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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 However, facts and figures change rapidly and the given information may soon be outdated again.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 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-co.de

- Please quote the information presented in these slides as follows: ©Fraunhofer ISE: Photovoltaics Report, updated: 25 October 2019
Quick Facts

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<tr>
<td>PV market*</td>
<td>3.6 / 8 / 100 GW</td>
<td>2018</td>
<td>BNA / SPE / IHS</td>
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<td>Cumulative installation</td>
<td>46 / 119 / 488 GW</td>
<td>End of 2018</td>
<td>BP / BP / IRENA</td>
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<td>PV power generation</td>
<td>46 / 127 / 585 TWh</td>
<td>2018</td>
<td>ISE / BP / BP</td>
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<td>PV electricity share</td>
<td>8.7% (net) / gross: 3.9% / 2.2%</td>
<td>2018</td>
<td>ISE / BP / BP</td>
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<td><strong>Worldwide</strong></td>
<td></td>
<td></td>
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<tr>
<td>c-Si share of production</td>
<td>95%</td>
<td>2017</td>
<td>IHS</td>
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<td><strong>Germany</strong></td>
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<tr>
<td>Price PV rooftop system</td>
<td>~ 1300 €/kWp</td>
<td>End of 2018</td>
<td>BSW</td>
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<tr>
<td>LCOE PV power plant</td>
<td>3.7 to 6.8 ct€ / kWh</td>
<td>End of 2018</td>
<td>ISE</td>
</tr>
<tr>
<td>PV-Tender Price</td>
<td>4.33 ct€ / kWh</td>
<td>Feb. 2018</td>
<td>BNA</td>
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* Not yet confirmed
Executive Summary
PV Market: Global

- Photovoltaics is a fast growing market: The Compound Annual Growth Rate (CAGR) of PV installations was 36.8% between year 2010 to 2018.

- Concerning PV module production in 2017, China&Taiwan hold the lead with a share of 70%, followed by Rest of Asia-Pacific & Central Asia (ROAP/CA) with 14.8%. Europe contributed with a share of 3.1% (compared to 4% in 2016); USA/CAN contributed 3.7%.

- In 2018, Europe’s contribution to the total cumulative PV installations amounted to 25% (compared to 26% in 2017). In contrast, installations in China accounted for 36% (compared to 32% in 2017).

- Si-wafer based PV technology accounted for about 95% of the total production in 2017. The share of multi-crystalline technology is now about 62% (compared to 70% in 2016) of total production.

- Market shifts from subsidy driven to competitive pricing model (Power Purchase Agreements PPA).

- Batteries and storage solutions get increasing importance e.g. to achieve higher self-consumption rates.
Executive Summary
PV Market: Focus Germany

- In 2018, Germany accounted for about 9% (45.9 GWp) of the cumulative PV capacity installed worldwide (515 GWp) with about 1.6 million PV systems installed in Germany. In 2018 the newly installed capacity in Germany was about 2.81 GWp; in 2017 it was 1.66 GWp.

- PV covered 8.7% of Germany’s net electricity demand in 2018. Renewable sources delivered about 43% of the total net power consumption in 2018 in Germany.

- In 2018 about 28 Mio. t CO₂ equivalent GHG emissions have been avoided due to 46 TWh electrical energy generated by PV in Germany.

- PV system performance has strongly improved. Before 2000 the typical Performance Ratio was about 70%, while today it is in the range of 80% to 90%.
Executive Summary
Solar Cell / Module Efficiencies

- The record lab cell efficiency is 26.7% for mono-crystalline and 22.3% for multi-crystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 23.4% 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 18%.

- 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.
Executive Summary
Energy Payback Time

- Material usage for silicon cells has been reduced significantly during the last 13 years from around 16 g/Wp to about 4 g/Wp due to increased efficiencies, thinner wafers and wires as well as larger ingots.

- The Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 2.5 years to balance the input energy, while PV systems in the South equal their energy input after 1.5 years and less, depending on the technology installed.

- A PV system located in Sicily with multi-Si modules has an Energy Payback Time of around one year. Assuming 20 years lifespan, this kind of system can produce twenty times the energy needed to produce it.

- The Energy Payback Time for CPV-Systems in Southern Europe is less than 1 year.
Executive Summary

Inverters

- Inverter efficiency for state-of-the-art brand products 98% and higher.

- The market share of string inverters is estimated to be 52%. These inverters are mostly used in residential, small and medium commercial applications in PV systems up to 150 kWp. The market share of central inverters, with applications mostly in large commercial and utility-scale systems, is about 44%. A small proportion of the market (about 1%) belongs to micro-inverters (used on the module level). It is estimated that 3 GWp of DC/DC converters, also called “power optimizers”, have been installed in 2017.

- The specific net retail price of all inverters in Germany is about 12 €-cents/Wp. Central inverters tend to be cheaper than string inverters.

- Trends: 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.
Executive Summary

Price Development

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

- The Experience Curve – also called Learning Curve - shows that in the last 38 years the module price decreased by 24% with each doubling of the cumulated module production. Cost reductions result from economies of scale and technological improvements.
1. PV Market

- By region
- By technology
PV Module Production by Region 1997-2017
Percentage of Total MWp Produced

Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE GmbH 2018
PV Module Production by Region
Global Annual Production

Data: Up to 2009: Navigant Consulting; since 2010: IHS. Numbers for 2018 estimated. Graph: PSE GmbH 2019
Global Cumulative PV Installation

Data: IRENA. Graph: PSE GmbH 2019
Global Cumulative PV Installation by Region

Status 2018

The total cumulative installations amounted to 488 GWp at the end of year 2018.

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

Data: IRENA. Graph: PSE GmbH 2019
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 GmbH 2019
While the larger PV-systems account for about a third of the total installed capacity, the number of large-scale systems with more than 500 kWp is only about 1% of the total installed systems.

Data: Bundesnetzagentur. Graph: PSE GmbH 2019
Electrical Capacity of Renewable Energy Sources

Germany

In 2018 about 37.8% (224 TWh) of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.

Data: BMWi / AGEE-Stat.; Data up to 2012: BMU, BDEW; Data electricity generation: energy Charts by Prof. Dr. Bruno Burger. Graph: PSE GmbH 2019
In 2018 Greenhouse Gas emissions of about 28 Mio. t CO₂-equivalent were avoided due to 46 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2019. Graph: PSE GmbH 2019
Annual PV Production by Technology
Worldwide (in GWp)

About 103* GWp PV module production in 2018

*2018 production numbers reported by different analysts vary to some extend. We estimate that total PV module production is realistically around 103 GWp for year 2018.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2019

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PV Production by Technology
Percentage of Global Annual Production

Production 2017 (GWp)
- Thin film: 4.5
- Multi-Si: 60.8
- Mono-Si: 32.2

Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi-proportion from cell production). Graph: PSE GmbH 2018
Market Share of Thin-Film Technologies
Percentage of Total Global PV Production

Production 2017 (GWp)
- CdTe 2.3
- a-Si 0.3
- CIGS 1.9

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018
Thin-Film Technologies

Annual Global PV Module Production

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018
Low and High Concentrator PV Systems (LCPV/HCPV)

Annually Installed Capacity

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

Data: ISE 2018

For more details on CPV see ISE/NREL Report: Current Status of Concentrator Photovoltaics (CPV) Technology
2. Solar Cells / Modules / System Efficiency

- Development in the PV Industry
- Development in the Laboratories
- High Concentration Photovoltaics (HCPV)
- Performance Ratio (PR)
Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules

Development of Laboratory Solar Cell Efficiencies

Average Crystalline-Silicon PV Module Efficiency

Data source: IHS Markit 2019
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.
Performance Ratio Development for PV Systems

Germany

In the 1990’s
- Typical PR ~70 %
- Widely ranging PR values

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

Source: Fraunhofer ISE “1000 Dächer Jahresbericht” 1994 and 1997; 2011 system evaluation
3. Energy Return of Invest (EROI) & Energy Payback Time (EPBT)

- Silicon usage, wafer thickness and kerf loss for c-Si
- EPBT: Development and comparison
c-Si Solar Cell Development
Wafer Thickness [µm] & Silicon Usage [g/Wp]

Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV 2015; ISE 2016 without; 2017 and 2018 with recycling of Si. Graph: PSE GmbH 2019
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

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

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

Global Irrad.: 1000 kWh/m²/yr

Data: M.J. de Wild-Scholten 2013. Graph: PSE 2014
Energy Pay-Back Time of Multicrystalline Silicon PV Rooftop Systems - Geographical Comparison

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

- Inverter/Converter Price
- Inverter Concept Comparison
## Inverter/Converter Market 2017

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

5. Price Development

- Electricity costs
- Costs for rooftop systems
- Market incentives in Germany
- Price Learning Curve
Electricity Prices, PV Feed-In Tariffs (FIT) and bidding scheme in Germany

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

Data: BSW-Solar, BNA. Graph: PSE GmbH 2019
Average Price for PV Rooftop Systems in Germany (10kWp - 100kWp)

Data: BSW-Solar. Graph: PSE GmbH 2019
PV-Tender in Germany
Average, quantity weighted Award Value

Data: BNA. Graph: PSE GmbH 2019

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FHG-SK: ISE-PUBLIC
Price Learning Curve
Includes all Commercially Available PV Technologies

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

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS. Graph: PSE GmbH 2019
Price Learning Curve by Technology
Cumulative Production up to Q4. 2017

Estimated cumulative production up to Q4, 2017:
- c-Si: 405 GWp
- Thin Film: 33 GWp

Crystalline Technology
(from Q2-2006 to Q4-2017) LR 29
Thin Film Technology
(from Q2-2006 to Q4-2017) LR 25

Data: from 2006 to 2010 estimation from different sources: Navigant Consulting, EUPD, pvXchange; from 2011: IHS. Graph: PSE GmbH 2018
Further Reading
Selected studies and analyses

- ISE Energy Charts
- Study: Levelized Cost of Electricity - Renewable Energy Technologies
- Recent facts about photovoltaics in Germany
- Power Generation from Renewable Energy in Germany - Assessment of 2017
- What will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050
- Meta Study: Future Crosssectoral Decarbonization Target Systems in Comparison to Current Status of Technologies
- Study: Current Status of Concentrator Photovoltaic (CPV) Technology

Please click on the link to find the respective information.
## Abbreviations

<table>
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<th>Abbr.</th>
<th>Explanation</th>
<th>Abbr.</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
<td>HCPV</td>
<td>High Concentrator Photovoltaic</td>
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<td>Al-BSF</td>
<td>Aluminum Back Surface Field</td>
<td>HJT (also HIT)</td>
<td>Heterojunction with Intrinsic Thin-Layer</td>
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<td>BIPV</td>
<td>Building Integrated PV</td>
<td>IBC</td>
<td>Interdigitated Back Contact (solar cells)</td>
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<tr>
<td>BOS</td>
<td>Balance of System</td>
<td>LCPV</td>
<td>Low Concentrator Photovoltaic</td>
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<tr>
<td>CdTe</td>
<td>Cadmium-Telluride</td>
<td>MJ</td>
<td>Multi Junction</td>
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<tr>
<td>Cu(In,Ga)Se₂</td>
<td>Copper Indium (Gallium)Diselenide</td>
<td>MPP</td>
<td>Maximum Power Point</td>
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<td>CPV</td>
<td>Concentrating Photovoltaic</td>
<td>n-type</td>
<td>Negatively doped wafer (with phosphorous)</td>
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<tr>
<td>c-Si</td>
<td>Crystalline Silicon</td>
<td>PERX</td>
<td>Passivated emitter and rear cell</td>
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<td>Cz</td>
<td>Czochralski Method</td>
<td>PR</td>
<td>Performance Ratio</td>
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<td>DC</td>
<td>Direct current</td>
<td>p-type</td>
<td>Positively doped wafer (with boron)</td>
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<td>EEG</td>
<td>Renewable Energy Law (Erneuerbare Energie Gesetz)</td>
<td>PV</td>
<td>Photovoltaic</td>
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<td>EPBT</td>
<td>Energy PayBack Time</td>
<td>RE</td>
<td>Renewable Energies</td>
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<td>EROI</td>
<td>Energy Return of Invest</td>
<td>ROI</td>
<td>Return on Investment</td>
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<td>FZ</td>
<td>Floating Zone</td>
<td>Si</td>
<td>Silicon</td>
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<td>GaAs</td>
<td>Gallium Arsenide</td>
<td>SiC</td>
<td>Silicon carbide</td>
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<td>GaN</td>
<td>Gallium nitride</td>
<td>VAT</td>
<td>Value Added Tax</td>
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Acknowledgements

This work has been carried out with contributions from:

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<th>Institution</th>
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<tr>
<td>Bruno Burger</td>
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<td>Klaus Kiefer</td>
<td>ISE</td>
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<tr>
<td>Christoph Kost</td>
<td>ISE</td>
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<tr>
<td>Sebastian Nold</td>
<td>ISE</td>
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<td>Simon Philipps</td>
<td>ISE</td>
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<tr>
<td>Ralf Preu</td>
<td>ISE</td>
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<tr>
<td>Jochen Rentsch</td>
<td>ISE</td>
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<tr>
<td>Thomas Schlegl</td>
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<td>Gerhard Stryi-Hipp</td>
<td>ISE</td>
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<td>Harry Wirth</td>
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<td>Werner Warmuth</td>
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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.

simon.philipps@ise.fraunhofer.de
warmuth@pse-co.de