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  - Solar Cells / Modules / System Efficiency
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Introduction

Preliminary Remarks

- The intention of this presentation is to provide up-to-date information. However, facts and figures change rapidly and the given information may soon be outdated again.

- This work has been carried out under the responsibility of Dr. Simon Philipps (Fraunhofer ISE) and Werner Warmuth (PSE AG).

- The slides have been made as accurate as possible and we would be grateful to receive any comments or suggestions for improvement. Please send your feedback to simon.philipps@ise.fraunhofer.de and also to werner.warmuth@pse.de

- Please quote the information presented in these slides as follows: ©Fraunhofer ISE: Photovoltaics Report, updated: 17 November 2016
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.
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 CO₂ 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

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In 2015 about 33% of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.
In 2015 ca. 27 Mio. t of CO₂ emissions were avoided due to 38.4 TWh PV electricity consumed in Germany.

According to the Federal Environmental Agency (UBA) the CO₂ avoidance factor of PV is 715 grams of CO₂-eq /kWhₑl.
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

Production 2015 (GWp)
- Thin film: 4.2
- Multi-Si: 43.9
- Mono-Si: 15.1

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage of Thin-Film Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>11%</td>
</tr>
<tr>
<td>2001</td>
<td>11%</td>
</tr>
<tr>
<td>2002</td>
<td>9%</td>
</tr>
<tr>
<td>2003</td>
<td>7%</td>
</tr>
<tr>
<td>2004</td>
<td>5%</td>
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<td>2005</td>
<td>5%</td>
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<td>2006</td>
<td>4%</td>
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<td>2007</td>
<td>4%</td>
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<td>2008</td>
<td>6%</td>
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<td>2009</td>
<td>9%</td>
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<td>2010</td>
<td>12%</td>
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<td>2011</td>
<td>17%</td>
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<tr>
<td>2012</td>
<td>14%</td>
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<tr>
<td>2013</td>
<td>12%</td>
</tr>
<tr>
<td>2014</td>
<td>10%</td>
</tr>
<tr>
<td>2015</td>
<td>7%</td>
</tr>
</tbody>
</table>

Production 2015 (GWp)
- Cd-Te: 2.5
- a-Si: 0.6
- CI(G)S: 1.1

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

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


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Current Efficiencies of Selected Commercial PV Modules
Sorted by Bulk Material, Cell Concept and Efficiency

Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2015.
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**
Performance Ratio Development for PV Systems

Germany

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

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

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

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

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 AG 2014
Energy Pay-Back Time of Multicrystalline Silicon PV Rooftop Systems - Geographical Comparison

4. Inverters

- Inverter/Converter Price
- Inverter Concept Comparison
# Inverter/Converter Market 2015

<table>
<thead>
<tr>
<th>Inverter / Converter</th>
<th>Power</th>
<th>Efficiency</th>
<th>Market Share (Estimated)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>String Inverters</td>
<td>up to 100 kWp</td>
<td>up to 98 %</td>
<td>~ 37 %</td>
<td>• 11 - 19 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Easy to replace</td>
</tr>
<tr>
<td>Central Inverters</td>
<td>More than 100 kWp</td>
<td>up to 98.5 %</td>
<td>~ 61 %</td>
<td>• ~ 10 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• High reliability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Often sold only together with service contract</td>
</tr>
<tr>
<td>Micro-Inverters</td>
<td>Module Power Range</td>
<td>90%-95 %</td>
<td>~ 2 %</td>
<td>• ~ 35 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Ease-of-replacement concerns</td>
</tr>
<tr>
<td>DC / DC Converters (Power Optimizer)</td>
<td>Module Power Range</td>
<td>up to 98.8 %</td>
<td>n.a.</td>
<td>• ~ 10 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Ease-of-replacement concerns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Output is DC with optimized current</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Still a DC / AC inverter is needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• ~ 1 GWp installed in 2014</td>
</tr>
</tbody>
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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)

Historical Price Development Germany for 10 to 100 kWp roof-top PV-Systems

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

Estimated cumulative production up to Q4, 2015:
- c-Si: 235 GWp
- Thin Film: 24 GWp

Crystalline Technology
(from Q2-2006 to Q4-2015) LR 28.2
Thin Film Technology
(from Q2-2006 to Q4-2015) LR 25.2

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:

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<td>Werner Warmuth</td>
<td>PSE</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.

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

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