Karlsruher Institut für Technologie

"Solar Energy" WS 2021/2022

3G rule for attending in person lectures at KIT:

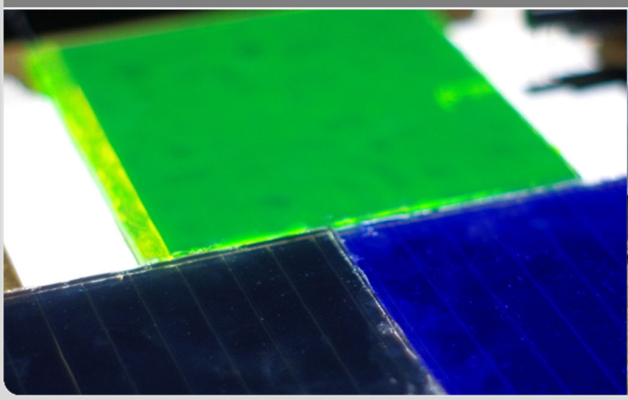
- *geimpft* – vaccinated
- *genesen* – recovered
- *getestet* – tested

Karlsruher Institut für Technologie

"Solar Energy" WS 2021/2022

Lecture 1: Introduction

Prof. Dr. Bryce S. Richards
Institute of Microstructure Technology (IMT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen
Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe



Information

"Solar Energy" lecture (23745) and tutorials (23750)

Lecturers: Prof. Dr. Bryce Richards

CN office: IMT, room 304, Tel: 0721-608-26562

CS office: LTI, room 211, Tel: 0721-608-41998

E-Mail: bryce.richards@kit.edu (try this first)

URL: http://www.imt.kit.edu/richards.php

Tenure-Track-Prof. Dr. Ulrich Paetzold

CN office: IMT, room 356, Tel: 0721-608-26357

CS office: LTI, room 211, Tel: 0721-608-41998

E-Mail: ulrich.paetzold@kit.edu

URL: http://www.imt.kit.edu/richards.php

Information

"Solar Energy" lecture (2313745) and tutorials (2313716)

Tutors: Benni

E-Mail: benjamin.hacene@kit.edu

Emmanuel

E-Mail: emmanuel.ogunniyi@kit.edu

Information

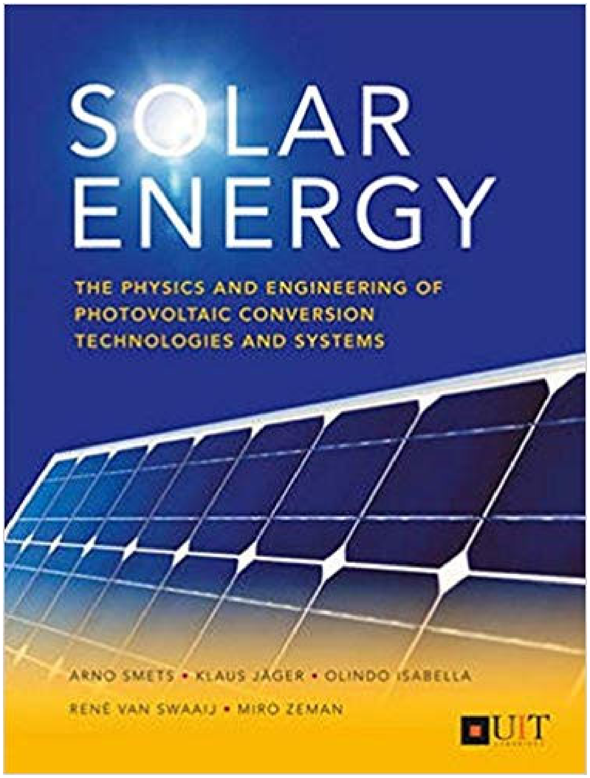
- Slides will be available as PDF files for download from ILIAS https://ilias.studium.kit.edu ⇒ **2313745 – Solar Energy - WS 2021/22**
- Six tutorial sessions throughout the course – N.B. tutorial dates on Campus system likely incorrect ⇒ correct schedule is on ILIAS
- Several other events planned to enhance your learning experience:
  - One lab demonstration
  - One excursion – to the KIT Solar Park (1MW PV installation)
- Exam will be a 2 hour written exam: likely date **8th Mar 2022**

Textbook

- "*Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems*" (2016)

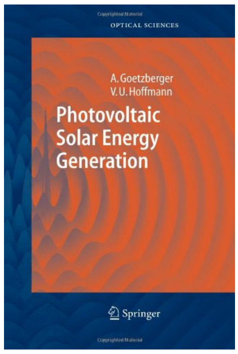
  by Smets, Jäger, Isabella, van Swaaij (TU Delft)
- Amazon: €31 (paperback)

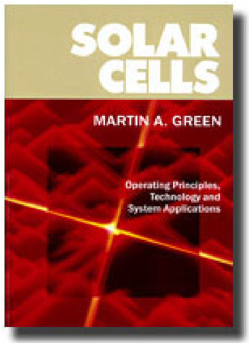
  €0 (Kindle, UK only)
- Technological focus
- Lectures largely follow chapters in textbook:
  - Some chapters skipped
  - Some material supplemented



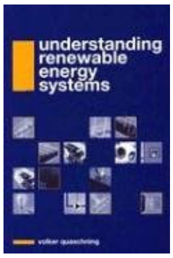
Other Resources

- "*Photovoltaic Solar Energy Generation*" by Adolf Goetzberger and Volker U. Hoffmann, Springer, 2010
- "*Solar Cells – Operating Principles, Technology and System Applications*", by Martin A. Green, Prentice-Hall 1986
- "*Understanding Renewable Energy Systems*" by Volker Quaschning, Earthscan 2016
- "PV*CDROM*" by Christiana Honsberg and Stuart Bowden, https://www.pveducation.org/pvcdrom/welcome-to-pvcdrom



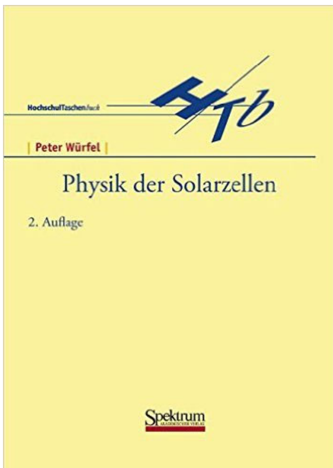


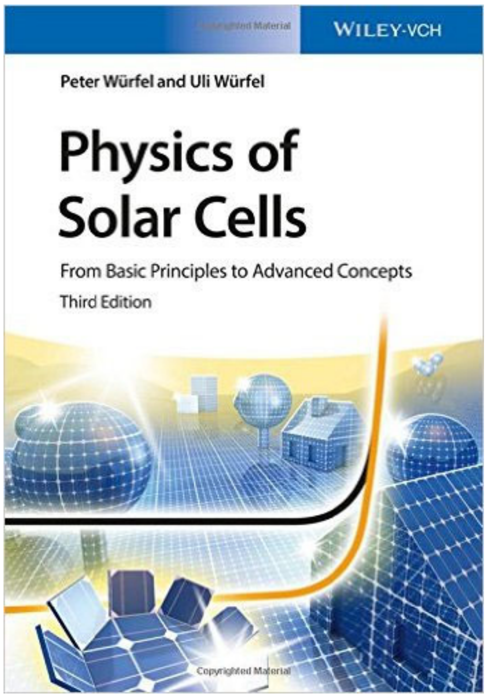
PVEDUCATION.ORG



Other Resources

- "*Physics of Solar Cells*" by Peter Würfel and Uli Würfel, Wiley
- Written by an ex-professor from Institute of Applied Physics at KIT
- Will mostly appeal to physics and chemistry students
- 2x cheaper if you can read German!





Lecture Schedule

12:00-13:30

LTI Hörsaal, Geb. 30.34, Monday 10:00 – 11:30	LTI Hörsaal, Geb. 30.34, Thursday ~~XX:XX-XX:XX~~
Mon 18 Oct 2021	Thu 21 Oct 2021
Lecture 1: Introduction (Chpt 1 – 3) (Prof. Richards)	Lecture 2: Solar Radiation (Chpt 5) (Prof. Richards)
Mon 25 Oct 2021	Thu 28 Oct 2021
Lecture 3: Basics of Electrodynamics & Semiconductor Physics (Chpt. 4 & 6) (Prof. Paetzold)	Lecture 4: Generation & Recombination (Chpt 7) (Prof. Paetzold)
Mon 1 Nov 2021	Thu 4 Nov 2021
NO LECTURE or TUTORIAL	Tutorial 1: Chpts 1 – 6
Mon 8 Nov 2021	Thu 11 Nov 2021
Lecture 5: Semiconductor Junctions (Chpt 8) (Prof. Paetzold)	Lecture 6: Solar Cell Parameters (Chpt 9) (Prof. Paetzold)
Mon 15 Nov 2021	Thu 18 Nov 2021
Lecture 7: Crystalline Silicon Solar Cells (Chpt 11 & 12) (Prof. Richards)	Tutorial 2: Chpts 7 – 9
Mon 22 Nov 2021	Thu 25 Nov 2021
Lecture 8: Thin-Film Solar Cells: inorganic (Chpt 13) (Prof. Richards)	Lecture 9: Thin-Film Solar Cells: OPV/perovskite (Chpt 13) (Prof. Paetzold)
Mon 29 Nov 2021	Thu 2 Dec 2021
Lecture 10: PV Modules (Chpt 15) (Prof. Richards)	Tutorial 3: Chpts 11 – 13
Mon 6 Dec 2021	Thu 9 Dec 2020
Lecture 11: PV Systems & Components (Chpt 17 & 19) (Prof. Richards)	Lecture 12: Location Issues + PV System Design + PV in developing countries (Chpt 18 & 20) (Prof. Richards)

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12:00-13:30

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Mon 13 Dec 2021	Thu 16 Dec 2020
Lecture 13: PV System Economics & Environmental Aspects (Chpt 21) (Prof. Paetzold)	Tutorial 4: Chpts 15, 17, 19
Mon 20 Dec 2021	Thu 23 Dec 2021
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 27 Dec 2021	Thu 30 Dec 2021
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 3 Jan 2022	Thu 6 Jan 2022
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 10 Jan 2022	Thu 13 Jan 2022
Demo: Getting hands-on with solar cells (TBA)	Lecture 14: Spectral conversion for PV (extra) (Prof. Richards)
Mon 17 Jan 2022	Thu 20 Jan 2022
Tutorial 5: Chpts 18 & 20-21	Lecture 15: Light management for PV (Chpt 10 + extra) (Prof. Paetzold)
Mon 24 Jan 2022	Thu 27 Jan 2022
Lecture 16: Losses, Efficiency Limits and Third Gen. Concepts (Chpts 10 & 16) (Prof. Paetzold)	Lecture 17: Tandem Solar Cells (extra) (Prof. Paetzold)
Mon 31 Jan 2022	Thu 3 Feb 2022
Tutorial 6: Chpt 10 + 16 + extra	EXCURSION Visit to KIT Solar Park (Prof. Richards)
Mon 7 Feb 2022	Thu 10 Feb 2022
Mock exam	Review and Q&A session (Prof. Paetzold & Prof. Richards)

Questions?

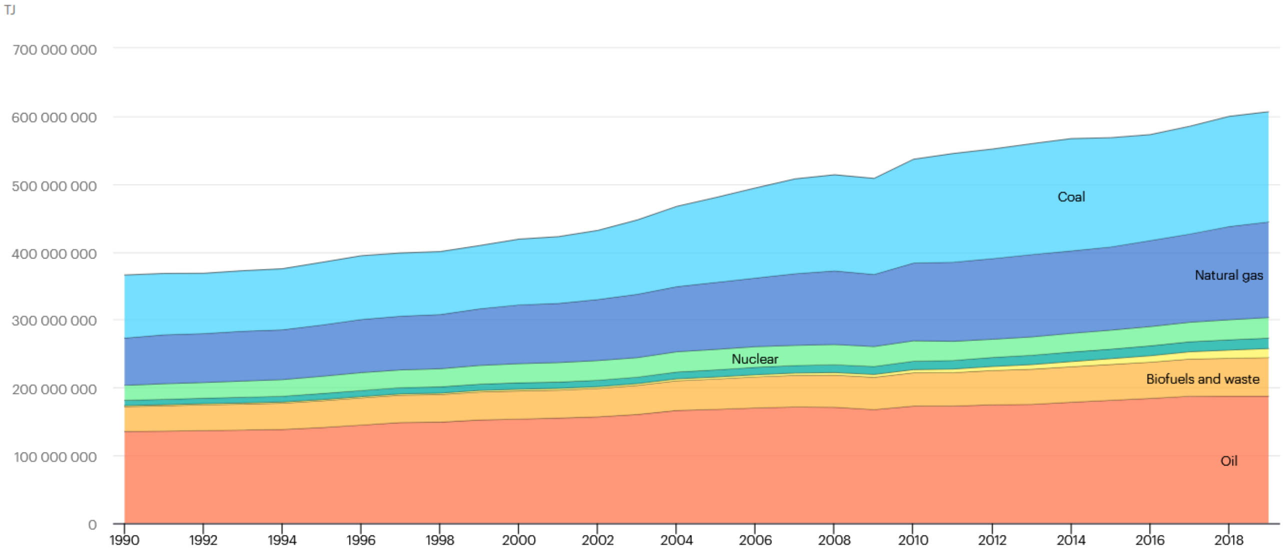
Solar Energy Conversion

- Course deals primarily with conversion of sunlight directly into electrical energy $\equiv$ **<u>photovoltaic devices</u>** or **<u>solar cells</u>**
- The course does <u>not</u> cover:
  - Solar thermal – very efficient and best suited for heating and cooling applications (e.g. no energy conversion step). Steam can be used to drive a turbine to produce electricity, but only realistic in very large scale plants
  - Solar fuels – artificial photosynthesis driven by sunlight
  - Wind energy – driven by the sun in the sense that sunshine is responsible for setting up the temperature gradients that cause air currents to flow
  - Biomass – sunlight used to grow plants which can then be combusted or converted into liquid fuels

Energy Mix

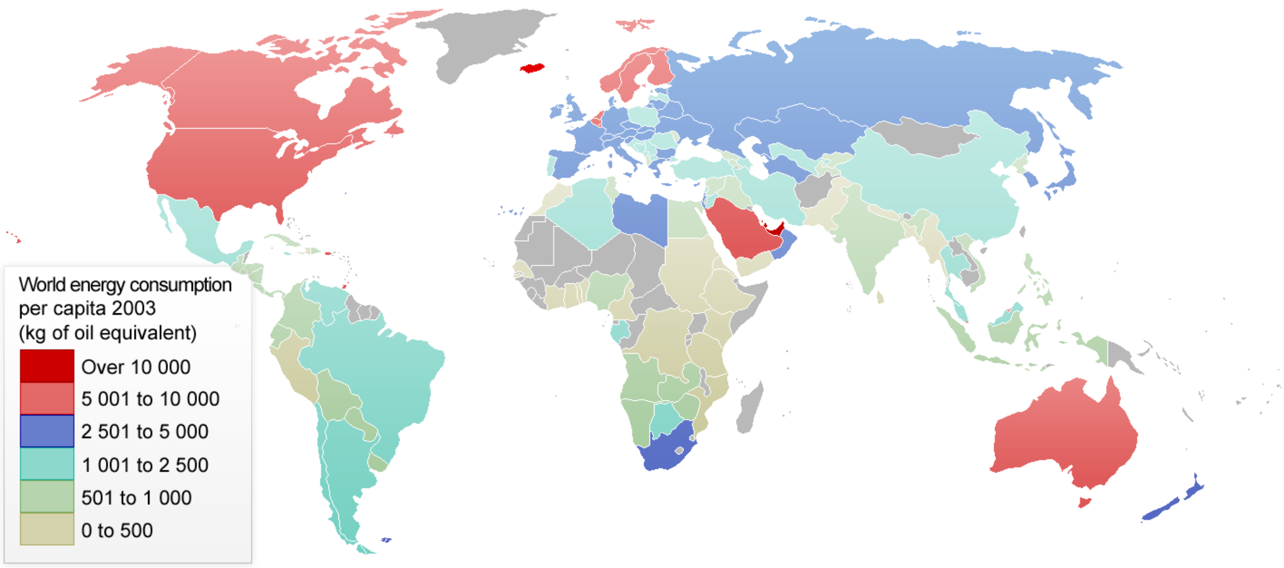
Total energy supply (TES) by source, World 1990-2018

- Energy demand steadily increasing
- Solar (thermal + PV) + wind supplied ~2% of total energy in 2019
- Units: ktoe = “1000s tonnes of oil equivalent”; 1 ktoe = 11.63 GWh
  1 TJ = 0.278 GWh



Source: https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource

Energy consumption per capita



Source: from International Energy Agency (IEA) Statistics Division data; Energy Balances of OECD Countries, 2006 edition and Energy Balances of Non-OECD Countries, 2006 edition.

Energy consumption per capita

Bundesministerium
für Wirtschaft
und Technologie

	1990	1991	2004	2005	2006	2007	2008	2009	2010
WELT	**69,8**	**69,3**	**73,3**	**74,5**	**75,4**	**76,2**	**77,0**	**75,4**	
AFRIKA	**25,7**	**26,0**	**27,2**	**27,2**	**27,2**	**27,6**	**28,5**	**28,1**	
NORDAMERIKA	**261,5**	**258,7**	**260,2**	**260,3**	**255,7**	**257,6**	**249,8**	**235,6**	**239,8**
- USA	320,2	318,5	329,2	327,7	321,5	324,0	312,7	294,5	301,4
SÜDAMERIKA	**40,3**	**40,2**	**46,1**	**47,7**	**49,4**	**49,8**	**51,1**	**50,2**	
ASIEN (Nicht-OECD-Länder) ohne China	**18,7**	**19,2**	**24,7**	**25,1**	**26,0**	**26,4**	**26,8**	**27,6**	
- Indien	15,7	16,0	20,1	20,5	21,4	22,2	22,6	24,3	
CHINA	**32,0**	**31,4**	**50,7**	**54,4**	**59,5**	**62,4**	**67,0**	**71,2**	
MITTLERER OSTEN	**70,0**	**75,4**	**113,0**	**117,2**	**121,4**	**121,4**	**126,4**	**126,9**	
EUROPA (OECD - Länder)	**135,0**	**136,1**	**144,4**	**143,9**	**143,8**	**141,7**	**140,6**	**133,1**	**137,8**
EUROPA (EU - 27)	**144,9**	**144,8**	**152,0**	**151,6**	**150,7**	**148,2**	**147,0**	**138,6**	
- Deutschland	185,4	180,4	174,3	172,0	173,5	168,9	170,6	162,9	169,8
- Frankreich	161,6	170,1	180,7	180,0	176,6	173,6	174,4	166,3	171,1
- Großbritannien	151,5	155,9	155,2	154,6	151,3	144,3	141,9	133,3	137,5
- Italien	108,3	110,8	131,0	131,4	129,4	126,3	123,2	114,5	118,7
- Spanien	96,7	100,1	136,4	136,8	134,4	134,2	127,5	115,3	116,0
- Niederlande	184,0	192,7	203,4	202,3	196,9	202,8	202,6	198,0	209,6
EUROPA (Nicht-OECD-Länder)	**98,5**	**82,2**	**132,7**	**134,4**	**138,6**	**139,8**	**142,4**	**131,5**	
Frühere SU	**203,4**	**200,2**	**188,0**	**190,1**	**196,8**	**198,0**	**203,1**	**190,9**	
Asien	**24,9**	**25,1**	**36,8**	**38,6**	**40,7**	**42,2**	**44,2**	**46,0**	
- Japan	148,5	149,5	171,2	170,6	170,3	168,8	162,7	155,2	163,3
OECD-Länder gesamt	**181,8**	**175,8**	**179,5**	**181,3**	**183,6**	**187,7**	**188,2**	**187,5**	**189,7**

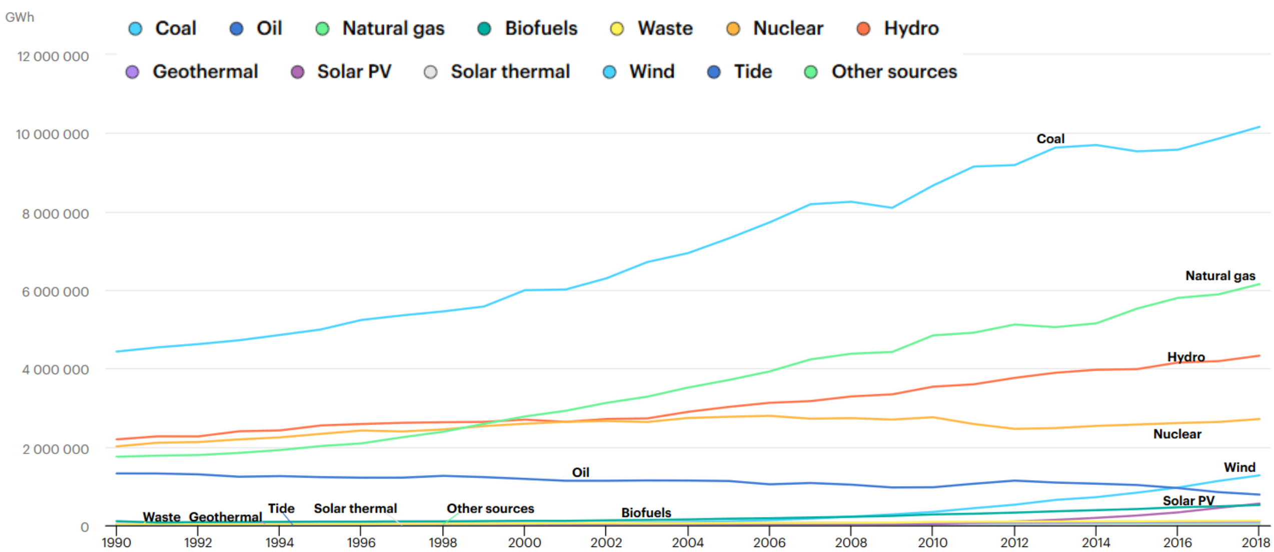
Germany in 2010: 170 GJ

In Germany, the average person is consuming this much power at any one time: $$\frac{170 \cdot 10^9\mathrm{J}}{365 \cdot 24 \cdot 3600\mathrm{s}} \approx 5400\ \mathrm{W}$$

Electricity Supply

Electricity generation by source, World 1990-2018

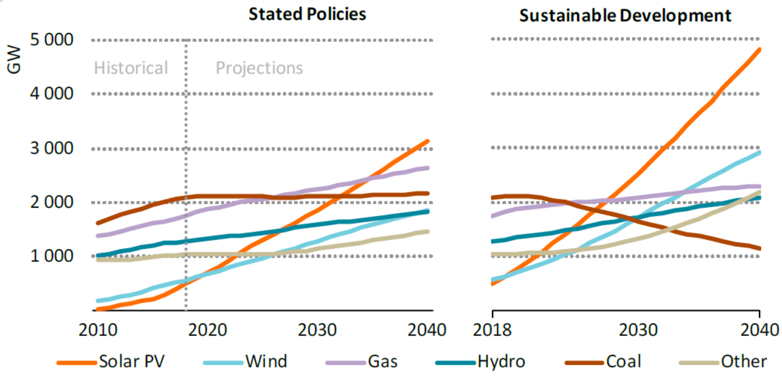
- Overall electricity demand also steadily increasing
- PV supplied ~2% of total electricity in 2018 (2.5% in 2019)

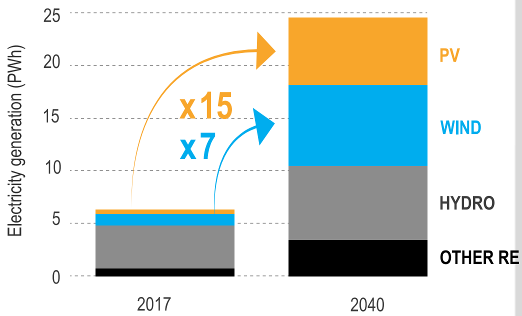


Source: https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=ElecGenByFuel

Electricity Consumption

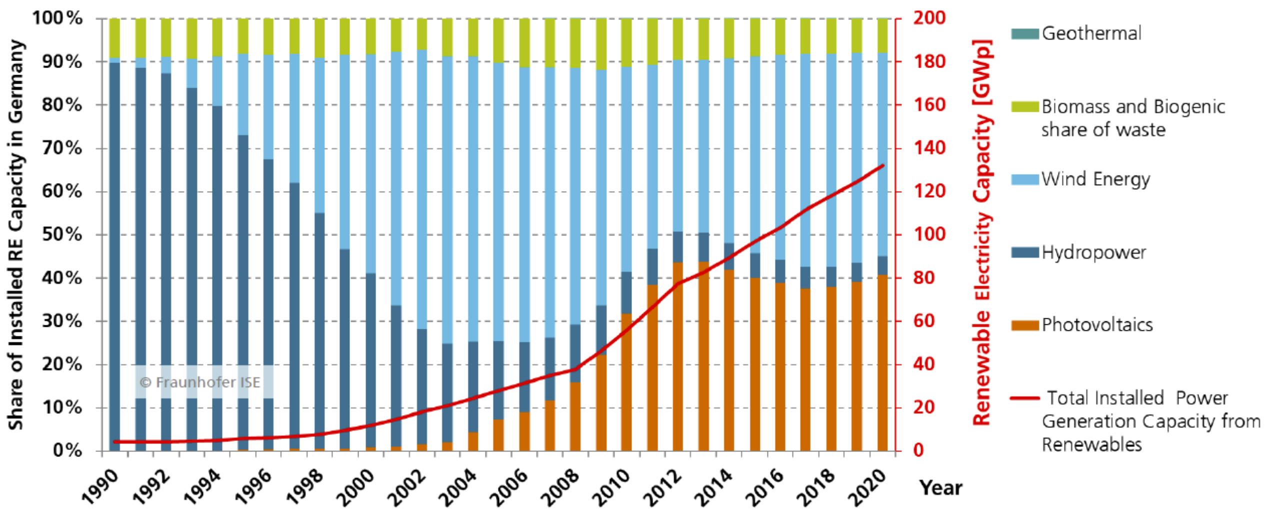
- PV to account for more global installed capacity than any other energy source by late'20s to mid-'30s (depending on scenario)





Source: IEA (2019), *World Energy Outlook 2019*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2019

Germany: Renewable Electricity



In 2020, ~45% (244 TWh) of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi

Source https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Germany: CO_2 Emissions Avoided

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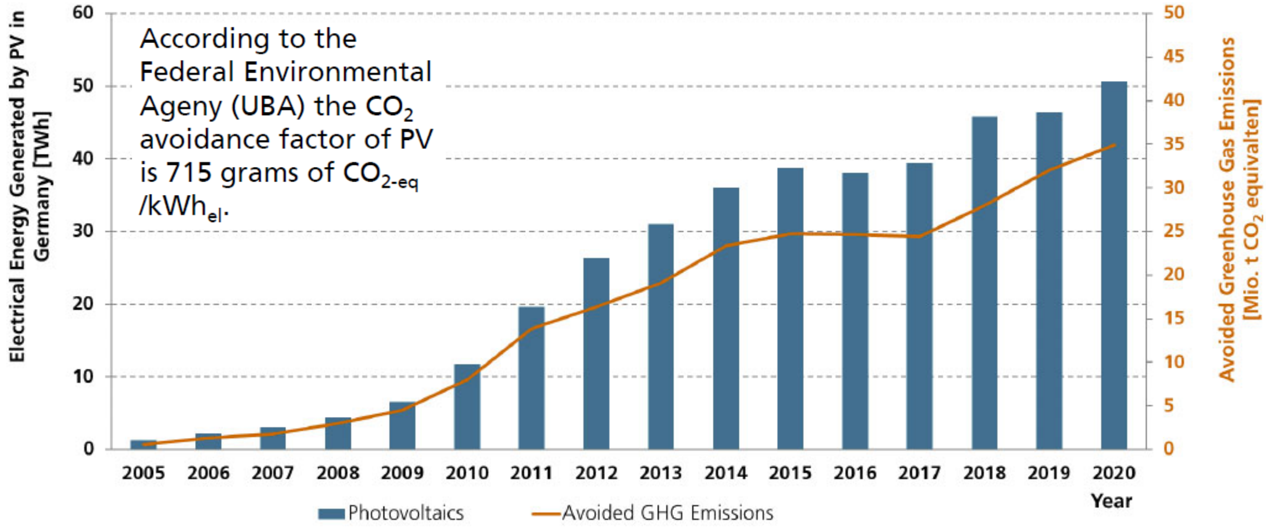
In 2020, greenhouse gas emissions of about 35 Mio. t CO_2-equivalent were avoided due to 50.6 TWh PV electricity consumed in Germany.



Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Germany: Installed Capacity

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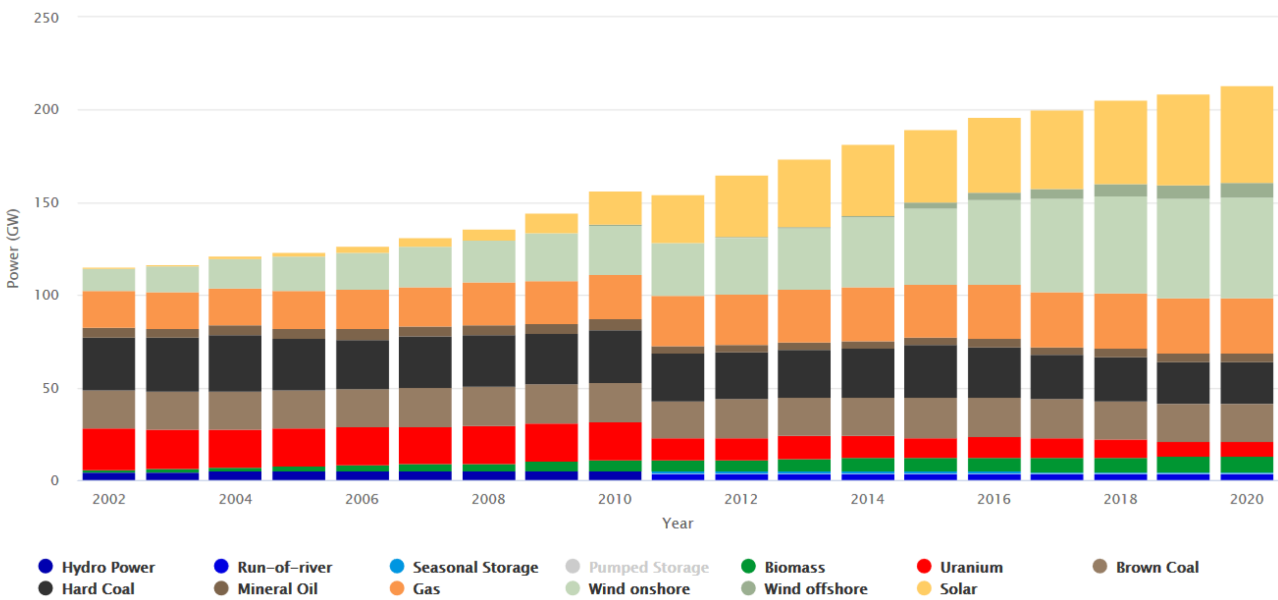
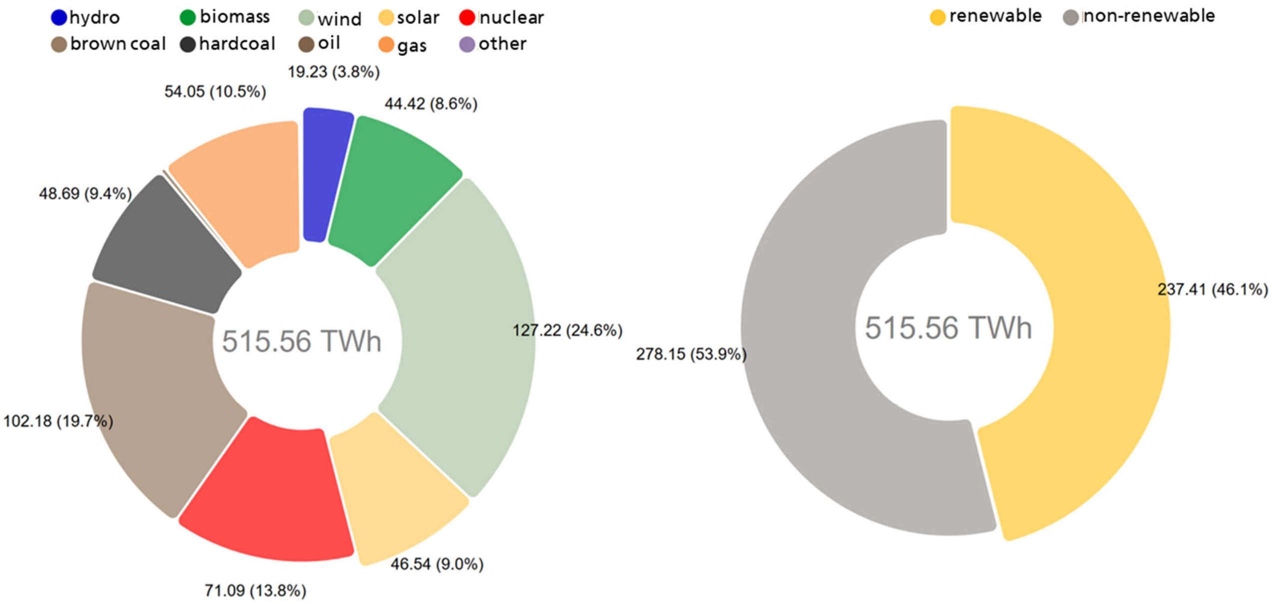


Source: https://energy-charts.info/charts/installed_power/chart.htm?l=en&c=DE

Electricity Production Figures

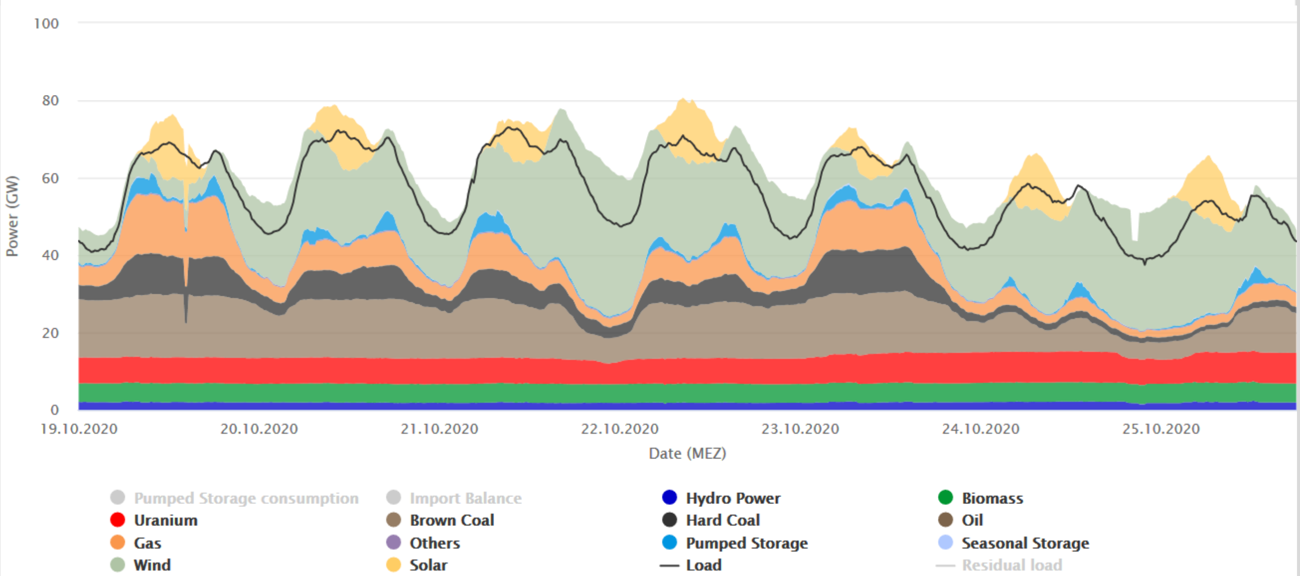
- 2019 data:



Source: https://www.ise.fraunhofer.de/en/press-media/news/2019/Public-net-electricity-generation-in-germany-2019.html

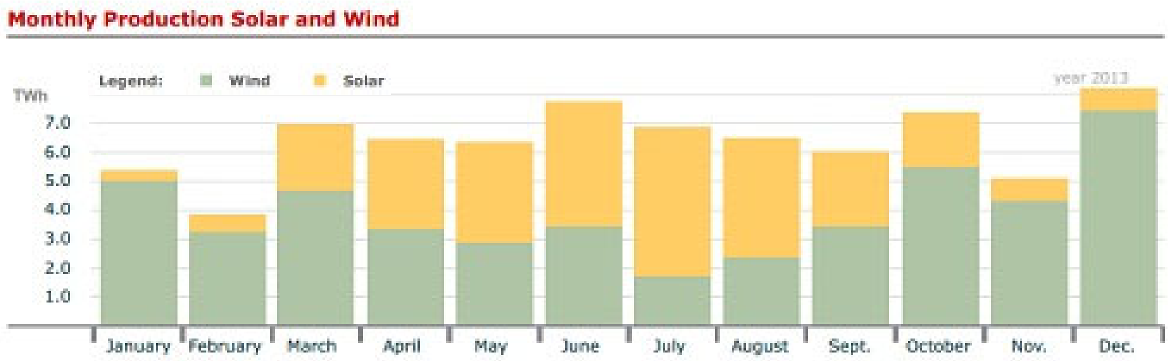
Electricity Production Figures

- Week 43 2020:



Source: https://thstlewpg.wordpress.com/2016/12/31/germany-electricity-statistics/

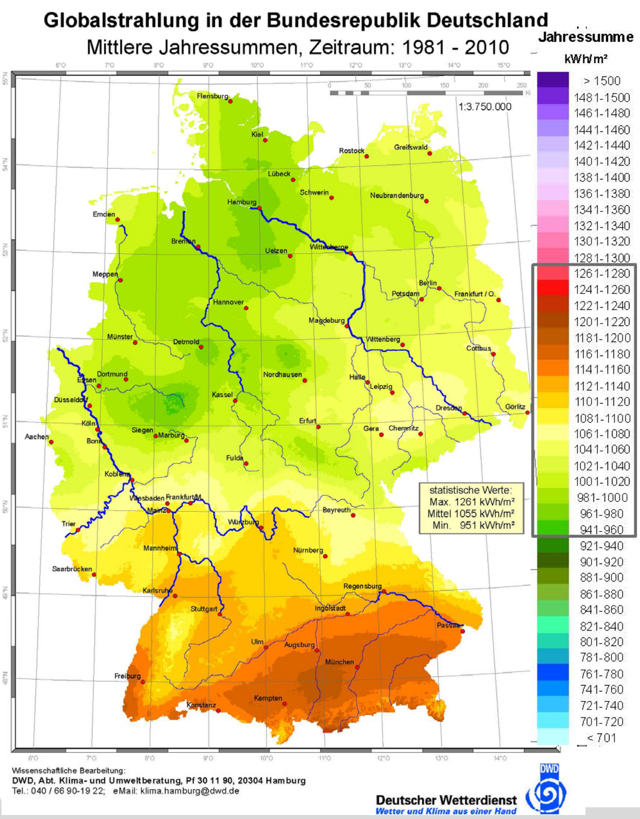
Solar & Wind Electricity



- In the year shown (2013), maximum solar & wind electricity production occurred in Dec (8.2 TWh), while minimum was less than half in Feb (3.9 TWh)
- Overall, good complementarity between more in winter months and more solar power in summer months

Source: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/recent-facts-about-photovoltaics-in-germany.pdf

Solar Radiation – Germany



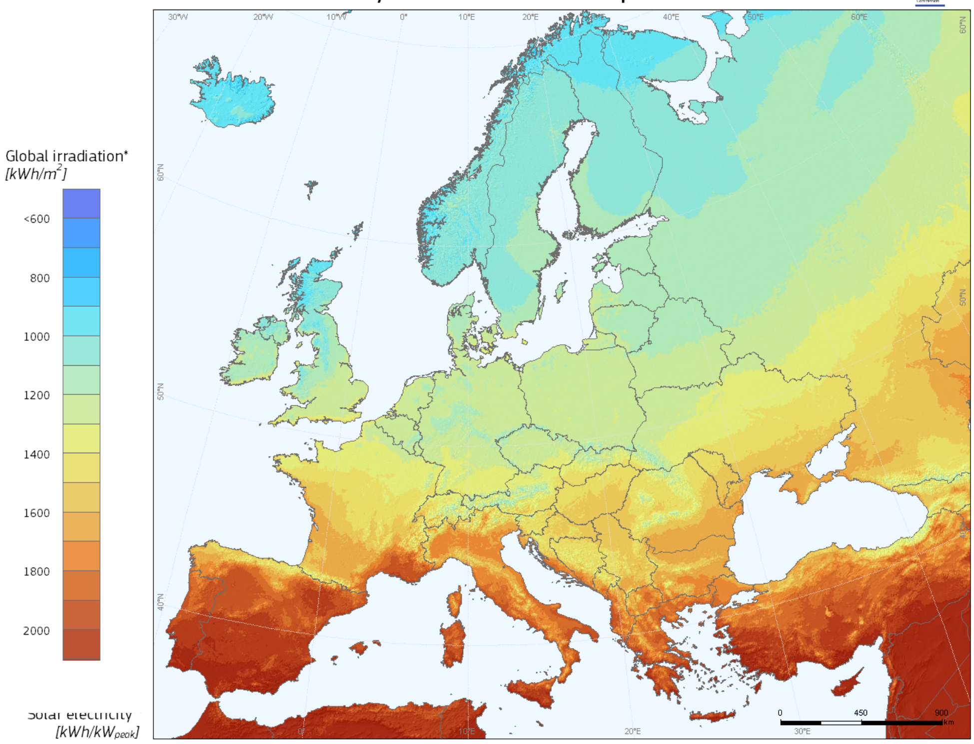
Average amount of solar radiation falling onto a horizontal plane at different locations in Germany

Typically each 1m^2 receives about 1000 – 1200 kWh of solar radiation per year

Source: German Weather Service http://www.dwd.de/bvbw/generator/DWDWWW/Content/Oeffentlichkeit/KU/KU1/KU12/Klimagutachten/Solarenergie/Globalkarten__entgeltfrei/VielJ_C3_A4hrigeMittelwerte/Jahr__1981-2010,templateId=raw,property=publicationFile.pdf/Jahr_1981-2010.pdf

Solar Radiation – Europe

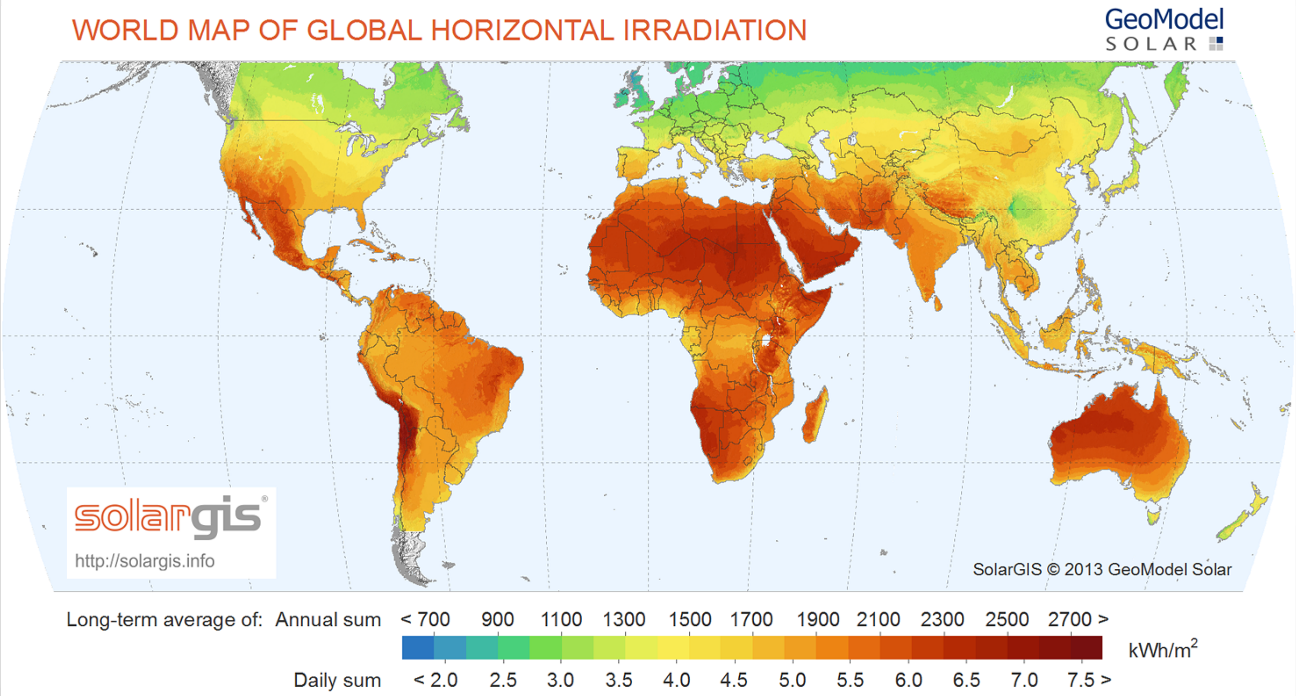
Photovoltaic Solar Electricity Potential in European Countries



Values for Europe vary greatly with northerly regions receiving ~800 kWh/m^2 while southern Spain, Italy and Greece >2000 kWh/m^2

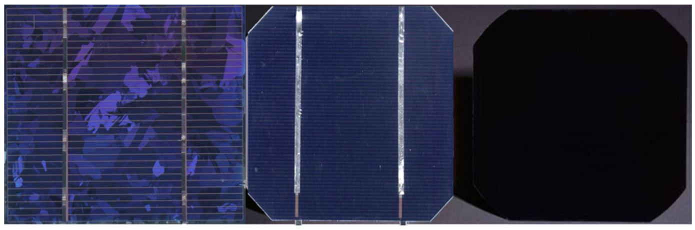
Source: http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm

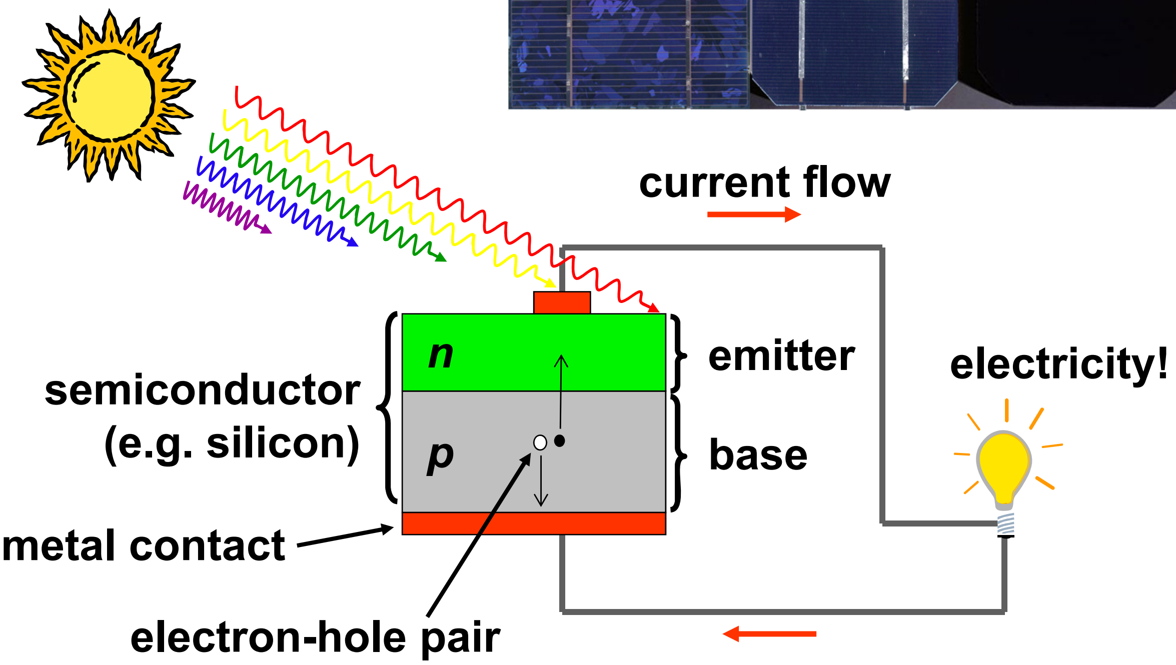
Solar Radiation – World



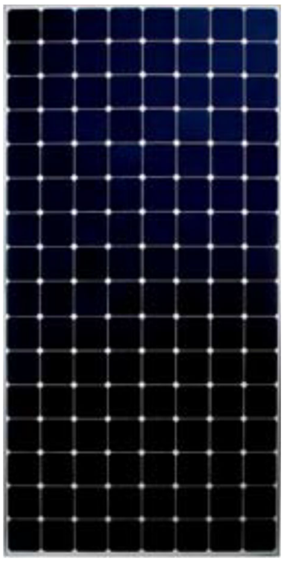
Source: http://solargis.info/doc/free-solar-radiation-maps-GHI

Solar Cell – Brief Overview





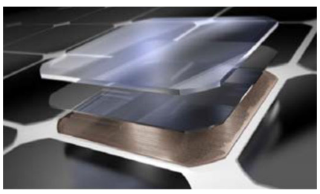
Typical Photovoltaic Module



Data for 470 W_p (watt-peak) module measured under “standard test conditions” (STC = 1000 W/m^2 solar radiation at 25°C under air-mass 1.5 spectrum)

Area = 3.16m^2

Electrical Data			
	SPR-X21-470-COM	SPR-X21-460-COM	SPR-X20-445-COM
Nominal Power (Pnom)[5]	470 W	460 W	445 W
Power Tolerance	+5/−0%	+5/−0%	+5/−0%
Avg. Panel Efficiency[6]	21.7%	21.3%	20.6%
Rated Voltage (Vmpp)	77.6 V	77.3 V	76.5 V
Rated Current (Impp)	6.06 A	5.95 A	5.82 A
Open-Circuit Voltage (Voc)	91.5 V	90.5 V	90.0 V
Short-Circuit Current (Isc)	6.45 A	6.39 A	6.24 A
Max. System Voltage	1000 V UL & 1000 V IEC		
Maximum Series Fuse	15 A		
Power Temp Coef.	−0.29% / ° C		
Voltage Temp Coef.	−223.2 mV / ° C		
Current Temp Coef.	2.9 mA / ° C		

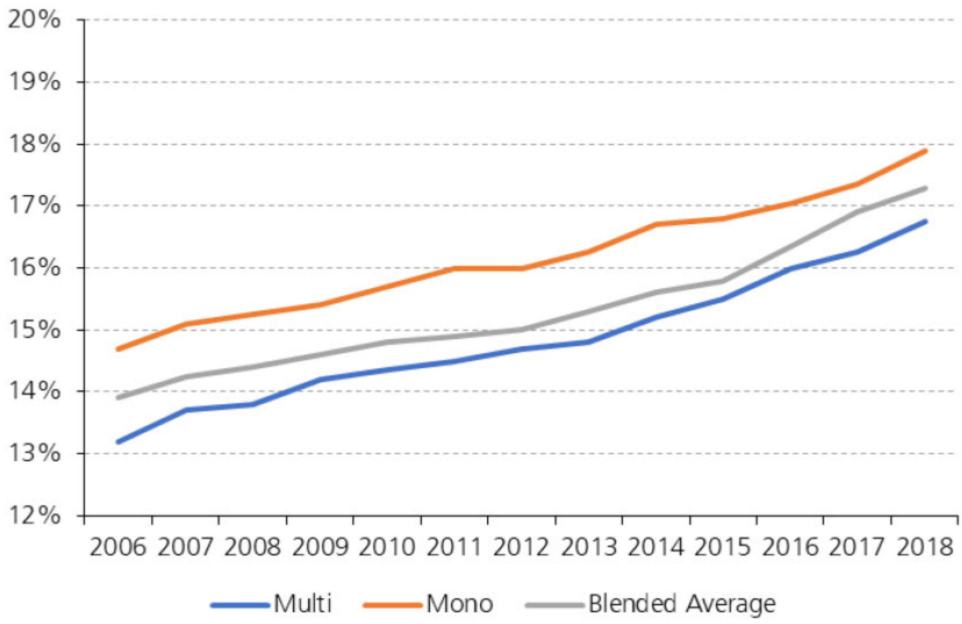


Operating Condition And Mechanical Data	
Temperature	−40° F to +185° F (−40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class B
Solar Cells	128 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, 1230 mm cables / MC4 compatible
Weight	56 lbs (25.4 kg)
Max. Load	Wind: 50 psf, 2400 Pa front & back Snow: 112 psf, 5400 Pa front
Frame	Class 2 silver anodized; stacking pins

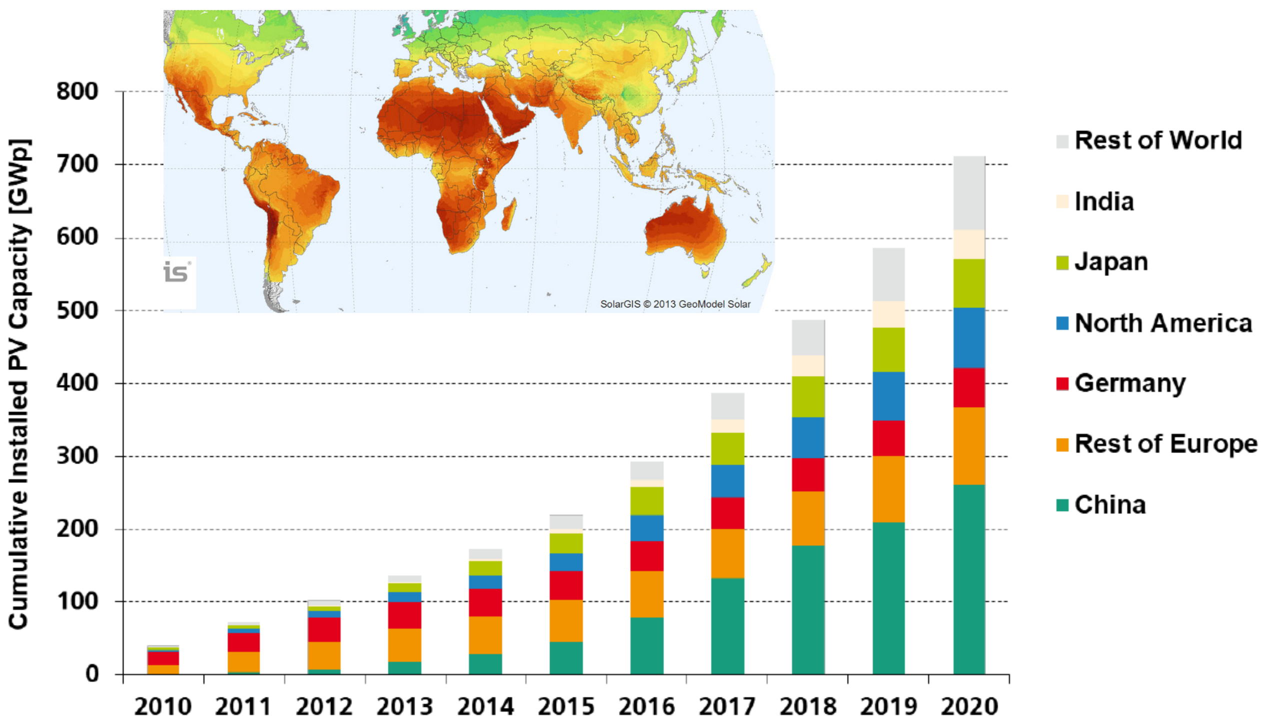
Source: https://us.sunpower.com/solar-resources/sunpower-x-series-commercial-x21-470-com-x21-460-com-x21-445-com

Typical Photovoltaic Module

- Average module efficiencies today 18% for a silicon PV panel (best 22%)
- Slowly-but-steadily increasing over time

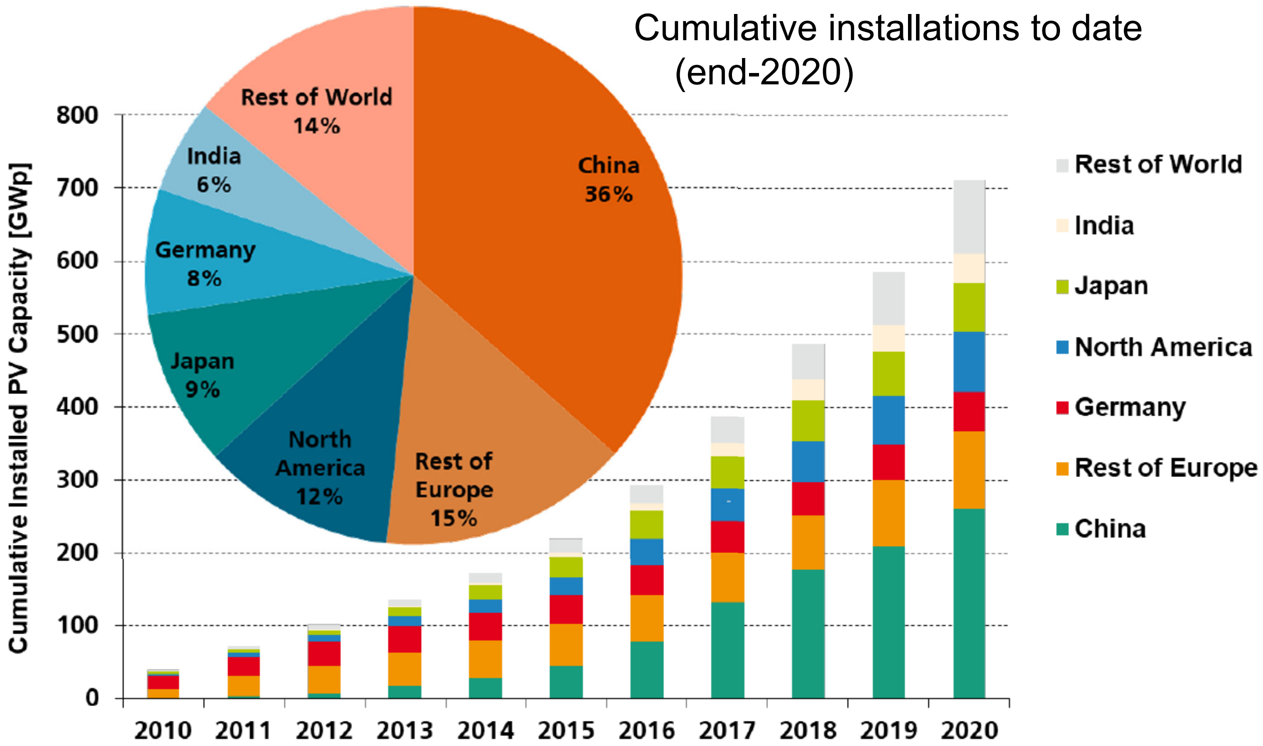


Where is PV Installed?



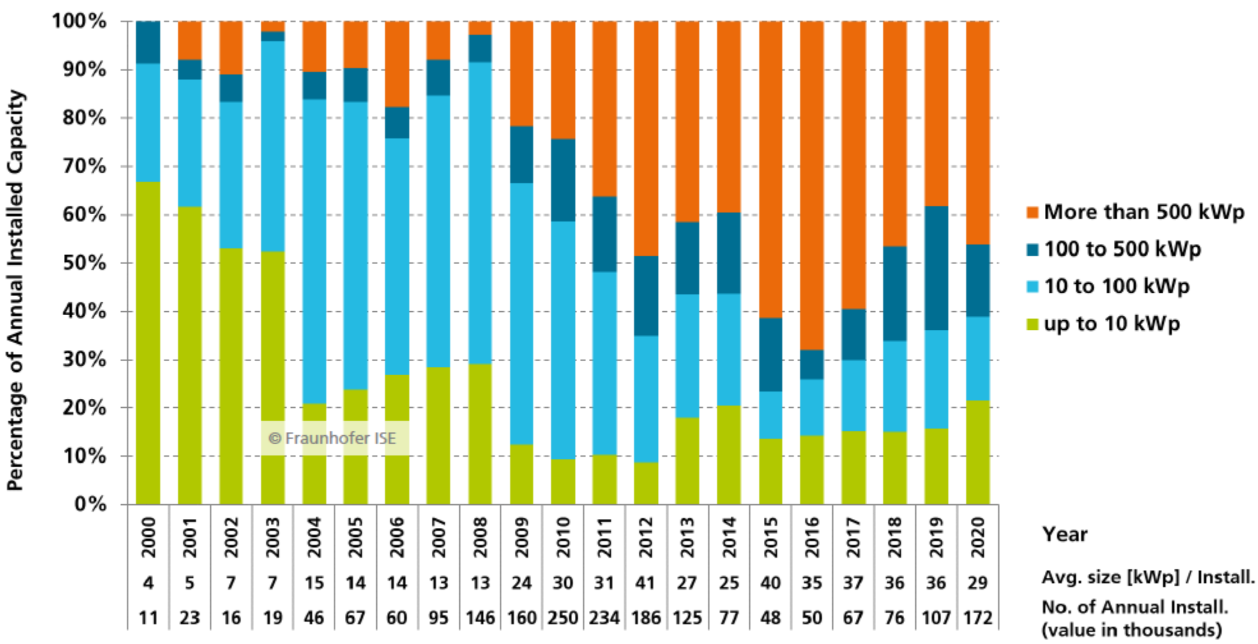
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Where is PV Installed?



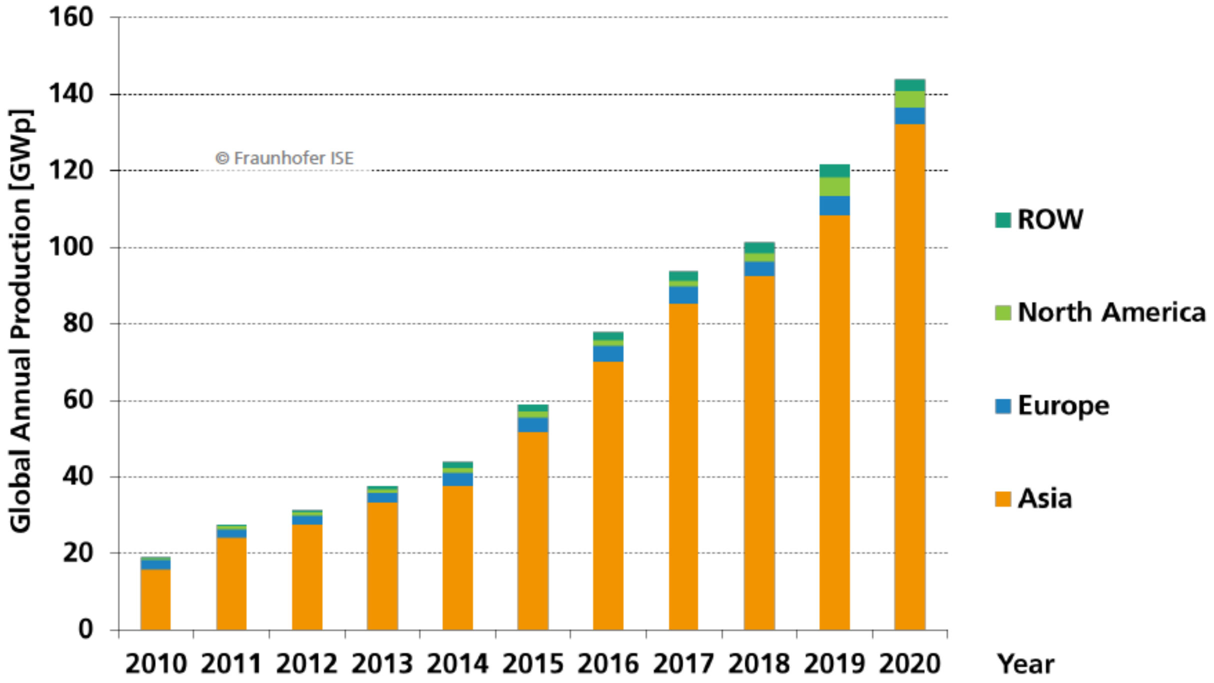
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

German PV System Sizes



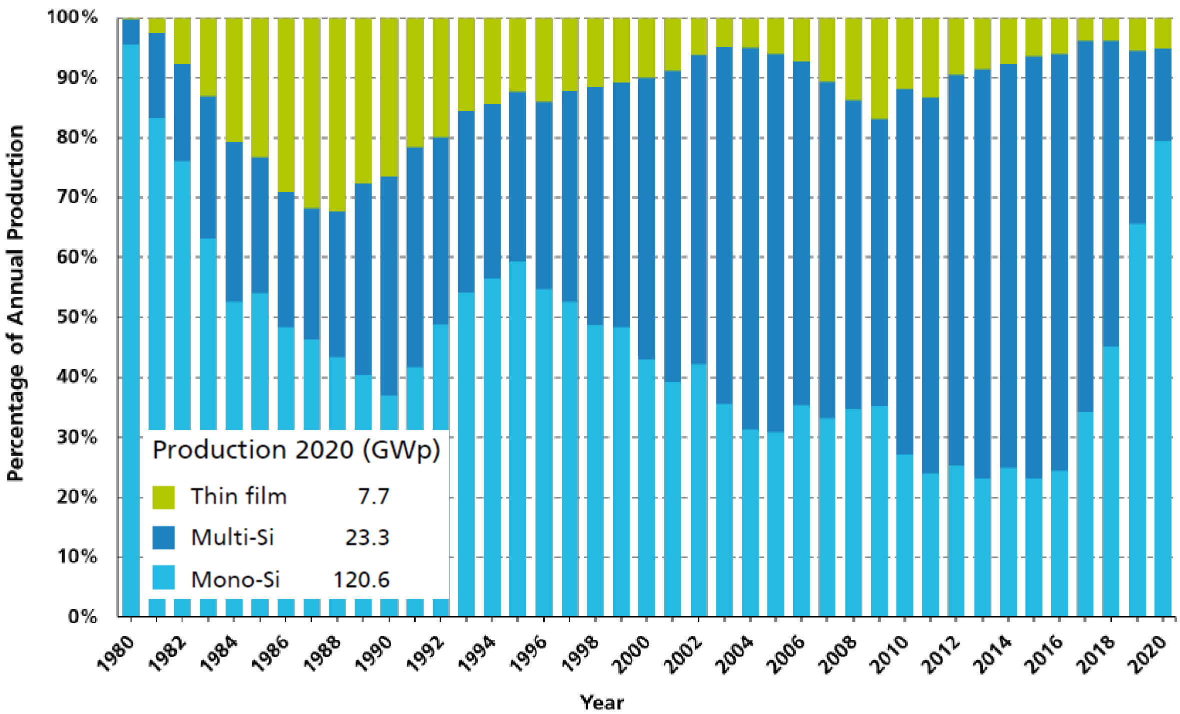
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Where is PV Produced?



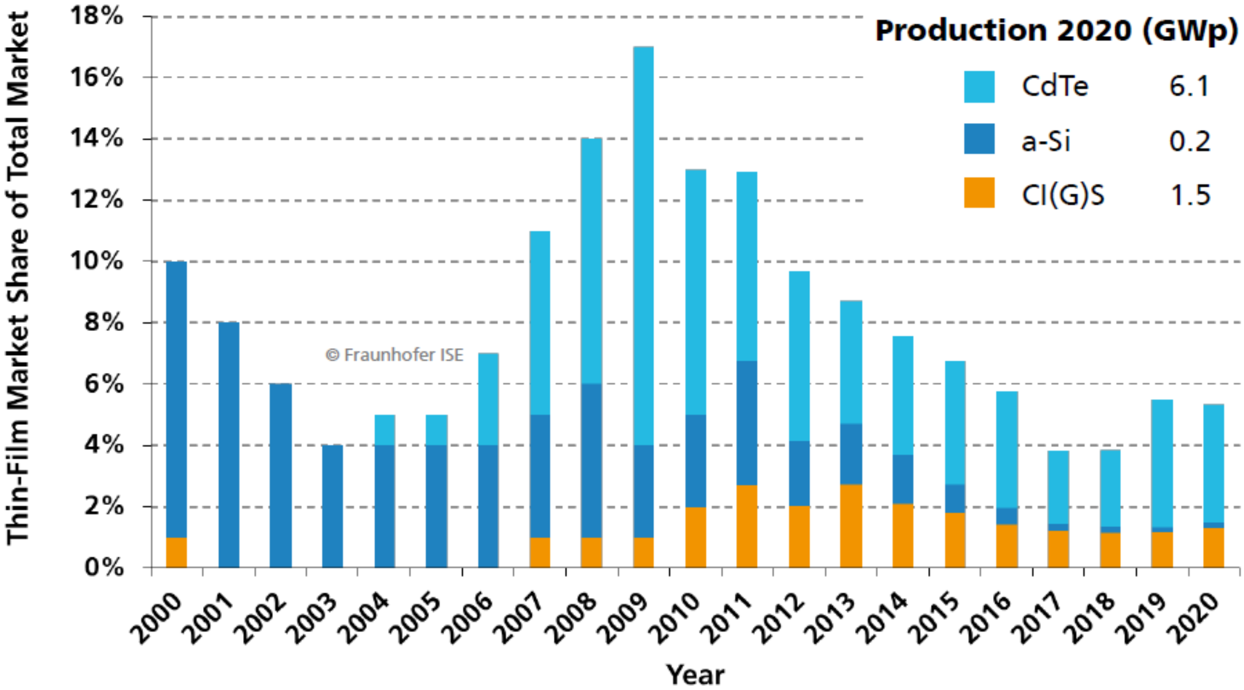
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

What PV Technologies are Produced?



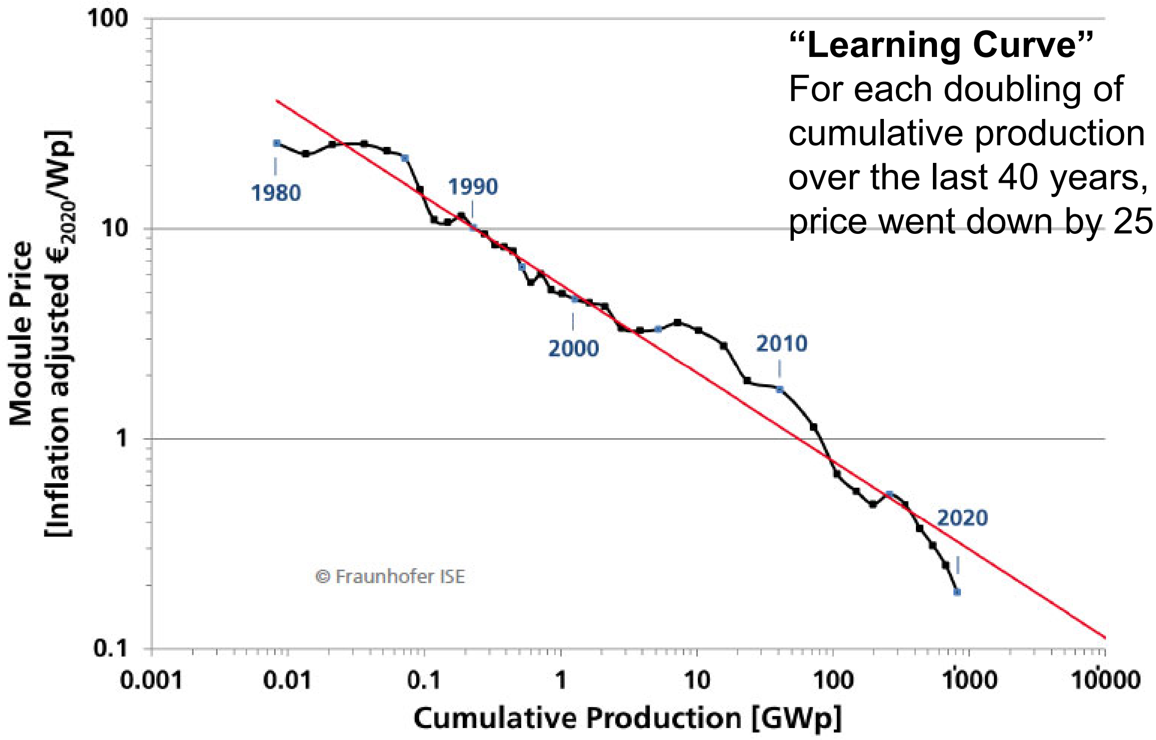
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

What PV Technologies are Produced – Thin-Film?



Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

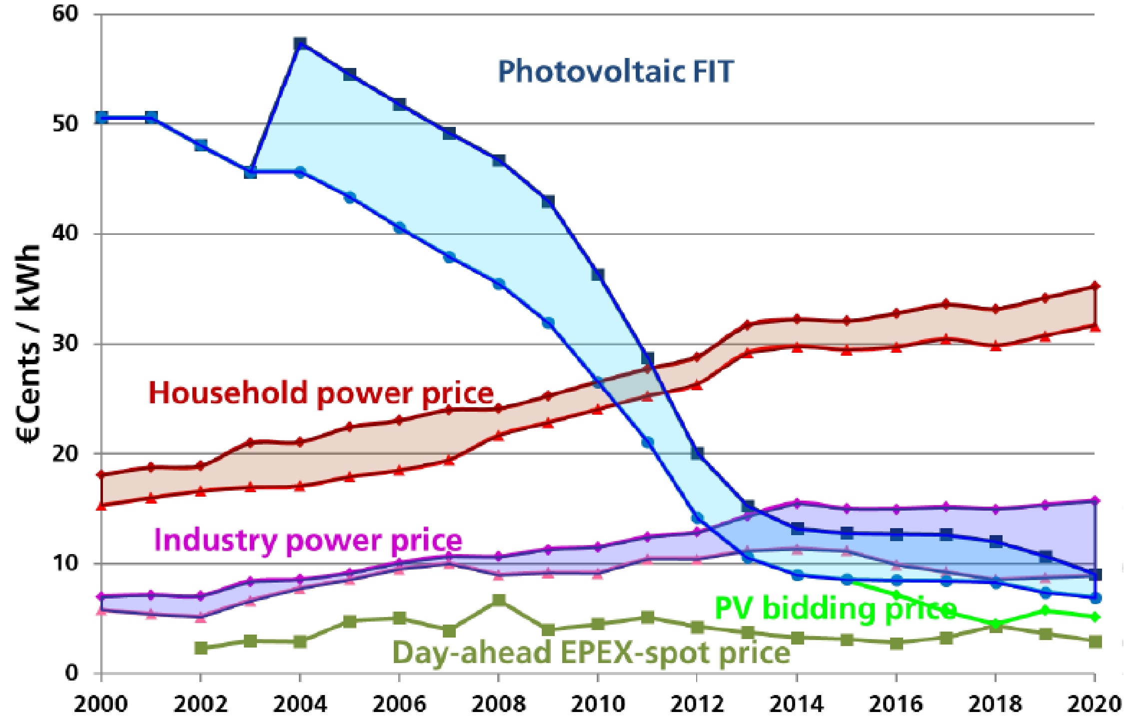
PV Module Costs over Time



"Learning Curve"
For each doubling of cumulative production over the last 40 years, the price went down by 25%

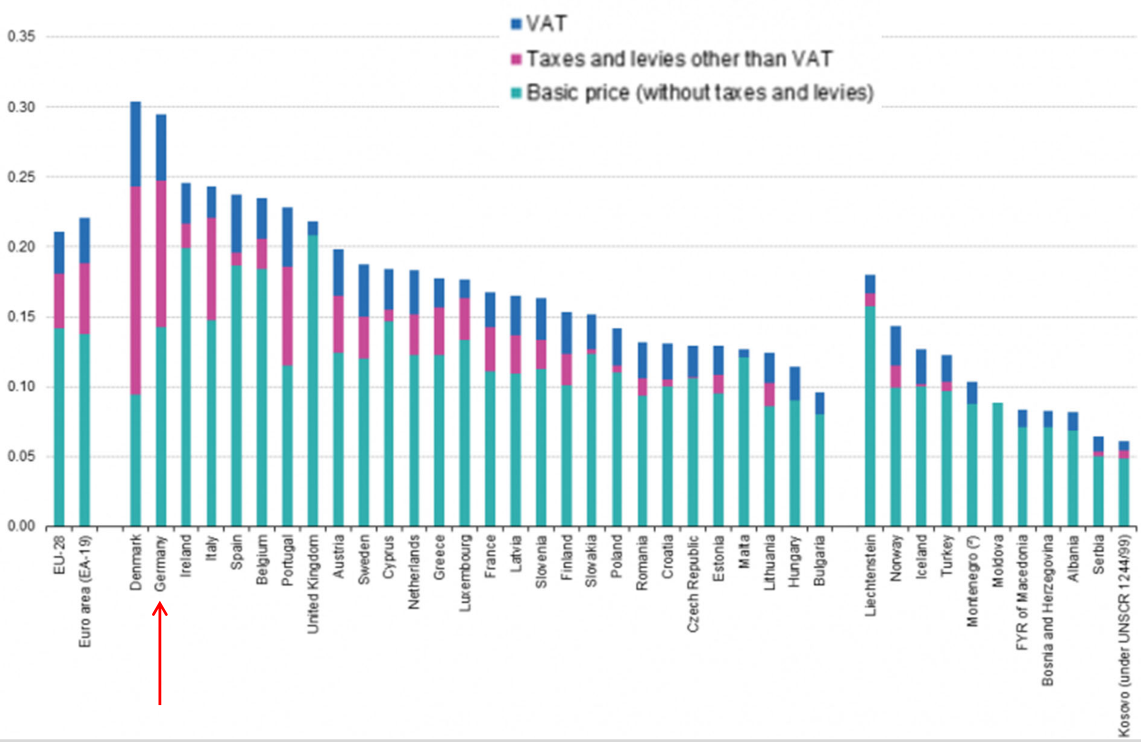
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Electricity Prices, PV Feed-In Tariffs (FIT)



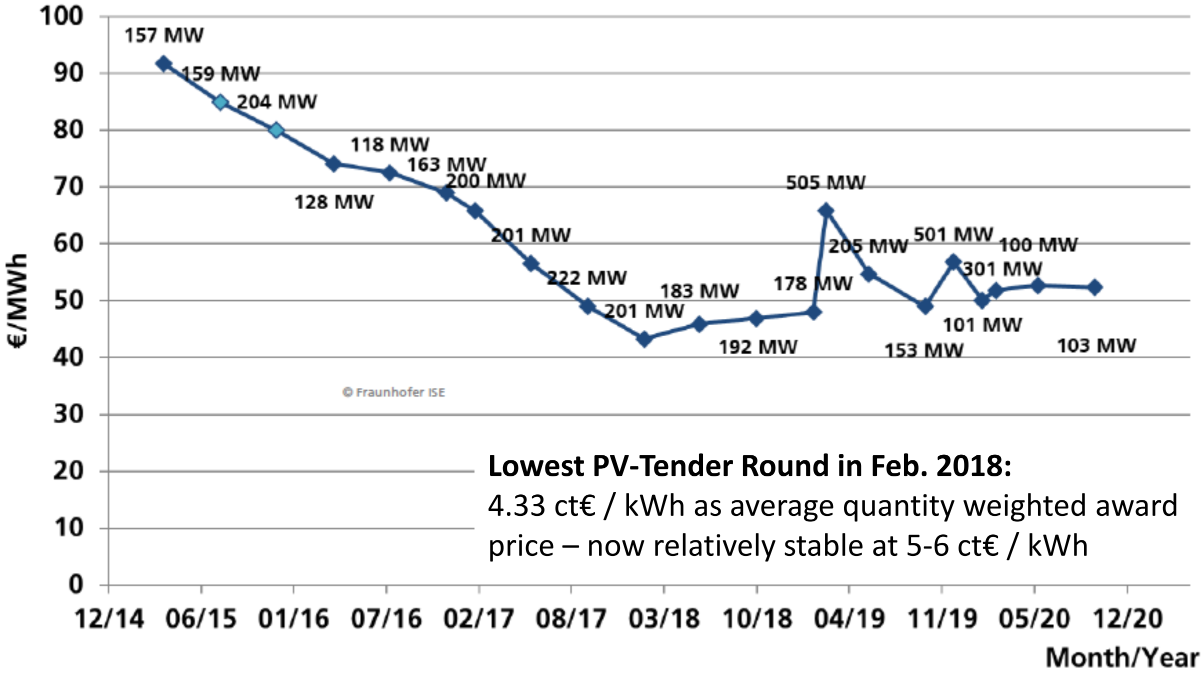
Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Electricity Prices



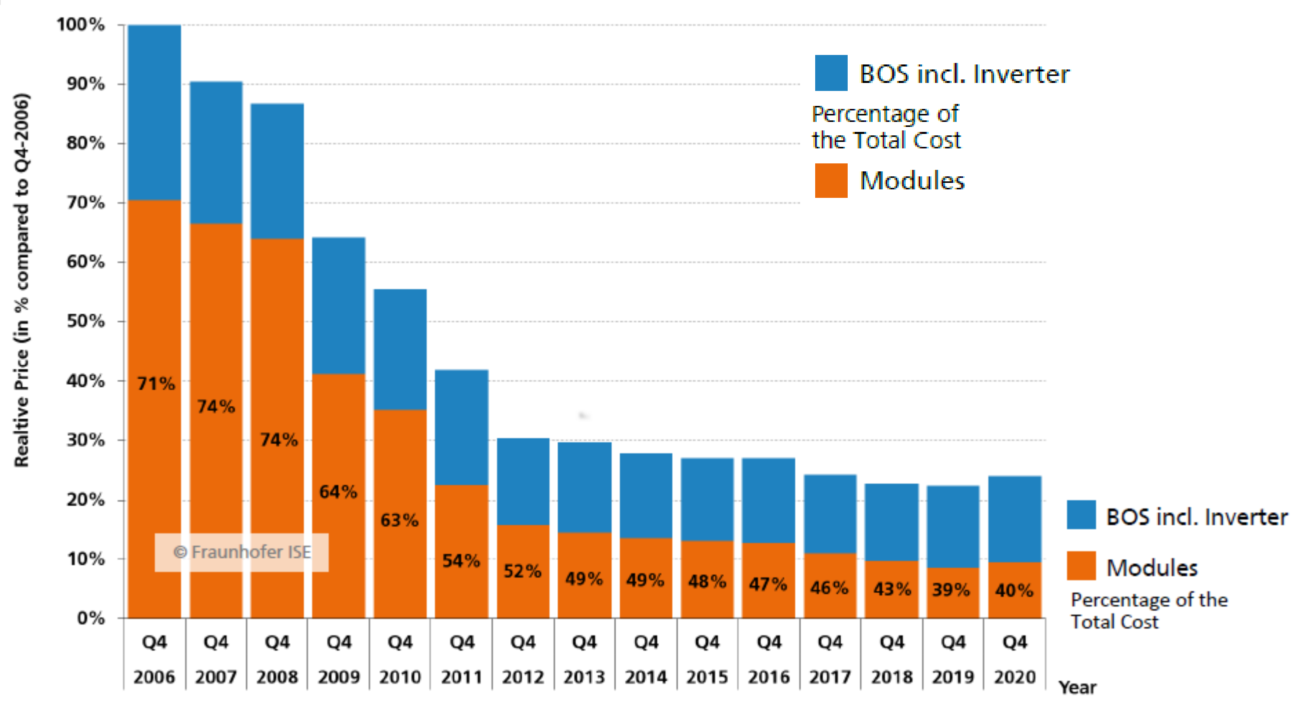
Source: http://ec.europa.eu/eurostat/statistics-explained/index.php/
File:Electricity_prices_for_household_consumers,_second_half_2015_%28%C2%B9%29_%28EUR_per_kWh%29_YB16.png

Electricity Prices



Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Electricity Costs and Grid Parity



Source: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

PV Only?

Total electricity demand in Germany is ~ 600 TWh

So to have 100% of this supplied by PV operating at an efficiency of 20% we would need an area of about 3000 km^2 …

… i.e. a square of about 55 km x 55 km

$\Rightarrow$ a bit bigger than Luxembourg

Final Thought

… but at an installed cost of 1 €/W$_p$ this would require an investment of….
€ 600·10^9 !

What about storage?

- Day/night?

- Seasonal?

Coming up

Lectures on:

- Solar radiation
- Physics of solar cells

Other solar opportunities:

- 2313716 – Praktikum Solarenergie („Solar Energy Lab“)
- MSc projects

Questions?