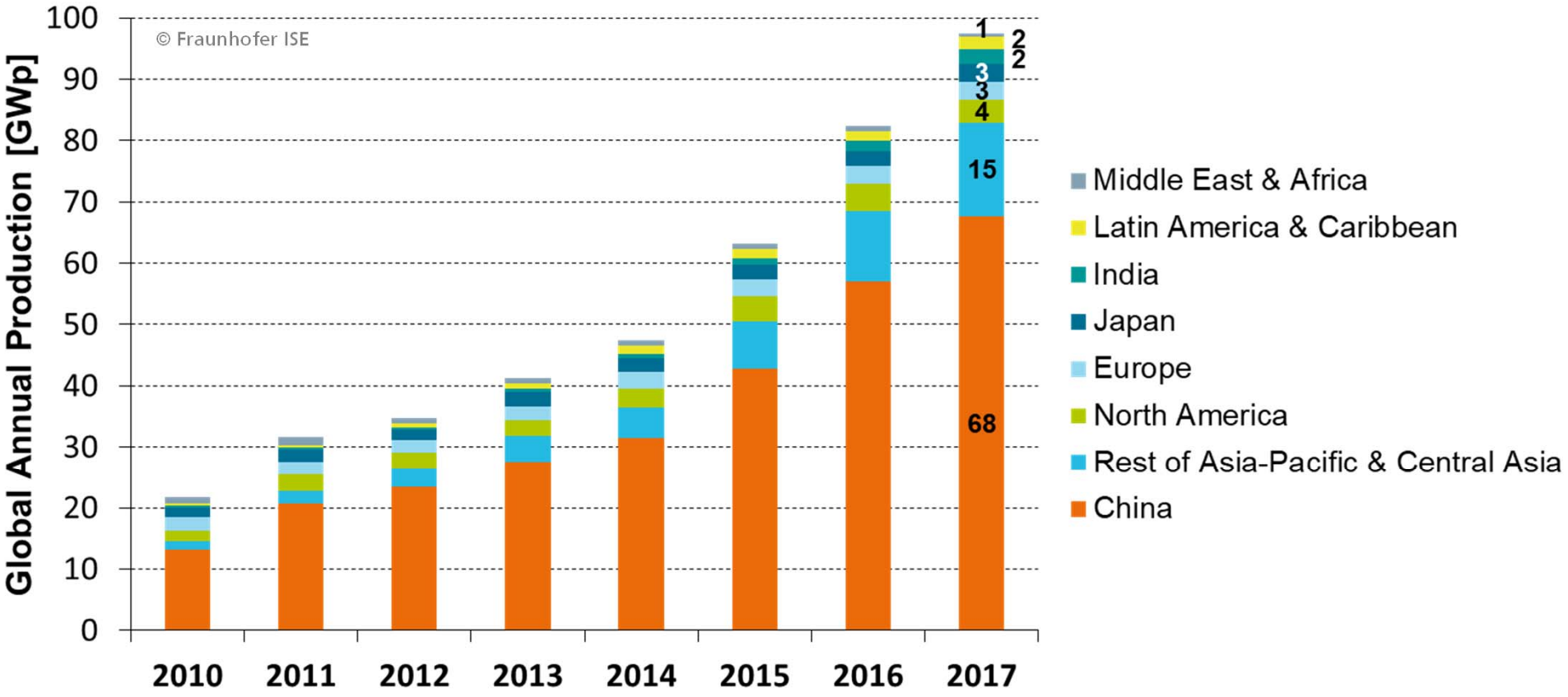
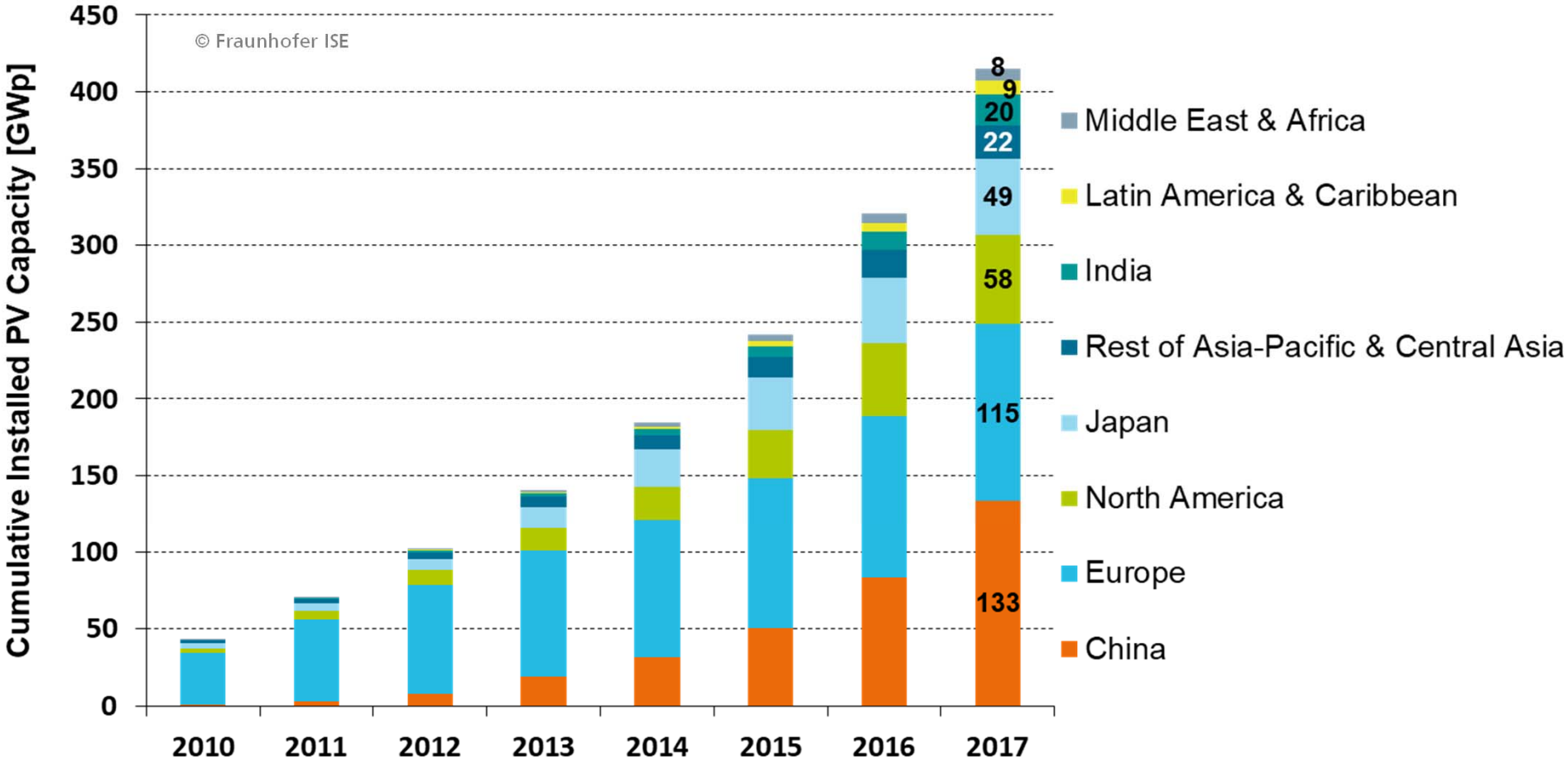
PV Industry Production by Region
Global Annual Production



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE GmbH 2018

Global Cumulative PV Installation until 2017 (includes off-grid)



Data: IHS. Graph: PSE GmbH 2018

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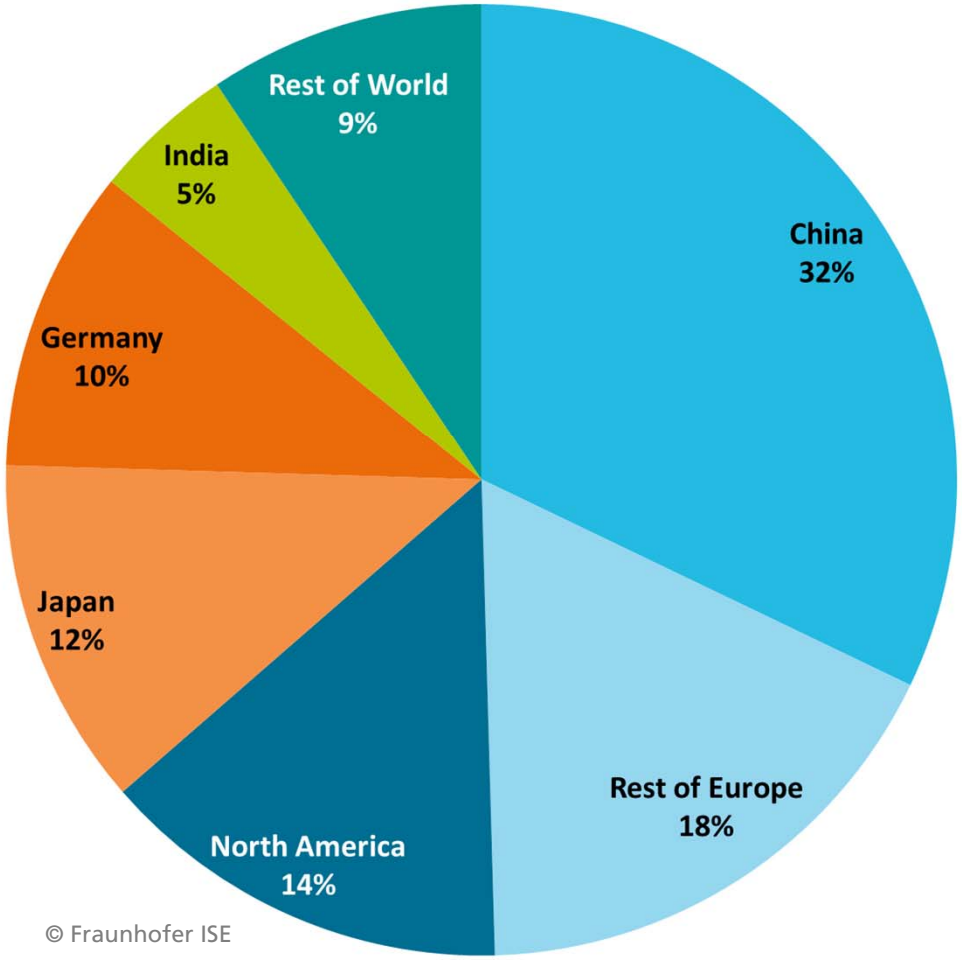
Global Cumulative PV Installation by Region
Status 2017



The total cumulative installations amounted to 415 GWp at the end of year 2017.

All percentages are related to total global installations, including off-grid systems.

Data: IHS. Graph: PSE GmbH 2018

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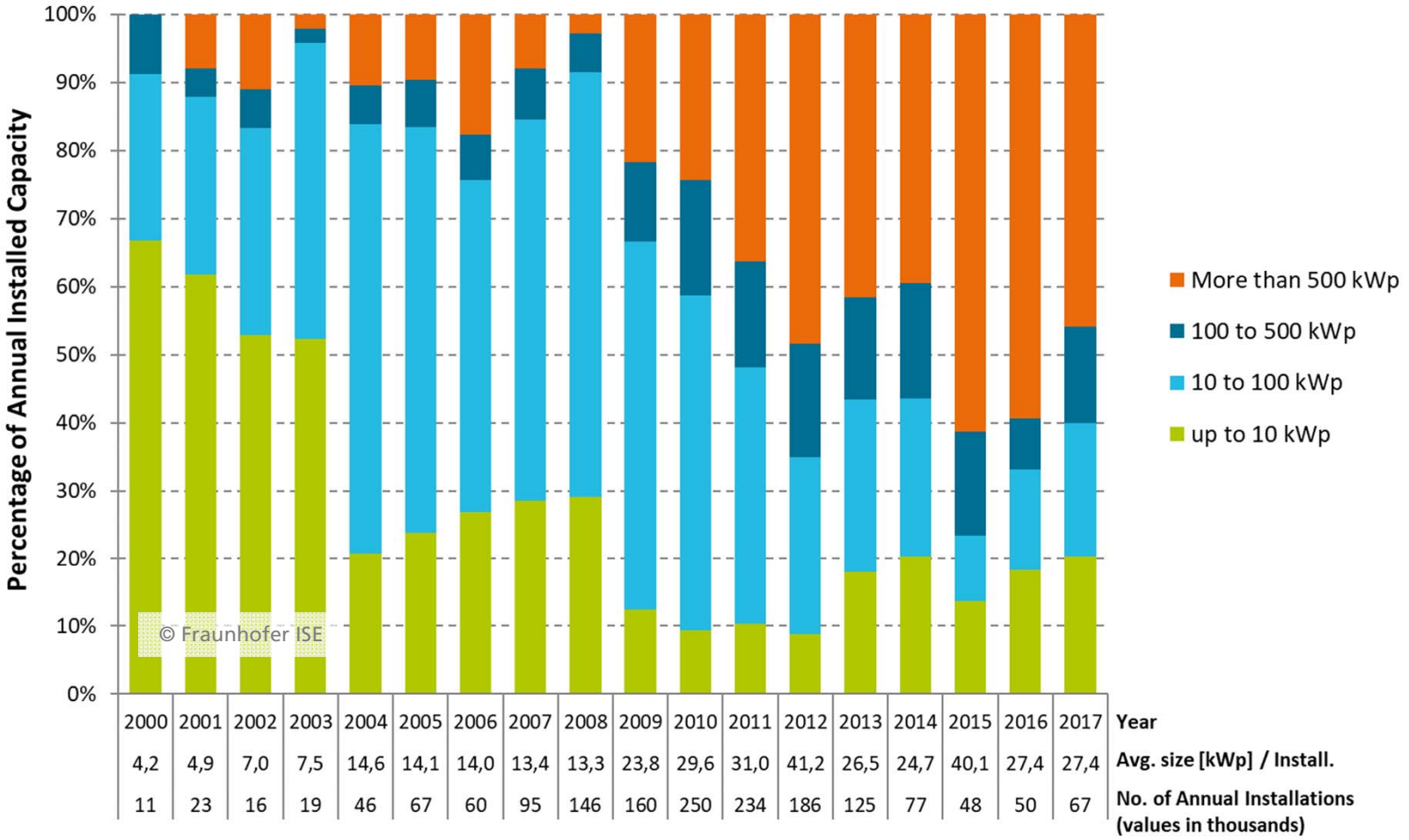
Number of PV Systems Annually Installed in Germany

Percentage of Annual Capacity



Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Avg. size [kWp] / Install.	4,2	4,9	7,0	7,5	14,6	14,1	14,0	13,4	13,3	23,8	29,6	31,0	41,2	26,5	24,7	40,1	27,4	27,4
No. of Annual Installations (values in thousands)	11	23	16	19	46	67	60	95	146	160	250	234	186	125	77	48	50	67

Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur. Graph: PSE GmbH 2018

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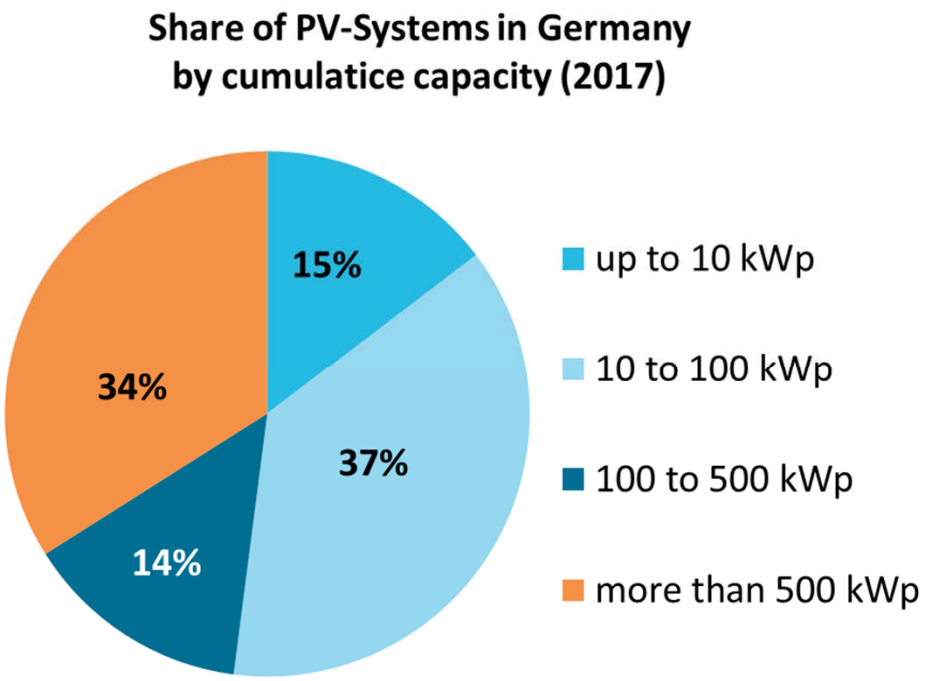
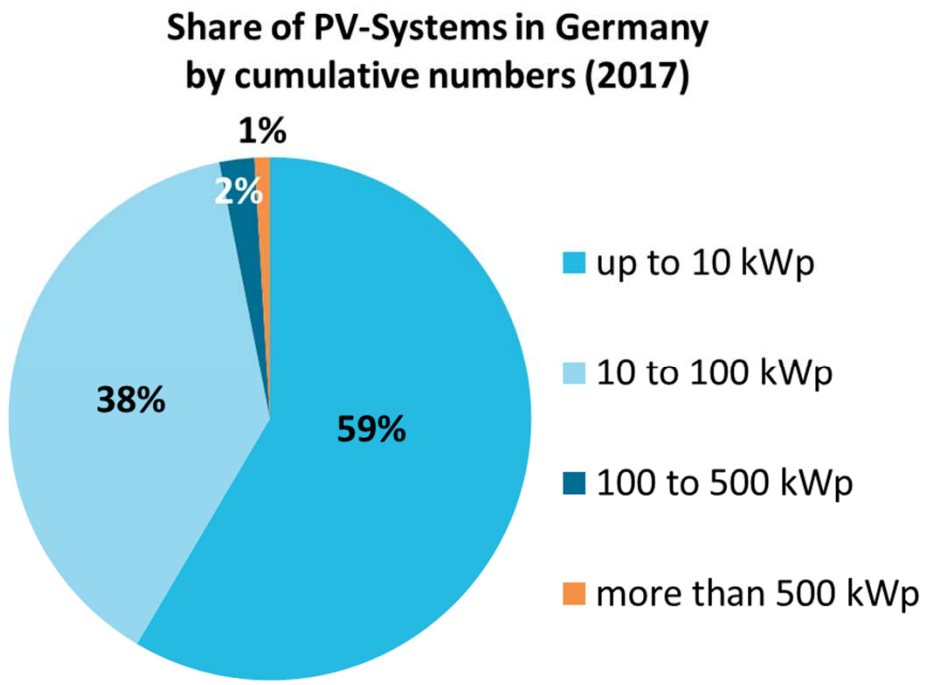
Share of Capacity and Number of PV-Systems Installed

Percentage of Cumulative Installations in Germany





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. Graph: PSE GmbH 2018

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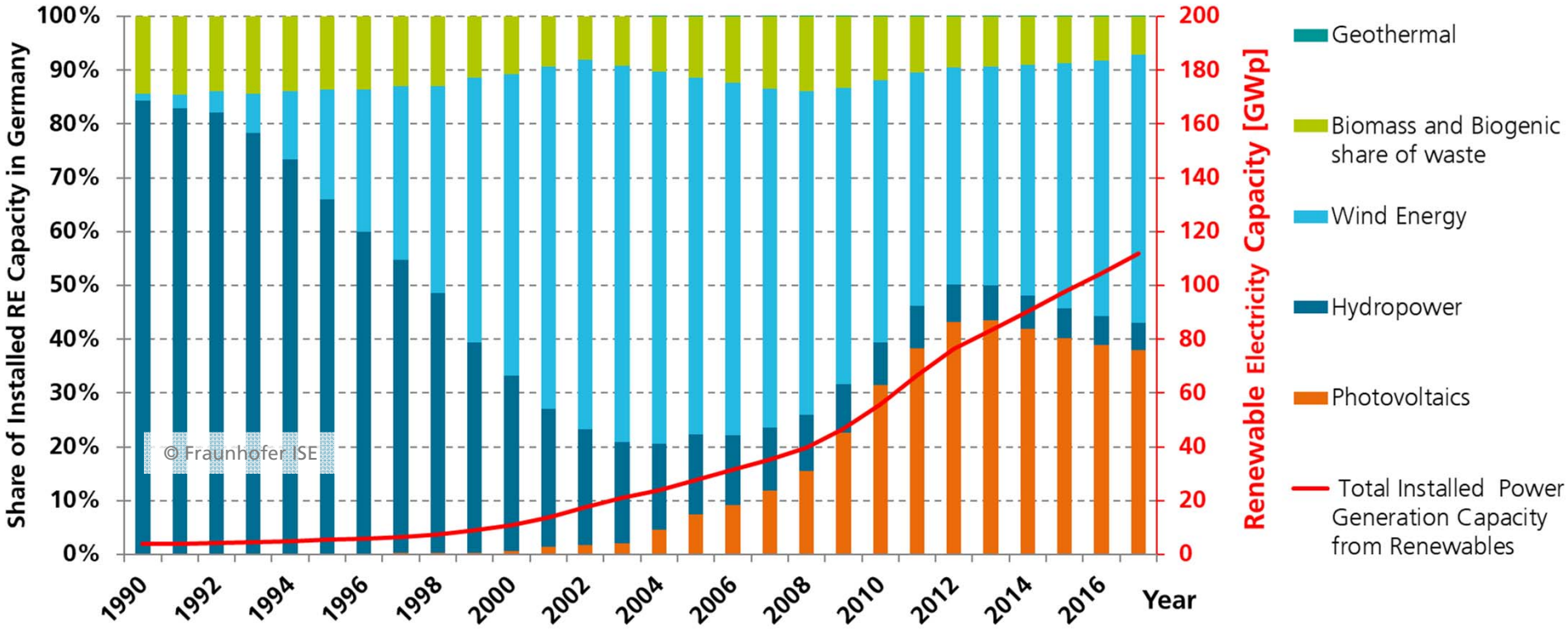
Electrical Capacity of Renewable Energy Sources
Germany



In 2017 about 36% (210 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 GmbH 2018

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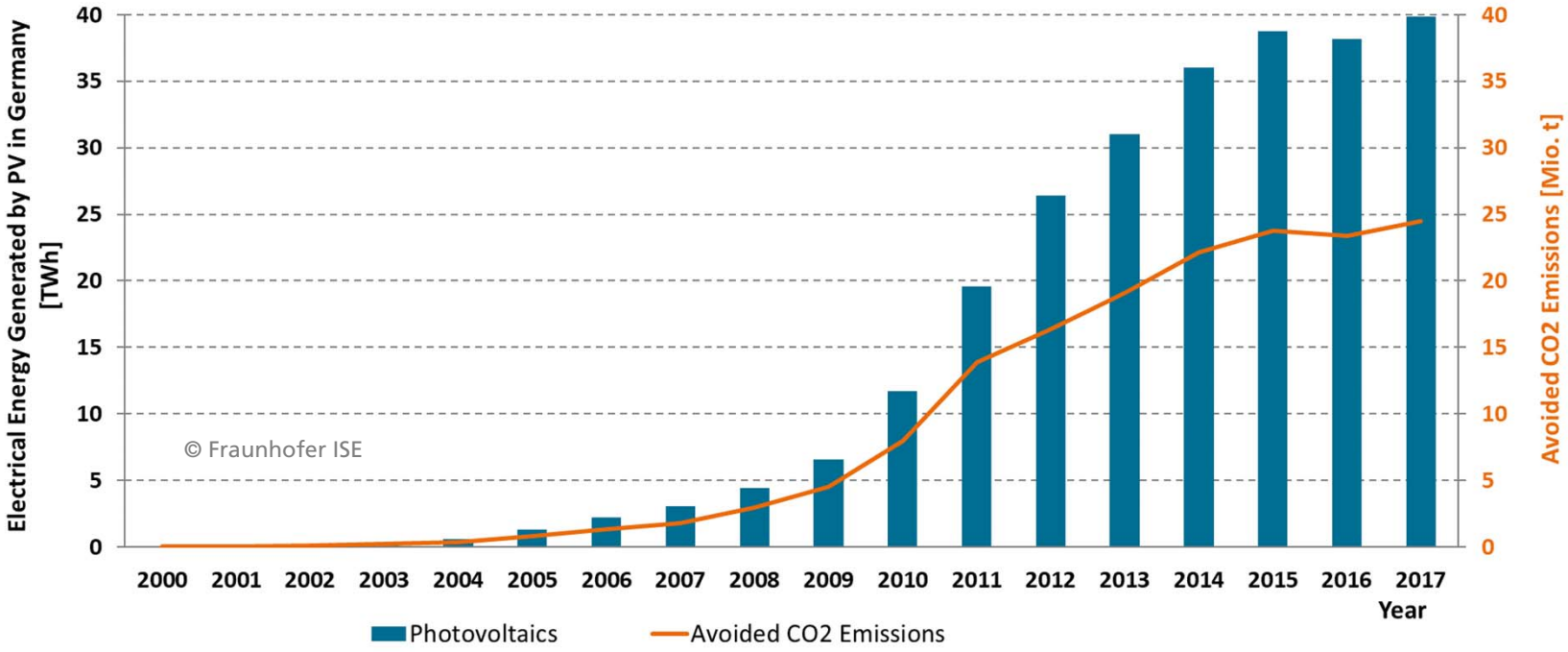
PV Energy Generated and Resulting CO_2 Avoided Emissions

Germany



- In 2017 about 19 Mio. t of CO_2 emissions were avoided due to 38.4 TWh PV electricity consumed in Germany.
- According to the Federal Environmental Ageny (UBA) the CO_2 avoidance factor of PV in 2017 is 489 grams of $CO_{2\text{-eq}}/kWh_{el}$.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2018. Graph: PSE GmbH 2018

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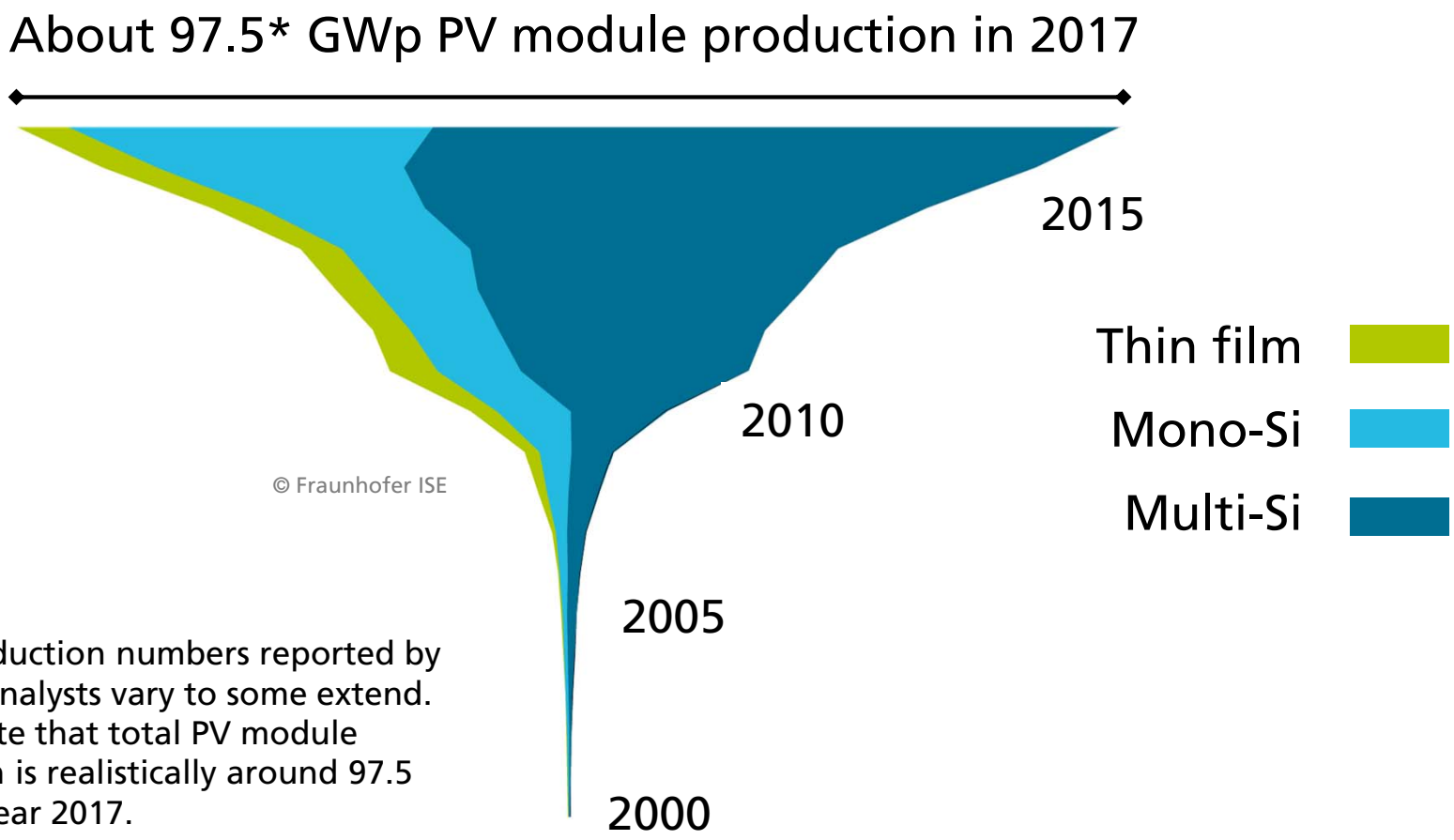
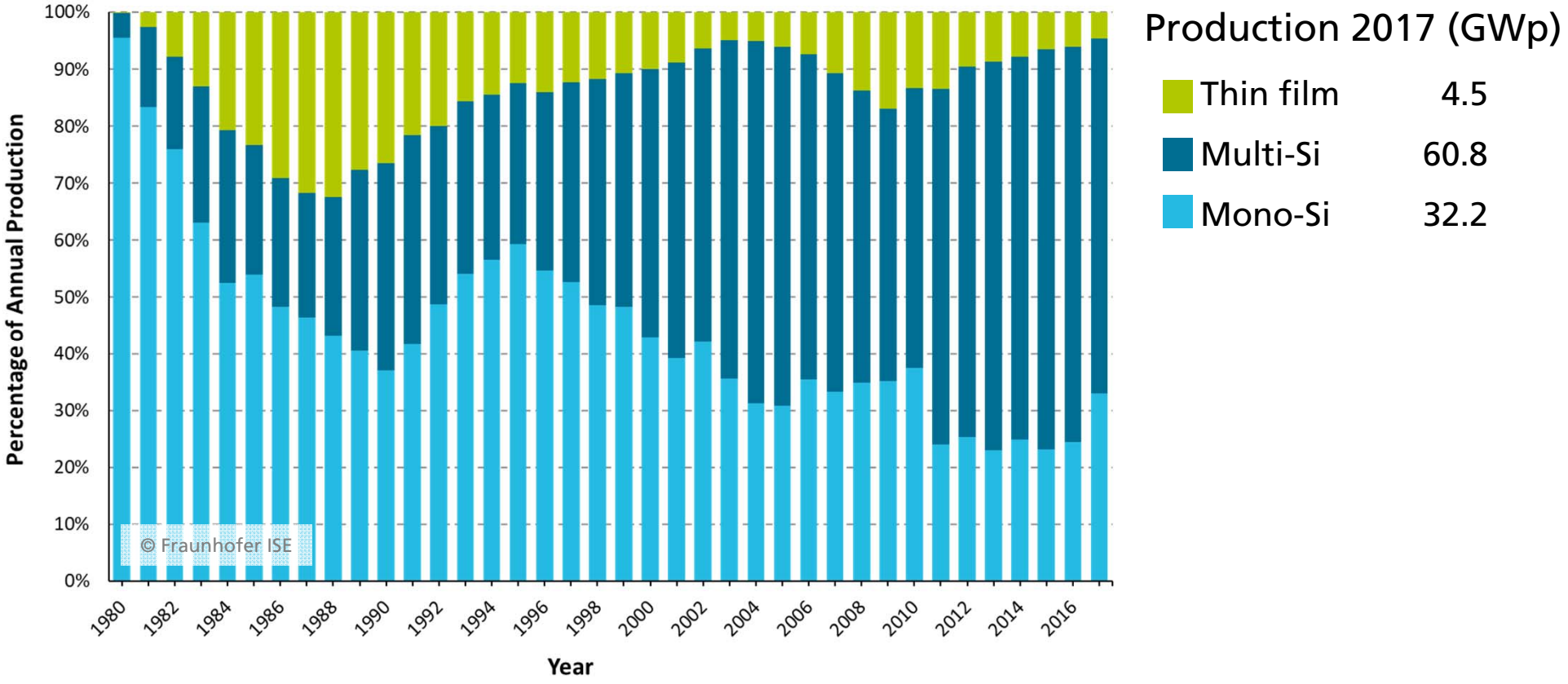
Annual PV Production by Technology
Worldwide (in GWp)



*2017 production numbers reported by different analysts vary to some extend. We estimate that total PV module production is realistically around 97.5 GWp for year 2017.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

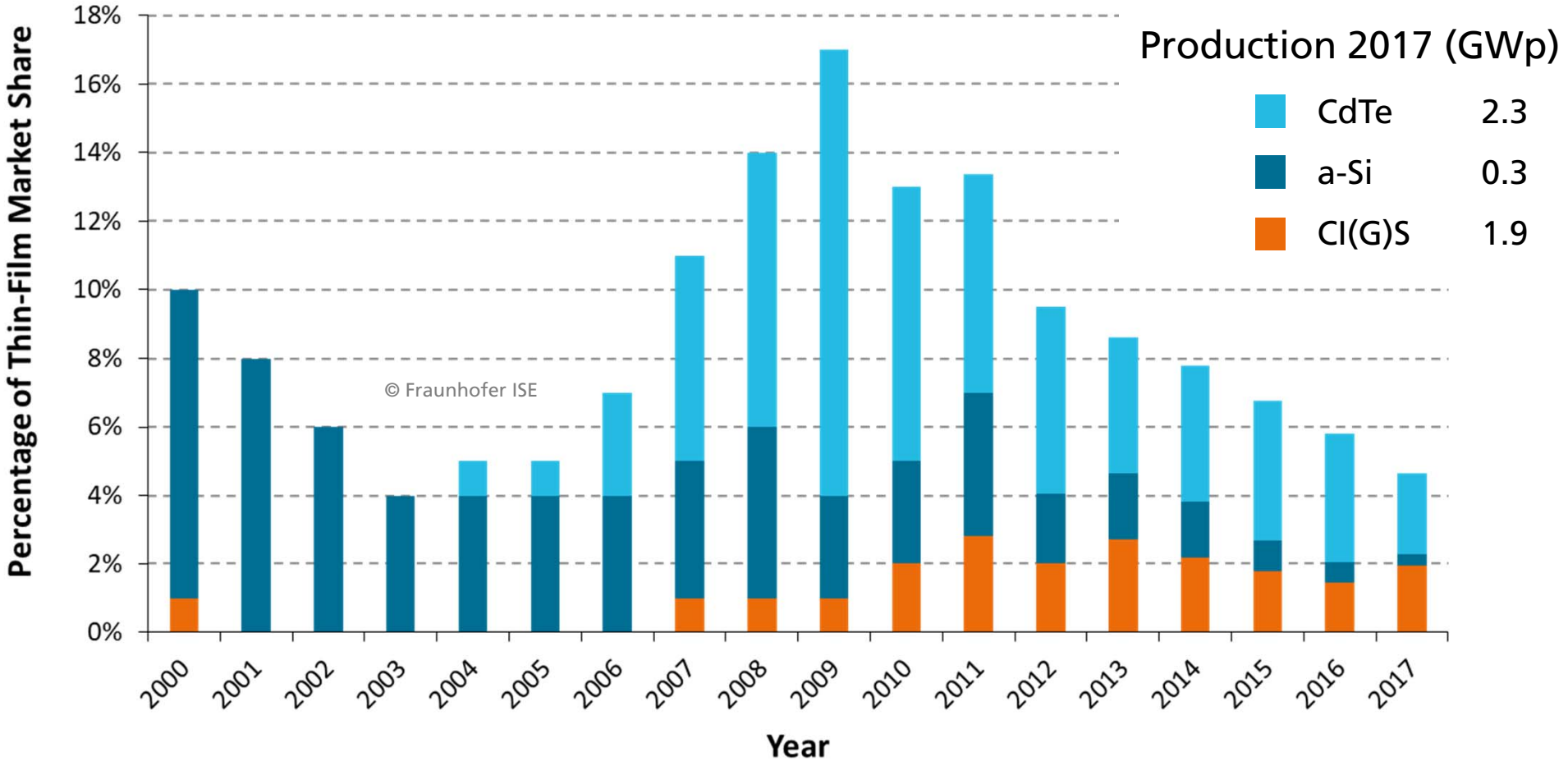
PV Production by Technology
Percentage of Global Annual Production



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE GmbH 2018

Market Share of Thin-Film Technologies

Percentage of Total Global PV Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

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Thin-Film Technologies

Annual Global PV Module Production

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

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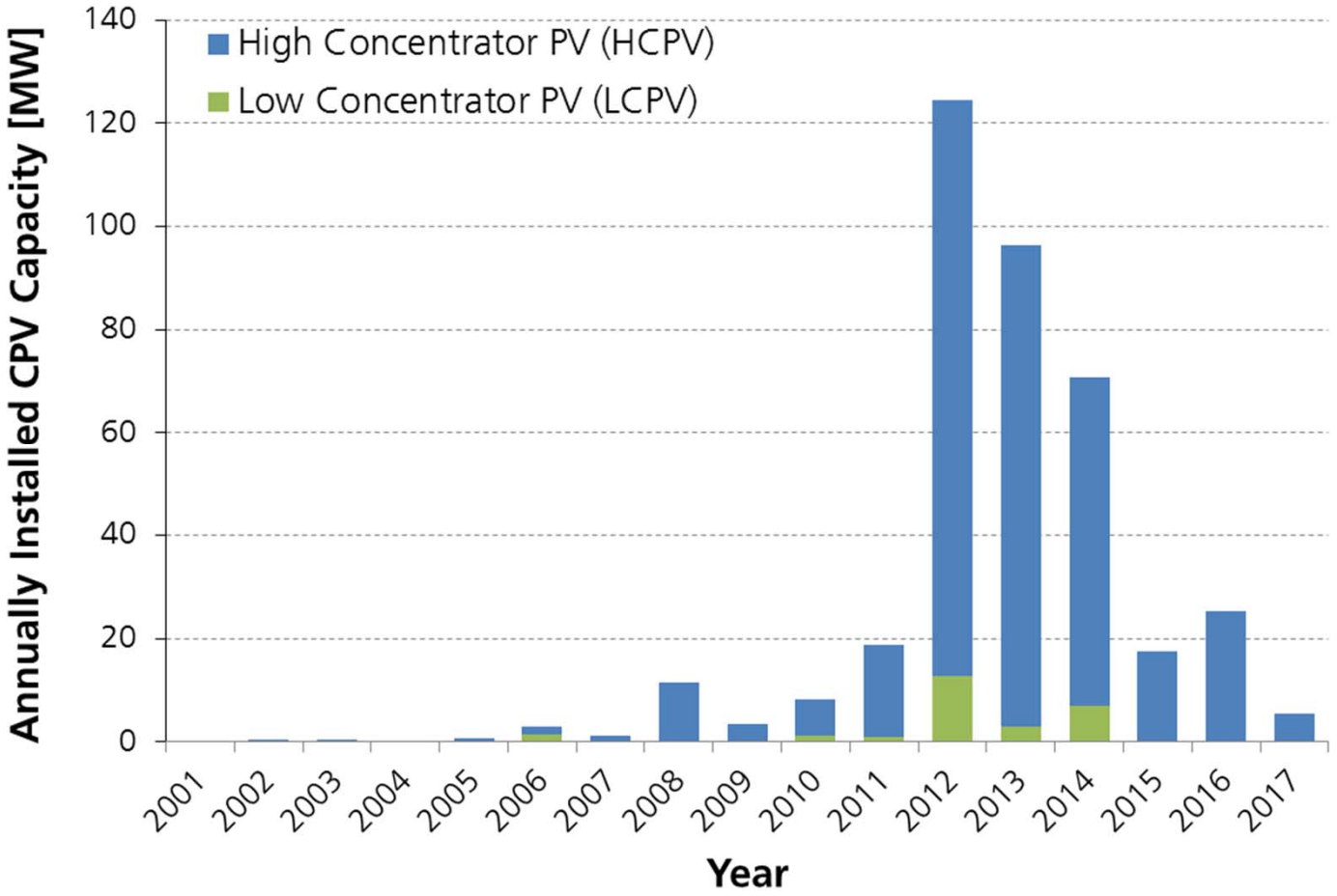
Low and High Concentrator PV Systems (LCPV/HCPV)

Annually Installed Capacity



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

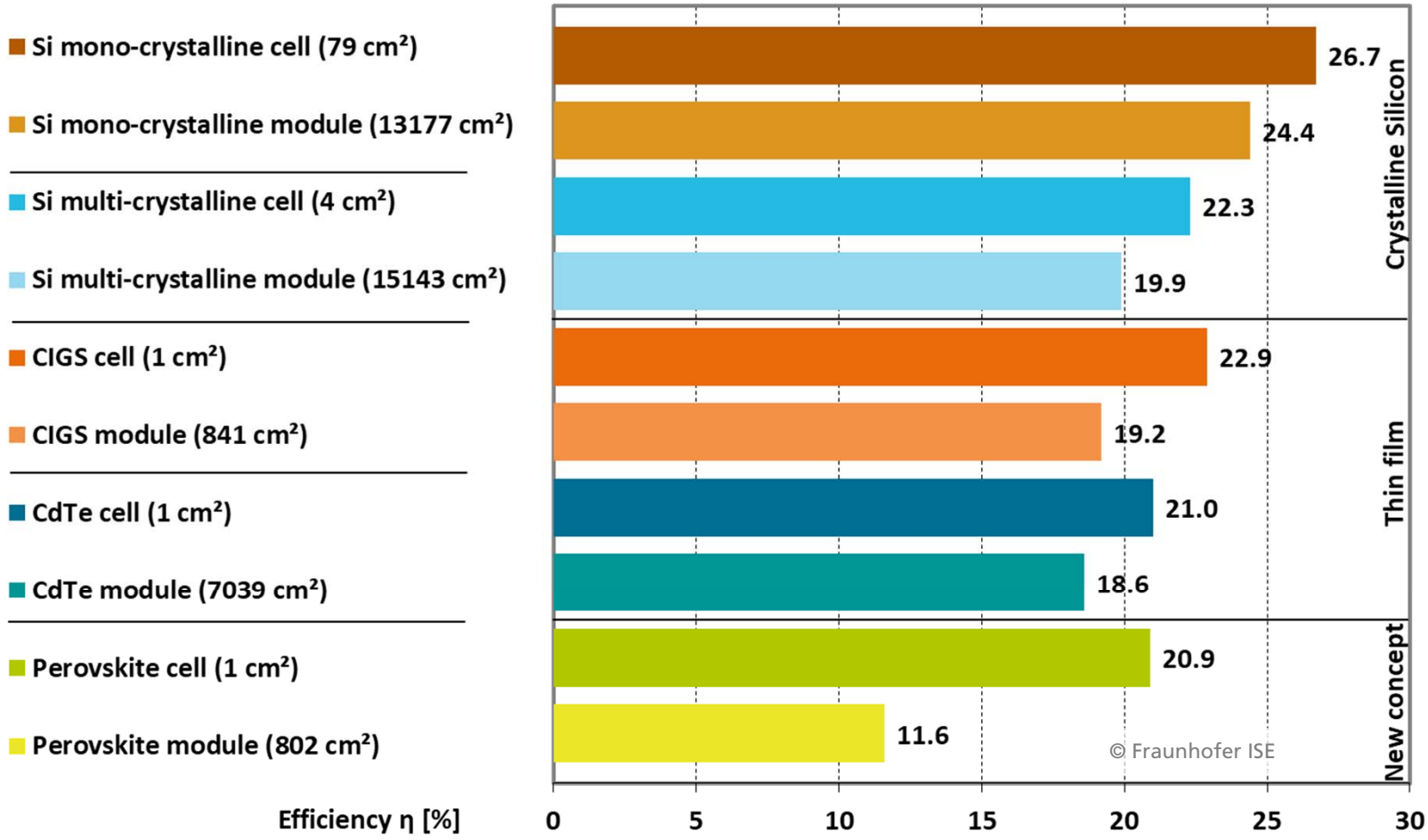
Data: ISE 2018

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

2. Solar Cells / Modules / System Efficiency

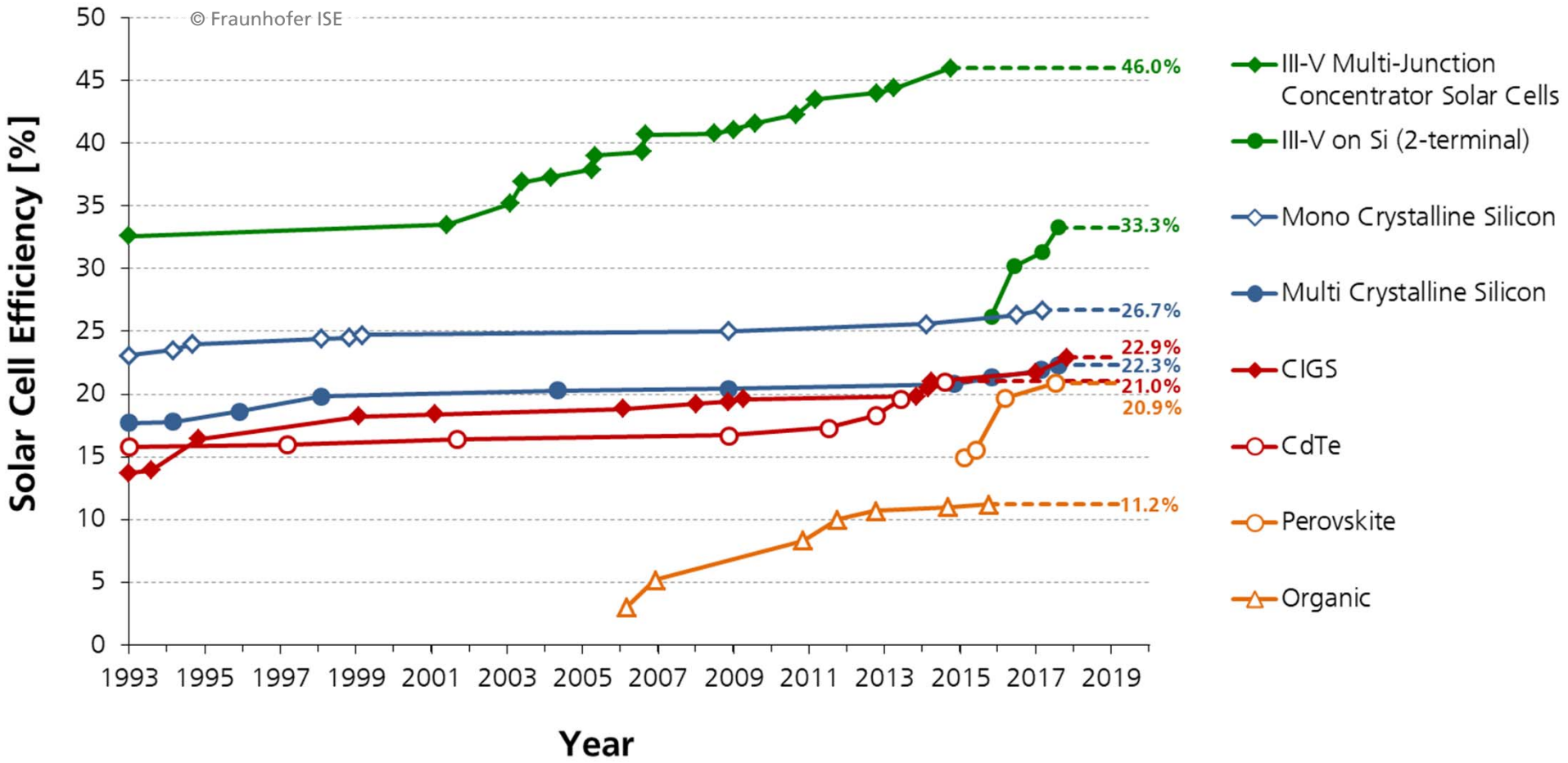
- Development in the PV Industry
- Development in the Laboratories
- High Concentration Photovoltaics (HCPV)
- Performance Ratio (PR)

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



Data: Green et al.: Solar Cell Efficiency Tables (Version 53), Progress in PV: Research and Applications 2018. Graph: Fraunhofer ISE 2019

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 53), Progress in Photovoltaics: Research and Applications, 1993-2018. Graph: Fraunhofer ISE 2019

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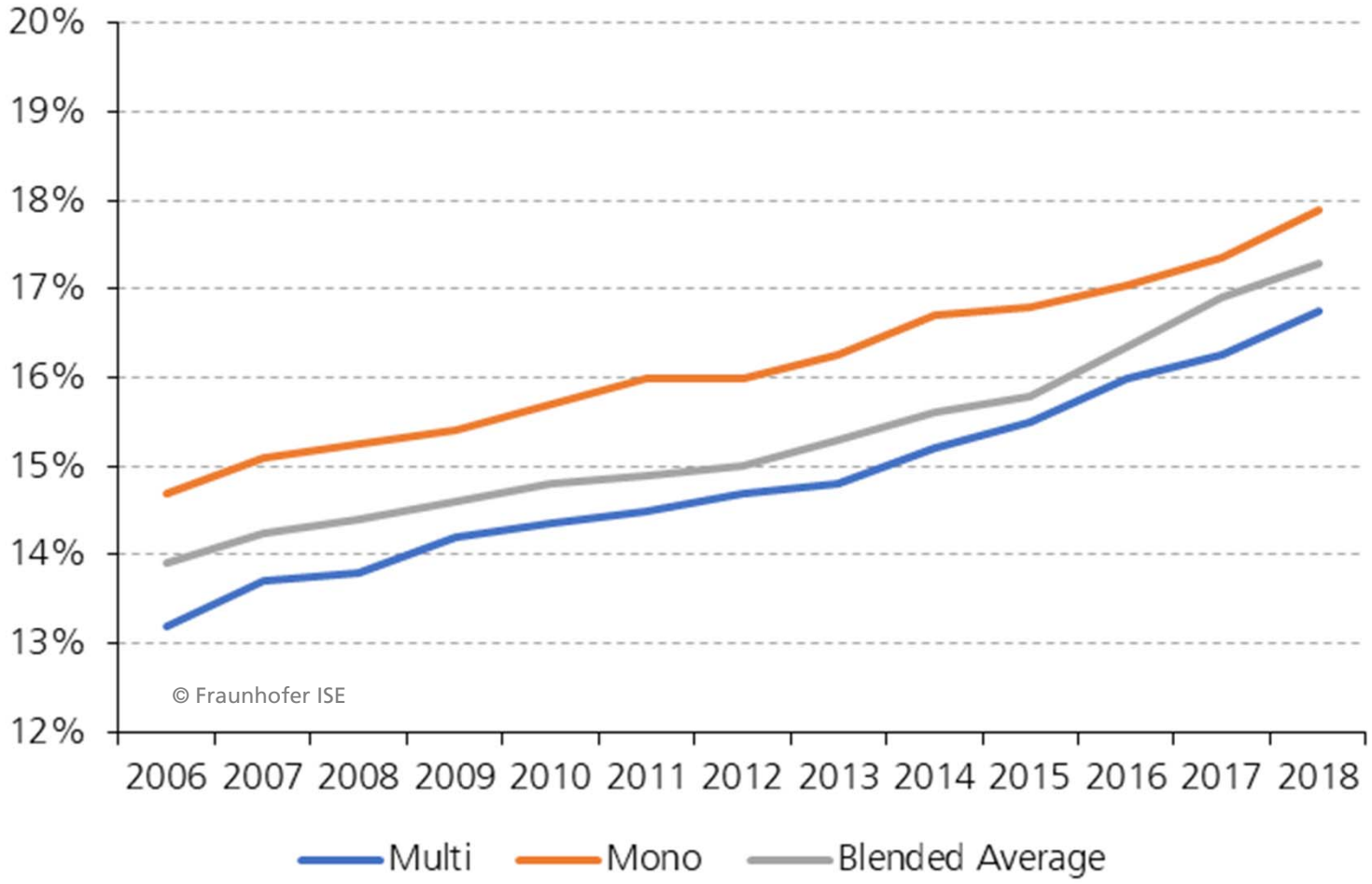
Average Crystalline-Silicon PV Module Efficiency



Data source: IHS Markit 2019

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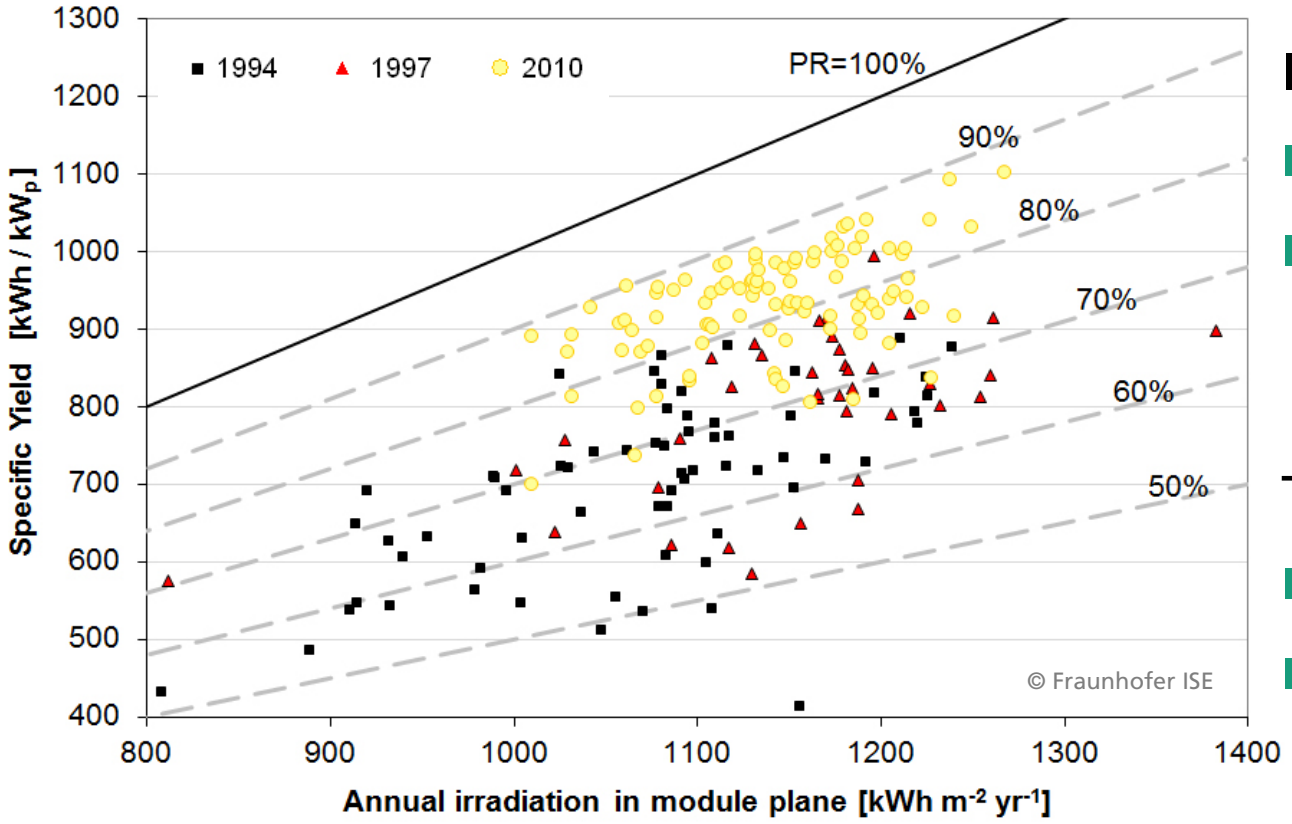
Performance Ratio Development for PV Systems
Germany



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

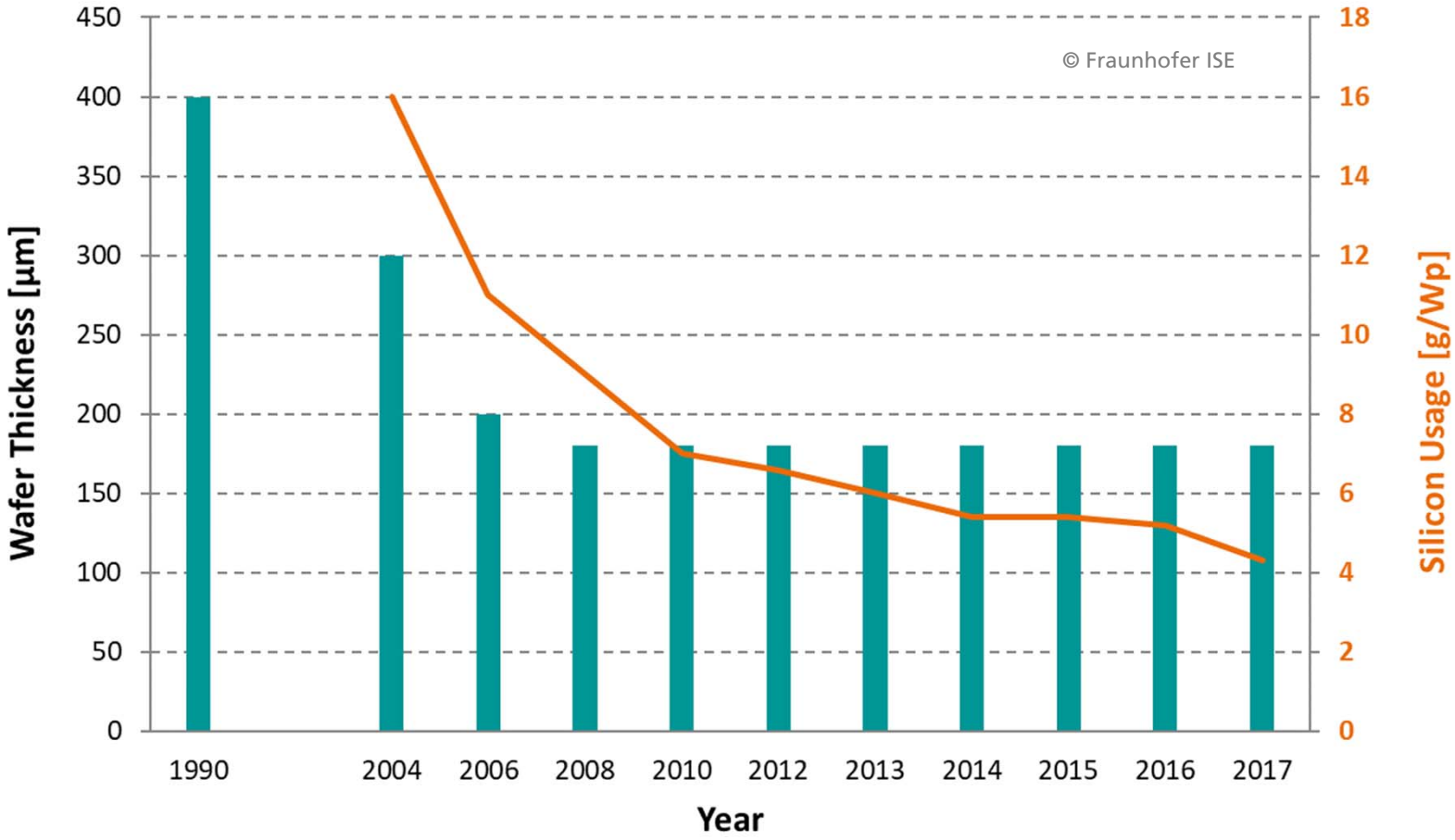
Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation

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 and 2017 with recycling of Si. Graph: PSE GmbH 2018

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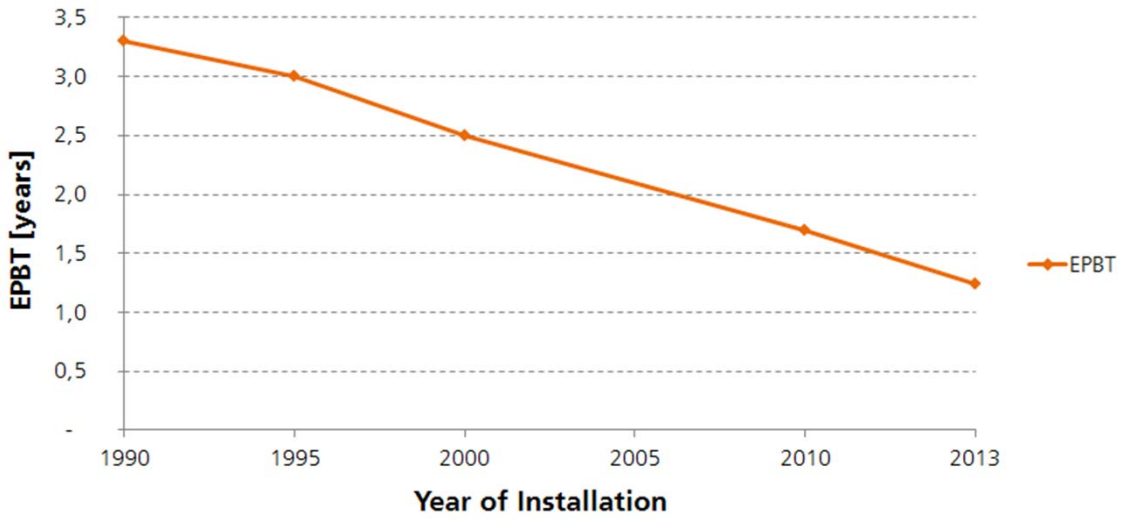
Historic Trend in Energy Payback Time of Crystalline Silicon PV Modules

Depending on the technology and location of the PV system, the EPBT today ranges from 0.7 to 2 years.

Rooftop PV systems produce net clean electricity for approx. 95 % of their lifetime, assuming a life span of 30 years or more.

EPBT of multicrystalline PV rooftop systems installed in Southern Europe*

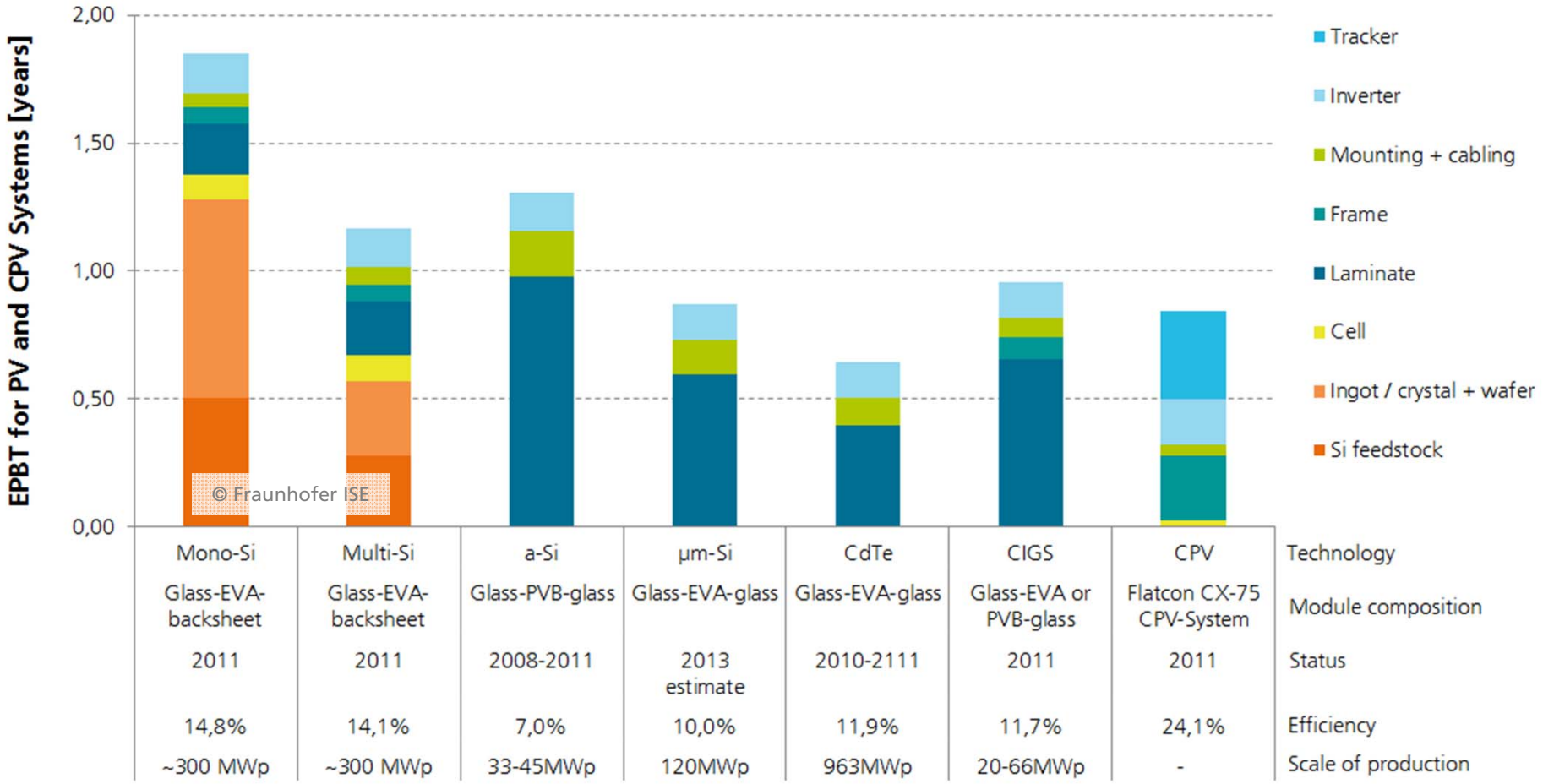


*Irradiation: 1700 kWh/m²/a at an optimized tilt angle

Data: EPIA Sustainability Working Group Fact Sheet 2011; since 2010: M.J. de Wild-Scholten 2013. Graph: PSE 2014

Energy Pay-Back Time for PV and CPV Systems
Different Technologies located in Catania, Sicily, Italy

Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr



Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE 2014

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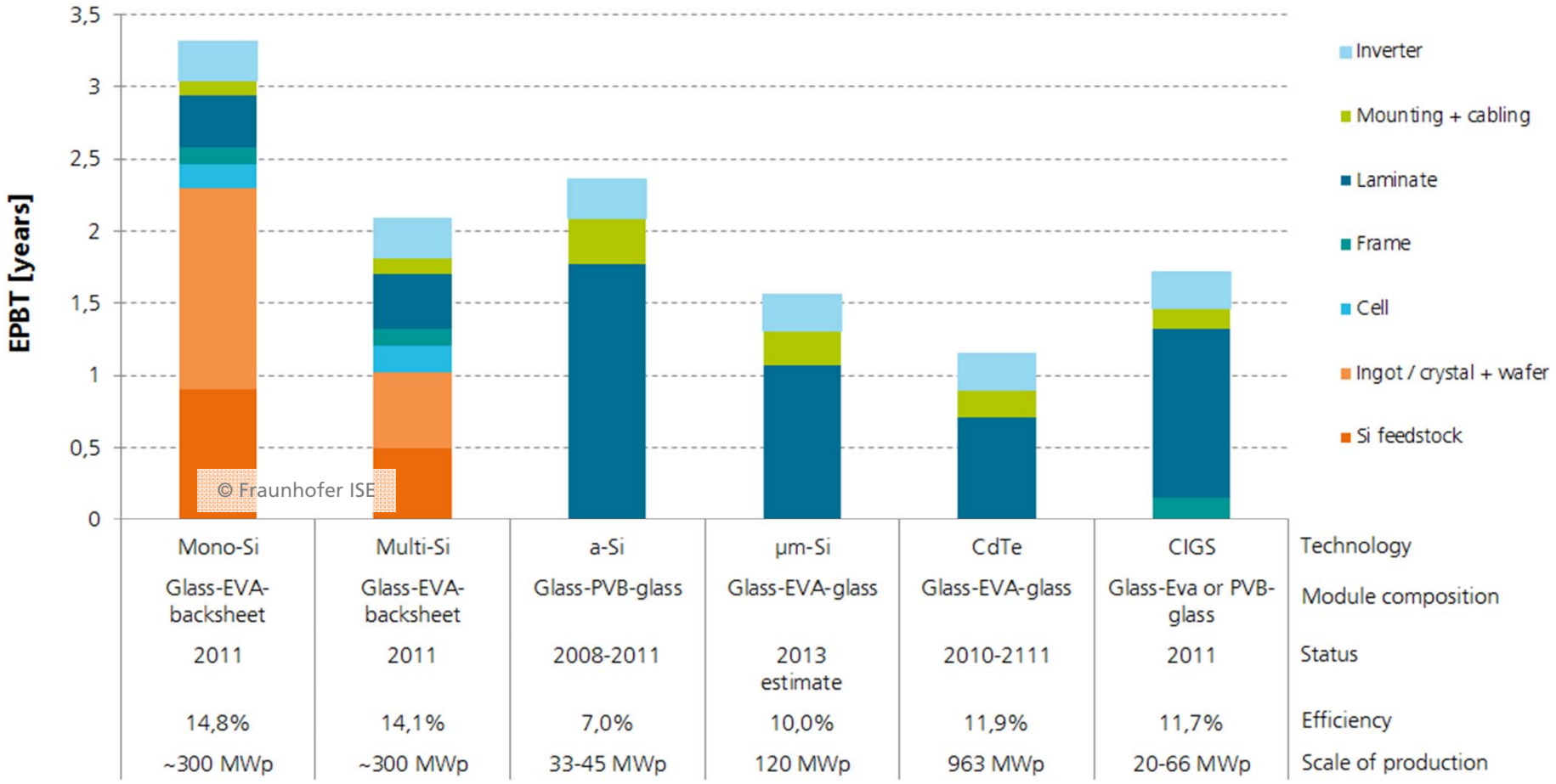
Energy Pay-Back Time of Rooftop PV Systems
Different Technologies located in Germany

Global Irrad.: 1000 kWh/m²/yr



Data: M.J. de Wild-Scholten 2013. Graph: PSE 2014

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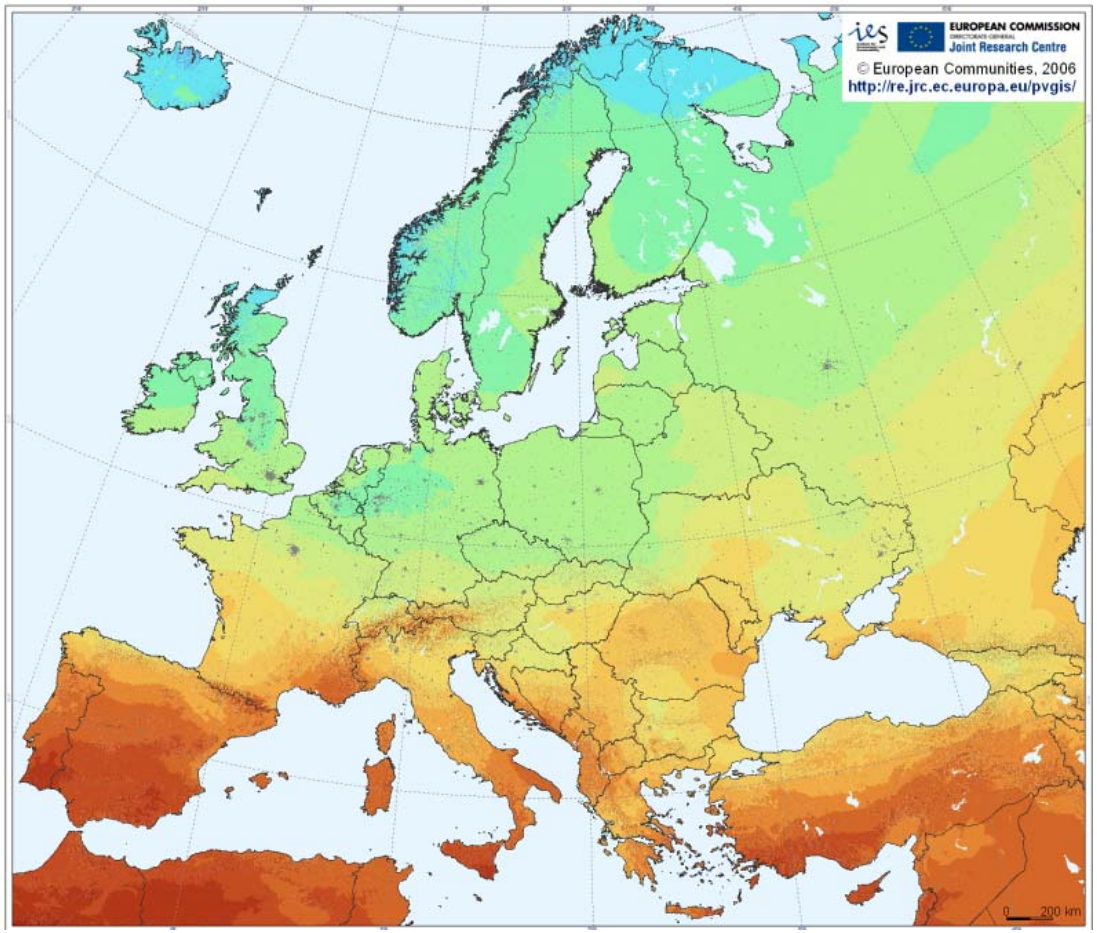
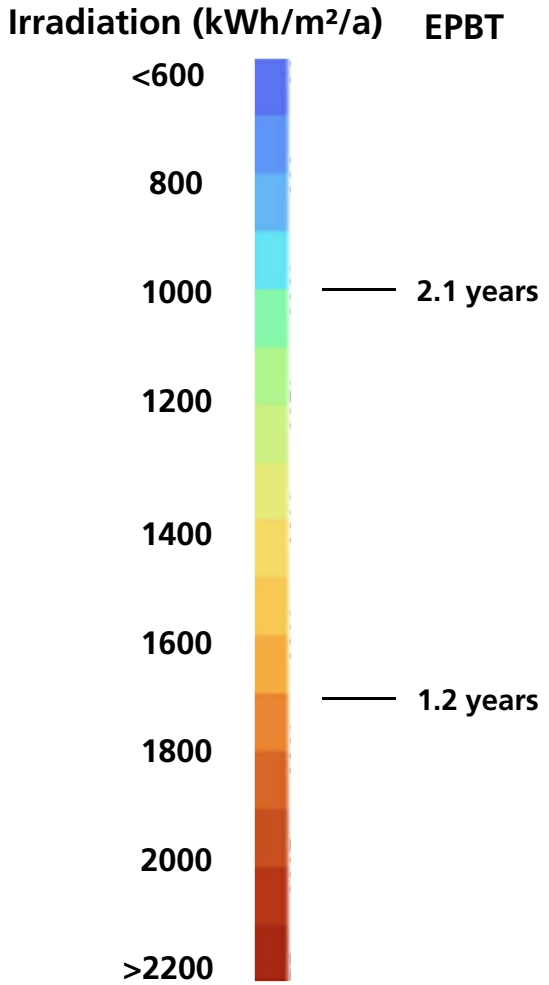
Energy Pay-Back Time of Multicrystalline Silicon PV Rooftop Systems - Geographical Comparison





Data: M.J. de Wild-Scholten 2013. Image: JRC European Commision. Graph: PSE 2014 (Modified scale with updated data from PSE and FraunhoferISE)

4. Inverters

- Inverter/Converter Price
- Inverter Concept Comparison

Inverter/Converter Market 2017

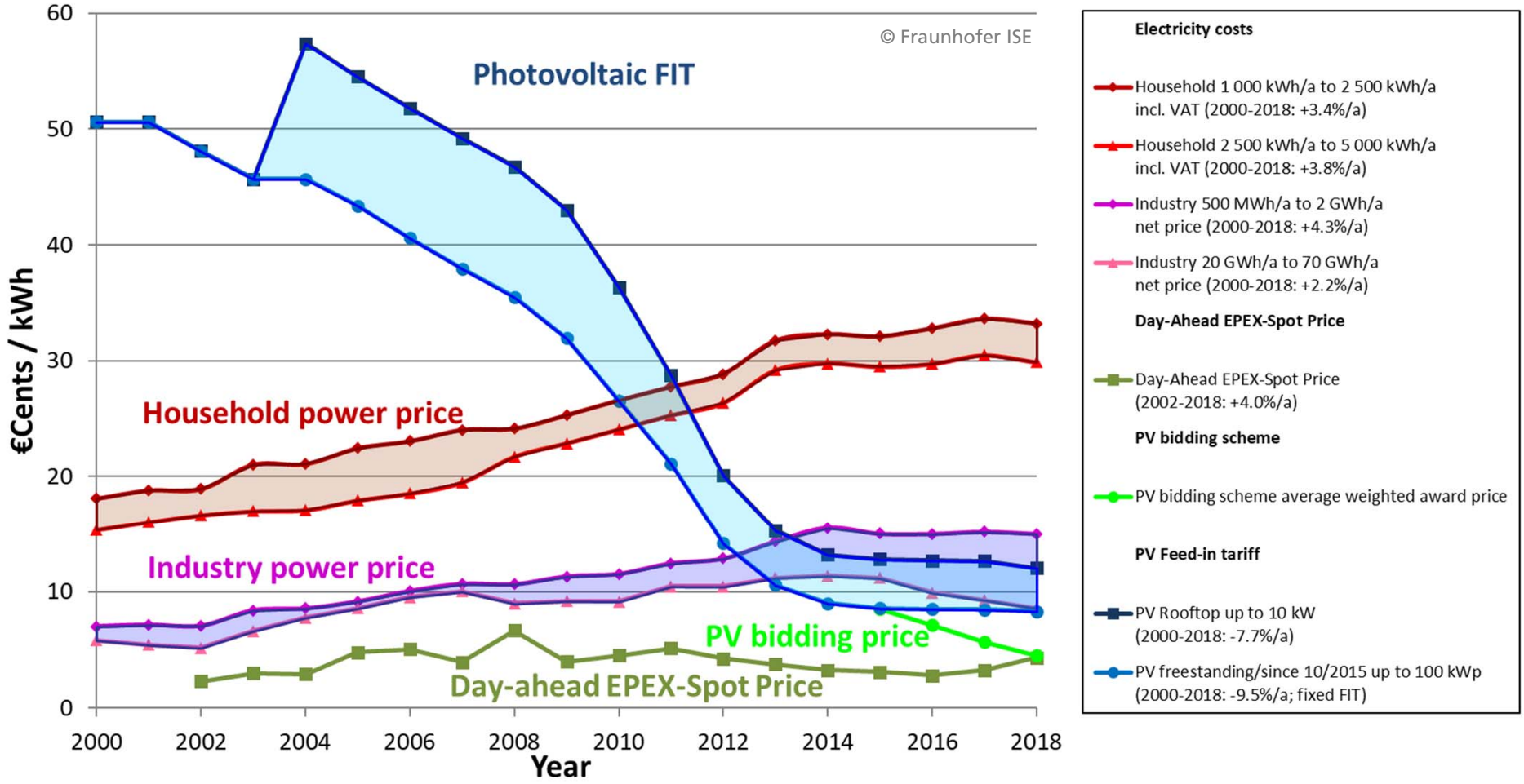
Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 150 kWp	up to 98%	~ 52%	• 6 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	~ 44%	• ~ 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 28 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8%	~ 3%	• ~ 9 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed • ~ 3 GWp installed in 2017

Data: IHS 2016. Remarks: Fraunhofer ISE 2018. Design: PSE GmbH 2018

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 2018 and BMWi Energiedaten. Design: B. Burger - Fraunhofer ISE , Update: 12 Mar. 2019

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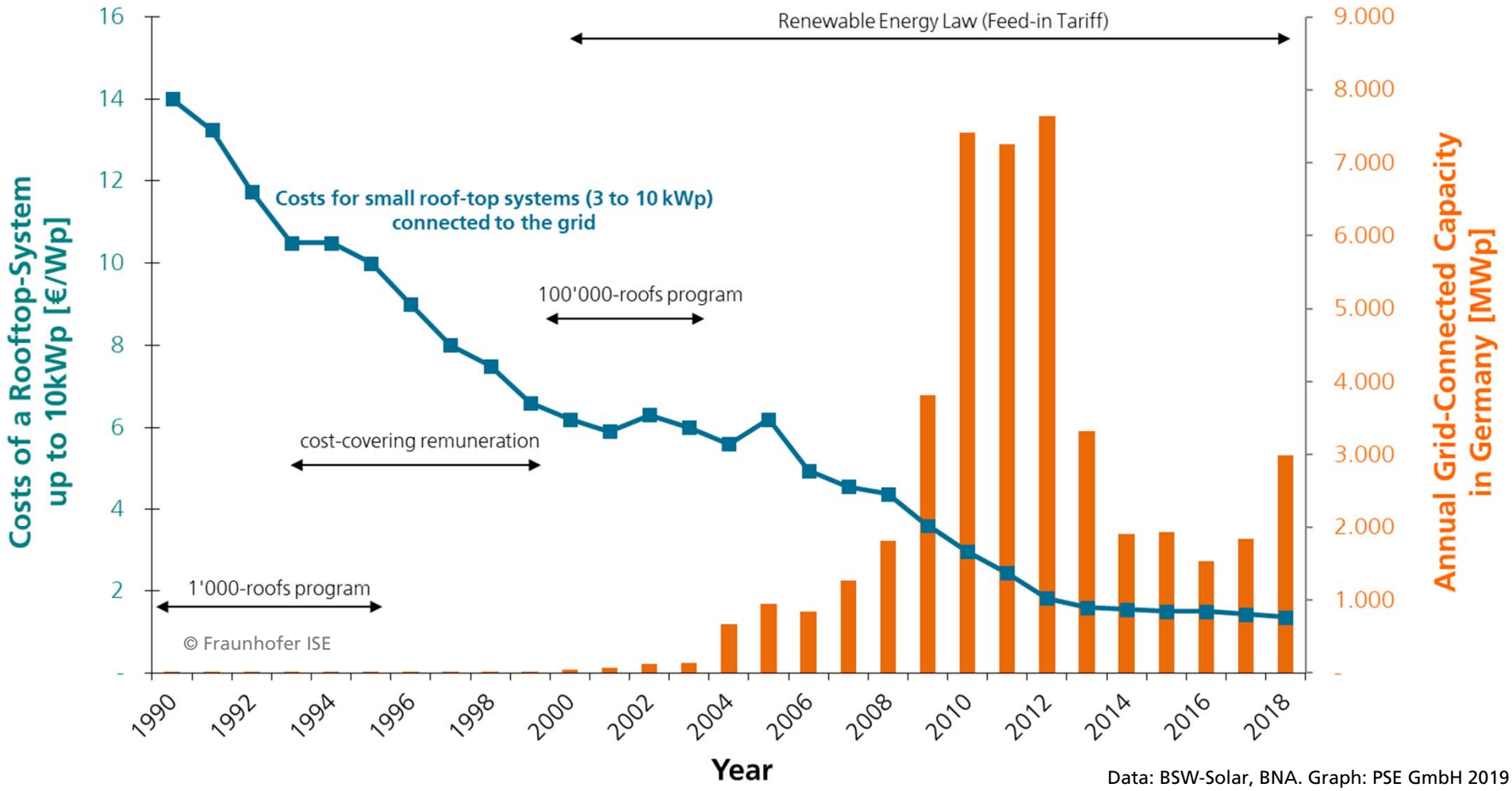
Investment for Small Rooftop PV Systems in Relation to Market Development and Subsidy Schemes in Germany



Data: BSW-Solar, BNA. Graph: PSE GmbH 2019

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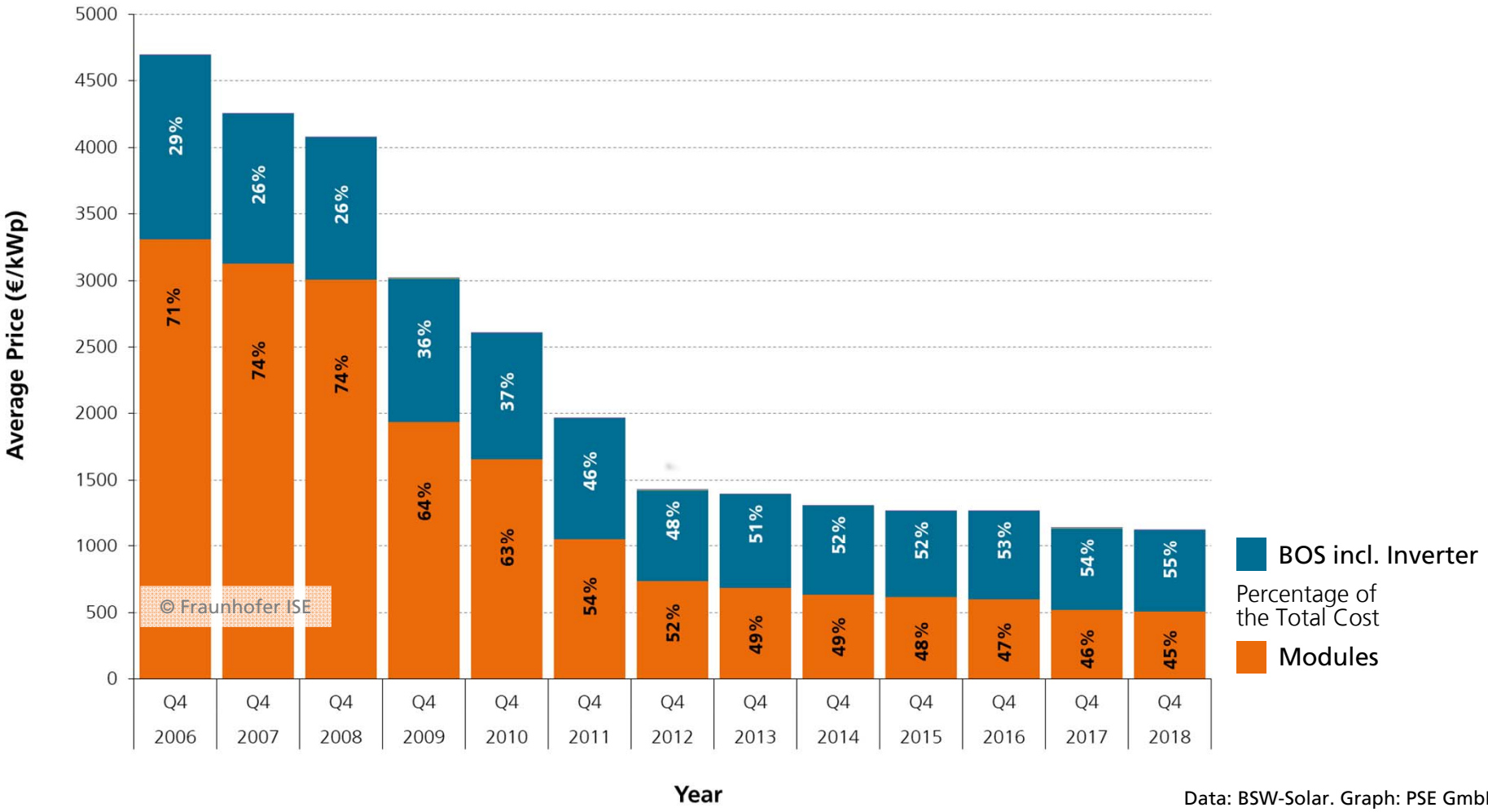
Average Price for PV Rooftop Systems in Germany (10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE GmbH 2019

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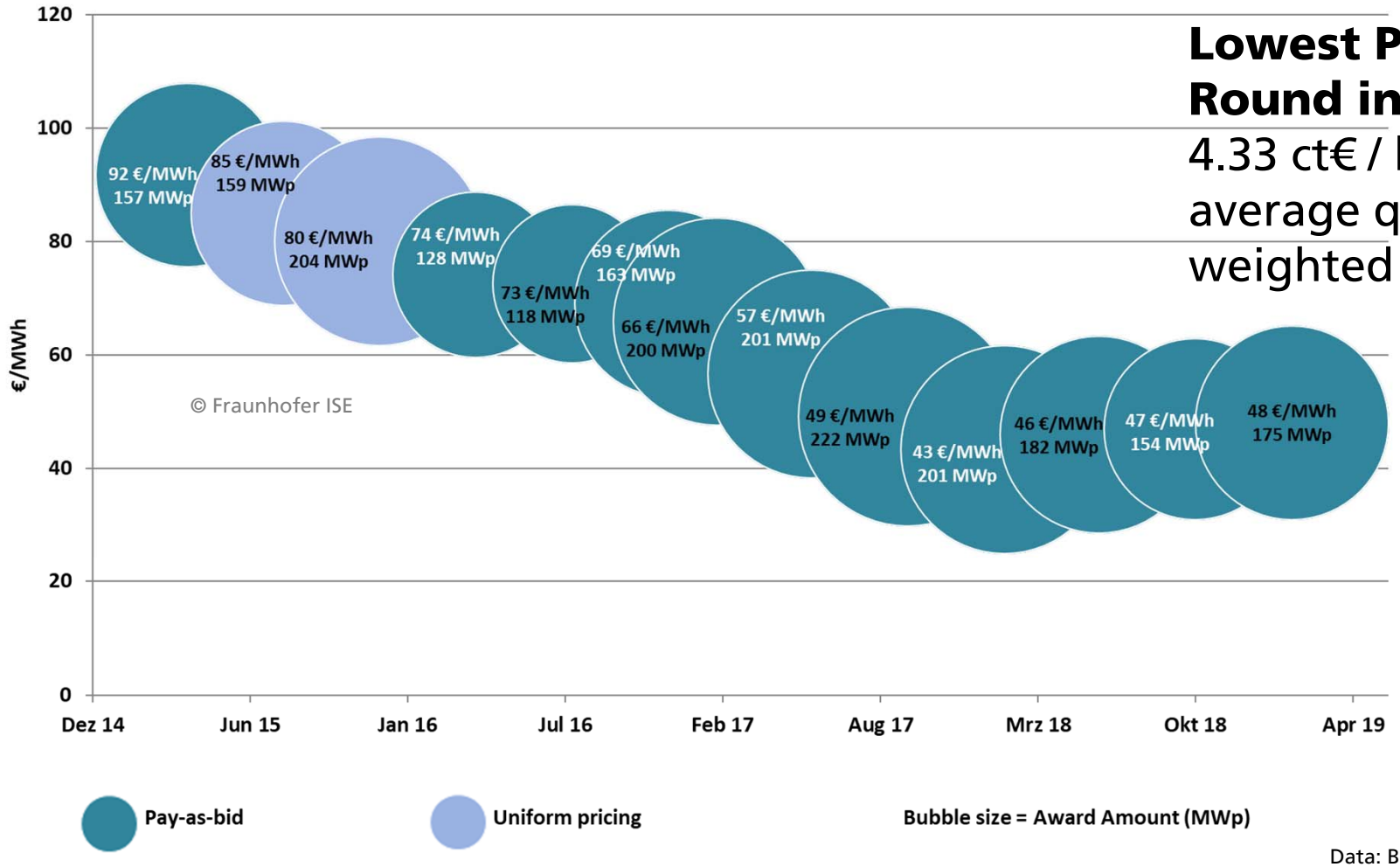
PV-Tender in Germany

Average, quantity weighted Award Value



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

Data: BNA. Graph: PSE GmbH 2019

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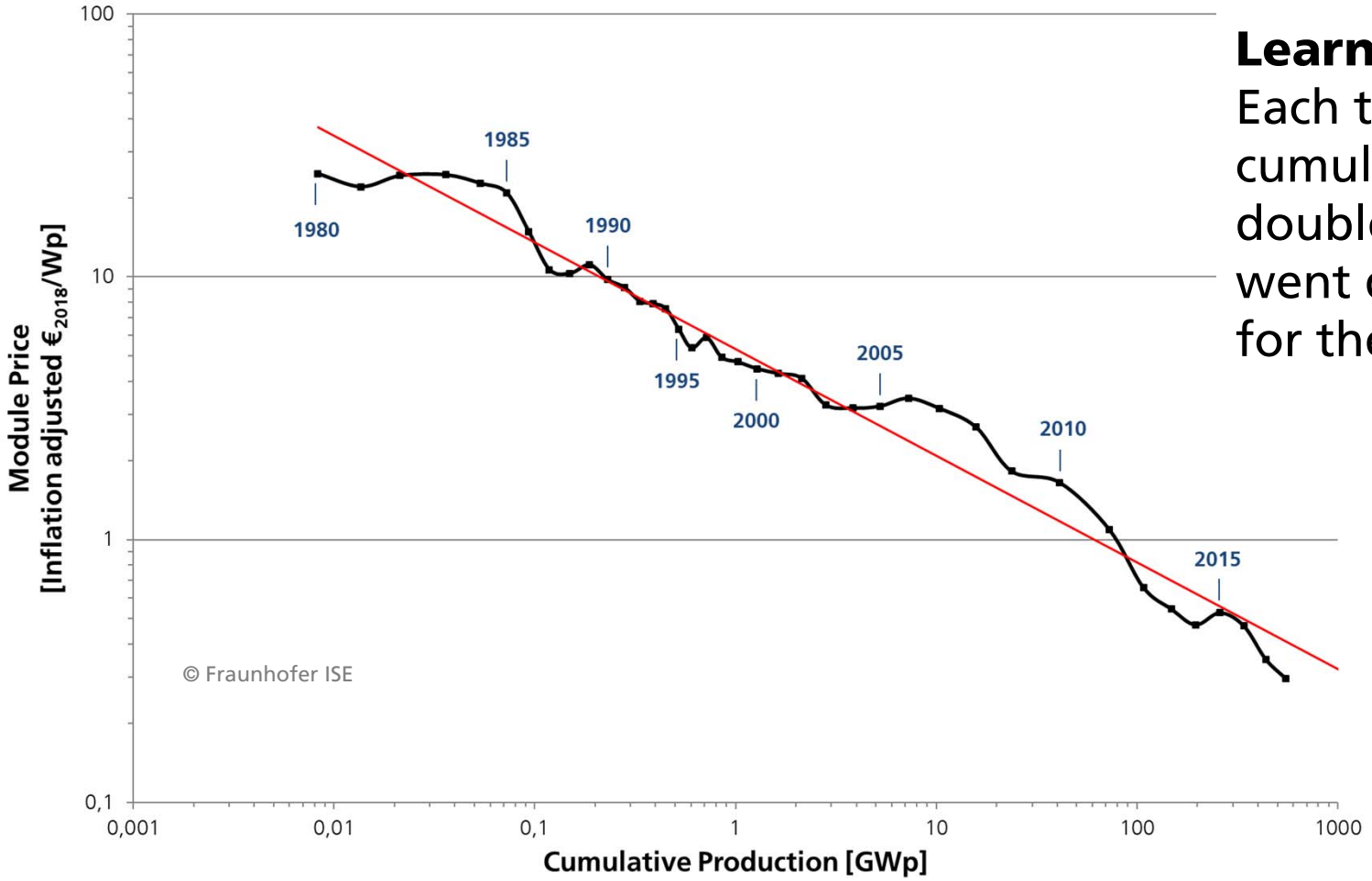
Price Learning Curve

Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative production doubled, the price went down by 24 % for the last 38 years.

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

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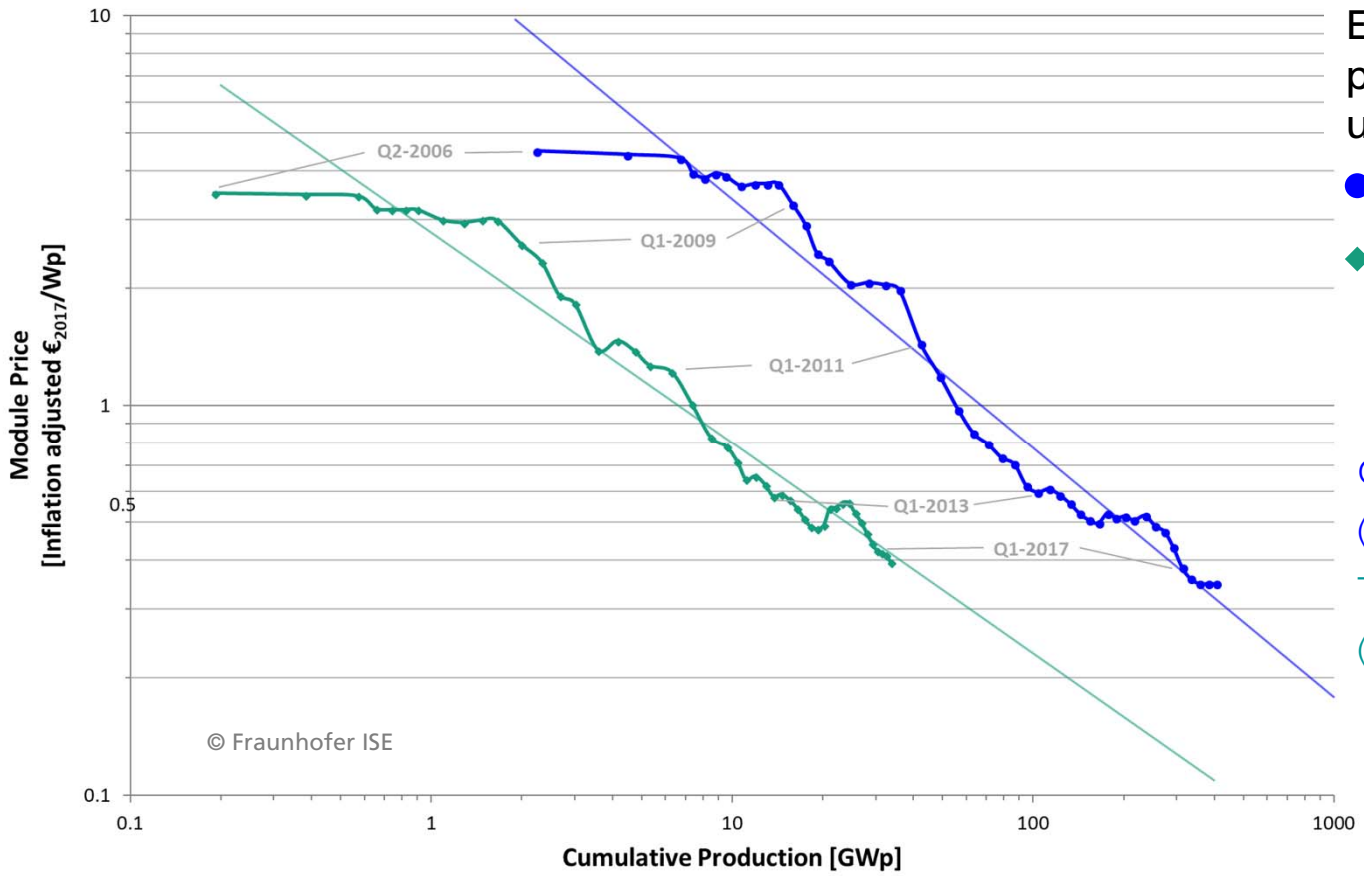
Price Learning Curve by Technology
Cumulative Production up to Q4. 2017



Estimated cumulative production up to Q4, 2017 :

- c-Si 405 GWp
- Thin Film 33 GWp

Crystalline Technology
(from Q2-2006 to Q4-2017) **LR 29**

Thin Film Technology
(from Q2-2006 to Q4-2017) **LR 25**

Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011: IHS. Graph: PSE GmbH 2018

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 - Assessment of 2017
- What will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050
- 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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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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