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# FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

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Photovoltaics Report

Freiburg, 24 October 2014

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  - PV Market
  - Solar Cells / Modules / System Efficiency
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# Introduction

## Preliminary Remarks

- Photovoltaics is a fast growing market: The Compound Annual Growth Rate (CAGR) of PV installations is 44 % during the period from 2000 to 2013.
- 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 However, facts and figures change rapidly and the given information may soon be outdated again.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 [warmuth@pse.de](mailto:warmuth@pse.de)
- Please quote the information presented in these slides as follows:  
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# Executive Summary

## PV Market

- China and Taiwan entered the mass production market in 2004 and ramped up a PV industry with strong growth rates. At the end of 2013 their market share was about 70 % of the worldwide shipments.
- Europe contributed 58 % of the total cumulated PV installations in 2013 (in 2012 it was 65 %). In contrast, installations in China and Taiwan accounted for 13 % of the total cumulated installations (in 2012 it was 8%).
- Si-wafer based PV technology accounted for about 90 % of the total production in 2013. The share of multi-crystalline technology is now about 55 % of total production.
- Within thin film technology in 2013, CdTe leads with an annual production of about 2 GWp. In 2013, the market share of all thin film technologies adds to around 10 % of the total annual production.

# Executive Summary

## PV Market: Focus Germany

- In 2013, Germany accounted for about 27 % (35.7 GWp) of the cumulative PV capacity installed worldwide (134 GWp). In 2013 newly installed capacity in Germany amounted to 3.3 GWp, which corresponds to half of that installed in 2012. In total, 1.4 million PV systems are installed in Germany.
- Up to the end of August 2014 new PV installations equivalent to 1.5 GWp were connected to the German grid.
- PV supplied about 5.3 % of Germany's electricity demand in 2013. Renewable sources delivered more than a quarter of the total electricity consumed in 2013.
- In 2013 about 20 Mio. t CO<sub>2</sub> emissions have been avoided due to 29.7 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 Cells / Modules Efficiency

- The record lab cell efficiency is 25 % for mono-crystalline and 20.4 % for multi-crystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 19.8 % for CIGS and 19.6 % for CdTe solar cells.
- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12 % to 16 %. At the same time, CdTe module efficiency increased from 9 % to 13 %.
- 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 44.7 % today. With this concentrator technology, module efficiencies of up to 36.7 % 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 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 stands at 98 % and above.
- The market share of string inverters is estimated to be 50 %. This kind of inverters are mostly used in residential, small and medium commercial applications. The market share of central inverters, mostly used in large commercial and utility-scale systems, is 48 %. A small proportion of the market (about 1.5 %) belongs to micro-inverters (used on module level). It was estimated that 0.75 GWp of DC / DC converters, also called “power optimizers”, have been sold in 2013.
- The specific net retail price in Germany is about 14 euro-cts/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.



# Executive Summary

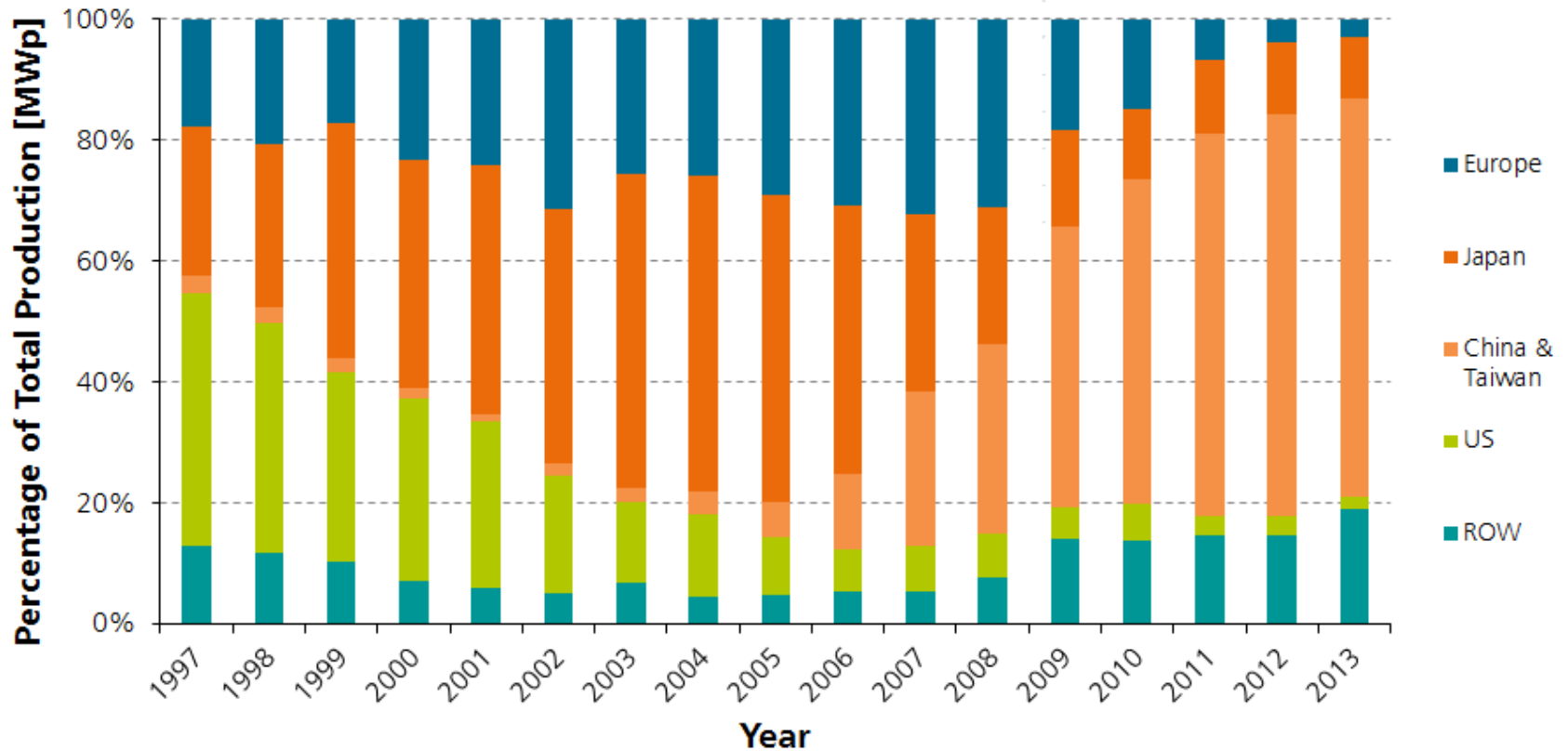
## Price Development

- In Germany prices for a typical 10 to 100 kWp PV rooftop-system were around 14,000 €/kWp in 1990. At the end of 2013, such systems cost about 1,350 €/kWp. This is a net-price regression of 89 % over a period of 23 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 30 years the module price decreased by about 20 % with each doubling of the cumulated module production. Cost reductions result from economies of scale and progress in research.

# 1. PV Market

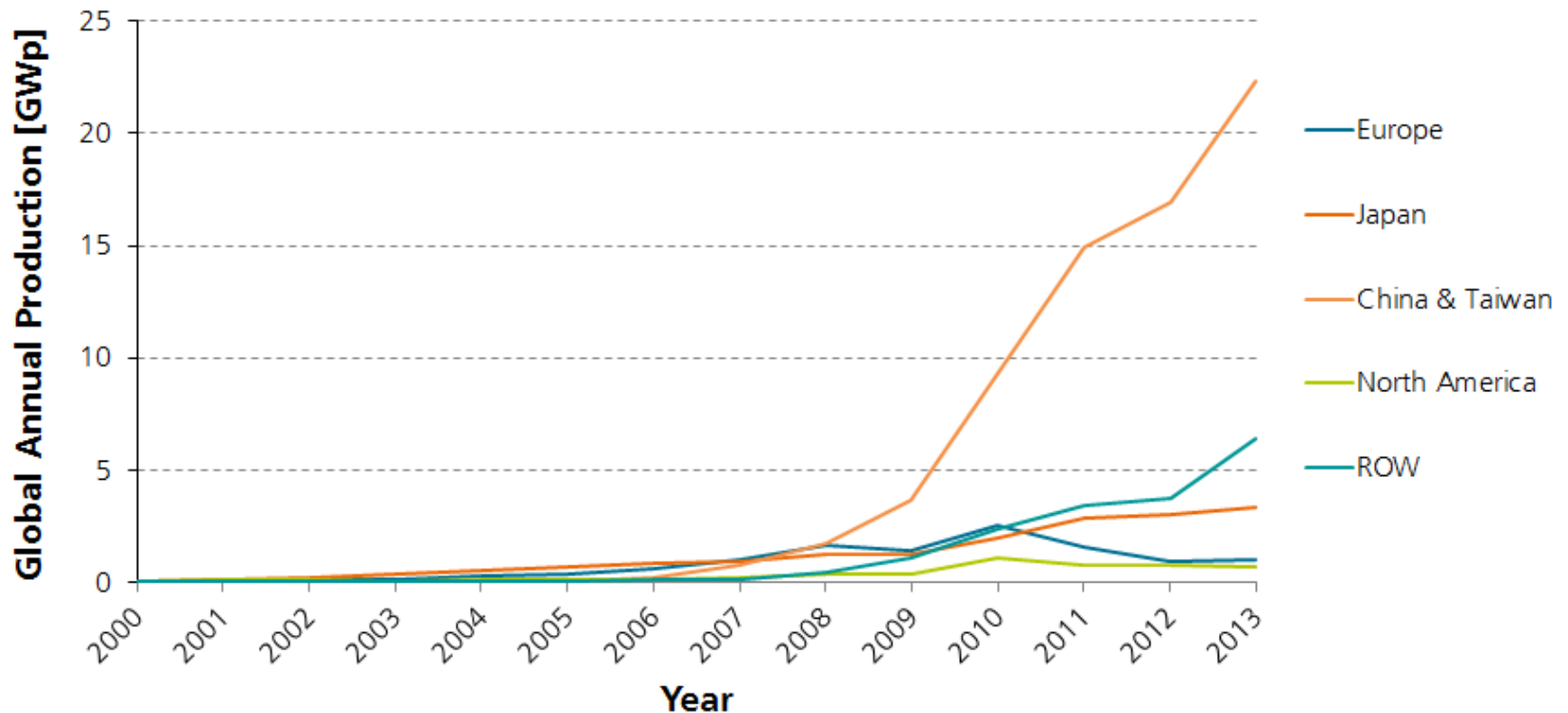
- By region
- By technology

# PV Cells/Modules Production by Region 1997-2013 (Percentage of Total MWp Produced)



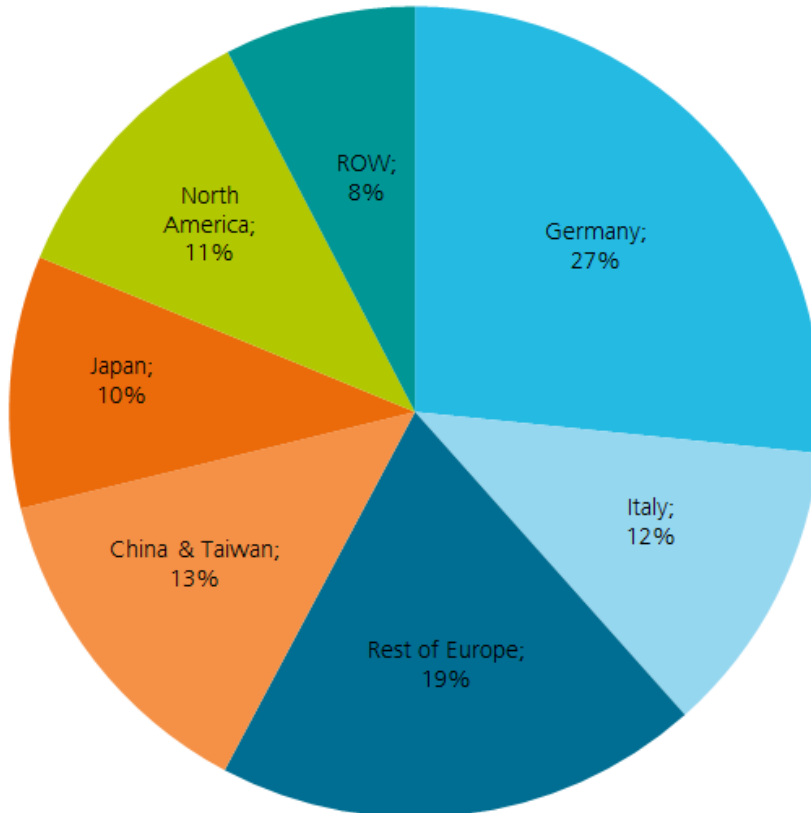
Data: Navigant Consulting and Paula Mints. Graph: PSE AG 2014

# PV Industry Production by Region (2000-2013)



Data: Navigant Consulting and Paula Mints. Graph. PSE AG 2014

# Global Cumulative PV Installation until 2013



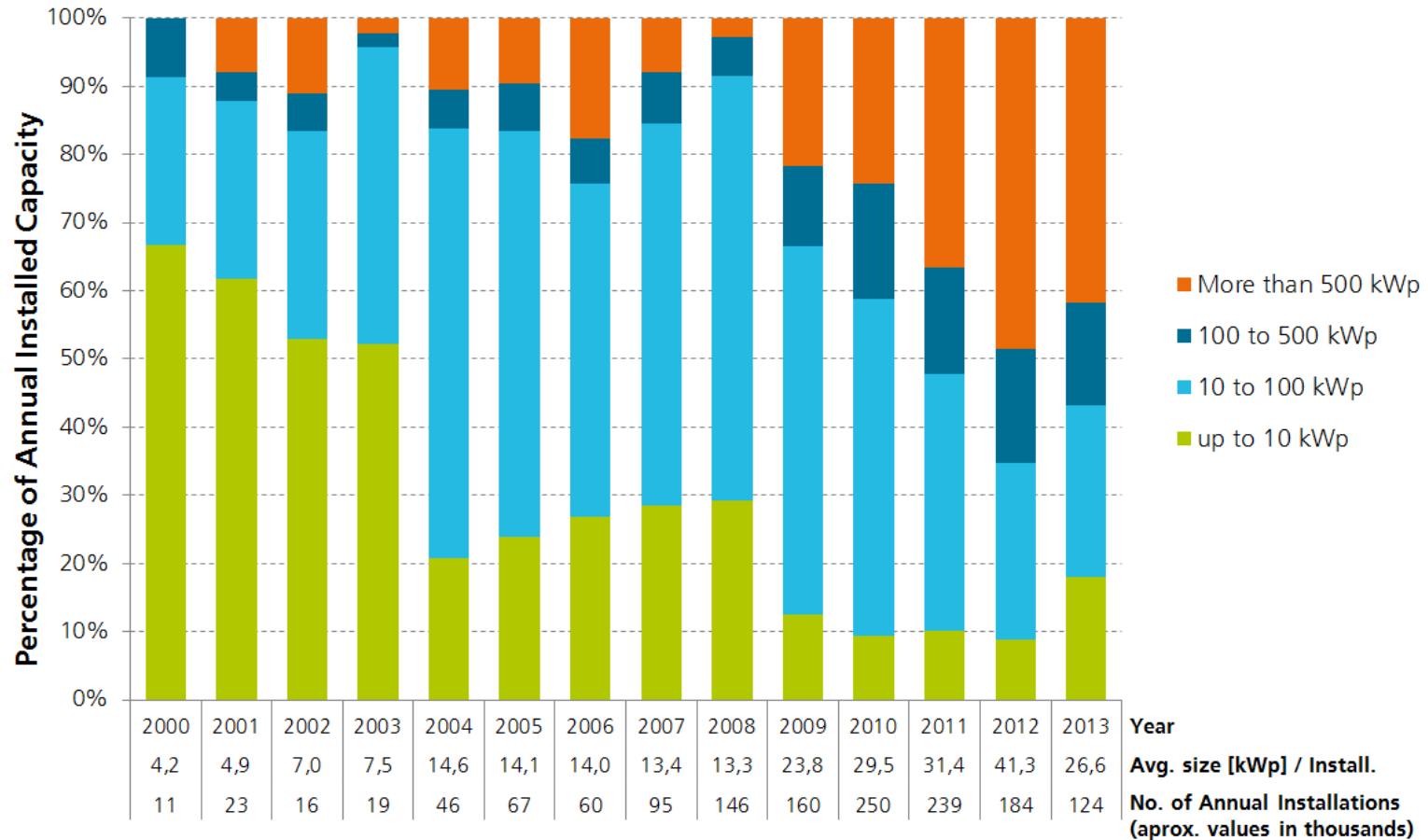
The total cumulative installations at the end of the year 2013 were about 134 GWp.

All percentages are related to the total global installation.

Data: from 2000 to 2011: EPIA; from 2012: IHS and Photon. Graph: PSE AG 2014

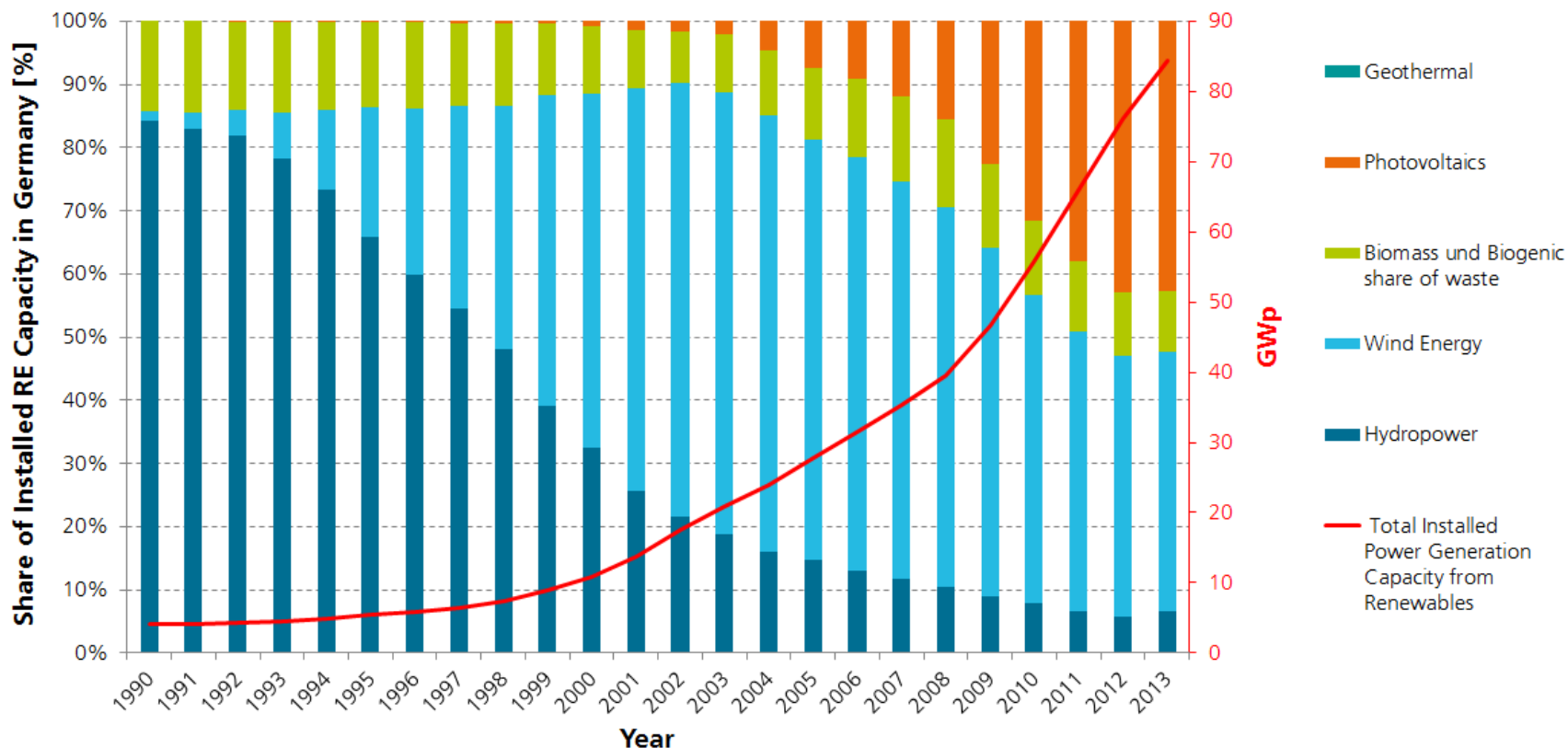
# PV Systems Yearly Installed in Germany

## Shares by System Size



Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur. Graph: PSE AG 2014

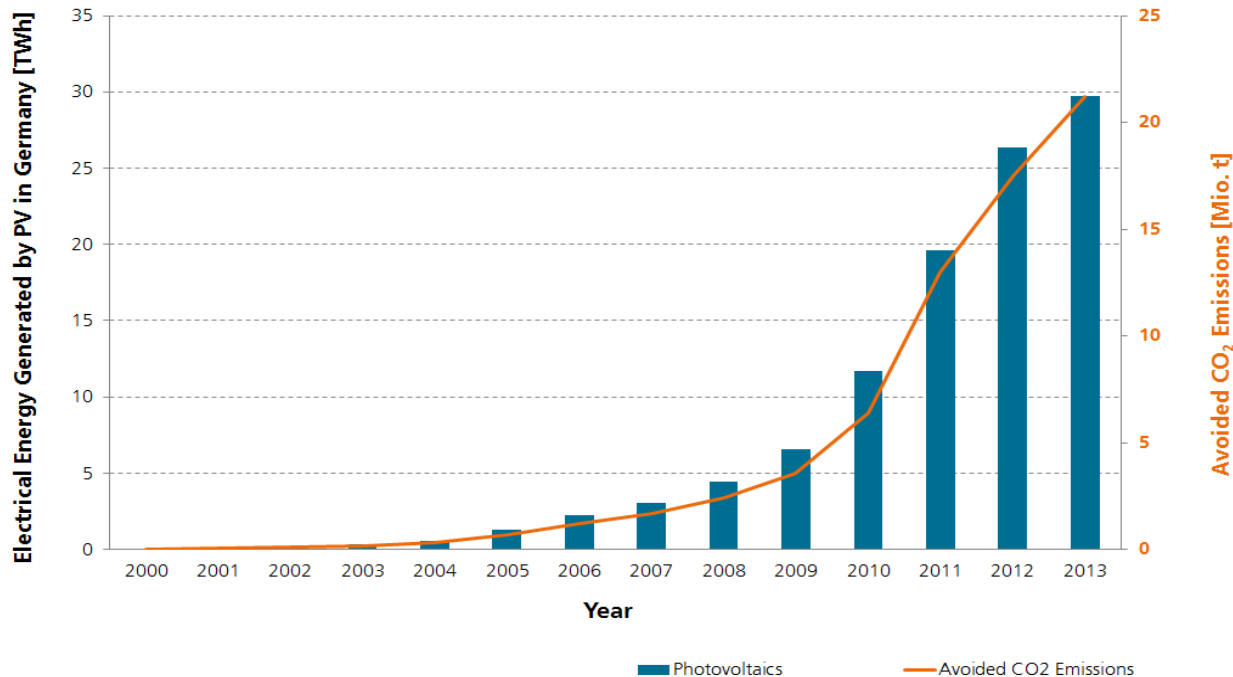
# Electrical Capacity of Renewable Energy Sources in Germany



In 2013 about 24% of the electricity in Germany has been generated by renewable energy (RE) sources according to BDEW.

Preliminary data 2013: BMWi / AGEE-Stat. Up to 2012 Data: BMU, BDEW. Graph: PSE AG 2014

# PV Energy Generated in Germany and the Resulting CO<sub>2</sub> avoided Emissions



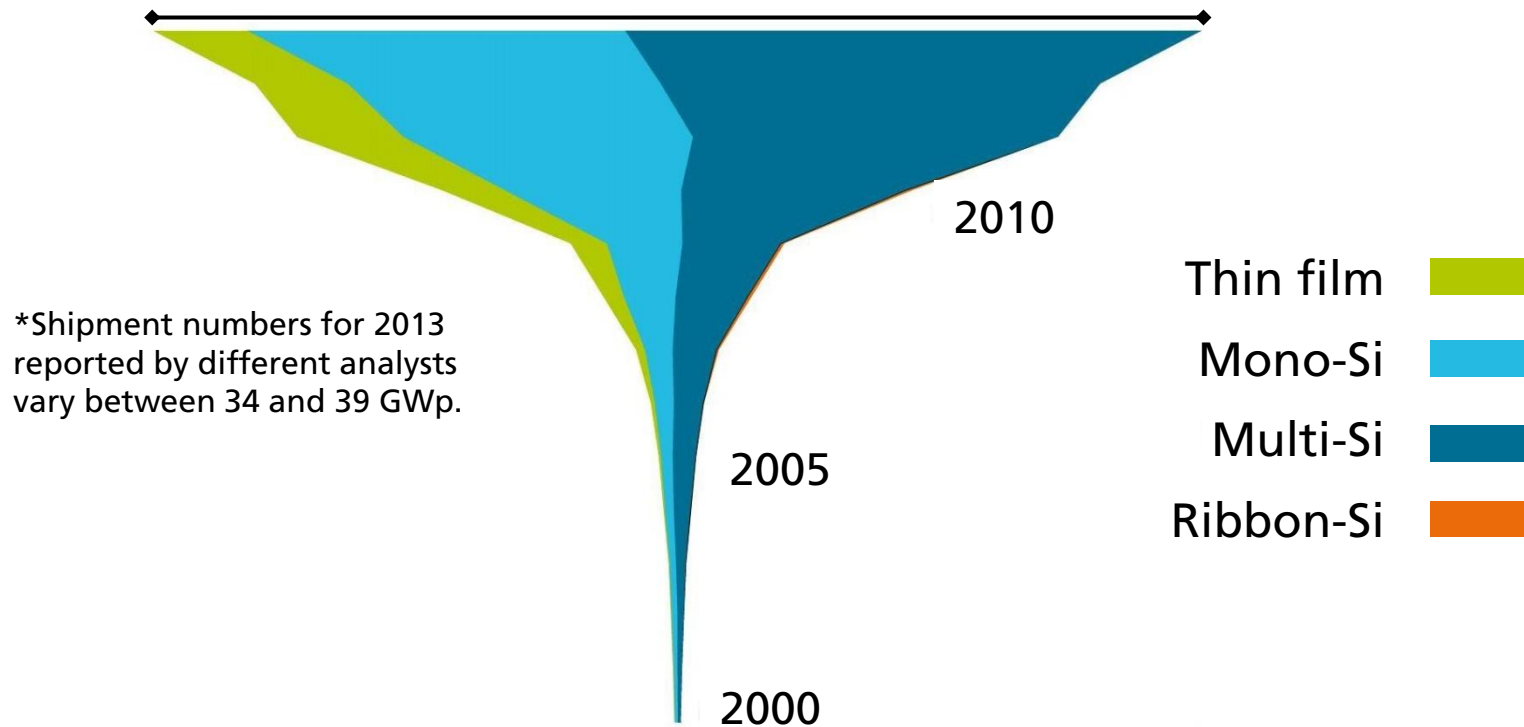
- In 2013 about 20 Mio. t of CO<sub>2</sub> emissions had been avoided due to 29.7 TWh electrical PV energy consumed in Germany.
- According to Federal Environmental Agency (UBA) the CO<sub>2</sub> avoidance factor in 2013 was 715 grams of CO<sub>2-eq</sub>/kWh<sub>el</sub>.

Data: BMU, BDEW, BMWi, UBA 2013. Graph: PSE AG 2014



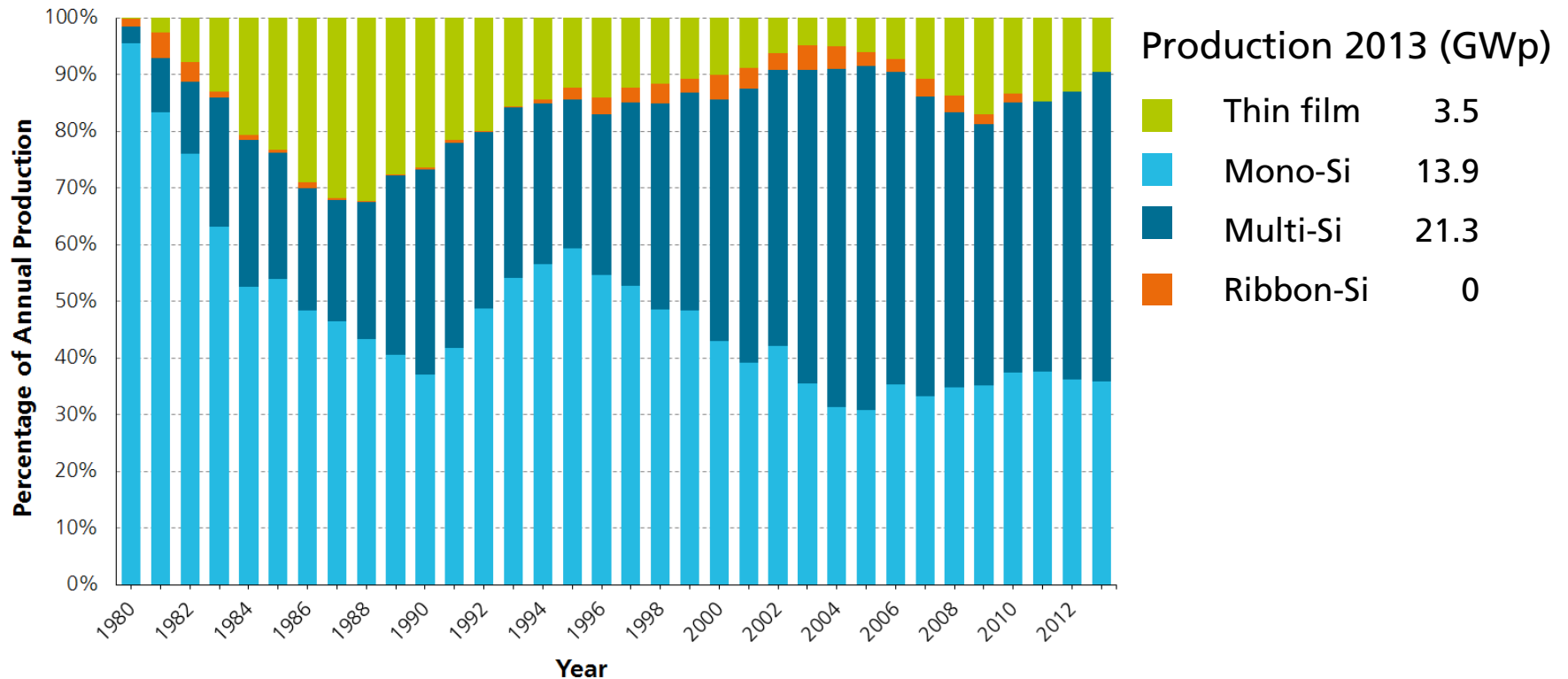
# Global Annual PV Production by Technology

About 39\* GWp PV module shipments  
in 2013



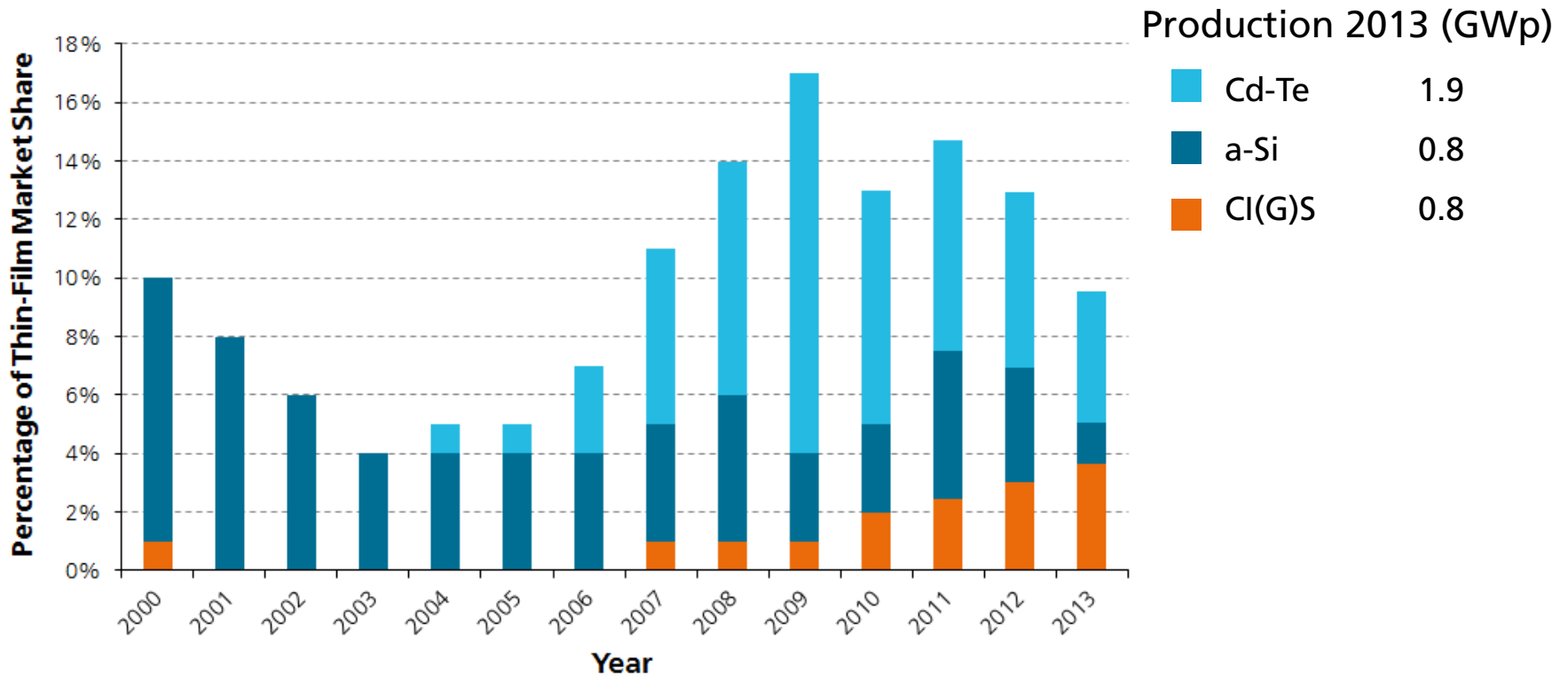
Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion estimated). Graph: PSE AG 2014

# PV Production Development by Technology



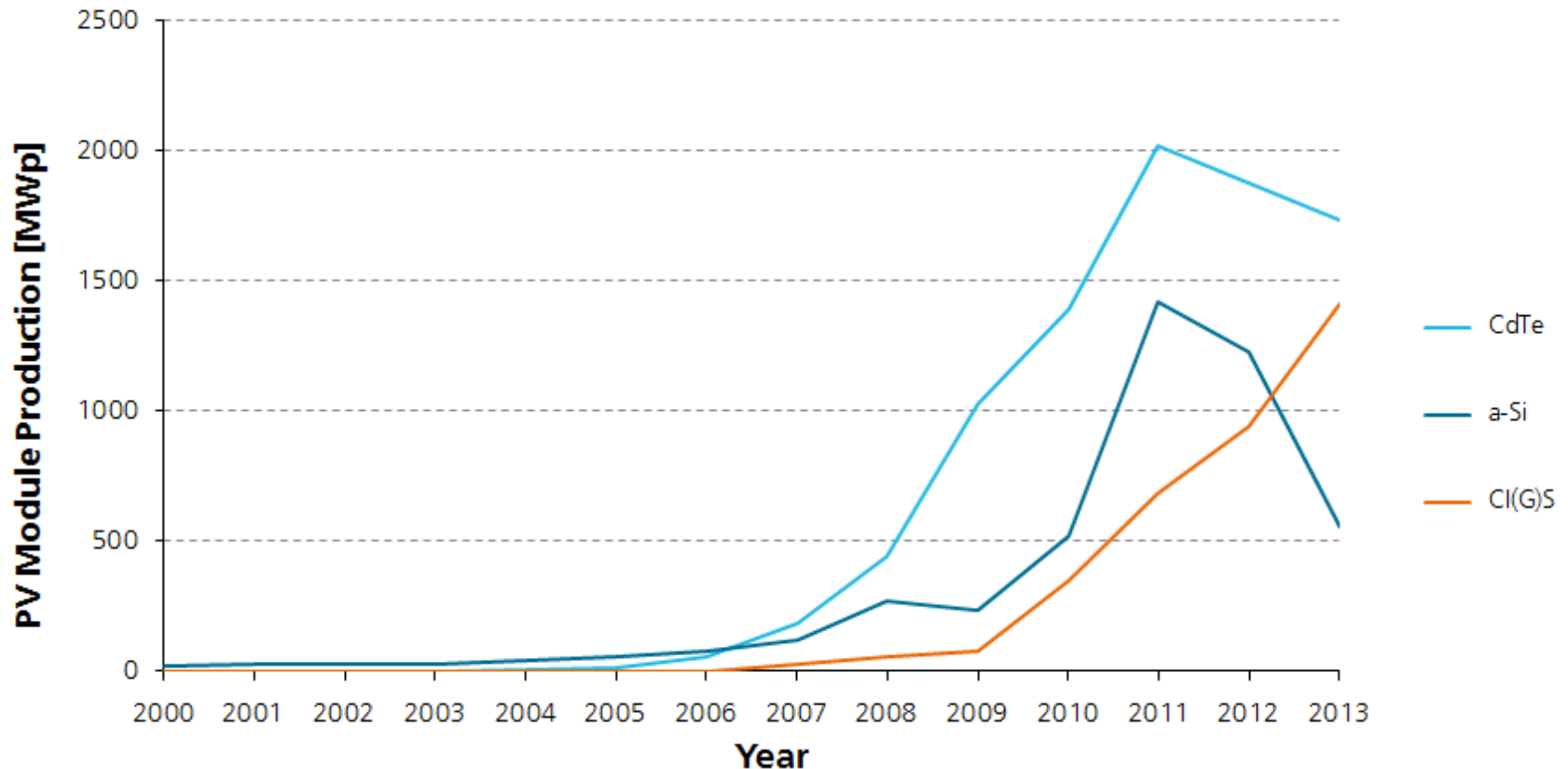
Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion estimated). Graph: PSE AG 2014

# Market Share of Thin-Film Technologies Related to Total Worldwide PV Production



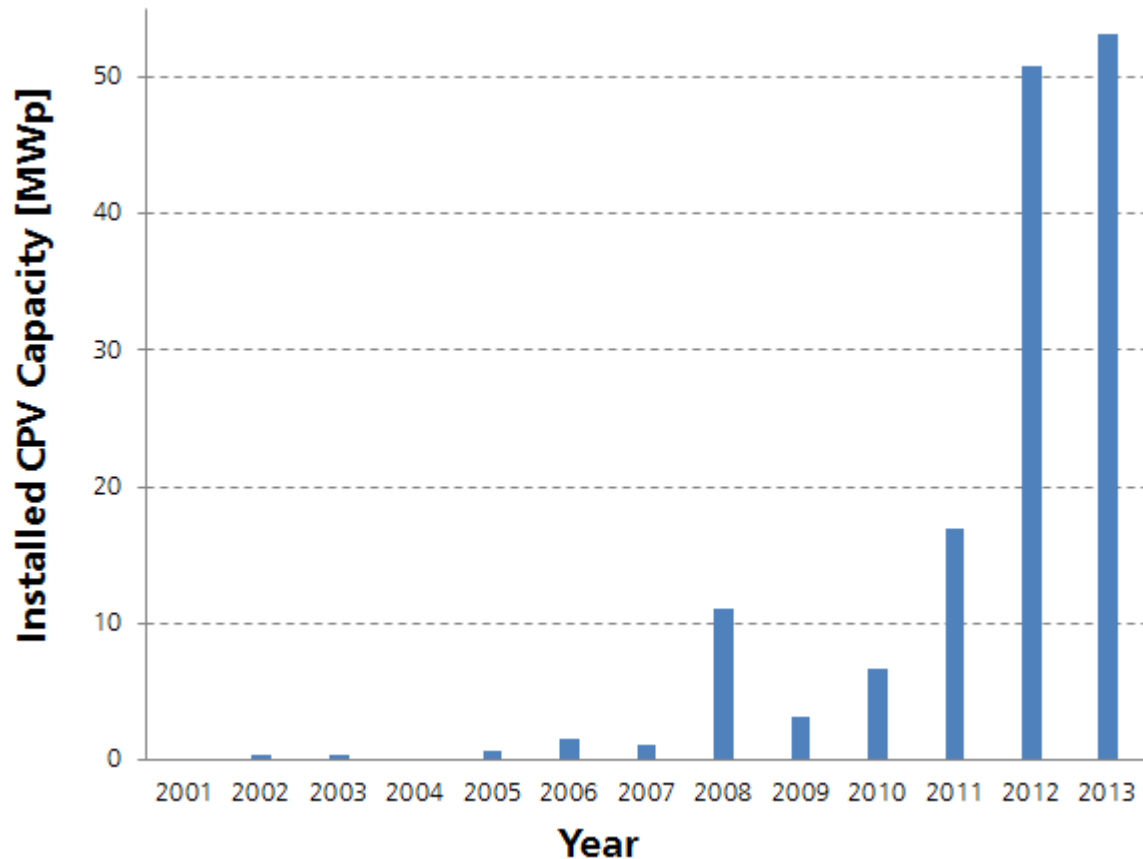
Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion estimated). Graph: PSE AG 2014

# Thin-Film Technologies Worldwide Annual PV Module Production in MWp



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion estimated). Graph: PSE AG 2014

# Yearly Installed Capacity of High Concentration Photovoltaic Systems (HCPV)\*



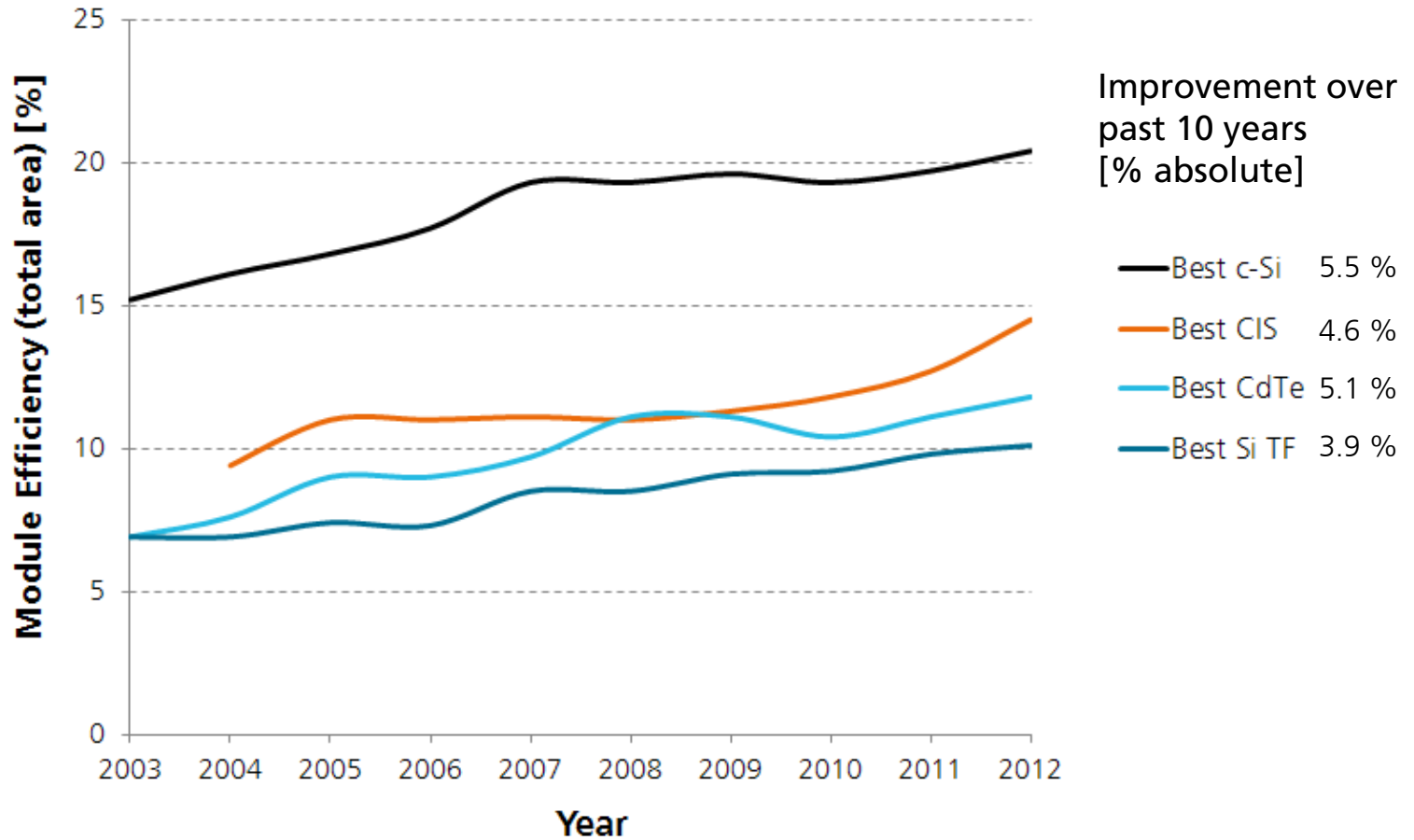
\*HCPV has a concentration factor from 300 up to 1000 suns

Data: ISE 2014. Graph: PSE AG 2014

## 2. Solar Cells / Modules / System Efficiency

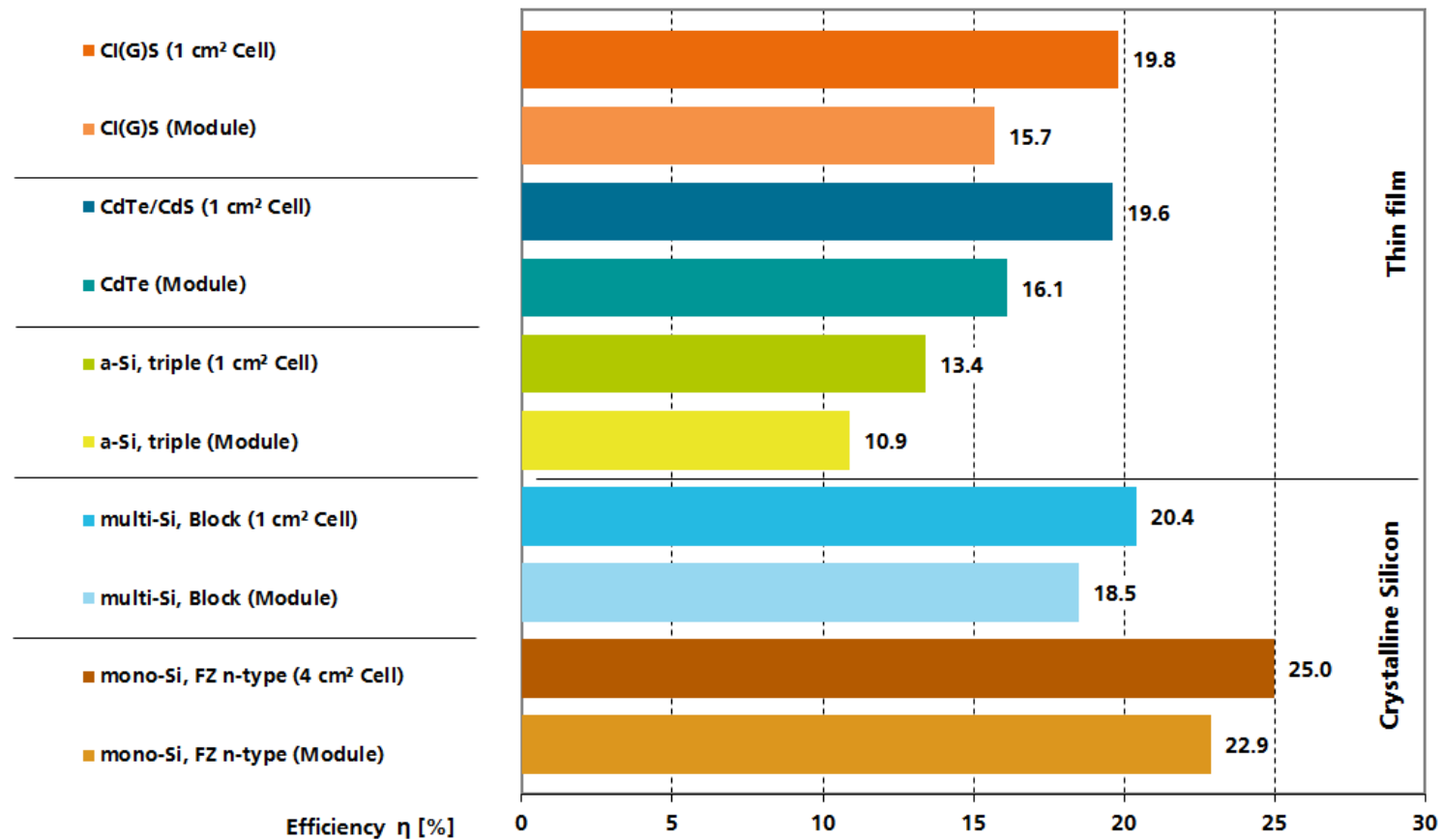
- Development in the PV Industry
- Development in the Laboratories
- High Concentration Photovoltaics (HCPV)
- Performance Ratio (PR)

# Industrial PV Module Efficiency [%] – Best Modules



Data: Photon 2/2003-2009, Photon Profi 2/2010-2/2012. Graph: Willeke Fraunhofer ISE 2013

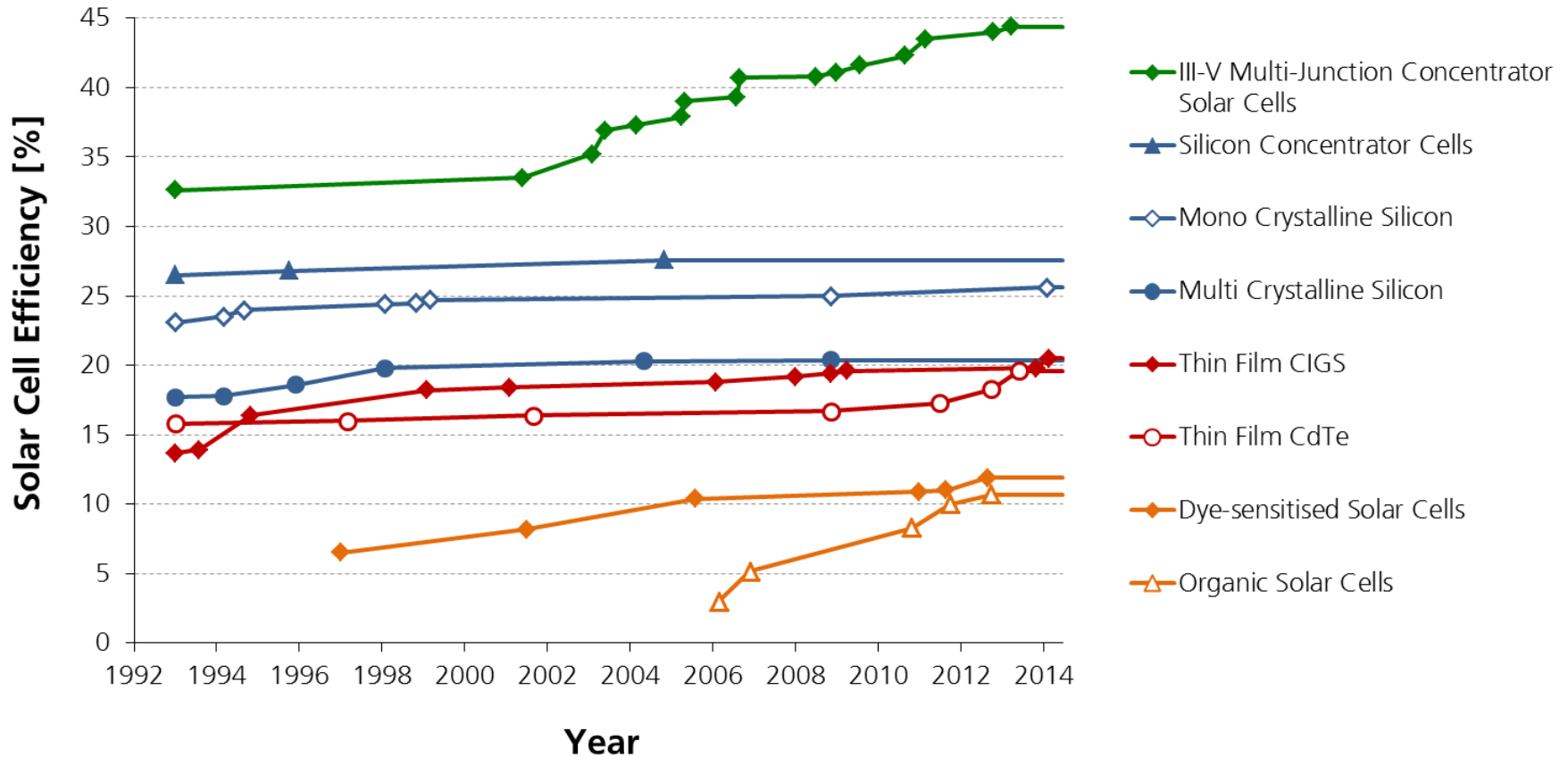
# Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables, (Version 1-43), Progress in PV: Research and Applications 2014. Graph: PSE AG 2014



# Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Version 1-43), Progress in PV: Research and Applications, 1993-2014. Graph: Simon Philipps, Fraunhofer ISE 2014

# High Concentration Photovoltaics (HCPV) Specific Aspects and Efficiencies

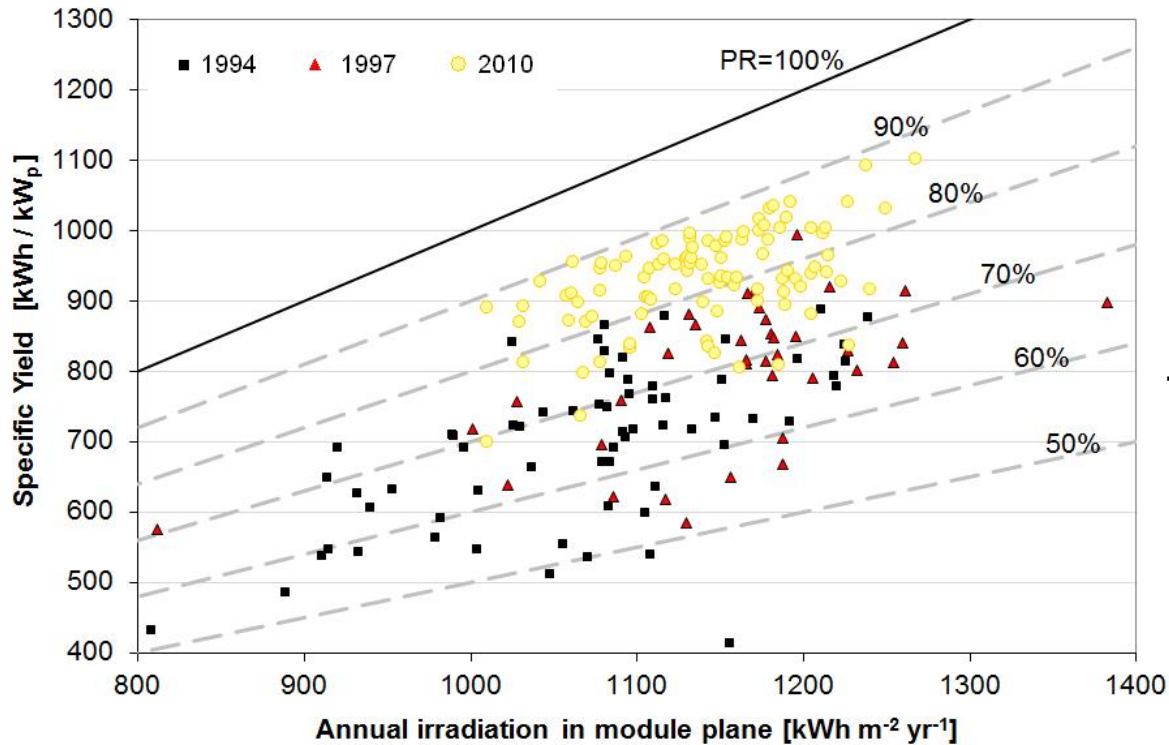
- HCPV is suitable for areas with high direct normal irradiance
- Concentrating optics are used to focus the light on small solar cells
- Concentration levels above 400 suns have become standard
- Various designs of HCPV systems are commercially available
- High efficiencies are achieved (see table)



Efficiencies	Lab Record	Commercial
Solar Cell	44.7 % (ISE, Soitec, CEA, HZB)	38-42%
Module	36.7% (ISE, Soitec, CEA)	26-32%
System (AC)	N.A.	24-28%

Source: Fraunhofer ISE, Progress in Photovoltaics, Sempruis 2012

# Performance Ratio Development of PV Systems in Germany



In the 1990's

- Typical PR ~70 %
- Very wide PR-range

Today

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

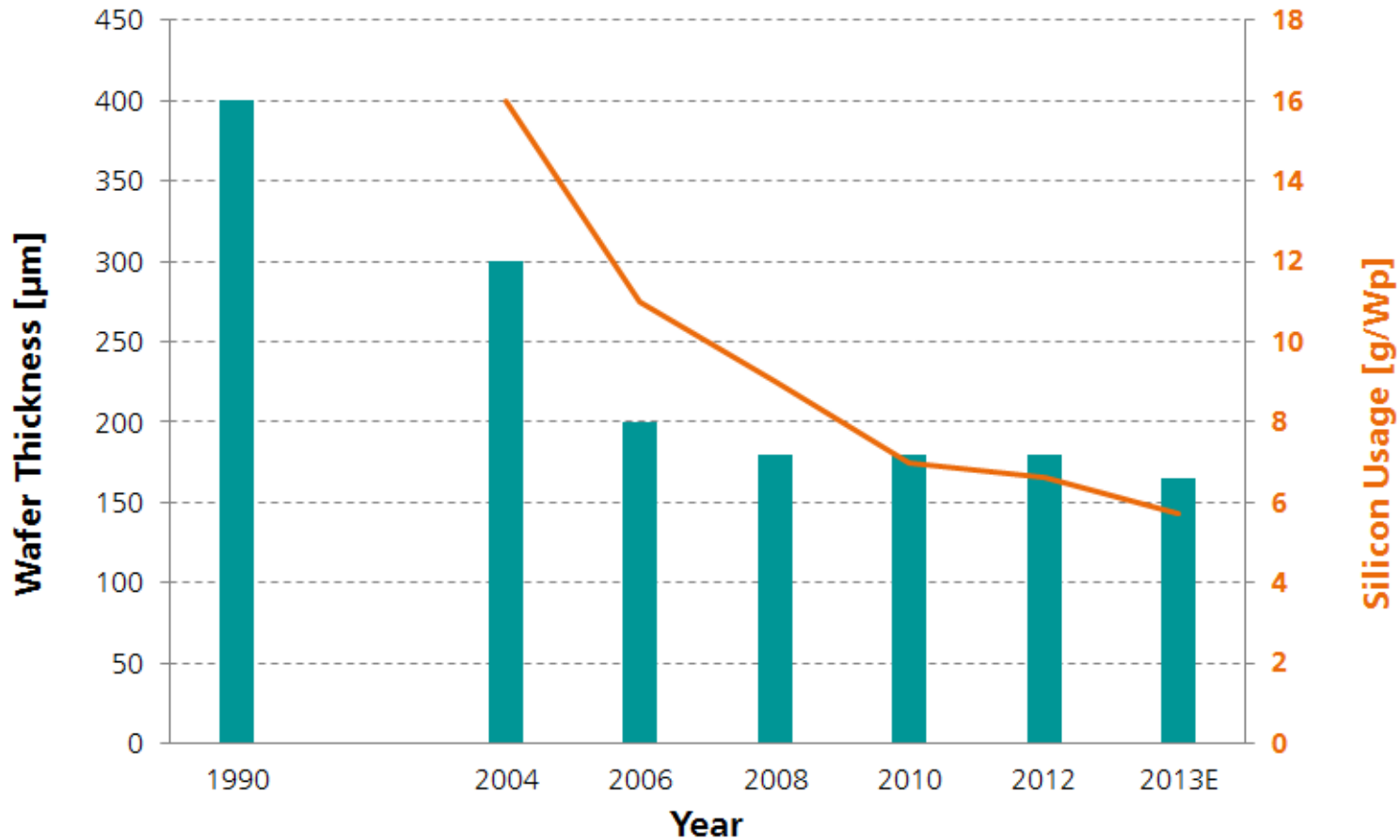
Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation

# 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]



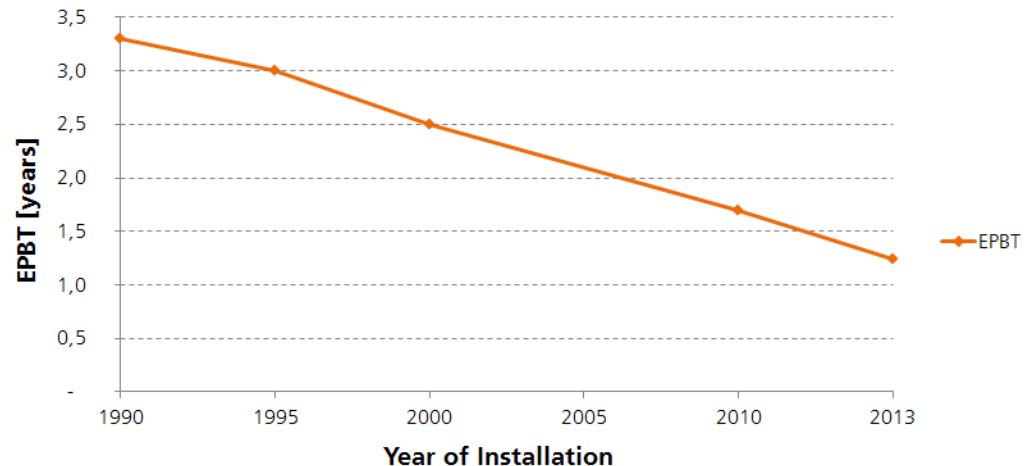
Data: until 2012: EU PV Technology Platform Strategic Research Agenda, for 2012: c-Si Roadmap ITRPV; 2013: Estimation. Graph: PSE AG 2013

# 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\*

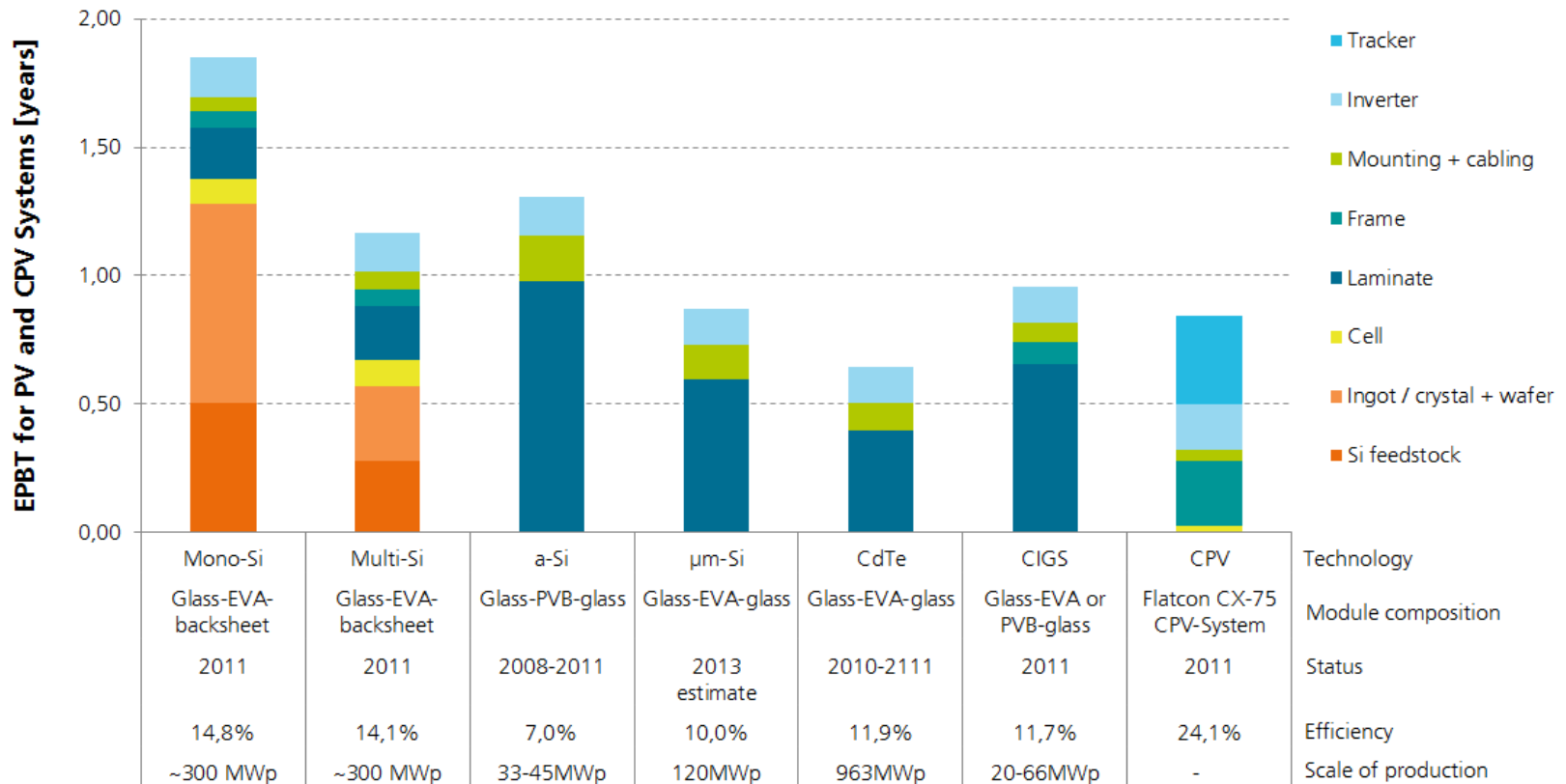


\*Irradiation: 1700 kWh/m<sup>2</sup>/a at an optimized tilt angle

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 from different Technologies in Catania, Sicily, Italy

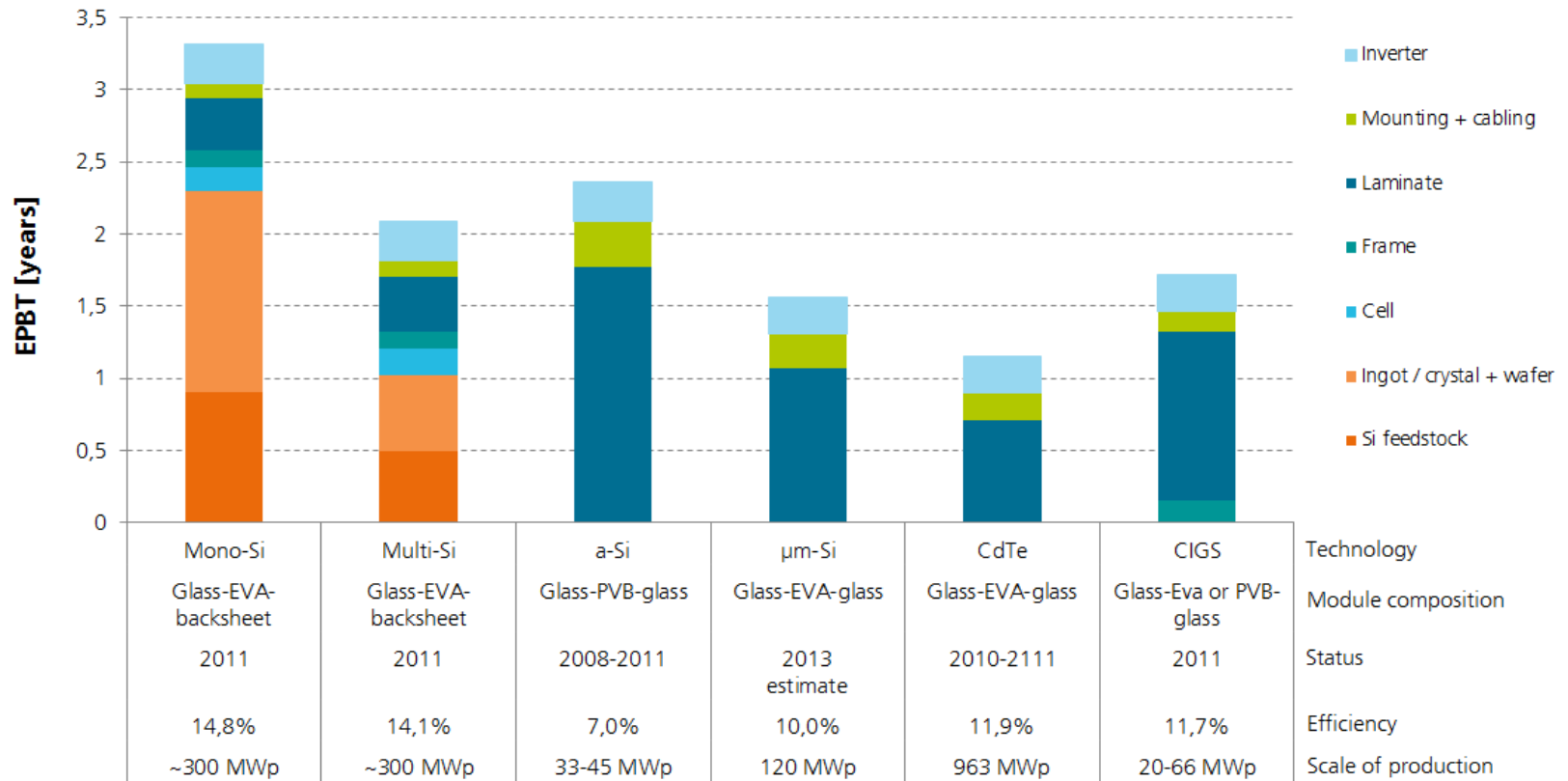
Global Irrad.: 1925 kWh/m<sup>2</sup>/yr, Direct Normal Irrad.: 1794 kWh/m<sup>2</sup>/yr



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 from different Technologies in Germany

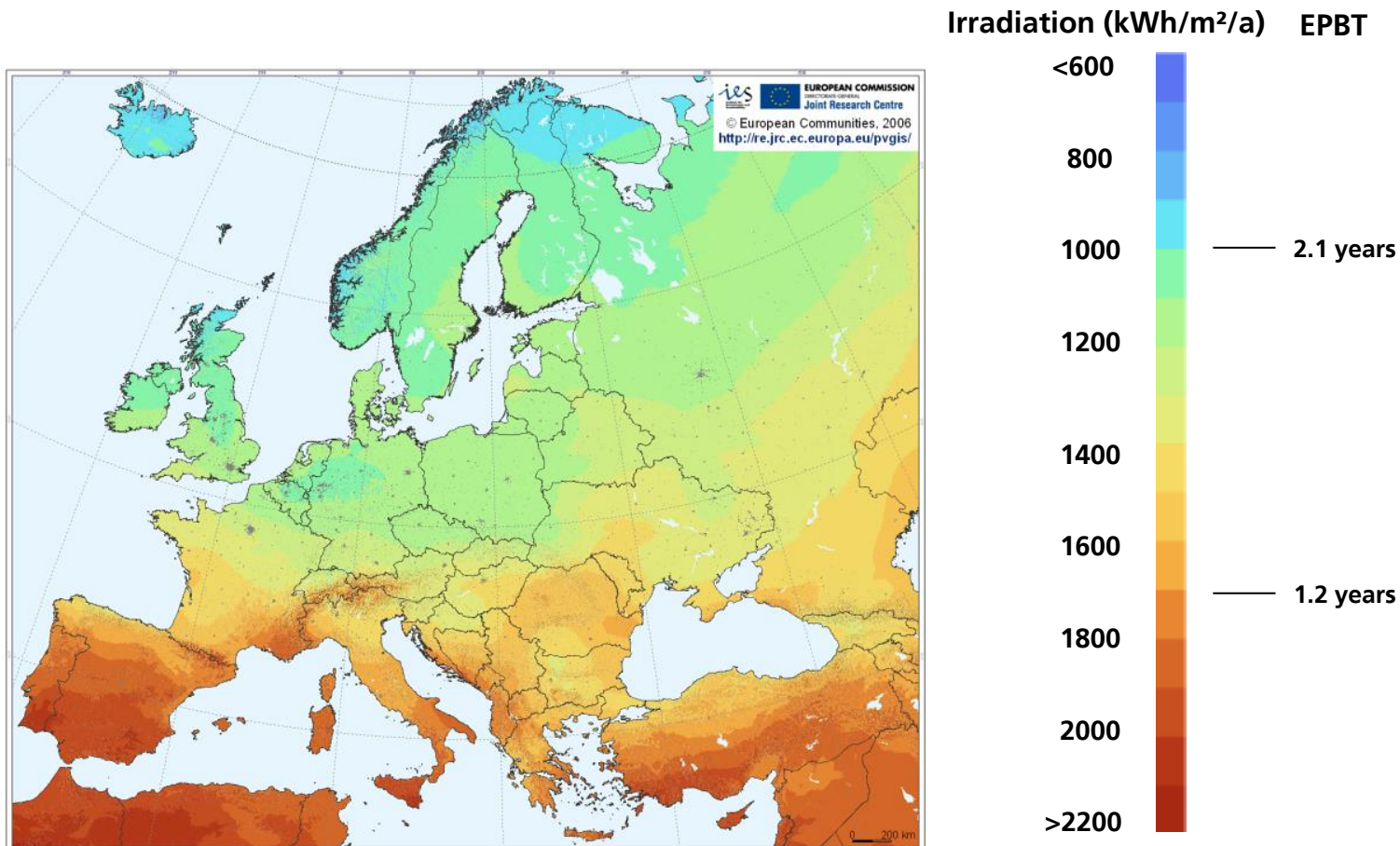
Global Irrad.: 1000 kWh/m<sup>2</sup>/yr



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

Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	Up to 100 kWp	98%	~ 50%	<ul style="list-style-type: none"> <li>• ~ 15 €-cents /Wp</li> <li>• Easy to replace</li> </ul>
Central Inverters	More than 100 kWp	Up to 98.5%	~ 48 %	<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%	~ 1.5 %	<ul style="list-style-type: none"> <li>• ~ 40 €-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>• ~ 40 €-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>• ~ 0.75 GWp installed in 2013</li> </ul>

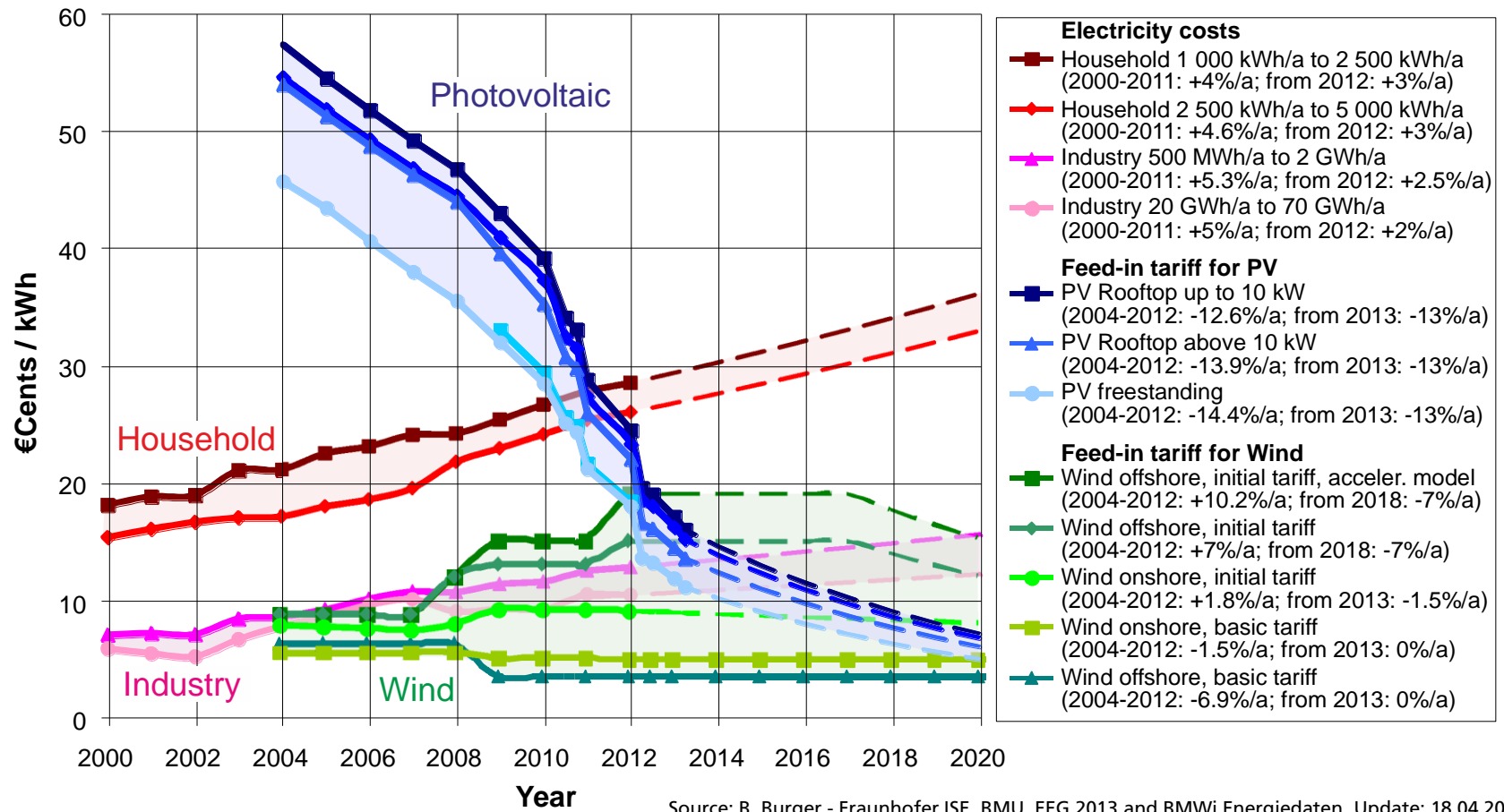
Data: IHS 2014. Remarks: Fraunhofer ISE 2014. Graph: PSE AG 2014

# 5. Price Development

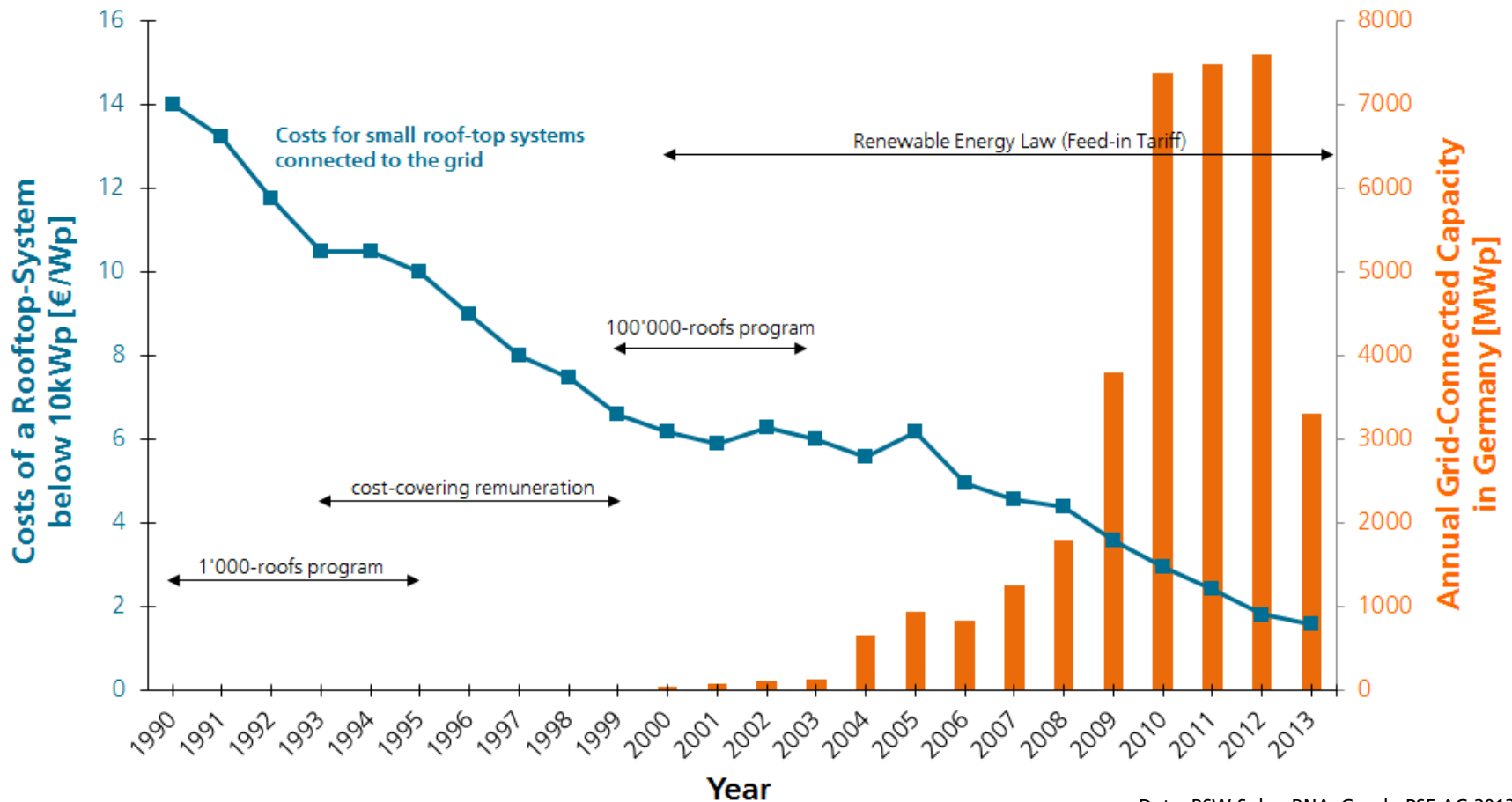
- Electricity costs
- Costs for rooftop systems
- Market incentives in Germany
- Price Learning Curve

# Electricity Costs and Feed-In Tariffs in Germany

Zu aktualisieren

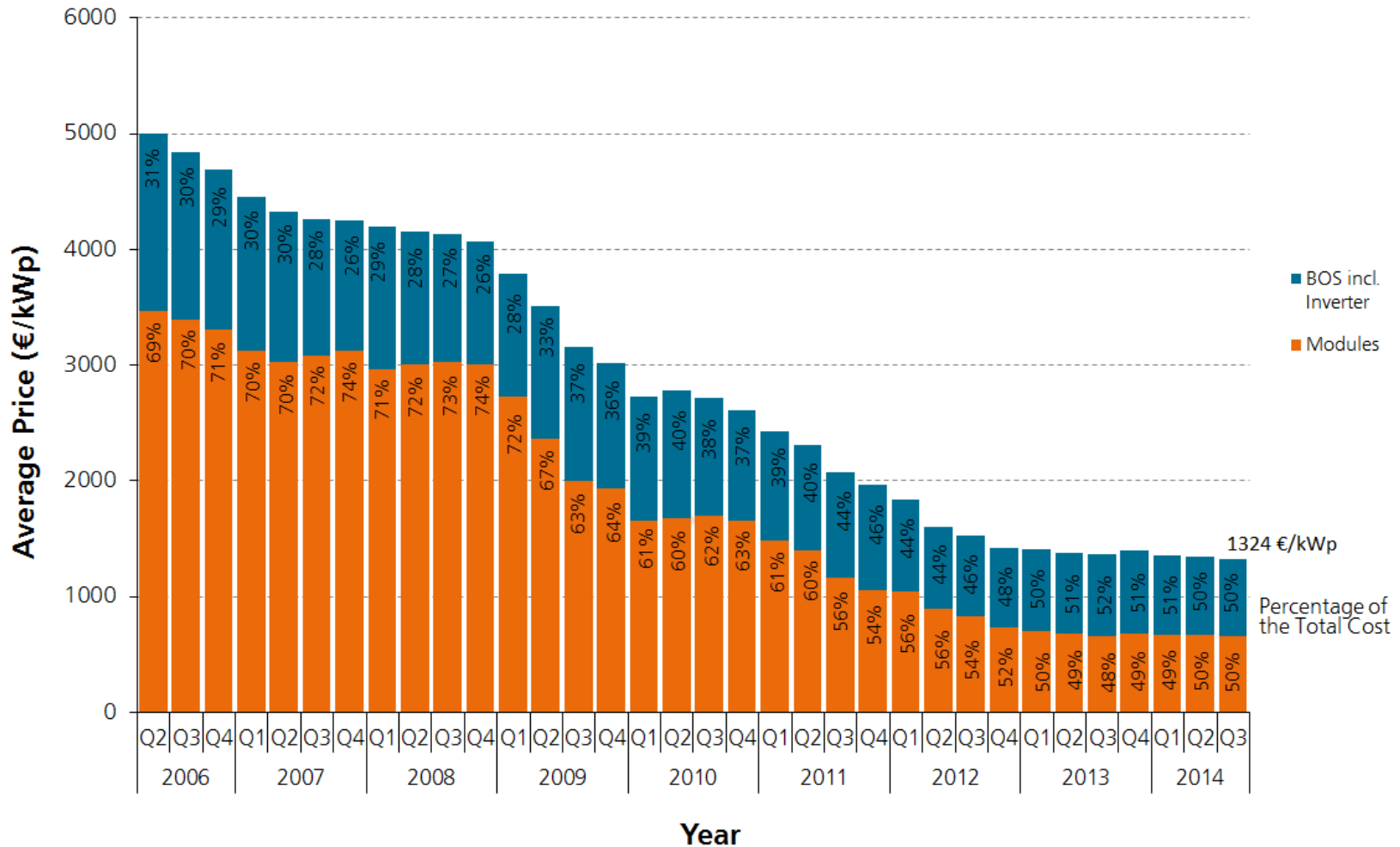


# Investment for Small Rooftop PV Systems in Relation to Market Development and Subsidy Schemes in Germany



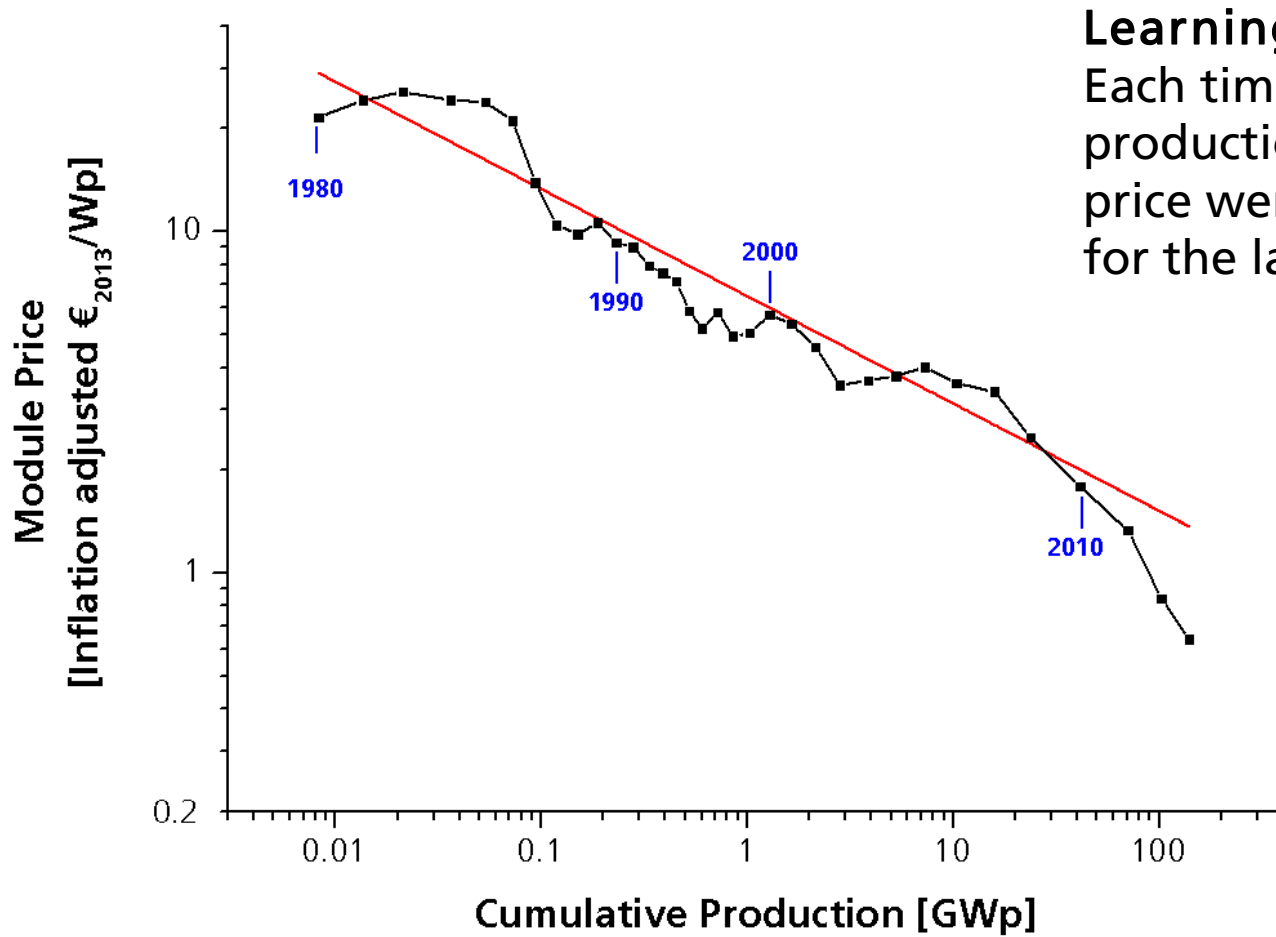
Data: BSW-Solar, BNA. Graph: PSE AG 2013

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



Data: BSW-Solar. Graph: PSE AG 2014

# Price Learning Curve (all bulk PV Technologies)



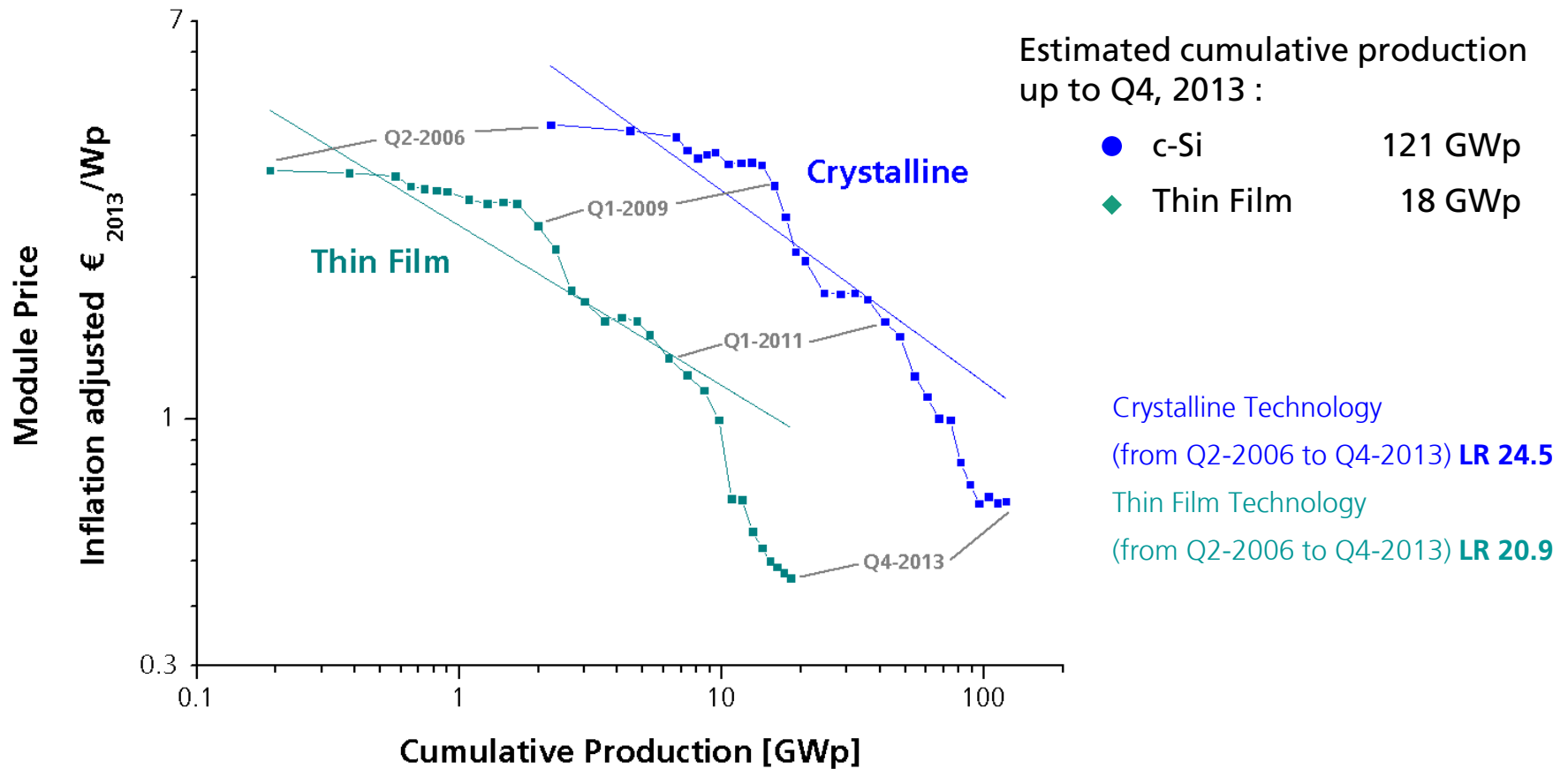
**Learning Rate:**  
Each time the cumulative production doubled, the price went down by 20 % for the last 33 years.

Data: Navigant Consulting, EuPD, IHS, pvXchange. Graph: PSE AG 2014



# Price Learning Curve by Technology

## Cumulative Production up to Q4. 2013



Data: Navigant Consulting; for 2012 and 2013: estimation from different sources (Navigant and IHS); EUPD; pvXchange. Graph: PSE AG 2014

# 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
Roland Schindler	ISE
Thomas Schlegl	ISE
Gerhard Stryi-Hipp	ISE
Gerhard Willeke	ISE
Harry Wirth	ISE
Ingo Brucker	PSE
Andreas Häberle	PSE
Volker Schacht	PSE
Werner Warmuth	PSE