

---

# PHOTOVOLTAICS REPORT

---



Prepared by

Fraunhofer Institute for Solar Energy  
Systems, ISE

with support of

PSE AG

Freiburg, 17 November 2016

[www.ise.fraunhofer.de](http://www.ise.fraunhofer.de)

---

# CONTENT

---

- Introduction
- Executive Summary
- Topics:
  - PV Market
  - Solar Cells / Modules / System Efficiency
  - Energy Payback Time (EPBT)
  - Inverters
  - Price Development
- Acknowledgements

# 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 However, facts and figures change rapidly and the given information may soon be outdated again.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](mailto:simon.philipps@ise.fraunhofer.de) and also to [werner.warmuth@pse.de](mailto:werner.warmuth@pse.de)
- Please quote the information presented in these slides as follows:  
©Fraunhofer ISE: Photovoltaics Report, updated: 17 November 2016

# Executive Summary

## PV Market: Global

- Photovoltaics is a fast growing market: The Compound Annual Growth Rate (CAGR) of PV installations was 42 % between 2000 to 2015.
- Concerning PV module production in 2015, China&Taiwan hold the lead with a share of 67 %, followed by Rest of Asia-Pacific & Central Asia (ROAP/CA) with 14%. Europe contributed with a share of 5 % (was 6% in 2014); USA/CAN contributed 3 %.
- In 2015, Europe's contribution to the total cumulative PV installations amounted to 40 % (compared to 48 % in 2014). In contrast, installations in China accounted for 21 % (compared to 17 % in 2014).
- Si-wafer based PV technology accounted for about 93 % of the total production in 2015. The share of multi-crystalline technology is now about 68 % of total production.
- In 2015, the market share of all thin film technologies amounted to about 8 % of the total annual production.

# Executive Summary

## PV Market: Focus Germany

- In 2015, Germany accounted for about 16 % (39.6 GWp) of the cumulative PV capacity installed worldwide (242 GWp) with about 1.5 million PV systems installed in Germany. In 2015 the newly installed capacity in Germany was about 1.4 GWp; in 2014 it was 1.9 GWp.
- PV covered about 7 % of Germany's electricity demand in 2015. Renewable sources delivered about 33% of the total net power consumption in 2015 in Germany.
- In 2015 about 24 Mio. t CO<sub>2</sub> 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 25.6 % for mono-crystalline and 20.8 % for multi-crystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 21.0 % for CdTe and 20.5 % for CIGS 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 about 23 % 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 10 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 37 %. 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 61 %. A small proportion of the market (about 2 %) belongs to micro-inverters (used on the module level). It is estimated that 1.5 GWp of DC / DC converters, also called “power optimizers”, have been installed in 2015.
- The specific net retail price of all inverters in Germany is about 10 €-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

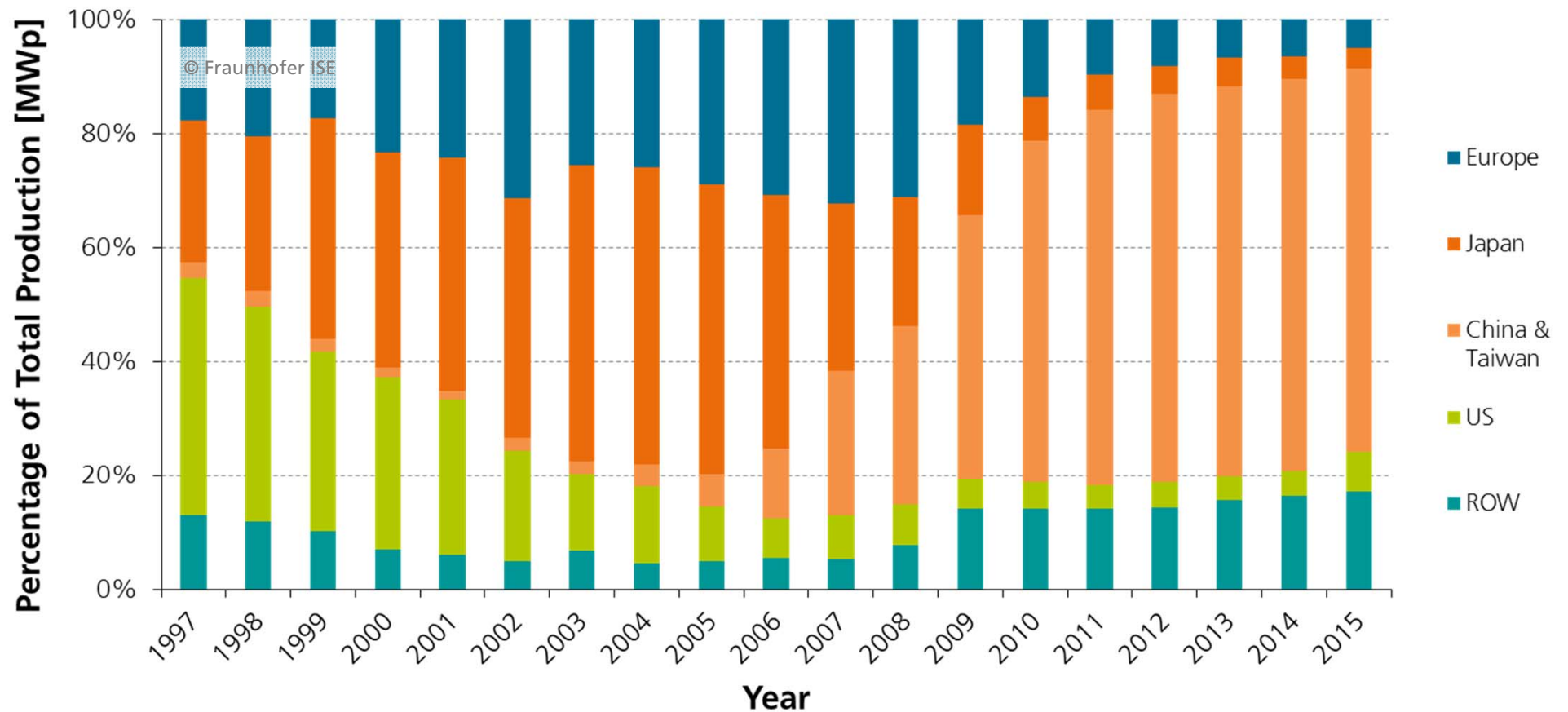
- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2015, such systems cost about 1,270 €/kWp. This is a net-price regression of about 90 % over a period of 25 years and is equivalent to an annual compound average price reduction rate of 9 % .
- The Experience Curve – also called Learning Curve - shows that in the last 35 years the module price decreased by 23 % 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 1997-2015

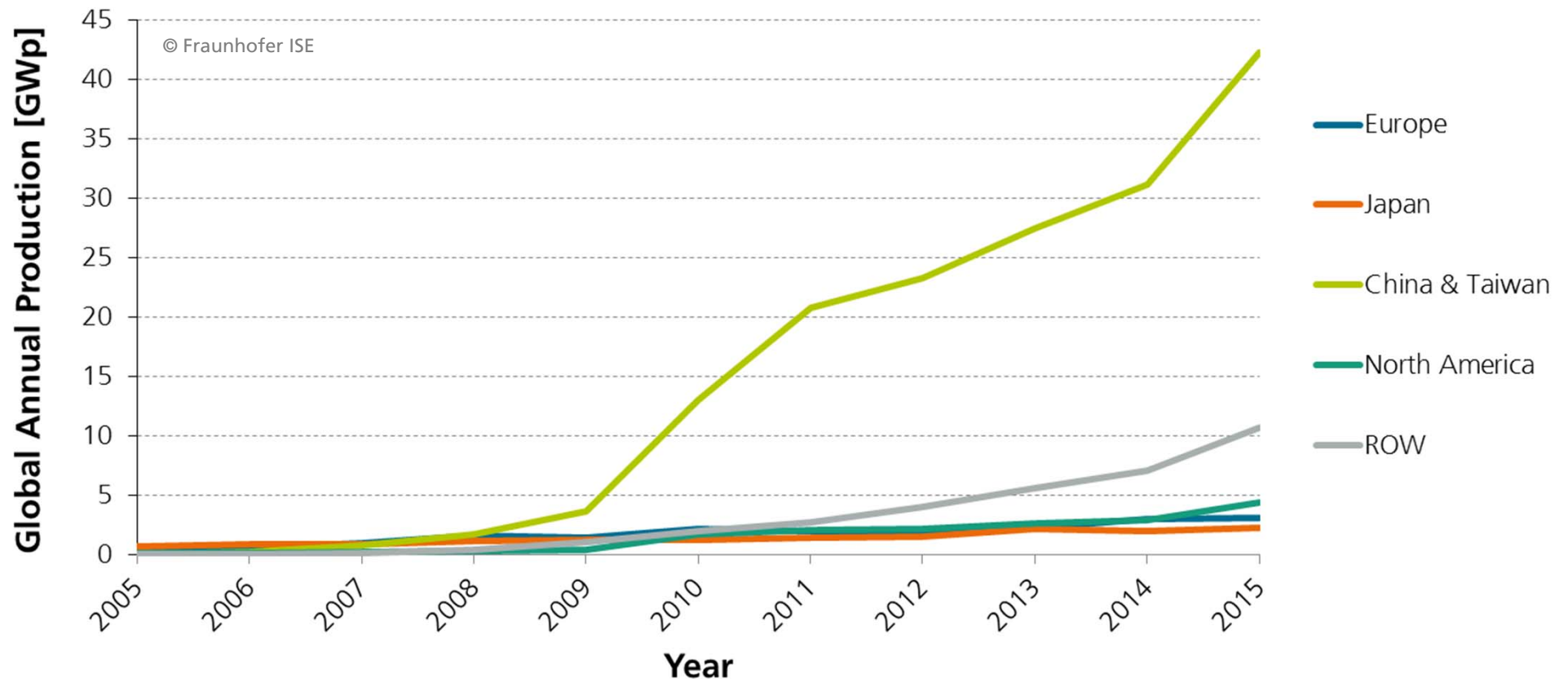
## Percentage of Total MWp Produced



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE AG 2016

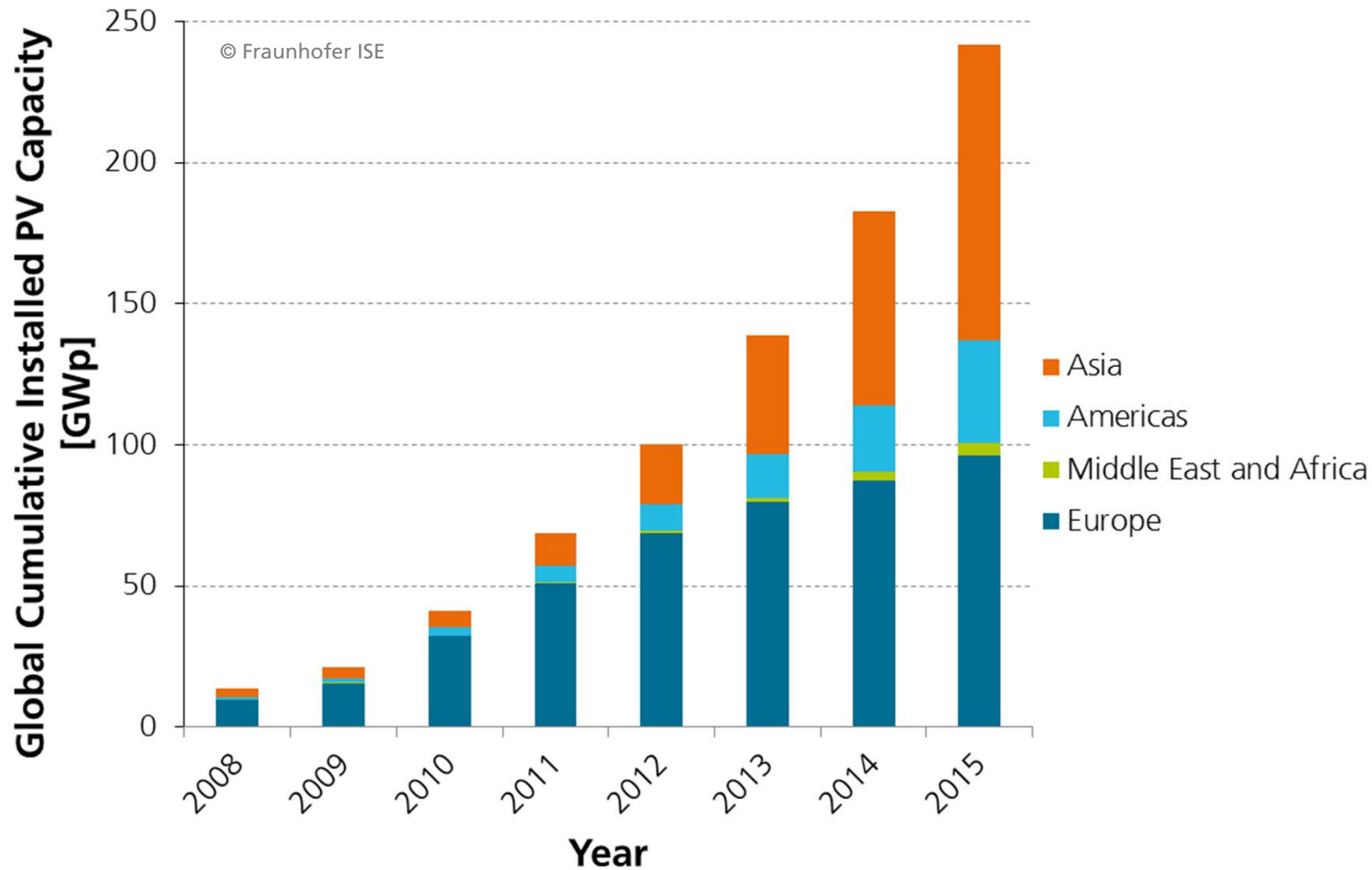
# PV Industry Production by Region (2005-2015)

## Global Annual Production



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE AG 2016

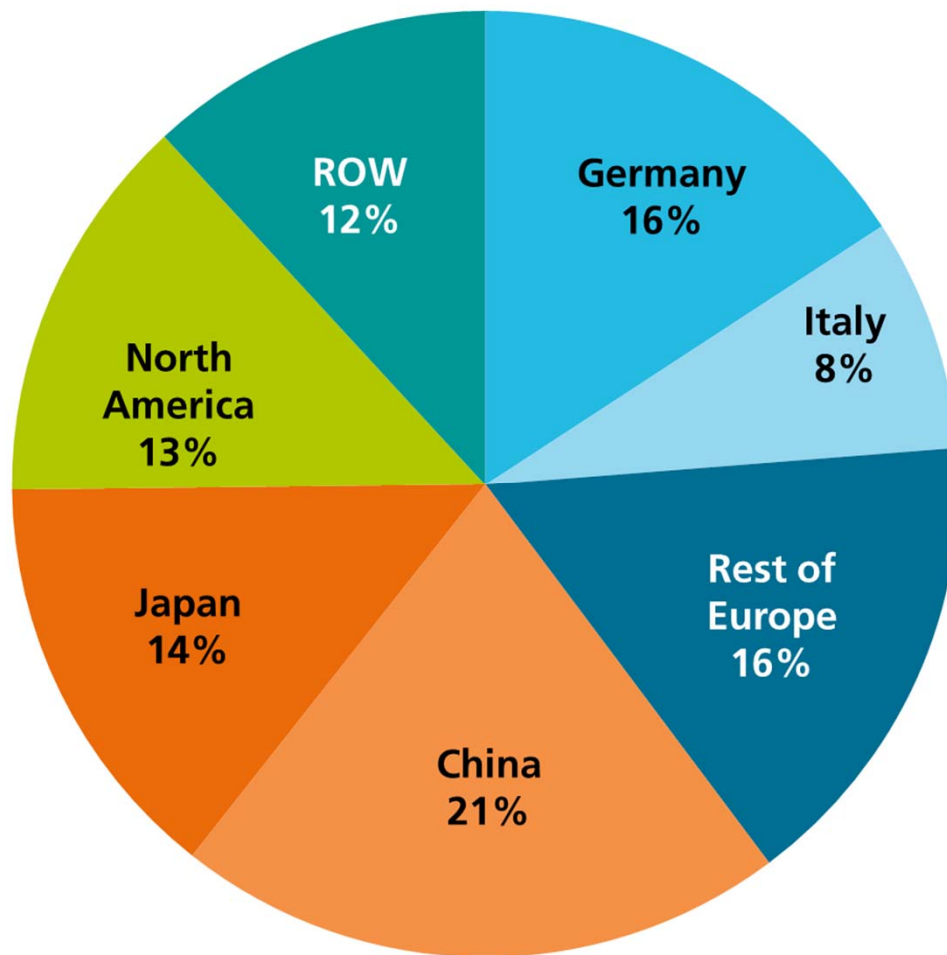
# Global Cumulative PV Installation until 2015



Data: IHS. Graph: PSE AG 2016

# Global Cumulative PV Installation by Region

## Status 2015



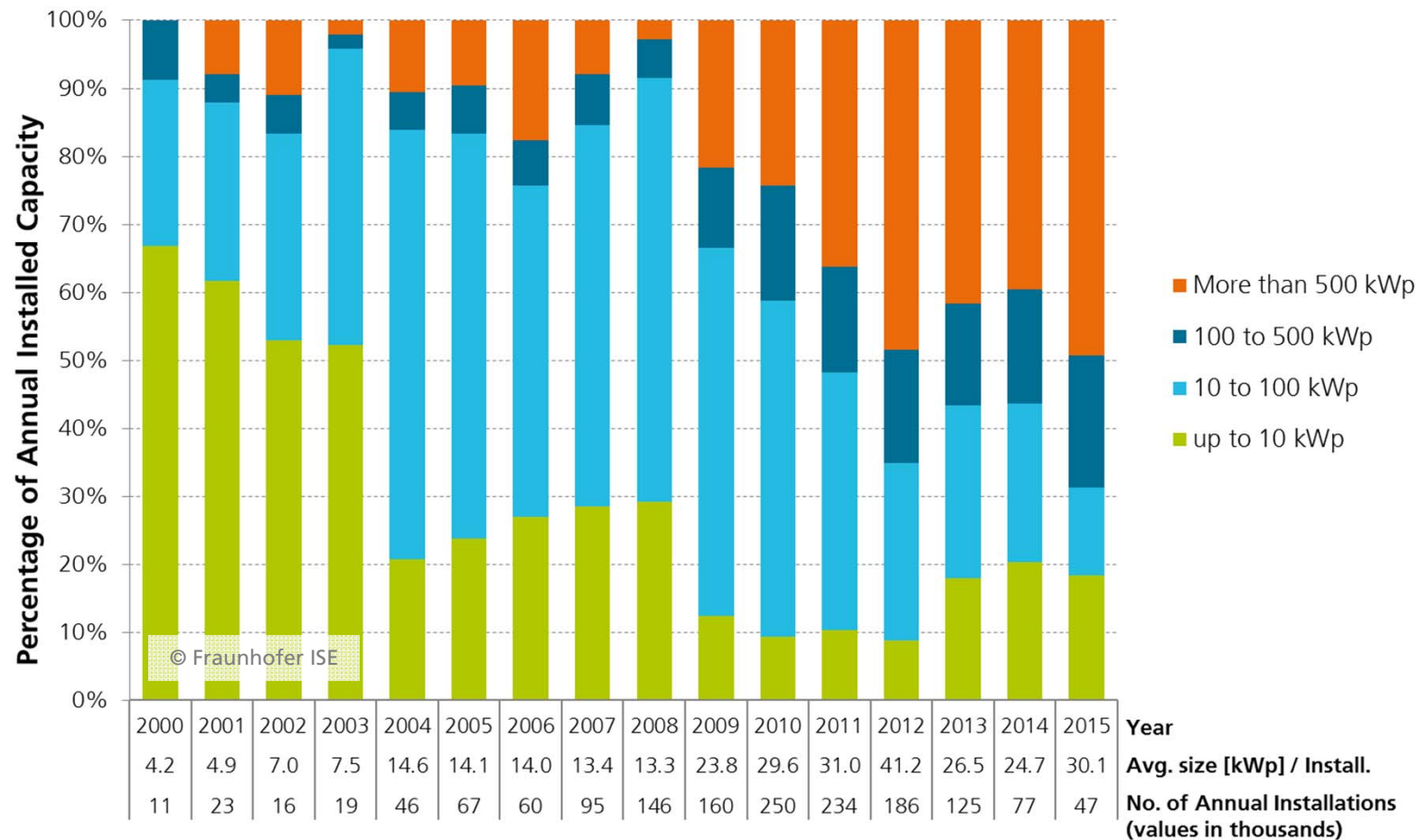
The total cumulative installations amounted to 242 GWp at the end 2015.

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

Data: IHS. Graph: PSE AG 2016

# Number of PV Systems Annually Installed in Germany

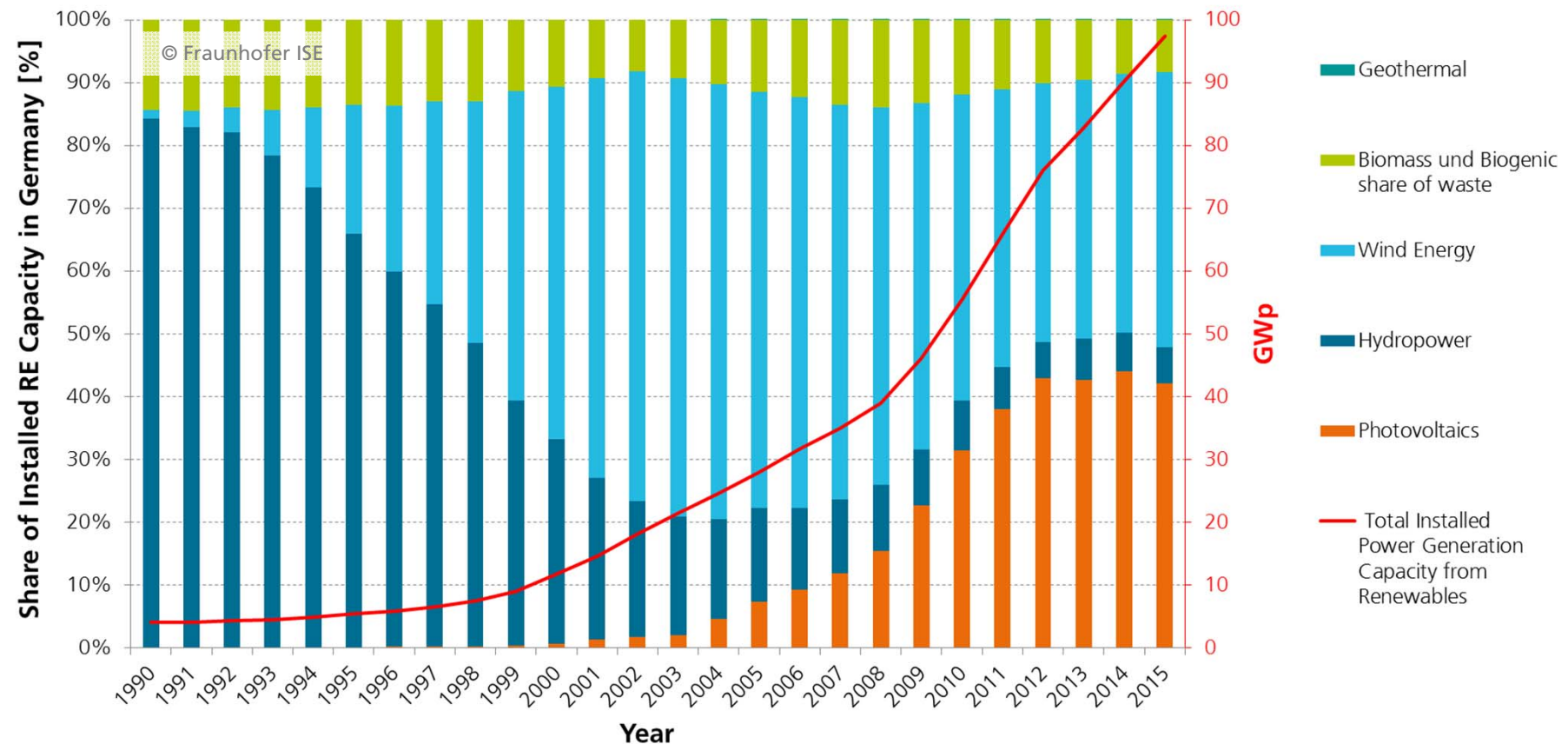
## Percentage of Annual Capacity



Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur. Graph: PSE AG 2016

# Electrical Capacity of Renewable Energy Sources

## Germany



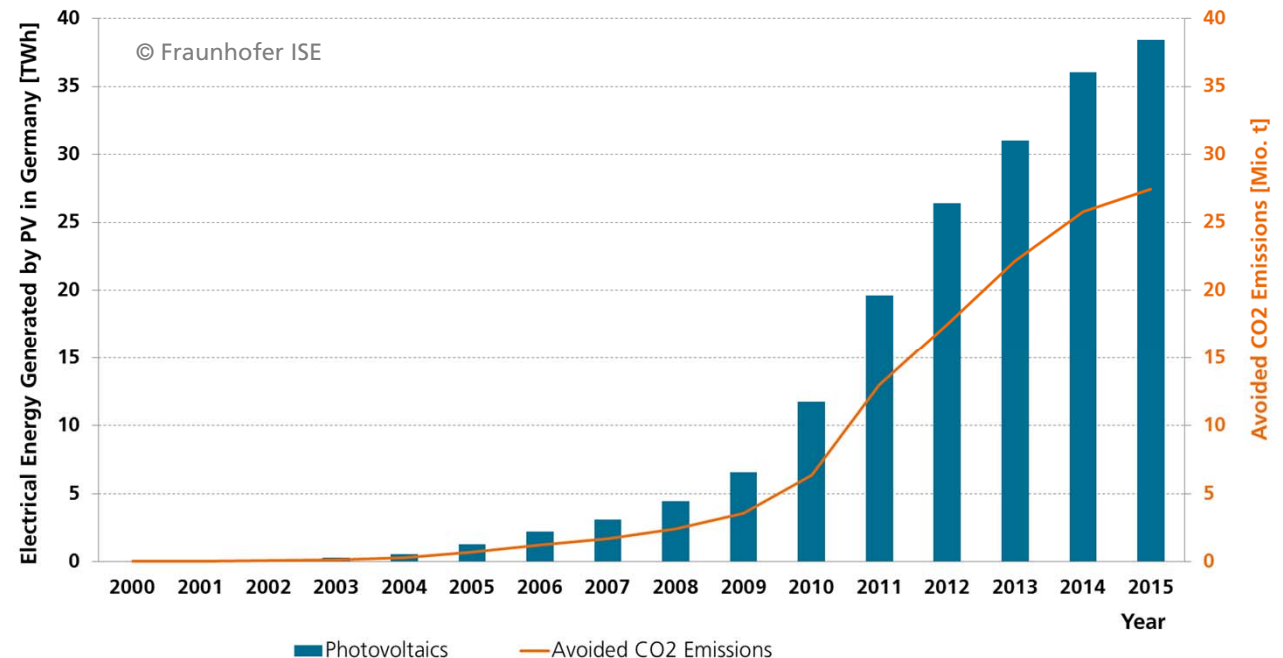
In 2015 about 33% of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.

Data: BMWi / AGEE-Stat.; Data up to 2012: BMU, BDEW. Graph: PSE AG 2016



# PV Energy Generated and Resulting CO<sub>2</sub> Avoided Emissions Germany

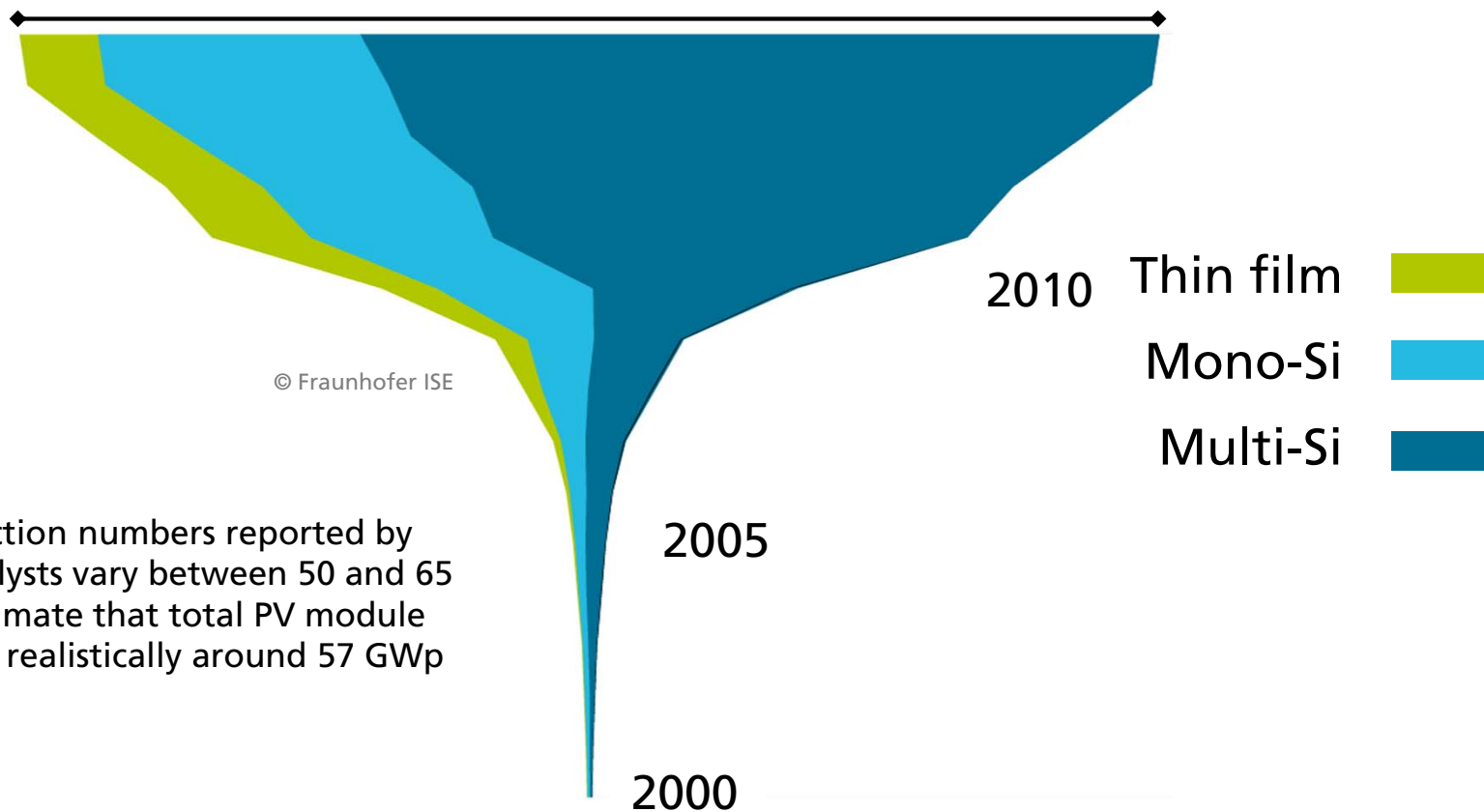
- In 2015 ca. 27 Mio. t of CO<sub>2</sub> emissions were avoided due to 38.4 TWh PV electricity consumed in Germany.
- According to the Federal Environmental Agency (UBA) the CO<sub>2</sub> avoidance factor of PV is 715 grams of CO<sub>2-eq</sub> /kWh<sub>el</sub>.



Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2013. Graph: PSE AG 2016

# Annual PV Production by Technology Worldwide (in GWp)

About 57\* GWp PV module production  
in 2015

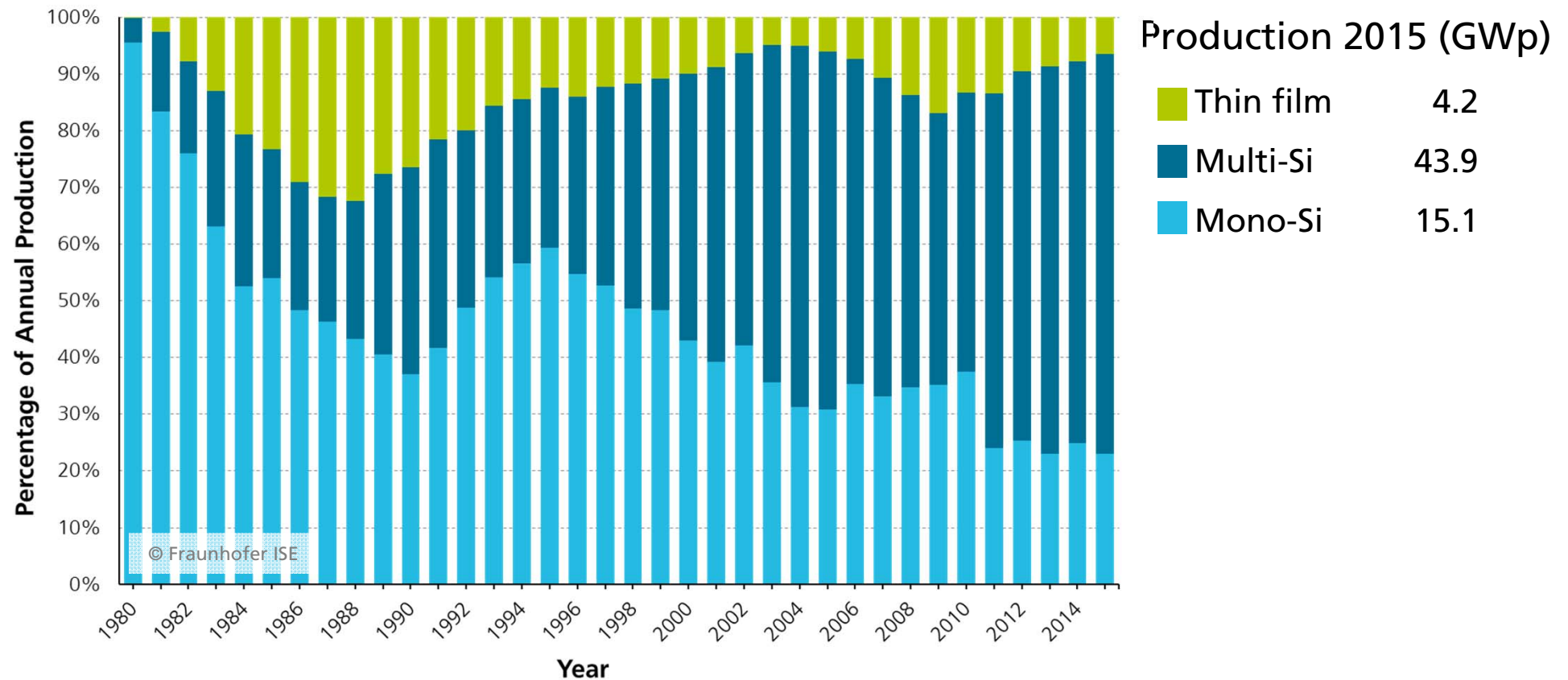


\*2015 production numbers reported by different analysts vary between 50 and 65 GWp. We estimate that total PV module production is realistically around 57 GWp for 2015.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2016

# PV Production by Technology

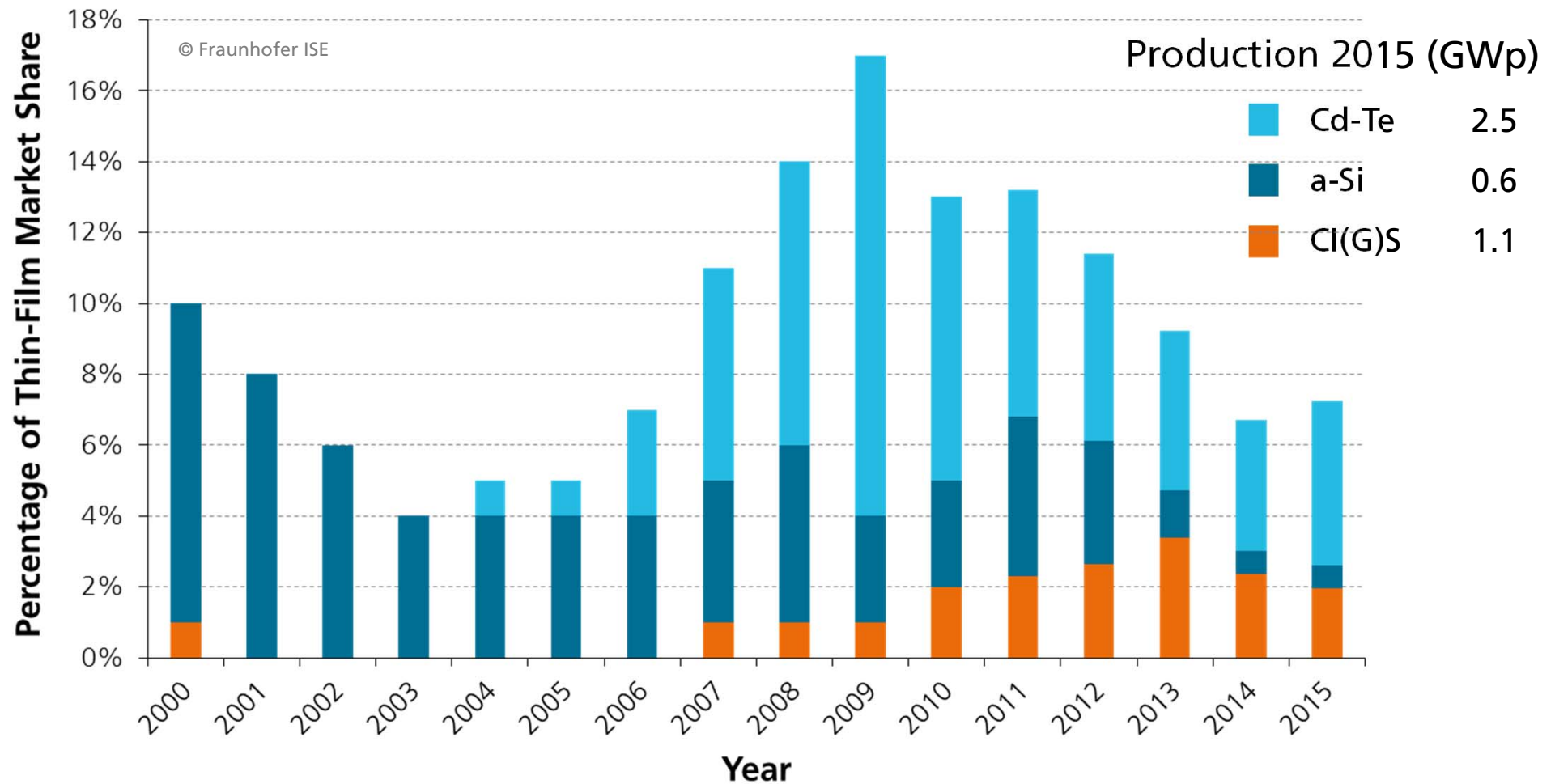
## Percentage of Global Annual Production



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE AG 2016

# Market Share of Thin-Film Technologies

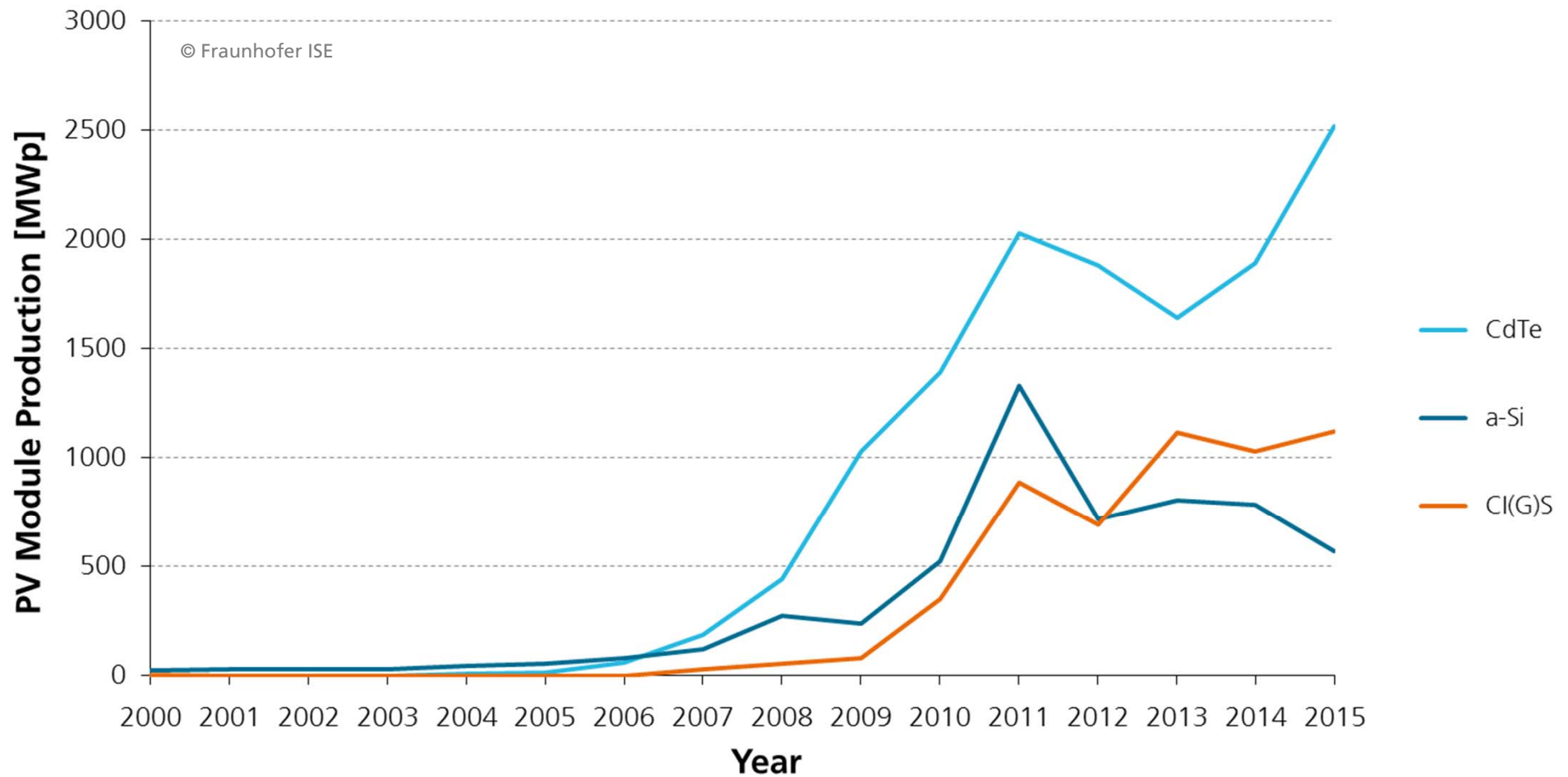
## Percentage of Total Global PV Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2016

# Thin-Film Technologies:

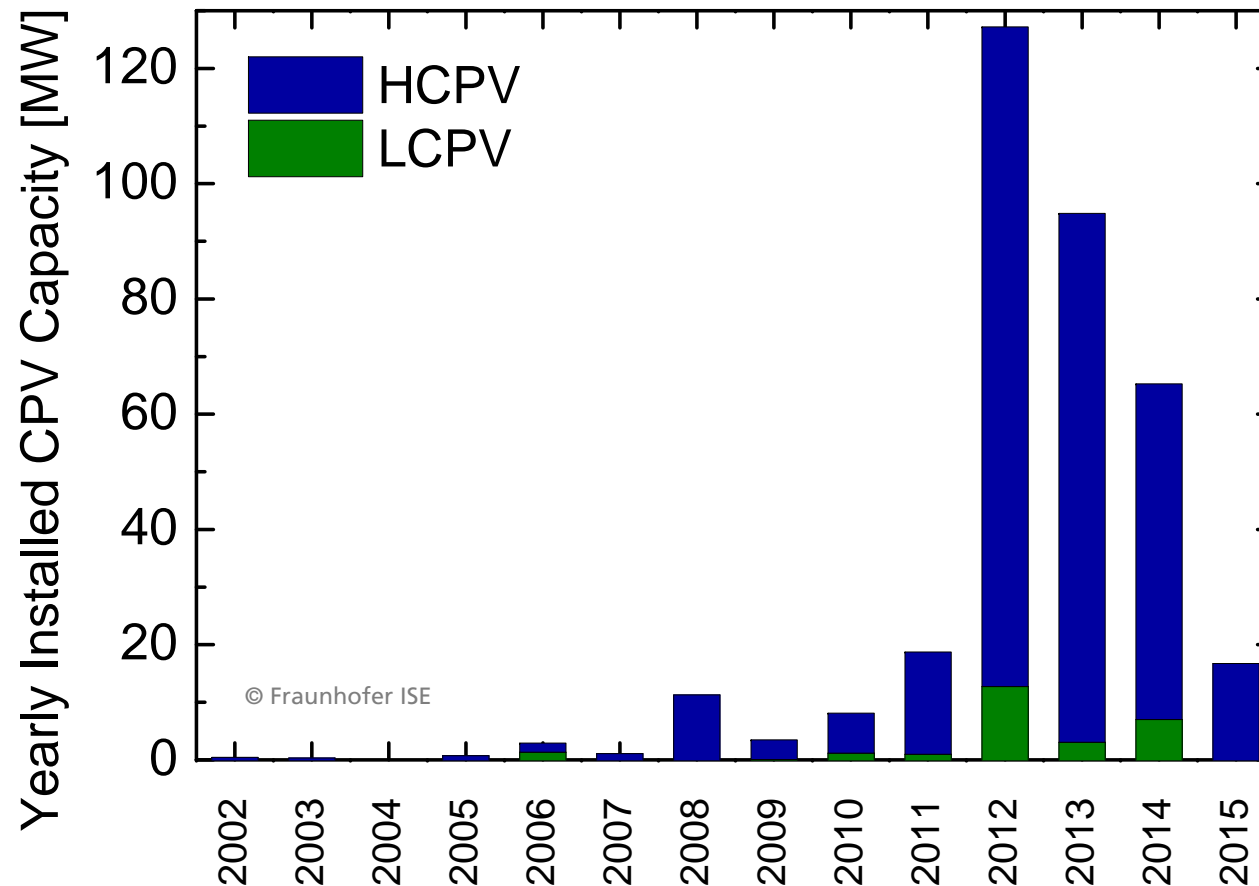
## Annual Global PV Module Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2016

# Low and High Concentrator PV Systems (LCPV/HCPV)

## Yearly Installed Capacity



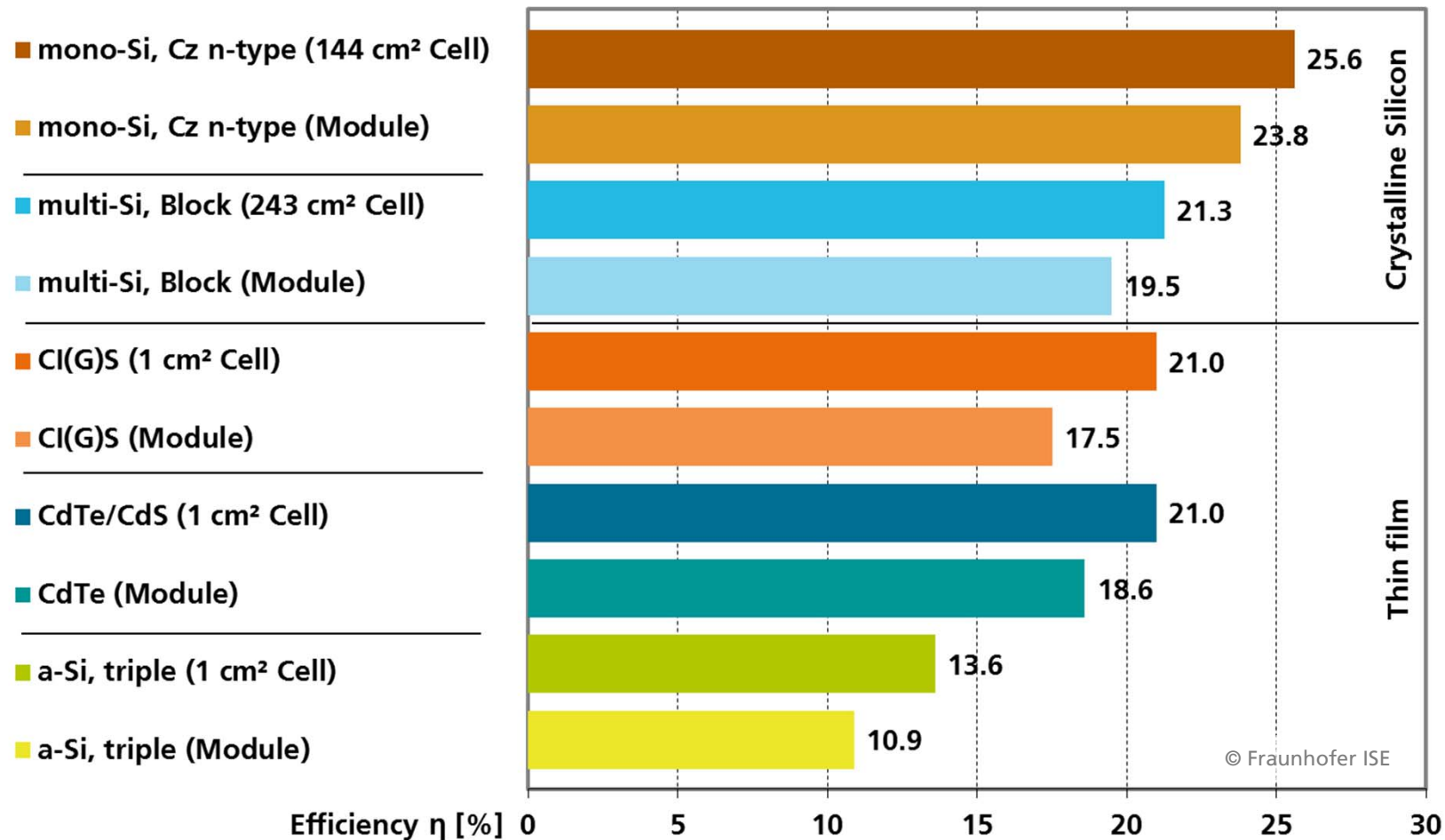
LCPV and HCPV have concentration factors below 100 suns and from 300 up to 1000 suns, respectively.

Data: ISE 2016

## 2. Solar Cells / Modules / System Efficiency

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

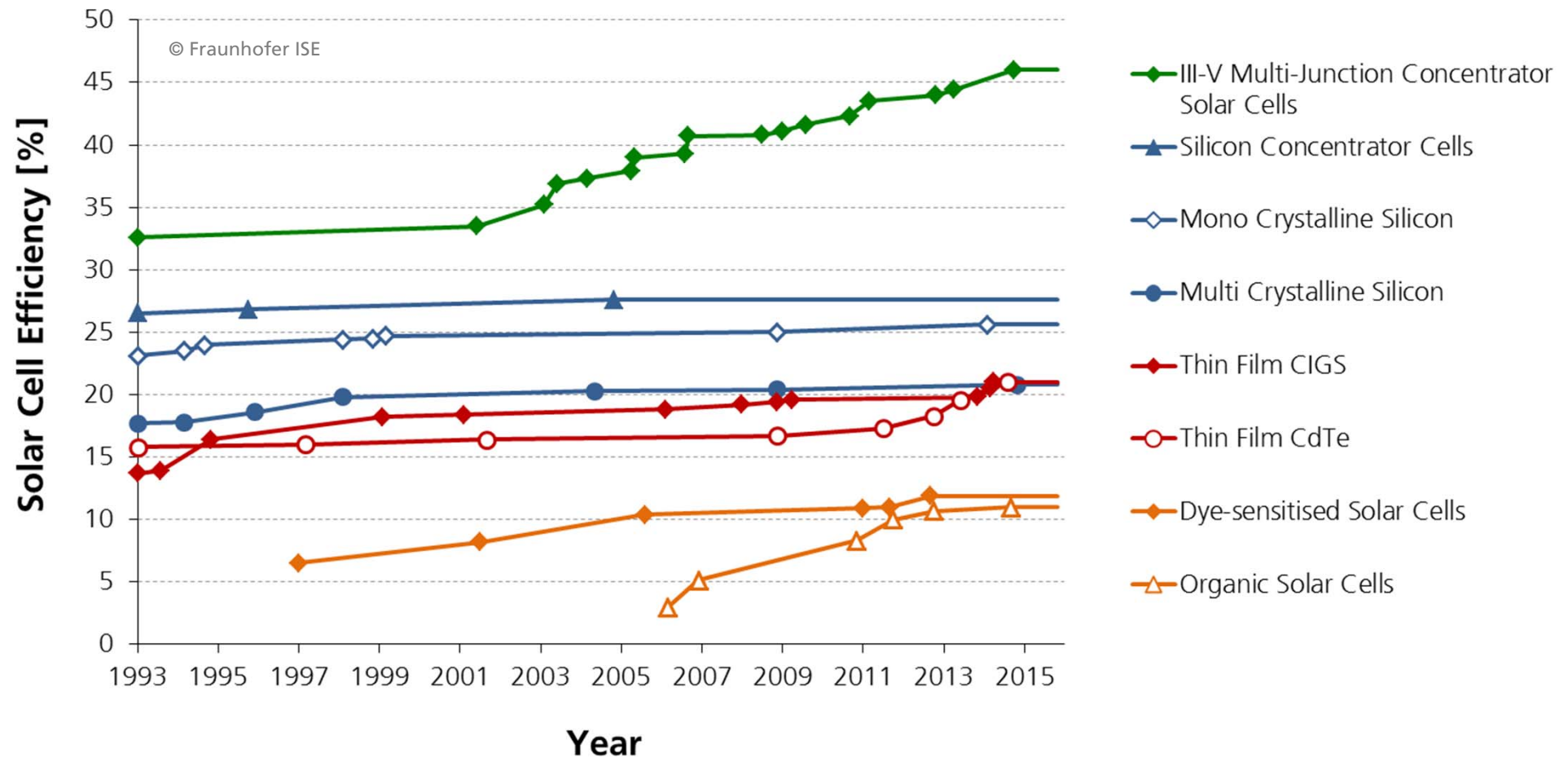
# Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables (Version 48), Progress in PV: Research and Applications 2016. Graph: PSE AG 2016

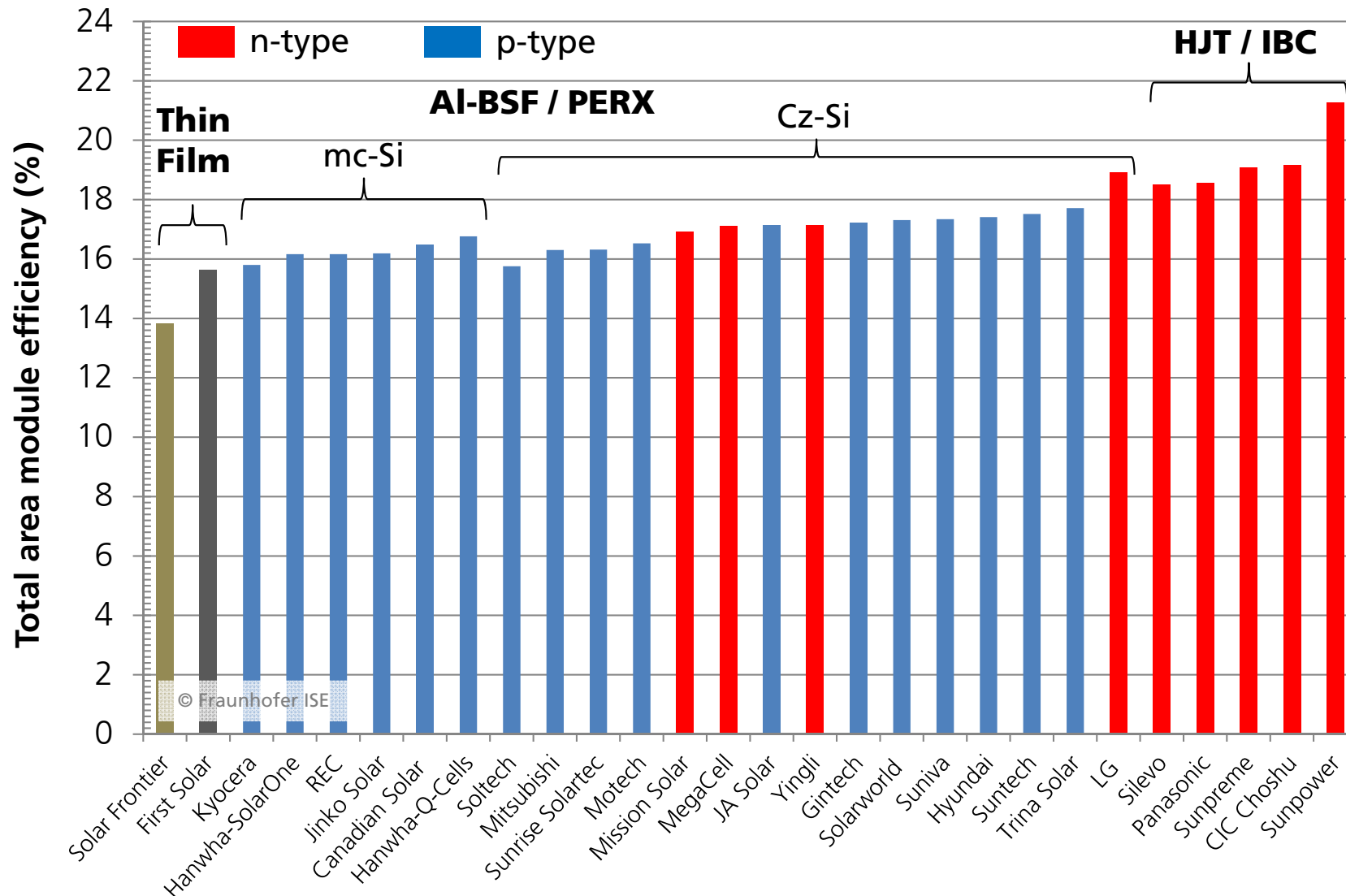


# Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1-48), Progress in Photovoltaics: Research and Applications, 1993-2016. Graph: Simon Philipps, Fraunhofer ISE 2016

# 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.

# 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

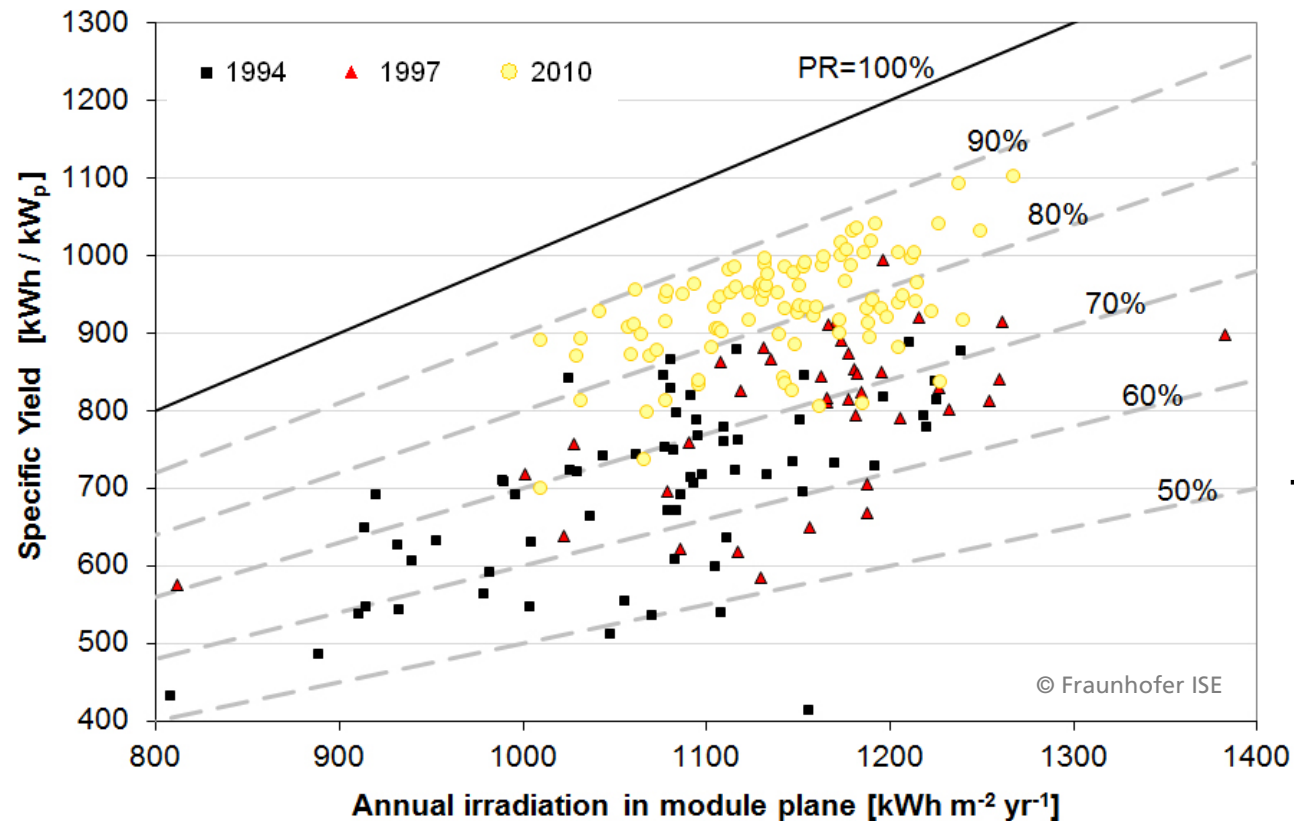


Efficiencies	Lab Record	Commercial
Solar Cell	46.0 % (ISE, Soitec, CEA)	38-43%
Minimodule	43.4% (ISE)	N.A.
Module	38.9% (Soitec)	27-33%
System (AC)	N.A.	25-29%

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

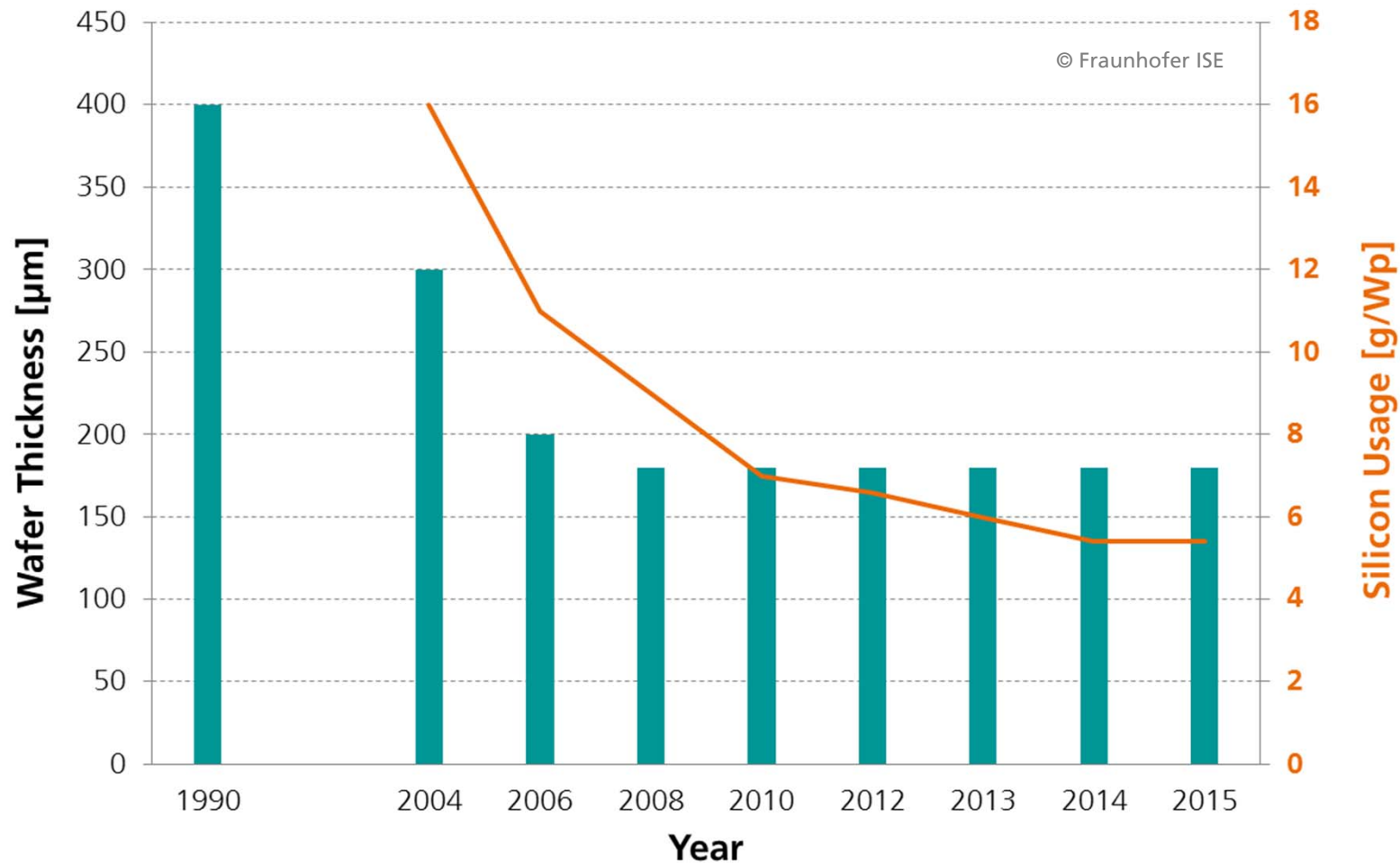
Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation

### 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 [ $\mu\text{m}$ ] & Silicon Usage [g/Wp]



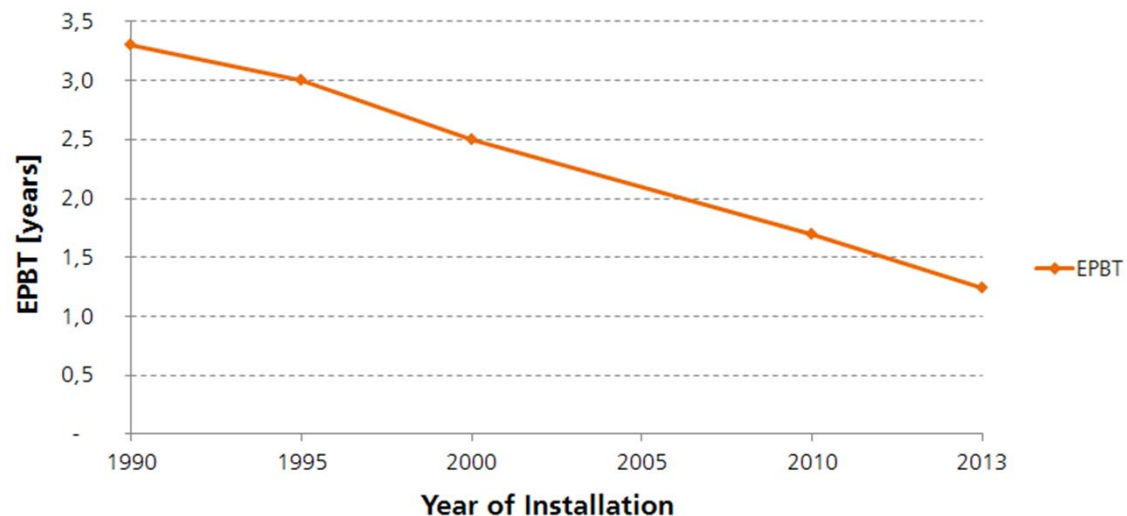
Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV 2015 Results. Graph: PSE AG 2016

# 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\*



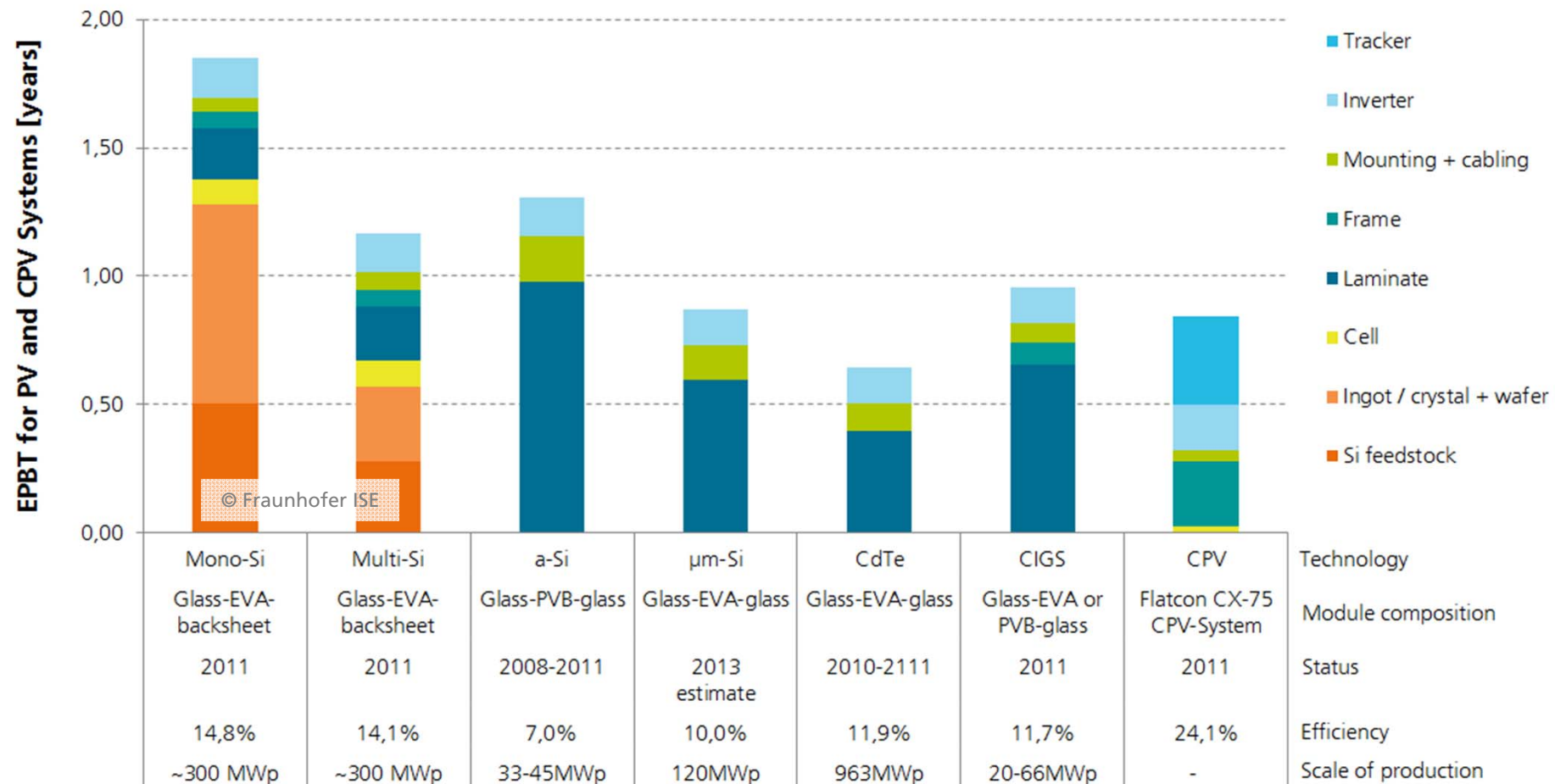
\*Irradiation: 1700 kWh/m<sup>2</sup>/a at an optimized tilt angle

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/m<sup>2</sup>/yr, Direct Normal Irrad.: 1794 kWh/m<sup>2</sup>/yr



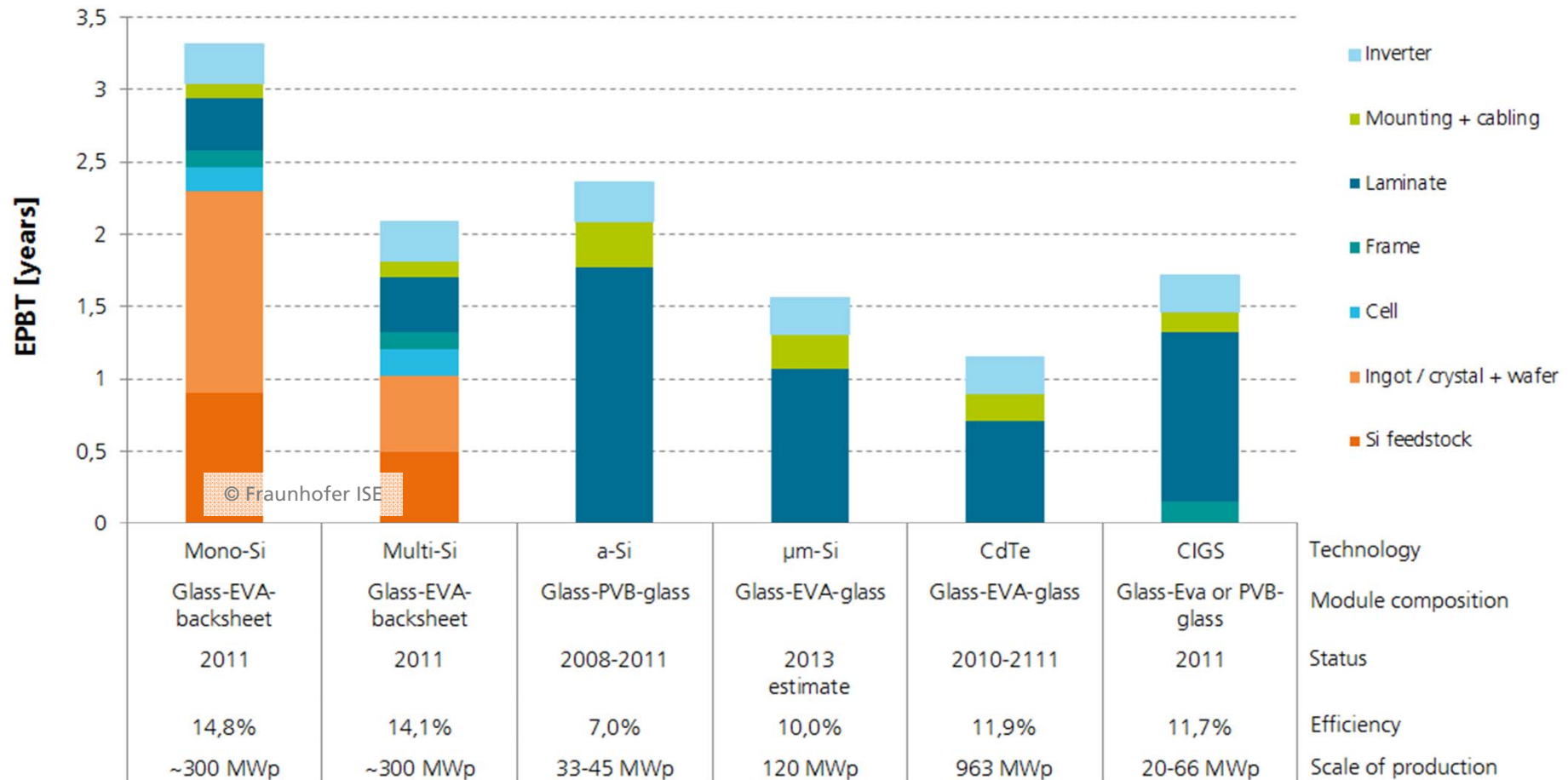
Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014



# Energy Pay-Back Time of Rooftop PV Systems

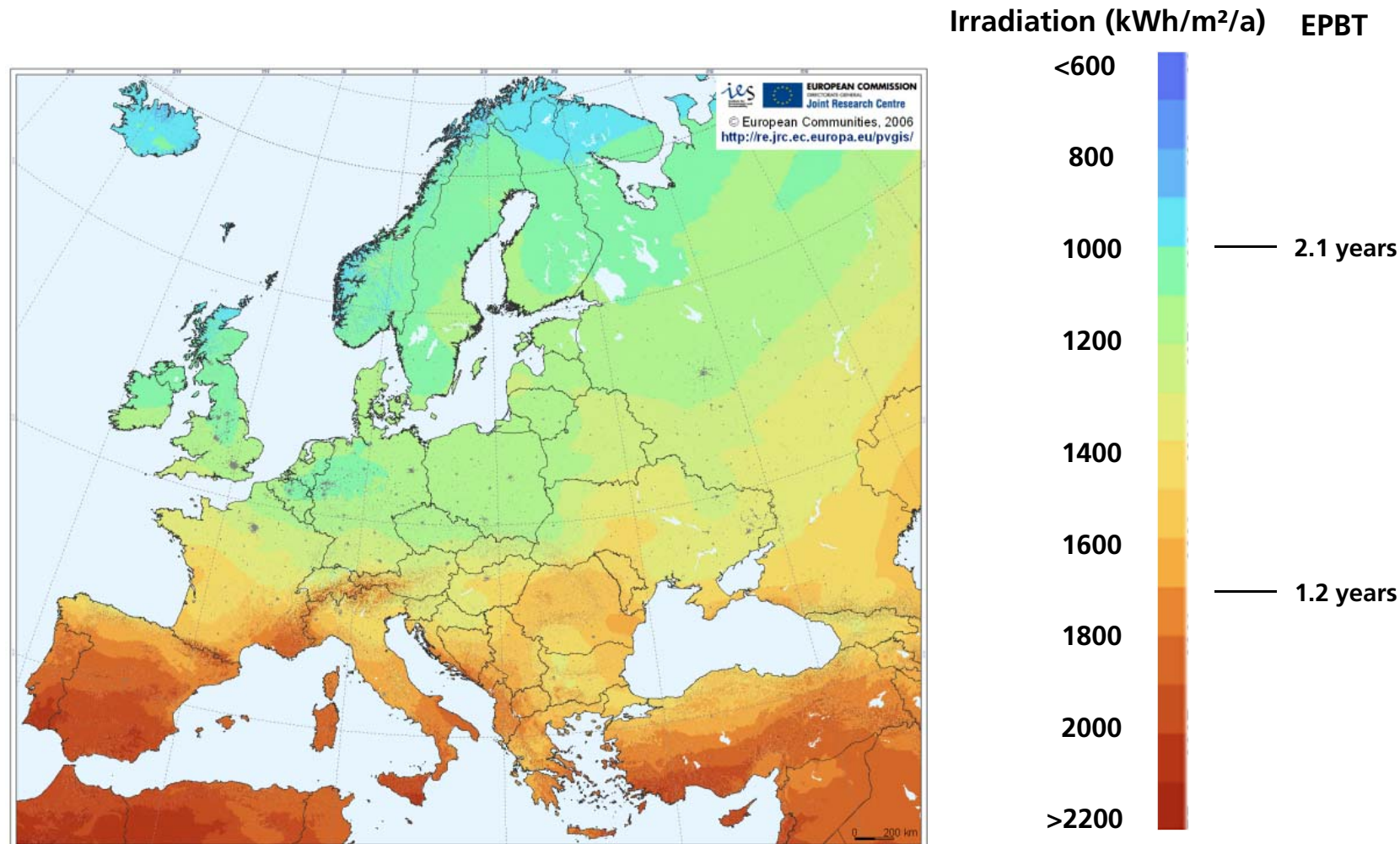
## Different Technologies located in Germany

Global Irrad.: 1000 kWh/m<sup>2</sup>/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 Commission. Graph: PSE AG 2014 (Modified scale with updated data from PSE AG and Fraunhofer ISE)

# 4. Inverters

- Inverter/Converter Price
- Inverter Concept Comparison

# Inverter/Converter Market 2015

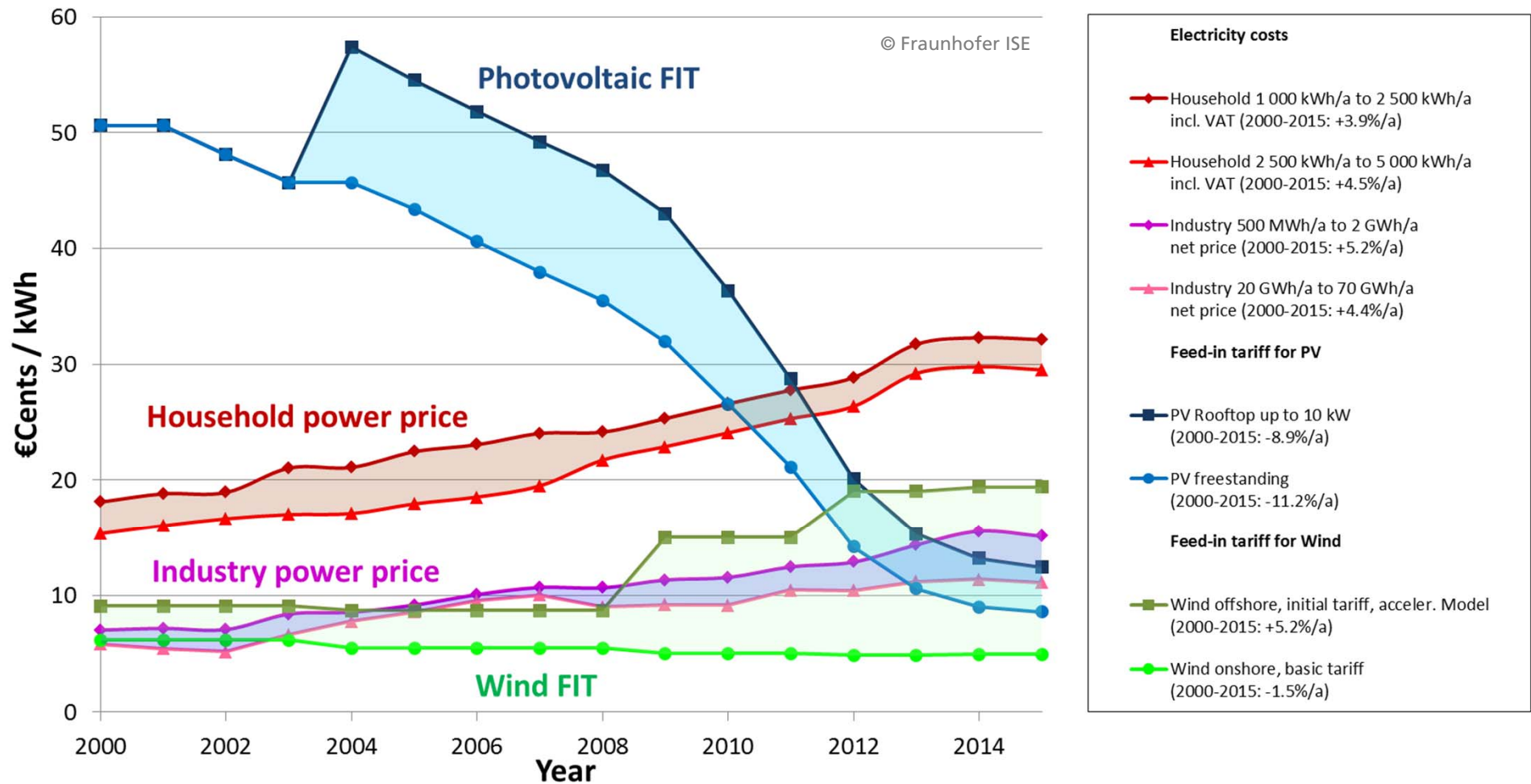
Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 100 kWp	up to 98 %	~ 37 %	<ul style="list-style-type: none"> <li>• 11 - 19 €-cents /Wp</li> <li>• Easy to replace</li> </ul>
Central Inverters	More than 100 kWp	up to 98.5 %	~ 61 %	<ul style="list-style-type: none"> <li>• ~ 10 €-cents /Wp</li> <li>• High reliability</li> <li>• Often sold only together with service contract</li> </ul>
Micro-Inverters	Module Power Range	90%-95 %	~ 2 %	<ul style="list-style-type: none"> <li>• ~ 35 €-cents /Wp</li> <li>• Ease-of-replacement concerns</li> </ul>
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8 %	n.a.	<ul style="list-style-type: none"> <li>• ~ 10 €-cents /Wp</li> <li>• Ease-of-replacement concerns</li> <li>• Output is DC with optimized current</li> <li>• Still a DC / AC inverter is needed</li> <li>• ~ 1 GWp installed in 2014</li> </ul>

Data: IHS 2015. Remarks: Fraunhofer ISE 2014. Graph: PSE AG 2016

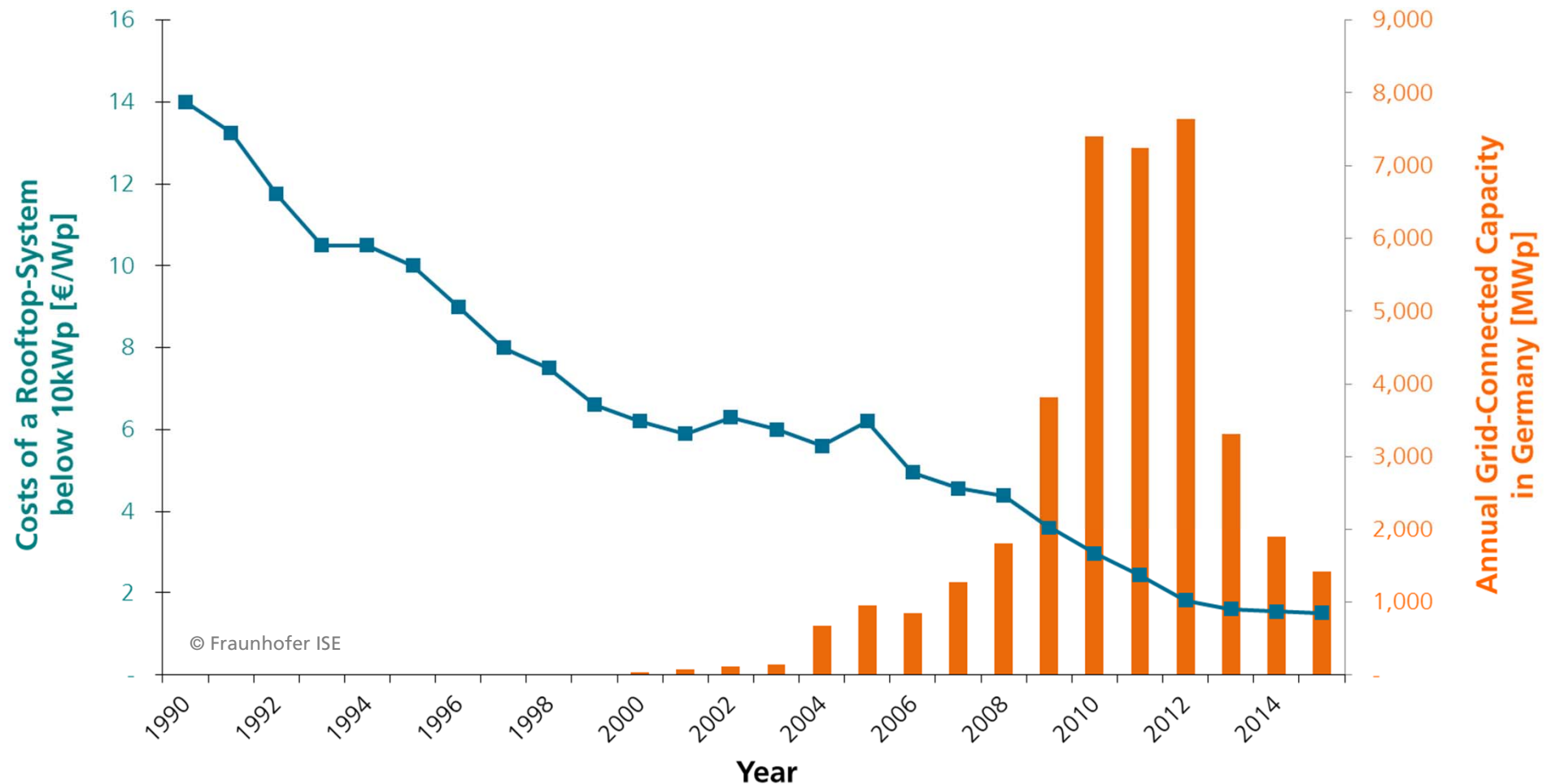
# 5. Price Development

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

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

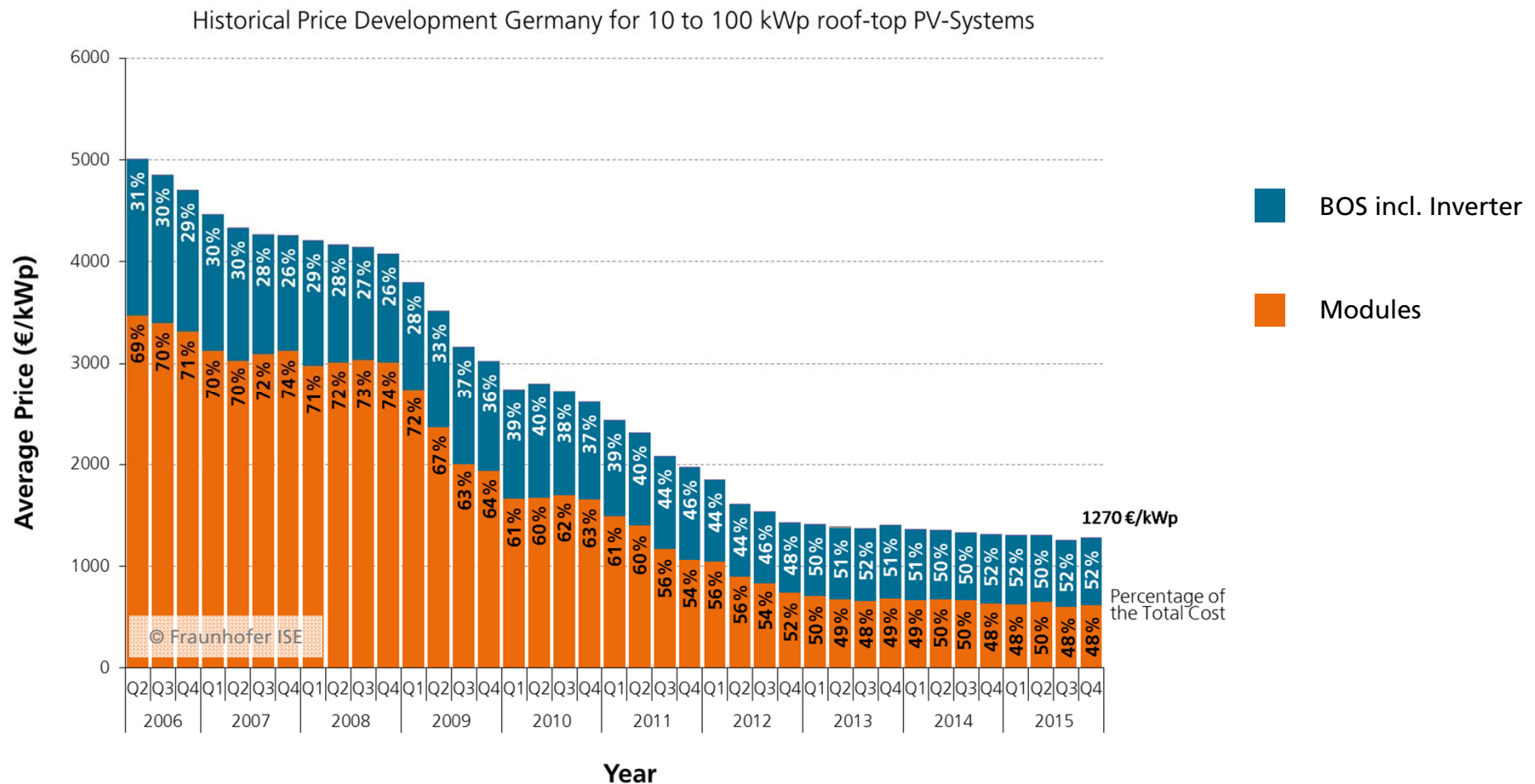


# Investment for Small Rooftop PV Systems in Relation to Market Development and Subsidy Schemes in Germany



Data: BSW-Solar, BNA. Graph: PSE AG 2016

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

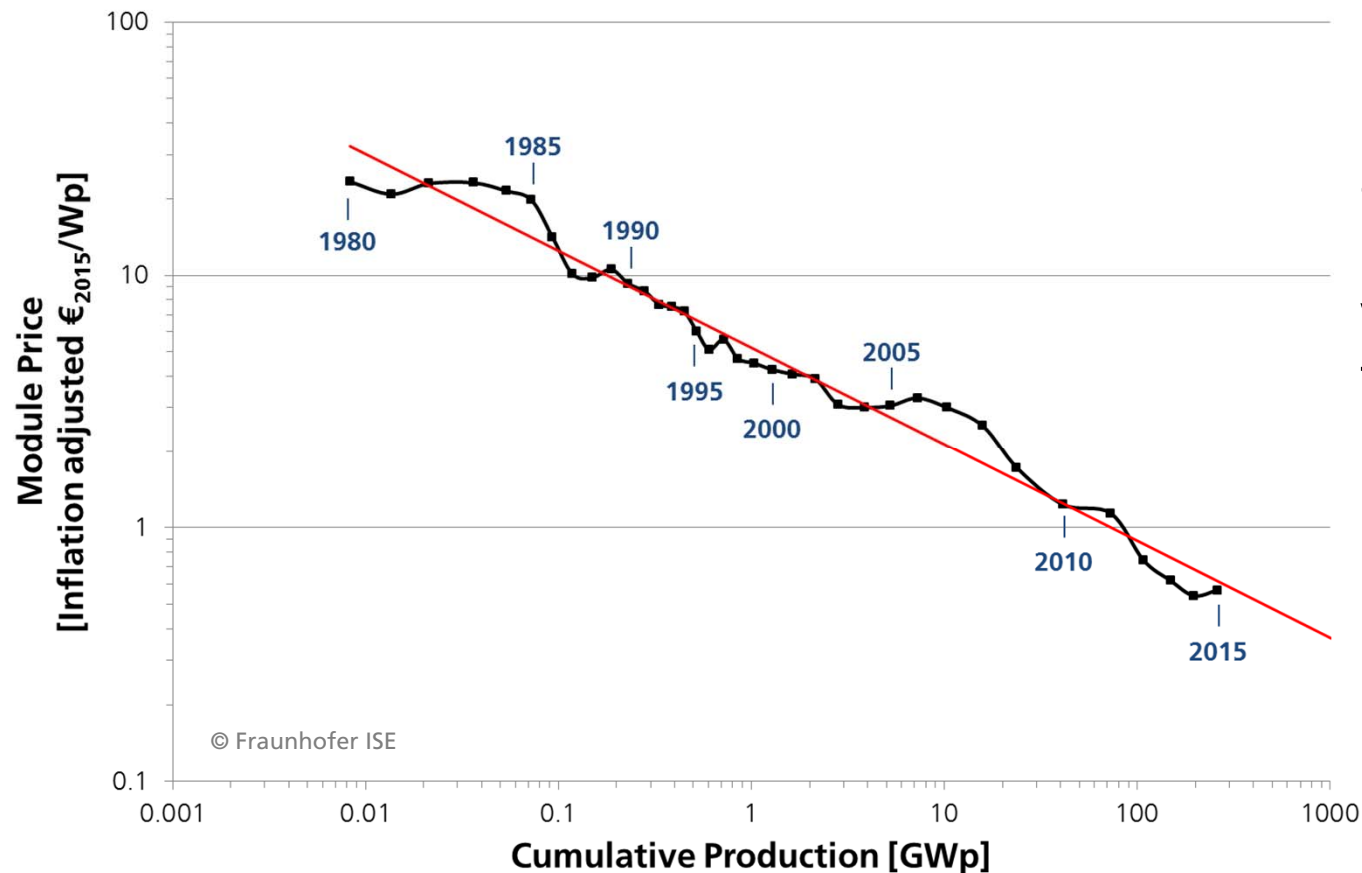


Data: BSW-Solar. Graph: PSE AG 2016



# Price Learning Curve

## Includes all Commercially Available PV Technologies

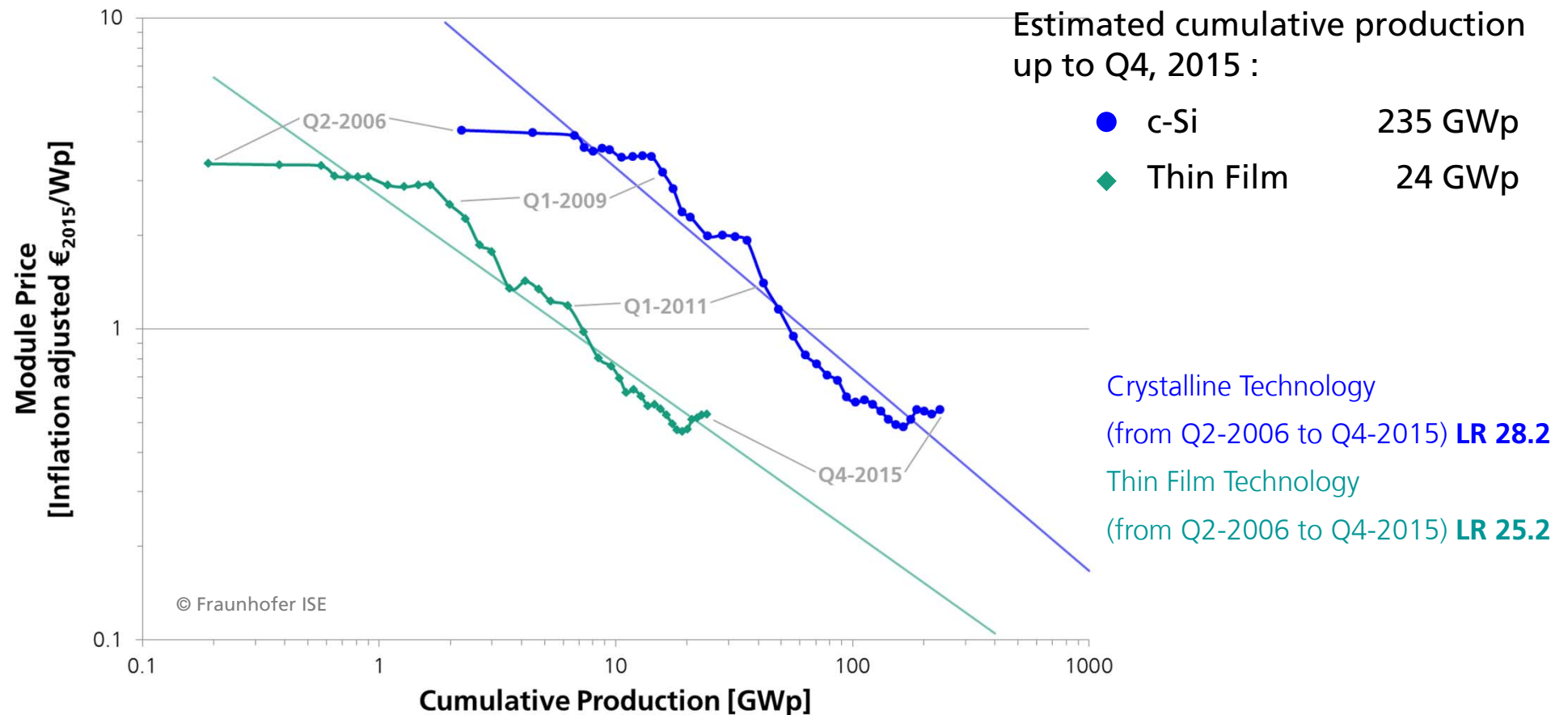


**Learning Rate:**  
Each time the cumulative production doubled, the price went down by 23 % for the last 35 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2015: IHS. Graph: PSE AG 2016

# Price Learning Curve by Technology

## Cumulative Production up to Q4. 2015



Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011 to 2015: IHS. Graph: PSE AG 2016

# Acknowledgements

This work has been carried out with contributions from:

Name	Institution
Bruno Burger	ISE
Klaus Kiefer	ISE
Christoph Kost	ISE
Sebastian Nold	ISE
Simon Philipps	ISE
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
Werner Warmuth	PSE

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.

[simon.philipps@ise.fraunhofer.de](mailto:simon.philipps@ise.fraunhofer.de)  
[werner.warmuth@pse.de](mailto:werner.warmuth@pse.de)