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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 However, facts and figures change rapidly, and the given information may soon be outdated again.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: ©Fraunhofer ISE: Photovoltaics Report, updated: 22 September 2022
## Quick Facts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Status</th>
<th>Reference</th>
<th>Date of data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Germany / EU27 / Worldwide</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PV installation market</strong></td>
<td>4.9 / 18.2 / 126 GW</td>
<td>End of 2020</td>
<td>BNA / SPE / BP</td>
<td>11/2021; 12/2020; 02/2022; 12/2021; 06/2022</td>
</tr>
<tr>
<td></td>
<td>5.3 / 25.9 / 133 GW</td>
<td>End of 2021</td>
<td>BNA / SPE / BP</td>
<td>07/2022; 12/2021; 04/2022</td>
</tr>
<tr>
<td><strong>Cumulative installation</strong></td>
<td>59.8 / 164.9 / 850 GW</td>
<td>End of 2021</td>
<td>ISE / SPE / IRENA</td>
<td></td>
</tr>
<tr>
<td><strong>PV power generation</strong></td>
<td>48.6\text{net} / 160.4\text{gross} / 1032.5\text{gross} TWh</td>
<td>2021</td>
<td>ISE / BP / BP</td>
<td>06/2022; 06/2022; 06/2022</td>
</tr>
<tr>
<td><strong>PV electricity share</strong></td>
<td>9.9%\text{net} / 5.5%\text{gross} / 3.6%\text{gross}</td>
<td>2021</td>
<td>ISE / BP / BP</td>
<td>08/2022; 06/2022; 06/2022</td>
</tr>
<tr>
<td><strong>Worldwide</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>c-Si share of production</strong></td>
<td>95%</td>
<td>2021</td>
<td>ISE</td>
<td>08/2022</td>
</tr>
<tr>
<td><strong>Record solar cell efficiency</strong></td>
<td>47.1 / 26.7 / 23.4 / 24.4 / 21.0%</td>
<td>06/2021</td>
<td>Green et al.</td>
<td>06/2021</td>
</tr>
<tr>
<td><strong>Germany</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Price PV rooftop system</strong></td>
<td>1,050 to 1,650 €/kWp</td>
<td>2022</td>
<td>BSW</td>
<td>05/2022</td>
</tr>
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<td><strong>LCOE PV power plant</strong></td>
<td>3.1 to 5.7 ct€ / kWh</td>
<td>2021</td>
<td>ISE</td>
<td></td>
</tr>
<tr>
<td><strong>Lowest/Latest PV-Tender Price</strong></td>
<td>4.33/5.00 ct€ / kWh</td>
<td>02/2018; 11/2021</td>
<td>BNA</td>
<td>11/2021</td>
</tr>
</tbody>
</table>
Executive Summary

PV Market: Global

- Photovoltaics is a fast-growing market: The Compound Annual Growth Rate (CAGR) of cumulative PV installations was 32% between year 2010 to 2021.

- In 2021 producers from Asia count for 93% of total c-Si PV module production. China (mainland) holds the lead with a share of 70%. Europe contributed with a share of 3%; USA/CAN with 3%.

- Wafer size increased and by keeping the number of cells larger PV module sizes are realized allowing a power range beyond 600 W per module.

- In 2021, Europe’s contribution to the total cumulative PV installations amounted to almost 22%. In contrast, installations in China accounted for 37% (with 33% in year 2020).

- Si-wafer based PV technology accounted for more than 95% of the total production in 2021. The share of mono-crystalline technology is about 84% of total c-Si production.

- Market shifts from subsidy driven to competitive pricing model (Power Purchase Agreements PPA).
Executive Summary
PV Market: Focus Germany

- In year 2021, Germany accounted for about 6.9% (59 GWp) of the cumulative PV capacity installed worldwide (848 GWp) with about 2.2 million PV systems installed in Germany. In 2021 the newly installed capacity in Germany was 5.3 GWp according to BNA; in 2020 it was 4.6 GWp.

- PV covered 9.9% of Germany’s net electricity generation in 2021 while all Renewable sources delivered about 45.9%.

- In 2021 about 34.4 Mio. t CO₂ equivalent GHG emissions have been avoided due to 48.6 TWh electrical energy generated by PV in Germany.

- PV system performance has strongly improved. Before year 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 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 23.7%.

- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 15% to 20% and more. 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.

* Only official lab record efficiencies with minimum cell area of 1 cm² are listed. Latest reference: Solar Cell Efficiency Tables (Version 60), Progress in Photovoltaics: Research and Applications, May 2022
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 2.5 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 produced in Europe and installed in Northern Europe need around 1.1 years to balance the input energy, while PV systems in the South equal their energy input after 0.9 years, 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.
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.
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 25% with each doubling of the cumulated global module production. Cost reduction results from economies of scale and technological improvements.
1. PV Market

- By region
- By technology
PV Module Production by Region 1990-2021
Percentage of Total MWp Produced

About 82% of the global PV module has been produced in Asia in year 2010. It increased to about 93% of total global production in year 2021. China (mainland) accounted with 138 GWp for 75% of the global module production in year 2021 according to IEA. The annual production has increased by a factor of 9.7 in these eleven years.
Status Quo – PV Production in Europe
Overview of PV production along the value chain – August 2022

Production capacities according to Value-added stage within Europe [GWp/a]*:

- **Module** 8.28
- **Solar cell** 0.76
- **Ingot & Wafer** 1.40
- **Poly-Si** 22.1 **
- **mg-Si** 38.2 ***

* without Turkey and Russia
** 2,800 kg/MWp poly-Si are currently required for ingot production
*** currently 3,150 kg/MWp mg-Si required for ingot production

Source: Map material: kartojm (fotolia) / europakarte.org

Data and Graph: Jochen Rentsch, Fraunhofer ISE 2022; last update: 23.08.2022
Status Quo – PV Production in Germany
Overview of PV production along the value chain – August 2022

Value-added stage
- mg-Si
- Poly-Si
- Ingot / Wafer
- Cell
- Module

Factory size
- > 1 GWp
- > 500 MWp
- > 100 MWp
- > 50 MWp

Source: Map material: kartoxjm (fotolia) / europakarte.org

Data and Graph: Jochen Rentsch, Fraunhofer ISE 2022; last update: 23.08.2022
Global Cumulative PV Installation
From 2010 to 2021

Data: IRENA 2022. Graph: PSE 2022. Date of data: Apr-2022
Global Cumulative PV Installation by Region
Status 2021

The total cumulative installations amounted to about 850 GWp at the end of year 2021.

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

Data: IRENA 2022. Graph: PSE 2022; Date of data: Apr-2022
The annual distribution of PV System size classes strongly depend on:

- Regulations
- Market incentives (like EEG)
- Tender procedures
- Bankability (trust of investors)

Source until year 2020: Fraunhofer ISE, own calculations based on EEG-master and -flow data (netztransparenz.de, Sept. 2021)

Source for year 2021: MaStR (05.07.2022) + Data validation algorithm
End of 2021 about 2.25 million grid-connected PV-Systems were installed in Germany.

Source: Fraunhofer ISE, own calculations based on MaStR (05.07.2022) and Data validation algorithm
At the end of 2021 a total cumulated PV capacity of about 59.8 GW was installed in Germany.

Source: Fraunhofer ISE, own calculation based on MaStR (05.07.2022) + Data validation algorithm
Electrical Capacity of Renewable Energy Sources
Germany

136.8 GW of total 234.2 GW net installed electricity generation capacity in Germany were from renewable energy (RE) sources in Germany in year 2021. This results in a RE share of 58.4% of total capacity.

Data: Energy Charts by Prof. Dr. Bruno Burger. Date of data: Jan-2022
In 2021 Greenhouse Gas emissions of about 34 Mio. t CO₂-equivalent were avoided due to 50 TWh PV electricity consumed in Germany.

Data: BMU, BDEW, BMWi, Federal Environmental Agency (UBA) 2022. Graph: PSE 2022
Annual PV Production by Technology
Worldwide (in GWp)

*2021 production numbers reported by different analysts vary to some extent. Different sources report a total PV module production between 183 and 190 GWp for year 2021.

Data: from 2000 to 2009: Navigant; from 2010: IHS Markit. Graph: PSE 2022. Date of data: Jan-2022
PV Production by Technology
Percentage of Global Annual Production

Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 IEA. Graph: PSE 2022. Date of data: July 2022

Production 2021* (GWp)
- Thin film: 10
- Multi-Si: 20
- Mono-Si: 160

*estimated numbers
Thin-Film technology contributed in year 2021 with about 5% to the total PV-market.

Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 IEA. Graph: PSE 2022. Date of data: July 2022
Thin-Film Technologies
Annual Global PV Module Production

Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 IEA. Graph: PSE 2022. Date of data: July 2022
2. Solar Cells / Modules / System Efficiency

- Development in the Laboratories
- Development in the PV Industry
- Performance Ratio (PR)
Development of Laboratory Solar Cell Efficiencies

Data: Solar Cell Efficiency Tables (Versions 1 to 60), Progress in Photovoltaics: Research and Applications, 1993-2022. Graph: Fraunhofer ISE 2022. Date of data: May 2022

Only official lab record efficiencies published in the Solar Cell Efficiency Tables, Progress in Photovoltaics: Research and Applications are included in the graph. The following novel results will be included as soon as they are published in the tables:

- III-V multi-junction solar cell, 47.6% by Fraunhofer ISE
- Perovskite on Si, 31.25% by CSEM / EPFL
### Efficiency Comparison of Technologies:
#### Best Lab Cells vs. Best Lab Modules

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si mono-crystalline cell (79 cm²)</td>
<td>26.7</td>
</tr>
<tr>
<td>Si mono-crystalline module (13177 cm²)</td>
<td>24.4</td>
</tr>
<tr>
<td>Si multi-crystalline cell (268 cm²)</td>
<td>24.4</td>
</tr>
<tr>
<td>Si multi-crystalline module (14818 cm²)</td>
<td>20.4</td>
</tr>
<tr>
<td>CIGS cell (1 cm²)</td>
<td>23.4</td>
</tr>
<tr>
<td>CIGS module (841 cm²)</td>
<td>19.2</td>
</tr>
<tr>
<td>CdTe cell (1 cm²)</td>
<td>21.0</td>
</tr>
<tr>
<td>CdTe module (23582 cm²)</td>
<td>19.5</td>
</tr>
<tr>
<td>Perovskite cell (1 cm²)</td>
<td>23.7</td>
</tr>
<tr>
<td>Perovskite module (804 cm²)</td>
<td>17.9</td>
</tr>
</tbody>
</table>

Data: Green et al.: Solar Cell Efficiency Tables (Version 60), Progress in PV: Research and Applications 2022. Graph: PSE 2022. Date of data: May 2022

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](http://www.cell-to-module.com)
Current Efficiencies and Power of Commercial PV Modules
Sorted by technology

Total weighted average efficiency of crystalline Silicon (c-Si) wafer-based modules is 20.4% in Q4-2021 (weighting factor is total shipments in year 2020). Lowest module efficiency in this group is 16.3% and highest value is 22.4%.

Top 10 manufacturers represent about 78% of total shipment volume and origin mainly in Asia.

Predominant c-Si technology is mono-PERC with half-cut cells and Multi-Busbar.

Note: Selection based on modules of Top 10 manufacturers in year 2020 (exception CIGS) with global available module data sheets at end of Oct-2021.
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
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 to 2020 with recycling of Si. Graph: PSE Projects GmbH 2021
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.

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

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

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**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 years
   - 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)*

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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
**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.

<table>
<thead>
<tr>
<th>Irradiation (GTI, kWh/m²/a)</th>
<th>EPBT</th>
</tr>
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<tbody>
<tr>
<td>&lt;600</td>
<td>1.3 years</td>
</tr>
<tr>
<td>800</td>
<td>1.0 year</td>
</tr>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td></td>
</tr>
<tr>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>&gt;2200</td>
<td></td>
</tr>
</tbody>
</table>

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
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
Energy Pay-Back Time of Silicon PV Rooftop Systems – Comparison of EPBT China / EU, local Irradiation and Grid Efficiency 2021

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. Calculations for year 2021 made at 22-July 2022
4. Inverters

- Inverter/Converter Market
## Inverter/Converter Market 2020

<table>
<thead>
<tr>
<th>Inverter / Converter</th>
<th>Power</th>
<th>Efficiency (DC/AC)</th>
<th>Market Share (Estimated)*</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>String Inverters</td>
<td>up to 150 kWp</td>
<td>up to 98%</td>
<td>64.4%</td>
<td>• 3 - 17 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DC/AC)</td>
<td></td>
<td>• Easy to replace</td>
</tr>
<tr>
<td>Central Inverters</td>
<td>More than 80 kWp</td>
<td>up to 98.5%</td>
<td>33.7%</td>
<td>• 3 - 5 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DC/AC)</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%-97%</td>
<td>1.4%</td>
<td>• ~ 25 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DC/AC)</td>
<td></td>
<td>• Ease-of-replacement concerns</td>
</tr>
<tr>
<td>Power Optimizer</td>
<td>Module Power Range</td>
<td>up to 99.5%</td>
<td>5.1%</td>
<td>• ~ 8 €-cents /Wp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DC/DC)</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>
</tbody>
</table>

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

5. Price Development

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

Data: BMU and BMWi Energiedaten 2021. Design: B. Burger - Fraunhofer ISE. Date of data: Jan. 2022
PV Market Development and Incentive Schemes in Germany

The EEG 2023 law relies on a massive expansion of renewable energies with total installed PV capacity of 215 GW in year 2030. In this year (2022), 7 GW of new PV system capacity are to be connected to the grid, next year 9 GW. From 2026, the expansion target is 22 GW of new installations on annual basis.

### Market Incentive

<table>
<thead>
<tr>
<th>Market Incentive</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>1’000 Roofs Program</td>
<td>1990</td>
<td>1995</td>
</tr>
<tr>
<td>Cost-covering remuneration</td>
<td>1993</td>
<td>1999</td>
</tr>
<tr>
<td>100’000 Roofs-Program</td>
<td>1999</td>
<td>2003</td>
</tr>
<tr>
<td>EEG</td>
<td>2000</td>
<td>ongoing</td>
</tr>
<tr>
<td>PV Tendering scheme</td>
<td>2015</td>
<td>ongoing</td>
</tr>
</tbody>
</table>

Data: BNA, Graph: B. Burger, Fraunhofer ISE Energy-Charts. Date of Data: 31-Jan-2022
PV-Tender in Germany

Average, quantity weighted Award Value

Lowest PV-Tender Round was in Feb. 2018 with 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 8.3 GW by Jun-2022 with 5.51 ct€ / kWh as latest average quantity weighted award price.

Special tenders are not displayed in the graph.
Global Weighted Average Levelised Costs of Electricity for Large PV Systems (with 5th percentile and 95th percentile)

The global weighted average LCoE was in year 2021 for large PV systems 0.041 €/kWh (= 41 €/MWh).

The 5th percentile is a value associated with the location within the data where 5% of data is below that value. In year 2021 the 5th percentile was 0.025 €/kWh (= 25 €/MWh).

The 95th percentile is the value where 5% of the data has a larger value. In year 2021 the 95th percentile was 0.101 €/kWh (= 101 €/MWh).

The LCoE decreased by about 17% on year-to-year basis in the last 11 years.

Data: IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: July 2022
Global Weighted Average Total Installed Costs For Large PV Systems  
(with 5th percentile and 95th percentile)

The global weighted average total cost for large PV systems was 725 €/kWp in year 2021. The 5th percentile is a value associated with the location within the data where 5% of data is below that value. In year 2021 the 5th percentile was 488 €/kWp. The 95th percentile is the value where 5% of the data has a larger value. In year 2021 the 95th percentile was 1658 €/kWp. Total installed cost for large PV systems decreased by about 14% on year-to-year basis in the last 11 years.

Data: IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: July 2022
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 10.8% on y-to-y basis in 2021 and annual average PV module cost increased by 20.0% due to COVID-19 market disturbances.
Breakdown of Utility-scale PV Total Installed Costs
By Country in 2021


Breakdown of cost components (average of available country data):

- Modules 37%
- Inverters 5%
- BoS hardware 22%
- Soft costs 18%
- Installation 18%
Price Learning Curve
Includes all Commercially Available PV Technologies

Learning Rate:
Each time the cumulative PV module production doubled the price went down by about 25% for the last 41 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2022
Price Learning Curve
Includes all Commercially Available PV Technologies

Learning Rate:
Each time the cumulative PV module production doubled the price went down by about 25% for the last 41 years.

Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; Graph: PSE 2022
Price Learning Curve by Technology
Cumulative Production up to Q4-2021

Estimated cumulative PV module production up to Q4-2021:
- c-Si: 958 GWp
- Thin Film: 62 GWp

Crystalline Technology
(from Q2-2006 to Q4-2021) LR 31
Thin Film Technology
(from Q2-2006 to Q4-2021) LR 29

Data: from 2006 to 2010 estimation from different sources: Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit. Graph: PSE 2022

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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

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

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Explanation</th>
<th>Abbr.</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
<td>HJT (also HIT)</td>
<td>Heterojunction with Intrinsic Thin-Layer</td>
</tr>
<tr>
<td>Al-BSF</td>
<td>Aluminum Back Surface Field</td>
<td>IBC</td>
<td>Interdigitated Back Contact (solar cells)</td>
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<tr>
<td>BIPV</td>
<td>Building Integrated PV</td>
<td>LCOE</td>
<td>Levelized Cost of Energy</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of System</td>
<td>LCPV</td>
<td>Low Concentrator Photovoltaic</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium-Telluride</td>
<td>MJ</td>
<td>Multi Junction</td>
</tr>
<tr>
<td>CI(G)S</td>
<td>Copper Indium (Gallium)Diselenide</td>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>CPV</td>
<td>Concentrating Photovoltaic</td>
<td>n-type</td>
<td>Negatively doped wafer (with phosphorous)</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline Silicon</td>
<td>PERX</td>
<td>Passivated emitter and rear cell</td>
</tr>
<tr>
<td>Cz</td>
<td>Czochralski Method</td>
<td>PR</td>
<td>Performance Ratio</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
<td>p-type</td>
<td>Positively doped wafer (with boron)</td>
</tr>
<tr>
<td>EEG</td>
<td>Renewable Energy Source Act (Erneuerbare-Energien-Gesetz)</td>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>EPBT</td>
<td>Energy PayBack Time</td>
<td>RE</td>
<td>Renewable Energies</td>
</tr>
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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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<td>HCPV</td>
<td>High Concentrator Photovoltaic</td>
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Acknowledgements

This work has been carried out with contributions from:

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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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