PHOTOVOLTAICS REPORT

Prepared by

Fraunhofer Institute for Solar Energy Systems, ISE

with support of PSE Projects GmbH

Freiburg, 30 June 2021

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CONTENT

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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 However, facts and figures change rapidly, and the given information may soon be outdated again.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 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:
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Quick Facts

Parameter	Value	Status	Reference
	Germany / EU27 / Worldwide		
PV market	4.9 / 18.2 / 135 GW	End of 2020	BNA / SPE / BNE
Cumulative installation	53.6 / 137.2 / 707.5 GW	End of 2020	ISE / SPE / IRENA
PV power generation	46.4 / 125 / 724 TWh	2019	ISE / BP / BP
PV electricity share	9.1% (net) / gross: 4.3% / 2.7%	2019	ISE / BP / BP
	Worldwide		
c-Si share of production	95%	2020	IHS Markit
Record solar cell efficiency: III-V MJ (conc.) / mono-Si / CIGS / multi-Si / CdTe	47.1 / 26.7 / 23.4 / 24.4 / 21.0%	June 2021	Green et al.
	Germany		
Price PV rooftop system	890 to 1,850 €/kWp	End of 2020	BSW
LCOE PV power plant	3.1 to 5.7 ct€ / kWh	2021	ISE
Lowest PV-Tender Price (Germany)	4.33 ct€ / kWh	Feb. 2018	BNA

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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 34% between year 2010 to 2020.
- In year 2020 producers from Asia count for 95% of total c-Si PV module production. China (mainland) holds the lead with a share of 67%. Europe contributed with a share of 3%; USA/CAN with 2%.
- Wafer size increased enabling larger PV module size allowing a power range from +600 W per module.
- In 2020, Europe's contribution to the total cumulative PV installations amounted to 22% (compared to 24% in 2019). In contrast, installations in China accounted for 33% (same value as the year before).
- Si-wafer based PV technology accounted for about 95% of the total production in 2020. The share of mono-crystalline technology is now about 84% (compared to 66% in 2019) of total c-Si production.
- Market shifts from subsidy driven to competitive pricing model (Power Purchase Agreements PPA).

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Executive Summary
PV Market: Focus Germany

- In 2020, Germany accounted for about 7% (54 GWp) of the cumulative PV capacity installed worldwide (707.5 GWp) with about 2 million PV systems installed in Germany. In 2020 the newly installed capacity in Germany was about 5 GWp; in 2019 it was 4 GWp.
- PV covered 9.2% of Germany's gross electricity demand in 2020 while all Renewable sources delivered about 45%.
- In 2020 about 35 Mio. t CO_2 equivalent GHG emissions have been avoided due to 50.6 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%.

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Executive Summary
Solar Cell / Module Efficiencies

- The record lab cell efficiency is 26.7% for mono-crystalline and 24.4% 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 25.5%.
- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 15% to 20%. 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.

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Executive Summary
Energy Payback Time

- Material usage for silicon cells has been reduced significantly during the last 16 years from around 16 g/Wp to less than 3 g/Wp due to increased efficiencies, thinner wafers and diamond wire sawing 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 1.2 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.

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Executive Summary
Inverters

- Inverter efficiency for state-of-the art brand products is 98% and higher.
- The market share of string inverters is estimated to be 64%. 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 34%.
  A small proportion of the market (about 1%) belongs to micro-inverters (used on the module level). The market share for DC / DC converters, also called “power optimizers”, is estimated to be 5% of the total inverter market.
- 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.

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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 2020, such systems cost only 7.4% of the price in 1990. This is a net-price regression of about 92% over a period of 30 years.
- The Experience Curve – also called Learning Curve - shows that in the last 40 years the module price decreased by 26% with each doubling of the cumulated module production. Cost reduction results from economies of scale and technological improvements.

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1. PV Market

- By region
- By technology

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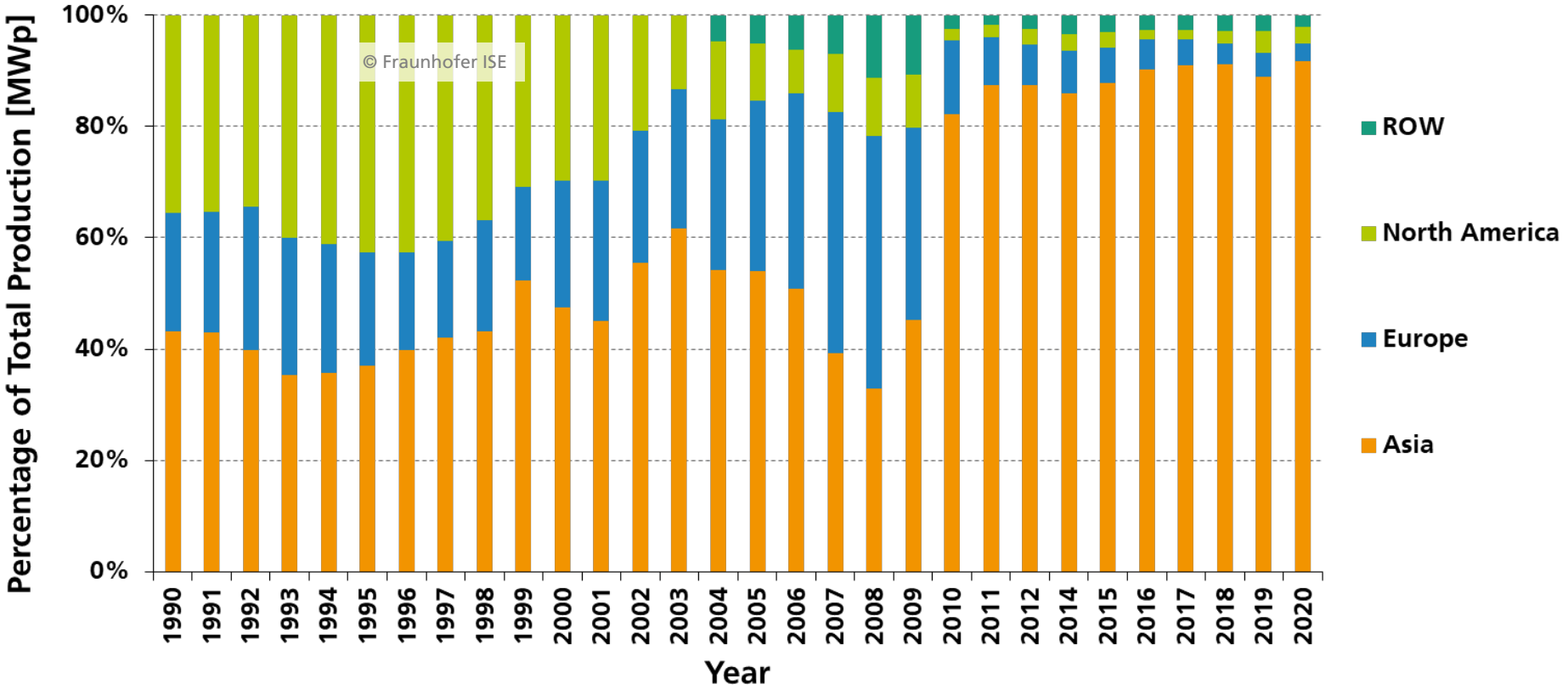
PV Module Production by Region 1990-2020

Percentage of Total MWp Produced



Data: Up to 2004 Strategies Unlimited; 2005 to 2009: Navigant Consulting; since 2010: IHS Markit. Graph: PSE Projects GmbH 2021

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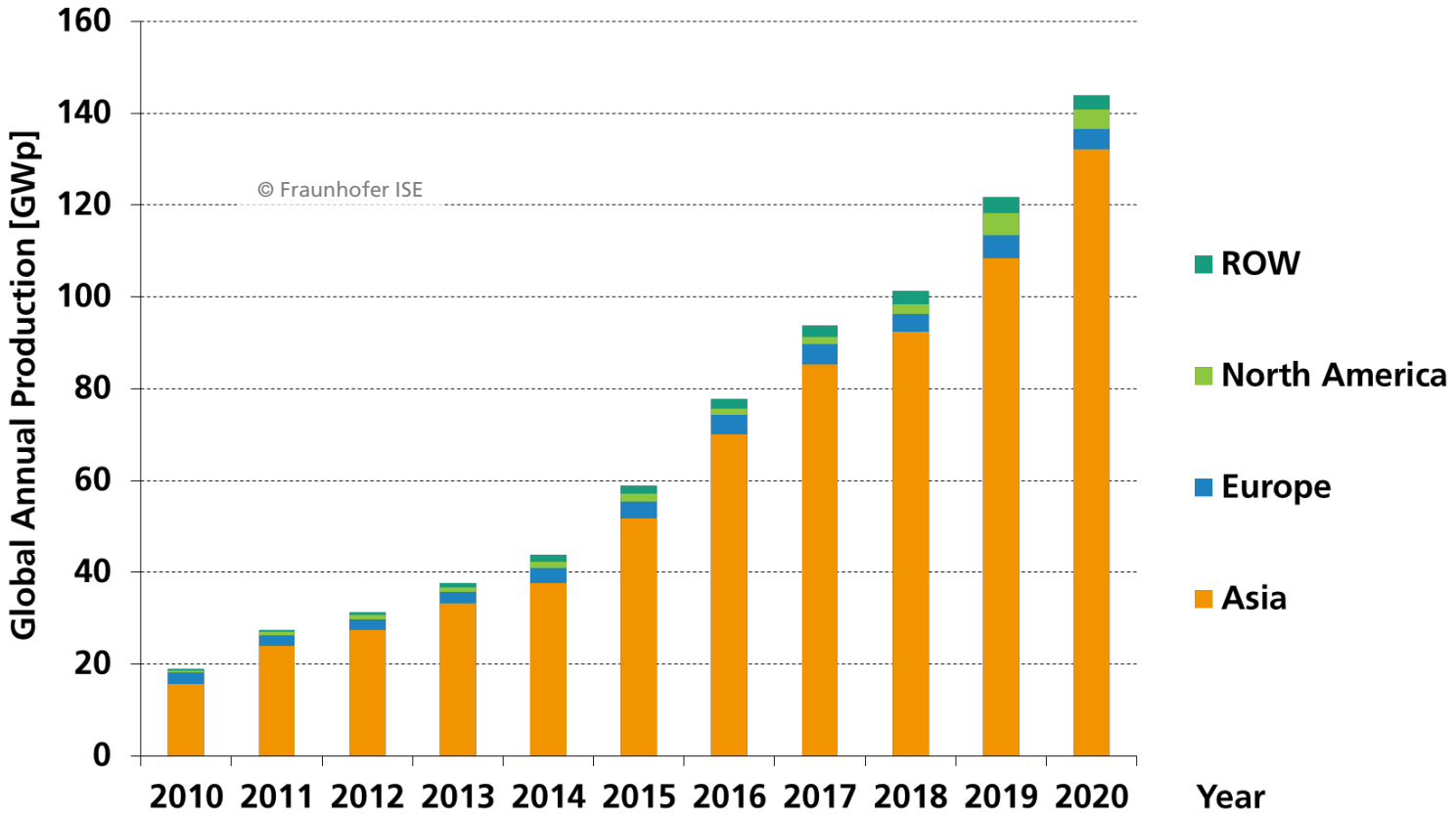
PV Module Production by Region

Global Annual Production



About 82% of the global PV module production was from Asia in year 2010. It increased to about 92% of total global production in year 2020. The annual production has increased by a factor of 7 in this decade.

Data: IHS Markit 2021. Graph: PSE Projects GmbH 2021

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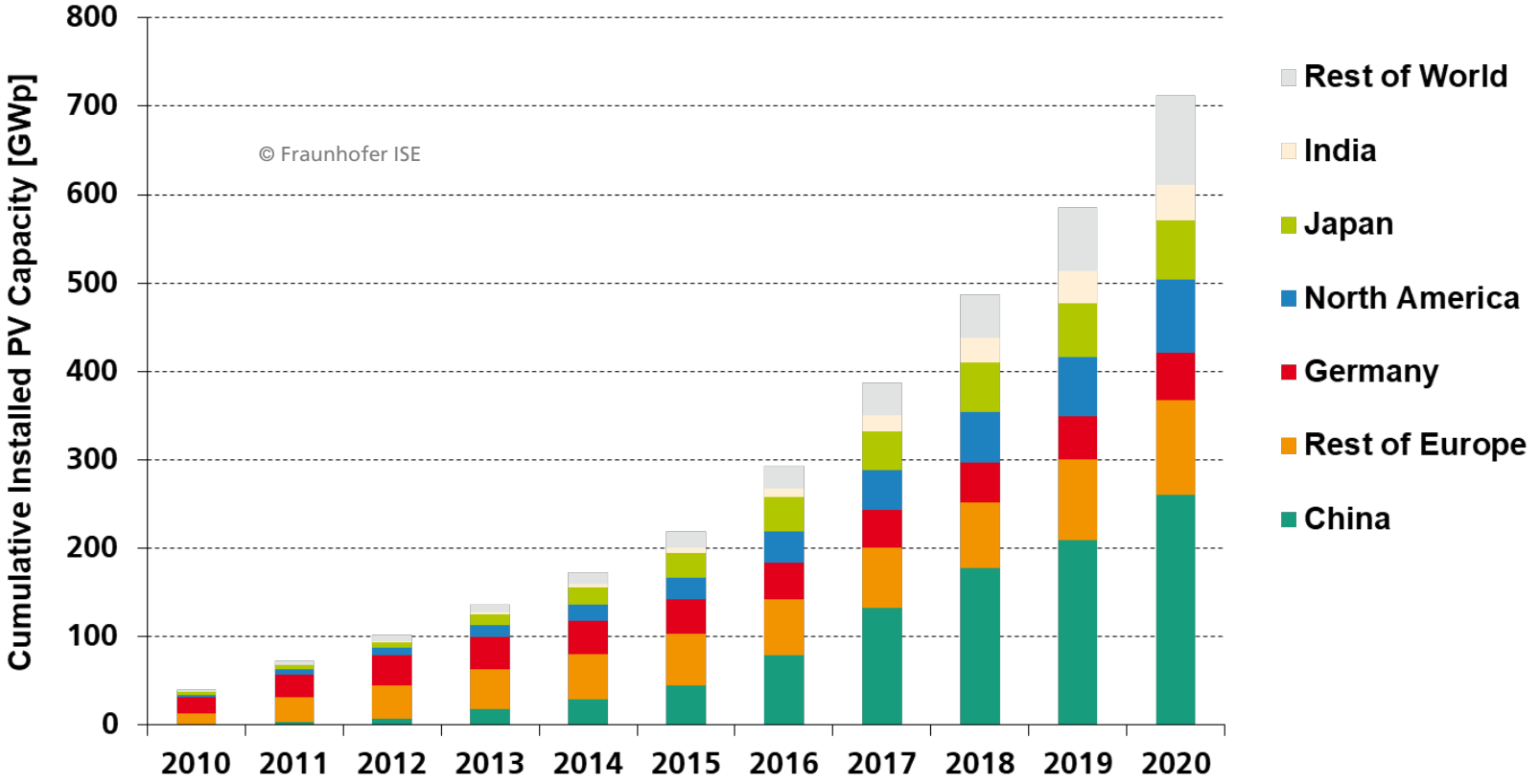
Global Cumulative PV Installation
From 2010 to 2020



Data: IRENA 2021. Graph: PSE Projects GmbH 2021

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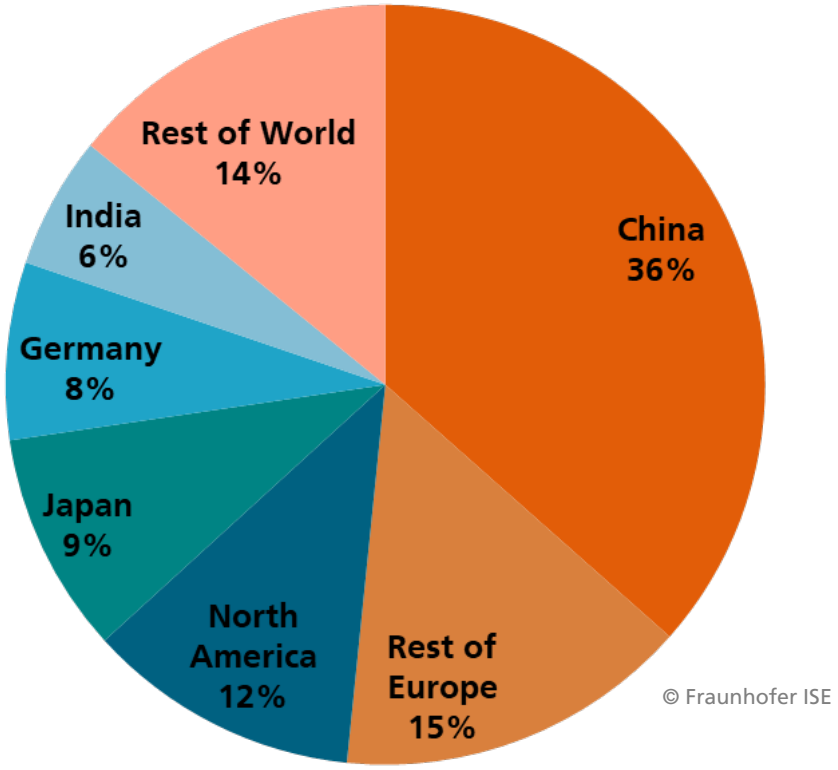
Global Cumulative PV Installation by Region

Status 2020



The total cumulative installations amounted to 708 GWp at the end of year 2020.

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

Data: IRENA 2021. Graph: PSE Projects GmbH 2021

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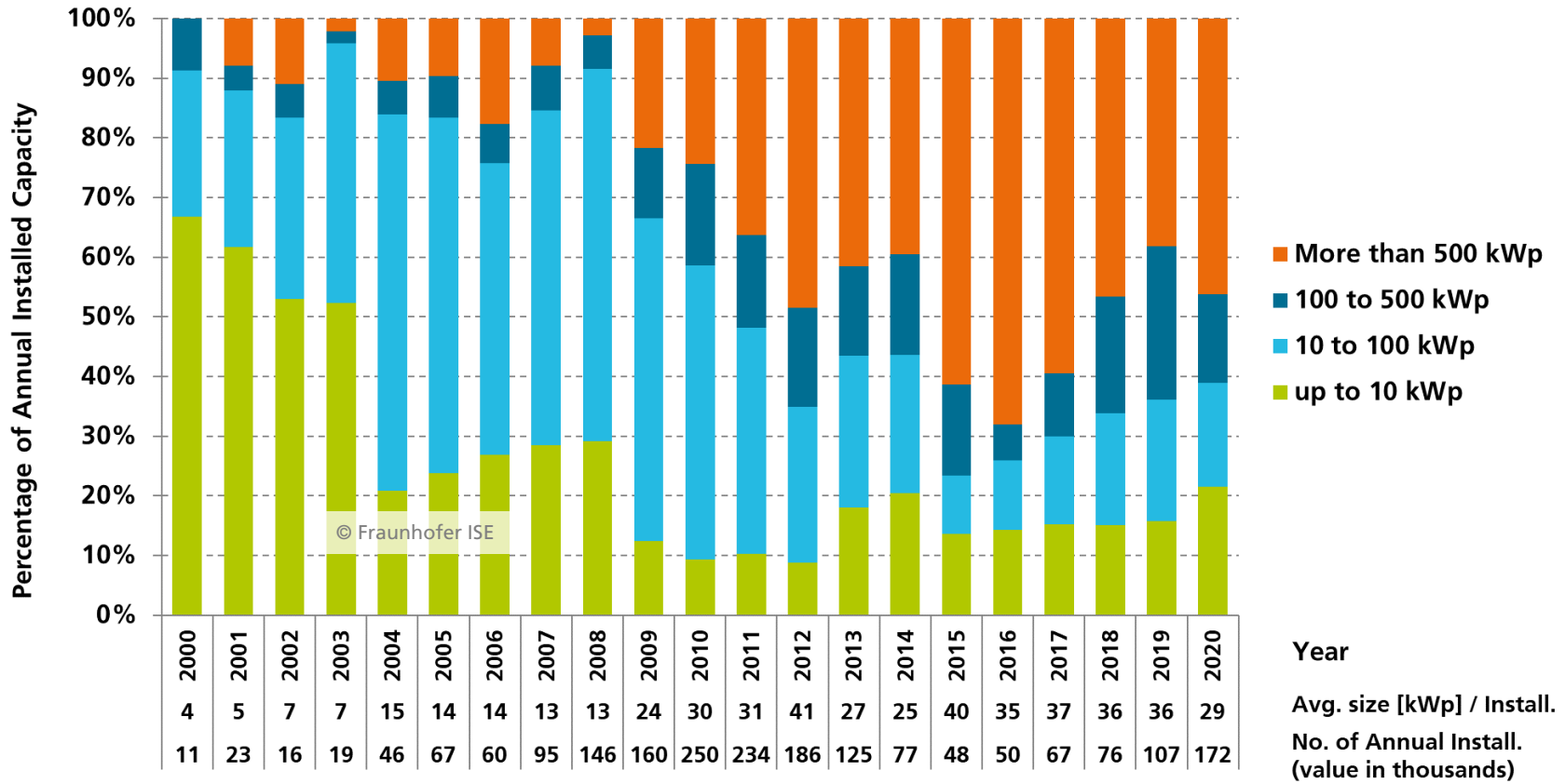
Number of PV Systems Annually Installed in Germany

Percentage of Annual Capacity by System Size



According to BNA at end of year 2020 in Germany a total cumulated PV capacity of 54 GW was installed.

Data: up to 2008: extrapolation from utilities data; since 2009: Bundesnetzagentur (BNA); The compilation is done by filtering initial PV-System operation date. Graph: PSE Projects GmbH 2021

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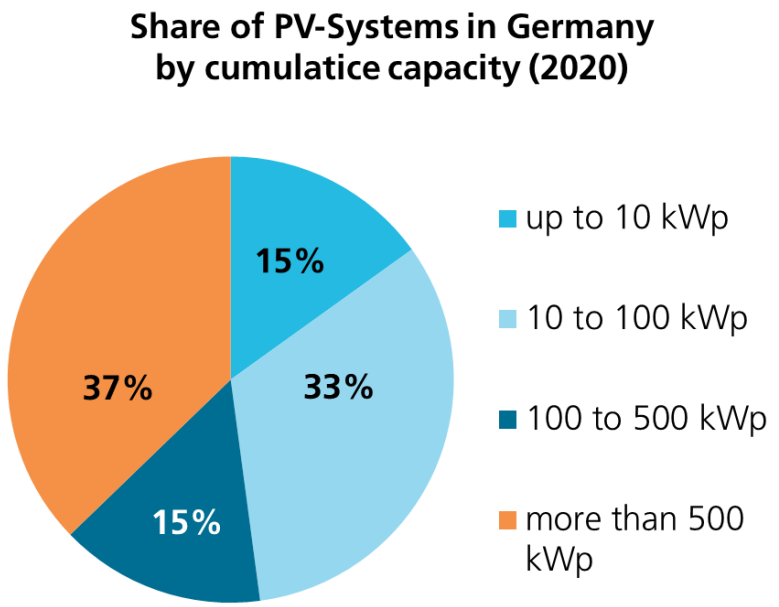
Share of Capacity and Number of PV-Systems Installed

Percentage of Cumulative Installations in Germany



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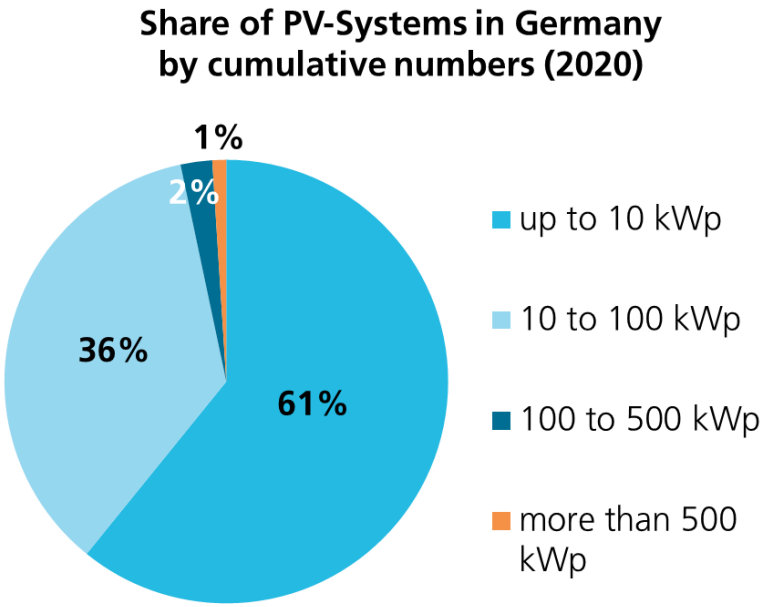

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While the larger PV-systems account for about a third of the total installed capacity, the number of large-scale systems with more than 500 kWp is only about 1% of the total installed systems.

Data: Bundesnetzagentur 2021. Graph: PSE Projects GmbH 2021

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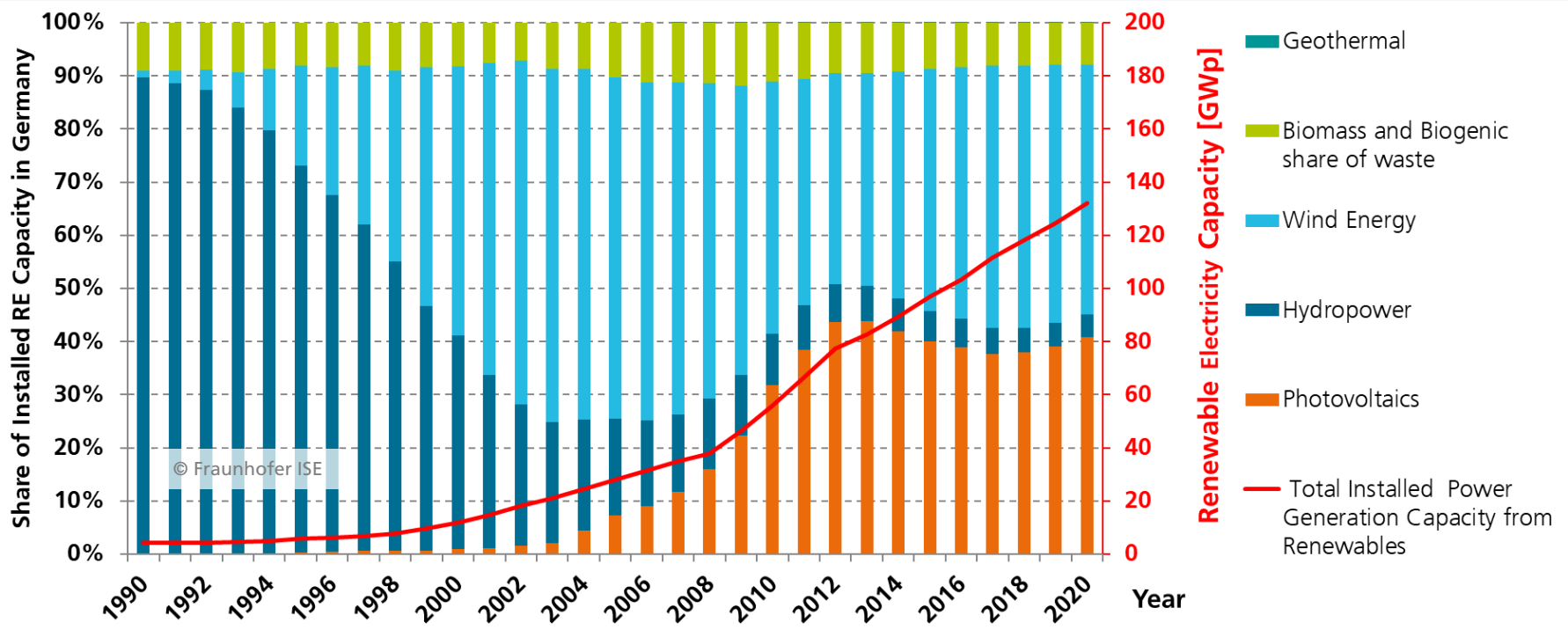
Electrical Capacity of Renewable Energy Sources

Germany



In year 2020 about 45% (251 TWh) of gross national electricity consumption was provided 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 2021

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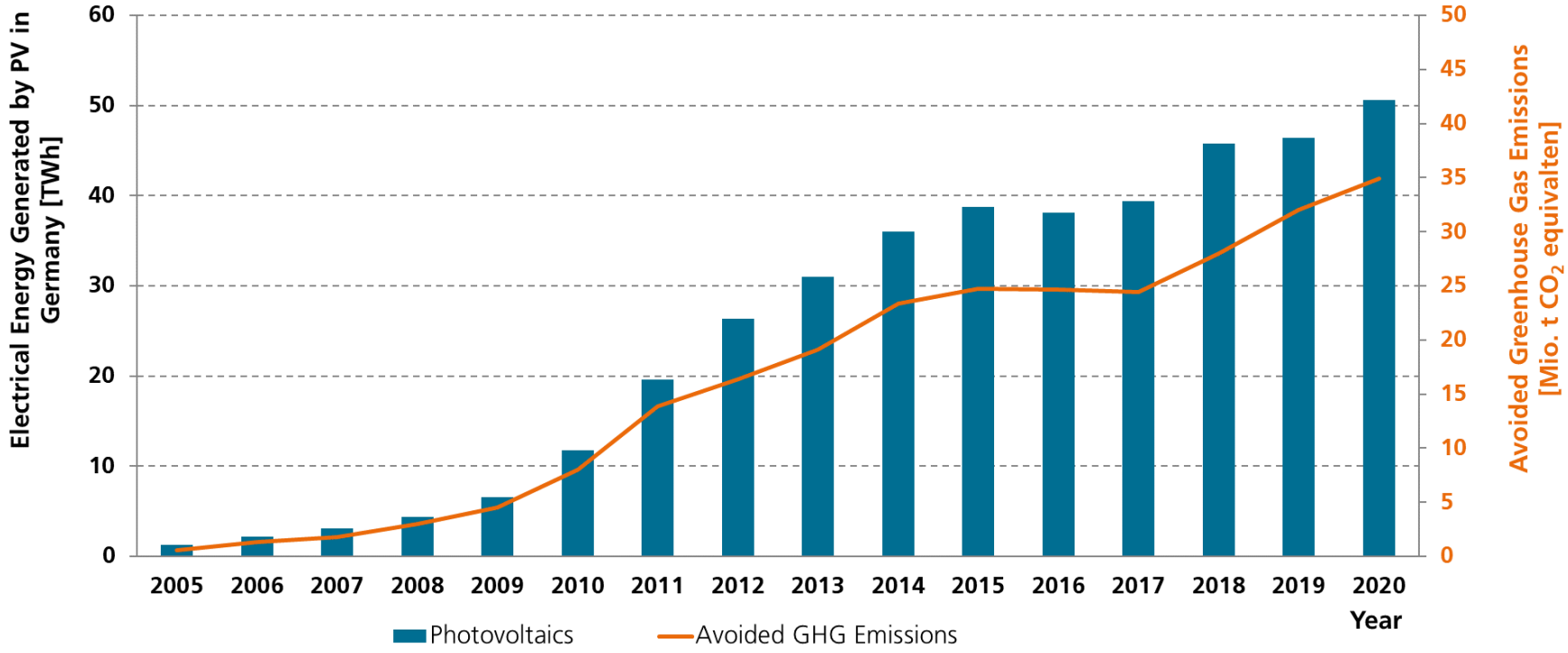
PV Energy Generated **and Resulting GHG Avoided Emissions**
Germany



- In 2020 Greenhouse Gas emissions of about 35 Mio. t CO_2-equivalent were avoided due to 50.6 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2021. Graph: PSE Projects GmbH 2021

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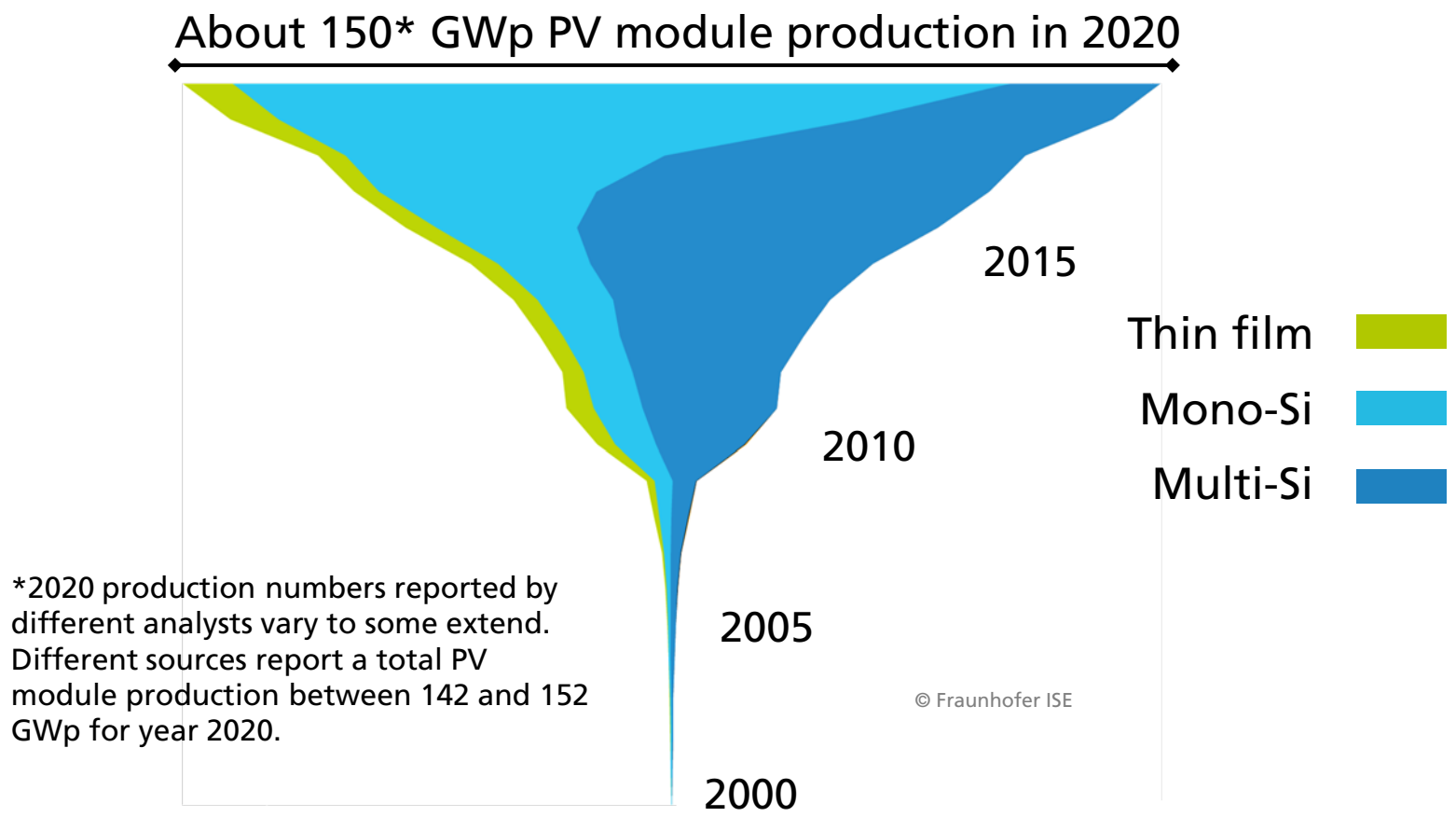
Annual PV Production by Technology
Worldwide (in GWp)



*2020 production numbers reported by different analysts vary to some extend. Different sources report a total PV module production between 142 and 152 GWp for year 2020.

Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2021

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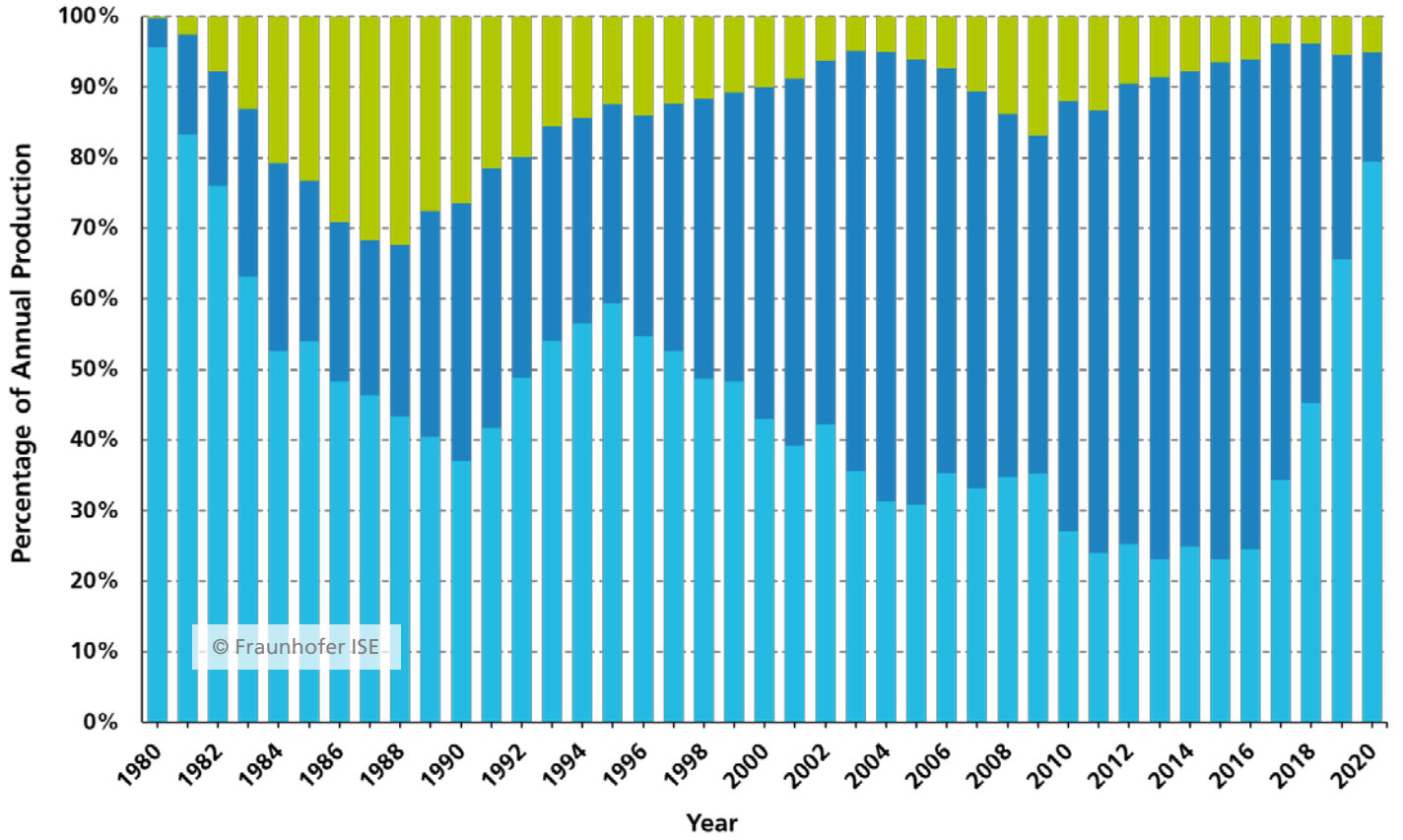
PV Production by Technology

Percentage of Global Annual Production



Production 2020 (GWp)

Thin film	7.7
Multi-Si	23.3
Mono-Si	120.6

Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2021

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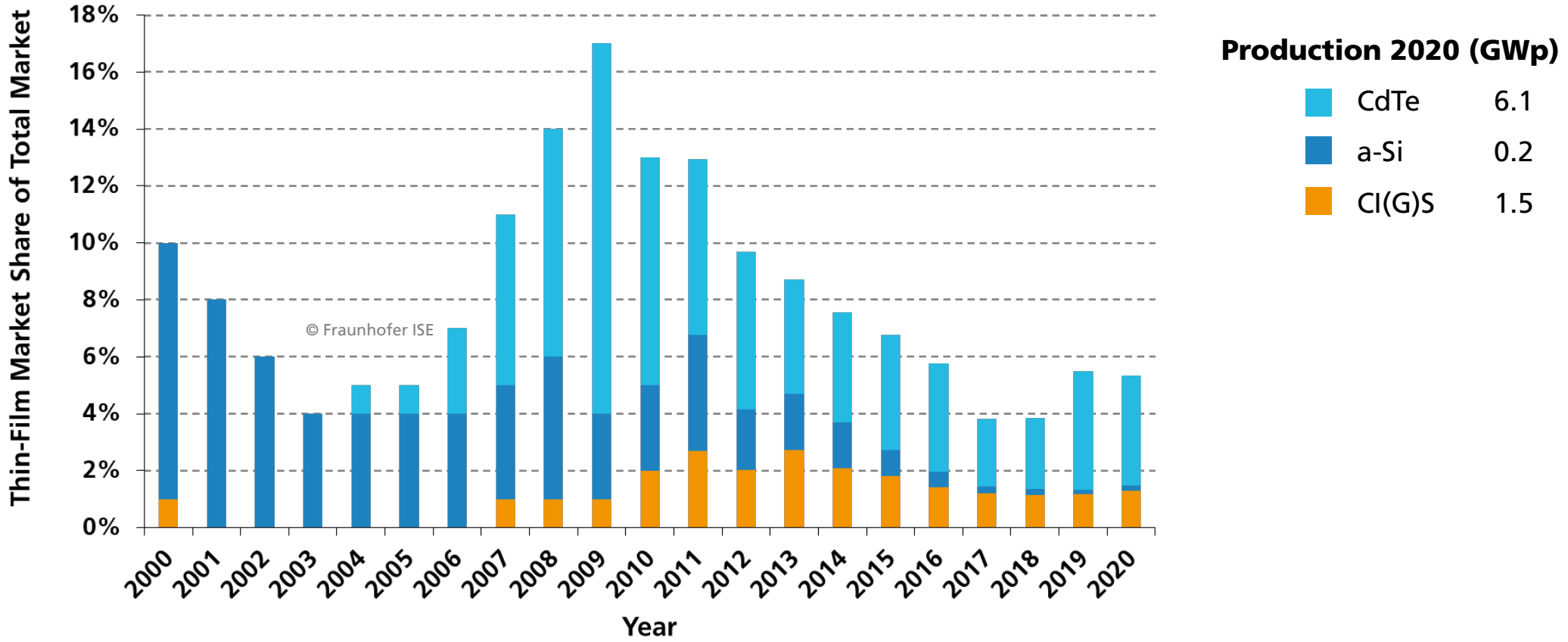
Market Share of Thin-Film Technologies

Percentage of Total Global PV Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2021

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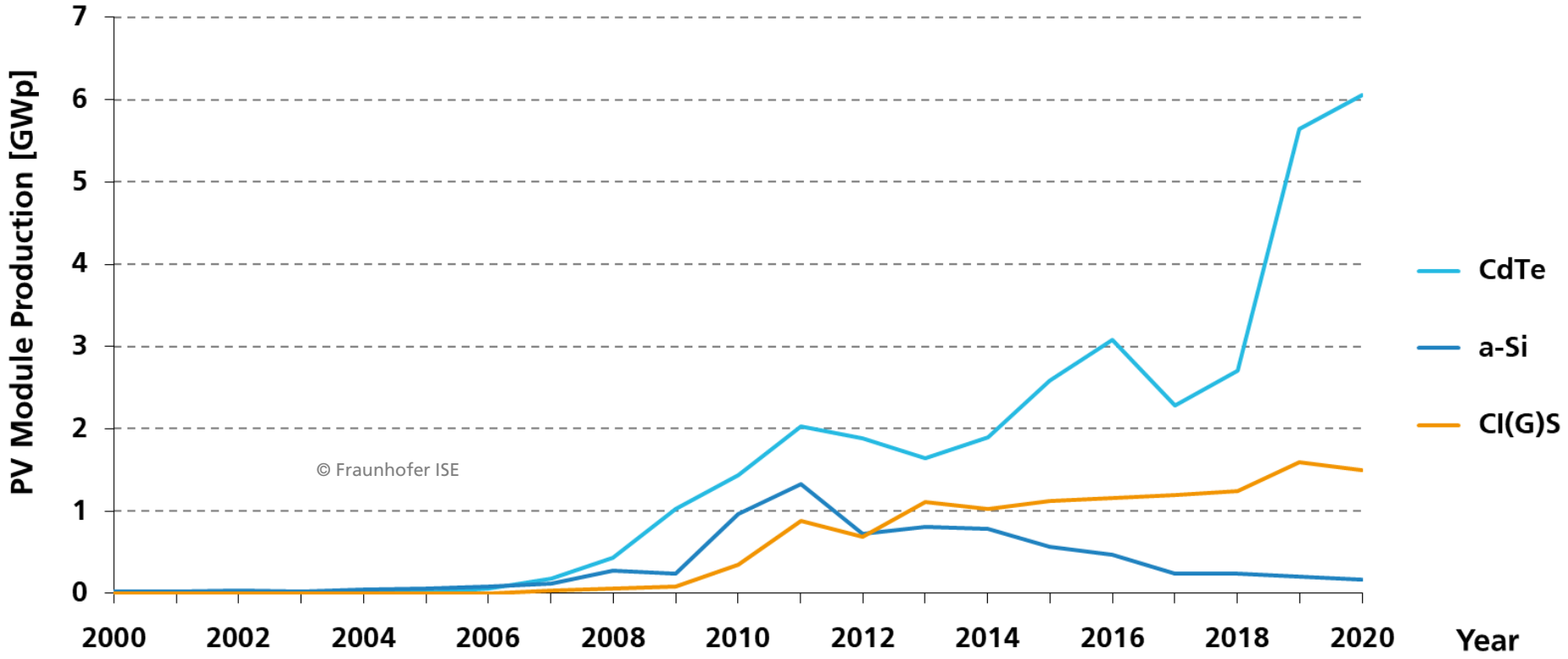
Thin-Film Technologies

Annual Global PV Module Production



Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE Projects GmbH 2021

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2. Solar Cells / Modules / System Efficiency

- Development in the Laboratories
- Development in the PV Industry
- Performance Ratio (PR)

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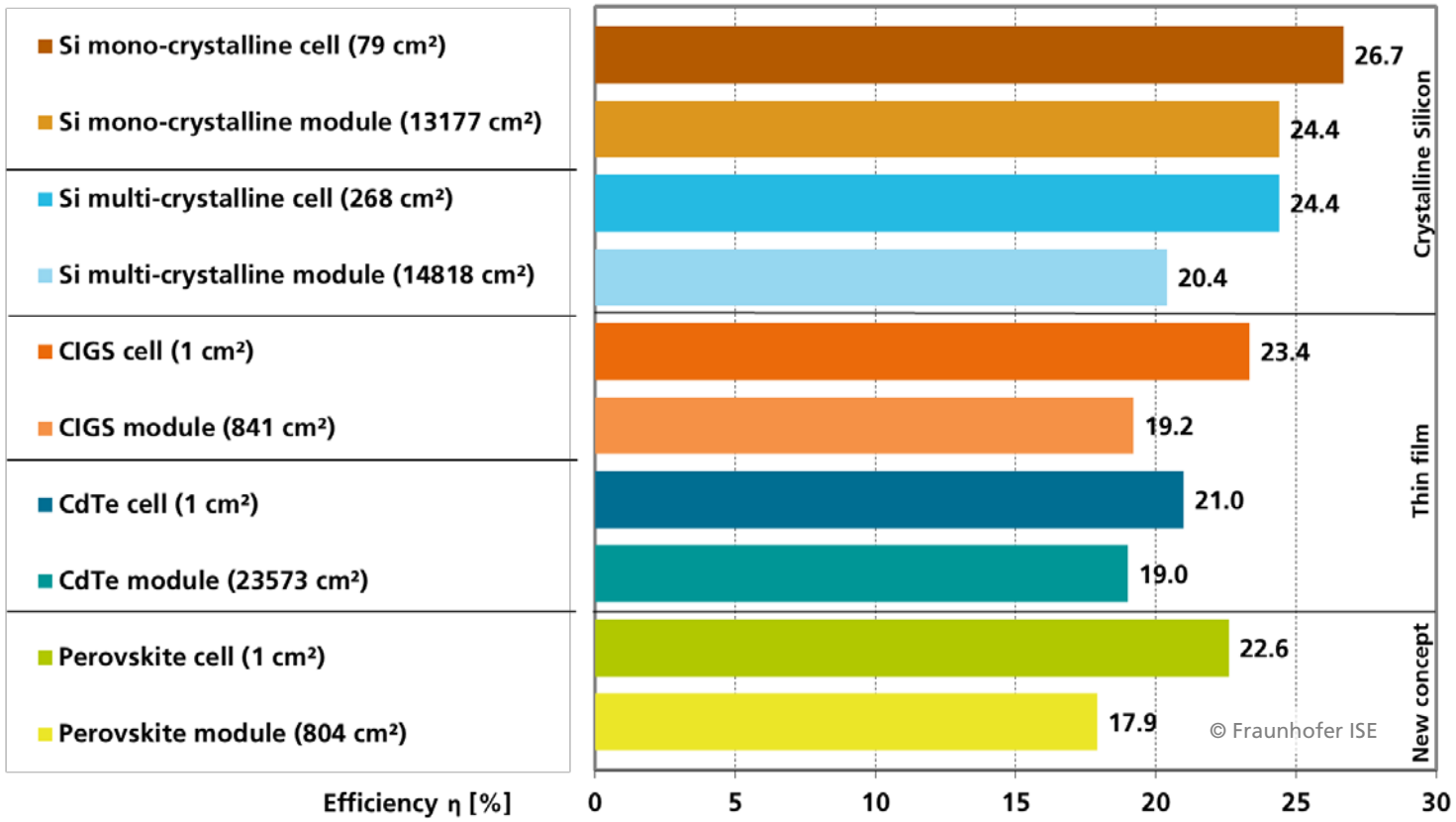
Efficiency Comparison of Technologies:
Best Lab Cells vs. Best Lab Modules



Note: In mass production Cell-to-Module ratio (CTM) improved in past years by reducing losses and using possible gains when integrating solar cells in modules. Fraunhofer ISE provides SmartCalc.CTM software suite for the precise CTM power loss analysis. It considers geometrical losses, optical losses & gains as well as electrical losses.

www.cell-to-module.com

Data: Green et al.: Solar Cell Efficiency Tables (Version 58), Progress in PV: Research and Applications 2020. Graph: PSE Projects GmbH 2021

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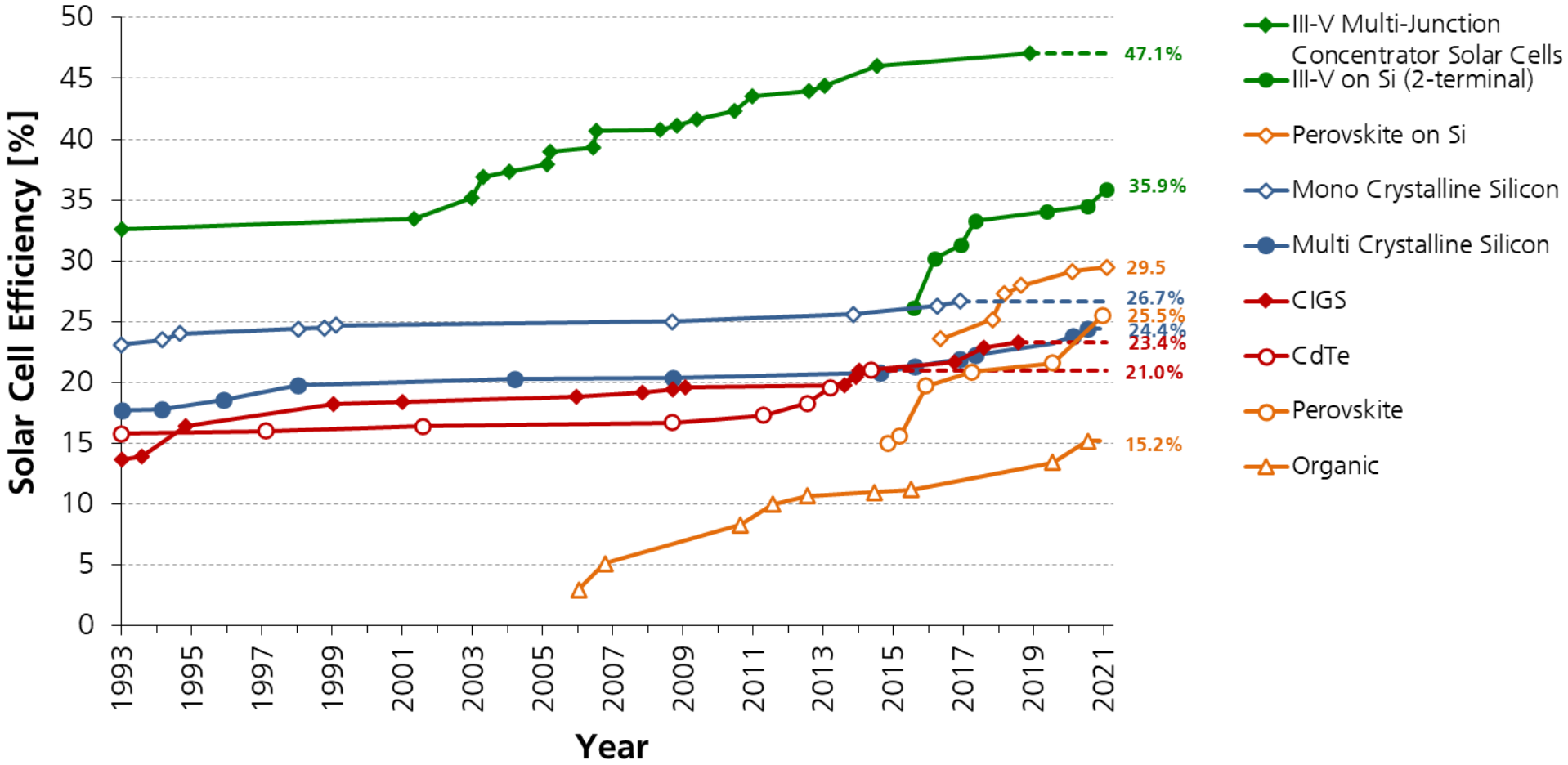
Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 58), Progress in Photovoltaics: Research and Applications, 1993-2021. Graph: Fraunhofer ISE 2021

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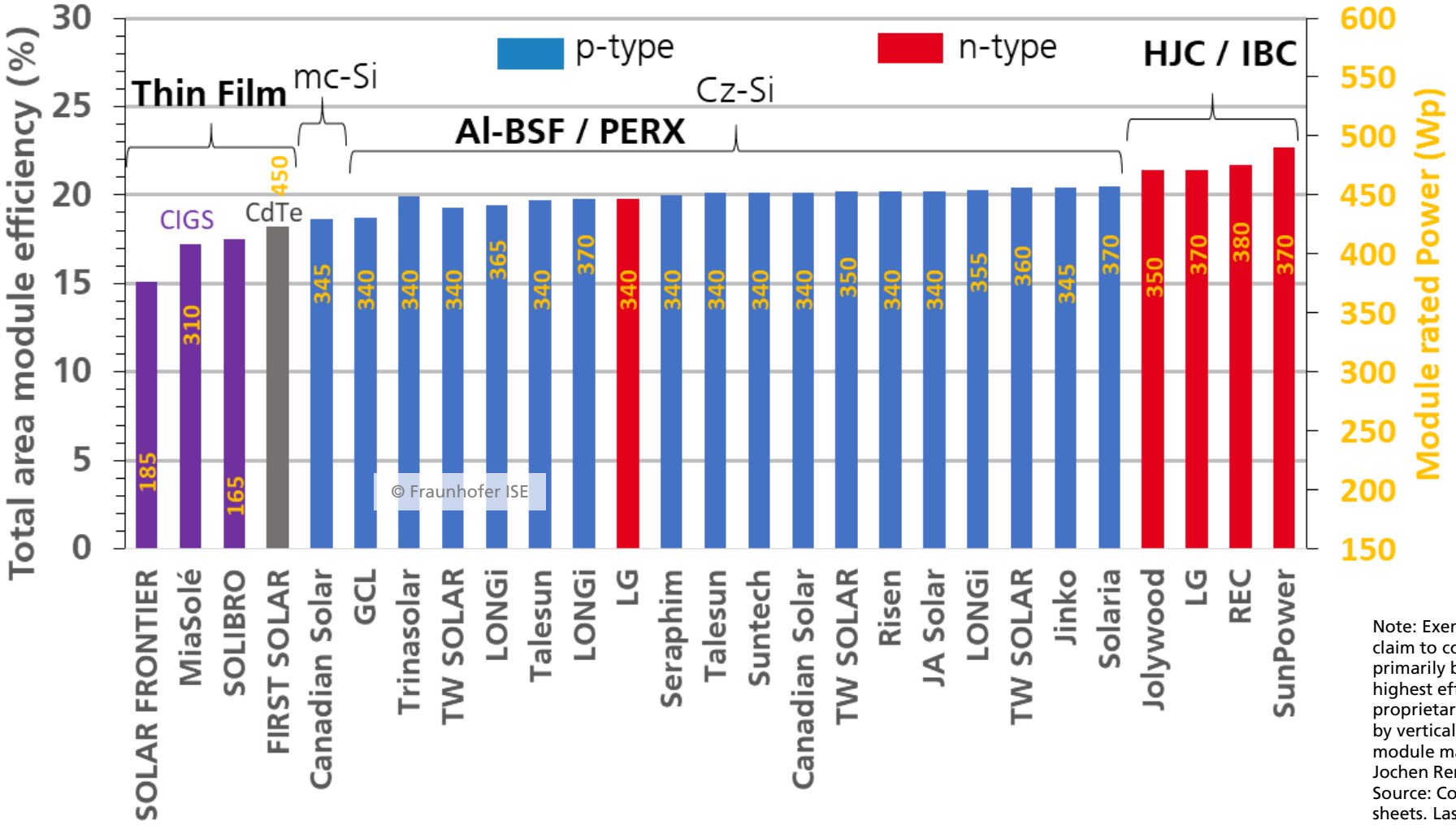
Current Efficiencies and Power of Selected Commercial PV Modules

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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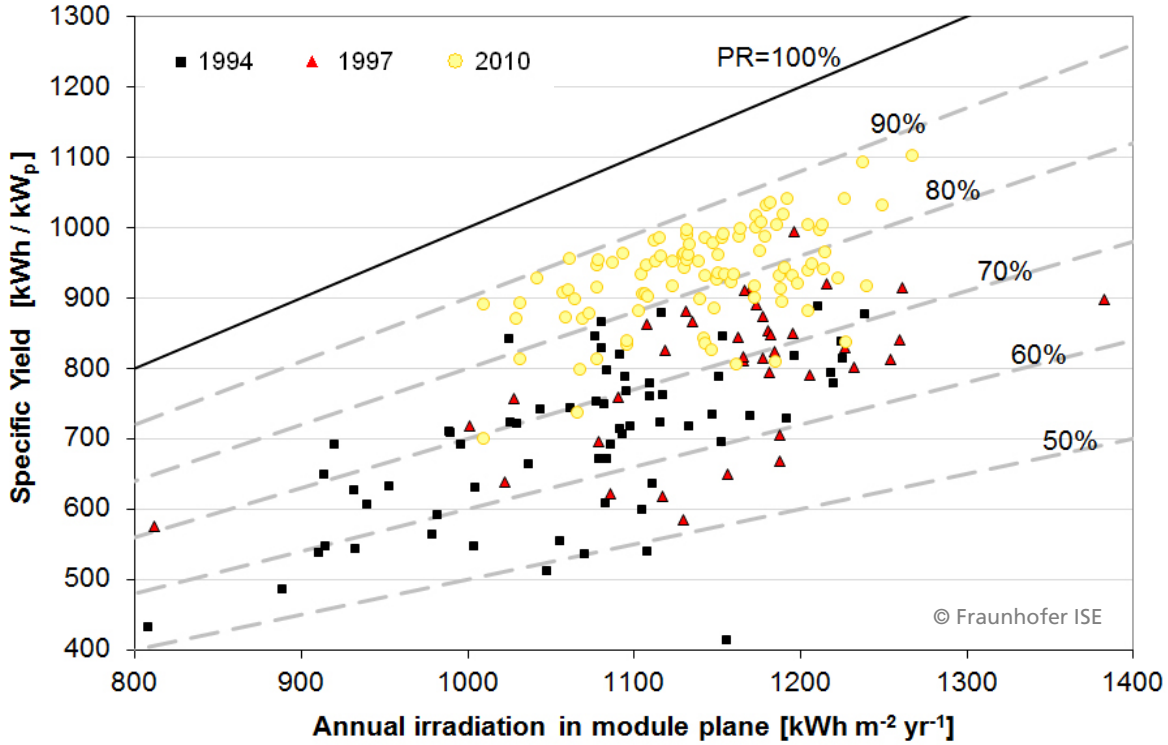
Performance Ratio Development for PV Systems

Germany



In the 1990's

- Typical PR ~70 %
- Widely ranging PR values

Today

- Typical PR ~83 %
- Less variance in PR as compared to 1990's

Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation, CPIA 2021

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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

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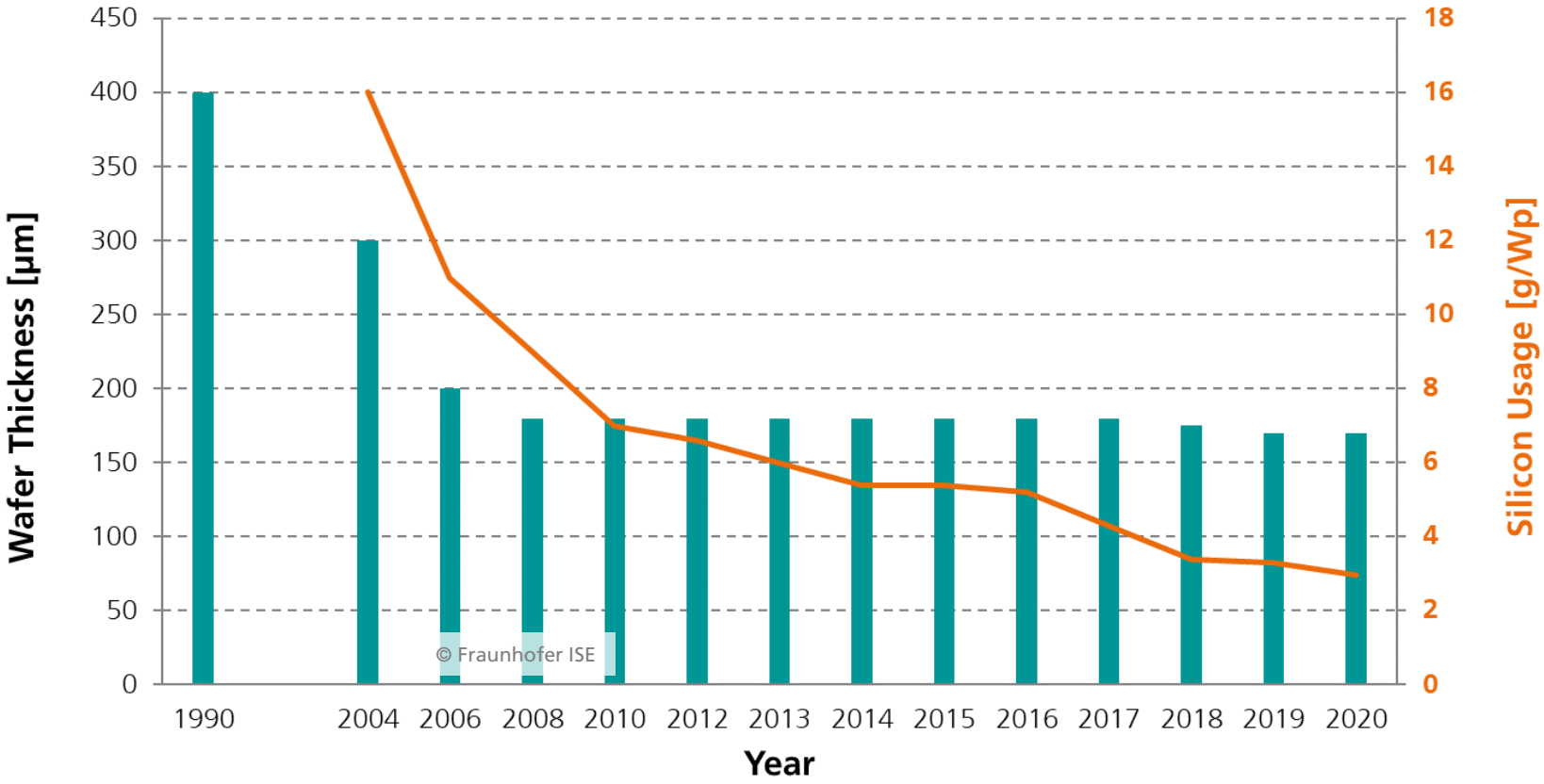
c-Si Solar Cell Development

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 2020 with recycling of Si. Graph: PSE Projects GmbH 2021

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Historic Trend in Energy Payback Time

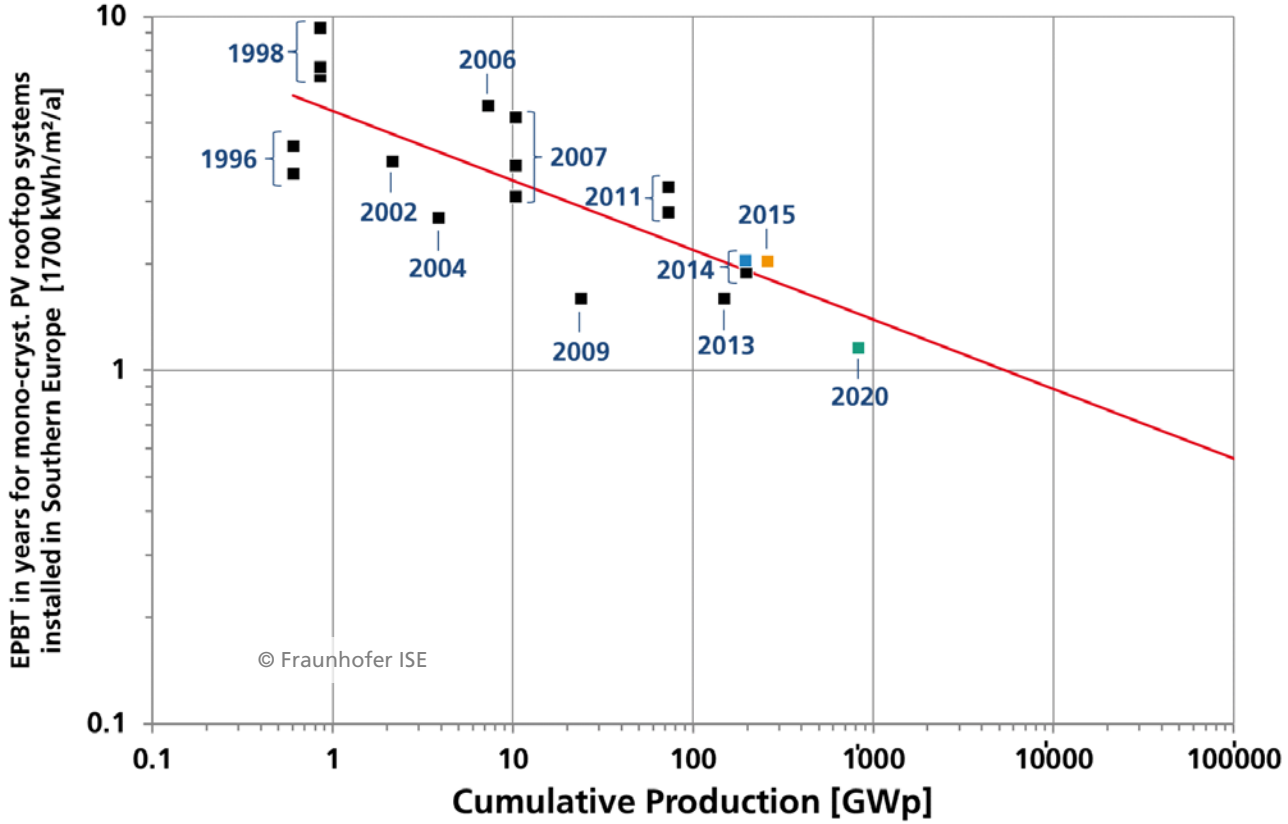
Harmonized Study data for mono-crystalline Silicon Rooftop PV-Systems

- **Learning Rate:**
  Each time the cumulative production doubled, the EPBT went down by 12.8 % for the last 24 years.

Harmonization methodology
based on Koppelaar (2016) harmonized results and harmonization parameters

1) Performance Ratio	
based on average annual PV yield during lifetime	
PV system lifetime	25
Degradation	0.70%
PR (initial)	80%
PR (incl. average degradation during lifetime)	**73.6%**
2) Grid efficiency	
for converting PV yield in primary energy equivalents	
grid efficiency	**35%**

EPBT of Leccisi (2016), Louwen (2014) and Friedrich (2020) were harmonized with 1) PR (incl. average degradation) and 2) grid efficiency to results of Koppelaar (2016)*



Irradiation: 1700 kWh/m²/a at an optimized tilt angle; **Years:** Estimated average year of original data

Data: Lorenz Friedrich, Fraunhofer ISE. Graph: PSE 2021

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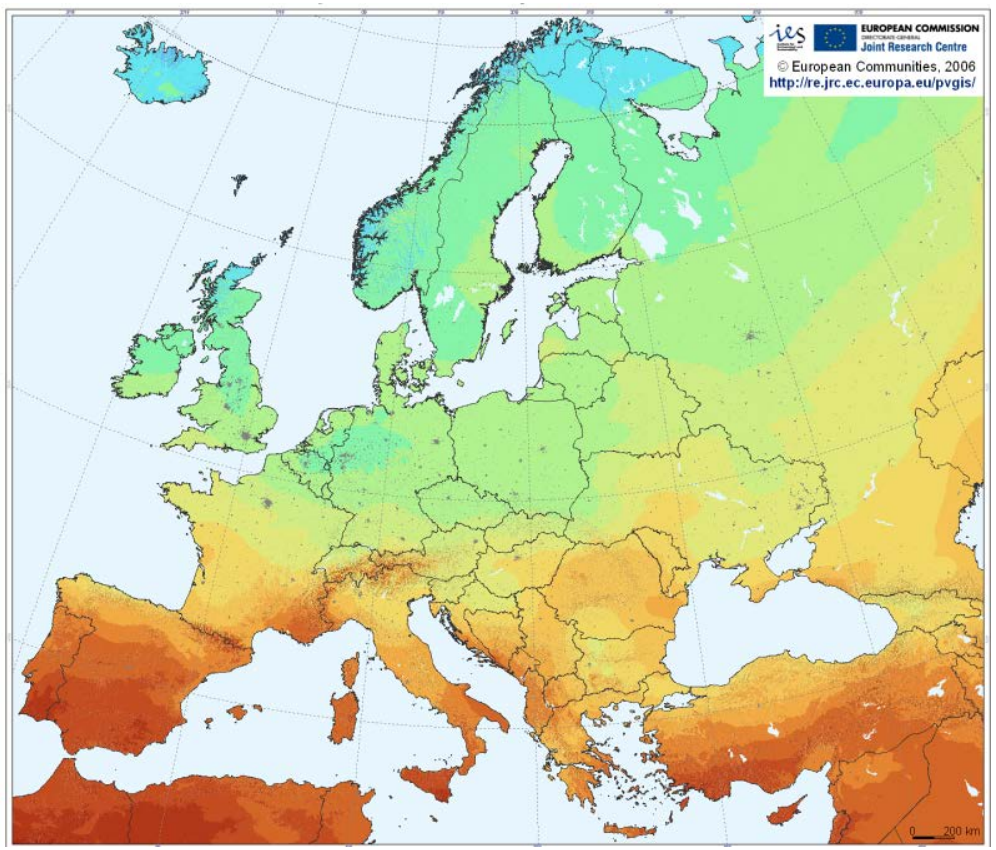
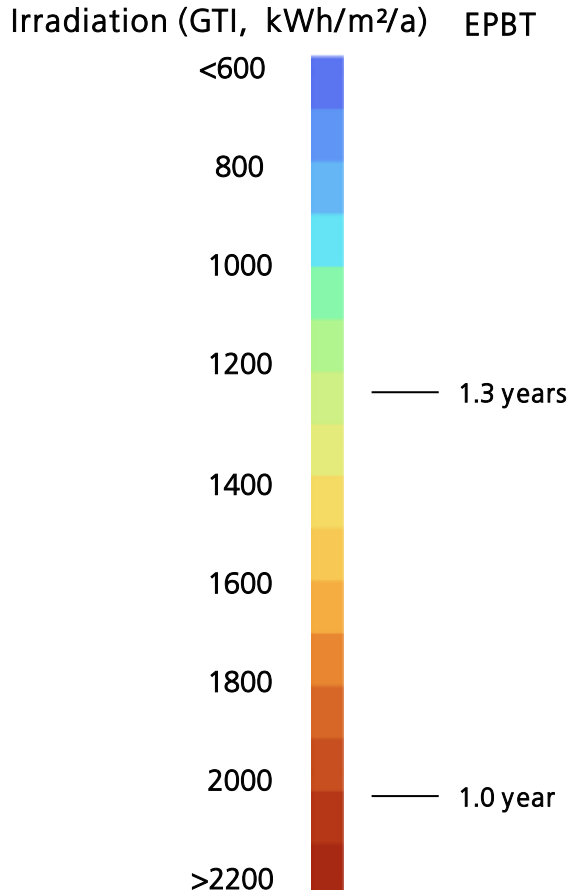
* Koppelaar (2016) - Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization, Renewable and Sustainable Energy Reviews
Leccidi et al. (2016) - The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update, Energies
Louwen et al. (2014) - Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs, Progress in Photovoltaics
Friedrich et al. (2020) - Global Warming Potential and Energy Payback Time Analysis of Photovoltaic Electricity by Passivated Emitter and Rear Cell (PERC) Solar Modules, submitted JPV

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

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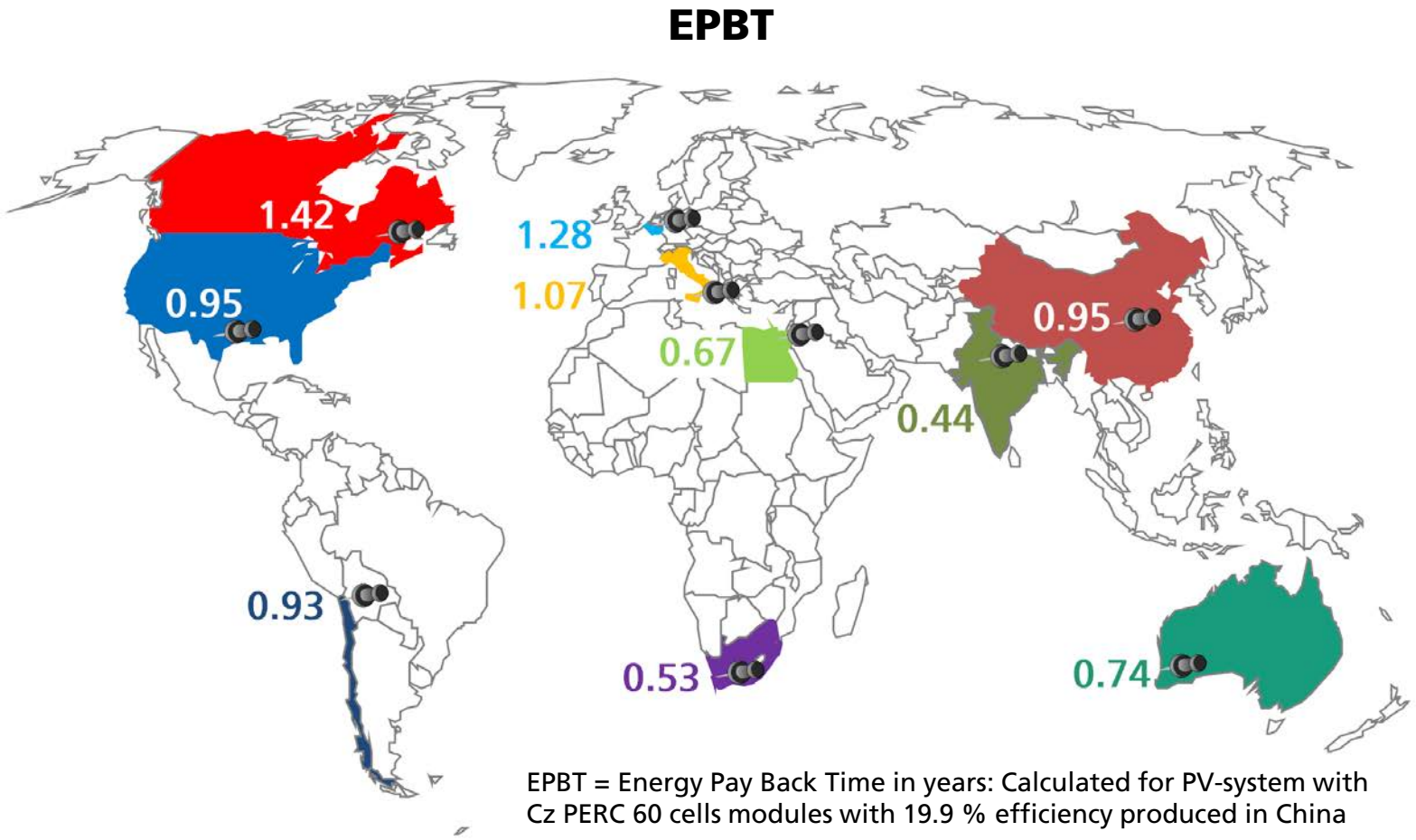
World Map EPBT of Silicon PV Rooftop Systems – Comparison of EPBT China

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

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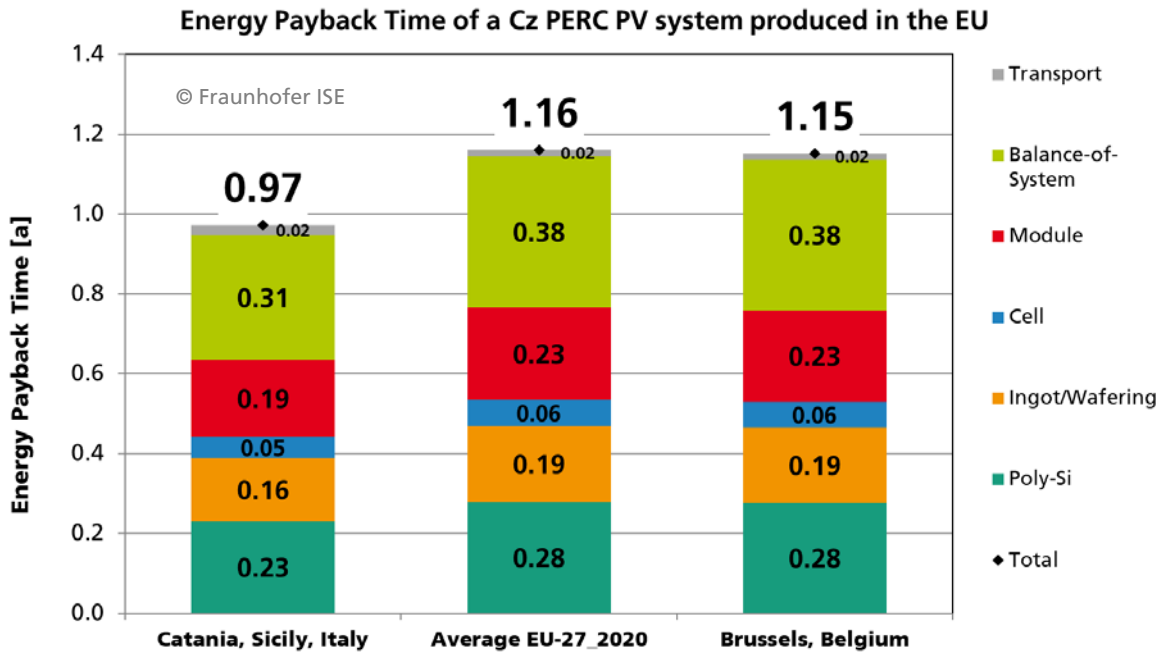
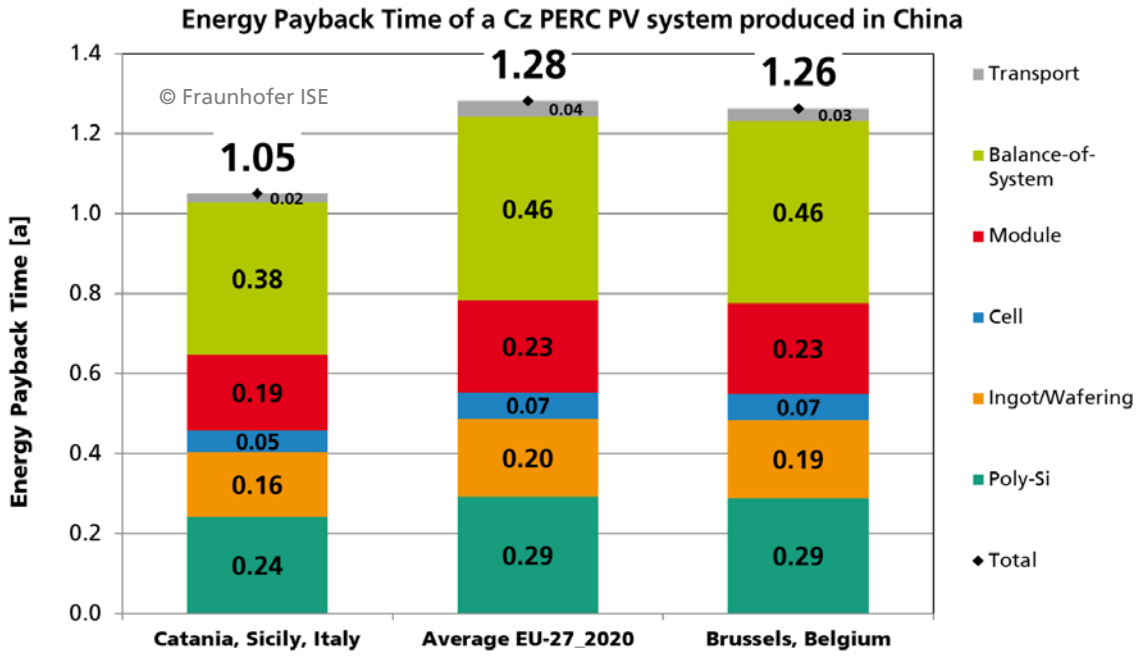
Energy Pay-Back Time of Silicon PV Rooftop Systems –
Comparison of EPBT China / EU, local Irradiation and Grid Efficiency





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

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4. Inverters

- Inverter/Converter Market

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Inverter/Converter Market 2020

Inverter / Converter	Power	Efficiency	Market Share (Estimated)*	Remarks
String Inverters	up to 150 kWp	up to 98%	64.4%	• 3 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	33.7%	• ~ 4 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-97%	1.4%	• ~ 25 €-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 2021. Remarks: Fraunhofer ISE 2020. Design: PSE 2021

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

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5. Price Development

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

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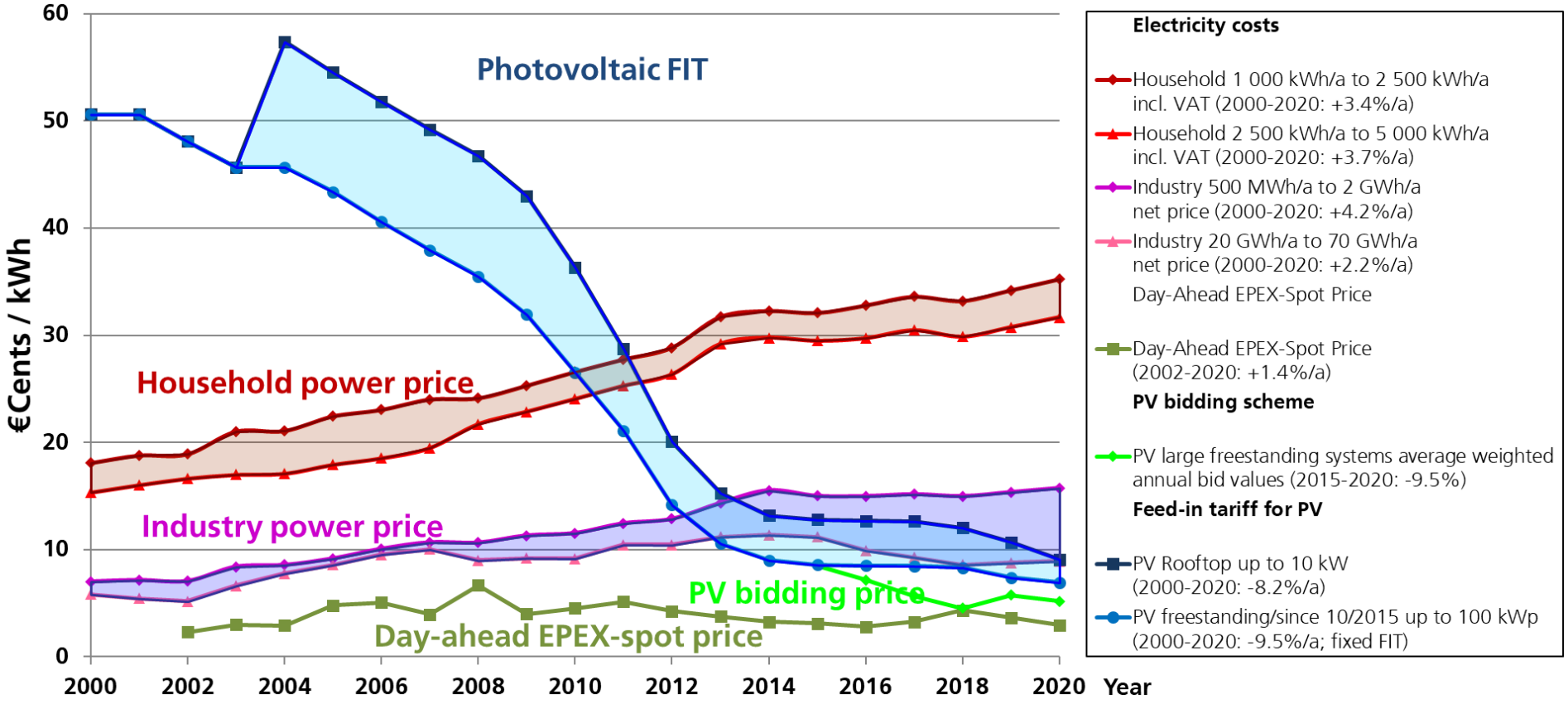
Electricity Prices, PV Feed-In Tariffs (FIT) and bidding scheme in Germany



Data: BMU and BMWi Energiedaten 2020. Design: B. Burger - Fraunhofer ISE , Update: 15-Feb. 2021

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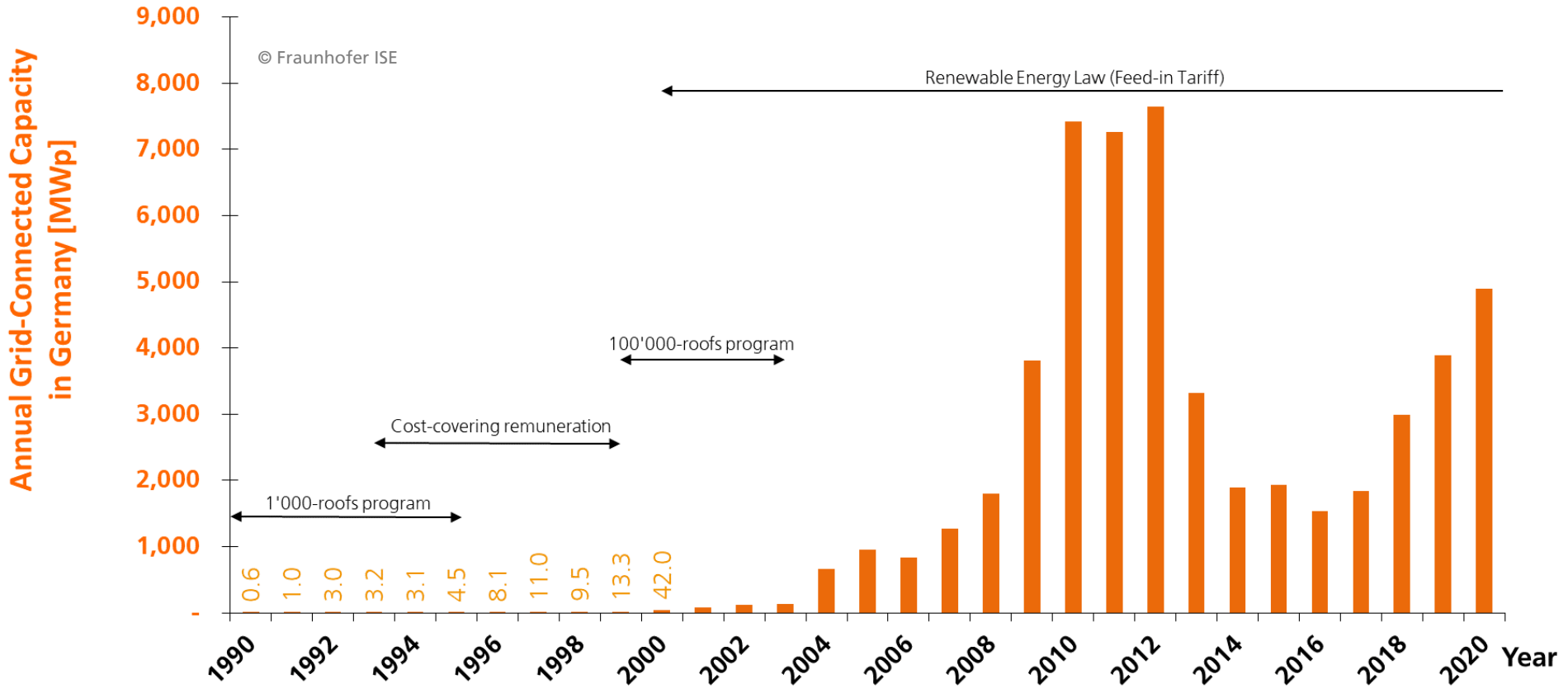
Market Development and Subsidy Schemes in Germany



Data: BNA. Graph: PSE 2021

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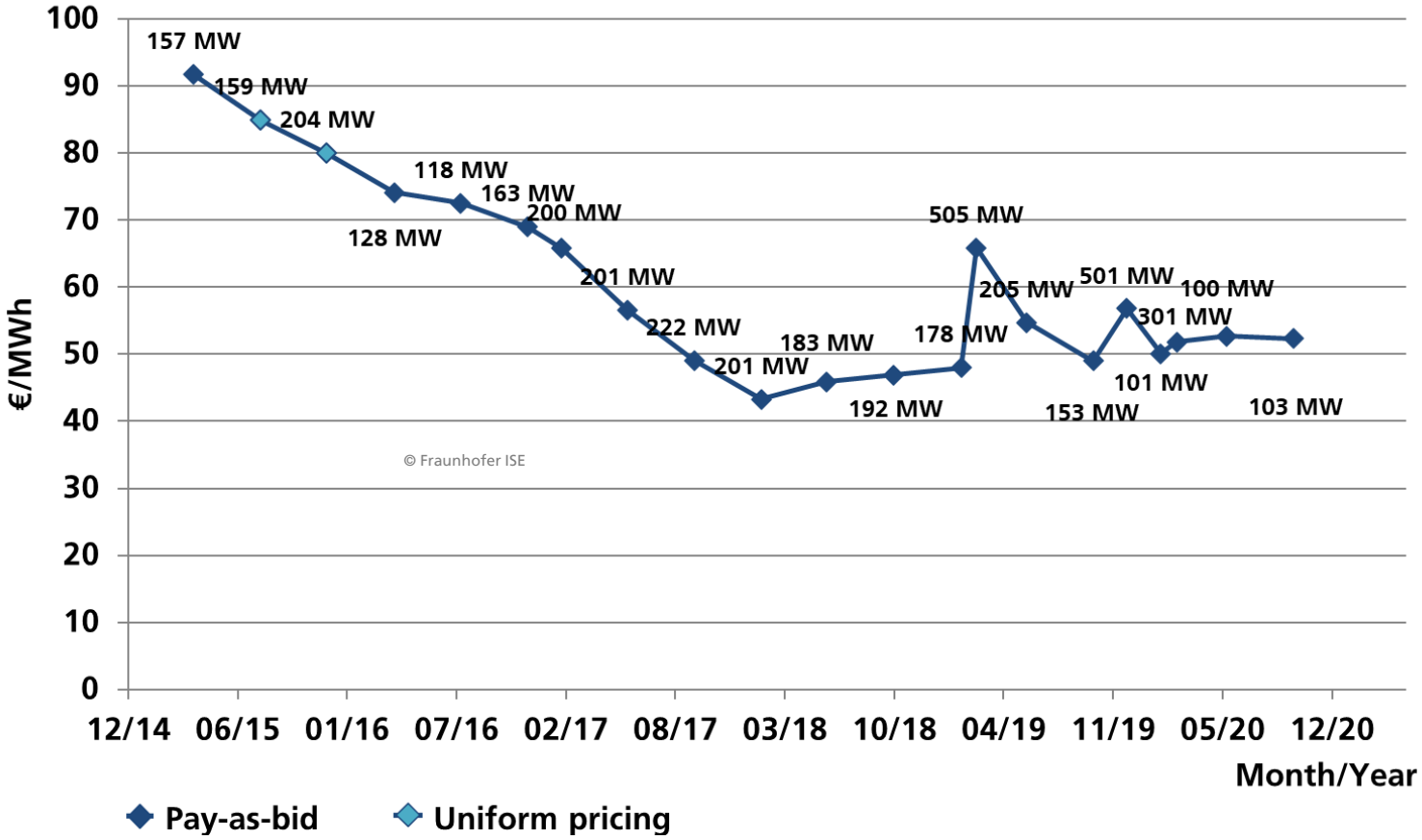
PV-Tender in Germany

Average, quantity weighted Award Value



Data: BNA. Graph: PSE 2021

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 5 GWp.

Special tenders are not displayed in the graph.

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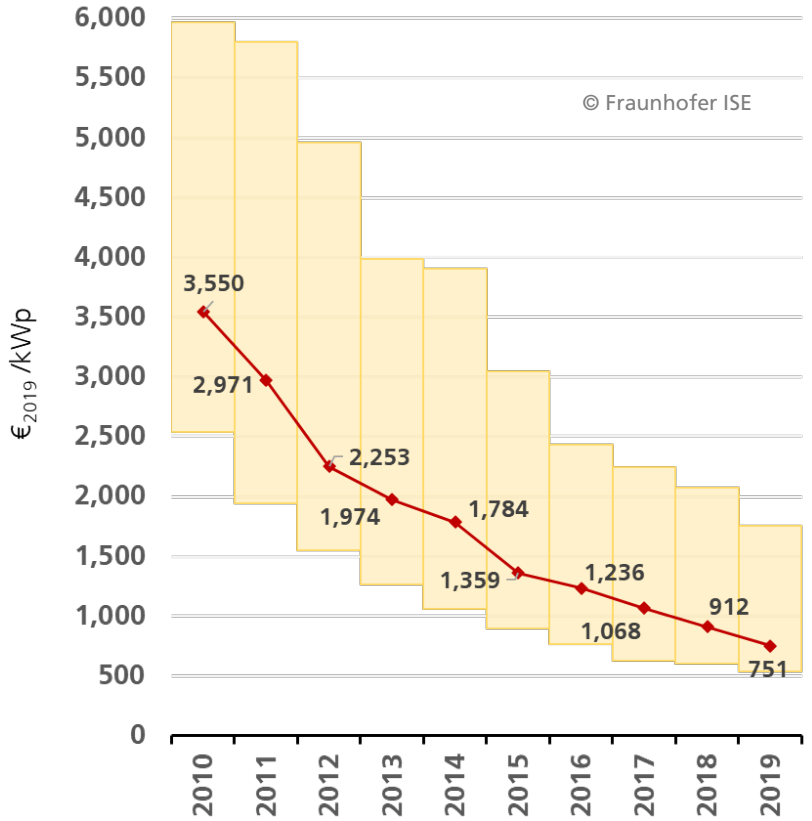
Global Weighted Average Total Installed Costs For Large PV Systems
(with 5th percentile and 95th percentile)



Total installed cost for large PV systems decreased by about 16% on year-to-year basis in the last decade.

The 5th percentile is a value associated with the location within the data where 5% of data is below that value. In year 2019 the 5th percentile was 539 €/kWp.

The 95th percentile is the value where 5% of the data has is a larger value. In year 2019 the 95th percentile was 1751 €/kWp.

Data: IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR.

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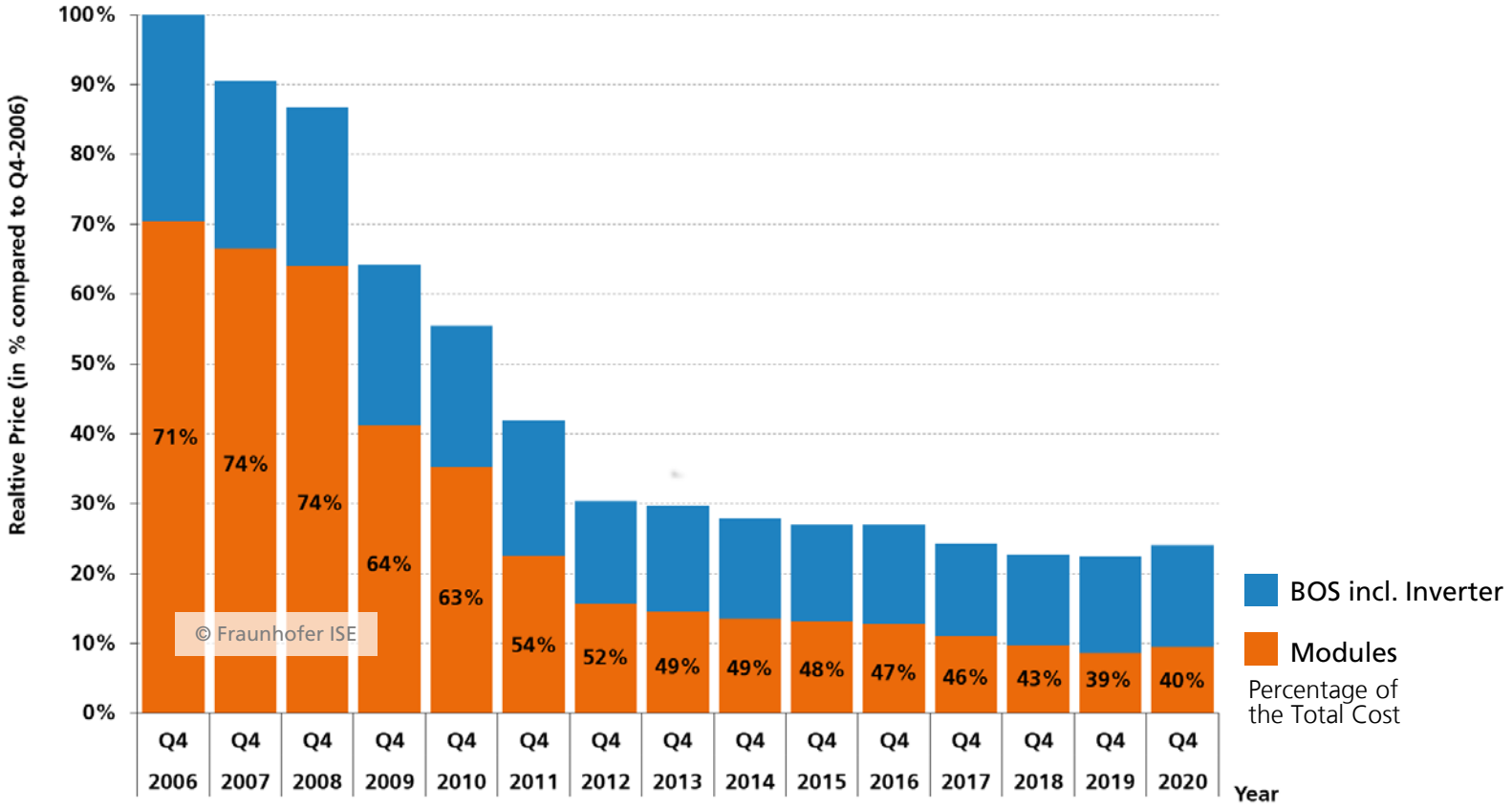
Price Development for PV Rooftop Systems in Germany
(10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE 2021

Balance of System (BOS) encompasses all components of a PV system other than the PV modules; like inverter, mounting system, switches, wiring and installation work. Annual average BOS cost increased by 2% on y-to-y basis in 2020 while annual average PV module cost decreased by 0.6%.

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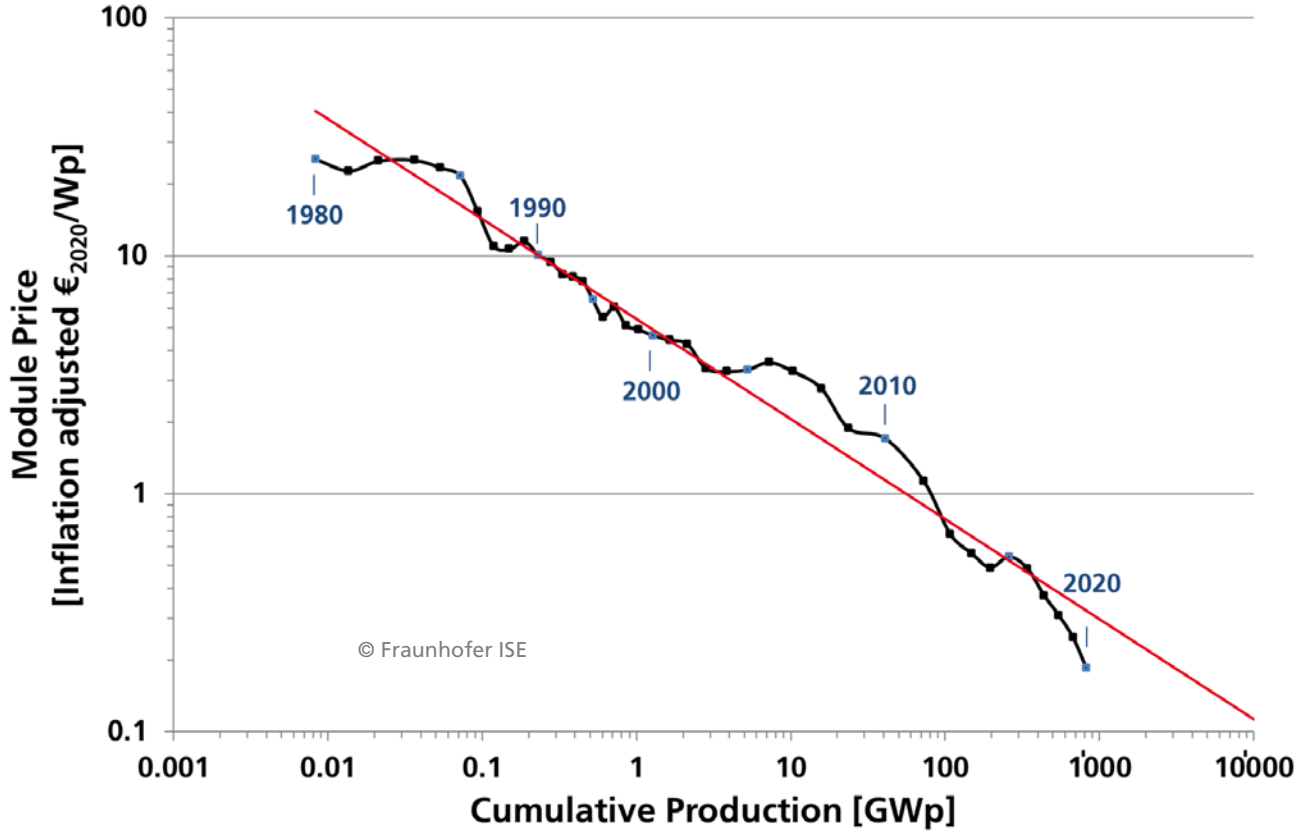
Price Learning Curve

Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative PV module production doubled, the price went down by 25% for the last 40 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2021

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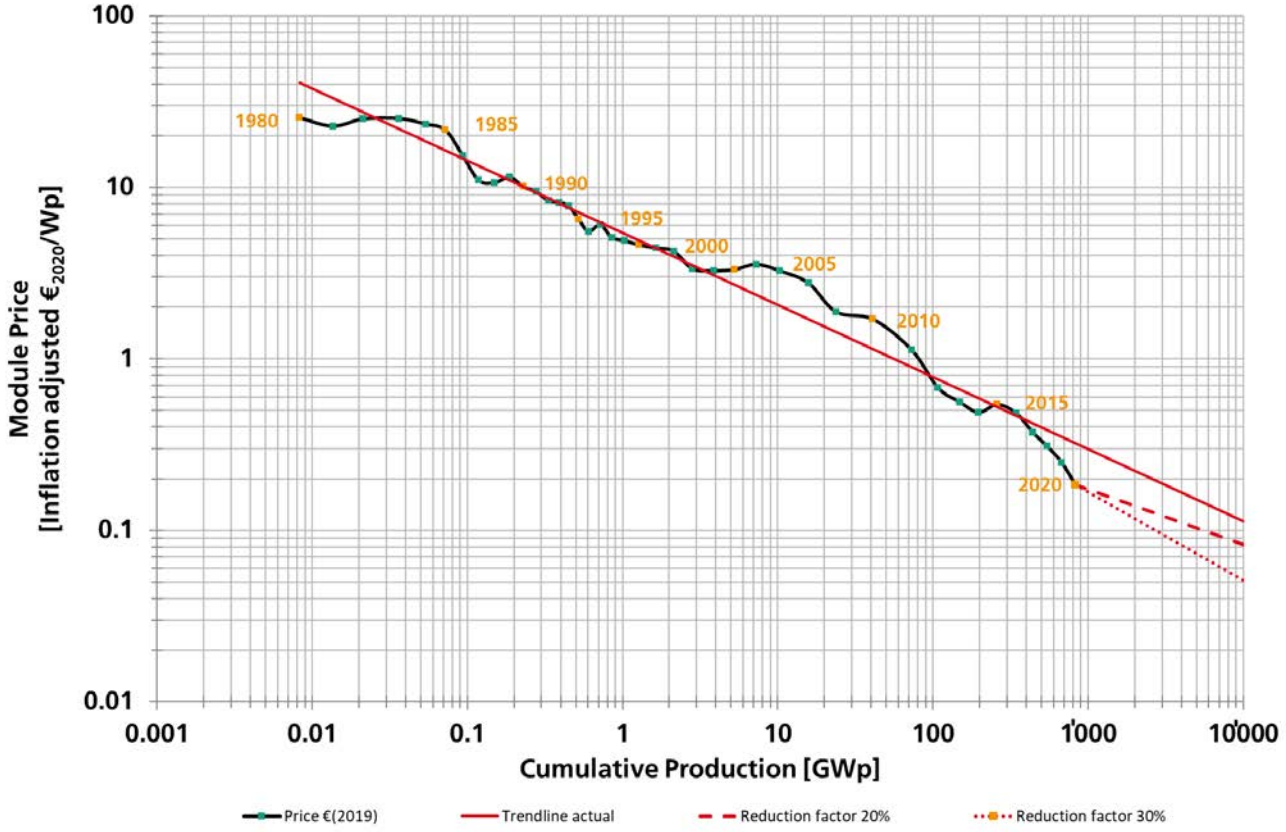
Price Learning Curve

Includes all Commercially Available PV Technologies



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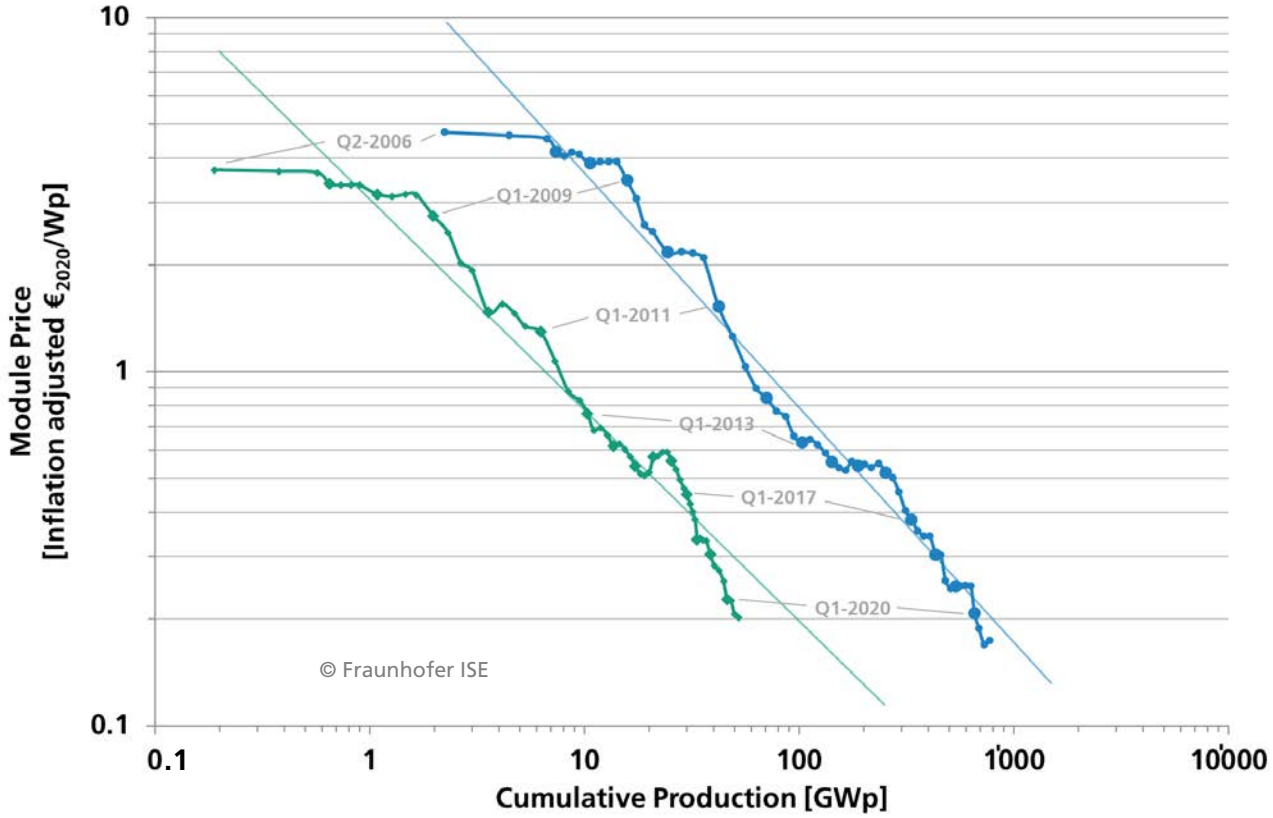
Price Learning Curve by Technology
Cumulative Production up to Q4-2020



Estimated cumulative PV module production up to Q4-2020:

- c-Si 773 GWp
- Thin Film 52 GWp

Crystalline Technology
(from Q2-2006 to Q4-2020) LR 32
Thin Film Technology
(from Q2-2006 to Q4-2020) LR 30

Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit. Graph: PSE 2021

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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.

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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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