PHOTOVOLTAICS REPORT

Prepared by

Fraunhofer Institute for Solar Energy Systems, ISE

with support of

PSE AG

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- Quick Facts
- Topics:
  - PV Market
  - Solar Cells / Modules / System Efficiency
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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 However, facts and figures change rapidly and the given information may soon be outdated again.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 AG).
- 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 werner.warmuth@pse.de
- Please quote the information presented in these slides as follows: ©Fraunhofer ISE: Photovoltaics Report, updated: 12 July 2017

Quick Facts

Parameter	Value	Status	Reference
Germany / European Union / Worldwide			
PV market	1.5 / 7.3 / 77.3 GW	2016	BNA / IHS / IHS
Cumulative installation	41 / 106 / 320 GW	End of 2016	BNA / IEA+IHS
PV power consumption	38.2 / 114.4 / 333 TWh	2016	BP
PV electricity share	6.9 / 3.4 / 1.3%	2016	ISE / BP / BP
Worldwide			
c-Si share of production	93%	2016	IHS
Record solar cell efficiency: III-V MJ (conc.) / mono-Si / multi-Si / CIGS / CdTe	46.0 / 26.7 / 21.9 / 21.7 / 21.0%	July 2017	Green et al.
Germany			
Price PV rooftop system	~ 1500 €/kWp	End of 2016	BSW
LCOE PV power plant	~ 8 ct€ / kWh	End of 2016	ISE&Agora

Executive Summary
PV Market: Global

- Photovoltaics is a fast growing market: The Compound Annual Growth Rate (CAGR) of PV installations was 40% between 2010 to 2016.
- Concerning PV module production in 2016, China&Taiwan hold the lead with a share of 68%, followed by Rest of Asia-Pacific & Central Asia (ROAP/CA) with 14%. Europe contributed with a share of 4% (was 5% in 2015); USA/CAN contributed 6%.
- In 2016, Europe's contribution to the total cumulative PV installations amounted to 33% (compared to 40% in 2015). In contrast, installations in China accounted for 26% (compared to 21% in 2015).
- Si-wafer based PV technology accounted for about 94% of the total production in 2016. The share of multi-crystalline technology is now about 70% of total production.
- In 2016, the market share of all thin film technologies amounted to about 6% of the total annual production.

Executive Summary
PV Market: Focus Germany

- In 2016, Germany accounted for about 13% (41.3 GWp) of the cumulative PV capacity installed worldwide (320 GWp) with about 1.6 million PV systems installed in Germany. In 2016 the newly installed capacity in Germany was about 1.5 GWp; in 2015 it was 1.4 GWp.
- PV covered about 7% of Germany's electricity demand in 2016. Renewable sources delivered about 33% of the total net power consumption in 2016 in Germany.
- In 2016 about 20 Mio. t CO_2 emissions have been avoided due to 38.2 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 21.9% for multi-crystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 21.7% 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 12 years from around 16 g/Wp to less than 6 g/Wp due to increased efficiencies and thinner wafers.
- 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 42%. These inverters are mostly used in residential, small and medium commercial applications. The market share of central inverters, with applications mostly in large commercial and utility-scale systems, is about 54%. A small proportion of the market (about 1%) belongs to micro-inverters (used on the module level). It is estimated that 2 GWp of DC / DC converters, also called “power optimizers”, have been installed in 2016.
- 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

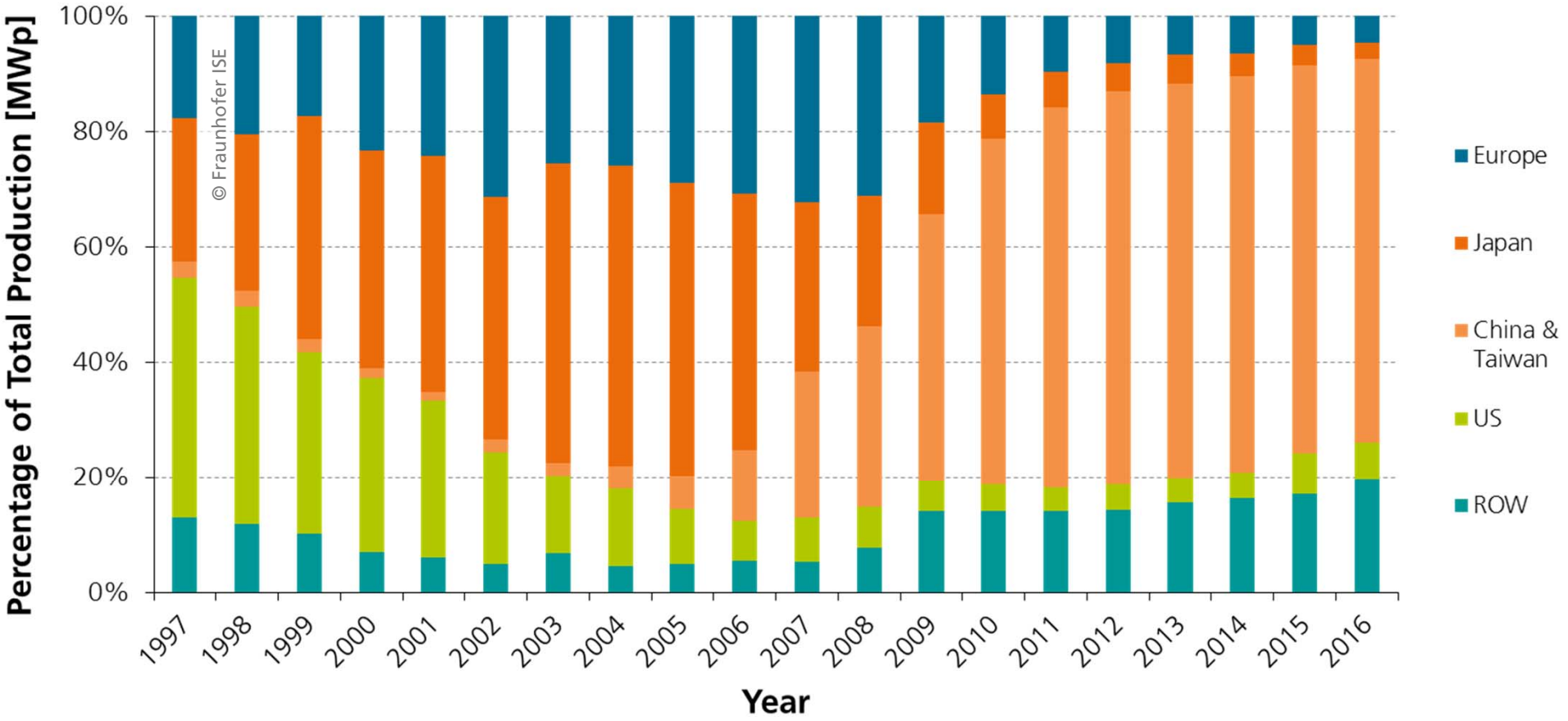
- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2016, such systems cost about 1,270 €/kWp. This is a net-price regression of about 90% over a period of 25 years and is equivalent to an annual compound average price reduction rate of 9% .
- The Experience Curve – also called Learning Curve - shows that in the last 36 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 1997-2016

Percentage of Total MWp Produced



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE AG 2017

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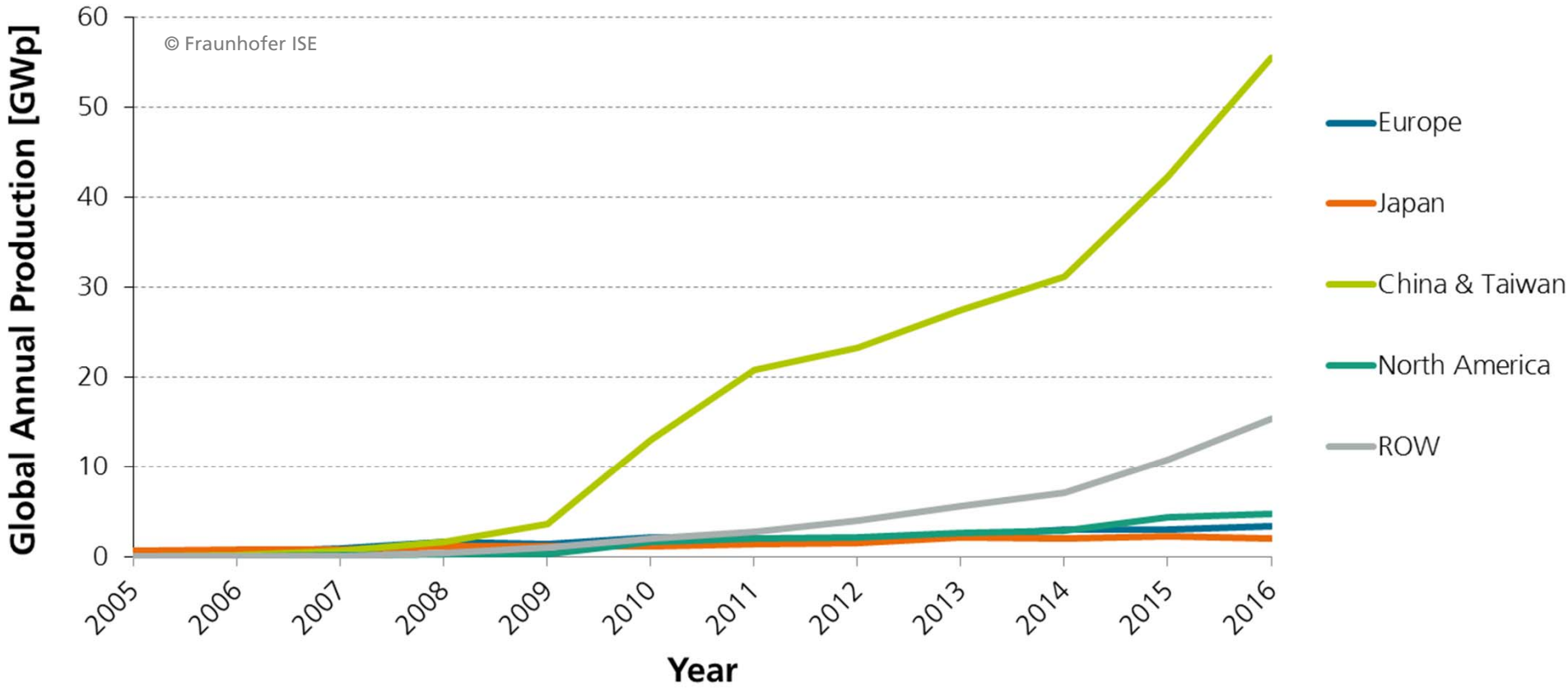
PV Industry Production by Region (2005-2016)

Global Annual Production



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE AG 2017

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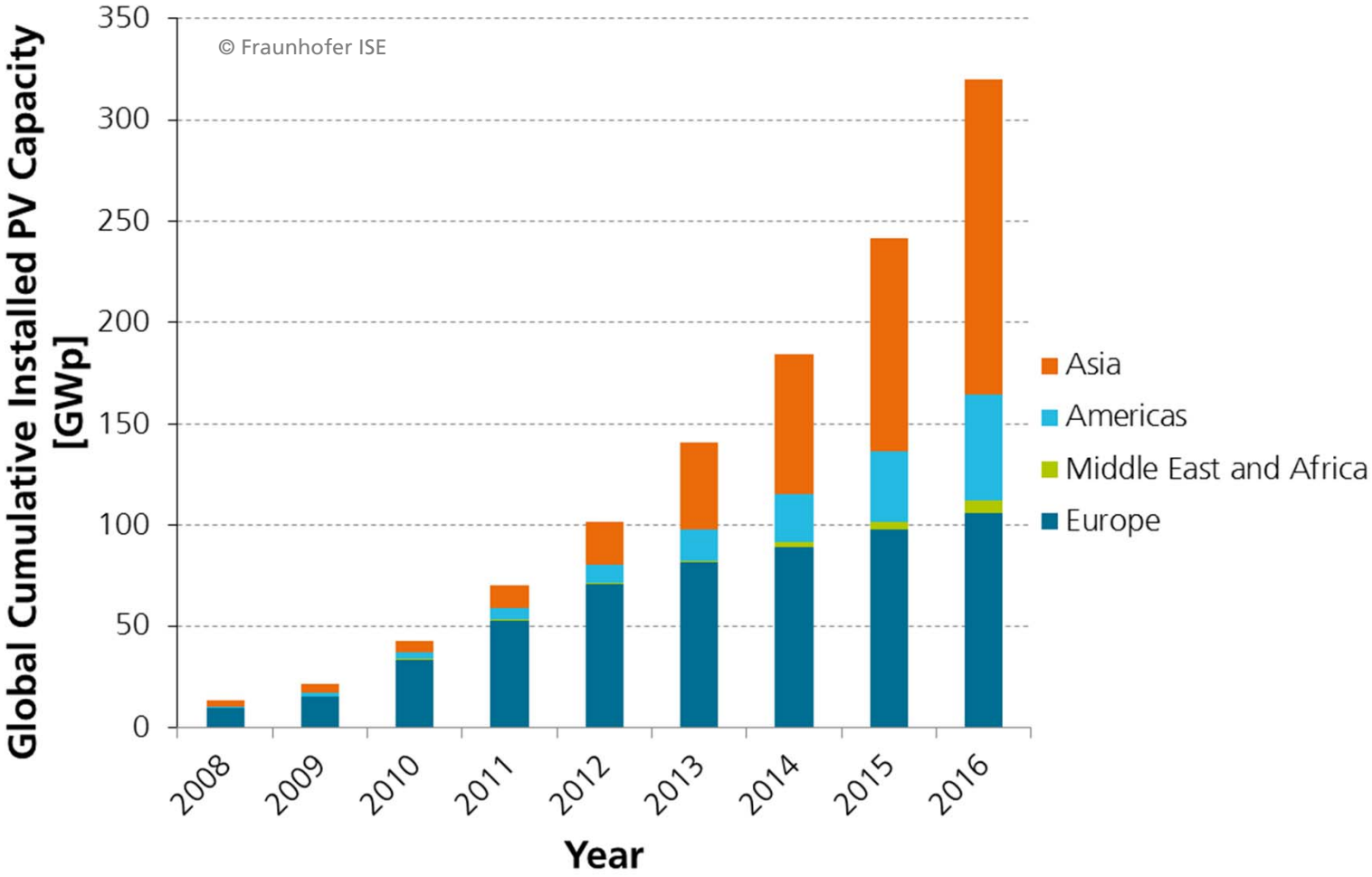
Global Cumulative PV Installation until 2016 (includes off-grid)



Data: IHS. Graph: PSE AG 2017

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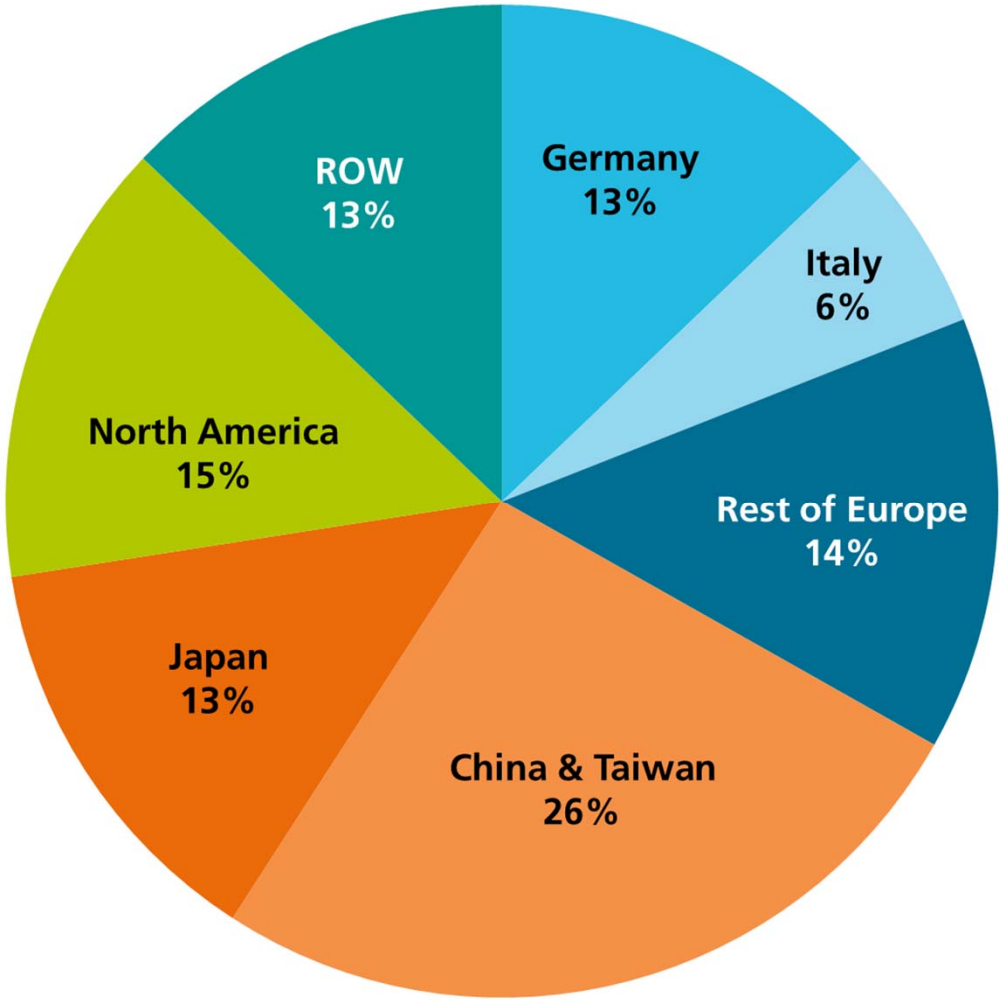
Global Cumulative PV Installation by Region
Status 2016



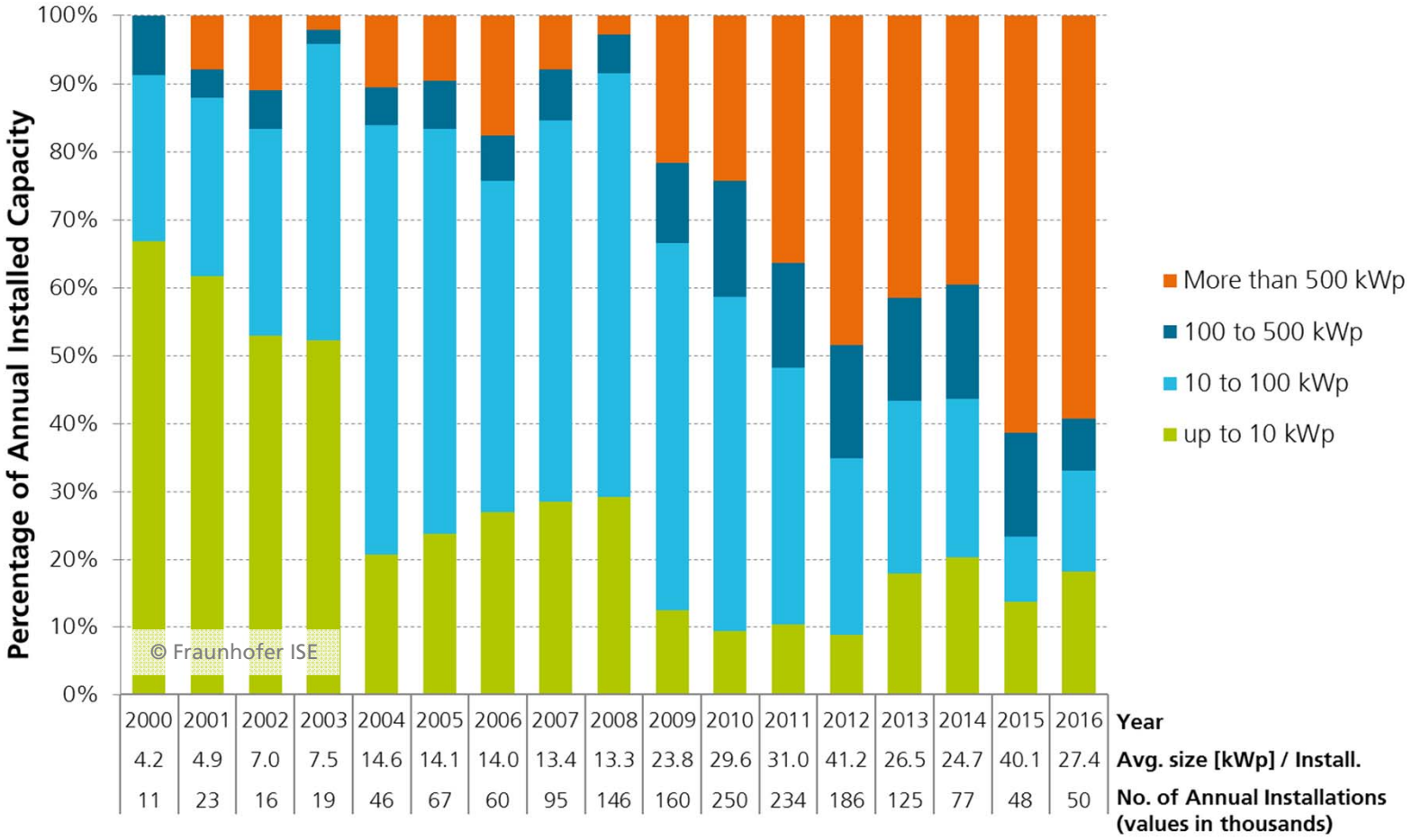
The total cumulative installations amounted to 320 GWp at the end 2016.

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

Data: IHS. Graph: PSE AG 2017

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
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
No. of Annual Installations (values in thousands)	11	23	16	19	46	67	60	95	146	160	250	234	186	125	77	48	50

Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur. Graph: PSE AG 2017

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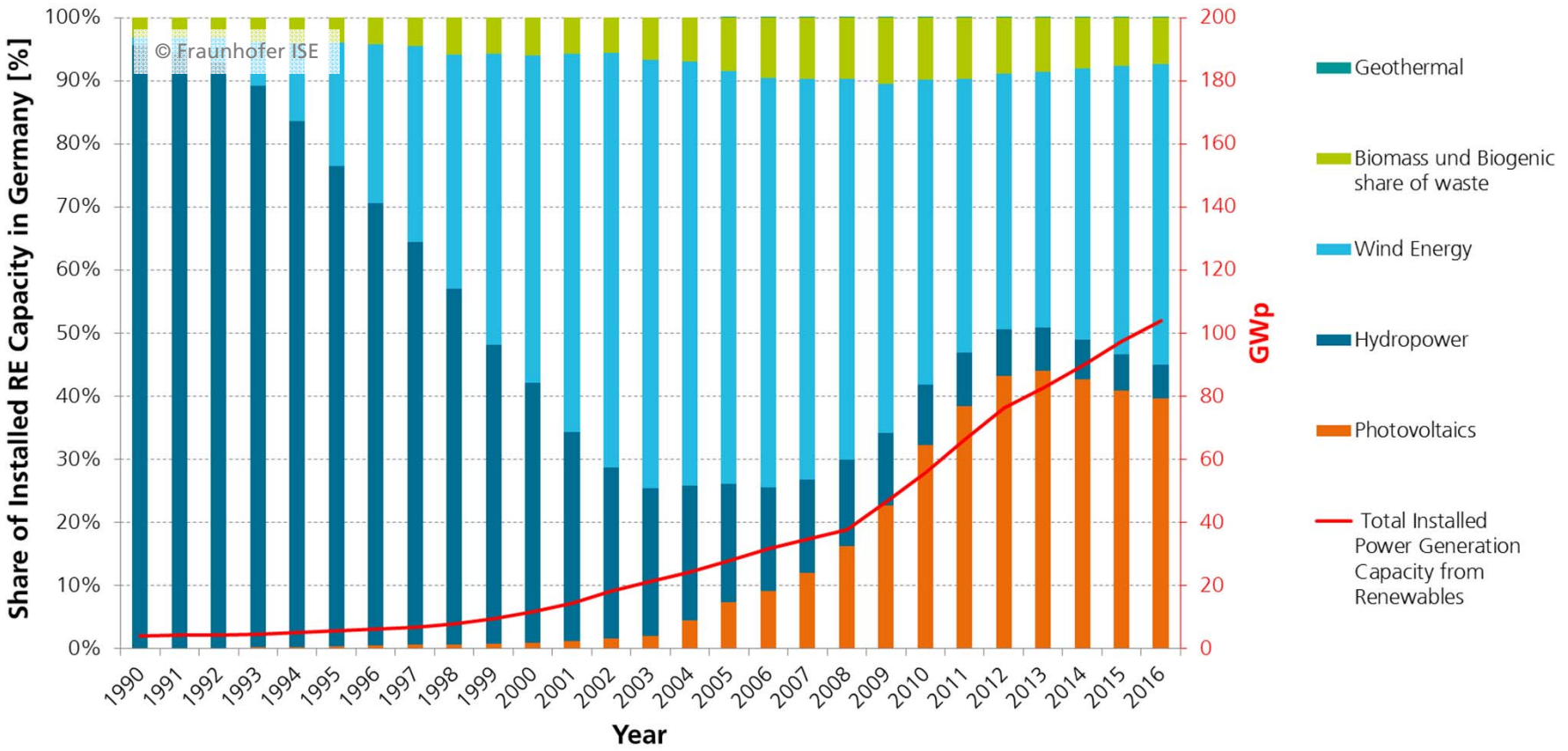
Electrical Capacity of Renewable Energy Sources
Germany



In 2016 about 32% 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. Graph: PSE AG 2017

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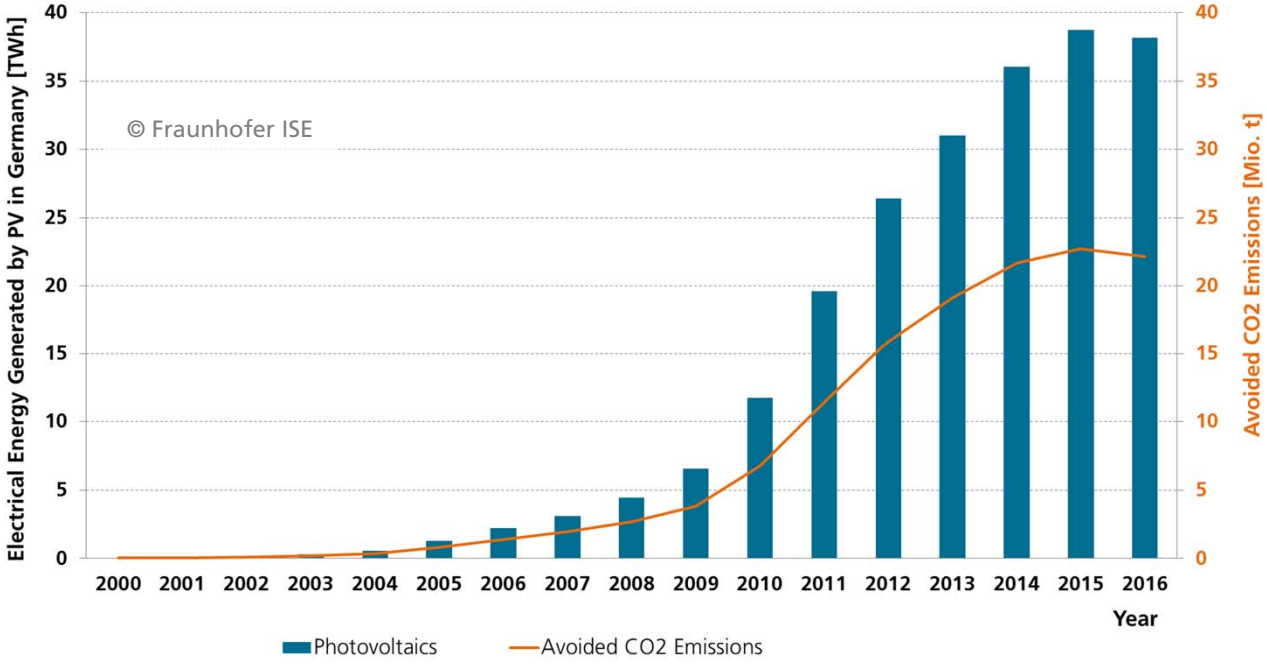
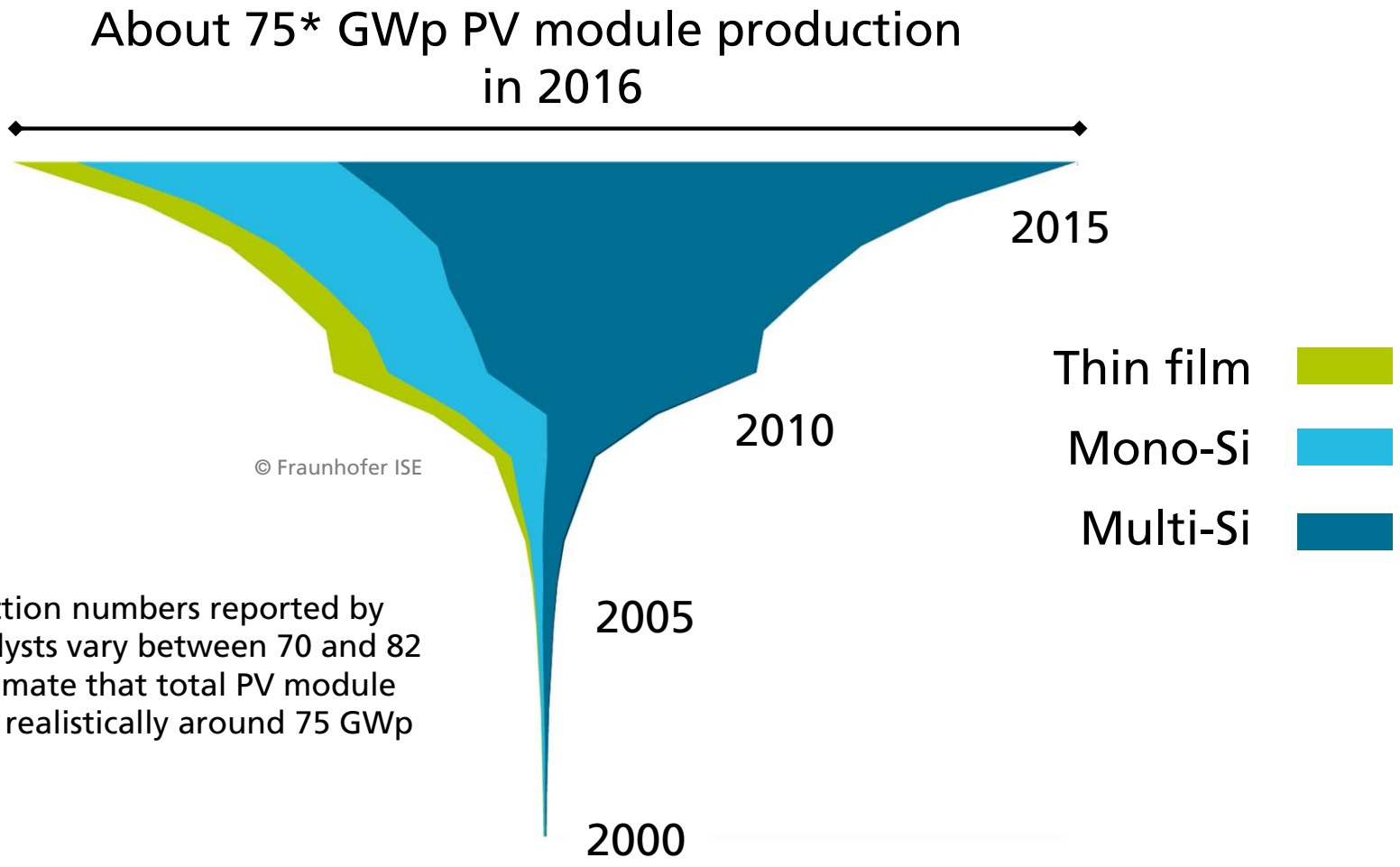
PV Energy Generated and Resulting CO_2 Avoided Emissions
Germany

- In 2016 ca. 22 Mio. t of CO_2 emissions were avoided due to 38.2 TWh PV electricity consumed in Germany.
- According to the Federal Environmental Ageny (UBA) the CO_2 avoidance factor of PV is 580 grams of $CO_{2\text{-eq}}$ /kWh_{el}.



Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2017. Graph: PSE AG 2017

Annual PV Production by Technology
Worldwide (in GWp)

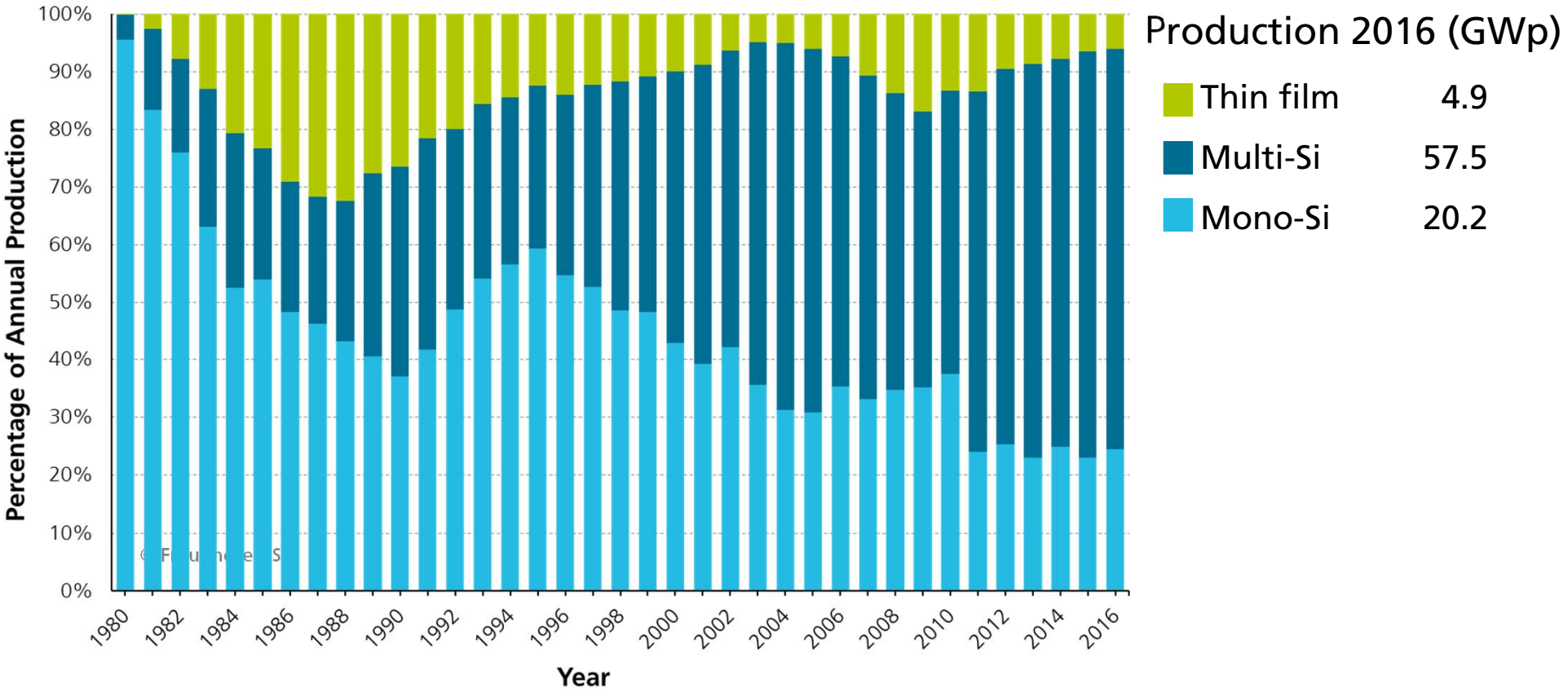


*2016 production numbers reported by different analysts vary between 70 and 82 GWp. We estimate that total PV module production is realistically around 75 GWp for 2016.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017

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 AG 2017

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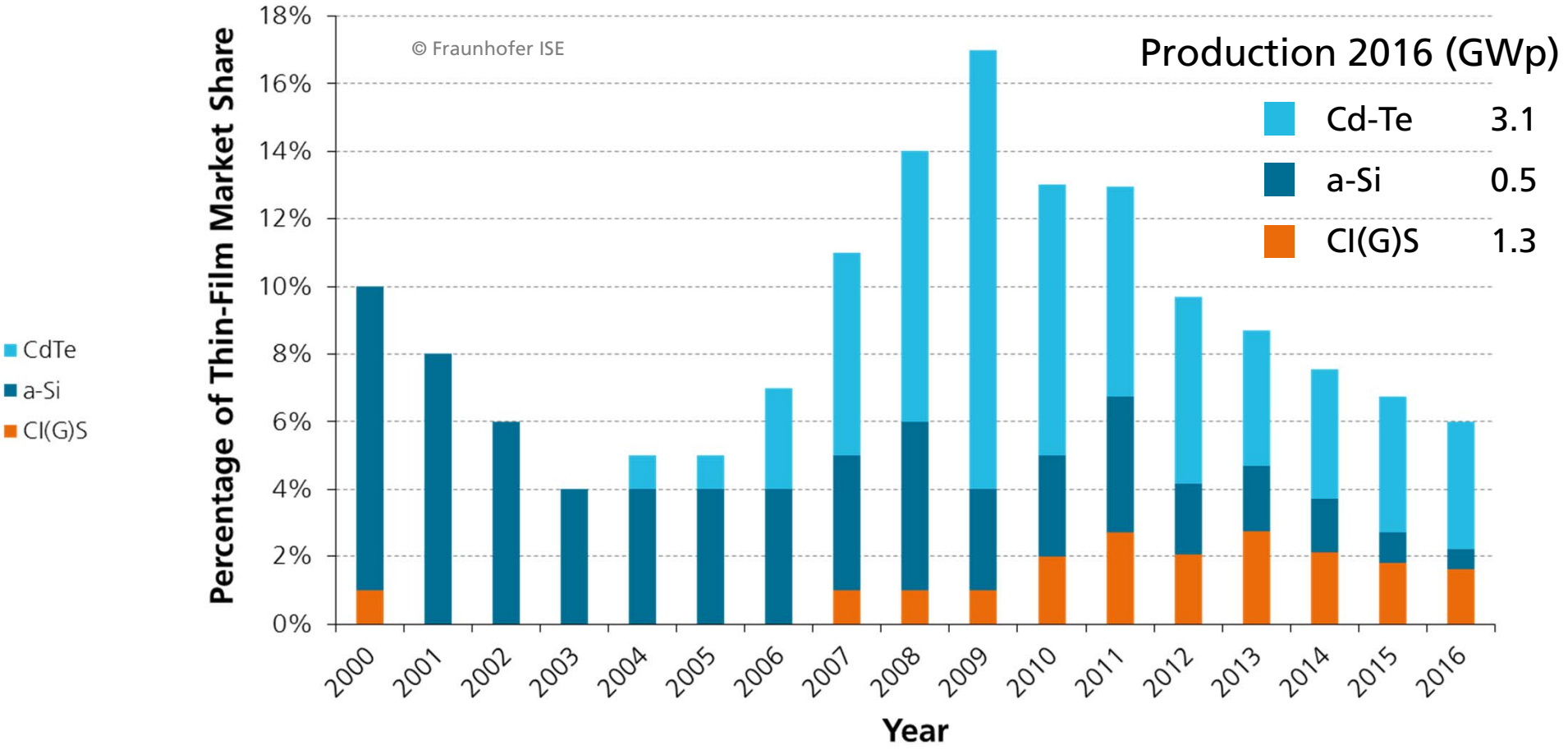
Market Share of Thin-Film Technologies

Percentage of Total Global PV Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017

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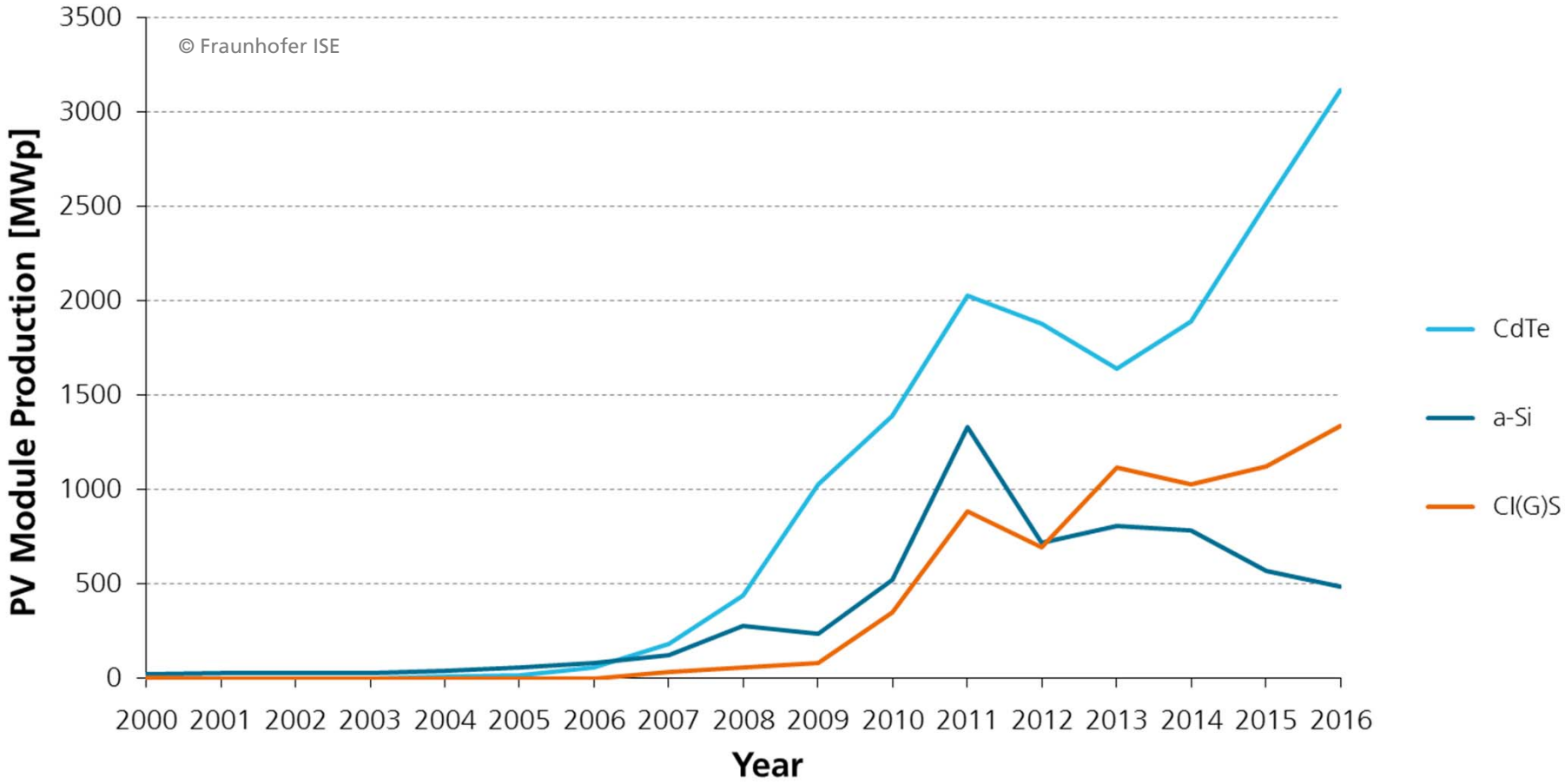
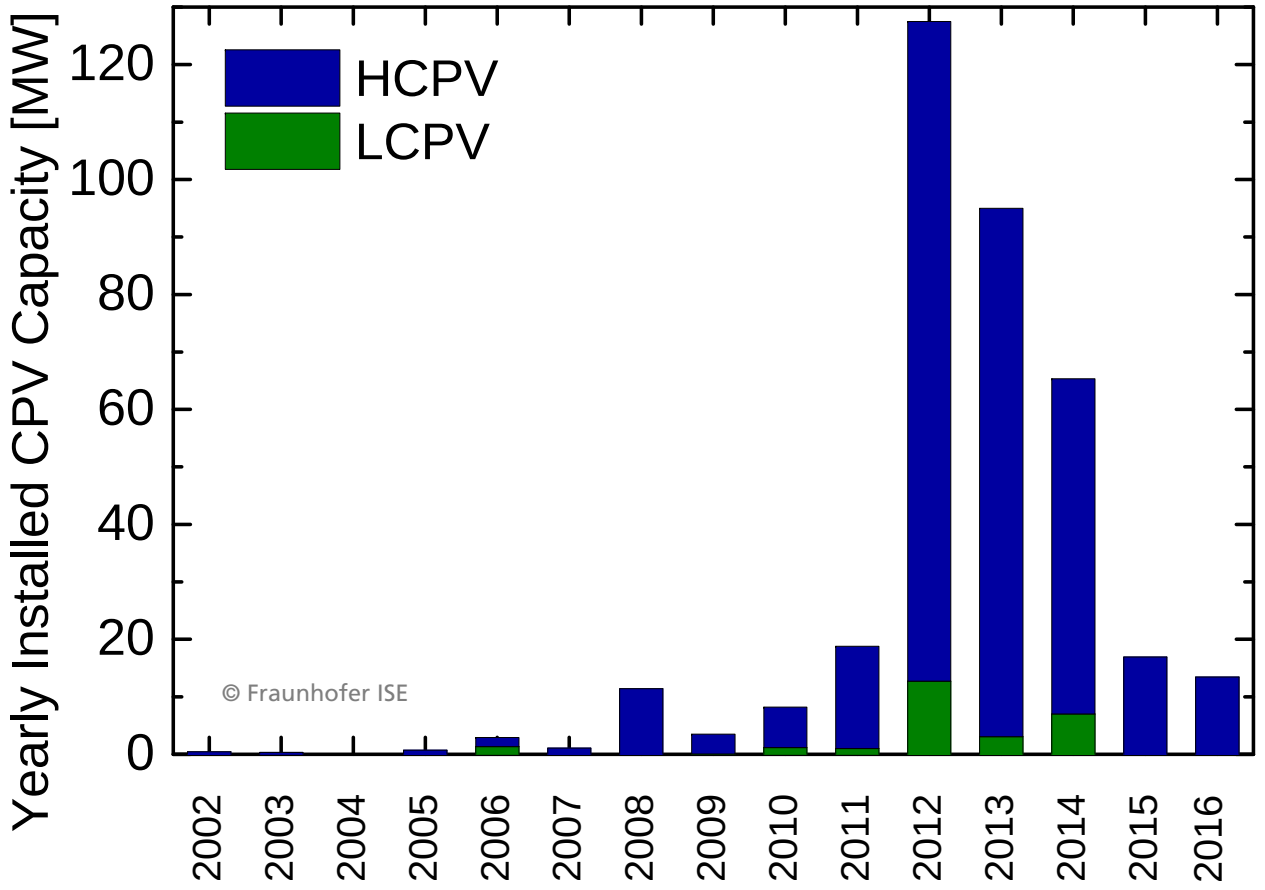
Thin-Film Technologies:
Annual Global PV Module Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017

Low and High Concentrator PV Systems (LCPV/HCPV)

Yearly Installed Capacity



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

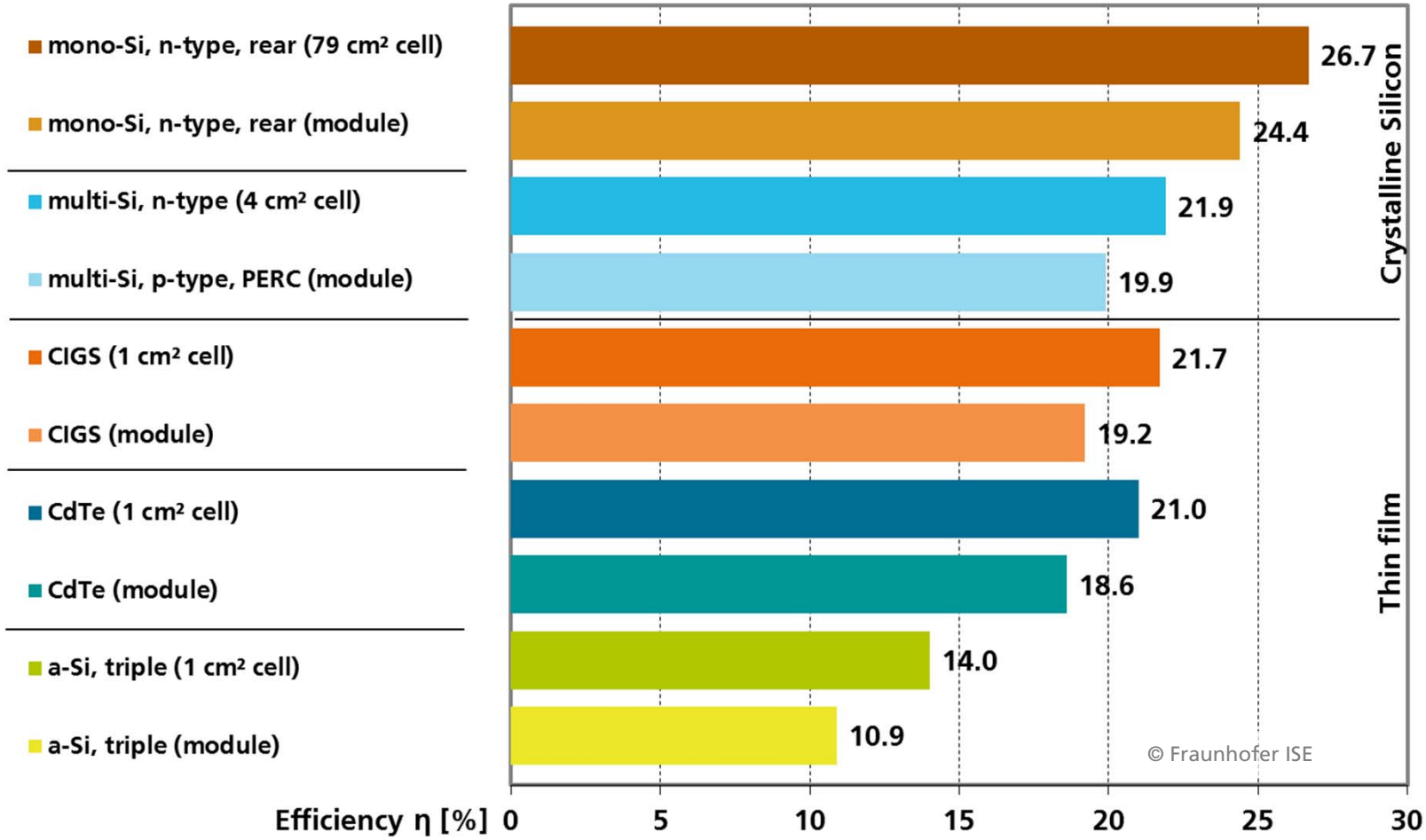
Data: ISE 2017

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

2. Solar Cells / Modules / System Efficiency

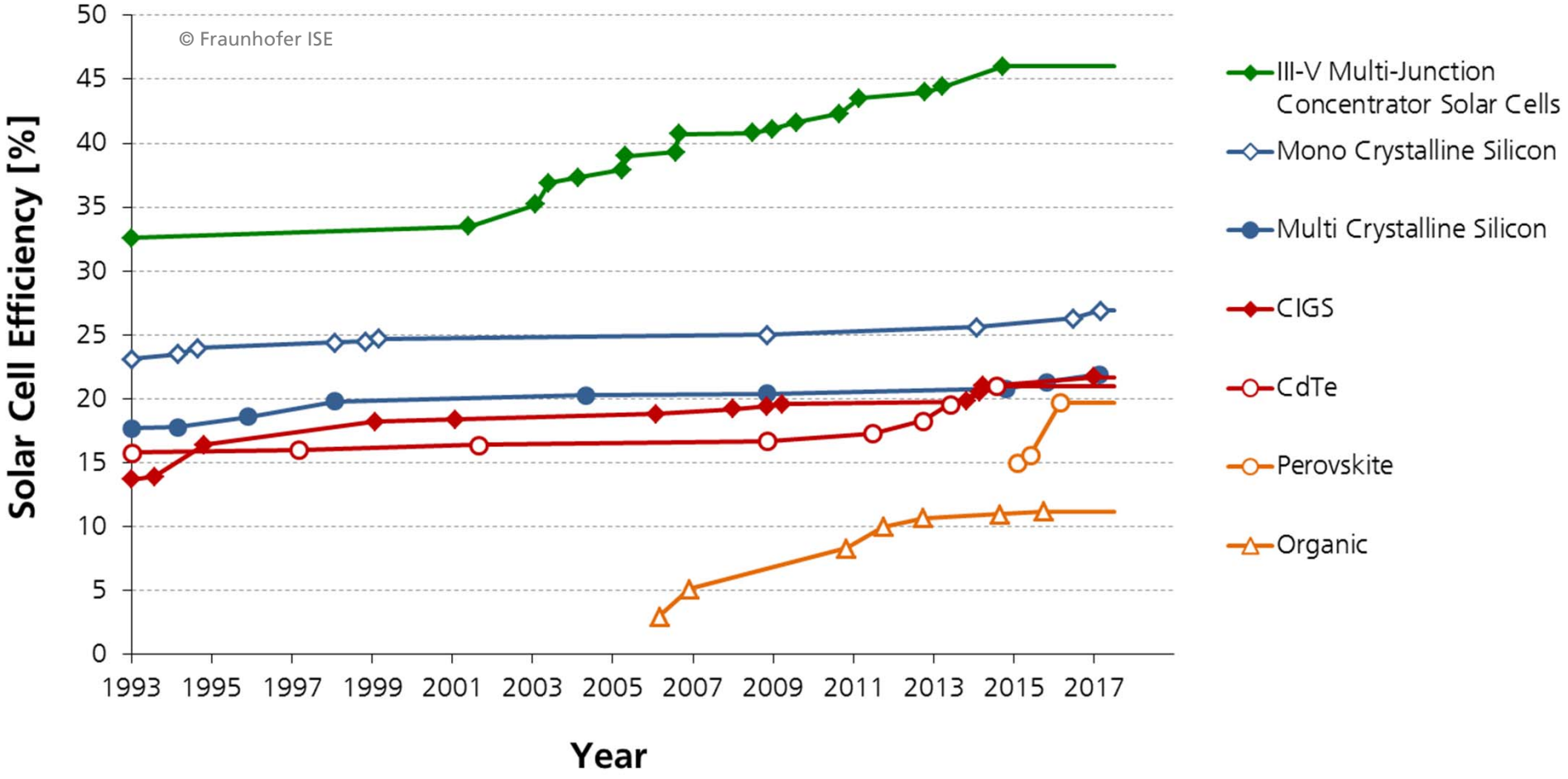
- Development in the PV Industry
- Development in the Laboratories
- High Concentration Photovoltaics (HCPV)
- Performance Ratio (PR)

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



Data: Green et al.: Solar Cell Efficiency Tables (Version 50), Progress in PV: Research and Applications 2017. Graph: PSE AG 2017

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1-50), Progress in Photovoltaics: Research and Applications, 1993-2017. Graph: Fraunhofer ISE 2017

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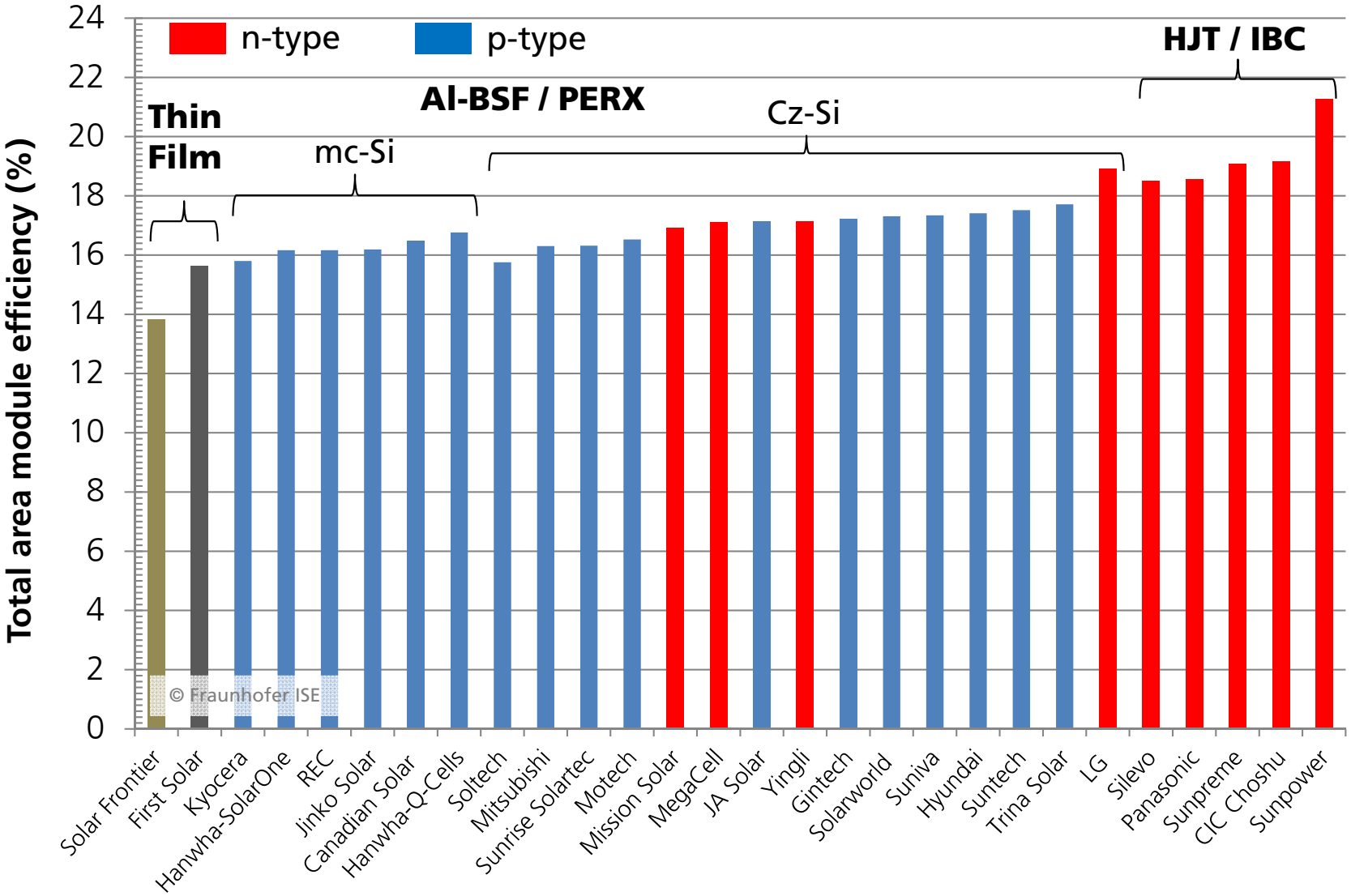
Current Efficiencies of Selected Commercial PV Modules

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. 2015.

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High Concentration Photovoltaics (HCPV)
Specific Aspects and Efficiencies

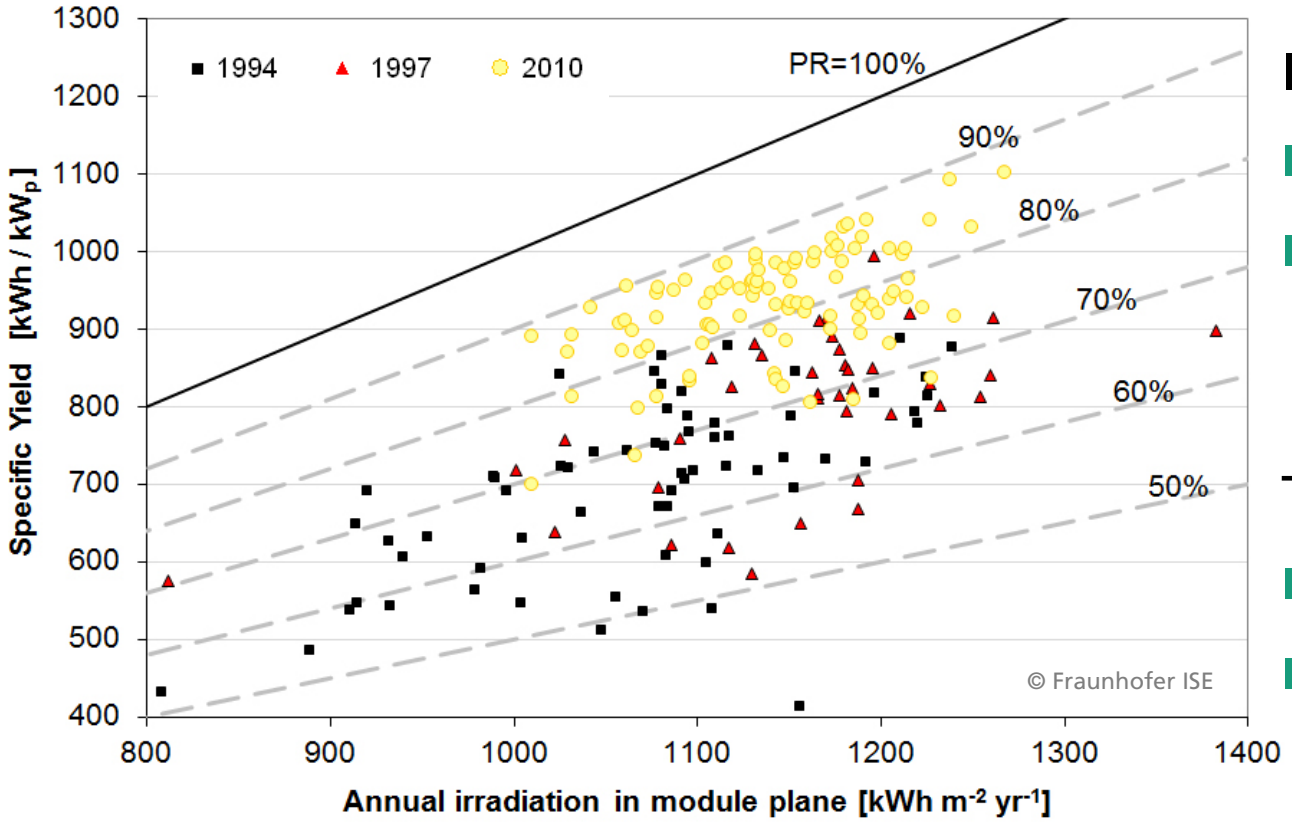
- HCPV is suitable for areas with high direct normal irradiance
- Concentrating optics are used to focus the light on small solar cells
- Concentration levels above 400 suns have become standard
- Various designs of HCPV systems are commercially available
- High efficiencies are achieved (see table)

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

Efficiencies	Lab Record	Commercial
Solar Cell	46.0 % (ISE, Soitec, CEA)	38-43%
Minimodule	43.4% (ISE)	N.A.
Module	38.9% (Soitec)	27-33%
System (AC)	N.A.	25-29%

Source: Fraunhofer ISE, Progress in Photovoltaics

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

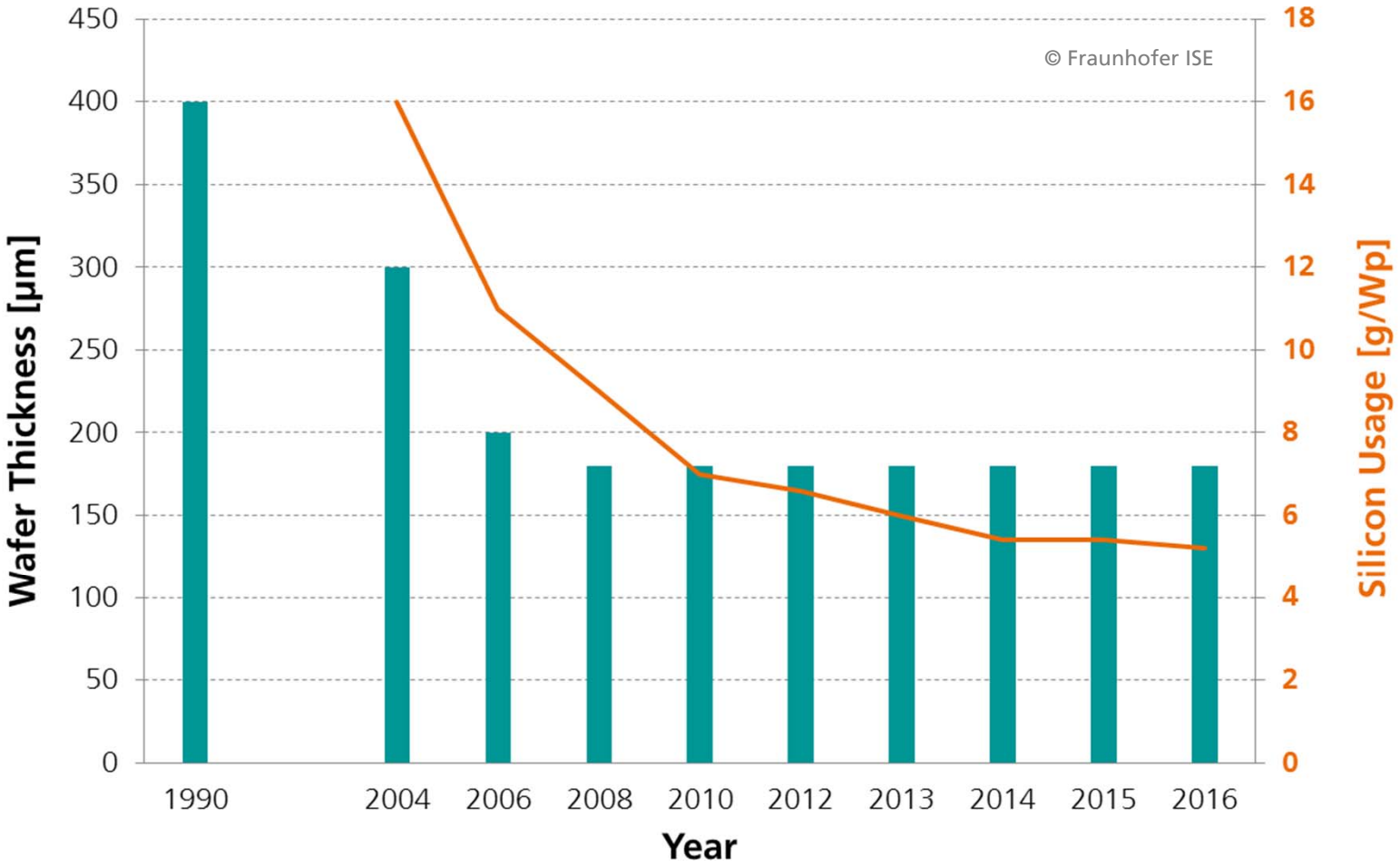
Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation

3. Energy 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 recycling of Si. Graph: PSE AG 2017

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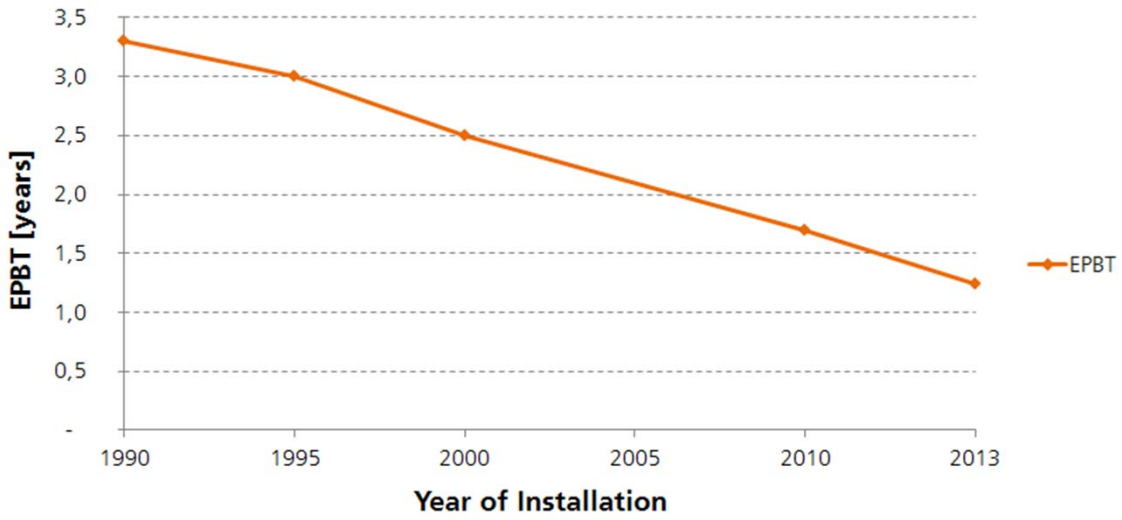
Historic Trend in Energy Payback Time of Crystalline Silicon PV Modules

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*

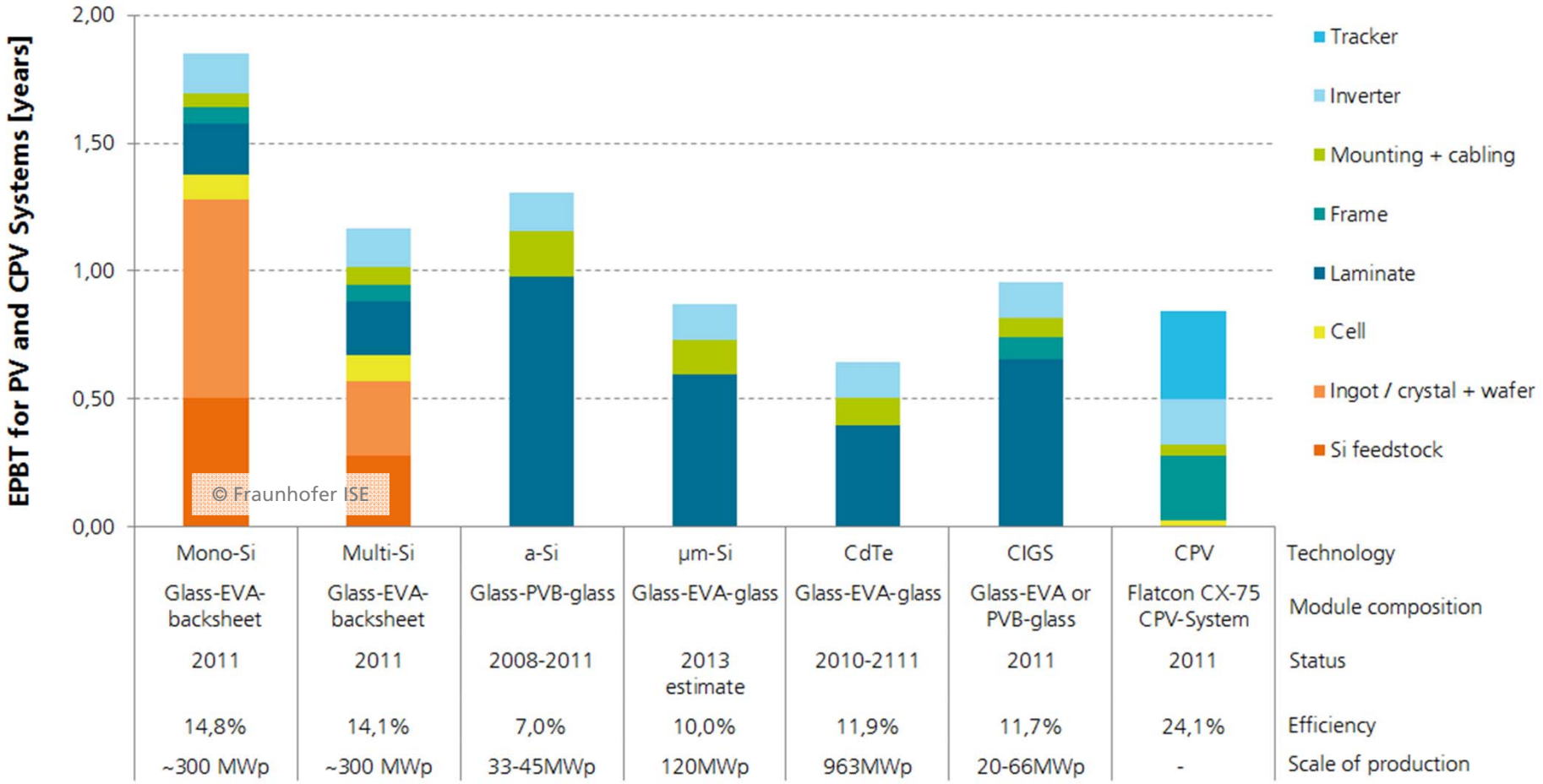


*Irradiation: 1700 kWh/m²/a at an optimized tilt angle

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

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

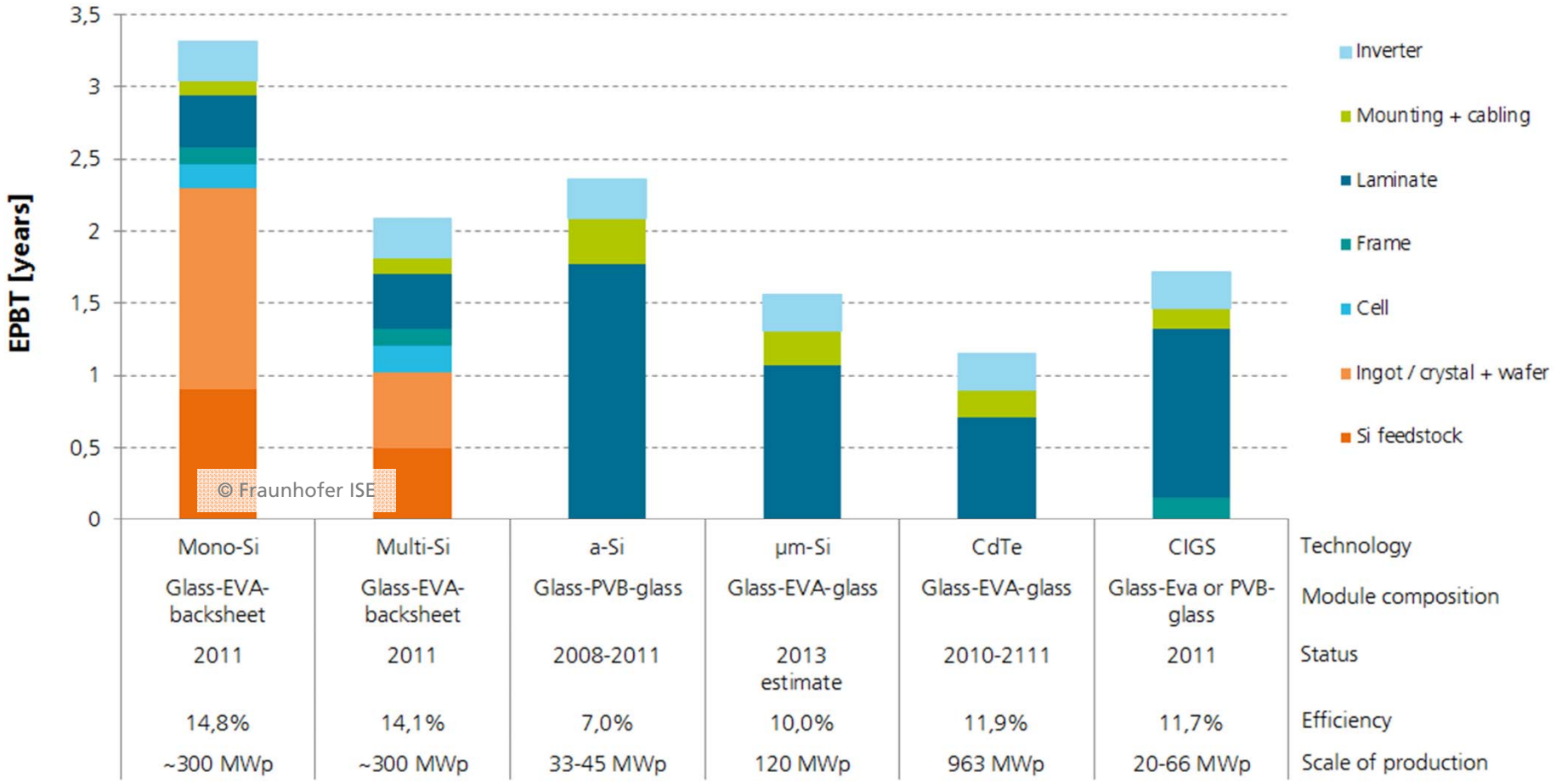
Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr



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 AG 2014

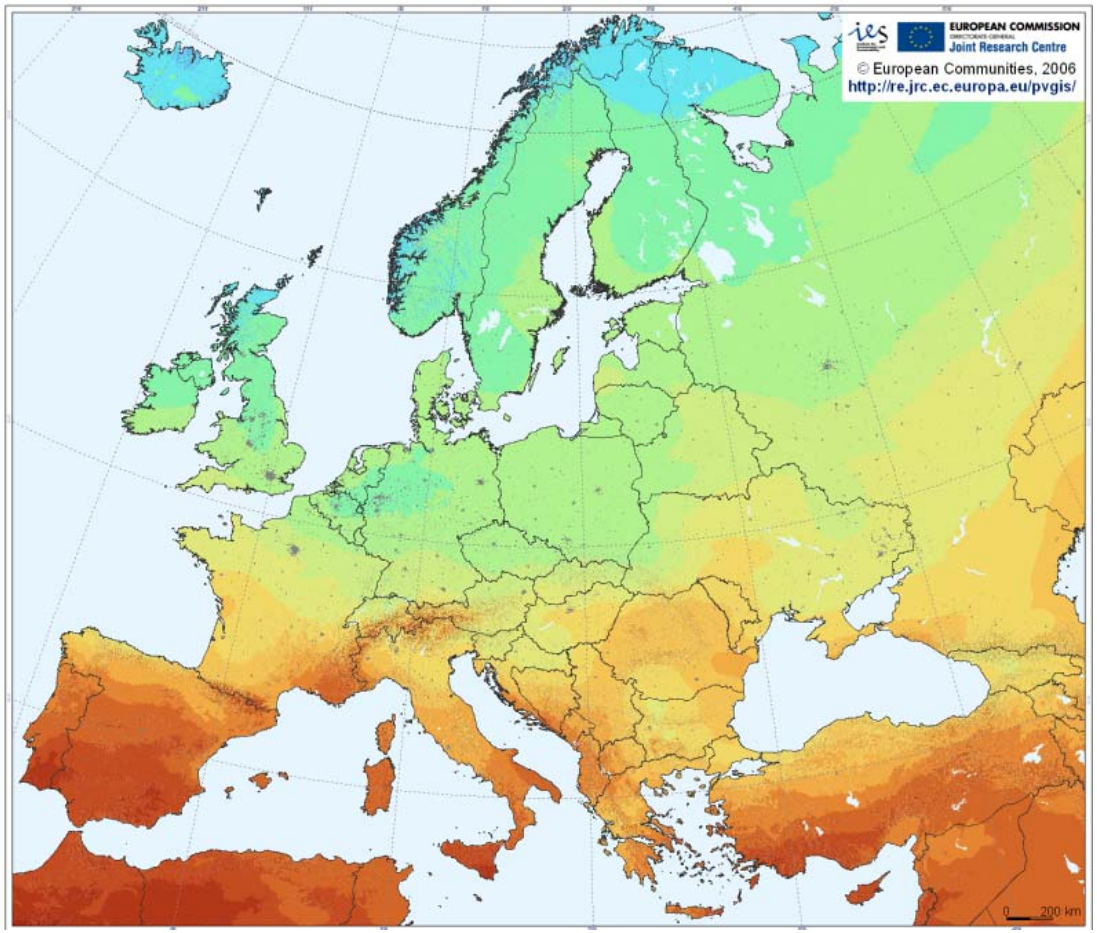
Energy Pay-Back Time of Rooftop PV Systems
Different Technologies located in Germany

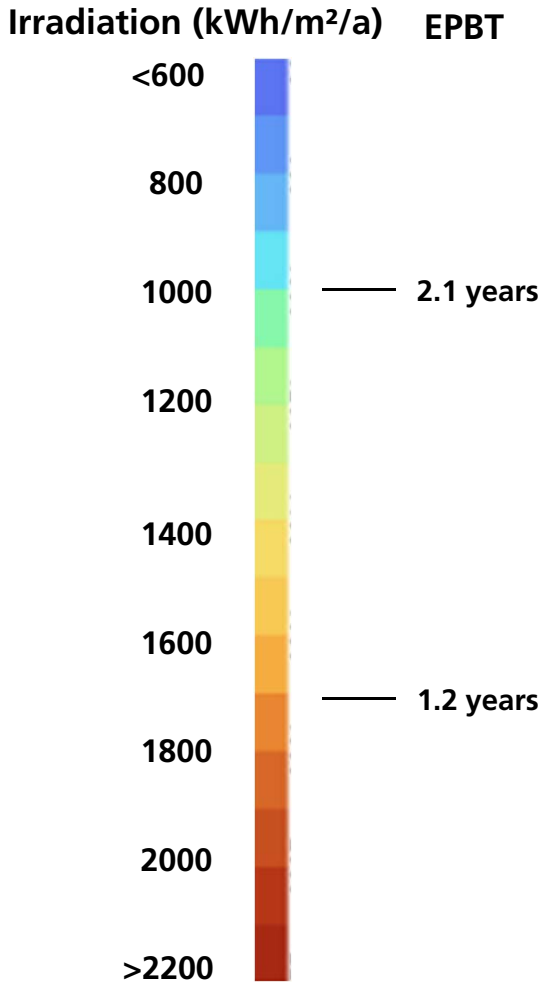
Global Irrad.: 1000 kWh/m²/yr



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

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 AG 2014 (Modified scale with updated data from PSE AG and FraunhoferISE)

4. Inverters

- Inverter/Converter Price
- Inverter Concept Comparison

Inverter/Converter Market 2016

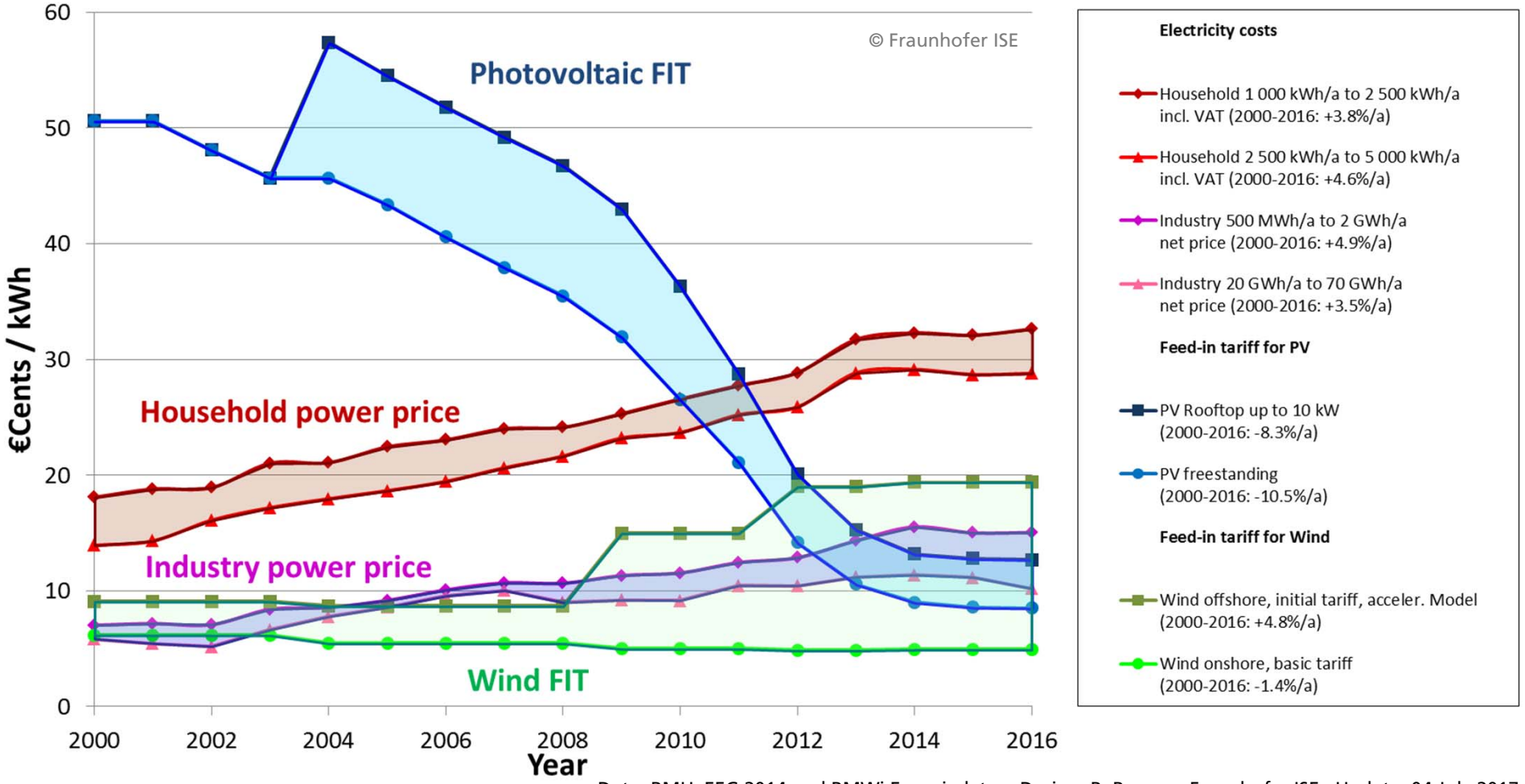
Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 100 kWp	up to 98%	~ 42%	• 7 - 20 €-cents /Wp • Easy to replace
Central Inverters	More than 100 kWp	up to 98.5%	~ 54%	• ~ 6 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 33 €-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 • ~ 2 GWp installed in 2016

Data: IHS 2016. Remarks: Fraunhofer ISE 2017. Graph: PSE AG 2017

5. Price Development

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

Electricity Costs and Feed-In Tariffs (FIT) in Germany



Data: BMU, EEG 2014 and BMWi Energiedaten. Design: B. Burger - Fraunhofer ISE , Update: 04 July 2017

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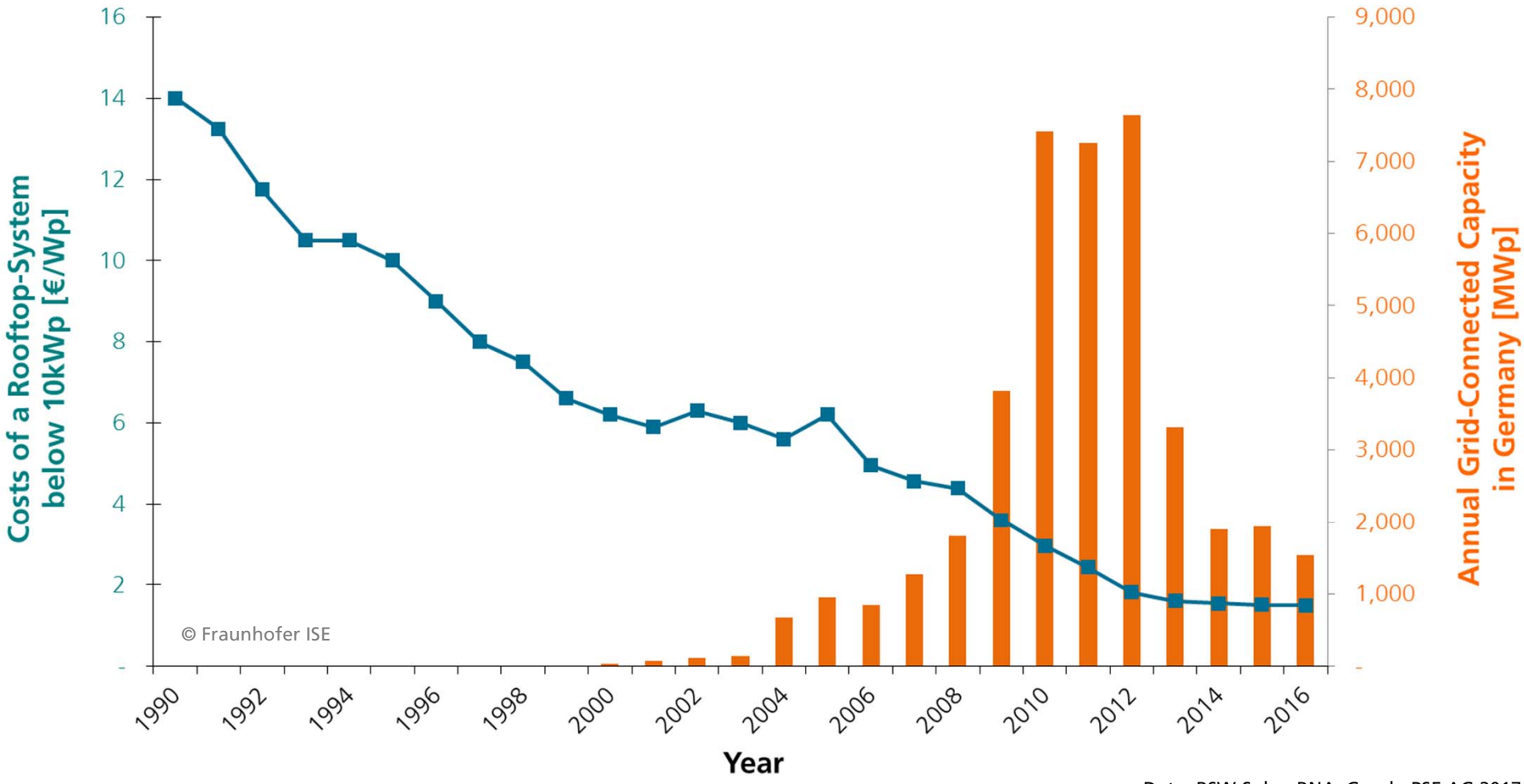
Investment for Small Rooftop PV Systems in Relation to Market Development and Subsidy Schemes in Germany



Data: BSW-Solar, BNA. Graph: PSE AG 2017

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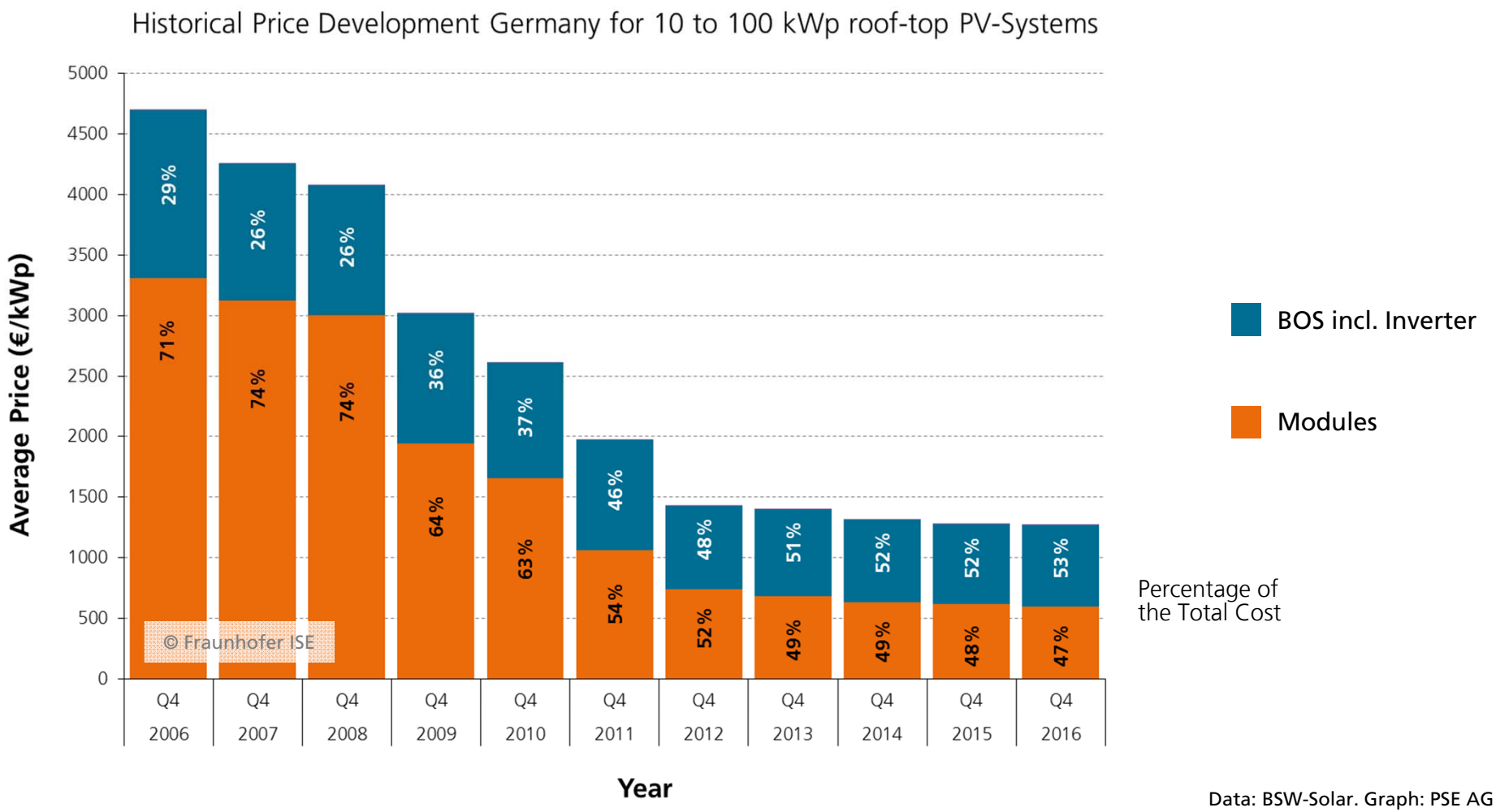
Average Price for PV Rooftop Systems in Germany (10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE AG 2017

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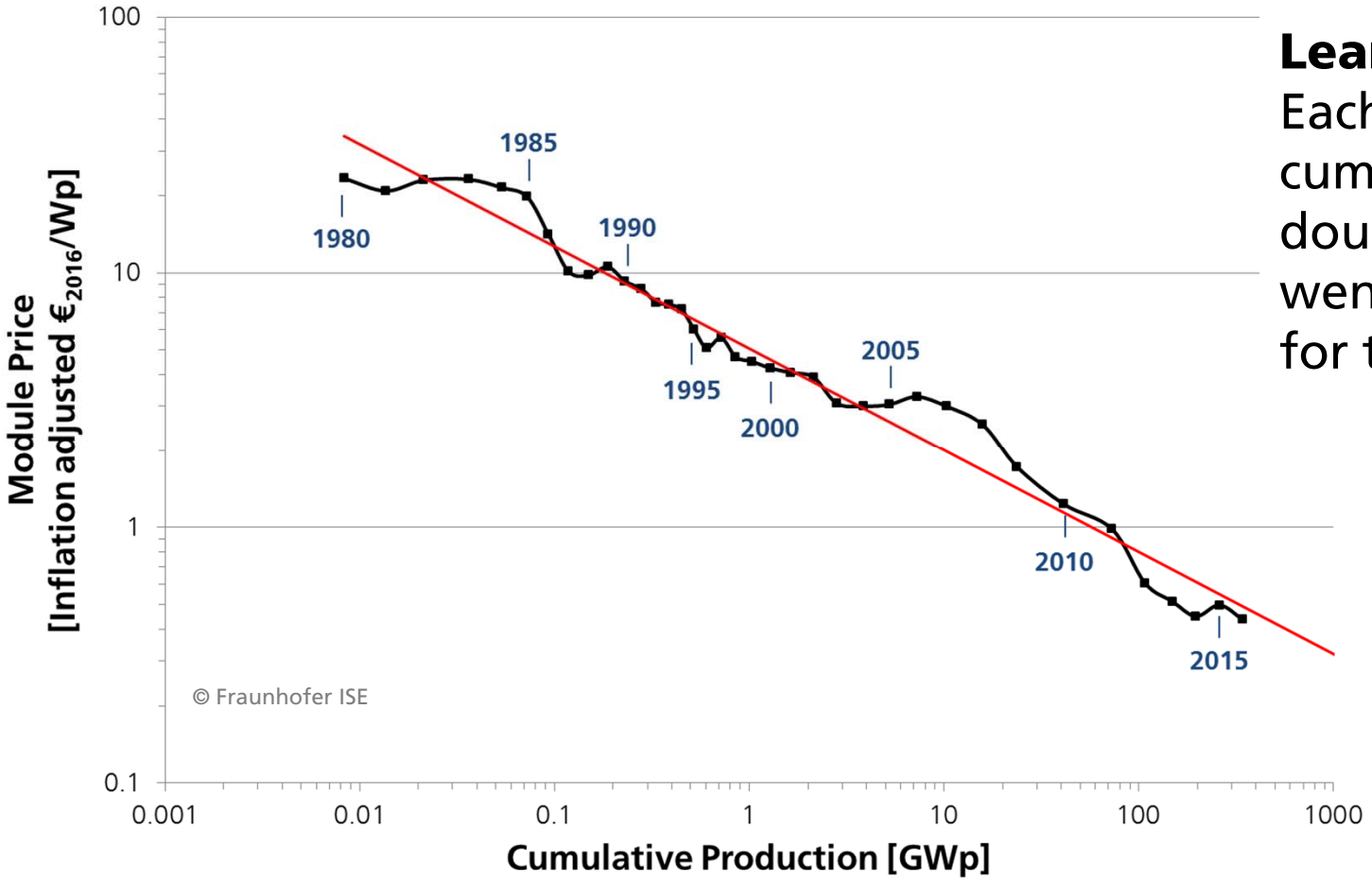
Price Learning Curve

Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative production doubled, the price went down by 24 % for the last 36 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2016: IHS. Graph: PSE AG 2017

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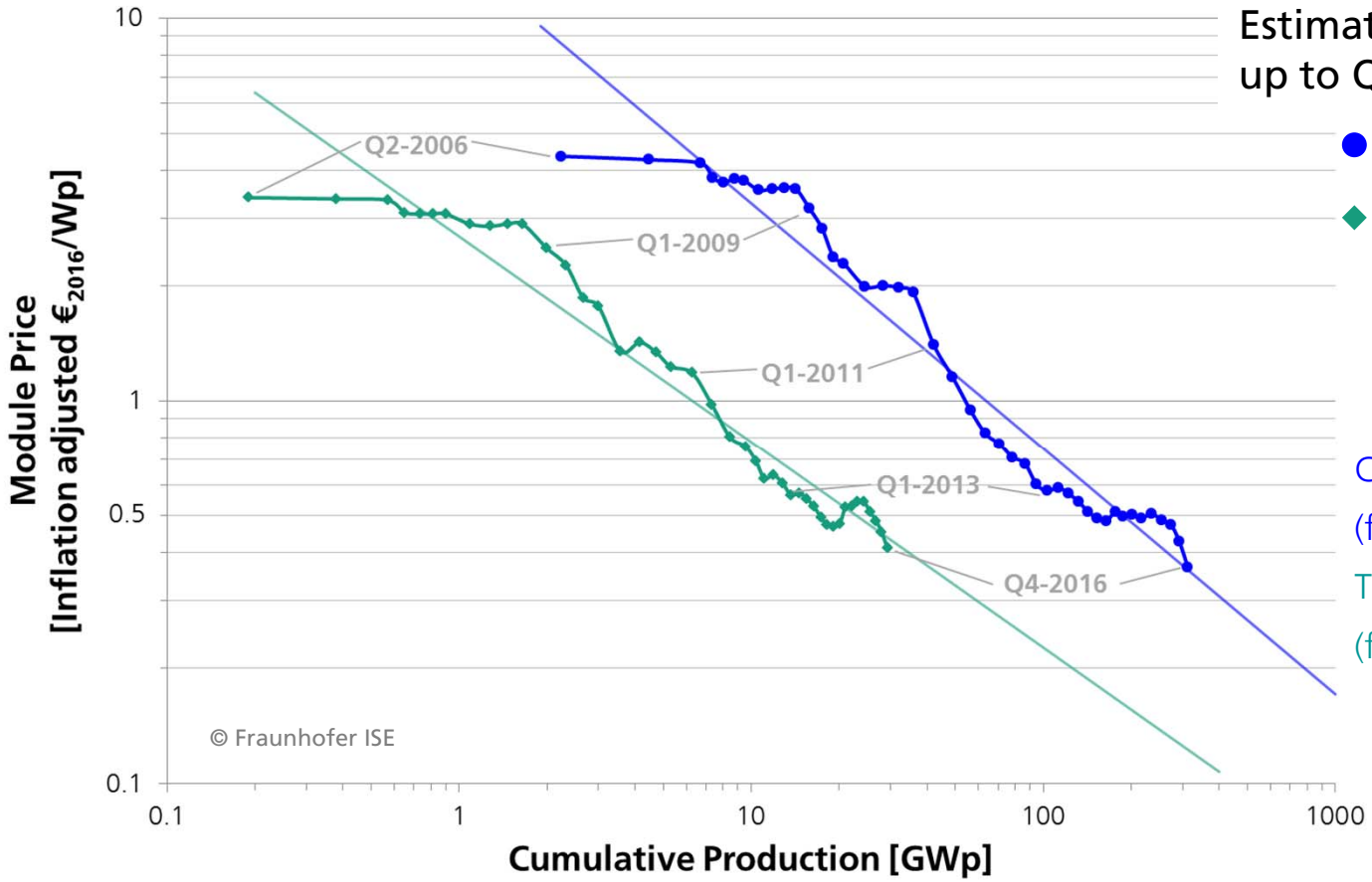
Price Learning Curve by Technology
Cumulative Production up to Q4. 2016



Estimated cumulative production up to Q4, 2016 :

- c-Si 312 GWp
- Thin Film 29 GWp

Crystalline Technology
(from Q2-2006 to Q4-2016) **LR 29**

Thin Film Technology
(from Q2-2006 to Q4-2016) **LR 25**

Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011 to 2016: IHS. Graph: PSE AG 2017

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Ralf Preu	ISE
Jochen Rentsch	ISE
Thomas Schlegl	ISE
Gerhard Stryi-Hipp	ISE
Gerhard Willeke	ISE
Harry Wirth	ISE
Ingo Brucker	PSE
Andreas Häberle	PSE
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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.

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

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