smart GREEN SCANS

Environmental aspects of photovoltaics

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12. Österreichische Photovoltaik-Tagung
Linz, Austria, 4 November 2014

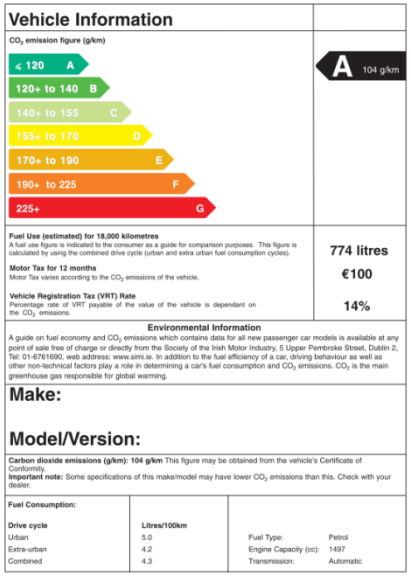
Why to evaluate environmental footprint of products?

Minimizing life-cycle environmental impacts:

- Process optimization;
- Product design;

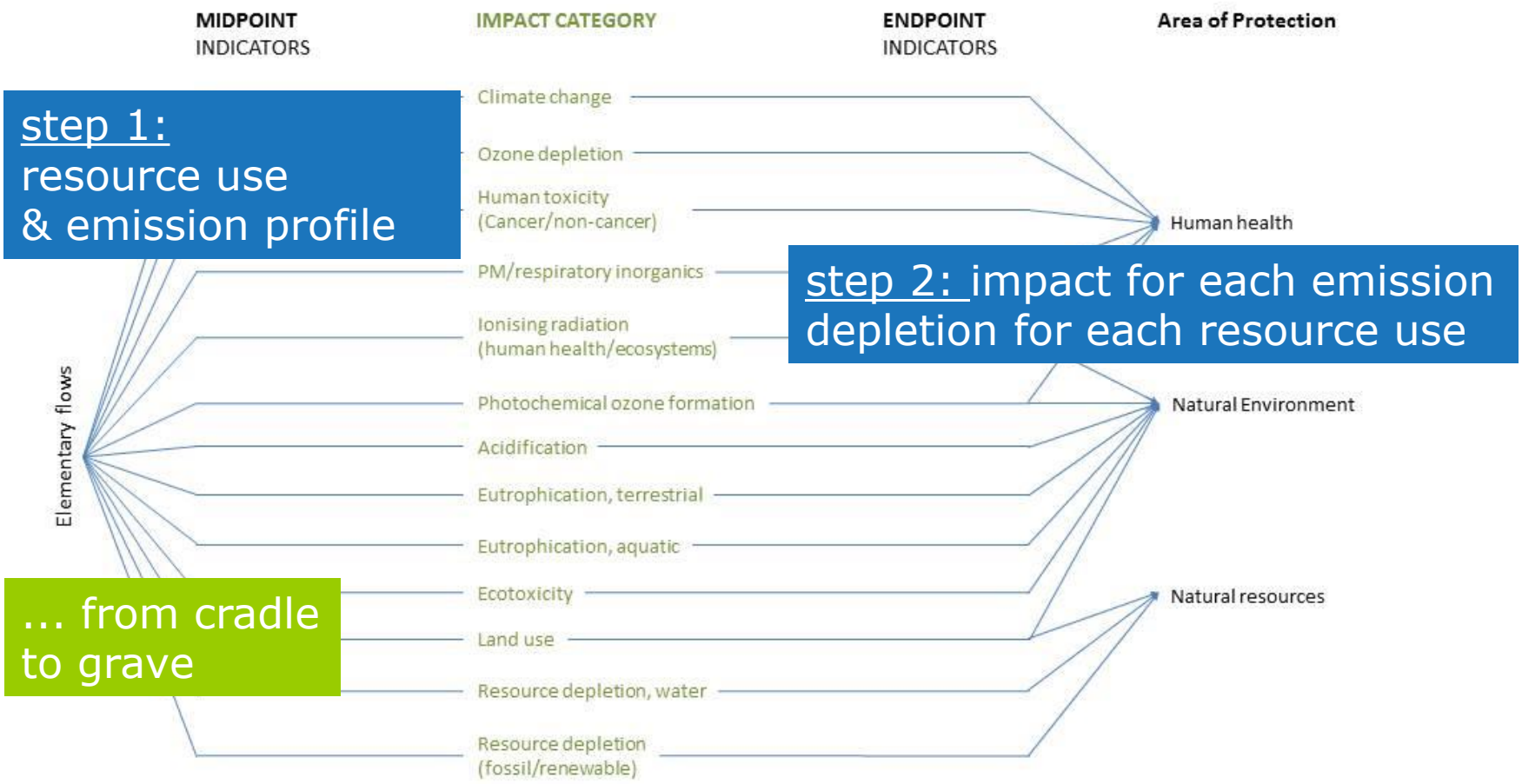
Communication of life-cycle environmental performance:

- Environmental claims;
- Setting criteria for ecolabels;
- Providing incentives.



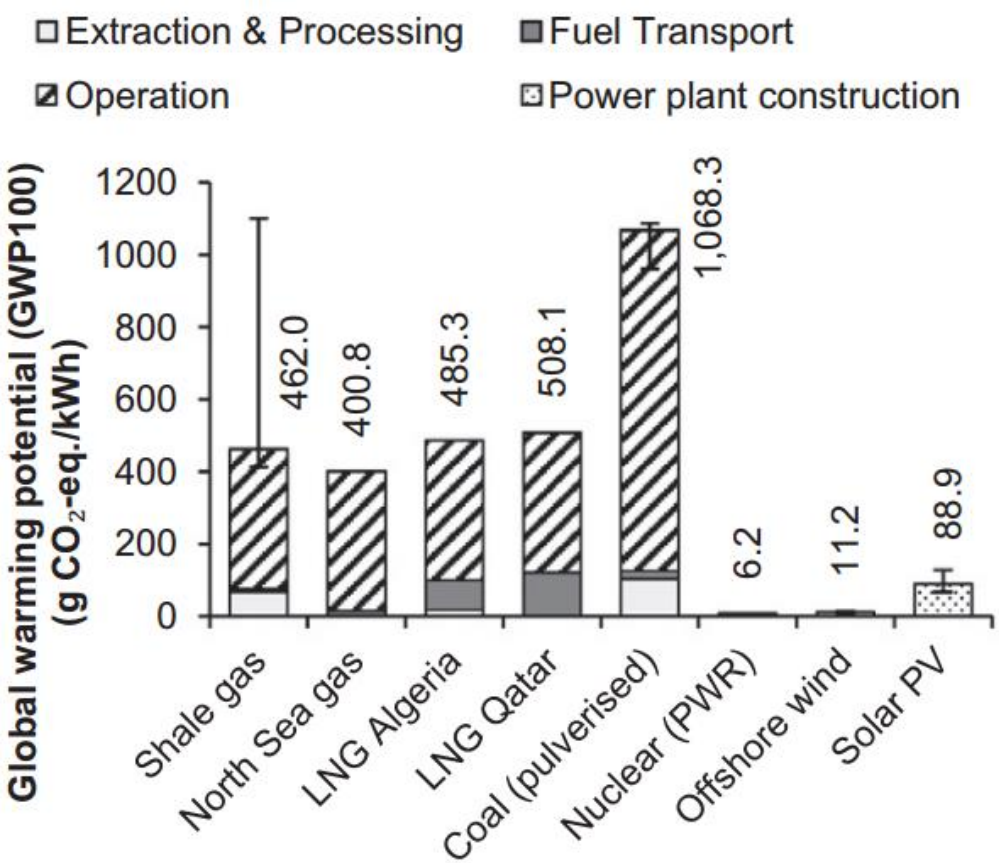
FRANCE:
low Simplified Carbon Footprint required for PV modules for power plants >250 kWp

How to calculate environmental impacts?



ILCD impact assessment method

Fair comparison?
Global Warming Potential/kWh



Stamford (2014) Applied Energy 134: 506-518
Stamford (2012) Int J Energy Res 36:1263–90

Solar PV:

- Time: 2005/2006 ☹
- Geography: UK production UK irradiation
- Technology: mono,multi, ribbon, aSi, CdTe, CIGS

Fair comparison needs rules depending on the goal of your study

- Product definition: which assumptions? type of installation, life time definition
- Function(s) of product / Multi-functionality (BIPV) / Allocation / Unit of analysis: results per kWp? per kWh?
- System boundaries: what to include/exclude? capital goods? which life cycle phases? cradle-to-gate or cradle-to-grave?
- Data quality requirements: technological, time and geographical representativeness; completeness, data gaps; uncertainty, transparency;
- Secondary data: which database? Transparent: ecoinvent, not-transparent: Gabi, ELCD.
- Impact assessment method: which method? which normalization/weighting factors?

Product Environmental Footprint (PEF) of Photovoltaic electricity generation

One of the pilots of the European Commission is Photovoltaic electricity generation

1. Development of the rules:
   PEFCR = Product Environmental Footprint Category Rules
2. PEF screening of different PV technologies
   - Most relevant processes;
   - Most relevant life-cycle stages;
   - Most relevant impact categories;
   - Hot spots.

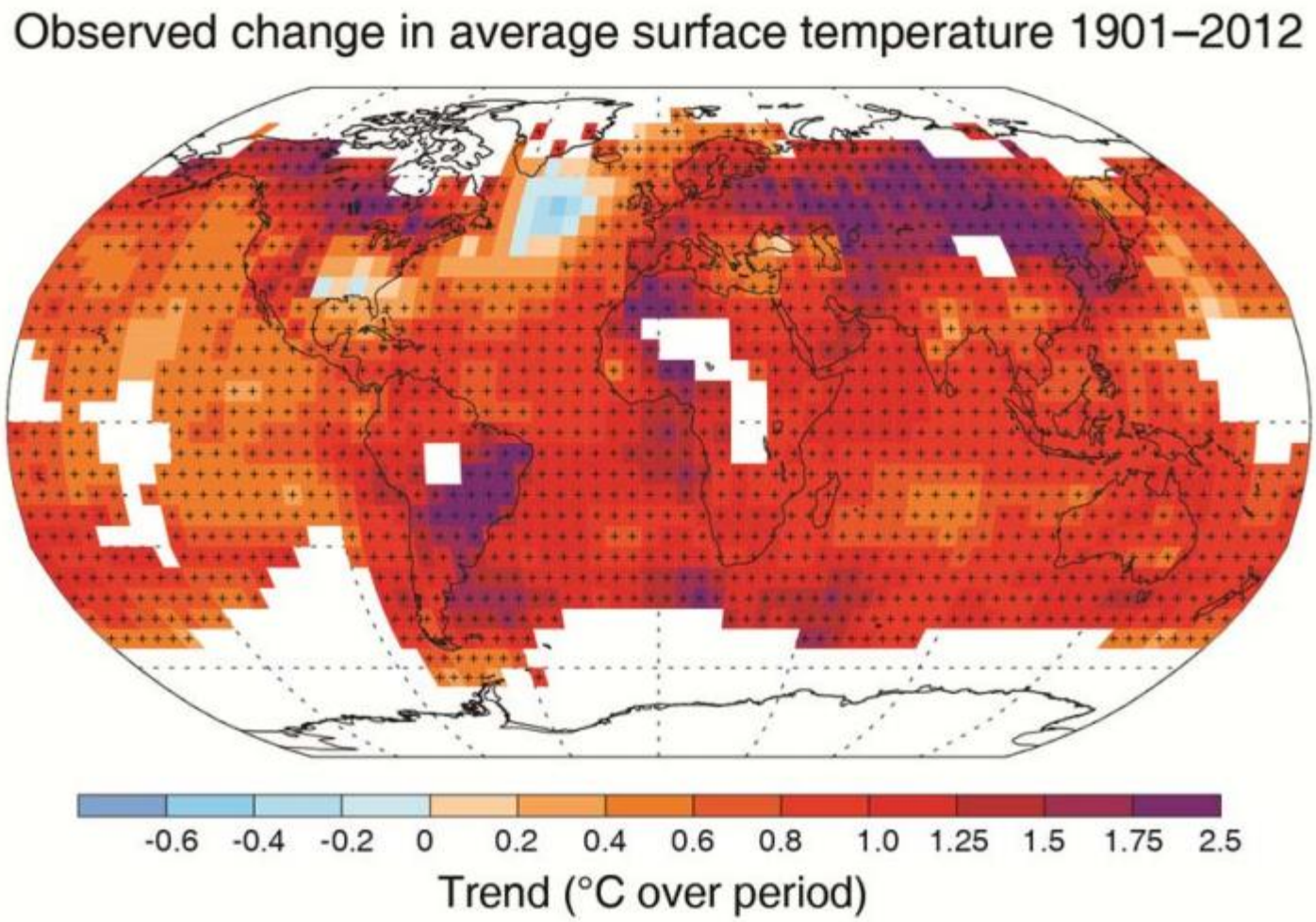
More info? Contact Andreas.Wade@FirstSolar.com

Most relevant processes for mono Si panel from China

photovoltaic panel, single-Si, at plant, China	MIN	MAX	Climate change	Ozone depletion	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Particulate matter	Ionizing radiation HH	Photochemical ozone formation	Acidification	Terrestrial eutrophication	Freshwater eutrophication	Marine eutrophication	Freshwater ecotoxicity	Land use	Water resource depletion	Mineral, fossil & ren resource depletion	Non renewable energy	Renewable energy	Nuclear waste
Solar cells	66	95	87	77	77	75	95	78	88	91	88	81	89	69	66	93	94	85	81	78
Interconnection: Cu, Sn, Pb, wire drawing	0	13	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	1
Factory	0	13	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1
Aluminum frame	1	11	3	4	11	6	1	8	1	1	1	4	1	6	2	4	1	3	[illegible]	9
Glass and tempering	0	7	3	7	1	1	1	3	4	3	5	2	4	1	5	1	0	4	1	3
Packaging	0	7	0	1	0	0	0	1	0	0	0	0	0	0	5	0	0	0	7	1
Junction box: plastic, bypass diode, silicone	0	7	1	7	1	1	0	2	1	0	1	1	1	1	0	1	0	2	1	2
Disposal and waste treatment	0	5	1	0	1	1	0	0	0	0	0	0	0	5	0	0	0	0	0	0
Transport	0	3	1	1	2	1	0	3	1	0	1	1	1	1	1	0	0	1	1	3
Backsheet: PVF / PET	0	2	1	2	1	1	0	2	1	1	1	1	1	1	1	0	1	2	0	2
Encapsulation: EVA + PE protection foil	0	2	1	1	1	0	0	1	1	0	0	1	0	1	1	0	0	2	1	2
Electricity	0	2	1	0	1	1	2	0	1	1	1	1	1	1	1	1	0	1	1	0
Chemicals	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Direct emissions	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

High data quality needed when contribution to impact is high

IPCC 5th Assessment Report
Climate Change 2013



IPCC 5th Assessment Report Climate Change 2013

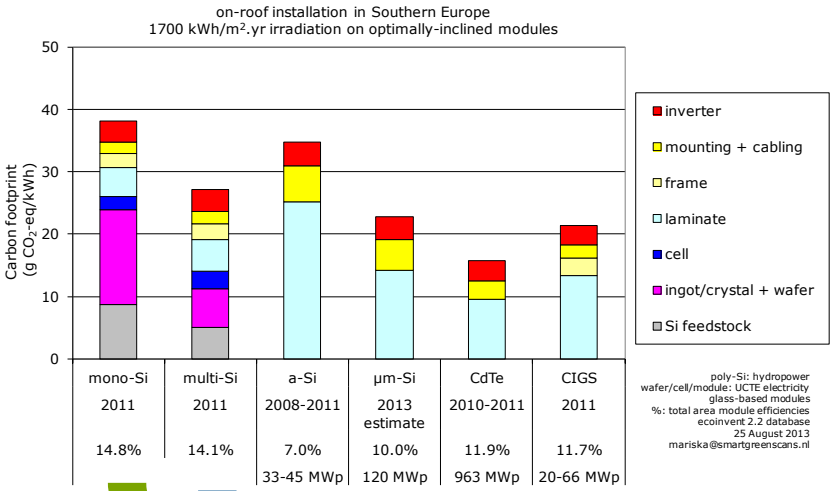
- *Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system.*
- *Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.*

Source: Working Group I, Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis, Summary for Policymakers

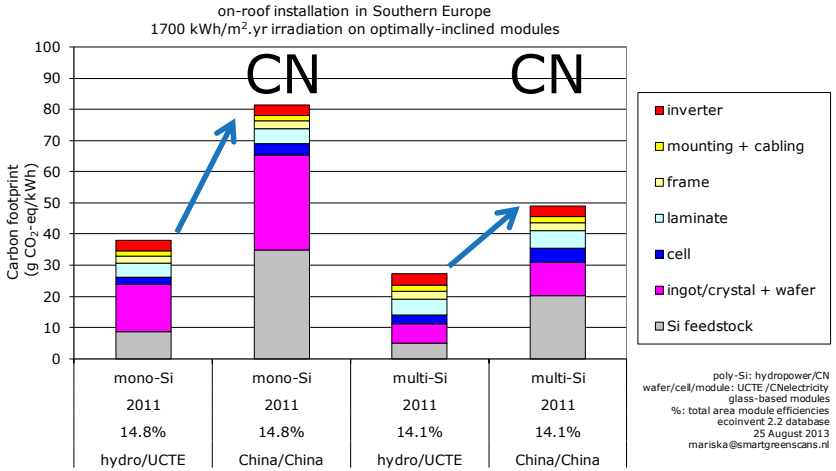
What is the mitigation potential of PV?

Carbon footprint - gram CO_2-eq/kWh

hydropower / UCTE

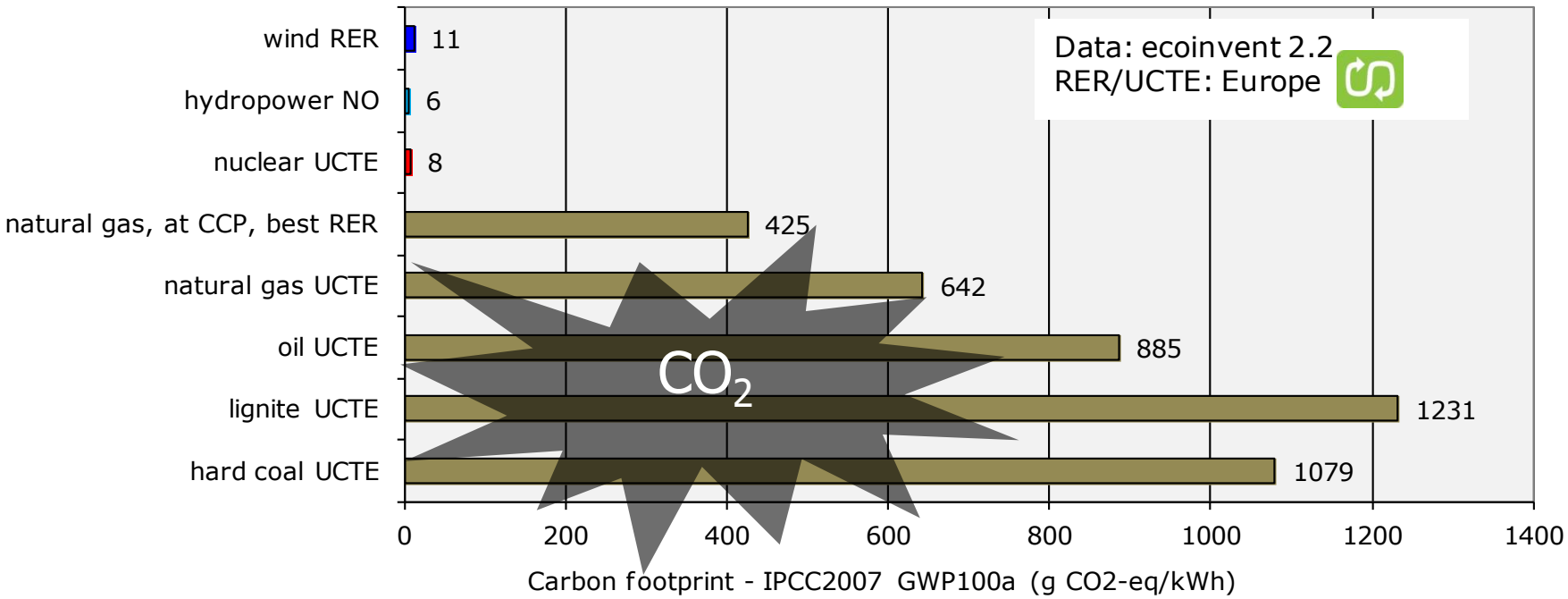


China electricity mix

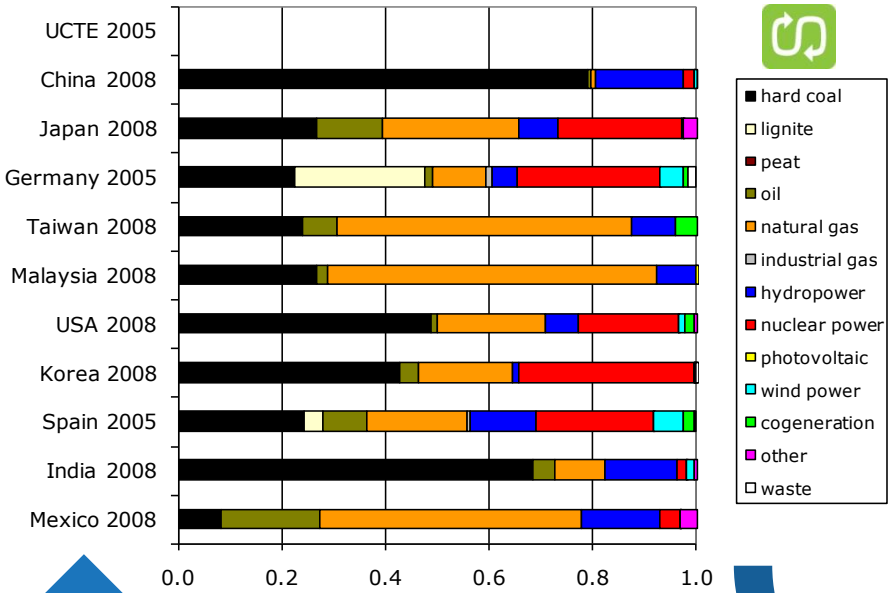


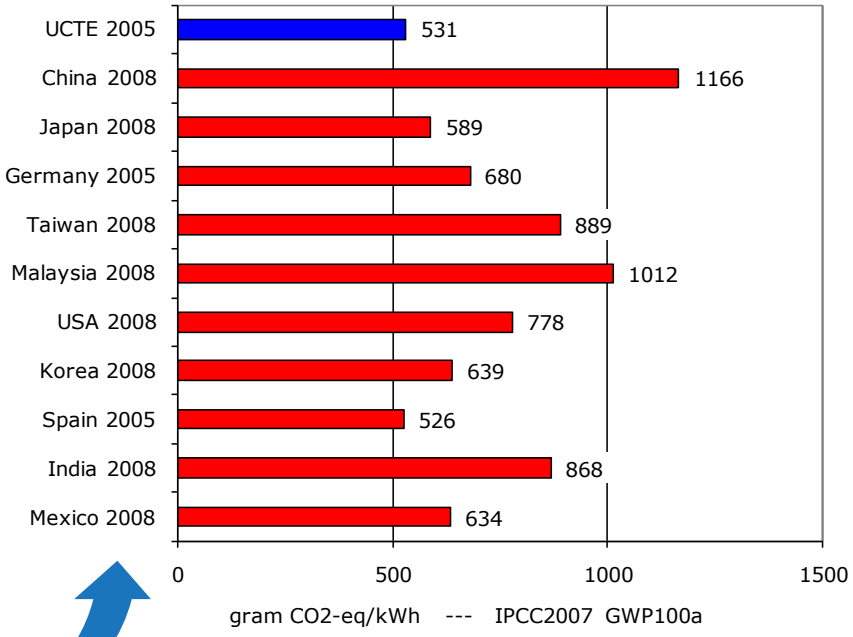
mono multi

Carbon footprint of electricity mixes



Country electricity mixes





top production locations

high uncertainty

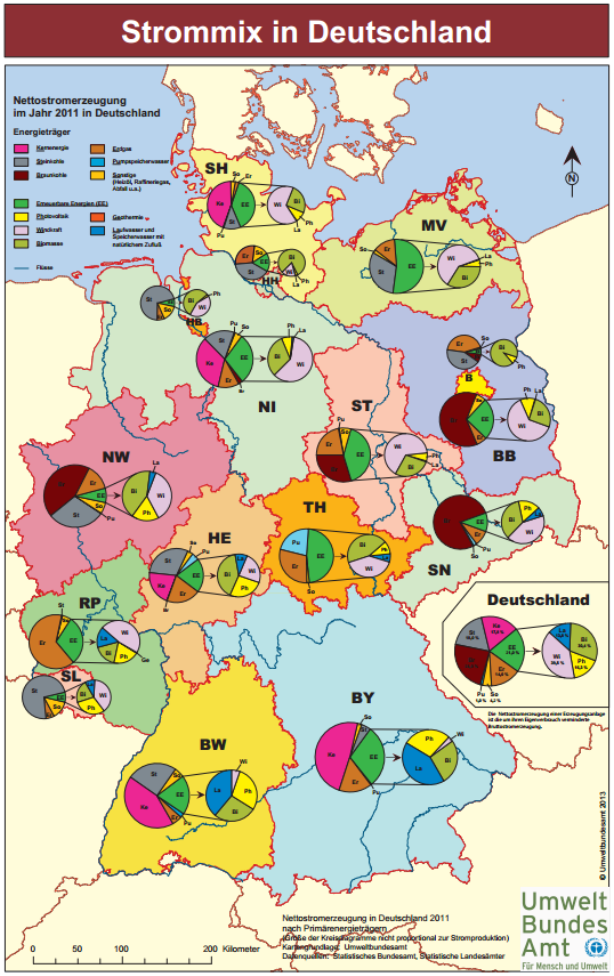
Regional electricity mixes

Year 2009 eGRID Subregion Resource Mix

eGRID subregion acronym	eGRID subregion name	Nameplate capacity (MW)	Net Generation (MWh)	Generation resource mix (percent)										
				Coal	Oil	Gas	Other fossil	Biomass	Hydro	Nuclear	Wind	Solar	Geo-thermal	Other unknown/ purchased fuel
AKGD	ASCC Alaska Grid	1,514.9	5,337,982.5	11.8133	13.6743	66.0333	0.0000	0.0000	8.4791	0.0000	0.0000	0.0000	0.0000	0.0000
AKMS	ASCC Miscellaneous	701.1	1,364,176.9	0.0000	31.2972	3.8526	0.0000	0.4773	63.8578	0.0000	0.5151	0.0000	0.0000	0.0000
AZNM	WECC Southwest	48,647.5	186,138,763.9	38.5979	0.0598	35.6808	0.0013	0.3166	6.0901	16.4726	0.5008	0.1012	2.1789	0.0000
CAMX	WECC California	73,662.1	212,768,947.3	7.3284	1.3637	53.0498	0.2087	2.7167	12.7172	14.9288	2.7635	0.3003	4.3676	0.2553
ERCT	ERCOT All	101,910.6	337,031,899.7	32.9816	1.0518	47.8308	0.1257	0.1215	0.1539	12.3127	5.3314	0.0000	0.0000	0.0906
FRCC	FRCC All	65,716.1	208,123,783.6	23.6531	4.4222	54.8319	0.6348	1.7398	0.0099	13.9907	0.0000	0.0046	0.0000	0.7130
HIMS	HICC Miscellaneous	881.5	3,019,123.5	1.9907	69.8707	0.0000	7.1345	3.3481	3.7312	0.0000	8.3278	0.0460	5.5510	0.0000
HIOA	HICC Oahu	1,925.6	7,991,409.4	18.0301	77.6079	0.0000	2.2104	2.1615	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MROE	MRO East	8,881.2	29,587,725.5	68.9039	2.3652	4.9759	0.1206	3.2381	2.7096	15.2808	2.3228	0.0000	0.0000	0.1030
MROW	MRO West	53,884.9	190,648,178.1	69.0860	0.1515	2.3997	0.1600	1.1844	4.3578	13.9045	8.6647	0.0000	0.0000	0.0914
NEWE	NPCC New England	36,906.5	121,742,618.3	11.8606	1.5048	41.9731	1.6223	5.9158	7.0413	29.7601	0.3110	0.0000	0.0000	0.0109
NWPP	WECC Northwest	68,188.2	269,325,957.1	29.8340	0.3352	15.1503	0.1462	1.0927	46.5021	2.4632	3.8023	0.0000	0.5541	0.1199
NYCW	NPCC NYC/Westchester	13,914.0	40,501,288.1	0.0000	1.7869	55.8586	0.4808	0.5357	0.0185	40.8410	0.4784	0.0000	0.0000	0.0000
NYLI	NPCC Long Island	6,002.5	9,431,561.8	0.0000	12.9940	77.3406	4.5546	5.1108	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NYUP	NPCC Upstate NY	24,408.3	88,081,534.5	14.4853	0.9024	18.9282	0.3570	1.5950	30.7898	30.5892	2.3530	0.0000	0.0000	0.0000
RFCE	RFC East	73,537.8	261,151,661.8	35.3677	0.7271	17.1304	0.8437	1.3211	1.2358	42.9614	0.4050	0.0055	0.0000	0.0023
RFCM	RFC Michigan	29,501.5	88,251,703.2	71.9861	0.4093	9.5071	0.5982	1.8820	0.0000	15.2782	0.3391	0.0000	0.0000	0.0000
RFCW	RFC West	146,174.7	561,623,124.7	69.8826	0.4022	3.5051	0.3533	0.5057	0.7949	23.5563	0.9355	0.0000	0.0000	0.0644
RMPA	WECC Rockies	17,516.6	62,070,098.9	67.7689	0.0435	22.5989	0.0000	0.0911	4.3045	0.0000	5.0659	0.0412	0.0000	0.0860
SPNO	SPP North	21,189.4	65,008,815.6	73.8362	0.2559	7.8088	0.0368	0.0289	0.1377	13.4882	4.4044	0.0000	0.0000	0.0000
SPSO	SPP South	43,413.8	149,443,609.2	55.2342	0.1667	33.8651	0.2189	1.2052	5.5274	0.0000	3.7798	0.0000	0.0000	0.0027
SRMV	SERC Mississippi Valley	50,443.7	165,358,644.7	22.7319	1.4534	45.0929	0.8605	1.9253	1.7370	25.9742	0.0000	0.0000	0.0000	0.2347
SRMW	SERC Midwest	27,319.6	112,061,747.1	79.7879	0.0884	1.0399	0.0122	0.1270	1.7552	17.0754	0.1140	0.0000	0.0000	0.0000
SRSO	SERC South	70,962.7	252,713,667.3	52.1843	0.3499	22.3083	0.0748	2.9228	4.0925	18.0664	0.0000	0.0000	0.0000	0.0010
SRTV	SERC Tennessee Valley	67,089.4	238,173,939.7	58.8034	0.9387	8.6065	0.0087	0.7817	8.5808	22.1286	0.1516	0.0000	0.0000	0.0000
SRVC	SERC Virginia/Carolina	80,187.5	293,154,419.6	45.1039	0.6421	8.9501	0.1921	2.0466	1.6491	41.3467	0.0000	0.0016	0.0000	0.0678
U.S.		1,134,441.5	3,951,097,802.2	44.4675	1.1174	23.3119	0.3414	1.3779	6.8033	20.2185	1.8614	0.6223	0.3799	0.0984

This is a representational map; many of the boundaries shown on this map are approximate because they are based on companies, not on strictly geographical boundaries.

USEPA eGRID2012 Version 1.0 p. 5



On-site electricity & heat production for poly-silicon production

Hydropower

Wacker Burghausen:
Alzwerke Power Station

Combined Heat & Power

Wacker Burghausen:
Combined-Cycle Gas Turbine

On-site PV electricity for PV module production

PV façade

Solar Fabrik in Freiburg:
1/5 of electricity demand

PV on flat roof

REC Singapore

World average carbon footprint of PV electricity

Manufacturing

- *Poly-silicon* capacities 2011/country
- *Ingot/wafers, mono/multi* production 2011/country
- *Solar cells, mono/multi* production 2011/country
- *PV modules, mono/multi/aSi/µmSi/CdTe/CIGS* production 2011/country
- *Balance-of-System* from ecoinvent 2.2
- LCA data: SmartGreenScans/ecoinvent 2.2 (SOLMAT 2013/119: 296-305)
- Technology market shares

→ **World average carbon footprint of PV system/kWp**

Installation

- Cumulative installations /country 2013
- Average irradiation /country

→ Carbon footprint/kWh /country 2013

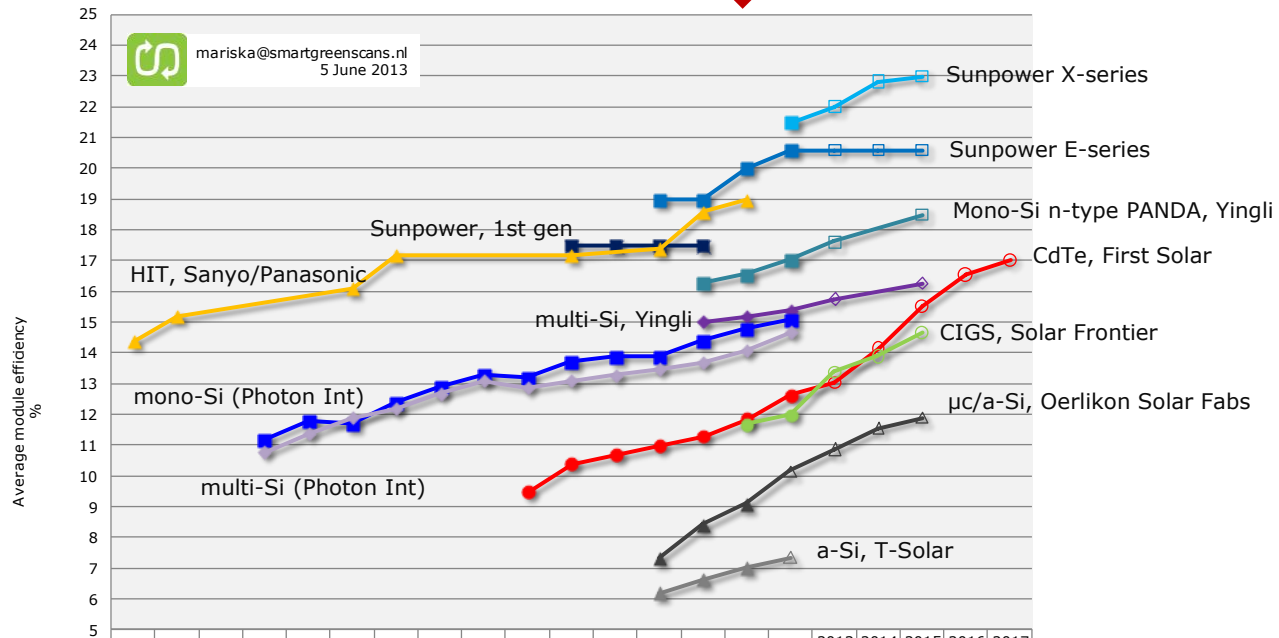
→ **World average carbon footprint of PV electricity/kWh**

Manufacturing / country

				Europe	Americas	Arabia-Africa	Asia-Pacific	China
xSi	**Solar Silicon**	**capacity 2011**	**Grunwald 2012**	**10%**	**23%**	**0%**	**26%**	**41%**
		capacity 2012	EPIA 2013	17%	28%		20%	35%
		production 2012	EPIA 2013	20%	34%		19%	27%
	Wafers	**production 2011**	**Mehta 2013**	**7%**	**1%**	**0%**	**25%**	**67%**
		capacity 2012	EPIA 2013	8%	1%		13%	78%
		production 2012	EPIA 2013	7%	1%		12%	80%
	Cells	**production 2011**	**Mehta 2013**	**6%**	**2%**	**0%**	**30%**	**62%**
		capacity 2012	EPIA 2013	5%	2%		22%	71%
		production 2012	EPIA 2013	5%	2%		27%	66%
	Modules	**production 2011**	**Mehta 2013**	**12%**	**4%**	**2%**	**15%**	**66%**
		capacity 2012	EPIA 2013	13%	3%		11%	73%
		production 2012	EPIA 2013	14%	4%		13%	69%
film-Si	**Modules**	**production 2011**	**Photon Int 2012**	**65%**	**13%**	**0%**	**22%**	**0%**
CdTe	**Modules**	**production 2011**	**Photon Int 2012**	**15%**	**14%**	**0%**	**70%**	**0%**
CIGS	**Modules**	**production 2011**	**Photon Int 2012**	**22%**	**19%**	**0%**	**59%**	**0%**

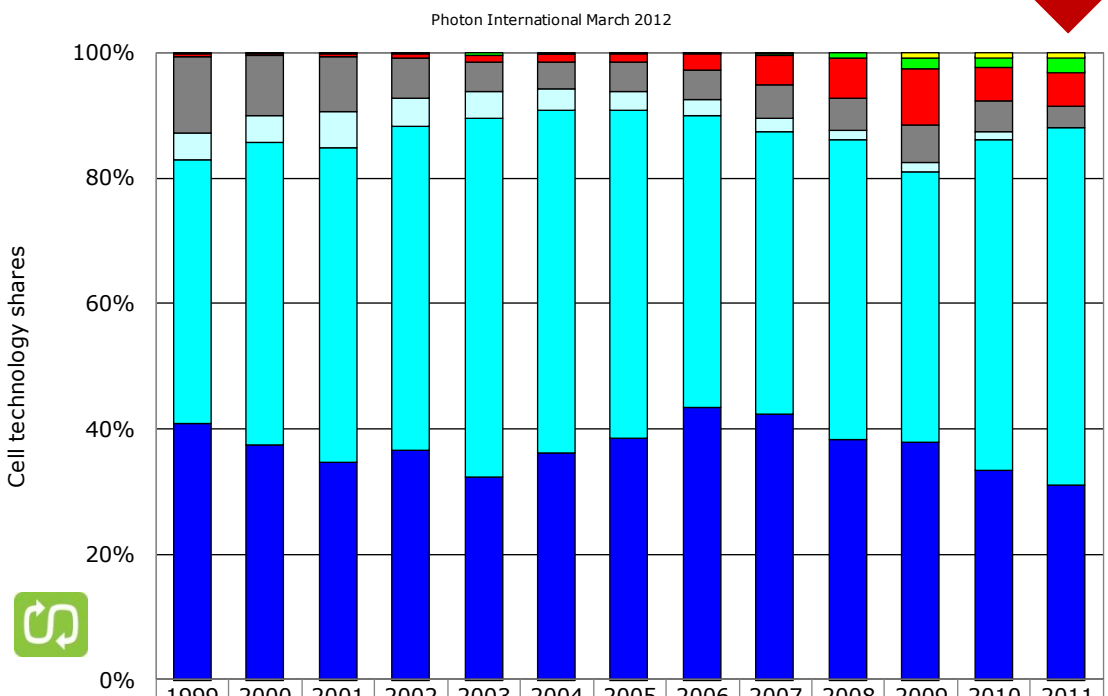
Grunwald (2012/9) Sun & Wind Energy
Mehta (2013) GTM Research report
EPIA (2013) Global Market Outlook for Photovoltaics 2013-2017
Hering (2012 March) Photon International

Average module efficiencies → Wp/m²



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013 e	2014 e	2015 e	2016 e	2017 e
Sunpower, X-series																21.5	22.0	22.8	23.0		
Sunpower, E-series													19.0	19.0	20.0	20.6	20.6	20.6	20.6		
Sunpower, 1st generation											17.5	17.5	17.5	17.5							
HIT, Sanyo/Panasonic	14.4	15.2				16.1	17.2				17.2		17.4	18.6	19.0						
Mono-Si n-type PANDA, Yingli, CN														16.3	16.6	17.0	17.6		18.5		
Multi-Si, Yingli, CN														15.0	15.2	15.4	15.7		16.3		
Mono-Si (Photon Int Feb 2013)				11.2	11.8	11.7	12.4	12.9	13.3	13.2	13.7	13.9	13.9	14.4	14.8	15.1					
Multi-Si (Photon Int Feb 2013)				10.8	11.4	11.9	12.2	12.7	13.1	12.9	13.1	13.3	13.5	13.7	14.1	14.7					
CdTe, First Solar										9.5	10.4	10.7	11.0	11.3	11.9	12.7	13.1	14.2	15.6	16.6	17.1
CIGS, Solar Frontier, JP															11.7	12.0	13.4	13.9	14.7		
µc/a-Si, Oerlikon Solar Fabs													7.4	8.4	9.1	10.2	10.9	11.6	11.9		
a-Si, TSolar, ES													6.20	6.63	7.05	7.35					

Cell technology market shares



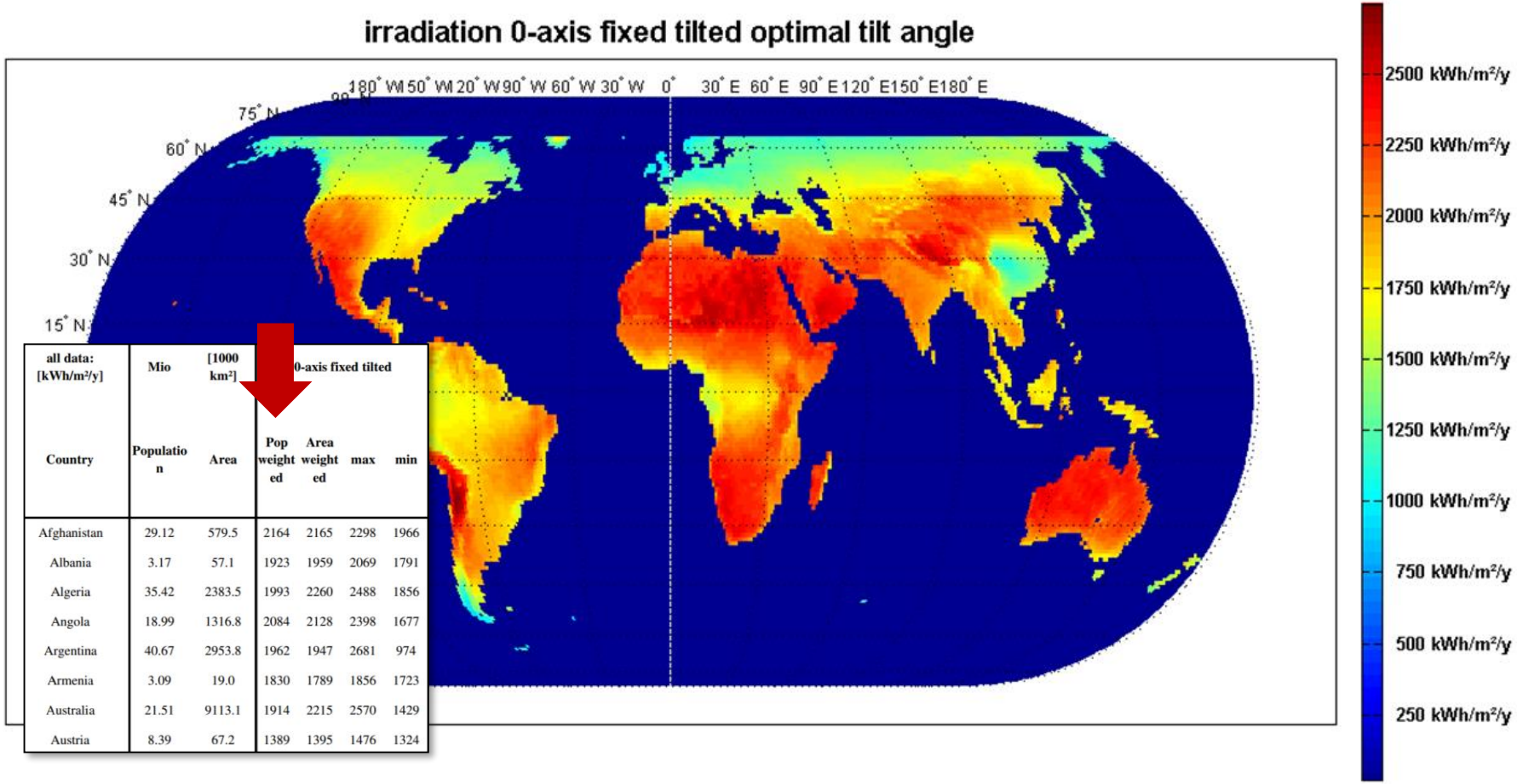
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.9	0.8	0.8
CIS	0.2	0.2	0.2	0.2	0.6	0.4	0.2	0.2	0.5	1.0	1.7	1.6	2.4
CdTe	0.5	0.3	0.5	0.7	1.1	1.1	1.4	2.7	4.7	6.4	9.0	5.3	5.5
a-Si/µc-Si	12.3	9.6	8.9	6.4	4.5	4.4	4.7	4.7	5.2	5.1	6.1	5.0	3.4
ribbon c-Si	4.1	4.3	5.6	4.6	4.4	3.3	2.9	2.6	2.2	1.5	1.4	1.2	0.0
multi c-Si	42.1	48.2	50.2	51.6	57.2	54.7	52.3	46.5	45.2	47.7	43.2	52.9	57.0
mono c-Si	40.8	37.4	34.6	36.4	32.2	36.2	38.4	43.3	42.2	38.3	37.8	33.2	30.9

57% multi
31% mono
6% CdTe
3% film-Si
2% CIS
1% other
0% ribbon

Carbon footprint / kWp

	Technology shares	Carbon footprint PV system
		kg CO2-eq/kWp
	2011	**2011**
mono c-Si	30.9	2728
multi c-Si	57.0	1536
ribbon c-Si	0.0	
a-Si/µc-Si	3.4	876
CdTe	5.5	574
CIS	2.4	750
other	0.8	
	100.0	**1798**
		weighted average

Average irradiation / country (world) population weighted



all data: [kWh/m²/y]	Mio	[1000 km²]	0-axis fixed tilted			
Country	Population	Area	Pop weighted	Area weighted	max	min
Afghanistan	29.12	579.5	2164	2165	2298	1966
Albania	3.17	57.1	1923	1959	2069	1791
Algeria	35.42	2383.5	1993	2260	2488	1856
Angola	18.99	1316.8	2084	2128	2398	1677
Argentina	40.67	2953.8	1962	1947	2681	974
Armenia	3.09	19.0	1830	1789	1856	1723
Australia	21.51	9113.1	1914	2215	2570	1429
Austria	8.39	67.2	1389	1395	1476	1324

Ch. Breyer, J. Schmid (2010) Population density and area weighted solar Irradiation: global overview on solar resource conditions for fixed tilted, 1-axis and 2-axes PV systems, 25th European Photovoltaic Solar Energy Conference, Valencia

Carbon footprint / World

Country - Irradiation - Cum. capacity - CF PV - CF country

Country	Irradiation on optimized angle	Irradiation	Cumulative installed capacity				Carbon footprint PV	Carbon footprint country
	Selected reference	Selected value	2013	2013	2013	2013	IPCC2007 GWP100a	IPCC2007 GWP100a
		kWh/m2.yr	MWp	MWp	MWp	MWp	g CO2-eq/kWh	g CO2-eq/kWh
			Selected	EPIA 2014	EurObserv'ER 2014	IEA PVPS status 20 March 2014		
	optimized angle, area weighted		EPIA, IEA		Total on grid + off grid			
WEIGHTED AVERAGE							**54.9**	
SUM / AVERAGE / WEIGHTED AVERAGE		**1518**	**135234**				55.2	
Australia	Breyer 2010	2215	3255			3255	39	
Austria	Huld 2014	1329	613	613	690.4	580	65	320
Belgium	Huld 2014	1237	2983	2983	2983.4	2983	69	
Bulgaria	Huld 2014	1633	1020	1020	1019.2	1020	53	620
Canada	Breyer 2010	1095	1210			1210	78	251
China	Breyer 2010	1911	18300			18300	45	1164
Croatia	Huld 2014	1581	20	20	21.7		54	345
Cyprus	Huld 2014	2233	32	32	34.8		38	904
Czech Republic	Huld 2014	1254	2175	2175	2132.8	2162	68	781
Denmark	Huld 2014	1192	548	548	531.4	532	72	639
Estonia	Huld 2014	1152	0	0	0.2		75	1147
Finland	Huld 2014	1056	11	11	11.2		81	392
France	Huld 2014	1520	4673	4673	4697.6	4632	56	92
Germany	Huld 2014	1251	35715	35715	36013.0	35500	69	680
Greece	Huld 2014	1924	2579	2579	2585.8	2579	45	1030
Hungary	Huld 2014	1494	22	22	15.4		57	714
Iceland	Huld 2014	963					89	22
India	Breyer 2010	2027	2319			2319	42	876
Ireland	Huld 2014	1175	3	3	1.0		73	799
Israel	Breyer 2010	2258	420			420	38	
Italy	Huld 2014	1768	17928	17928	17614.0	17600	49	650
Japan	Breyer 2010	1603	13643			13643	54	565
Korea, Republic of	Breyer 2010	1779	1467			1467	48	660
Latvia	Huld 2014	1176	1	1	1.5		73	248
Liechtenstein	Huld 2014	1345					64	
Lithuania	Huld 2014	1178	6	6	68.1		73	148
Luxembourg	Huld 2014	1243	30	30	100.0		69	539
Montenegro	Huld 2014	1565					55	
Macedonia, the former Yugoslav Republic of	Huld 2014	1711					50	1006
Malaysia	Breyer 2010	1844	73			73	47	1045
Malta	Huld 2014	2163	23	23	24.7		40	776
Mexico	Breyer 2010	2194	100			100	39	676
Netherlands	Huld 2014	1244	665	665	665.0	650	69	699
Norway	Huld 2014	1020	0	0		284	84	13
Poland	Huld 2014	1252	7	7	4.2		69	1162
Portugal	Huld 2014	2007	278	278	281.0		43	629
Romania	Huld 2014	1488	1151	1151	1022.0	1100	58	676
Serbia	Huld 2014	0						
Slovakia	Huld 2014	1339	524	524	537.1	524	64	380
Slovenia	Huld 2014	1459	212	212	254.8		59	504
Spain	Huld 2014	1970	5340	5340	4705.5	5566	44	526
Sweden	Huld 2014	1090	40	40	43.1	43	79	42
Switzerland	Huld 2014	1396	737	737		740	61	24
Taiwan	Breyer 2010	1628	376			376	53	
Thailand	Breyer 2010	1899	704			704	45	736
Turkey	Huld 2014	1876	18	18		15	46	
Ukraine	Breyer 2010	1424	616	616		616	60	521
United Kingdom	Huld 2014	1154	3375	3375	2739.3	2900	74	617
USA	NREL, average of cities California	2048	12022			12022	42	729

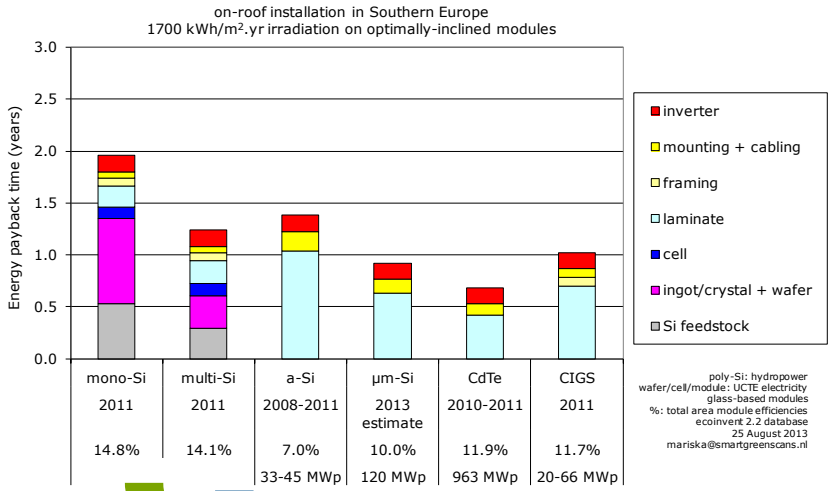
55 g CO_2-eq/kWh world average

65 g CO_2-eq/kWh Austria

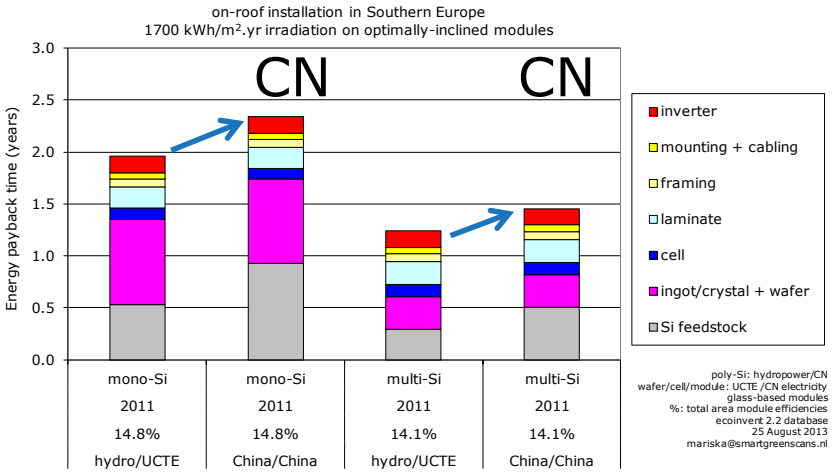
Carbon footprint country / PV = **Carbon mitigation potential**

Energy payback time

hydropower / UCTE



China electricity mix



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Acknowledgements