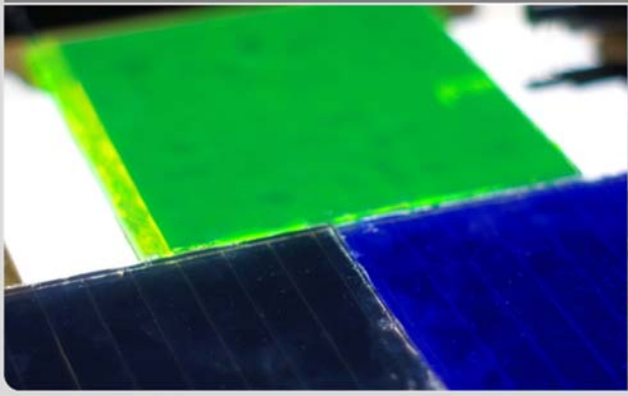
“Solar Energy” WS 2014/2015

Lecture 1: Overview

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

KIT Focus Optics & Photonics




Information

„Solar Energy“ lecture (23745) and tutorials (23750)

Lecturer: Prof. Dr. Bryce Richards

CN office: IMT, Building 307, Room 328, Tel: 0721-608-26562

CS office: LTI, Building 30.34, Room 211, Tel: 0721-608-41998

E-Mail: bryce.richards@kit.edu

URL: http://www.imt.kit.edu/388_1276.php

- A bit more about me…

Career

1990 – 1994	BSc Physics @ Victoria Univ. of Wellington, New Zealand
1995	Research assistant @ Max-Planck-Institut für Festkörperforschung (Abt. Cardona) Stuttgart, Germany: *Laser crystallisation of a-Si thin films for photovoltaics*
1996 – 1998	MEngSc Electrical Engineering @ Univ. New South Wales (UNSW), Australia *Optical characterisation of sputtered silicon thin films for photovoltaic applications*
1996 – 1998	Research assistant @ Pacific Solar (Sydney, Australia) *Optical and electrical characterisation of thin-film silicon on glass*
1998 – 2002	PhD Electrical Engineering @ UNSW *Novel applications of titanium dioxide for silicon solar cells*
2000 (2m)	R&D Engineer @ Eurosolare S.p.a. (Nettuno, Italy) *Technology transfer of simplified buried contact solar cell*

Career

2002 – 2005	Postdoctal researcher with Prof. Martin Green @ UNSW A) *Third generation PV: i) up-conversion, ii) down-conversion, iii) bandgap engineering via silicon quantum dots; B) PV-powered membrane filtration systems for water treatment*
2002 – 2005	Grad. Cert. in University Learning and Teaching @ UNSW *(additional degree to prepare for career as an academic)*
2005 – 2006	Postdoctal researcher with Prof. Andrew Blakers @ Australian National University, Canberra, Australia *As above, plus surface passivation of silicon wafers*
2006 (4m sabbatical)	Visiting academic @ ETH Zürich, Switzerland *CdTe and CIGS thin films solar cells*
2006 – 2014	Lecturer / Reader / Professor @ Heriot-Watt Univ., Edinburgh, U.K. *As above, plus wind-powered desalination systems*

Career

2013 (1yr sabbatical)	Visiting professor @ Univ. Dar es Salaam and Nelson Mandela African Inst. Science & Technology (Tanzania) A) *PV-powered water treatment system for contaminant removal in developing countries; B) Solar energy research capacity building*
1.4.2014 –	W3 Professor “Nanophotonics for Energy„ and co-director of both IMT (CN) and LTI (CS) *As above, plus i) metamaterials and nanostructured devices for solar energy harvesting, ii) advanced spectroscopy for characterisation of energy transfer within organic and inorganic semiconductors and luminescent materials*

Tutor

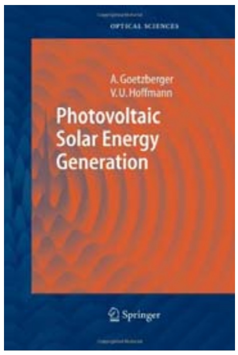
- Michael Oldenburg (BSc & MSc Physics, KIT)
- Office: IMT, Building 307, Room 224,
  Tel: 0721-608-22747,
  E-Mail: michael.oldenburg@kit.edu

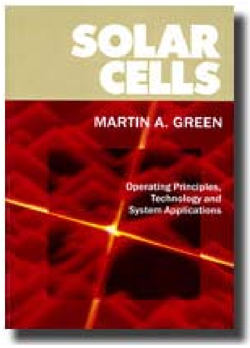
Information

- Slides will be available as PDF files for download from ILIAS https://ilias.studium.kit.edu
- Six tutorial sessions throughout the course
- One “Solar Energy” poster day – details TBA
- One excursion – TBA
- Exam will be a 2 hour written exam – date and time TBA

Recommended Reading

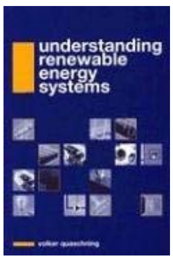
- “*Photovoltaic Solar Energy Generation*” by Adolf Goetzberger and Volker U. Hoffmann, Springer, 2010 (€130 – 160 Amazon)
- “*Solar Cells – Operating Principles, Technology and System Applications*”, by Martin A. Green, Prentice-Hall 1986 (A$44, UNSW bookshop, also in Chinese)
- “*Understanding Renewable Energy Systems*” by Volker Quashning, Earthscan 2005, (€40-45 Amazon)
- “PV*CDROM*” by Christiana Honsberg and Stuart Bowden, http://www.pveducation.org/pvcdrom (also in Korean)





PV EDUCATION.ORG

PV CDROM
Christiana Honsberg
and Stuart Bowden



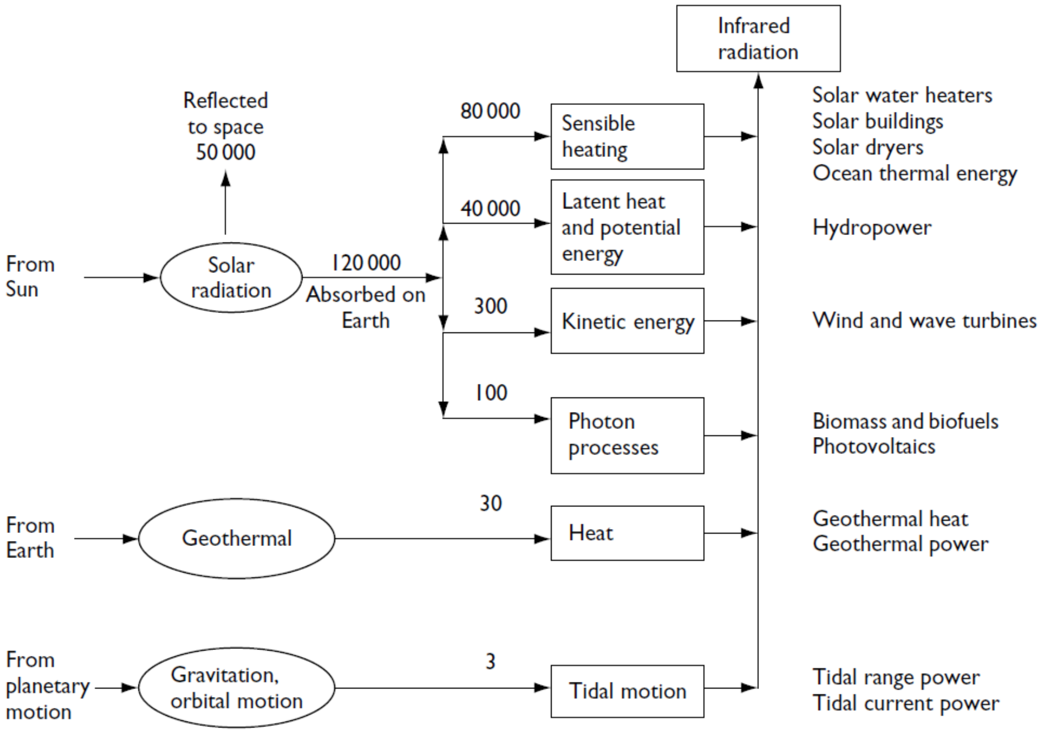
Lecture Schedule

EAS Lecture Theatre, Bldg.11.10 Room 107	LTI Lecture Theatre, Bldg. 30.34
Tue 21 Oct 2014	Thu 23 Oct 2014
Lecture: Introduction	Lecture: The Sun
Tue 28 Oct 2014	Thu 30 Oct 2014
Lecture: Semiconductor Basics	Lecture: p-n Junction
Tue 4 Nov 2014	Thu 6 Nov 2014
Tutorial #1: Sun, Semconductors & *p-n* junctions	Lecture: Silicon Solar Cell Design and Fabrication
Tue 11 Nov 2014	Thu 13 Nov 2014
Lecture: High-Efficiency Silicon Solar Cells	Lecture: Thin-Film PV – Inorganic #1
Tue 18 Nov 2014	Thu 20 Nov 2014
Tutorial #2: Silicon Solar Cells	Lecture: Thin-Film PV – Inorganic #2
Tue 25 Nov 2014	Thu 27 Nov 2014
Lecture: Thin-Film PV – Inorganic #3	Lecture: Thin-Film PV – Excitonic #1
Tue 2 Dec 2014	Thu 4 Dec 2014
Tutorial #3: Inorganic Thin-Film Solar Cells	Lecture: Thin-Film PV – Excitonic #2
Tue 9 Dec 2014	Thu 11 Dec 2014
Lecture: Third Generation PV #1	Lecture: Third Generation PV #2

Lecture Schedule

EAS Lecture Theatre, Bldg.11.10 Room 107	LTI Lecture Theatre, Bldg. 30.34
Tue 16 Dec 2014	Thu 18 Dec 2014
Tutorial #4: Excitonic and Third Gen PV	Lecture: PV Modules
Tue 23 Dec 2014	Thu 25 Dec 2014
NO LECTURE	NO LECTURE
Tue 6 Jan 2015	Thu 8 Jan 2015
NO TUTORIAL	Lecture: PV System Components #1
Tue 13 Jan 2015	Thu 15 Jan 2015
Lecture: PV System Components #2	POSTER DAY
Tue 20 Jan 2015	Thu 22 Jan 2015
Tutorial #5: PV Systems	Lecture: PV in Developing Countries
Tue 27 Jan 2015	Thu 29 Jan 2015
Lecture: Solar Thermal	EXCURSION
Tue 3 Feb 2015	Thu 5 Feb 2015
Tutorial #6: Solar Thermal + LCA	Lecture: Solar Fuels
Tue 10 Feb 2015	Thu 12 Feb 2015
Lecture: Energy Scenarios	Lecture: Review

Solar Energy Conversion

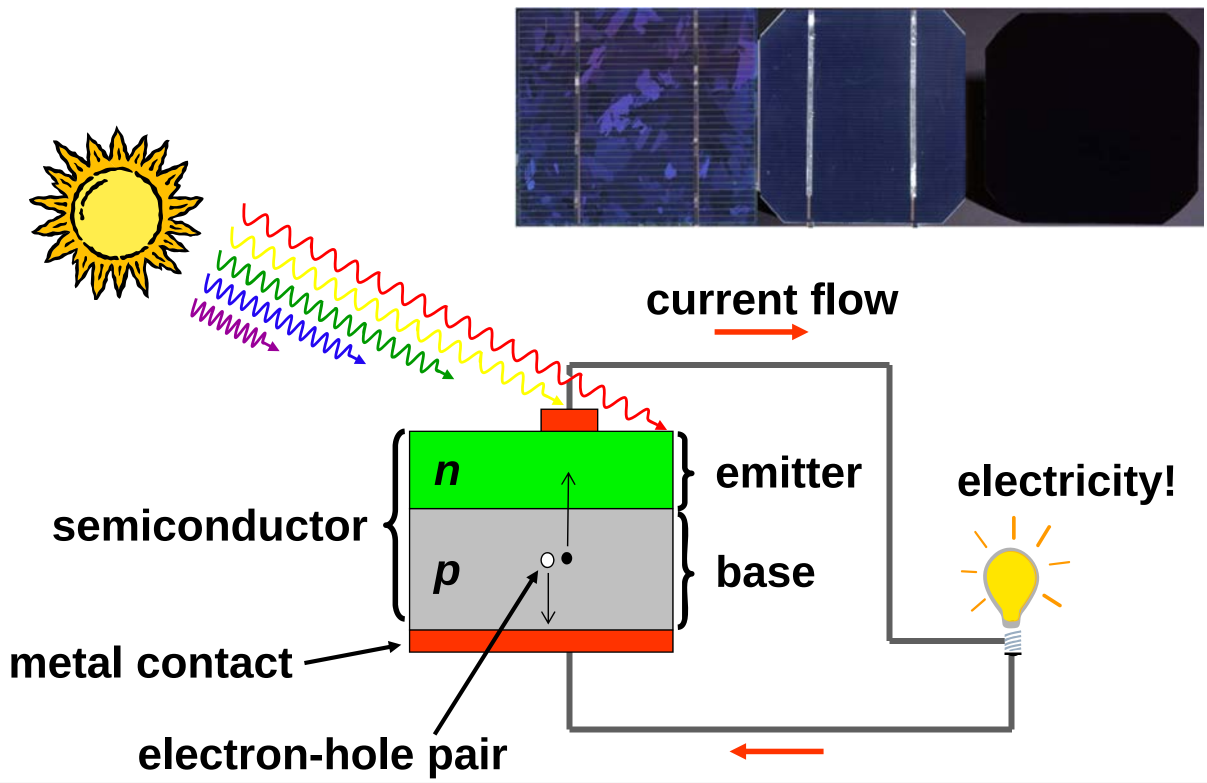


Source: "Renewable Energy Resources" Twidell & Weir, 2nd ed., Taylor & Francis, 2006

Solar Energy Conversion

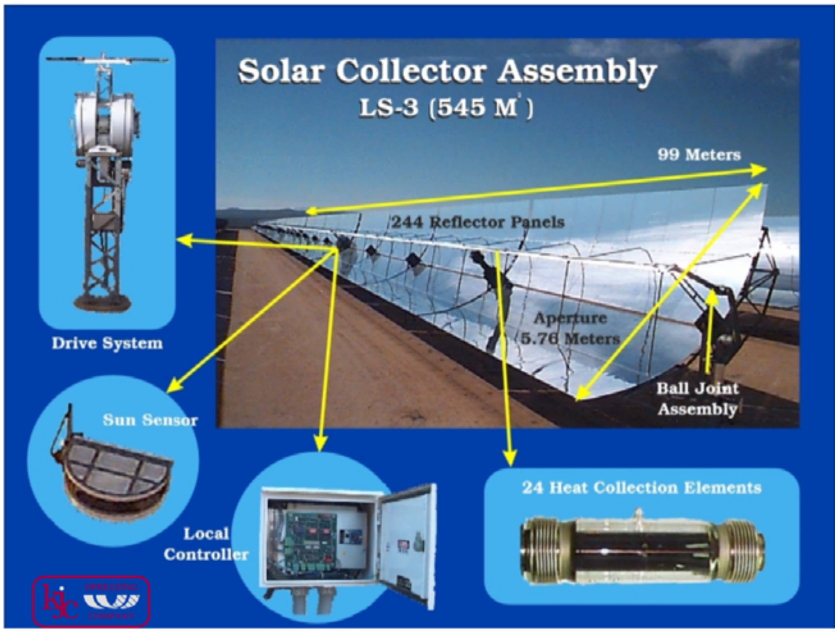
- Course deals primarily with conversion of sunlight directly into electrical energy ≡ **photovoltaic devices or solar cells**
- Two lectures near end of course:
  1) For heating and cooling applications usually more efficient to use collectors that harness **solar thermal** energy directly (e.g. no energy conversion step)
  2) Upcoming future area of **solar fuels**, produced from sunlight via artificial photosynthesis or other thermochemical reaction. The fuel – e.g. hydrogen, carbon dioxide or other organic compound – can be stored for later use
- Does not cover other solar-driven processes such as wind energy, biomass, etc…

Introduction to Solar Cells



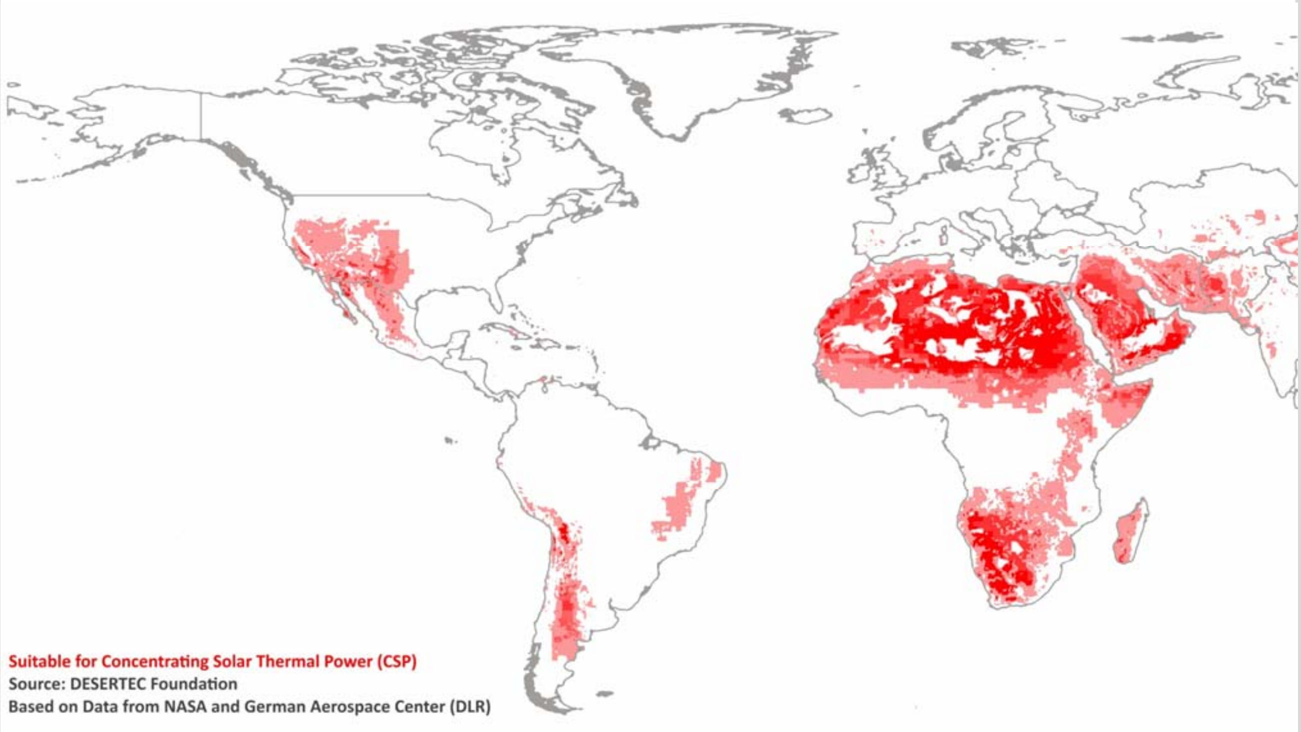
Electricity from Solar Thermal

- Large scale Solar Energy Generating Systems (SEGS) in California – 354MW
- 7.14MWh solar energy per 3m^2 collector produces 1MWh electricity
- Plans for internationally interconnected system, e.g. see Desertec and DLR



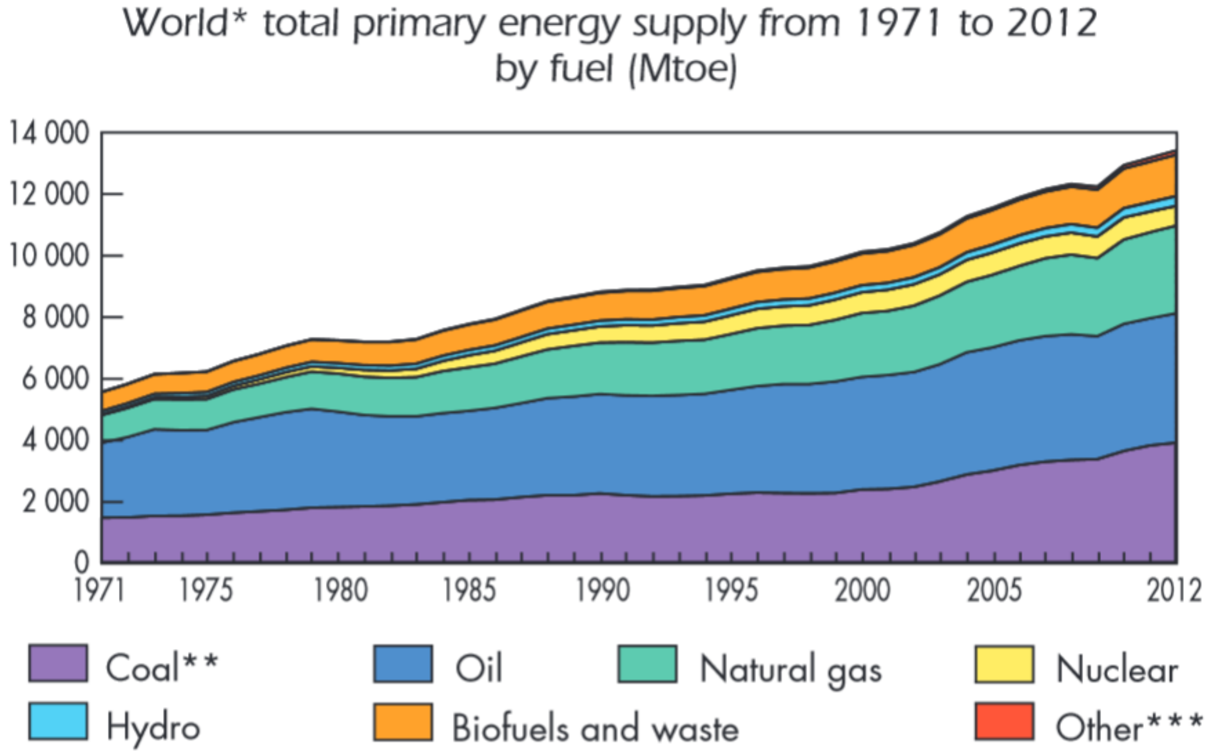
Source: http://www.nrel.gov/csp/troughnet/pdfs/cable_frier_calexpr.pdf

Electricity from Solar Thermal



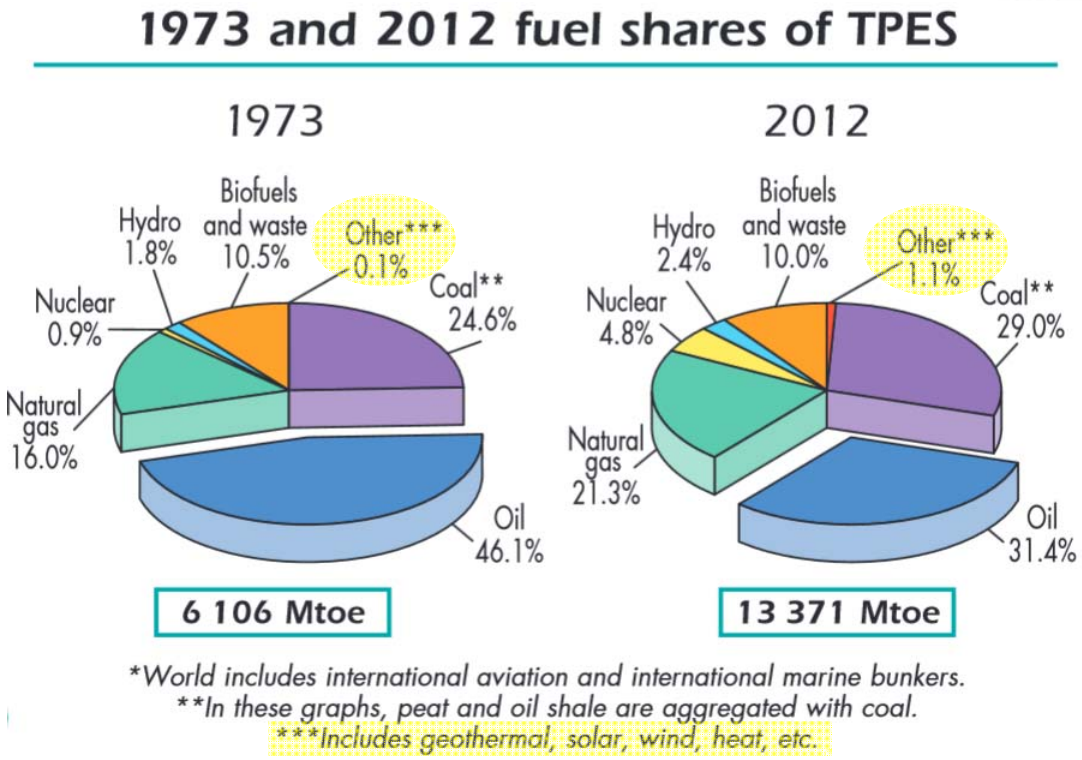
Source: http://www.dlr.de/dlr/desktopdefault.aspx/tabid-10176/372_read-2068#/gallery/3954

Why Solar Energy?



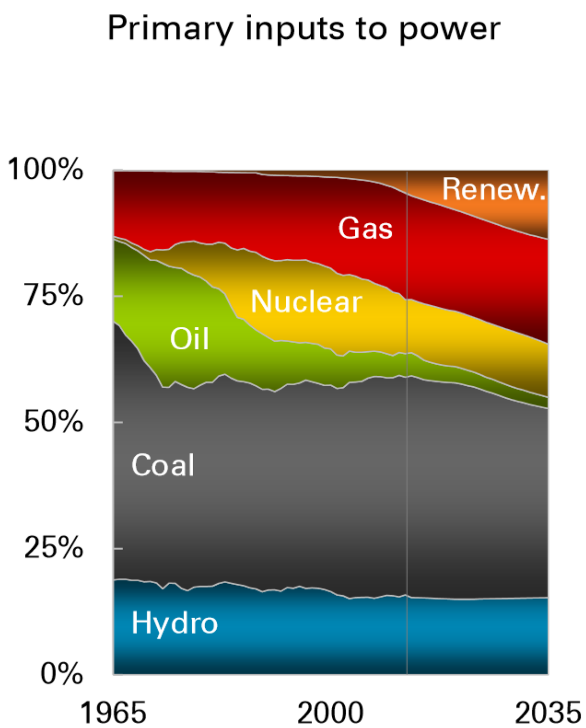
Source: http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf

Why Solar Energy?



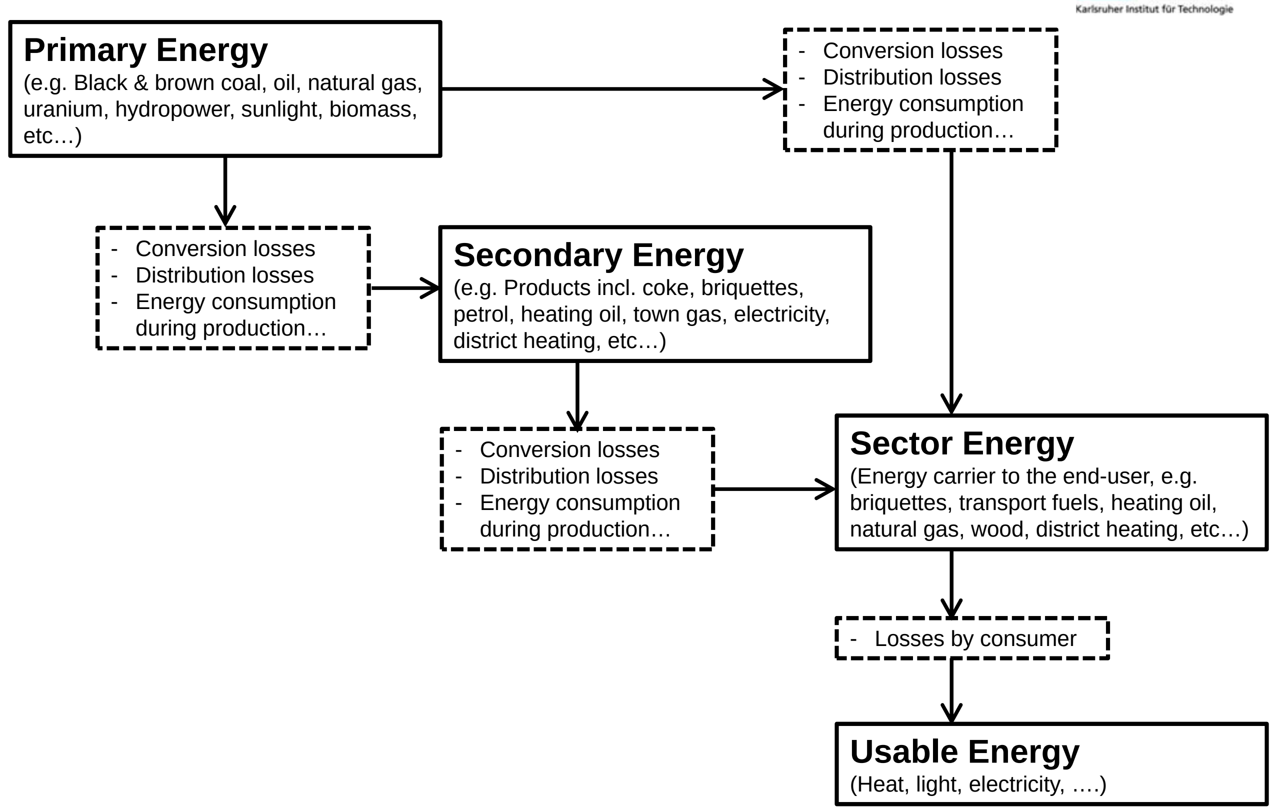
Source: http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf

Why Solar Energy?



Source: http://www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/Energy_Outlook_2035_booklet.pdf

Energy Sources



Energy

Some units of energy:

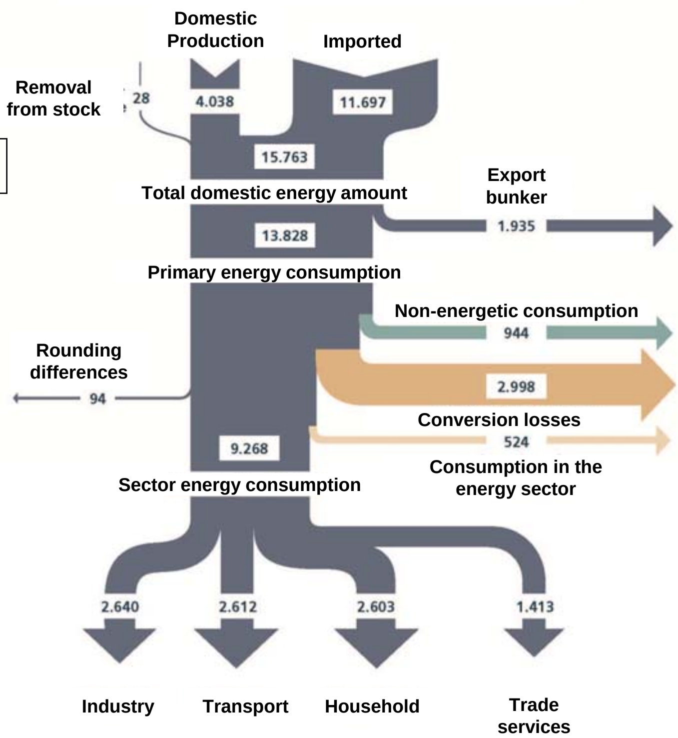
1 PJ = 1 Petajoule = 10^{15} J = 0.001 EJ

1 TWh = 1 Terawatt-hour
= 10^{9}kWh = 3.6 PJ

1 million tonnes of coal equivalent
= 1 tce ≅ 29.4 PJ

1 tonne of oil equivalent
= 1 toe ≅ 41.9 GJ

Energy Flow Diagram 2013 for Federal Republic of Germany (Petajoules)



Source: Adapted from http://www.ag-energiebilanzen.de/9-0-Energieflussbilder.html

The German Federal Ministry for Economic Affairs and Energy is an excellent source of energy data for Germany:

http://www.bmwi.de/DE/Themen/energie.html

Energy consumption per capita

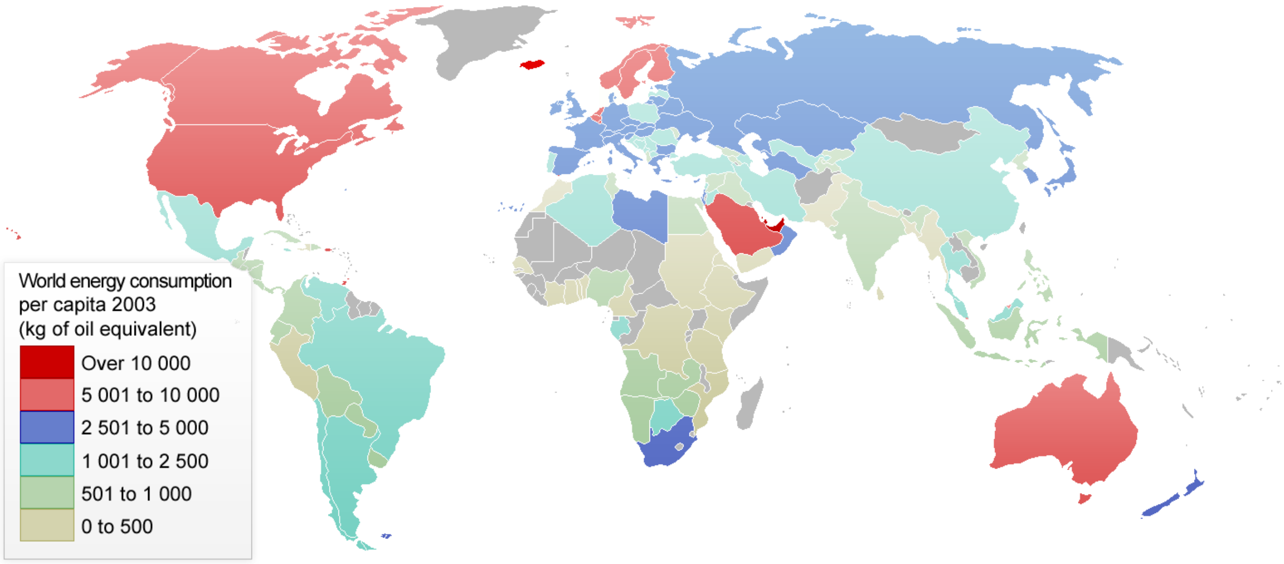
	1990	1991	2004	2005	2006	2007	2008	2009	2010
WELT	**69,8**	**69,3**	**73,3**	**74,5**	**75,4**	**76,2**	**77,0**	**75,4**	
AFRIKA	**25,7**	**26,0**	**27,2**	**27,2**	**27,2**	**27,6**	**28,5**	**28,1**	
NORDAMERIKA	**261,5**	**258,7**	**260,2**	**260,3**	**255,7**	**257,6**	**249,8**	**235,6**	**239,8**
- 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:

$$\frac{170 \cdot 10^9\,\mathrm{J}}{365 \cdot 24 \cdot 3600\,\mathrm{s}} \approx 5391\,\mathrm{W}$$

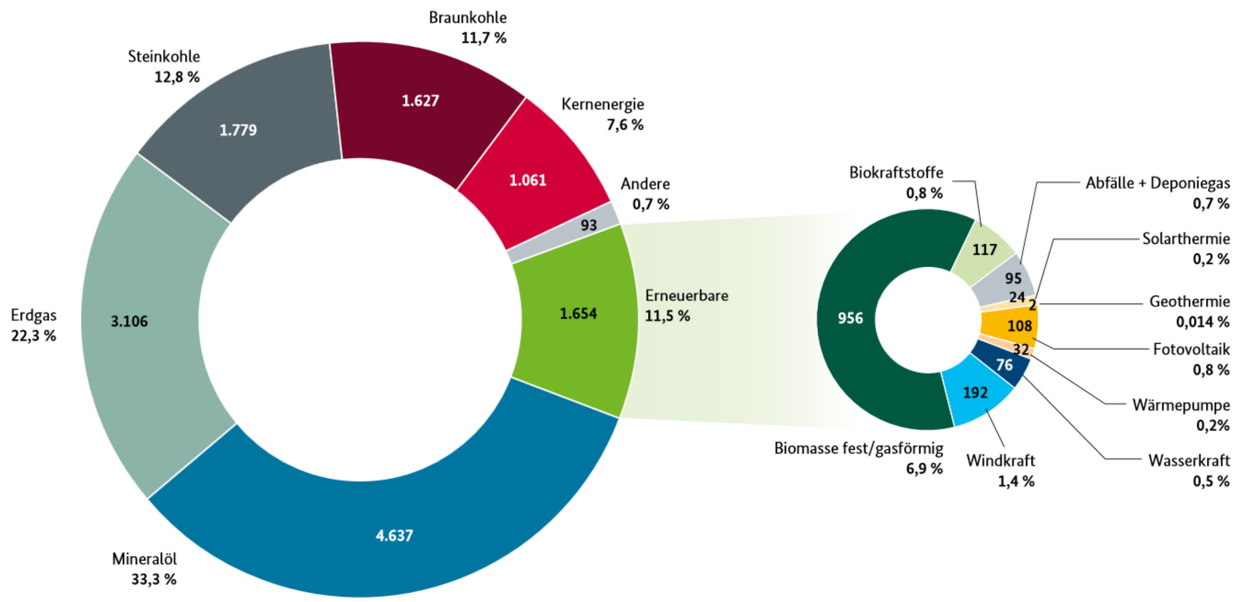
Energy consumption per capita



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.

Total Primary Energy Consumption

4. Primärenergieverbrauch in Deutschland 2013 (13.908 PJ*)



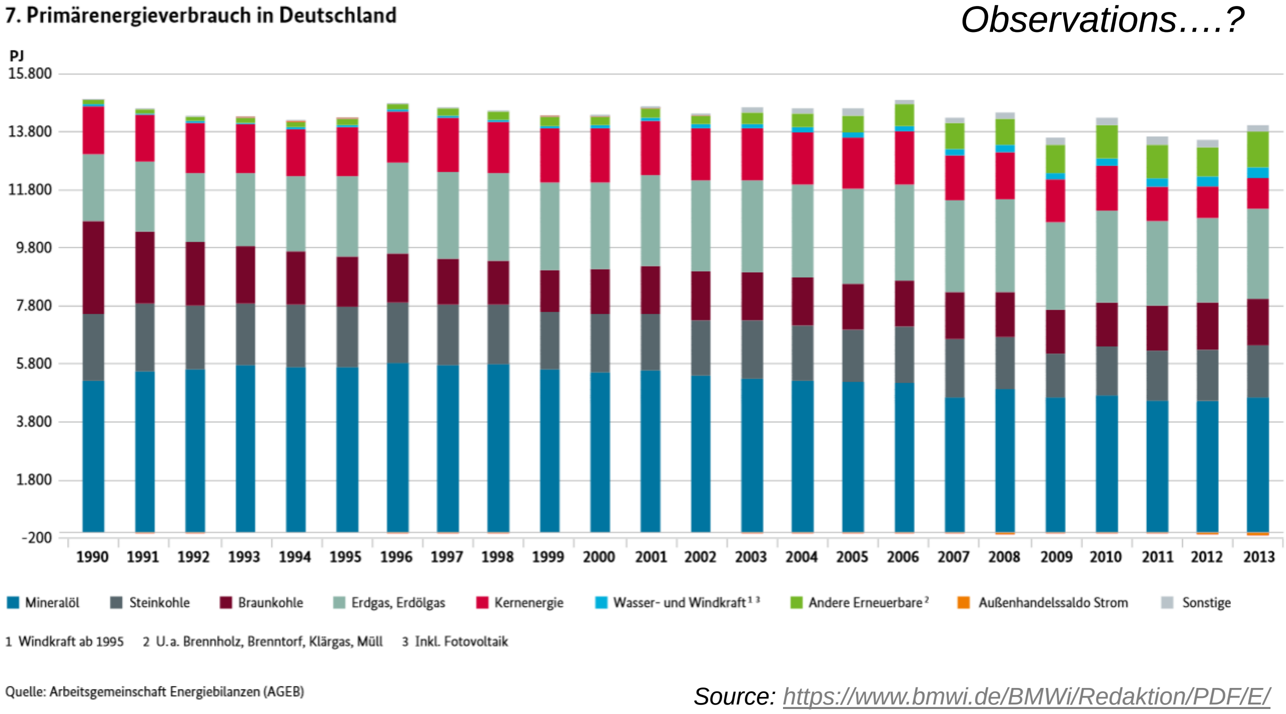
* Vorläufig

Quelle: Arbeitsgemeinschaft Energiebilanzen (AGEB), Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat)

Source: https://www.bmwi.de/BMWi/Redaktion/PDF/E/energiestatistiken-energiegewinnung-energieverbrauch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

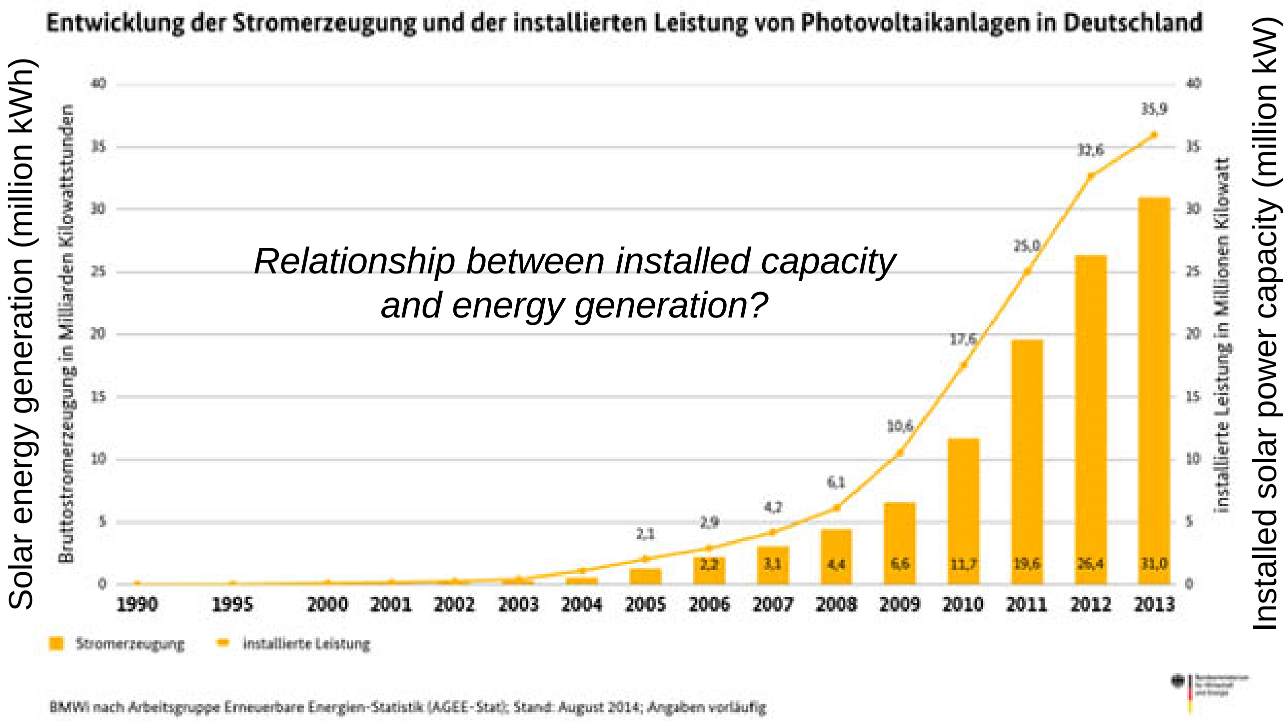
Total Primary Energy Consumption

Observations….?



Source: https://www.bmwi.de/BMWi/Redaktion/PDF/E/energiestatistiken-energiegewinnung-energieverbrauch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

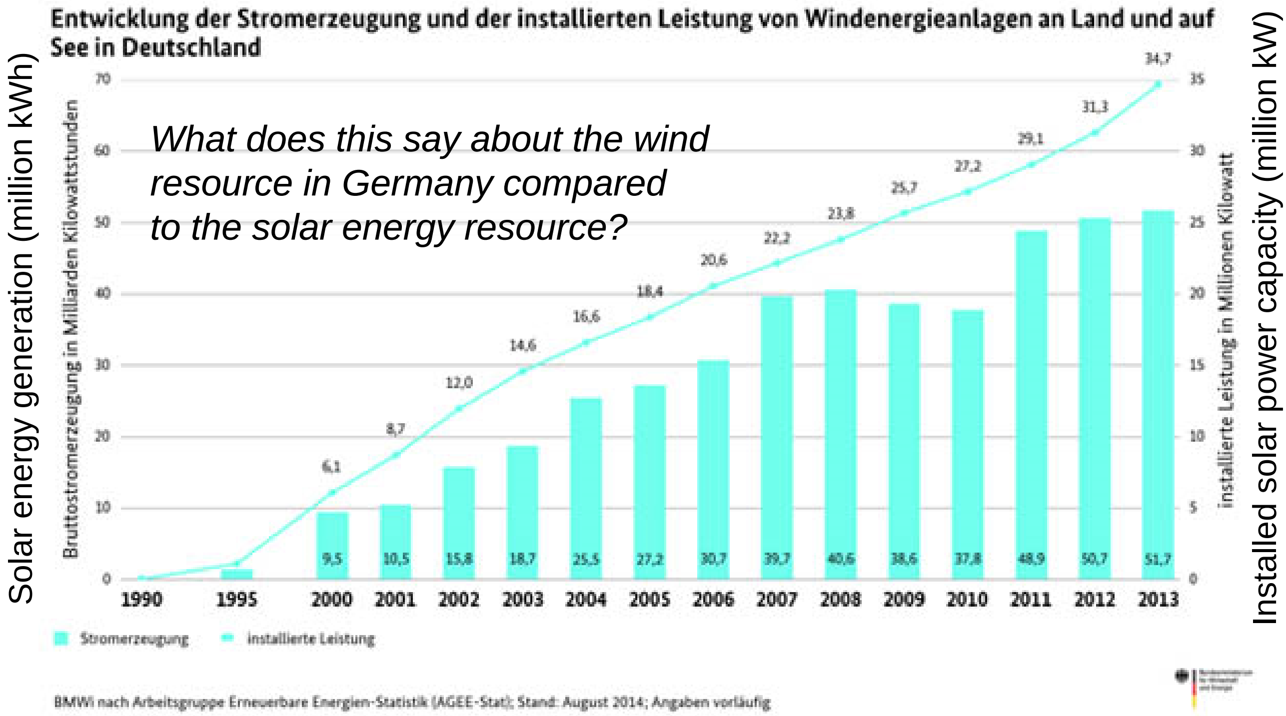
Solar Power in Germany



Source: http://www.erneuerbare-energien.de/EE/Redaktion/DE/Textbausteine/Banner/banner_photovoltaik.html

Wind Power in Germany

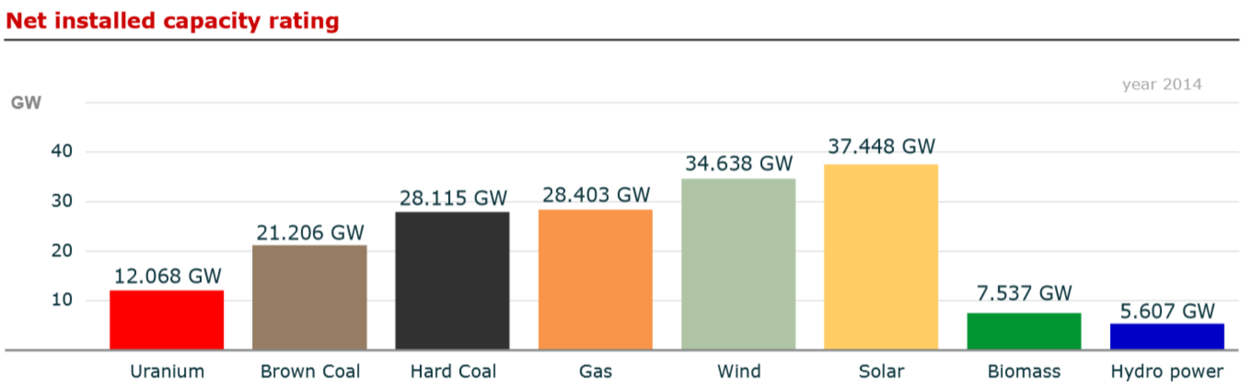
What does this say about the wind resource in Germany compared to the solar energy resource?



Source: http://www.erneuerbare-energien.de/EE/Redaktion/DE/Textbausteine/Banner/banner_windkraft.html

Recent Installed Capacity Figures

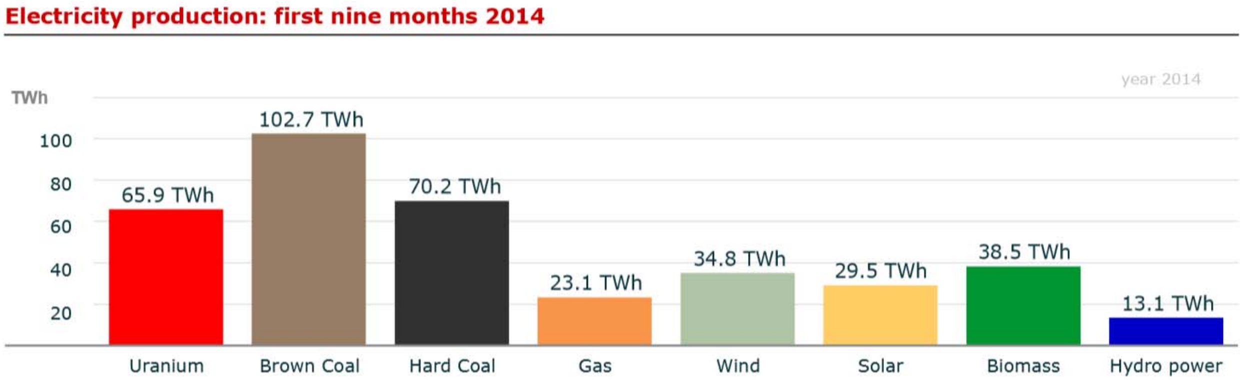
Installed power at July 16, 2014



Source: http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/data-nivc-/electricity-production-from-solar-and-wind-in-germany-2014.pdf

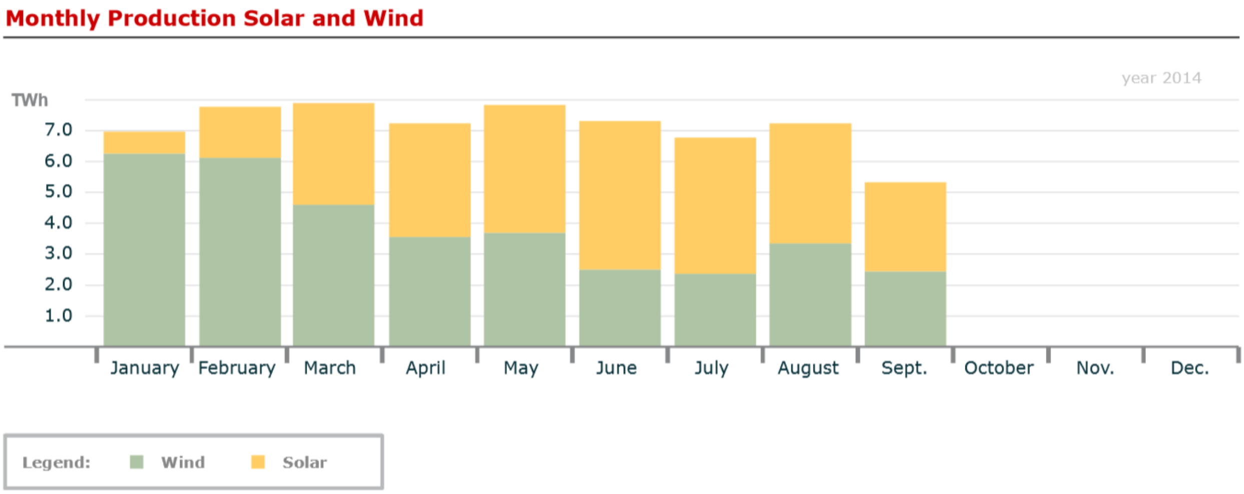
Recent Energy Production Figures

First nine months 2014



Source: http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/data-nivc-/electricity-production-from-solar-and-wind-in-germany-2014.pdf

Recent Energy Production Figures



Source: http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/data-nivc-/electricity-production-from-solar-and-wind-in-germany-2014.pdf

Typical Photovoltaic Module

Data for German-made 280 W_p (watt-peak) module measured under STC (1000 W/m^2 solar radiation at 25°C under air-mass 1.5 spectrum)

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

		SW 280
Maximum power	P_{max}	280 Wp
Open circuit voltage	U_{oc}	39.5 V
Maximum power point voltage	U_{mpp}	31.2 V
Short circuit current	I_{sc}	9.71 A
Maximum power point current	I_{mpp}	9.07 A

DIMENSIONS

Length	1675 mm
Width	1001 mm
Height	31 mm
Frame	Clear anodized aluminum
Weight	21.2 kg

COMPONENT MATERIALS

Cells per module	60
Cell type	Mono crystalline
Cell dimensions	156 mm x 156 mm
Front	4 mm tempered glass (EN 12150)

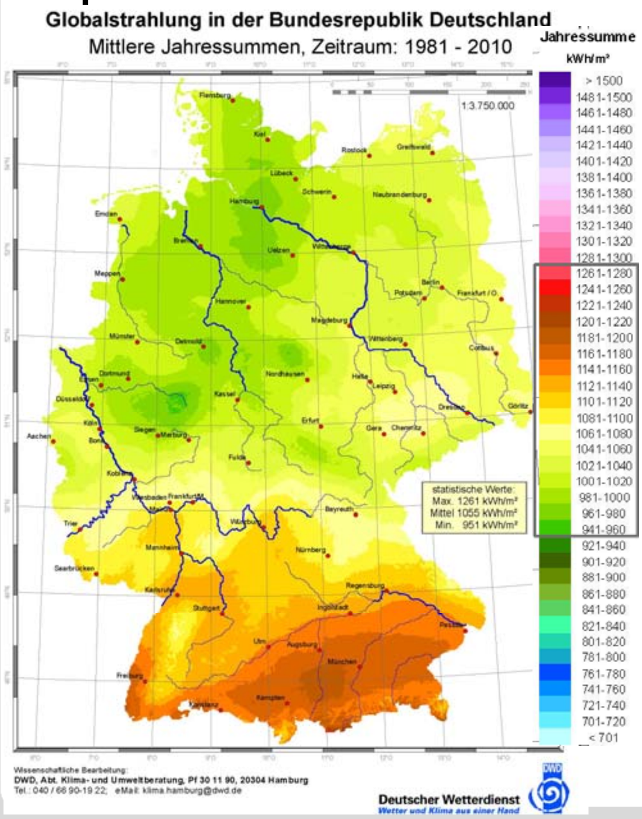
THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.040 %/K
TC U_{oc}	-0.30 %/K
TC P_{mpp}	-0.41 %/K

ADDITIONAL DATA

Power sorting	-0 Wp / +5 Wp
J-Box	IP65
Connector	MC4 / KSK4

$W_p \rightarrow$ Energy Production $\rightarrow$ Cost

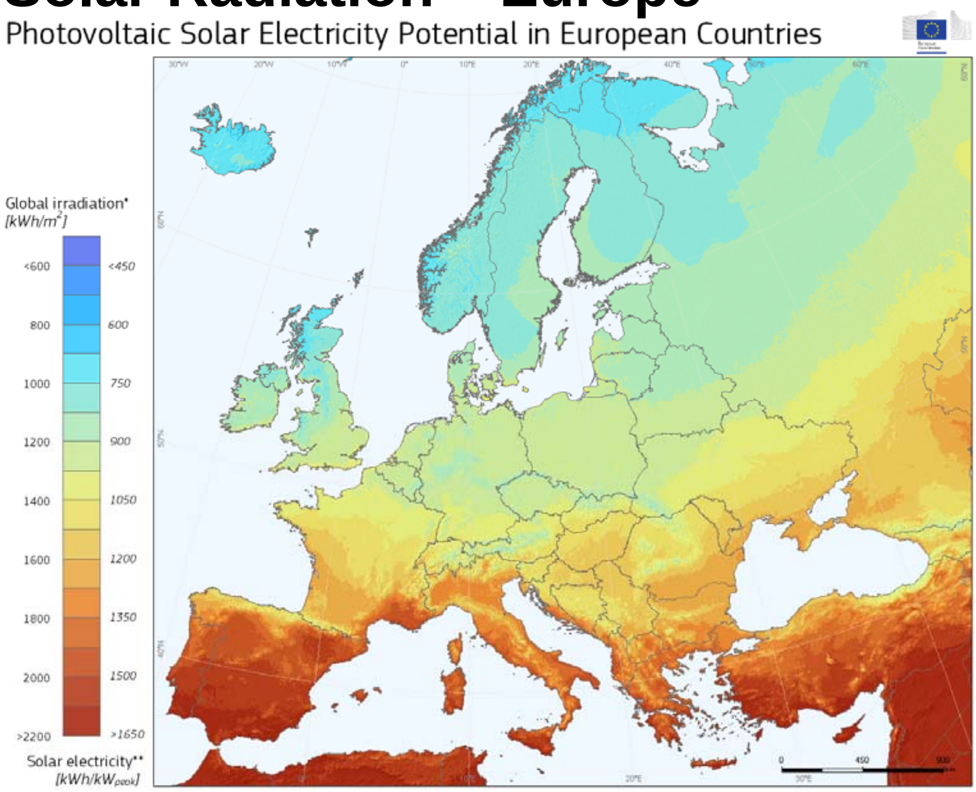


1 Wp of PV in Germany produces ~ 1 kWh of electrical energy per year

By taking into account investment costs, financing costs and maintenance costs, the cost of electricity (CoE) generation in units of € / kWh can be calculated

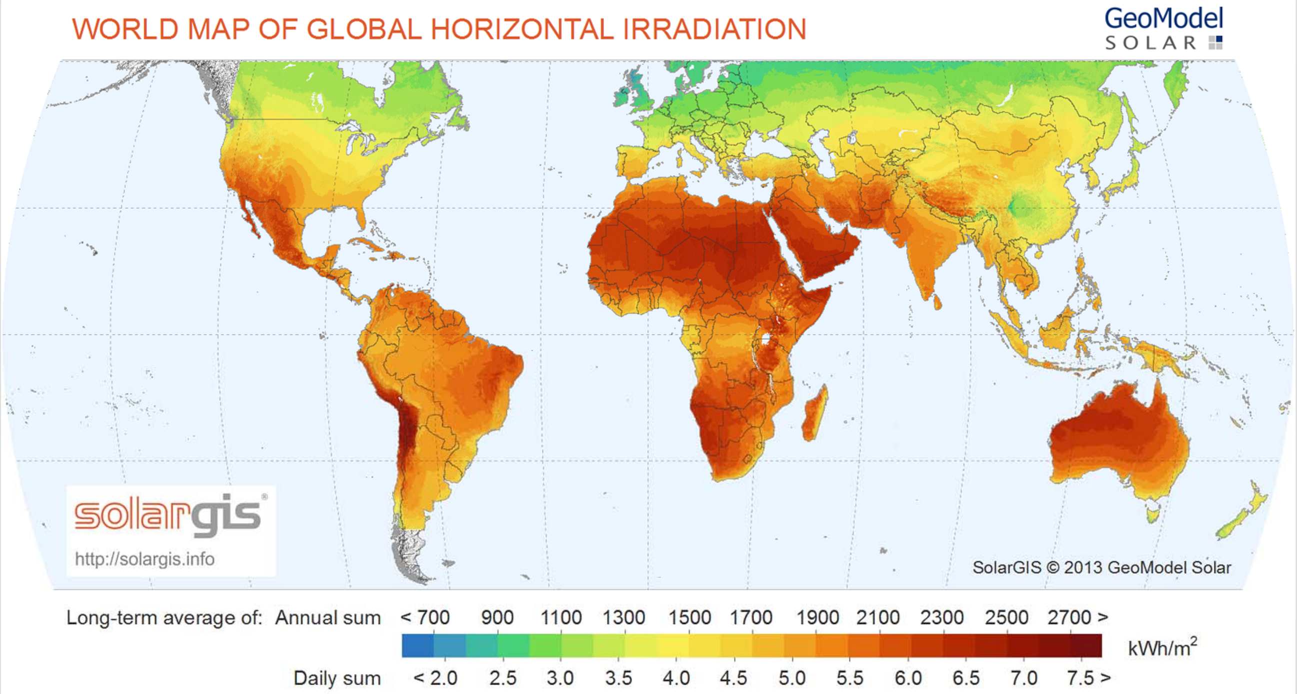
Source: German Weather Service http://www.dwd.de/bvbw/generator/DWDWWW/Content/Oeffentlichkeit/KU/KU1/KU12/Klimagutachten/Solarenergie/Globalkarten__entgeltfrei/VielJ_C3_A4hrigeMittelwerte/Jahr__1981-2010,templateId=raw,property=publicationFile.pdf/Jahr_1981-2010.pdf

Solar Radiation – Europe



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

Solar Radiation – World

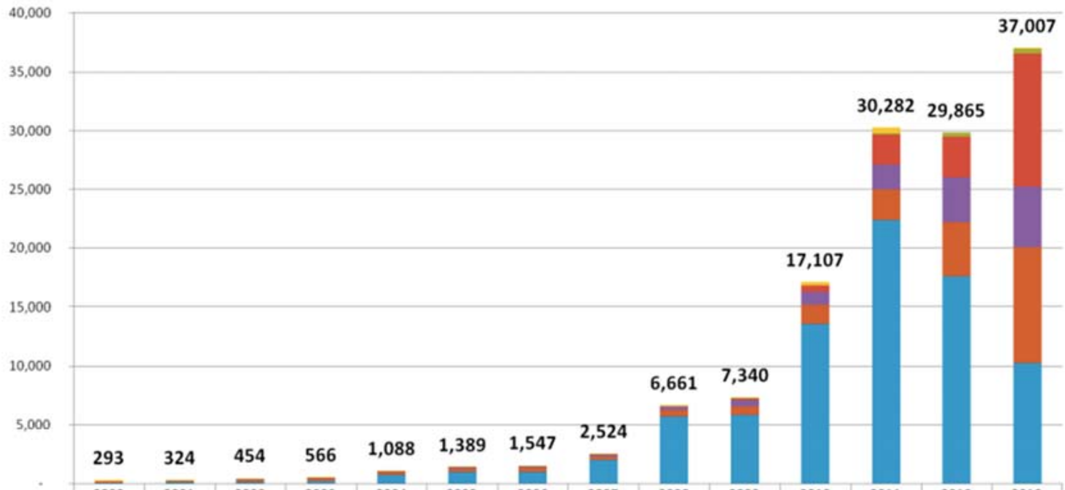


Some places possess solar radiation resource that is double that of Germany

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

Where is PV Installed?

Evolution of global annual installations 2000-2013 (MW)

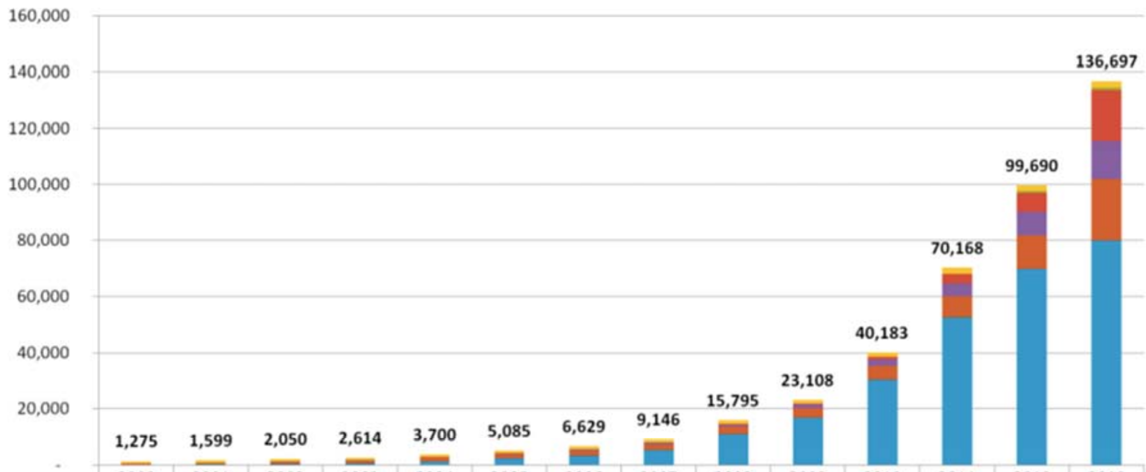


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	88	56	80	77	29	10	105	42	76	80	284	508	-	85
MEA	-	-	-	-	1	0	0	1	1	22	46	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,300
AMERICA	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,153
APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,616	22,407	17,580	10,253
TOTAL	293	324	454	566	1,088	1,389	1,547	2,524	6,661	7,340	17,107	30,282	29,865	37,007

Source: *http://cleantechnica.com/files/2014/04/global-annual-solar-installation.png*

Where is PV Installed?

Evolution of global cumulative installed capacity 2000-2013 (MW)

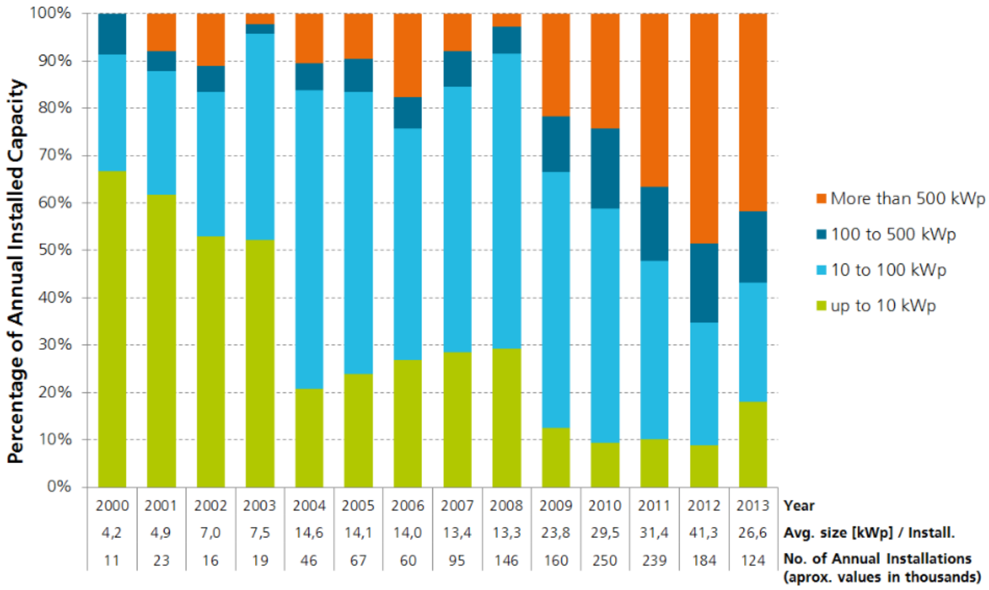


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,183
MEA	-	-	-	-	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,100
AMERICA	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,518
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	116	249	381	580	1,283	2,264	3,258	5,274	10,970	16,777	30,352	52,462	69,699	79,952
TOTAL	1,275	1,599	2,050	2,614	3,700	5,085	6,629	9,146	15,795	23,108	40,183	70,168	99,690	136,697

Source: *http://cleantechnica.com/files/2014/04/global-annual-solar-installation.png*

What sizes are the PV systems?

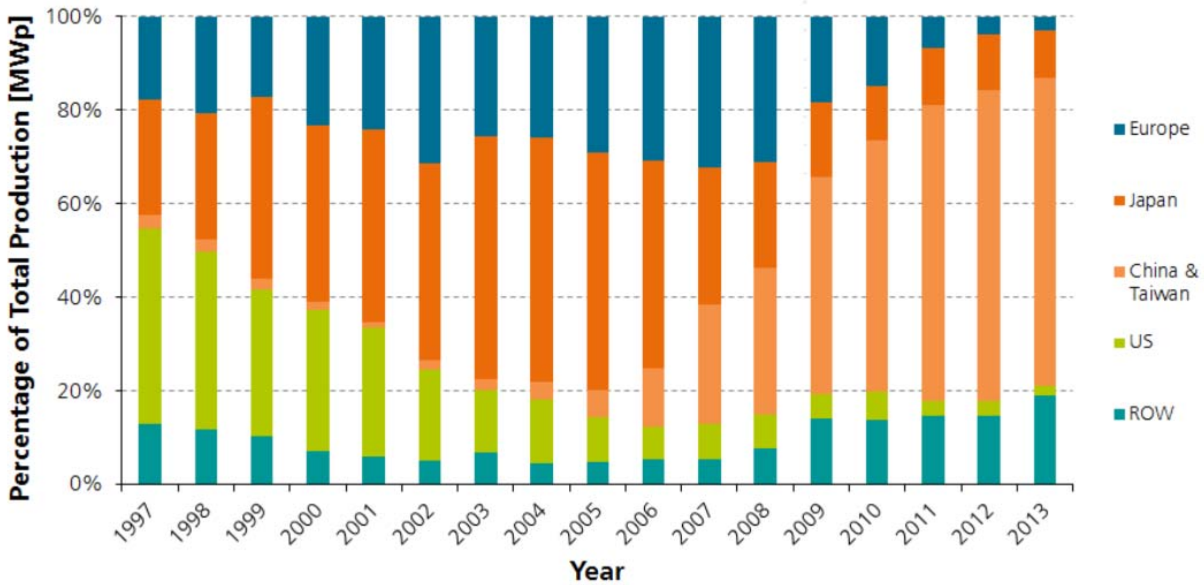
PV Systems Yearly Installed in Germany
Shares by System Size



Source: *http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf*

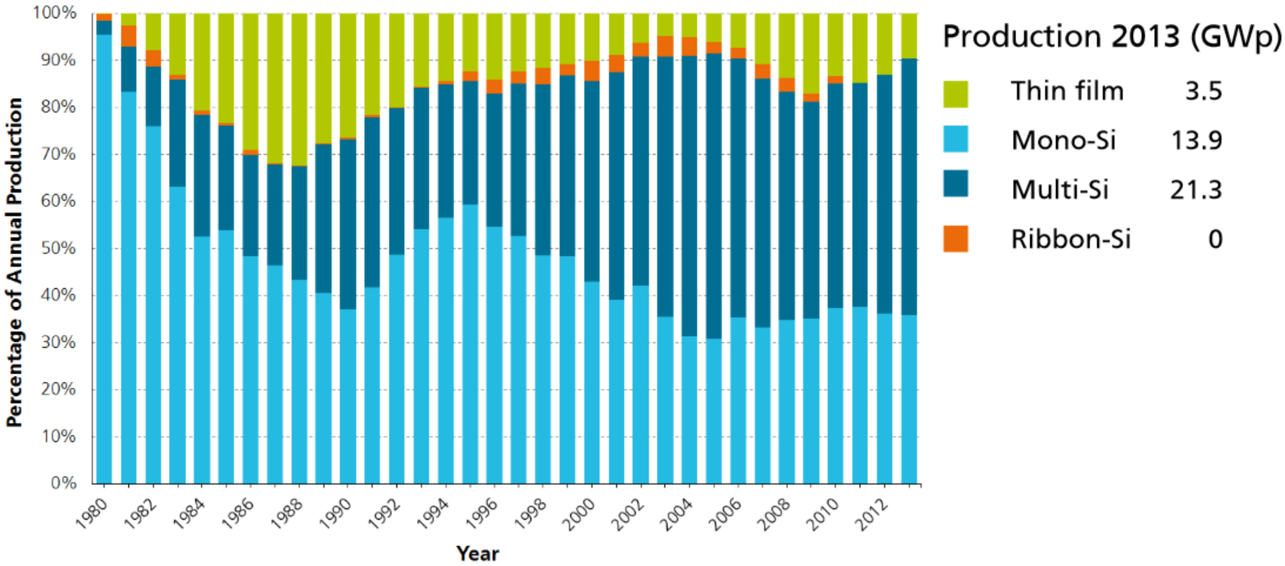
Where is PV Produced?

PV Cells/Modules Production by Region 1997-2013
(Percentage of Total MWp Produced)



Source: *http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf*

What PV Technologies are Produced?



Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

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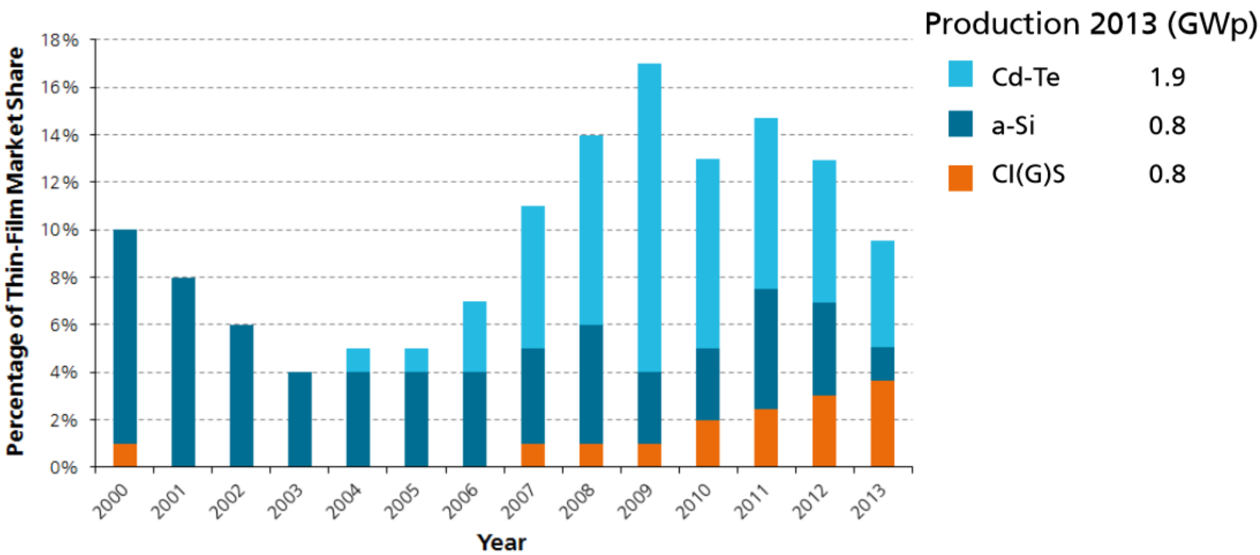
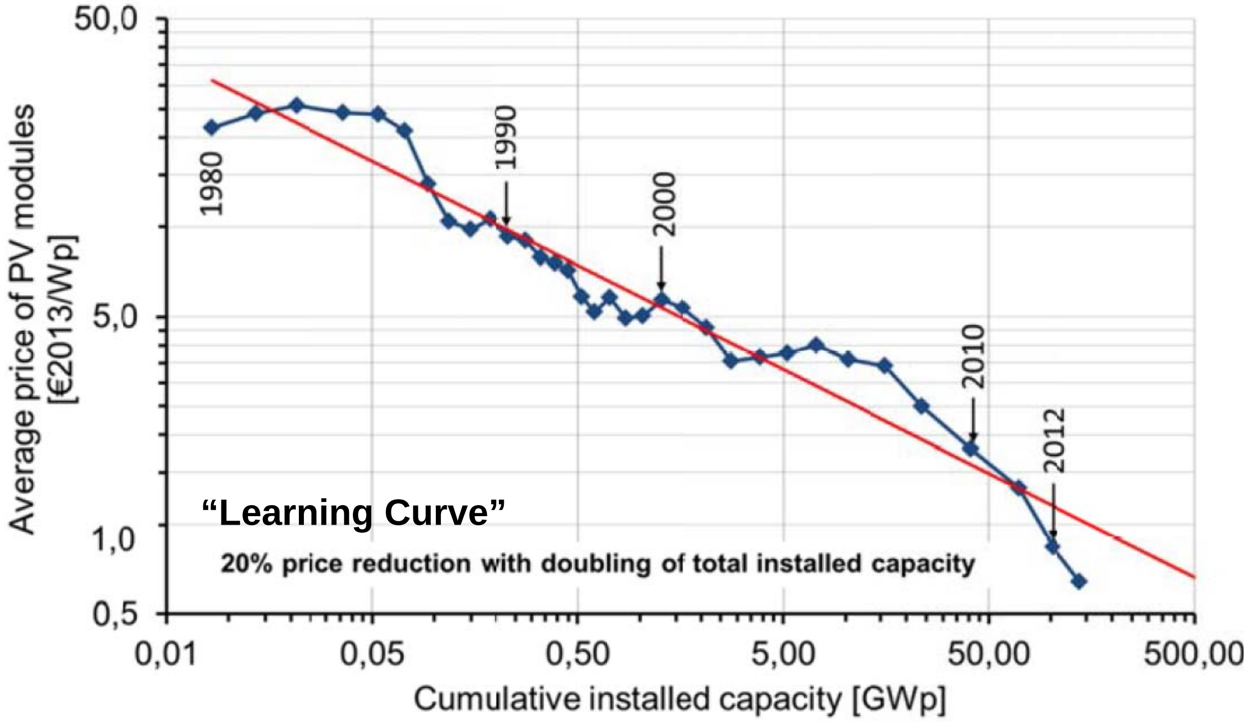


Source: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

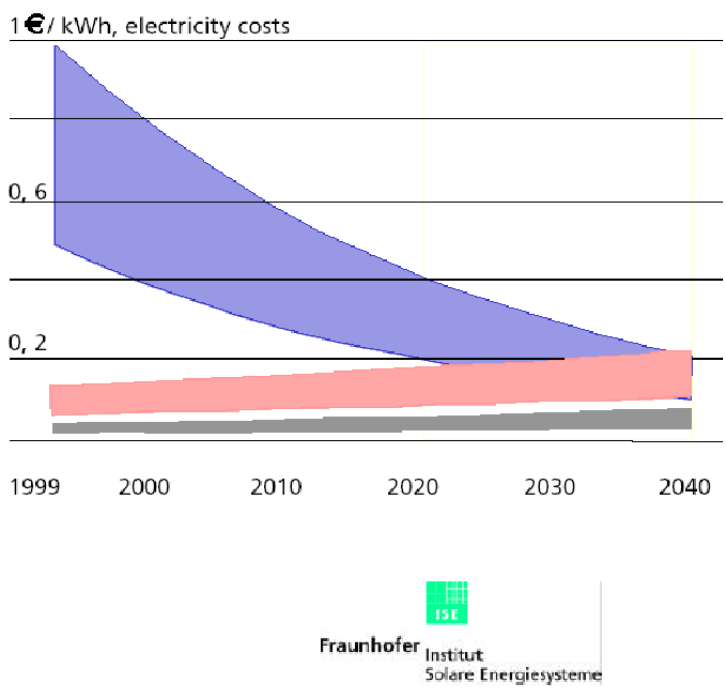
PV Module Costs over Time



Source: *http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/aktuelle-fakten-zur-photovoltaik-in-deutschland.pdf*

Electricity Costs and Grid Parity

The cost of generating solar power is in some places less than the cost of buying power from the electricity utility ≡ **"grid parity"**



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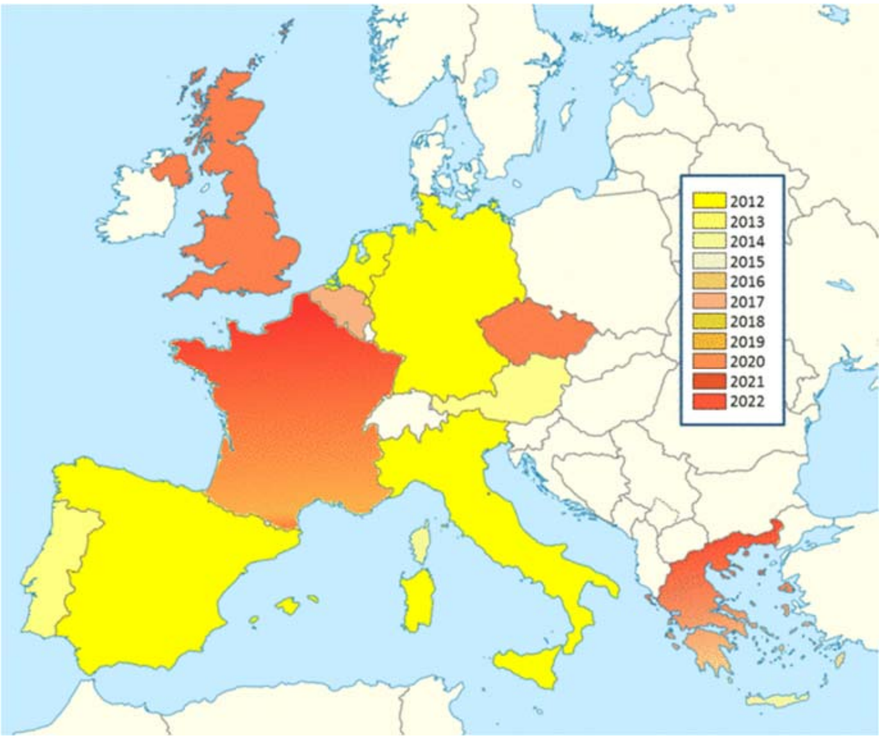
Electricity Costs and Grid Parity



Residential Sector:

If Germany isn't the sunniest country in Europe then why has grid parity been achieved here already?

Source: http://www.pvparity.eu/results/pv-competitiveness/

Final Thought

Total electricity demand in Germany is ~ 600 TWh

So to have 100% of this supppiled 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

Final Thought

Karlsruher Institut für Technologie

… but at a cost of 1 €/W_p this would require an investment of….
€ 600·10⁹ !

What about storage? (day/night, seasonal)

Hydrogen?

Batteries?

Pumped-hydro?

Flywheels?