Photovoltaik: wettbewerbsfähig von Kleinstsystemen in Entwicklungsländern bis großen „DESERTEC“ Kraftwerken

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Clausthal, 9. Mai 2012

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Reiner Lemoine and his Action

Reiner Lemoine was one of the Renewable Energy Pioniers

1978 Formation of *Wuseltronik*

Don't leave the planet to the stupid

1996 Formation of *Solon*

1999 Formation of *Q-Cells*

Reiner Lemoine
co-founder of Q-Cells

Reiner Lemoine and colleagues
co-founder of Wuseltronik in Berlin-Kreuzberg

2006 Formation of *Reiner Lemoine Stiftung (RLS)*

2010 Formation of ***Reiner Lemoine Institut (RLI)***

„Scheiß auf den Kommerz, lass uns was Richtiges machen.“

Reiner Lemoine, EE Pionier

„Am Ende des Tages treffen wir uns an der Kasse wieder.“

Klaus-Dieter Maubach, Eon Vorstand

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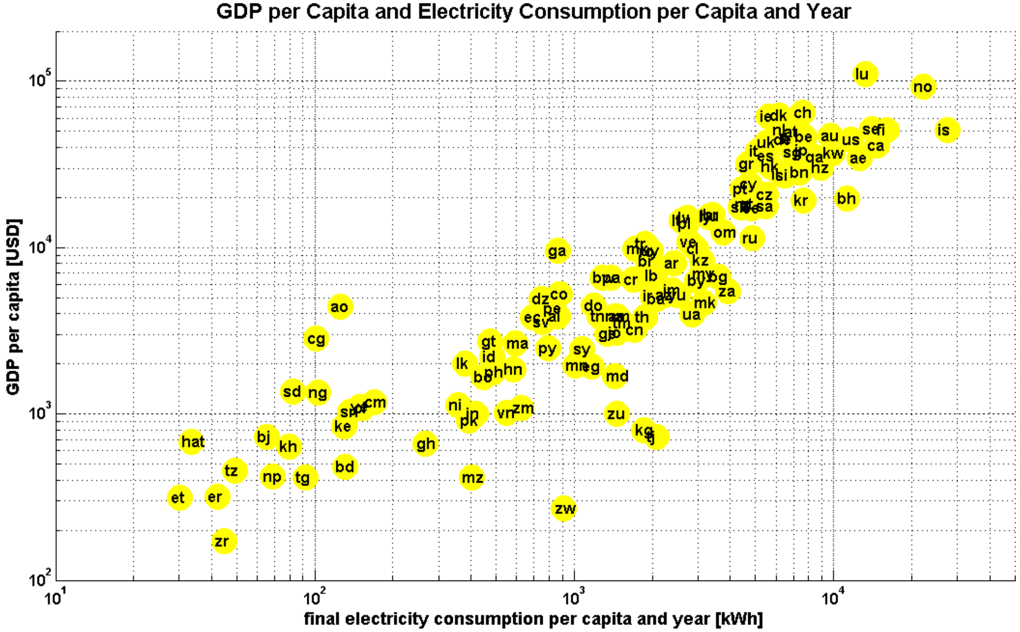
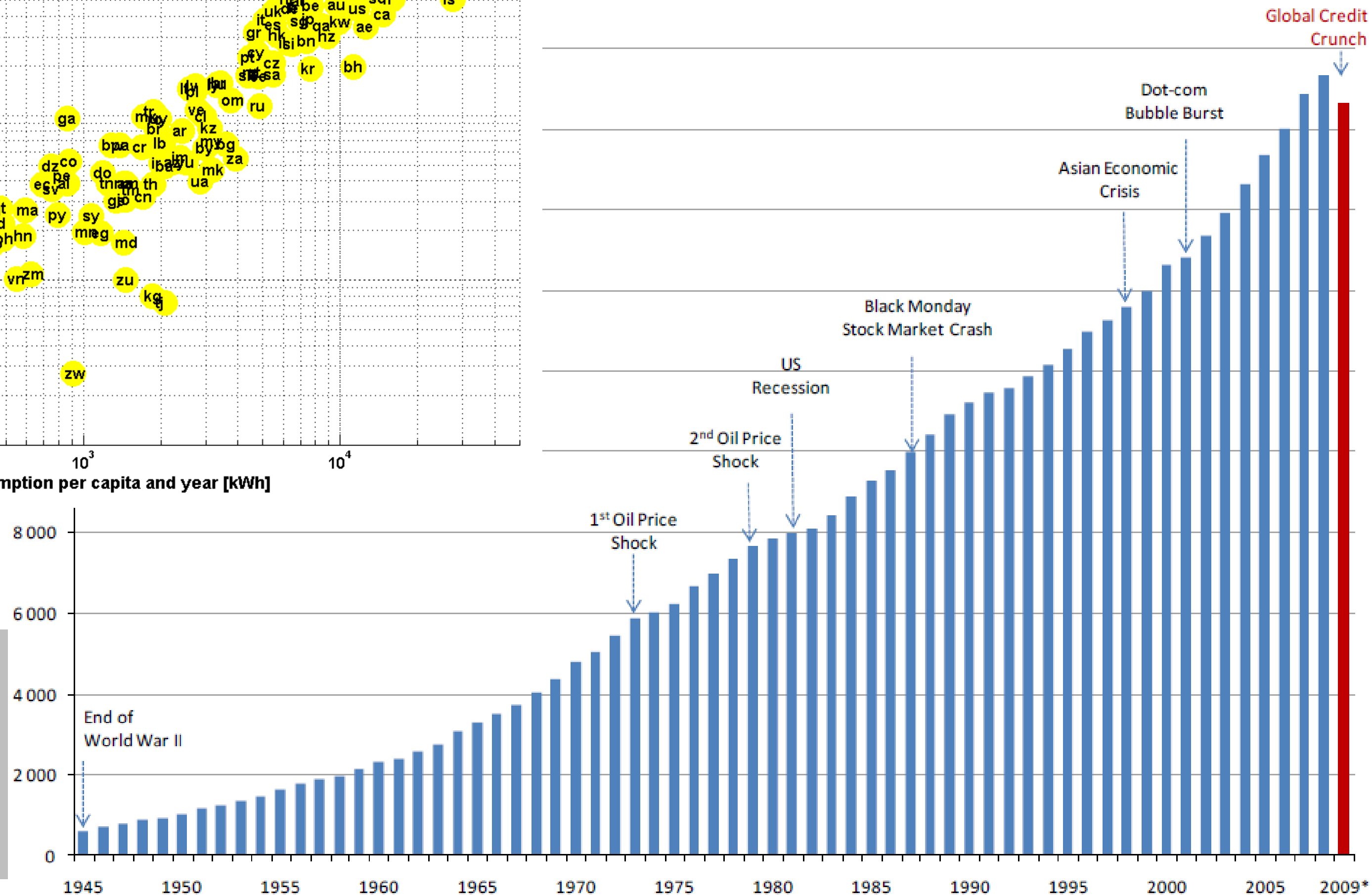
Outline

- **Energy Constraints**
- **PV Fundamentals: Overview**
- **PV Economics: Sustainability**
- **Off-Grid: Pico Systems and SHS**
- **Off-Grid: PV-Diesel and Mini-Grids**
- **Grid-Parity: Economic Market Potential**
- **Fuel-Parity: Economic Market Potential**
- **Hybrid Systems: PV and Wind**
- **Hybrid Systems: Renewable Methane**
- **100 % RE system: Mitteldeutschland**
- **DESERTEC: Large Scale Renewables**
- **Summary**

Electricity Constraints: Electricity Demand

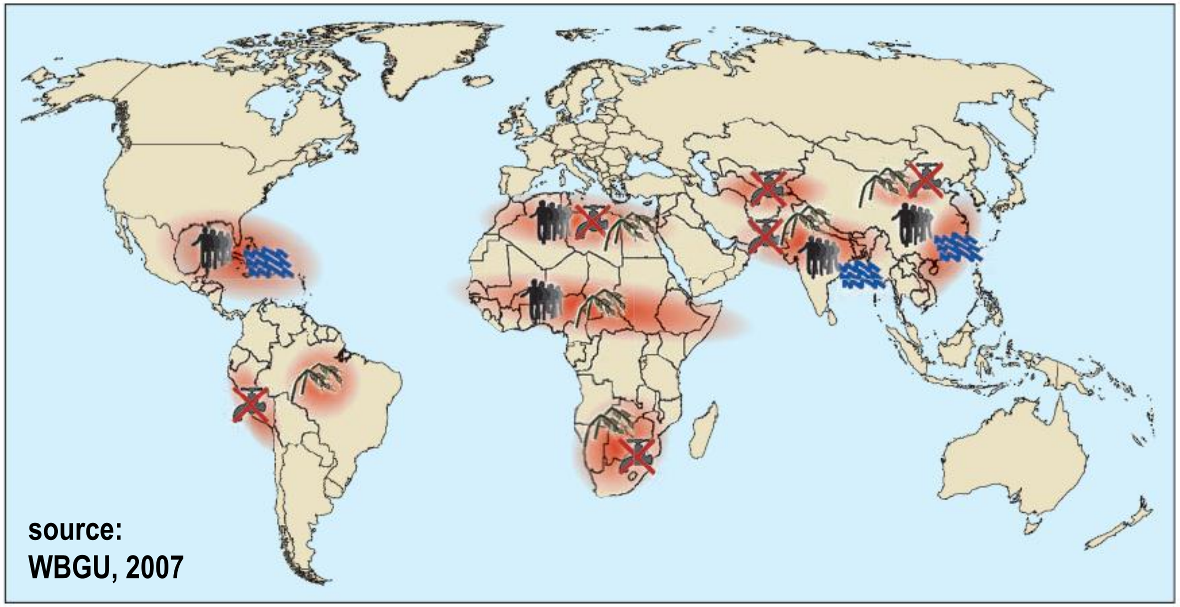




Global Demand Growth
2035: 35,000 TWh_{el}
>2050: 55,000 TWh_{el}

source: IEA, 2009

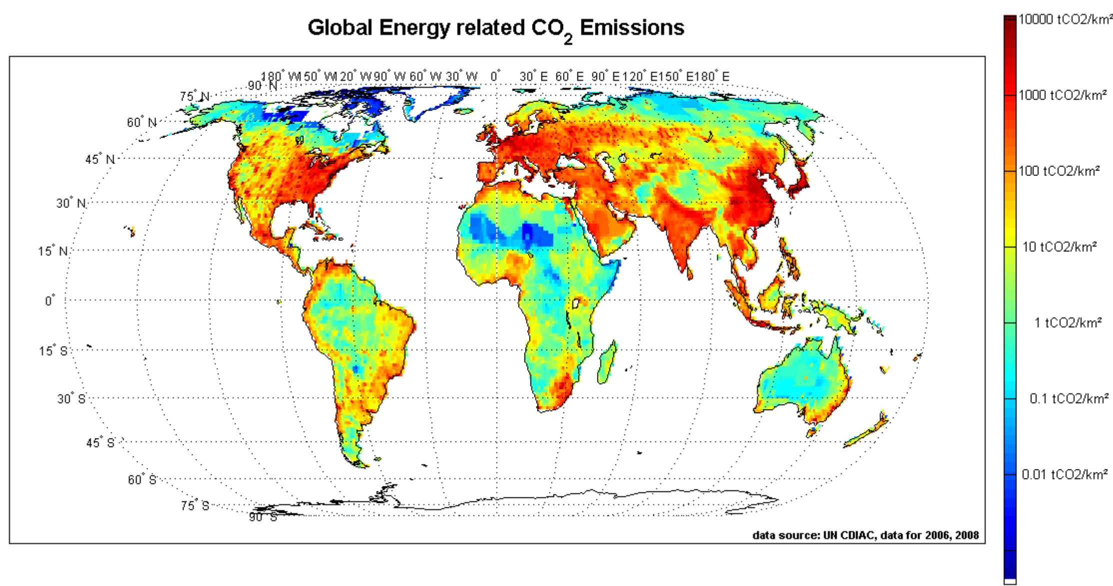
Electricity Constraints: Climate Change



- Climate Change induces security risk
- regional imbalance of emissions and impact
- China is in the lead
- no 1 driver for global societal collapse in 21st century

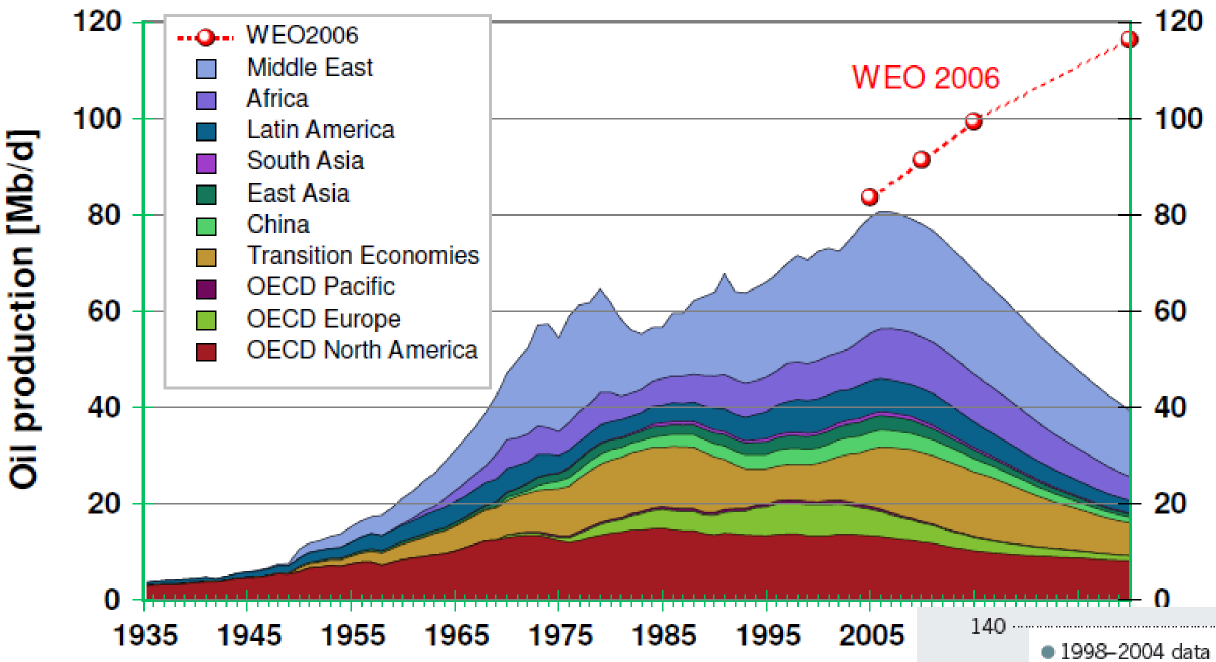
Conflict constellations in selected hotspots

- Climate-induced degradation of freshwater resources
- Climate-induced decline in food production
- Climate-induced increase in storm and flood disasters
- Environmentally-induced migration

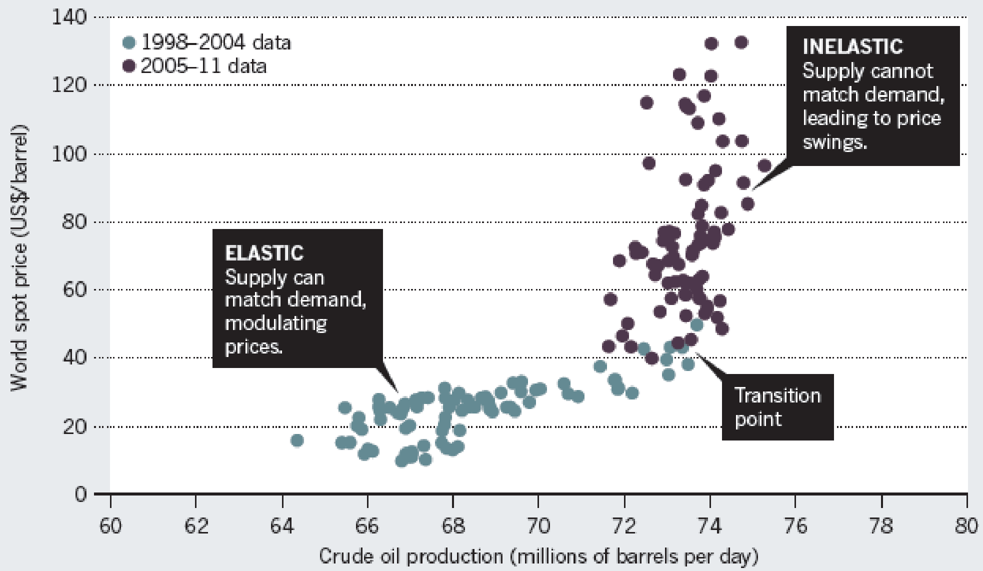


„Climate Change presents a unique challenge for economics: it is the greatest and widest-ranging market failure ever seen.“ Lord Nicholas Stern (fromer Chief Economist World Bank), 2006

Electricity Constraints: Diminishing Energy Fuels



source: Energy Watch Group, 2008;
Murray J. and King. D., 2012.
in nature



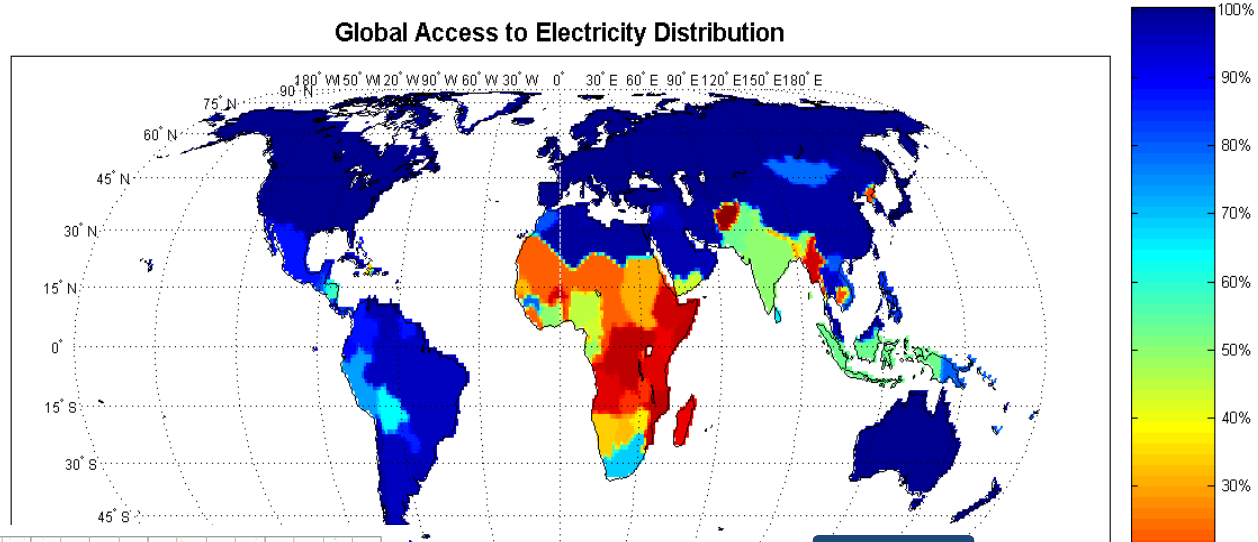
Key insights:

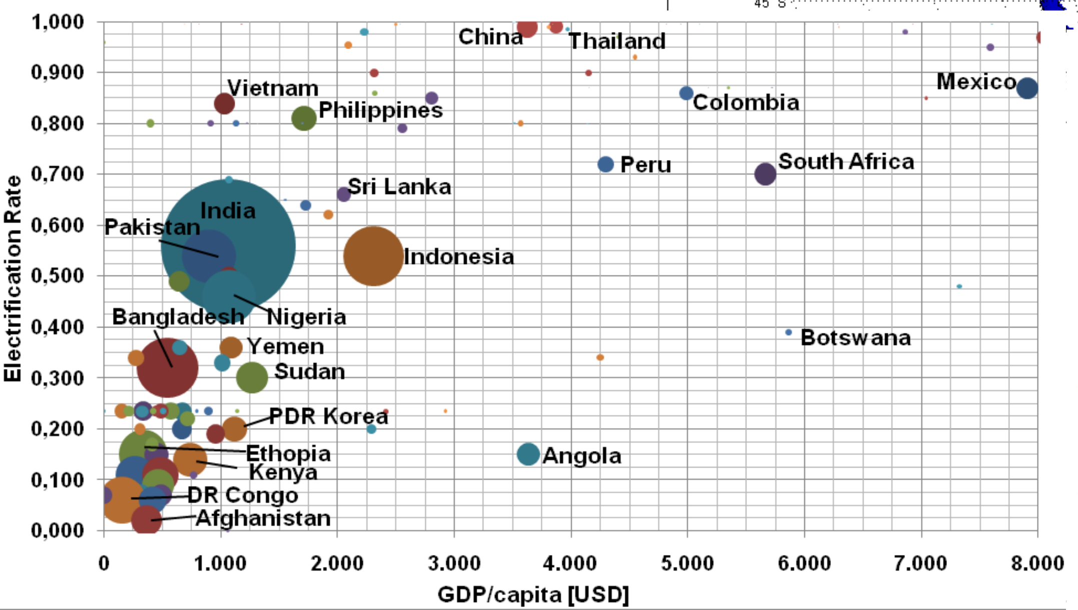
- historic global production peak reached for oil; gas, coal and uranium will follow
- major growth driver for the last 100 years will threaten global prosperity
- peace among nations at risk

Energy Constraints: Energy Injustice

source:

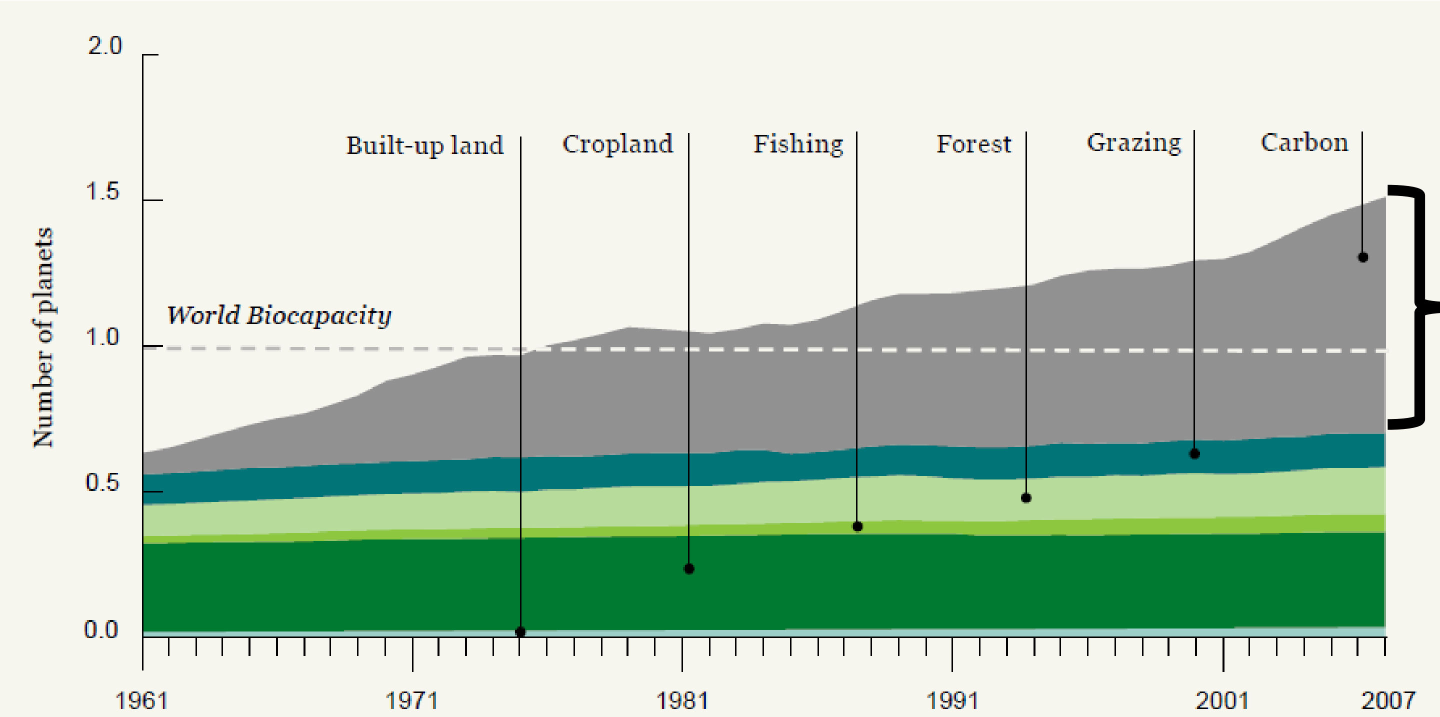
Breyer Ch., Werner C., et al., 2011. Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC





Country	Population [mio pop]	Electrification rate	People without electricity [mio pop]	GDP/capita [USD]	population weighted irradiation optimally tilted [kWh/m²/y]
India	1,214.5	0.560	534.4	1,070	2,032
Bangladesh	164.4	0.320	111.8	540	1,908
Indonesia	233.7	0.540	107.5	2,310	1,809
Nigeria	158.3	0.460	85.5	1,070	1,978
Pakistan	184.8	0.540	85.0	900	2,135
Ethiopia	85.0	0.150	72.2	340	2,205
DR Congo	67.8	0.060	63.8	160	1,848
Burma	50.5	0.110	44.9	270	1,939
Tanzania	45.0	0.110	40.1	480	2,043
Kenya	40.9	0.140	35.1	740	2,124
Uganda	33.8	0.090	30.8	460	1,980
Sudan	43.2	0.300	30.2	1,260	2,271
Afghanistan	29.1	0.020	28.5	360	2,164
Mozambique	23.4	0.060	22.0	410	2,026
Nepal	29.9	0.330	20.0	420	2,176
PDR Korea	24.0	0.200	19.2	1,110	1,874
Philippines	93.6	0.810	17.8	1,710	1,842
Madagascar	20.1	0.150	17.1	450	2,091
Angola	19.0	0.150	16.1	3,630	2,084
Yemen	24.3	0.360	15.5	1,080	2,295
South Africa	50.5	0.700	15.1	5,660	2,166

Energy Constraints: Ecological Footprint



decarbonised power systems are desperately needed

source: Wackernagel, 2010

Historic Collapse Pattern (Jared Diamond)
- Over Exploitation of Resources
- Climate Change Impact
- Non Adaptive Social Behaviour
- Military Conflicts
- Structural Change in Trade Routes

our performance is excellent, unfortunately under the wrong sign

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The Main PV Segments

Utility

- large power plants (> 1 MW)
- Utility or electricity wholesale market as customer

Commercial / Industrial

- Often > 100 kW installations
- Professional customers

Residential

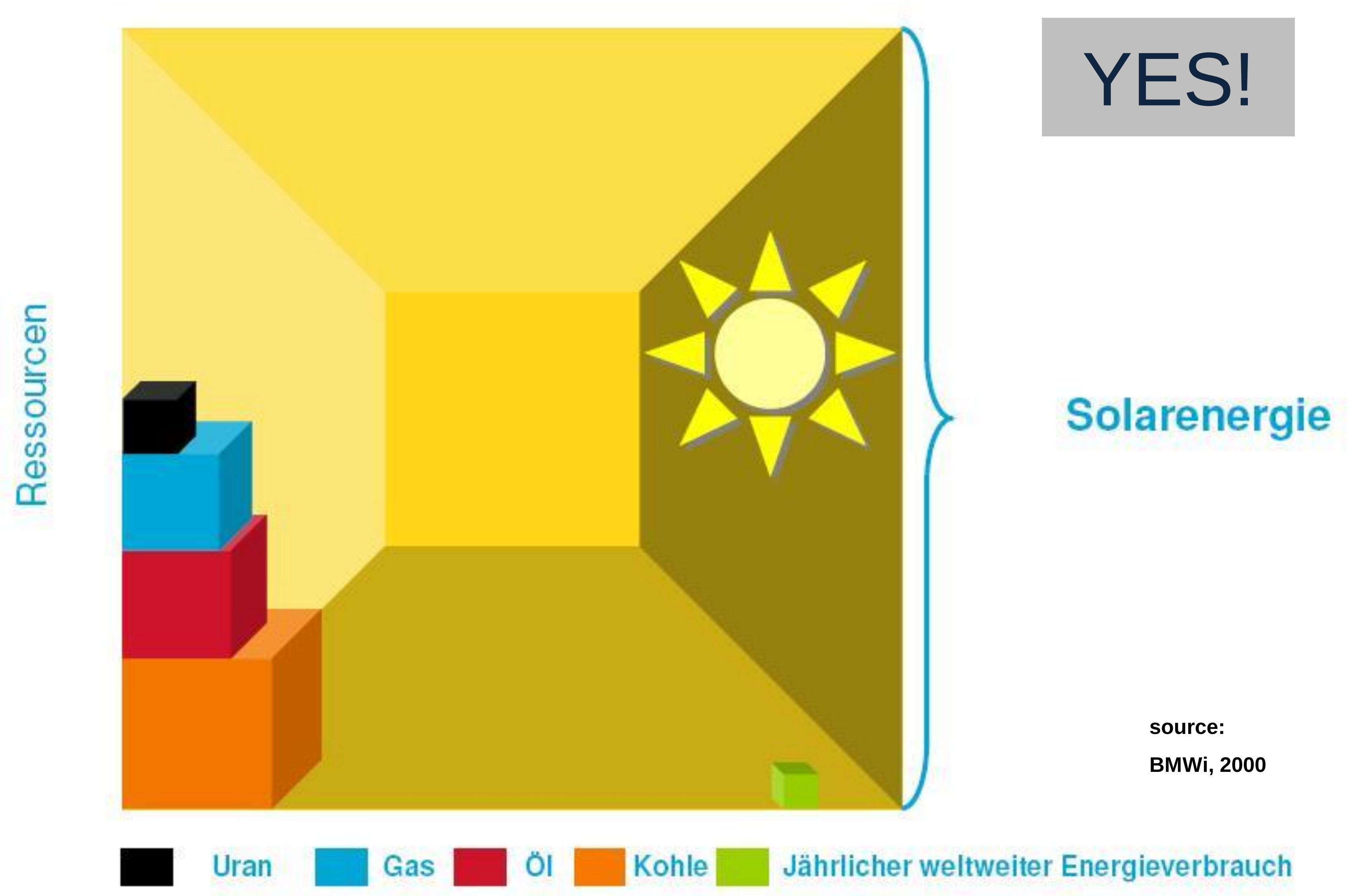
- Small and very small installations (< 10 kW)
- Mainly homeowners

Off-Grid

- Varying system sizes
- Varying customer types

PV can be used in all regions in the world, by the poorest to the richest, in decentral and central applications
- highly modular and flexibly adaptable to respective needs -

Do we have enough Sun?

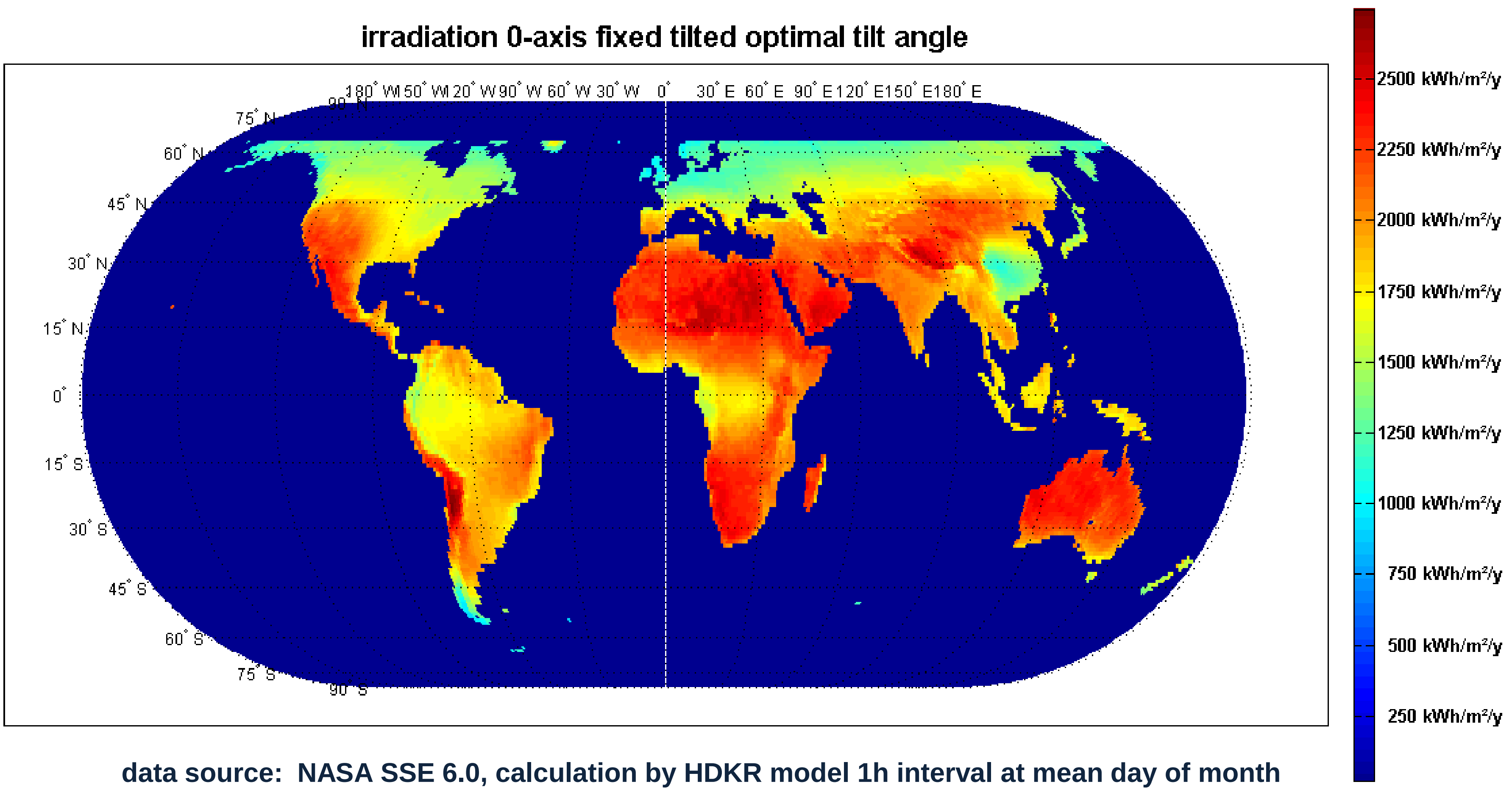


YES!

source:

BMWi, 2000

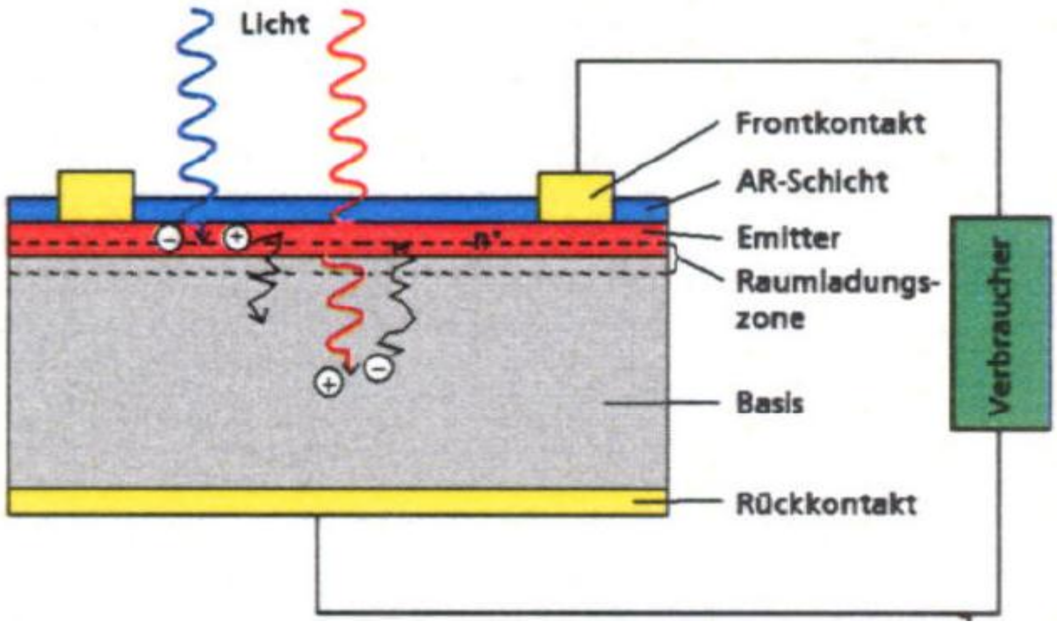
Solar Resource



data source: NASA SSE 6.0, calculation by HDKR model 1h interval at mean day of month for all months of the year

source: Breyer Ch. and Schmid J., 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 PVSEC/ WCPEC-5, Valencia, September 6–10

Do we understand a Solar Cell?
Photovoltaics: unique advantages

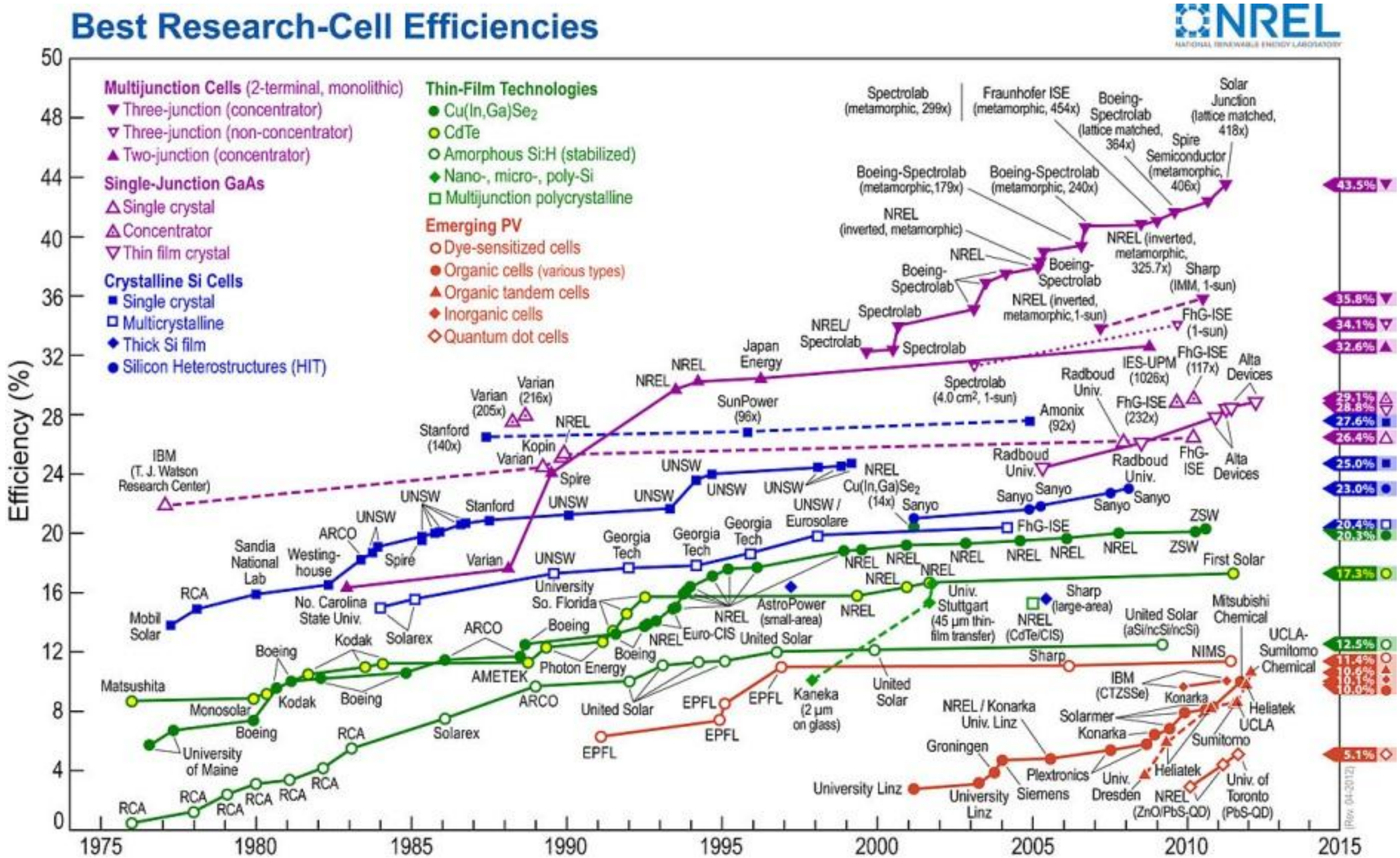


unique advantages

- no moving parts
- modularity
- direct convertion of solar radiation to electricity

source: Glunz, 2007

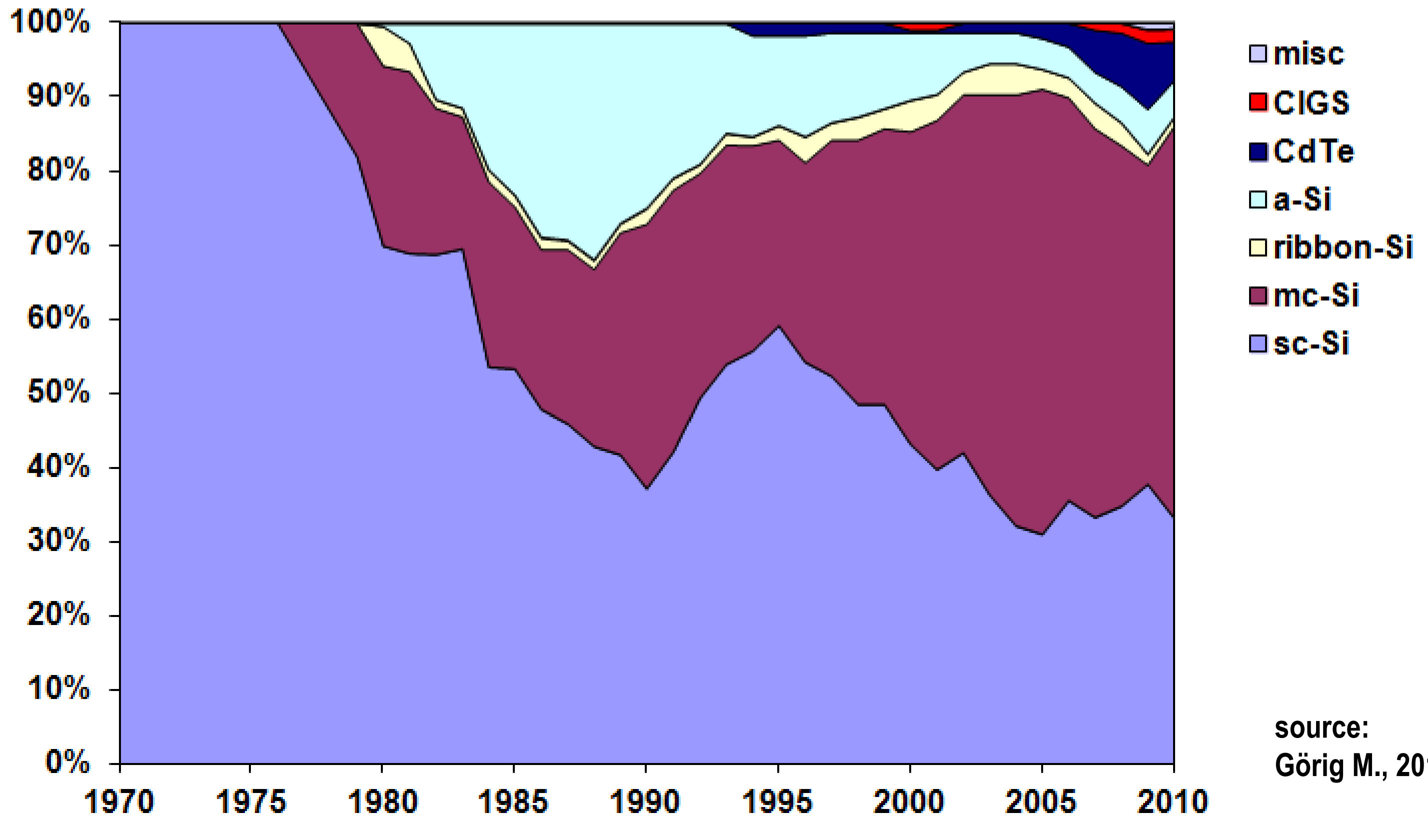
A short history of the solar cell efficiency



$$efficiency = \frac{generated\ electric\ power\ [W_{el}/m^2]}{incident\ radiative\ power\ [W_{rad}/m^2]}$$

Market Share of PV Technologies

ratio of PV technologies to total PV market



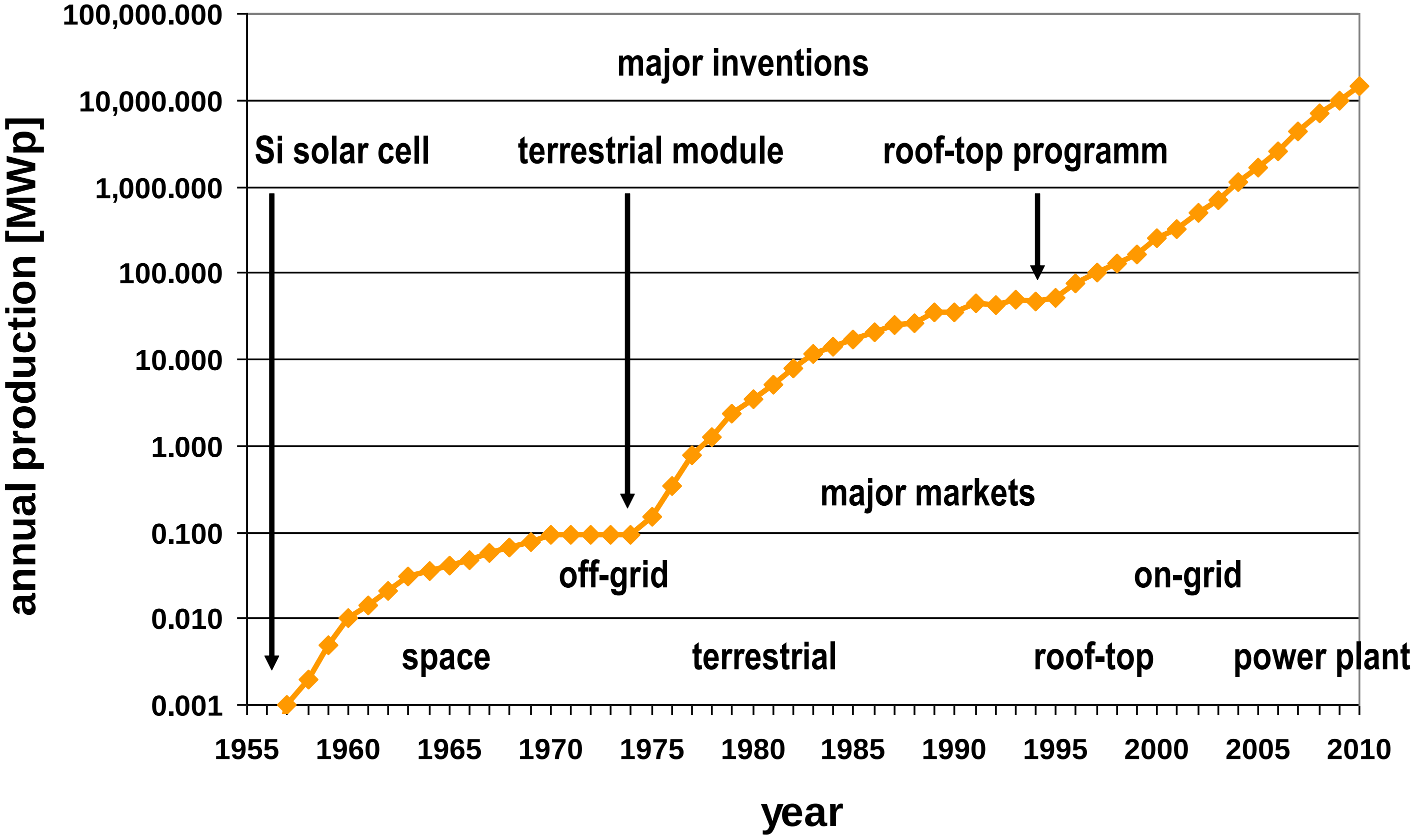
source:
Görig M., 2011. Bachelor Thesis

Physical limit of solar cell efficiency

N. cells	Description	Reflectors?	Optimum gaps (eV)				Eff (%)	records as of 2012
			E1	E2	E3	E4		
(Black body at 6000K)								
	1 sun, no angular restriction	Yes	1.31	–	–	–	31.0	25.0% sc-Si 1sun
1	1 sun no angular restiction	No	1.31	–	–	–	31.0	26.4% GaAs 1sun
	Maximum concentration	Yes	1.11	–	–	–	40.8	
	Maximum concentration	No	1.11	–	–	–	40.8	
	1 sun, no angular restriction	Yes	0.98	1.87	–	–	42.9	
2	1 sun no angular restiction	No	0.98	1.88	–	–	42.7	
	Maximum concentration	Yes	0.77	1.70	–	–	55.9	
	Maximum concentration	No	0.78	1.71	–	–	55.6	
	1 sun, no angular restriction	Yes	0.82	1.44	2.26	–	49.3	
3	1 sun no angular restiction	No	0.83	1.45	2.26	–	49.1	
	Maximum concentration	Yes	0.62	1.26	2.10	–	63.8	43.5% TJ 454suns
	Maximum concentration	No	0.63	1.27	2.11	–	63.5	
	1 sun, no angular restriction	Yes	0.72	1.21	1.77	2.55	53.3	
4	1 sun no angular restiction	No	0.73	1.23	1.78	2.56	53.0	
	Maximum concentration	Yes	0.52	1.03	1.61	2.41	68.8	
	Maximum concentration	No	0.53	1.05	1.68	2.41	68.4	
	1 sun, no angular restriction	Yes	–	–	–	–	69.9	
∞	1 sun no angular restiction	No	–	–	–	–	69.9	
	Maximum concentration	Yes	–	–	–	–	86.8	
	Maximum concentration	No	–	–	–	–	86.8	

source: Martini, 1996

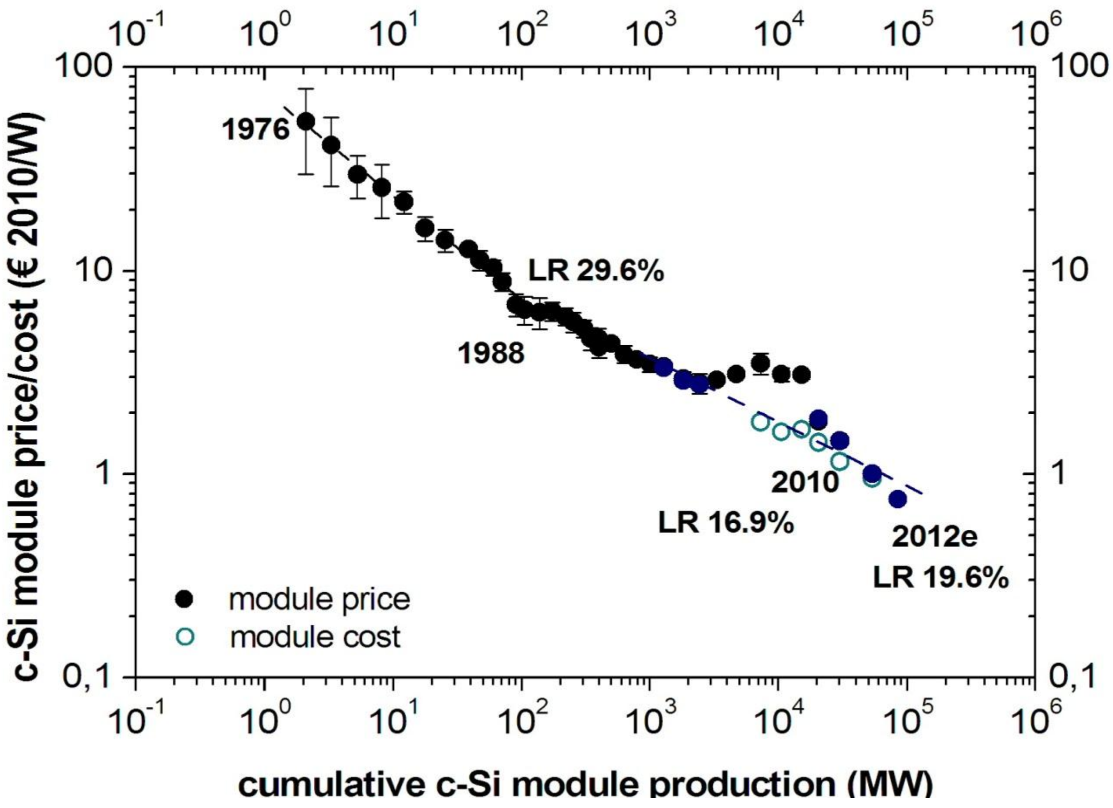
Historic PV Diffusion Phases



- constant high growth rates of >30% p.a. in all diffusion phases
- growth rate of 45% over last 15 years

source: Breyer Ch. et al., 2010. Research and Development Investments in PV – A limiting Factor for a fast PV Diffusion?, 25th EU PVSEC/ WCPEC-5, Valencia, September 6–10

PV Learning Rate: Stable over 50+ years



- learning rates in comparable industries
  - ~40% DRAMs (by getting smaller)
  - ~35% flat panels (by getting larger)
- typical learning rates in power sector
  - ~10% renewable power (wind, STEG)
  - negative nuclear power
- similar learning rates for PV inverter
- technology base for ongoing cost reduction is fast growing

PV „BACK ON TRACK“ ON 20% LEARNING CURVE

doubling of cumulated production volume

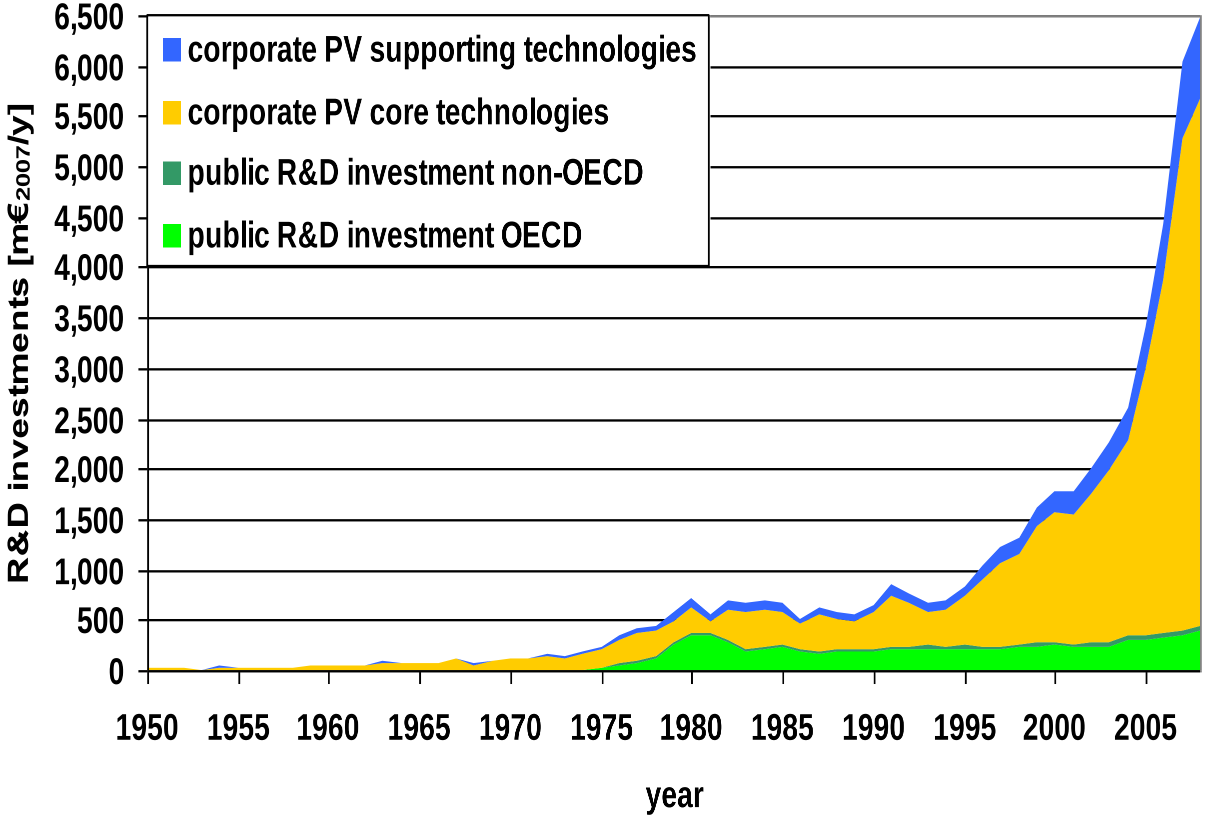
⬇

-20% price reduction

source: Kersten F., Görig M., Breyer Ch., et al., 2011. PV-Learning Curves: past and future drivers of cost reduction, 26th EU PVSEC, Hamburg, September 5–9

Breyer Ch., Kersten F., et al., 2010. Research and Development Investments in PV – A limiting Factor for a fast PV Diffusion?, 25th EU PVSEC/ WCPEC-5, Valencia, September 6–10

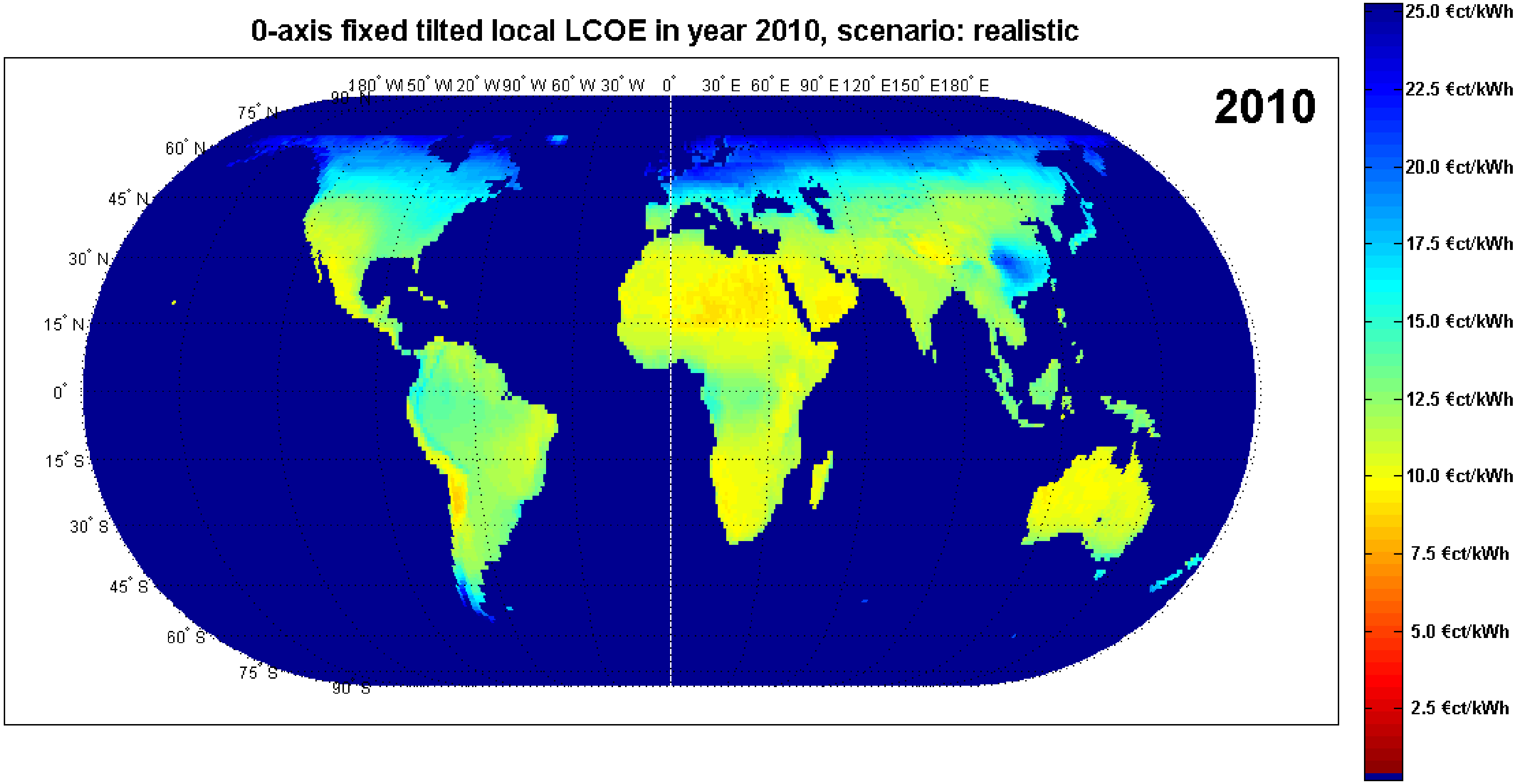
PV R&D Investments



source: Breyer Ch. et al., 2010. Research and Development Investments in PV – A limiting Factor for a fast PV Diffusion?, 25th EU PVSEC/ WCPEC-5, Valencia, September 6–10

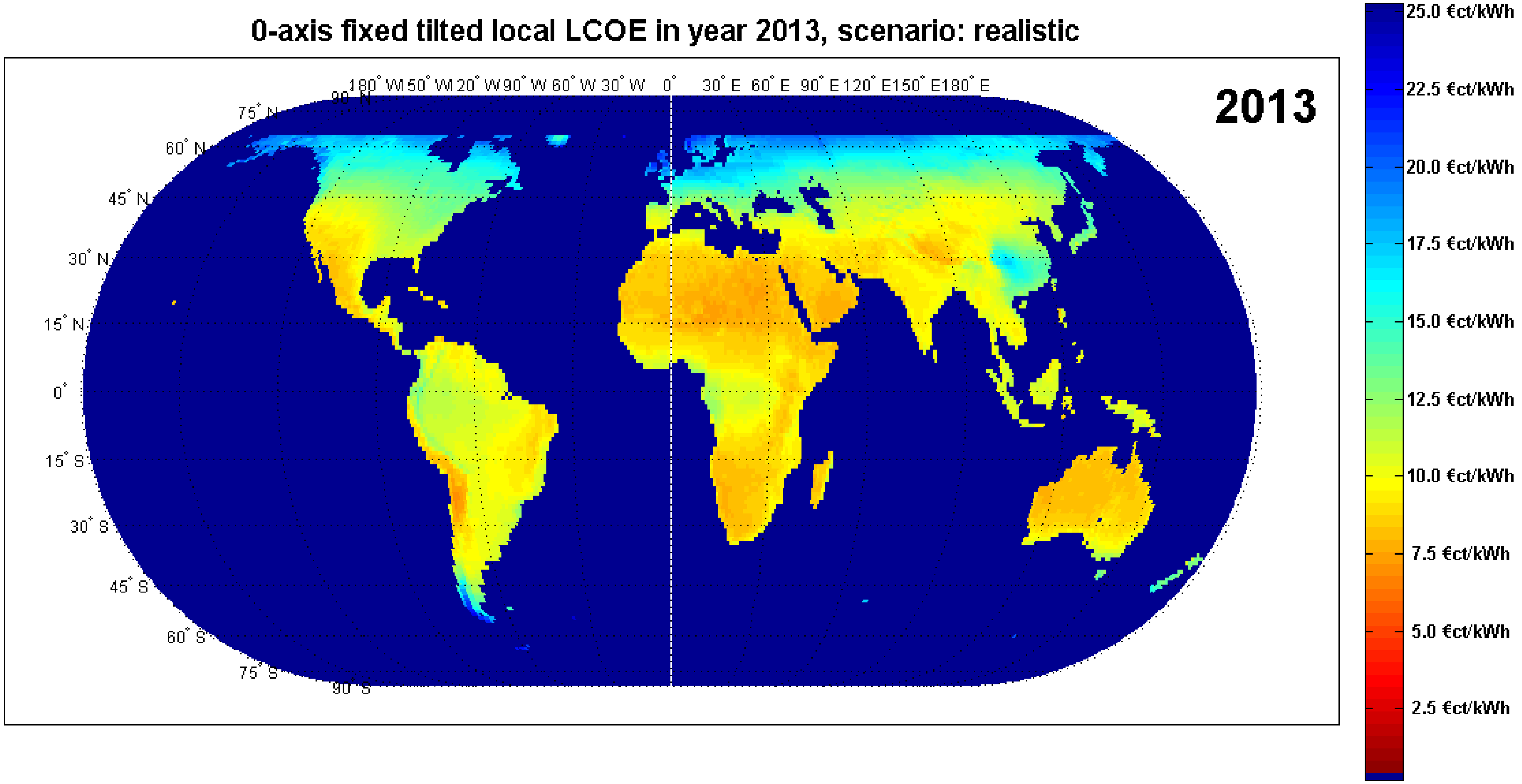
- global PV patent database used for estimate (years 1900 – 2008)
- PV market diffusion patterns are reflected in R&D investments
- bottom-up analysis of 100+ companies led to 3.1bn€ corporate R&D investments, at least
- 20% learning rate is likely to stay stable for the next 10 years, at least
- PV R&D is driven by companies to a large extend
- public R&D investments do not reflect PV potential (in OECD: nuclear energy is much higher funded than RES, efficicency, storage and grid together)
- global historic cumulated PV R&D investment is about 44-50 bn€ (less than 2% of nuclear)
- breakdown of public energy R&D investment reflect historic political failure in energy policy since early 1980s

PV Cost Dynamics



source: Breyer Ch. et al., 2010. Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, IEEE EnergyCon, Manama, December 18–22

PV Cost Dynamics



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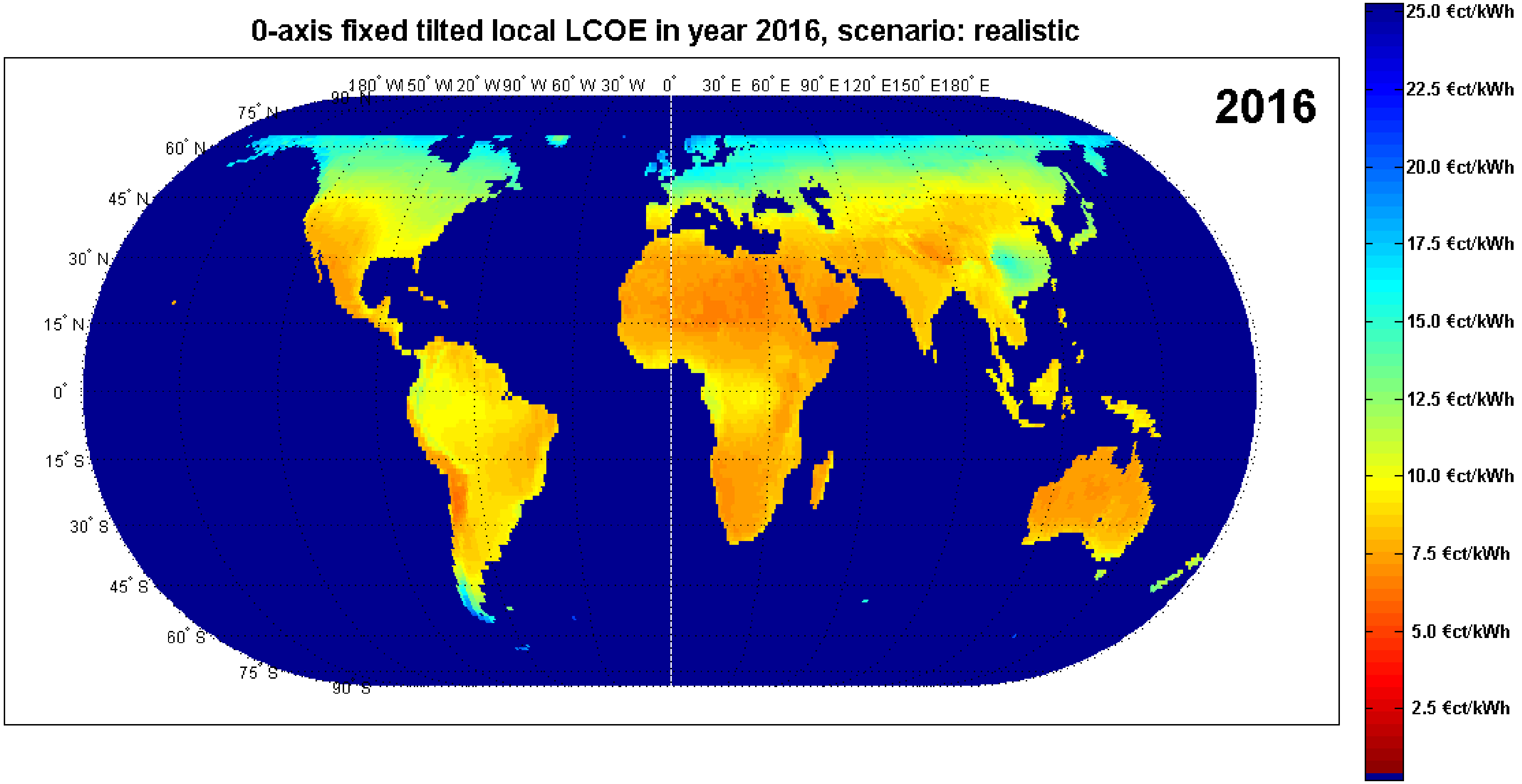

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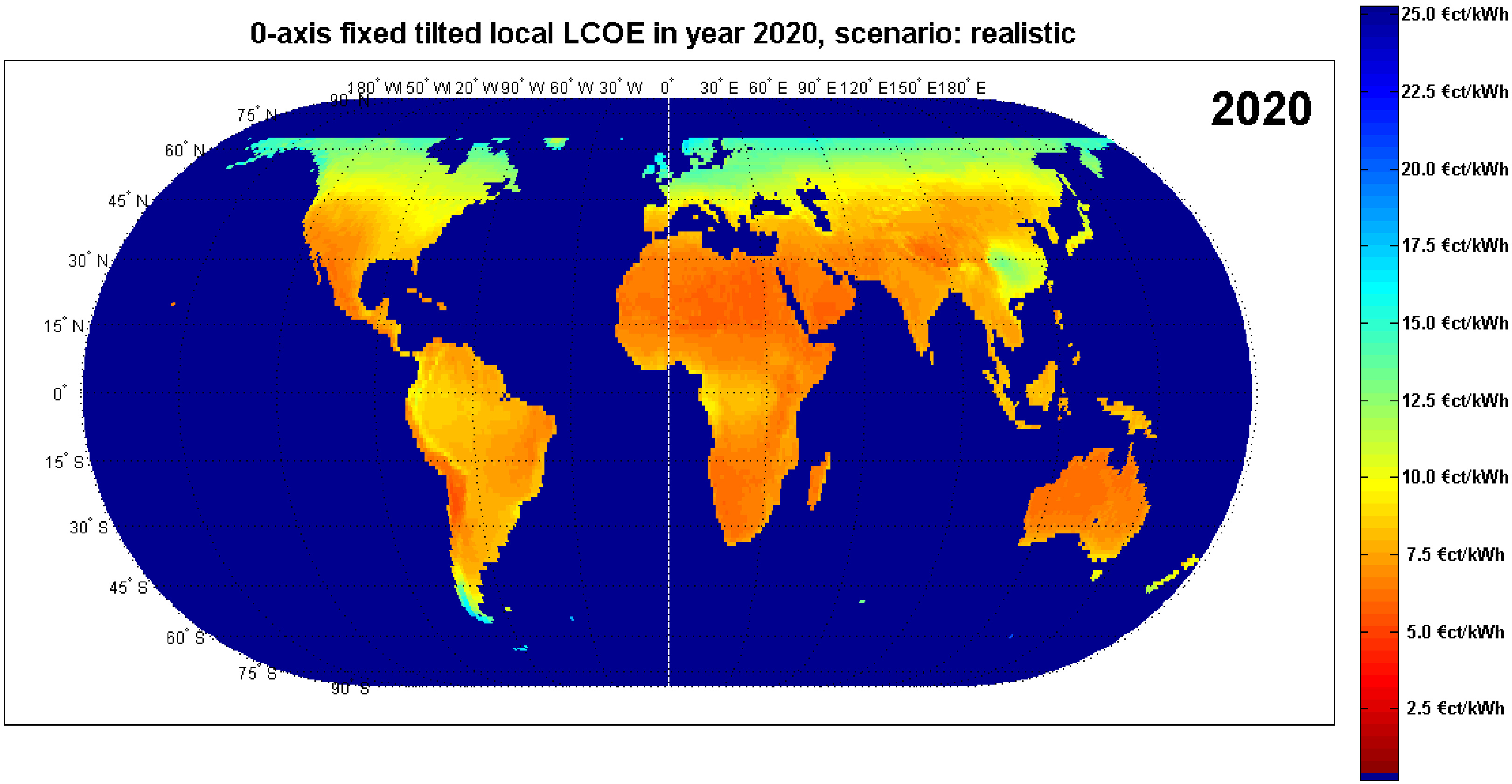

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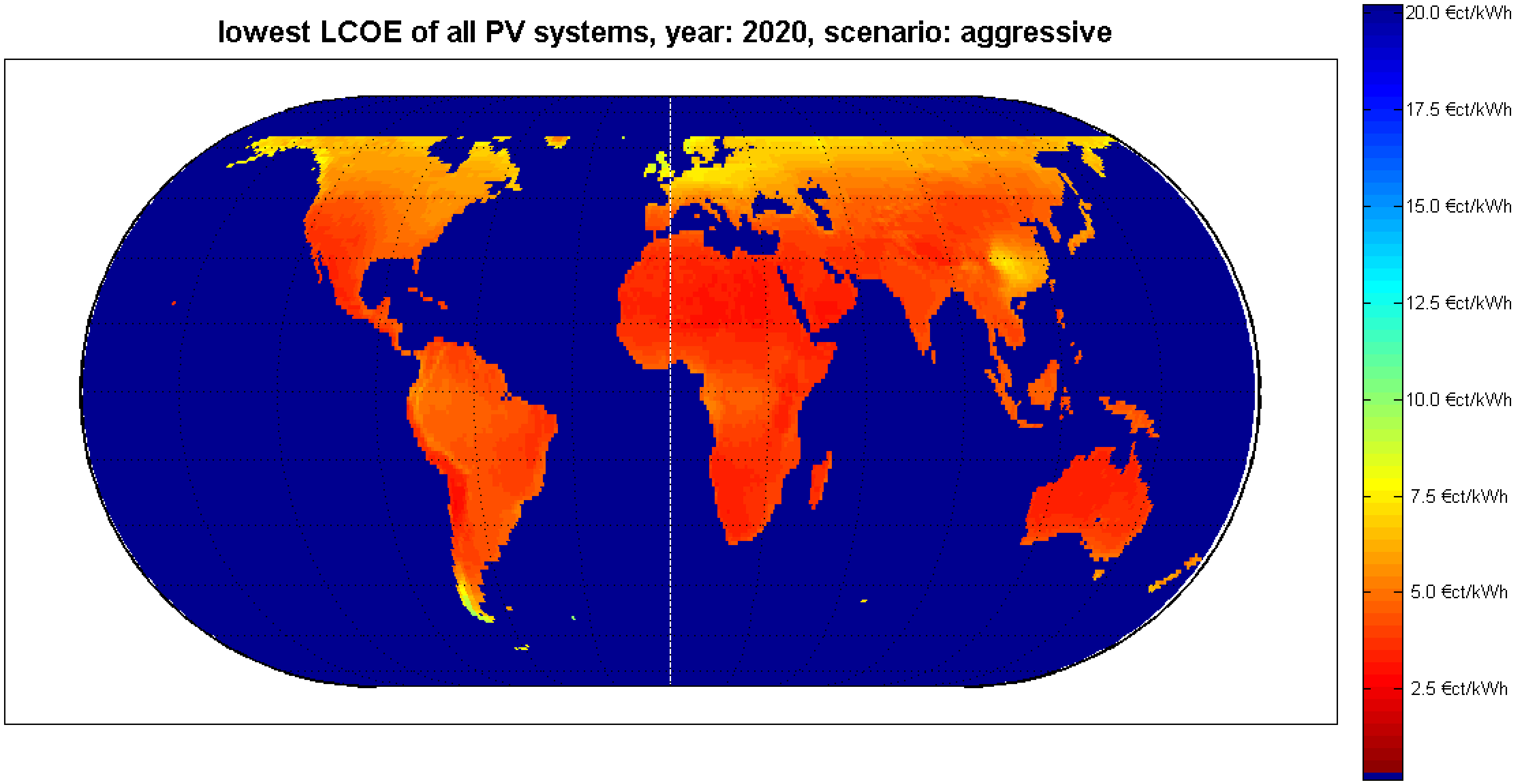
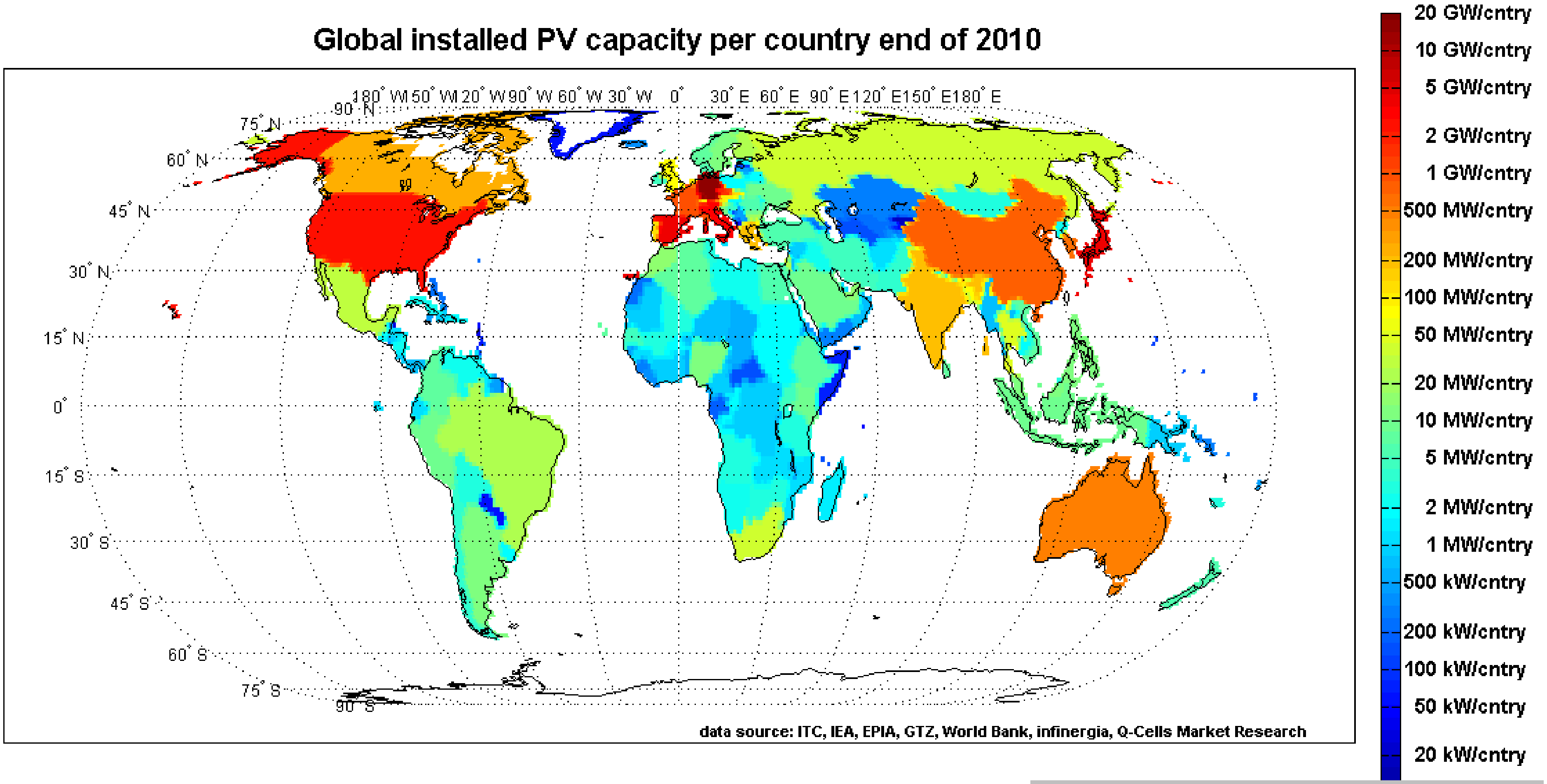
LCOE: global temporal dynamics



Global installed PV Capacity

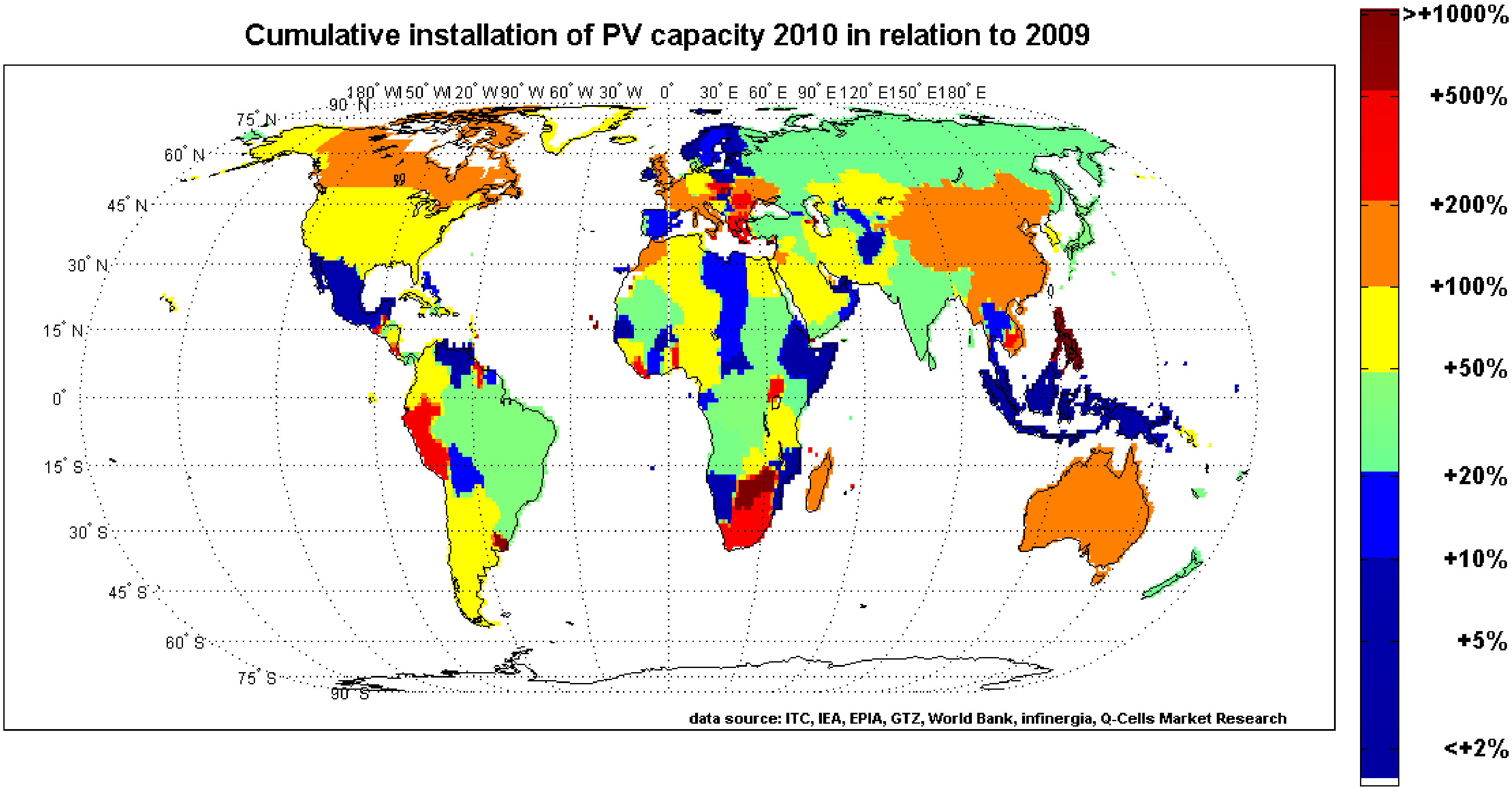
Global installed PV capacity per country end of 2010



source: Werner C., Breyer Ch., et al., 2011. Global Overview on cumulative installed Photovoltaic Power, 26th EU PVSEC, Hamburg, September 5-9

Germany in the lead by cumulated installations as of 2010

Global installed PV Capacity



source: Werner C., Breyer Ch., et al., 2011. Global Overview on cumulative installed Photovoltaic Power, 26th EU PVSEC, Hamburg, September 5-9

marjority of countries grew by more than 50% from 2009 to 2010

Global installed PV Capacity

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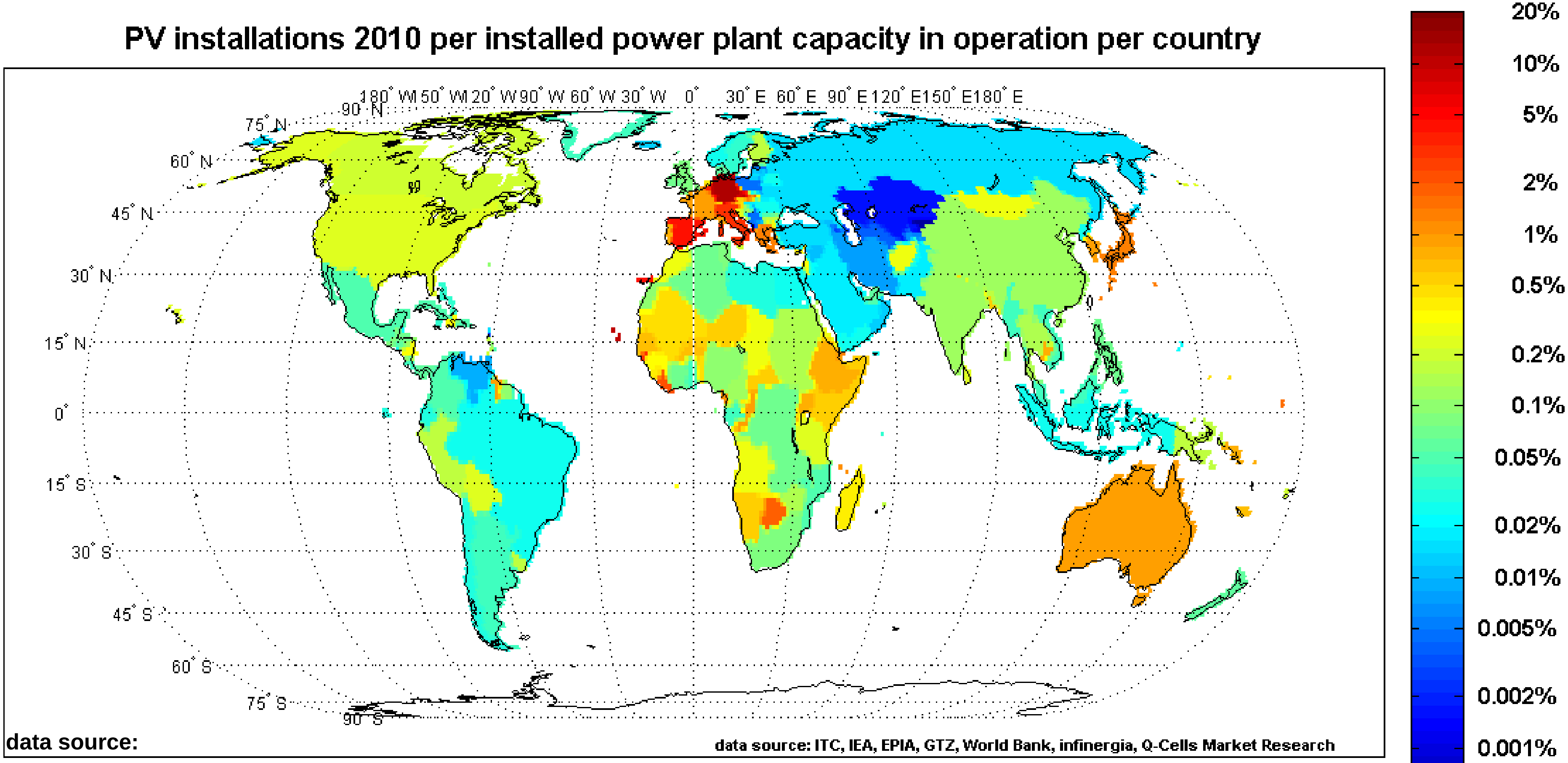
PV installations 2010 per installed power plant capacity in operation per country



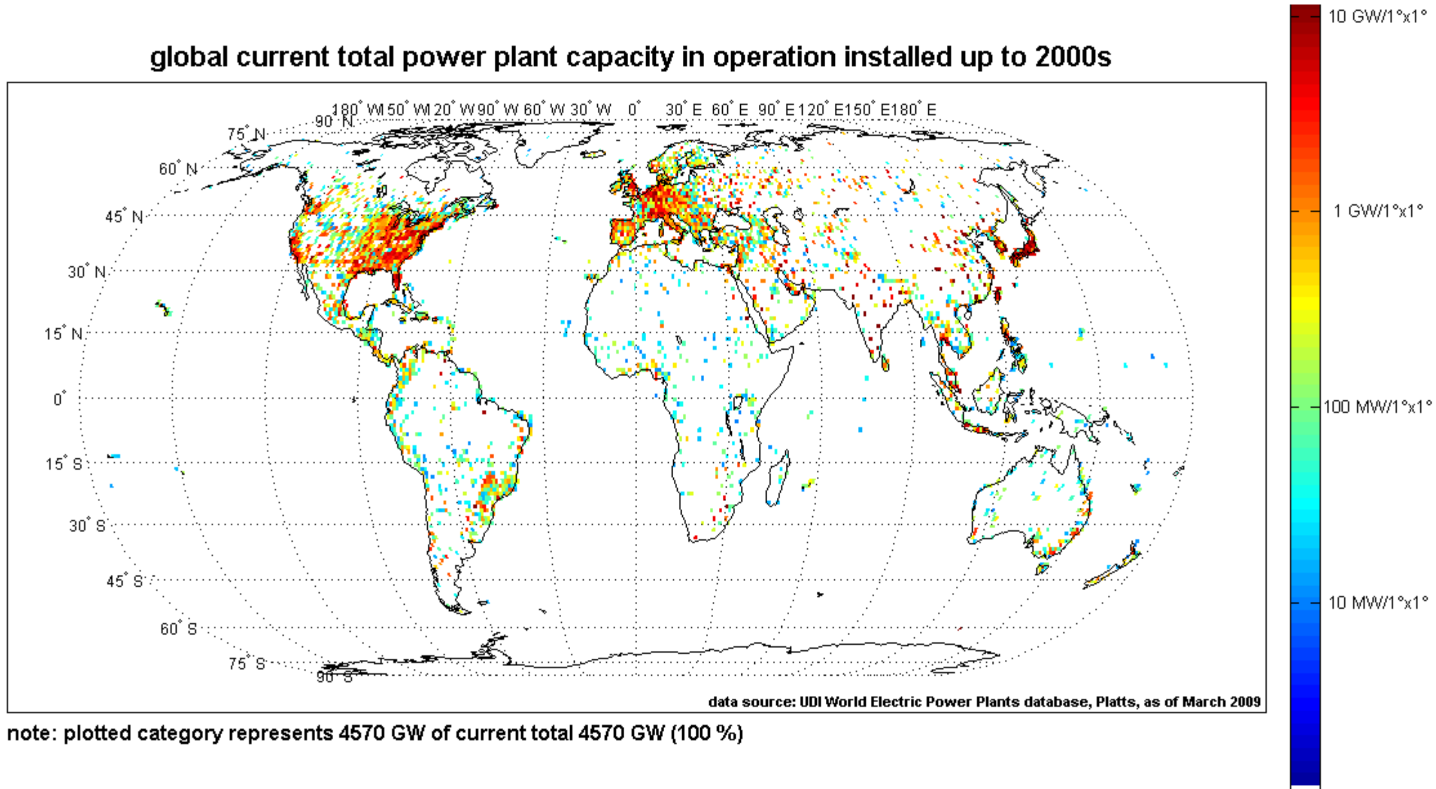
data source:

PV: Werner C., Breyer Ch., et al., 2011. Global Overview on cumulative installed Photovoltaic Power, 26th EU PVSEC, Hamburg, September 5-9

Conv.: UDI WEPP database, Platts

enormous market growth ahead, since ~50%+ of conventional power capacity base could be supplemented by PV (there is NO competition to wind power)

PV Potential and Power Plants of the World



Power plant capacity 2009: ~4,600 GW
Power plant capacity addings: ~150 GW/y
Electricity generation 2009: ~20,000 TWh

PV capacity total 2011: ~67 GW (~ 1.3% of capacity)
PV capacity addings 2011: ~27 GW (~ 18% of all conv. addings)
PV supply potential without storage ~10%: ~2,000 TWh
Electricity generation weighted fixed tilted irradiation: 1,700 kWh/m²/y
PV capacity potential at least: ~1,500 GW (@ 0.77 PR)

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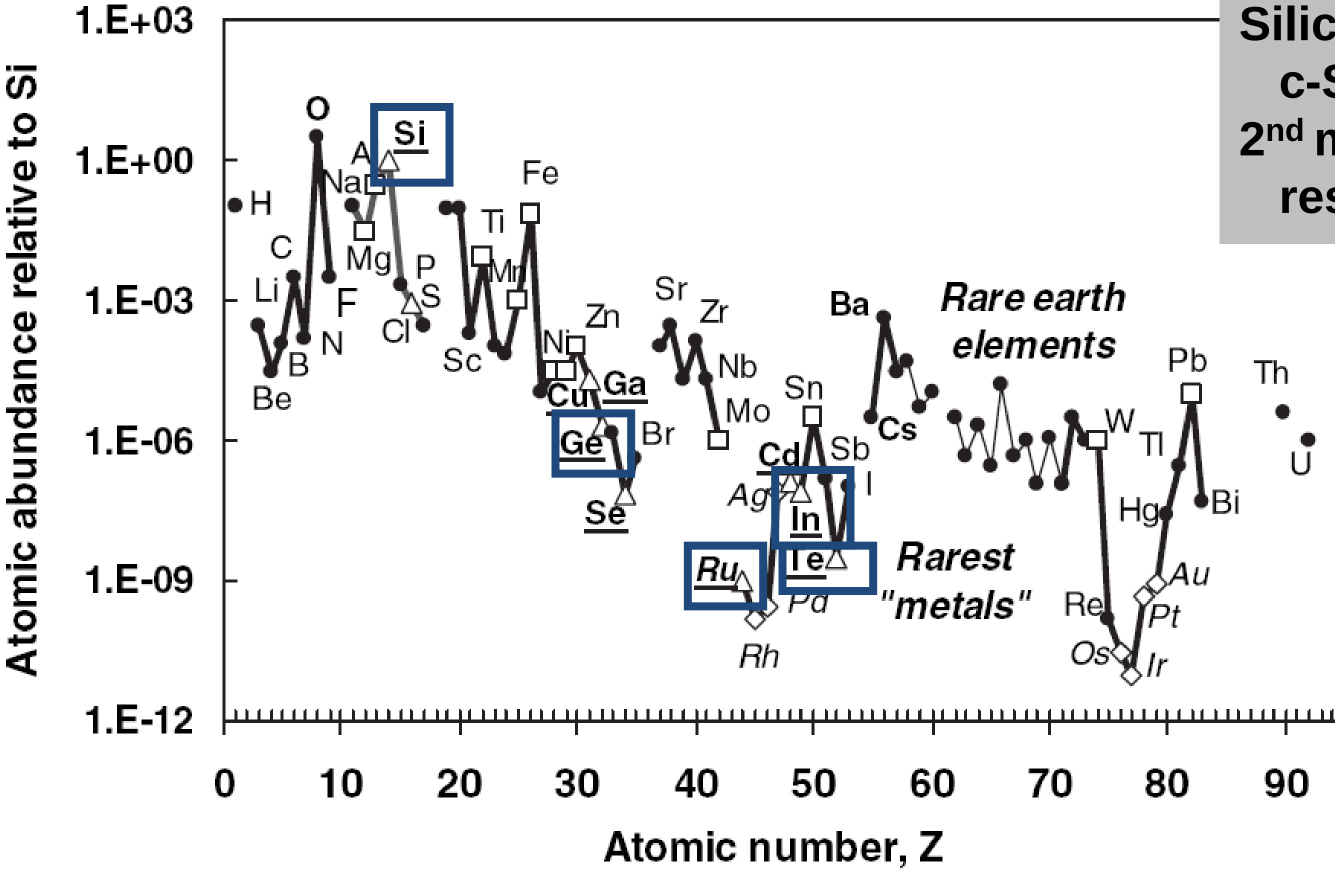
Availability of Active PV Materials



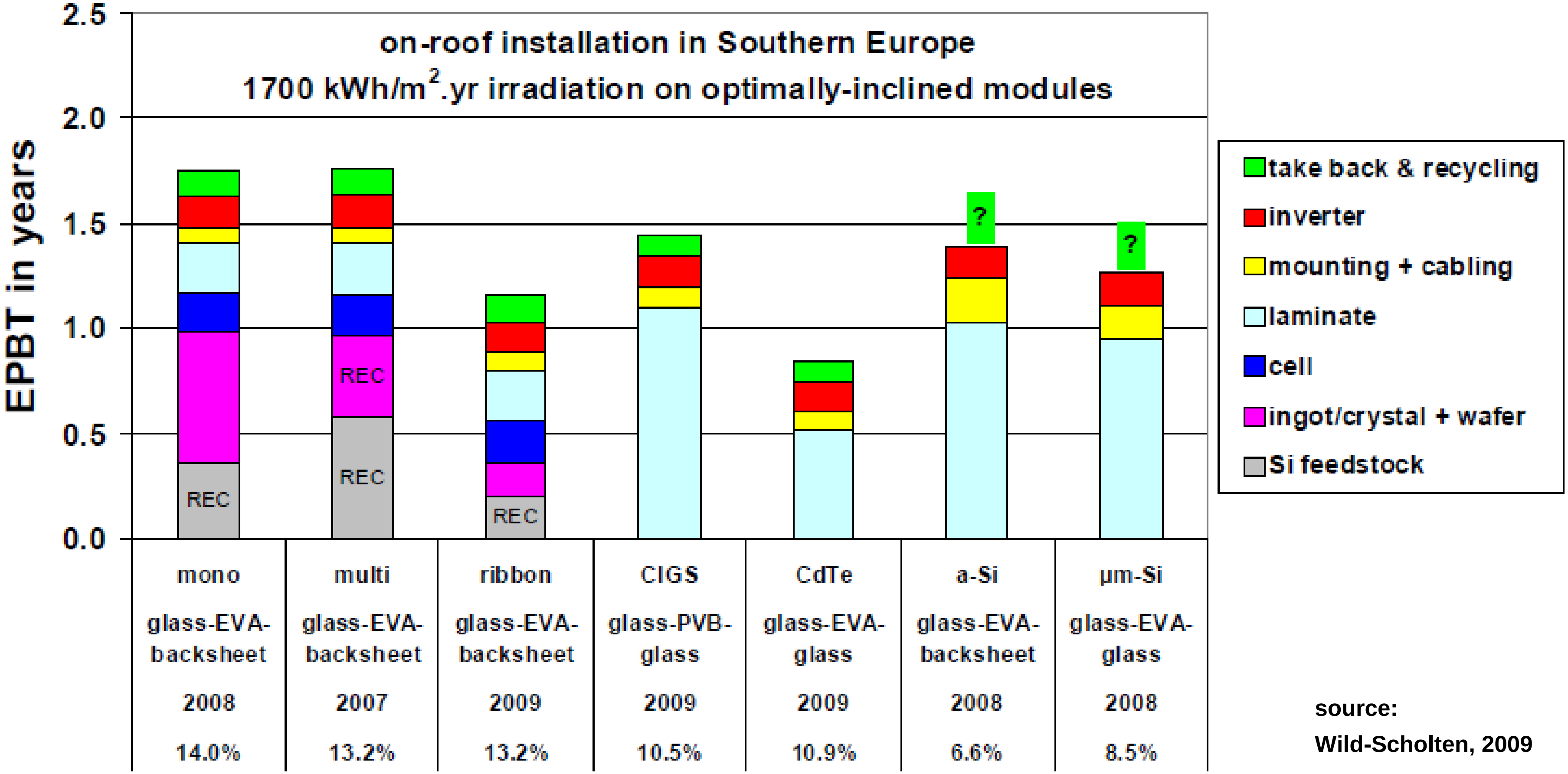
Silicon is basis for c-Si PV and glass
2nd most abundant resource on earth

source:
Green, 2006
Andersson, 2000
USGS, 1998

Te (CdTe):	**300 GWp/total*,**	**5 – 30 GWp/y****	(source: Cu/ Ni ores)
In (CIGS):	**90 GWp/total*,**	**7 – 70 GWp/y****	(source: Zn ores)
Ru (DSSC):	**6,000 GWp/total*,**	**11 – 20 GWp/y****	(source: platin-group)
Ge (a-Si/µc-Si):	**500 GWp/total*,**	**14 – 200 GWp/y****	(source: Zn ores)

* material reserves, 10% efficient modules
** annual production today and 2020 potential (efficiency, thickness, substitution, recovery, mining, extraction)

Energy Pay-Back Time



source:
Wild-Scholten, 2009

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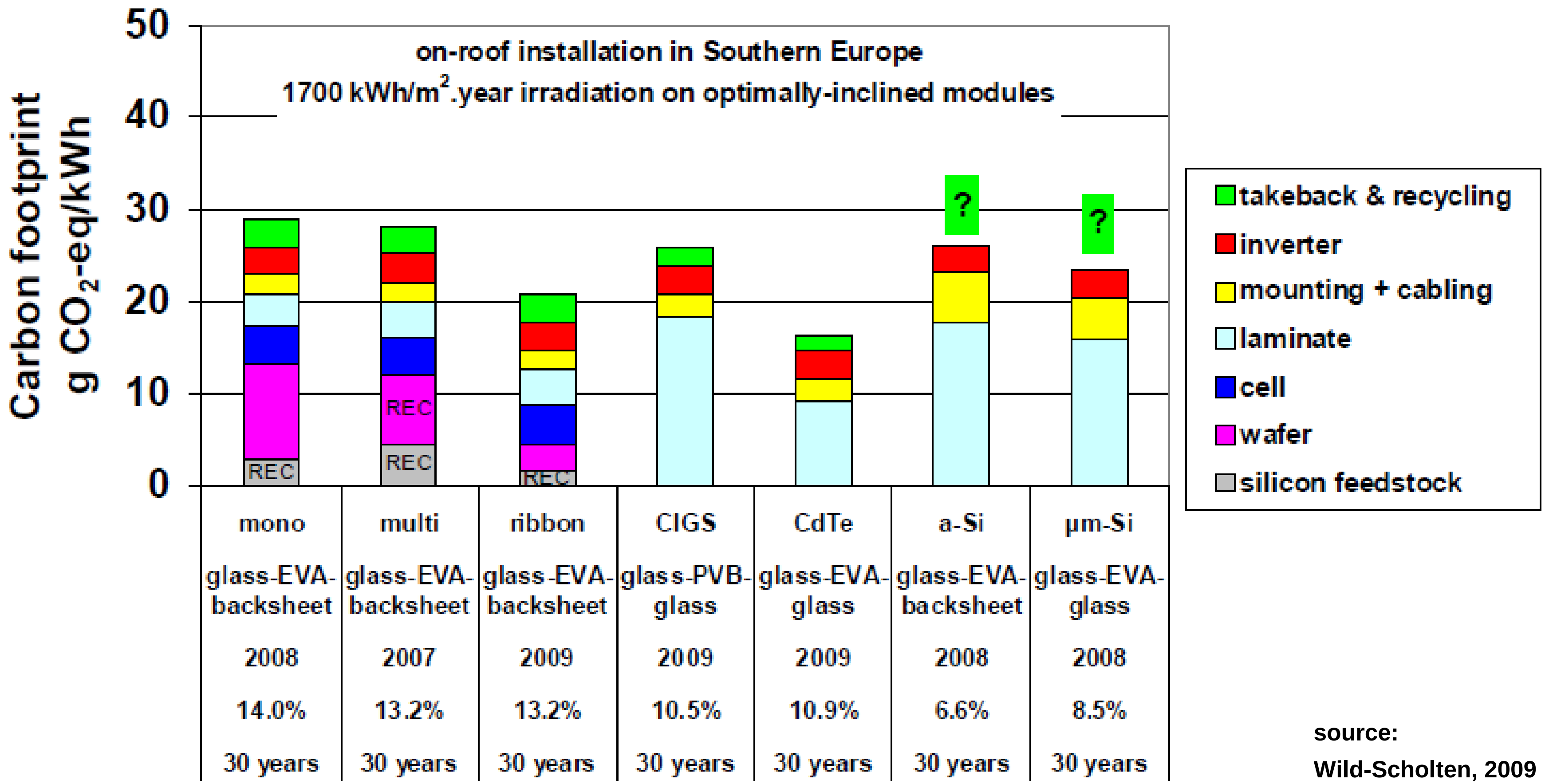
CO_2 Emissions

Carbon footprint PV = life-cycle CO_2-equivalent emissions



source:
Wild-Scholten, 2009

Energy Technologies - CO_2 Impact/ EPBT

Power technology	CO_2 emissions [g/kWh_{el}]	EROI
Hydro power	17 – 40	100:1
Wind power	7 – 24	20:1 – 50:1
Photovoltaic	12 – 42	16:1 – 51:1
Solar thermal power	22 – 33	50:1 – 70:1
Geothermal power	15 – 120	30:1 – 50:1
Biomass (Biogas)	120	n/a
Lignite coal power	1150 – 1210	not sustainable
Hard coal power	900 – 950	not sustainable
Clean coal with CCS	255 – 440	not sustainable
Natural gas power	400 – 760	not sustainable
Oil power	880	not sustainable
Nuclear power	66	not sustainable

source:

Breyer Ch., 2011. Economics of Hybrid Photovoltaic Power Plants, Dissertation, University of Kassel

Energy Return on Energy Investment (EROI)

$$EROI_{dynamic} = \frac{N}{EPBT} \cdot (1 - DR)^N$$

N = 30 y; EPBT = 0.8…1.7 y; DR = 0.3%/y

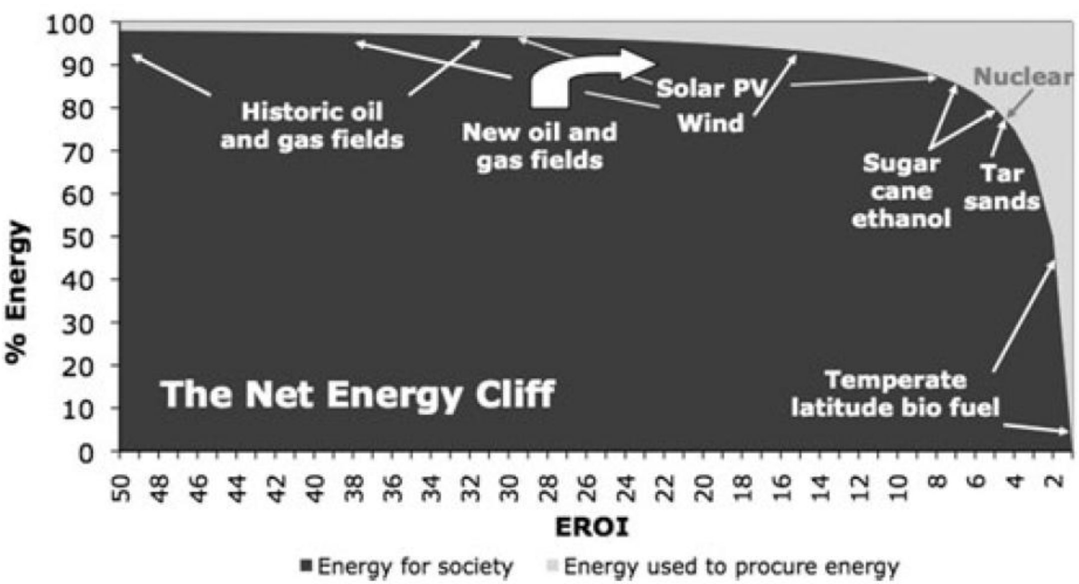
EROI = 16:1 – 33:1

$$N = \frac{\log(P_N / P_0)}{\log(1 - DR)}$$

P_N = 0.7; P_0 = 1; DR = 0.3…0.5%/y

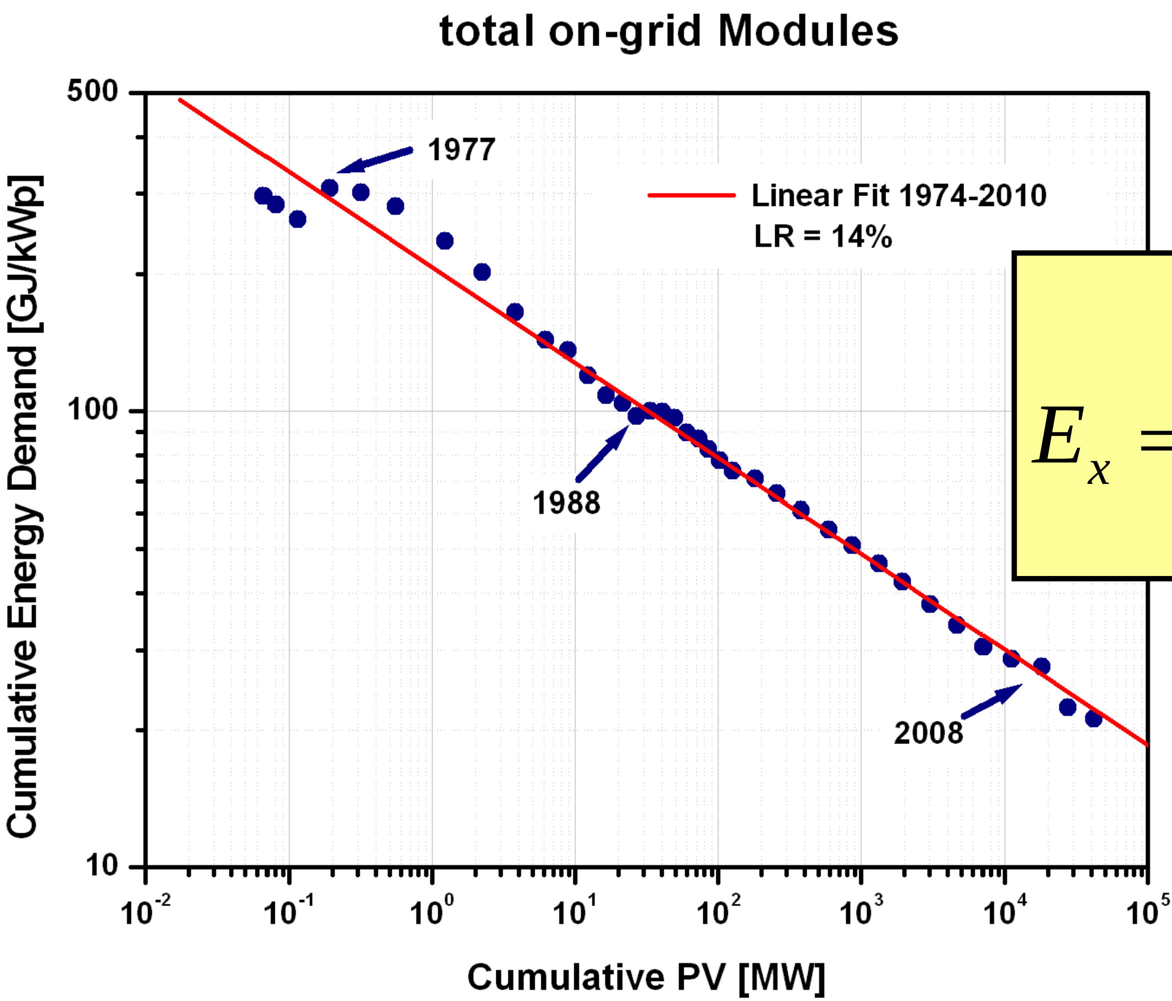
N = 70 – 120y !!!

N: system lifetime
EPBT: energy payback time
DR: system degradation rate p.a.
P_N: power of module in year N
P_0: power of module initally



source:
Murphy, 2010

Energetic Learning Curve



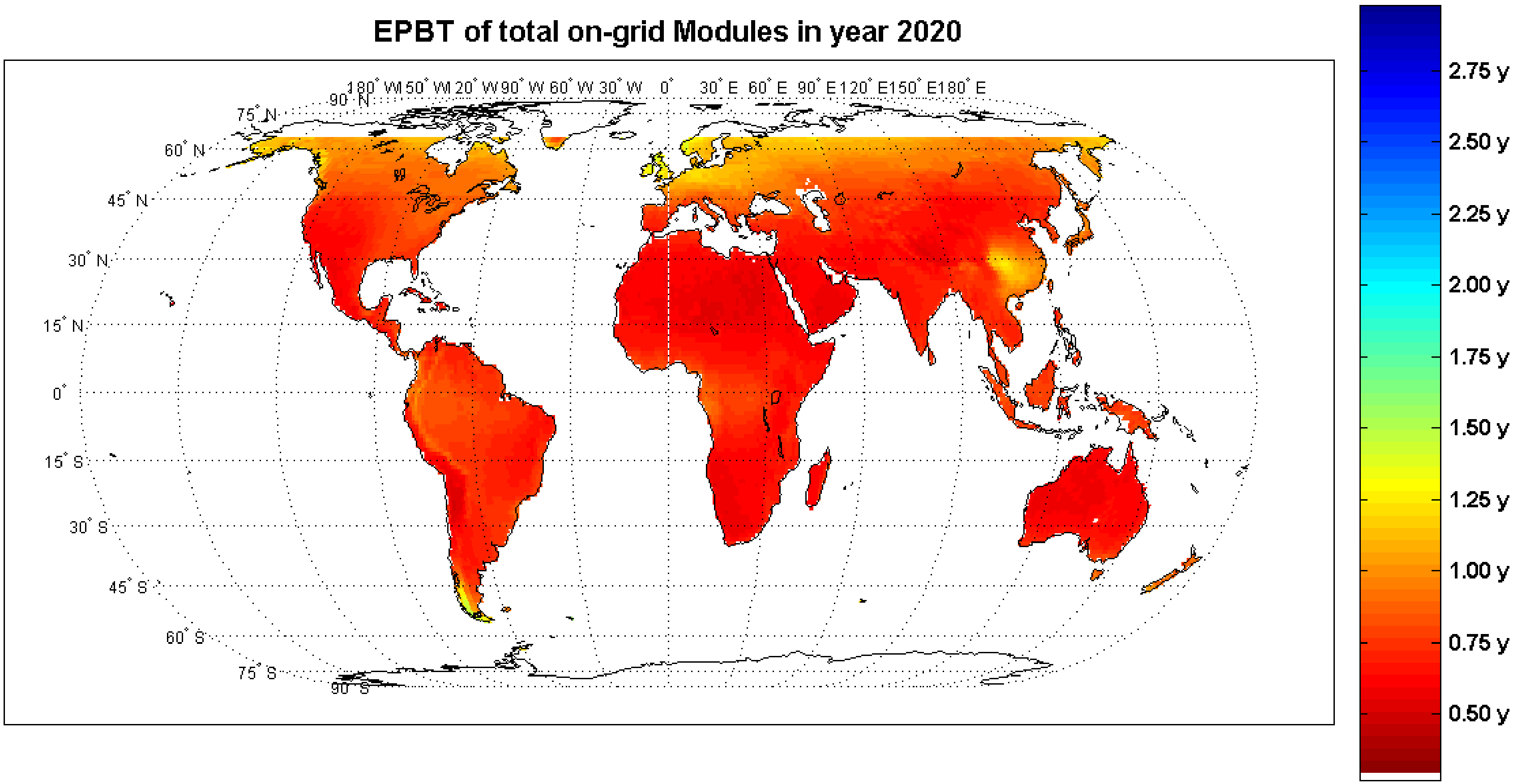
$$E_x = E_0 \cdot \left(\frac{P_x}{P_0} \right)^{\frac{\log(1-LR)}{\log 2}}$$

source:

Görig M. and Breyer Ch., 2012. Energy Learning Curves of PV Systems, 27th EU PVSEC, Frankfurt, September 24-28, accepted

Energetic Learning Curve: Projection of EPBT

EPBT of total on-grid Modules in year 2020



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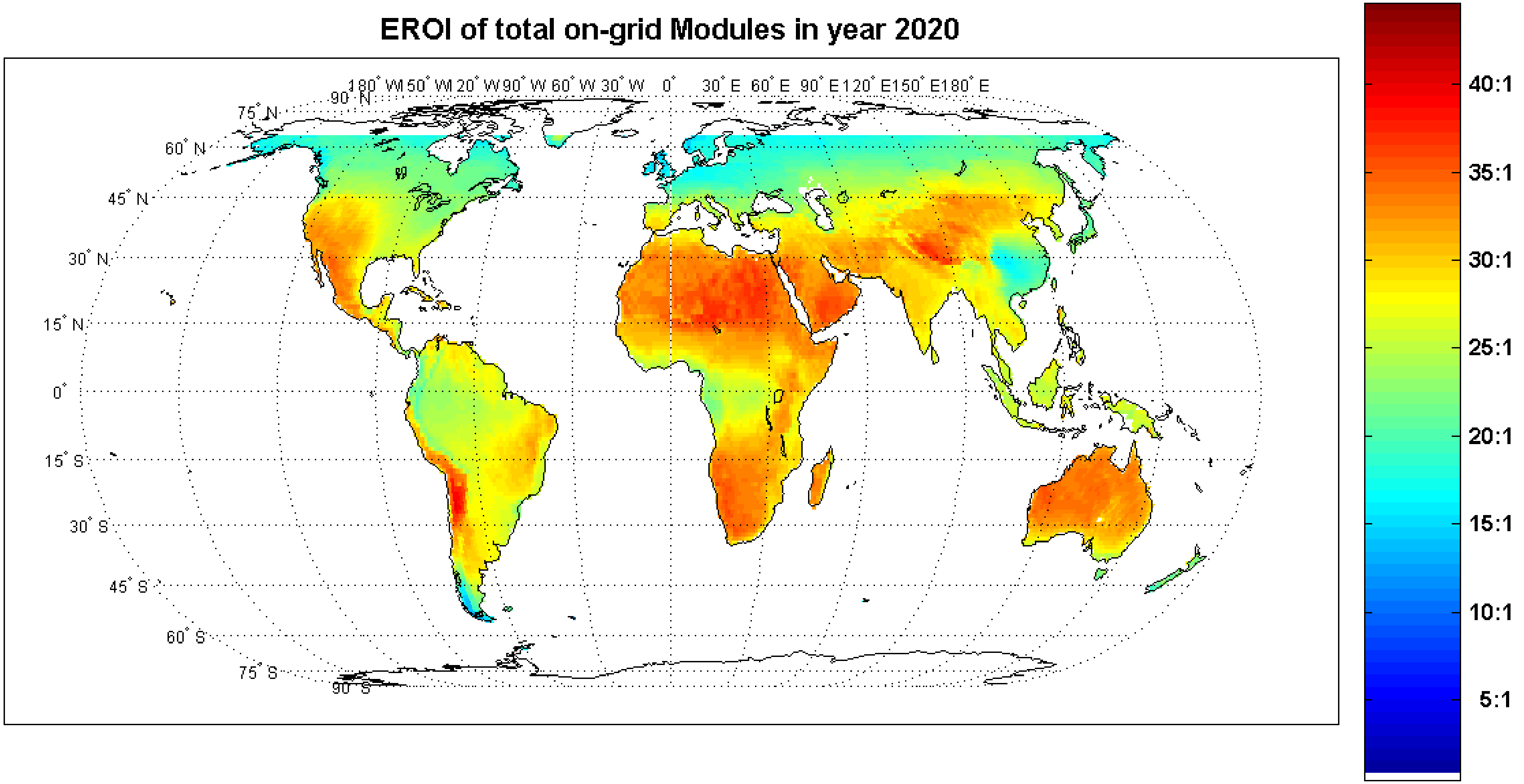
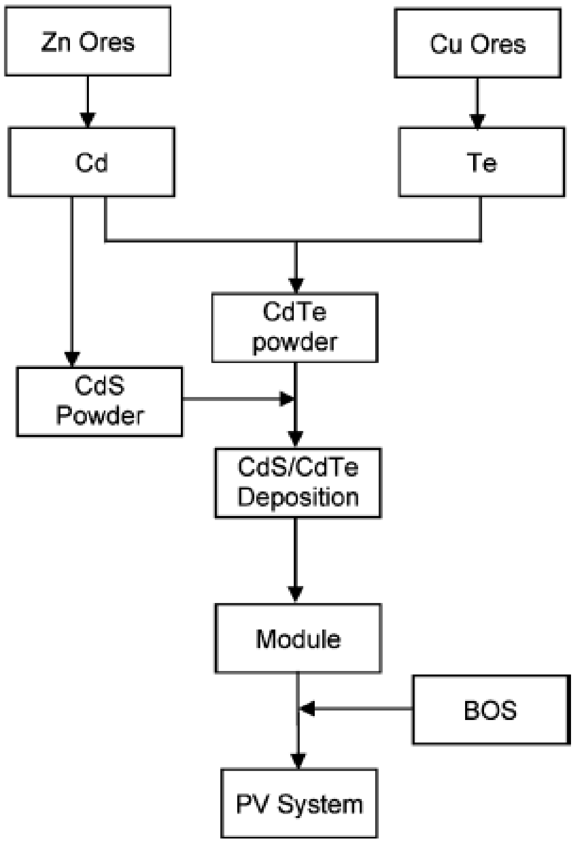
Energetic Learning Curve: Projection of EROI

EROI of total on-grid Modules in year 2020



source: Görig M. and Breyer Ch., 2012. Energy Learning Curves of PV Systems, 27th EU PVSEC, Frankfurt, September 24-28, accepted

Cadmium emissions and CdTe PV



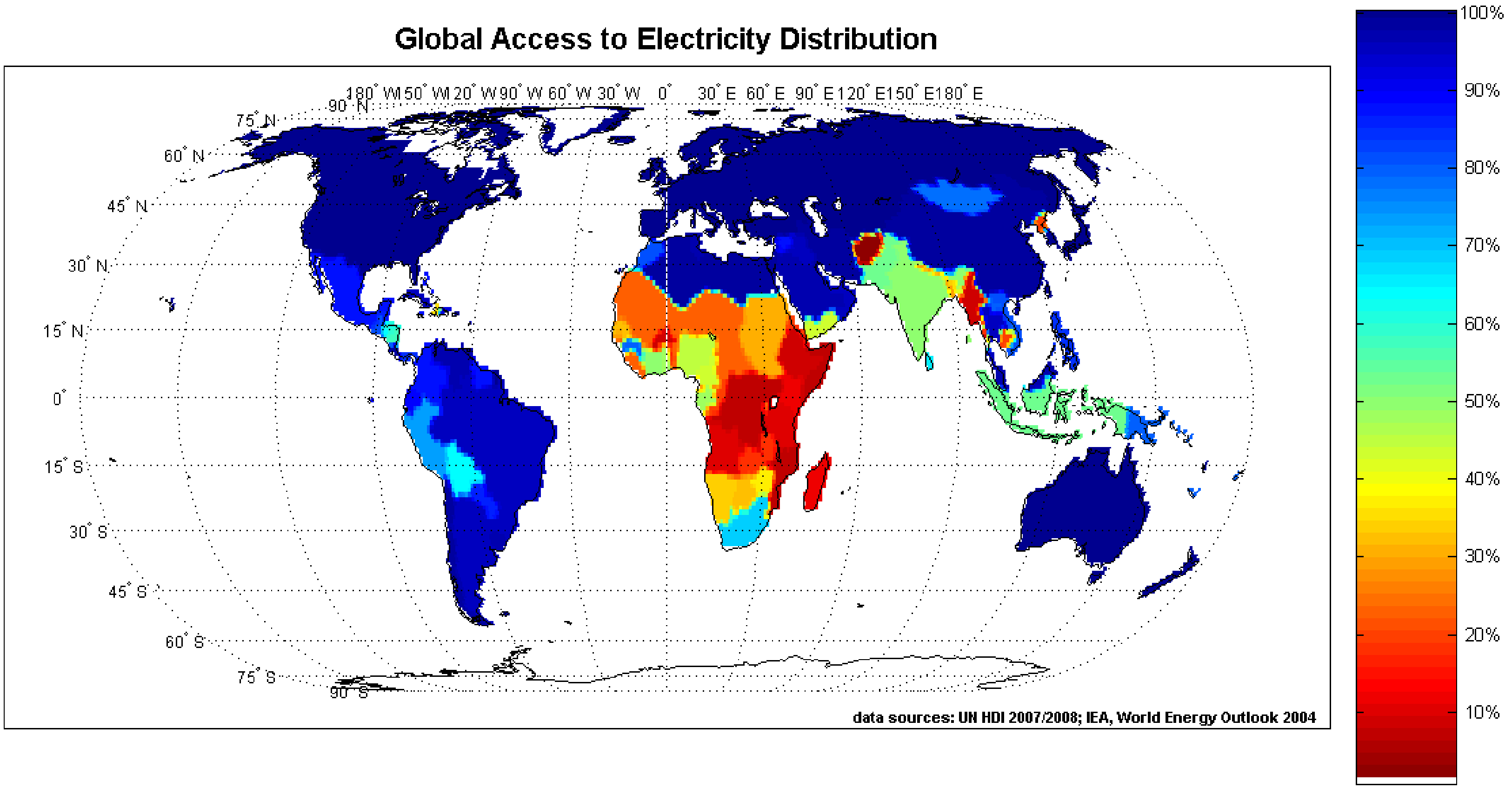
Air emissions	Emission reduction	Unit	Percentage
GHG	450	tonne CO_2-eq.	96
NO_x	0.8	tonne	95
SO_x	2	tonne	96
Arsenic	16	g	94
Cadmium	4	g	93
Chromium	17	g	89
Lead	50	g	93
Mercury	11	g	97
Nickel	240	g	97
Thorium-230	7	kBq	98
Uranium-238	34	kBq	98

Pollution prevented by using CdTe PV systems for each GWh of electricity generated compared with the UCTE grid mixture, 1,700 kWh/m²/y, PR 0.8, lifetime 30 y

source: Fthenakis, 2008

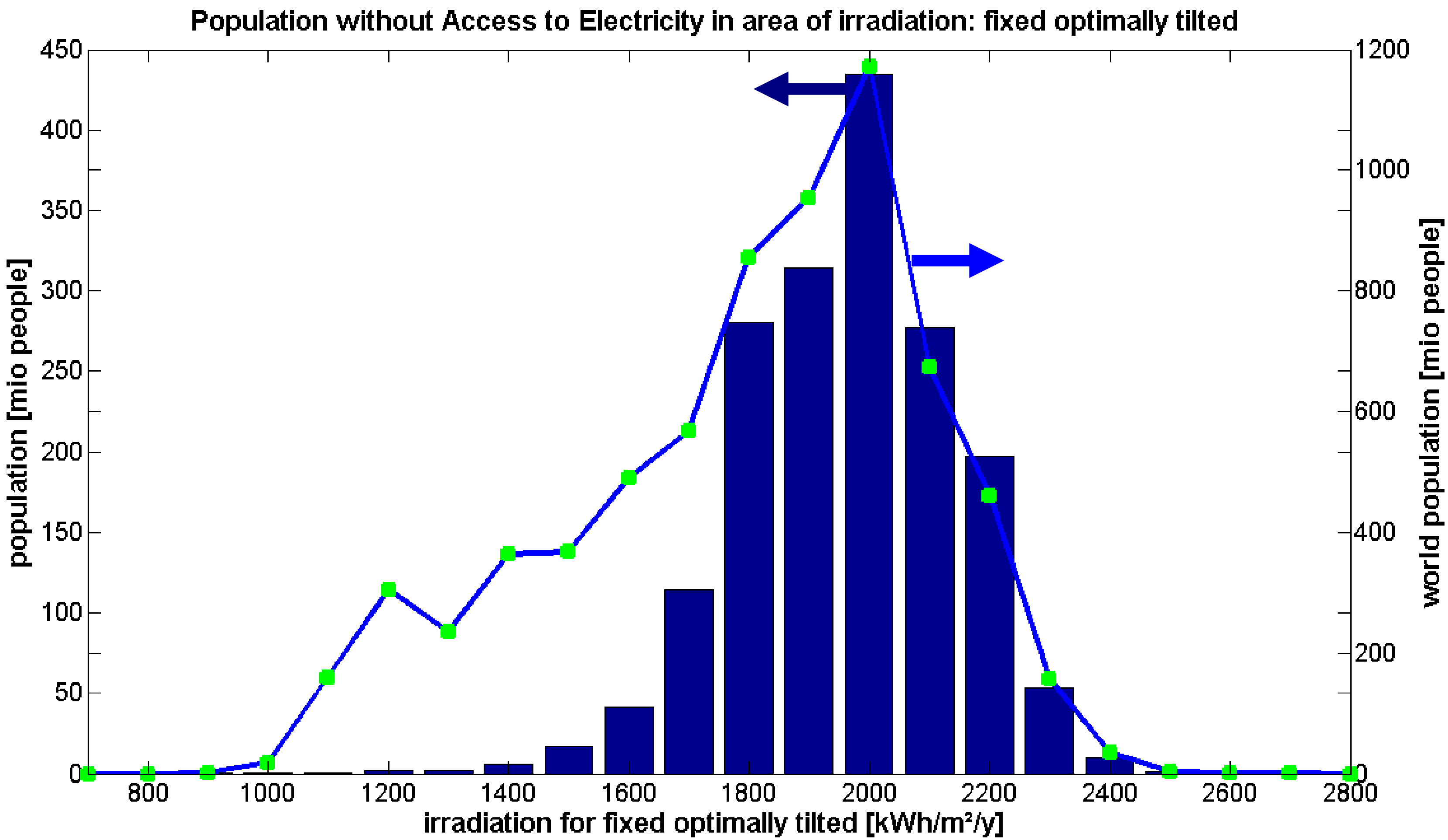
Outline

1.4 billion People without Access to Electricity



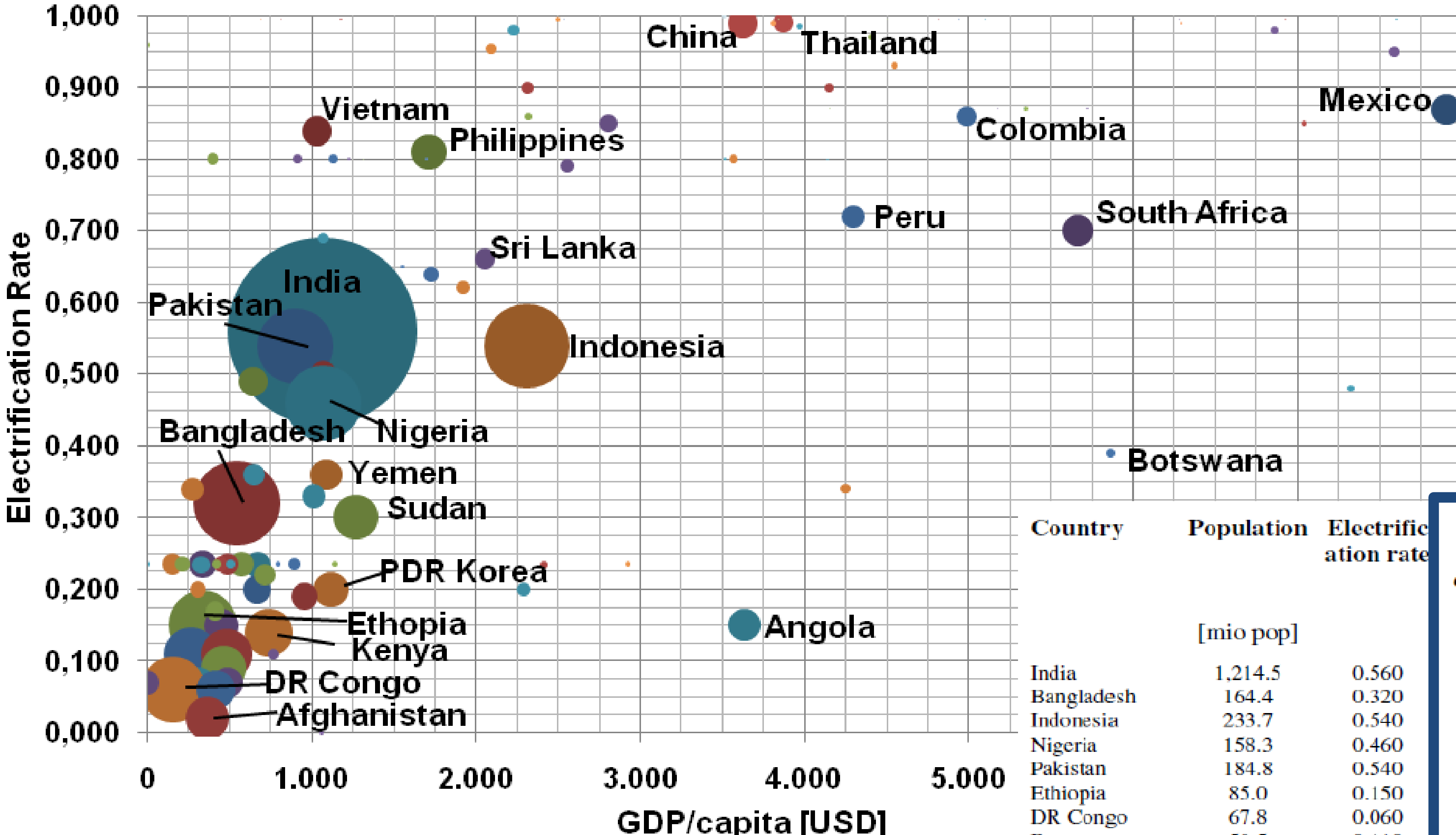
source: Breyer Ch., Werner C., et al., 2011. Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

No Electricity Access and Irradiation



source: Breyer Ch., Werner C., et al., 2011. Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

Electrification and Povertry



Country	Population [mio pop]	Electrification rate	People without electricity [mio pop]	GDP/capita [USD]	population weighted irradiation optimally tilted [kWh/m²/y]
India	1,214.5	0.560	534.4	1,070	2,032
Bangladesh	164.4	0.320	111.8	540	1,908
Indonesia	233.7	0.540	107.5	2,310	1,809
Nigeria	158.3	0.460	85.5	1,070	1,978
Pakistan	184.8	0.540	85.0	900	2,135
Ethiopia	85.0	0.150	72.2	340	2,205
DR Congo	67.8	0.060	63.8	160	1,848
Burma	50.5	0.110	44.9	270	1,939
Tanzania	45.0	0.110	40.1	480	2,043
Kenya	40.9	0.140	35.1	740	2,124
Uganda	33.8	0.090	30.8	460	1,980
Sudan	43.2	0.300	30.2	1,260	2,271
Afghanistan	29.1	0.020	28.5	360	2,164
Mozambique	23.4	0.060	22.0	410	2,026
Nepal	29.9	0.330	20.0	420	2,176
PDR Korea	24.0	0.200	19.2	1,110	1,874
Philippines	93.6	0.810	17.8	1,710	1,842
Madagascar	20.1	0.150	17.1	450	2,091
Angola	19.0	0.150	16.1	3,630	2,084
Yemen	24.3	0.360	15.5	1,080	2,295
South Africa	50.5	0.700	15.1	5,660	2,166

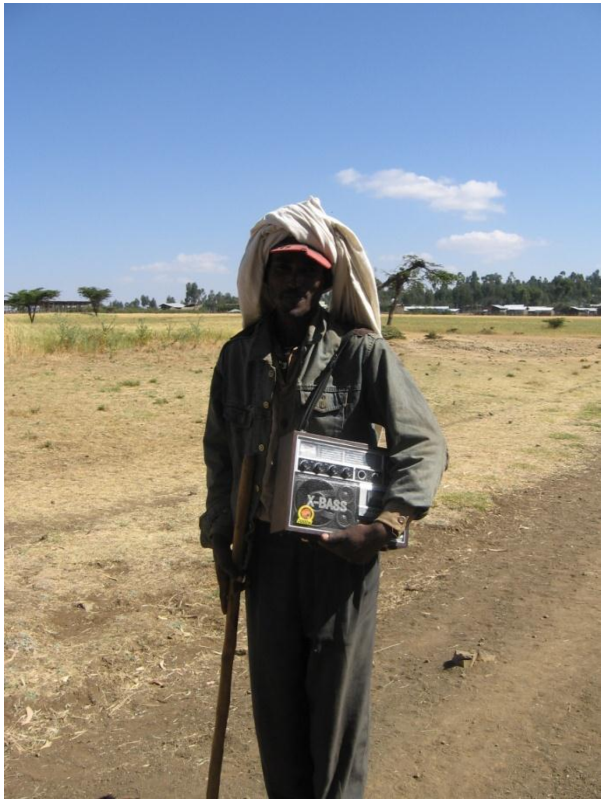
source:

Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

Conventional Energy Use in Rural Areas

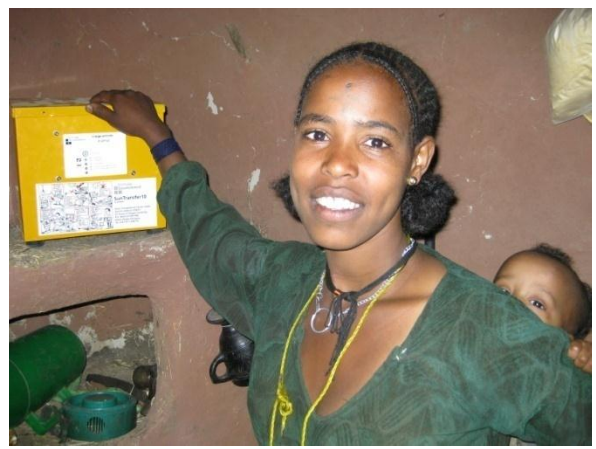
Light

Music



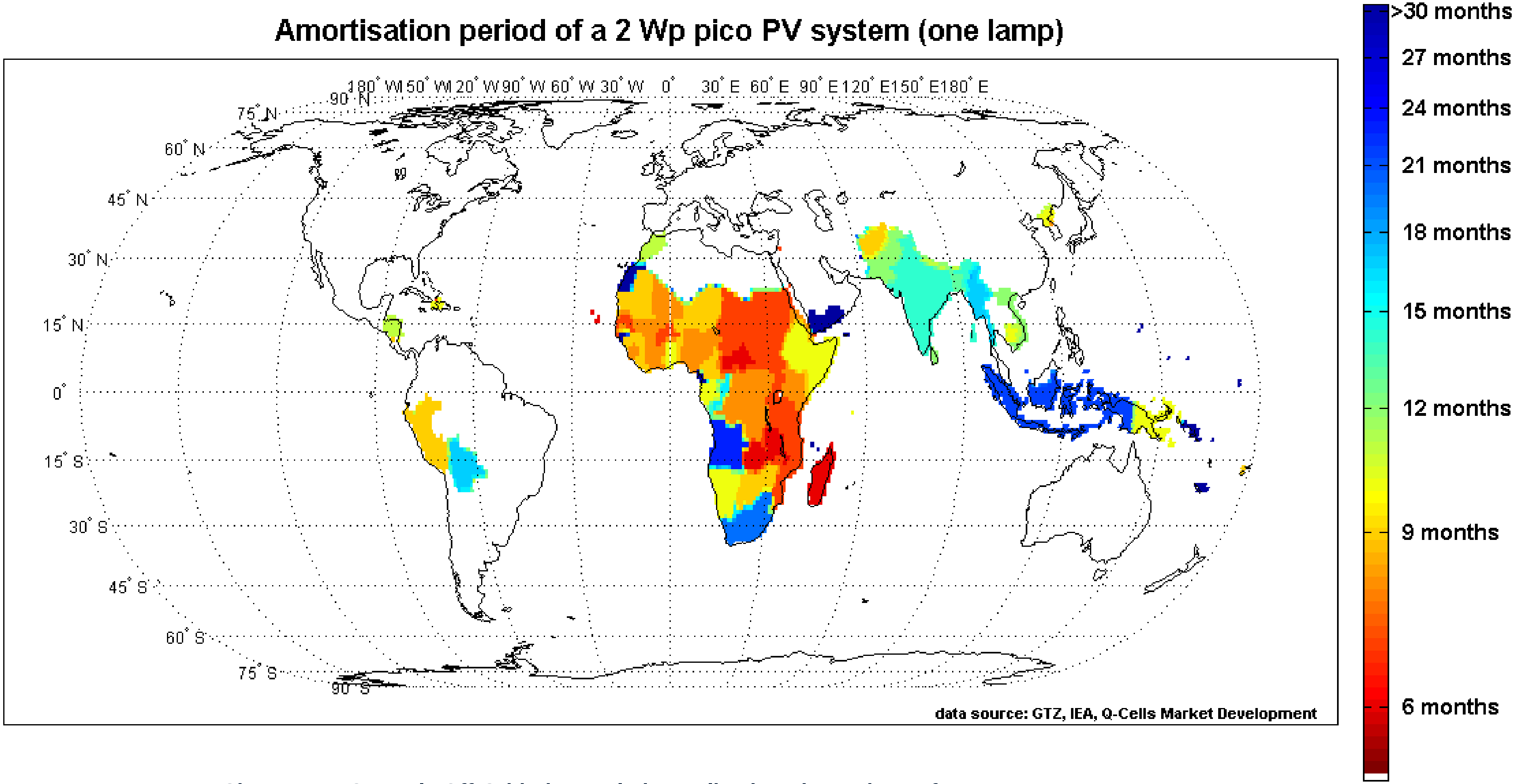
source: Breyer Ch. et al, 2009. Electrifying the Poor: Highly Economic Off-Grid PV Systems in Ethiopia, 24th EU PVSEC, Hamburg

Solar Home System (SHS) in Ethiopia



source: Breyer Ch. et al., 2009. Electrifying the Poor: Highly Economic Off-Grid PV Systems in Ethiopia, 24th EU PVSEC, Hamburg

SHS: Perfect Solution for the Poor



source: **Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC**

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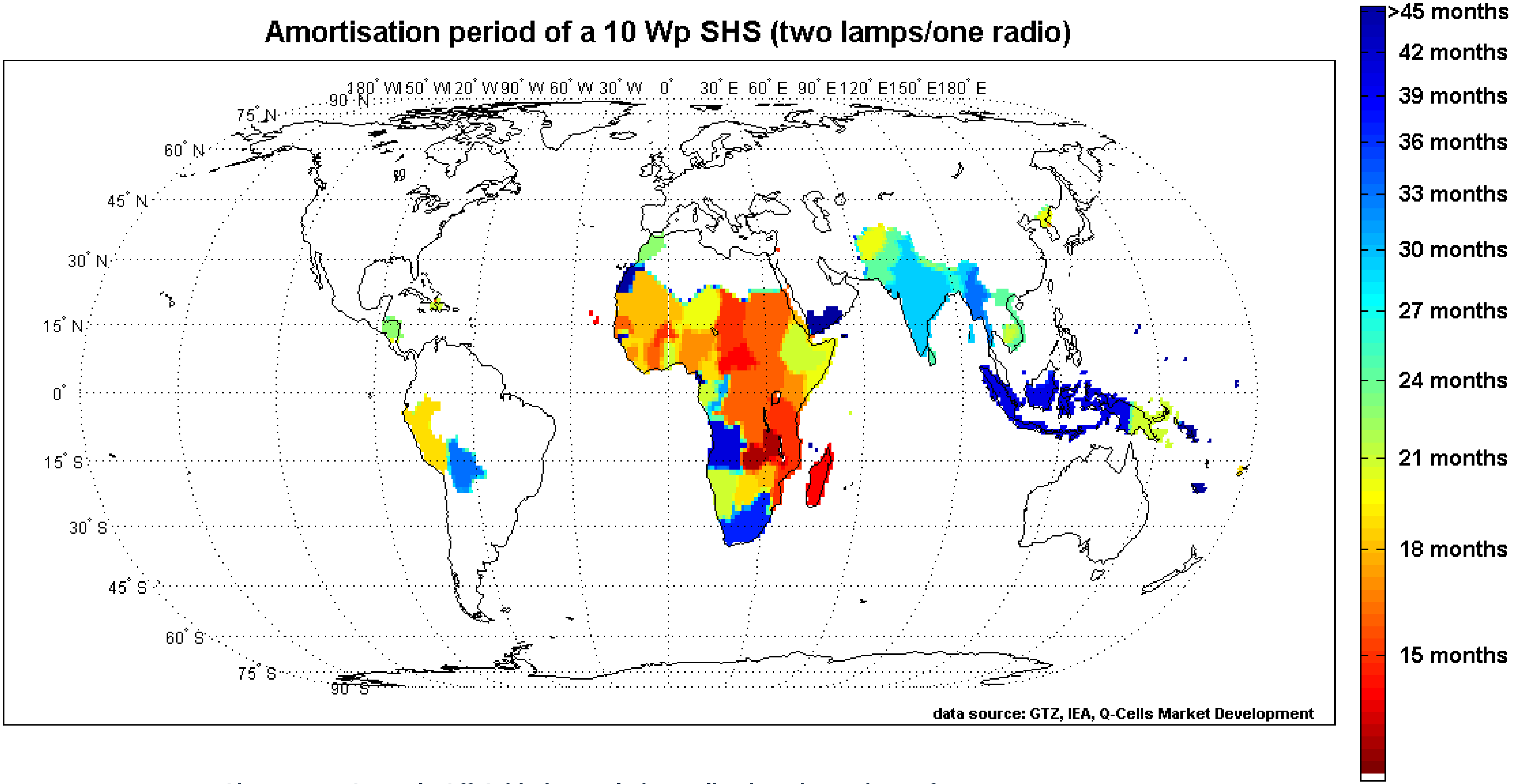
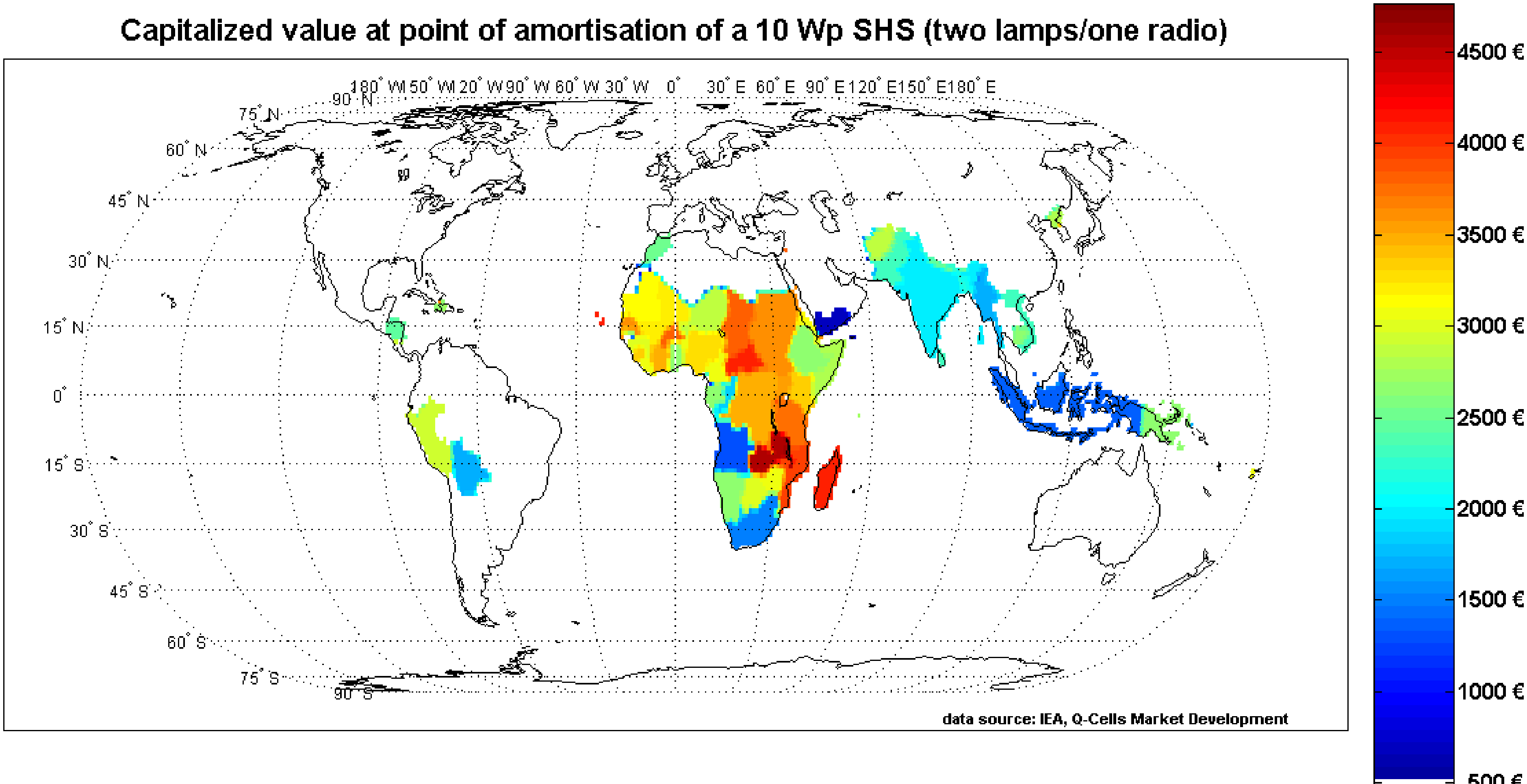


source: Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

SHS: Perfect Solution for the Poor

Capitalized value at point of amortisation of a 10 Wp SHS (two lamps/one radio)



source: Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

be aware: system cost in total < 250 €

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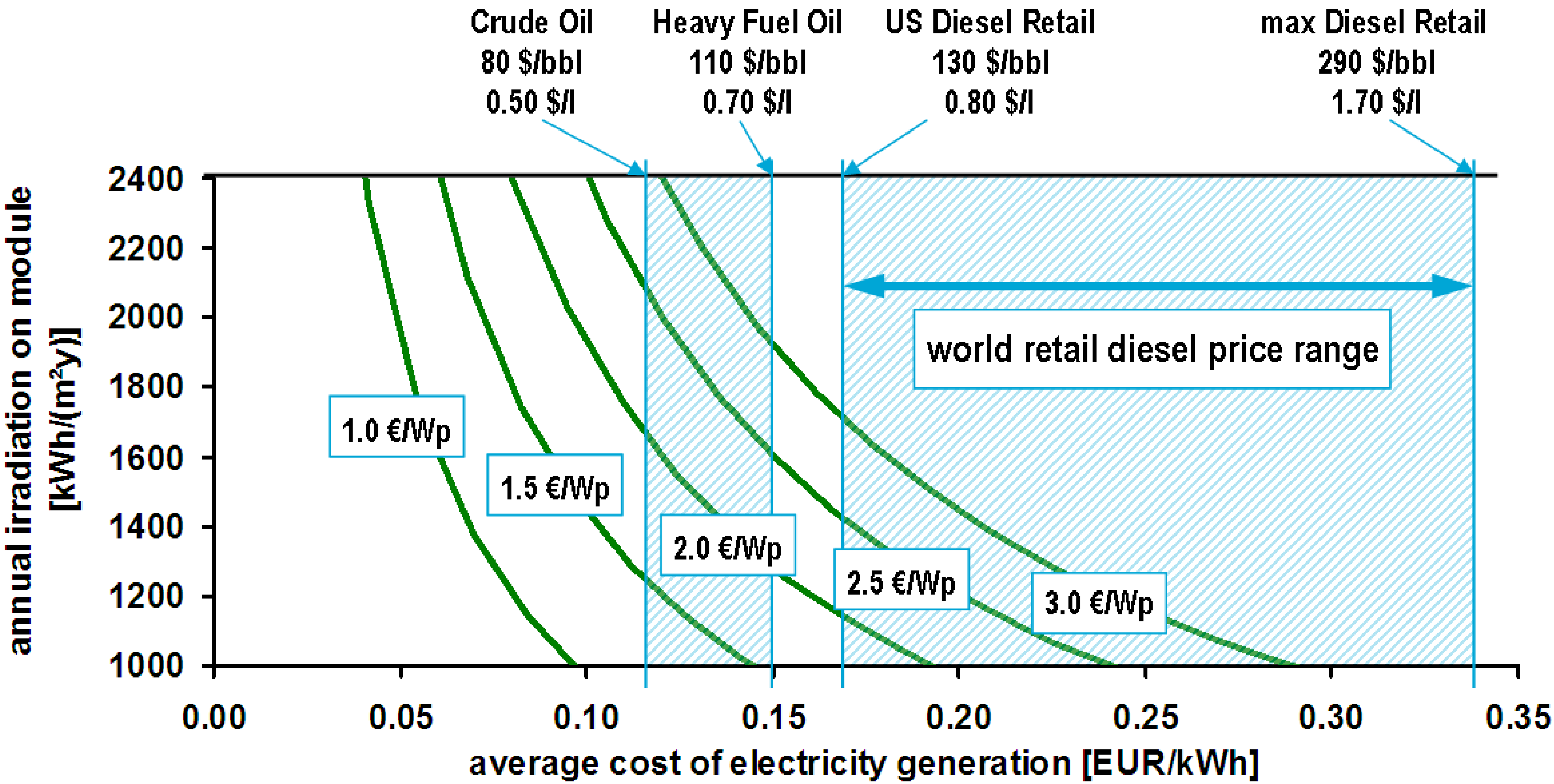
- DESERTEC: Large Scale Renewables
- Summary

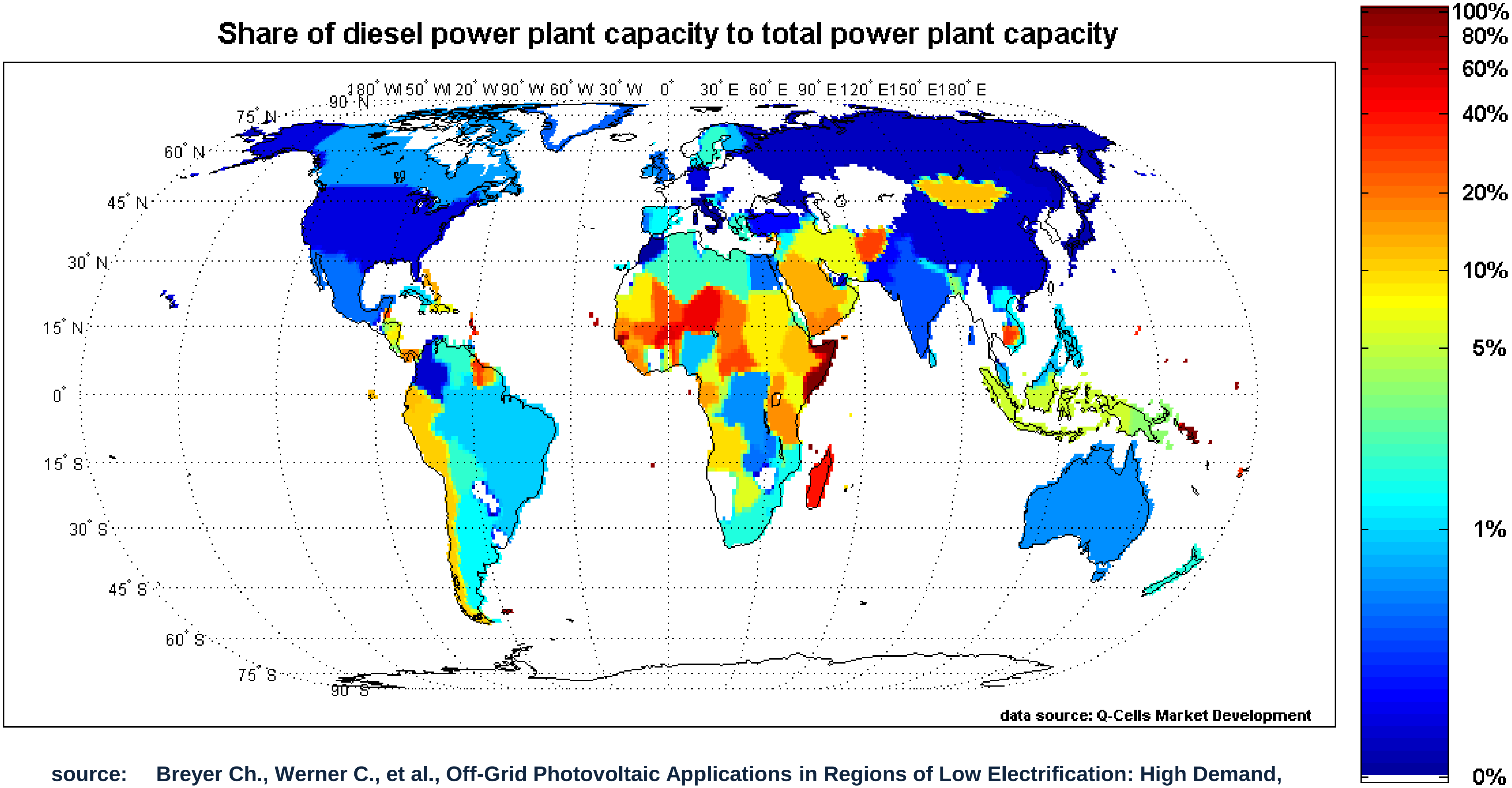
Christian Breyer ► christian.breyer@rl-institut.de

Diesel-Parity: PV capex, Irradiation, Oil Price



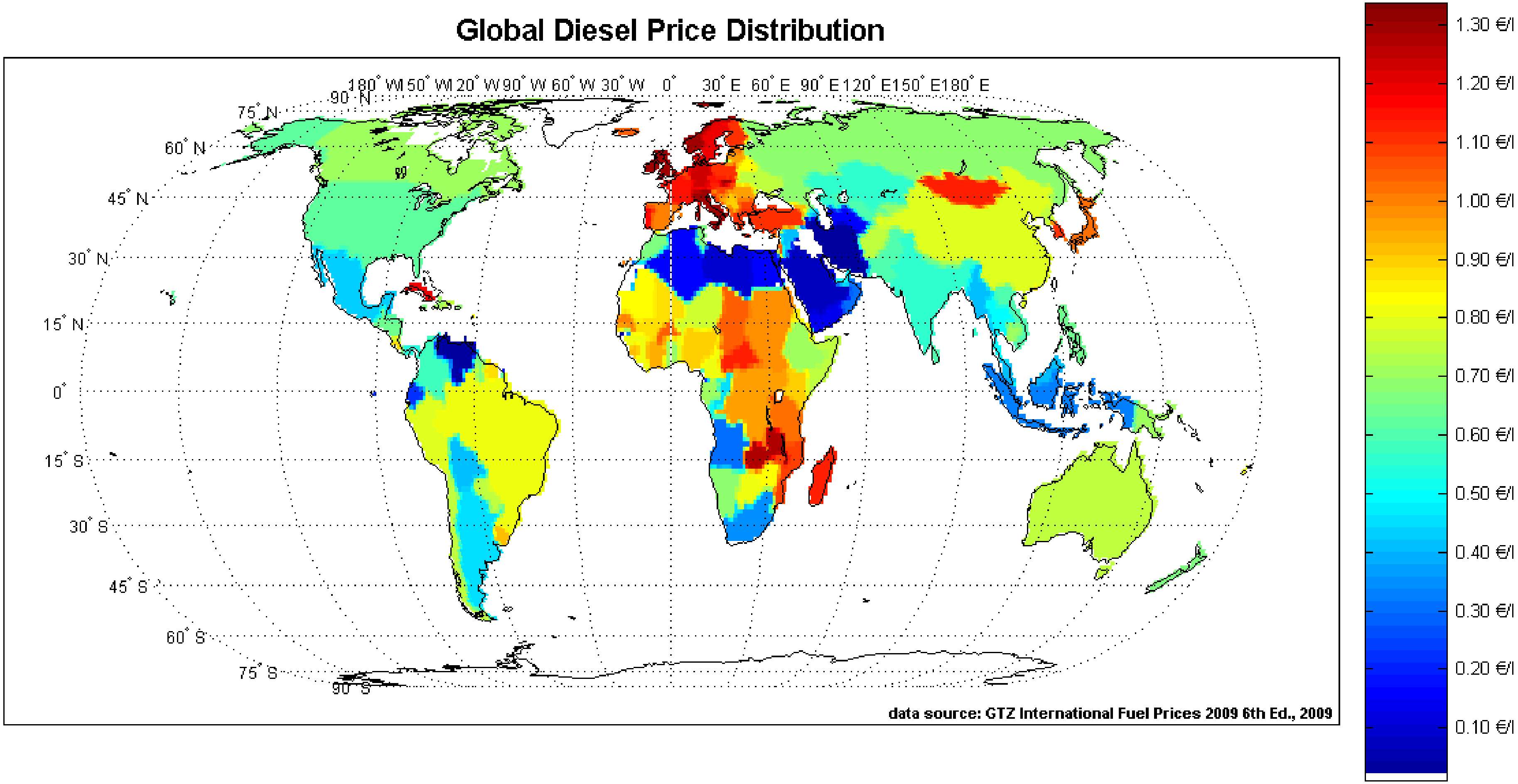
source: Breyer Ch., Gerlach A., et al., 2010. Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, IEEE EnergyCon, Manama, December 18–22

Off-Grid: Diesel-Grids



source: **Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC**

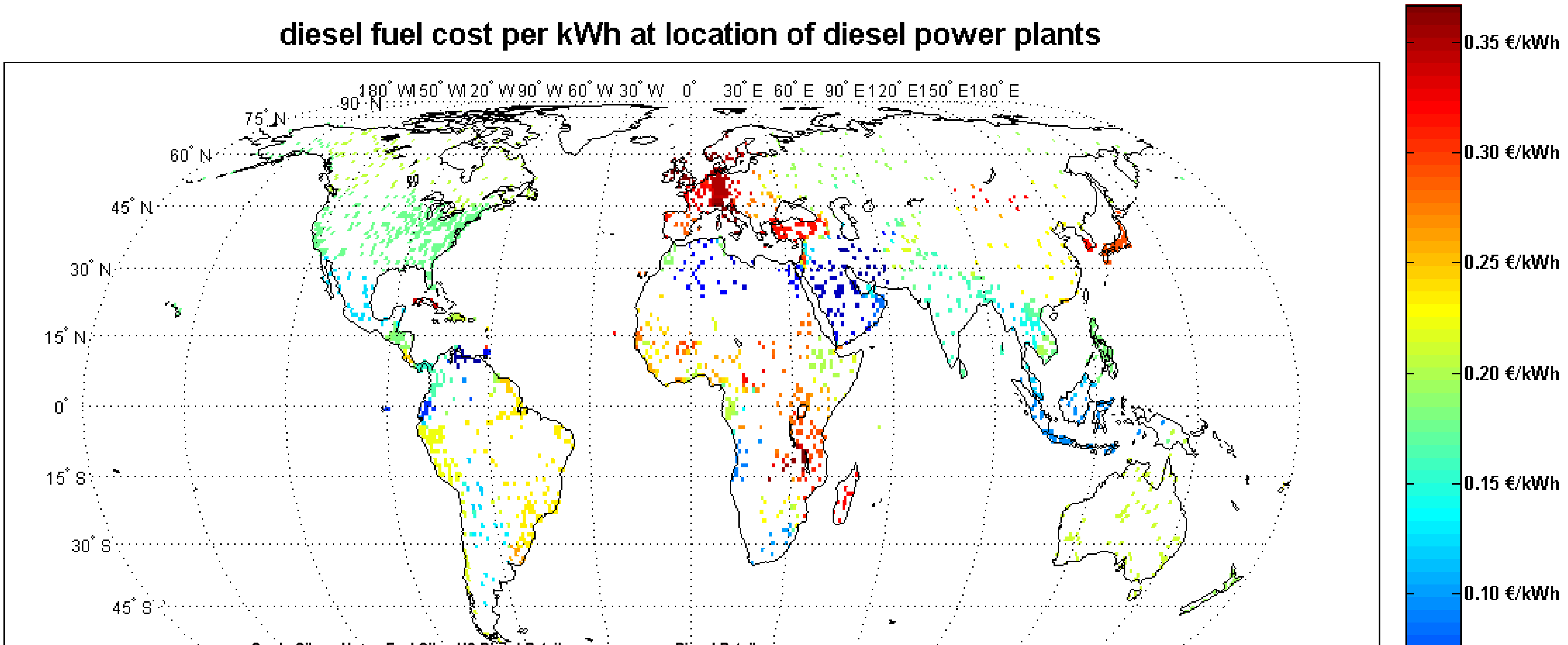
Off-Grid: Global Diesel Prices

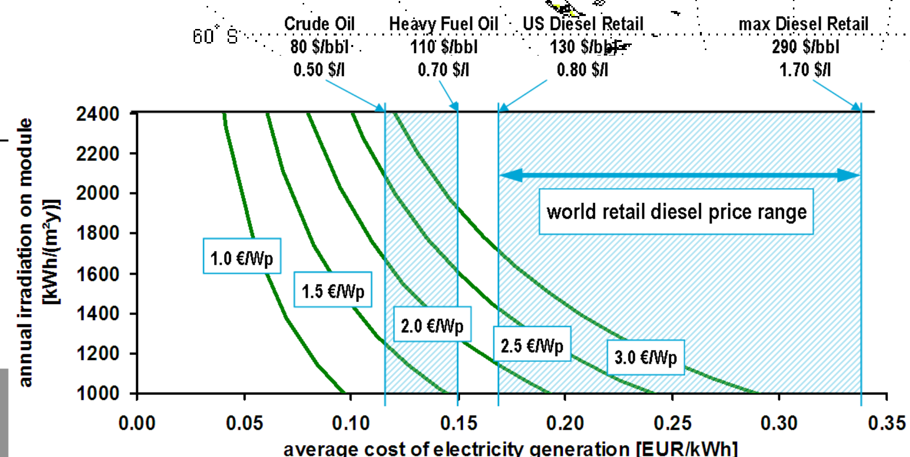


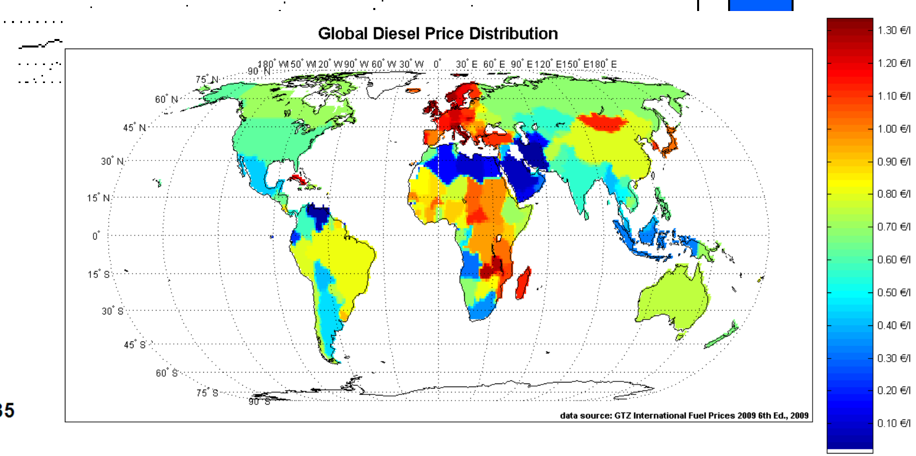
source: Breyer Ch., Werner C., et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC

Off-Grid: Diesel Fuel Cost

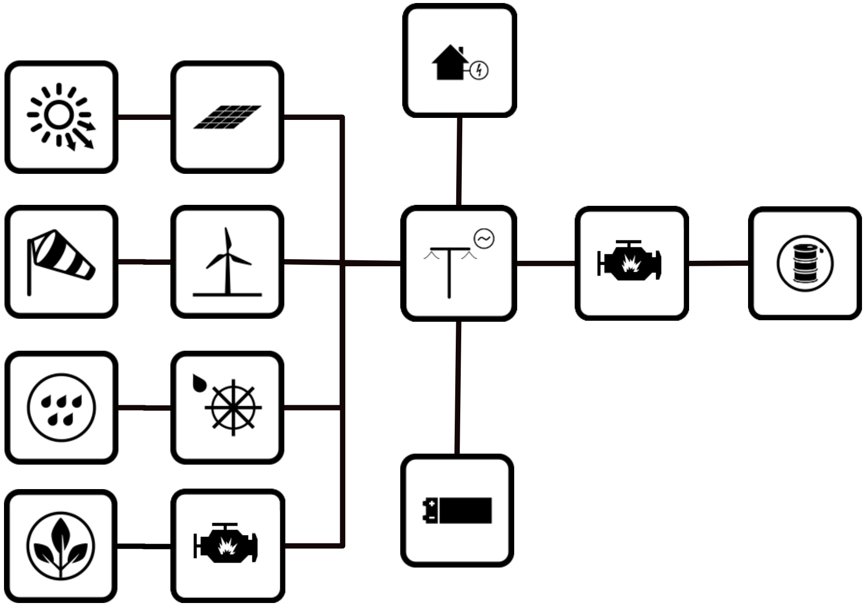
diesel fuel cost per kWh at location of diesel power plants







Off-Grid: Mini-Grid Structure



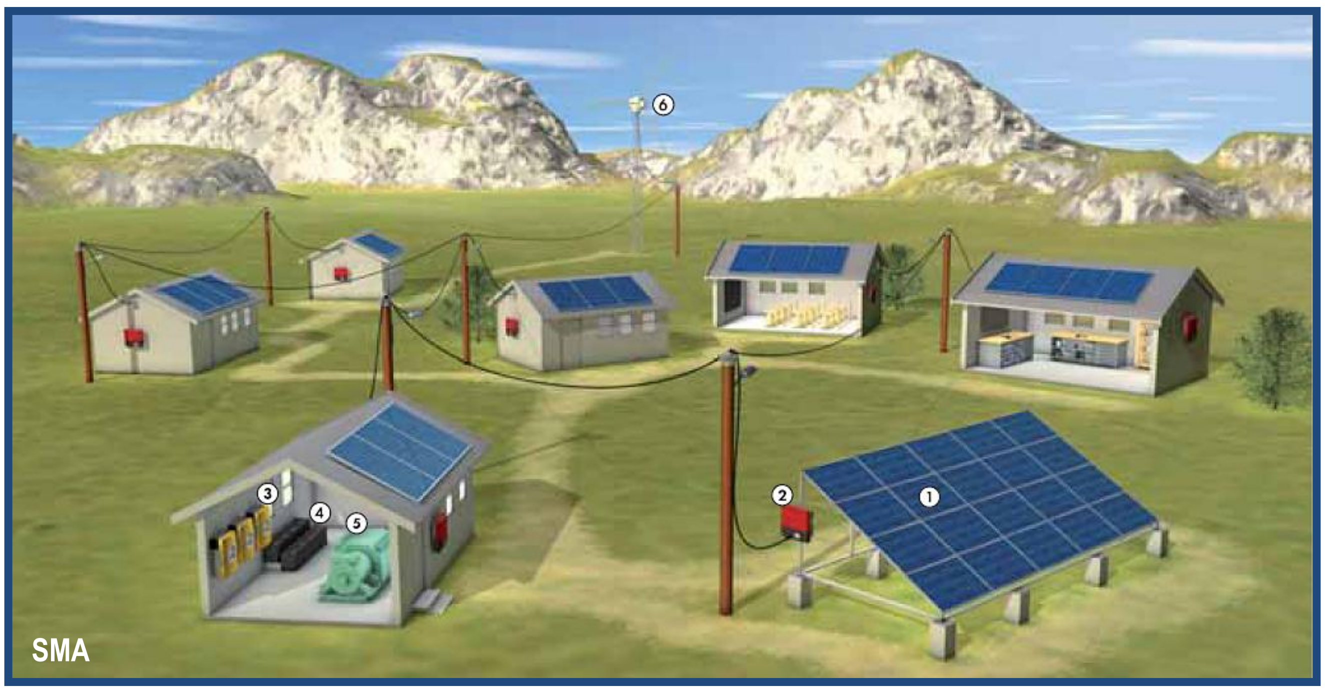
Literature overview (> 100 publications)

Hybrid Systems found

35 PV-Battery
49 PV-Diesel-Battery
44 PV-Wind-(Diesel)-Battery
7 PV-Wind-Hydro-(Diesel)-Battery
0 PV-Wind-Biogas-(Diesel)-Battery

source: Werner C. and Breyer Ch., 2012. Analysis of Mini-Grid Installations: An Overview on System Configurations, 6th European Conference on PV-Hybrids and Mini-Grids, Chambéry, April 26-27

Off-Grid: Mini-Grids



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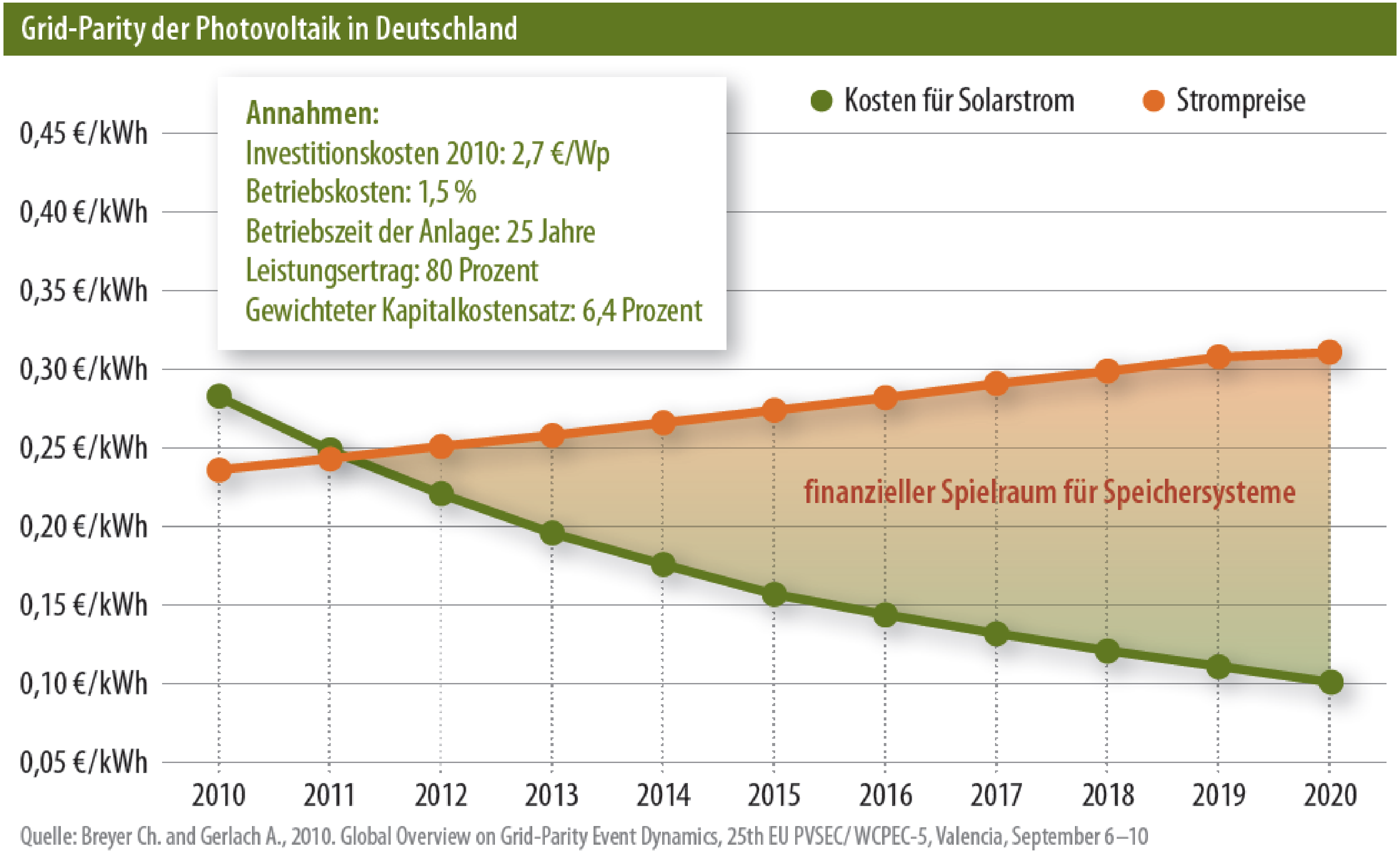
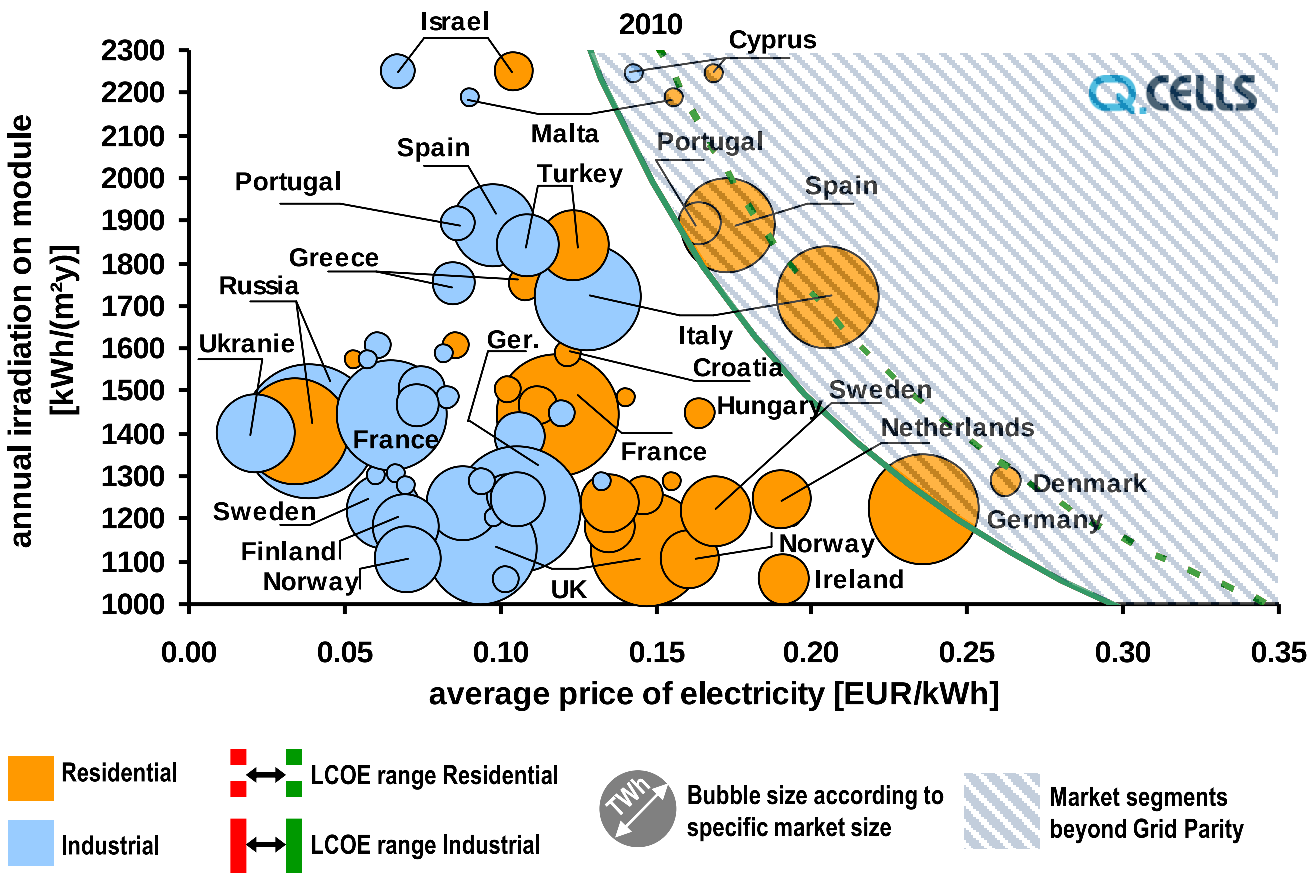
PV Netzparität (Endkunden Sicht)



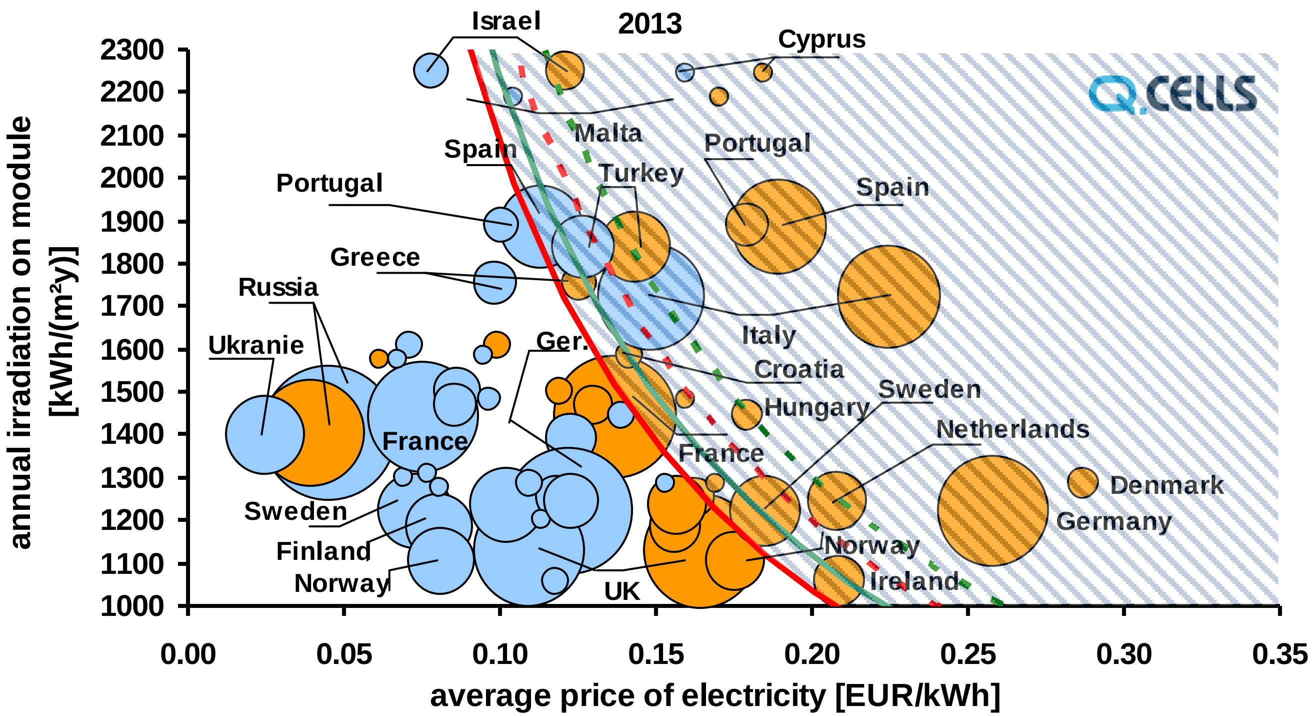
Quelle der Grafik: Photovoltaik, Januar 2012

2010 Europe



source: Ch. Breyer and A. Gerlach, Global Overview on Grid-Parity Event Dynamics , 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6–10

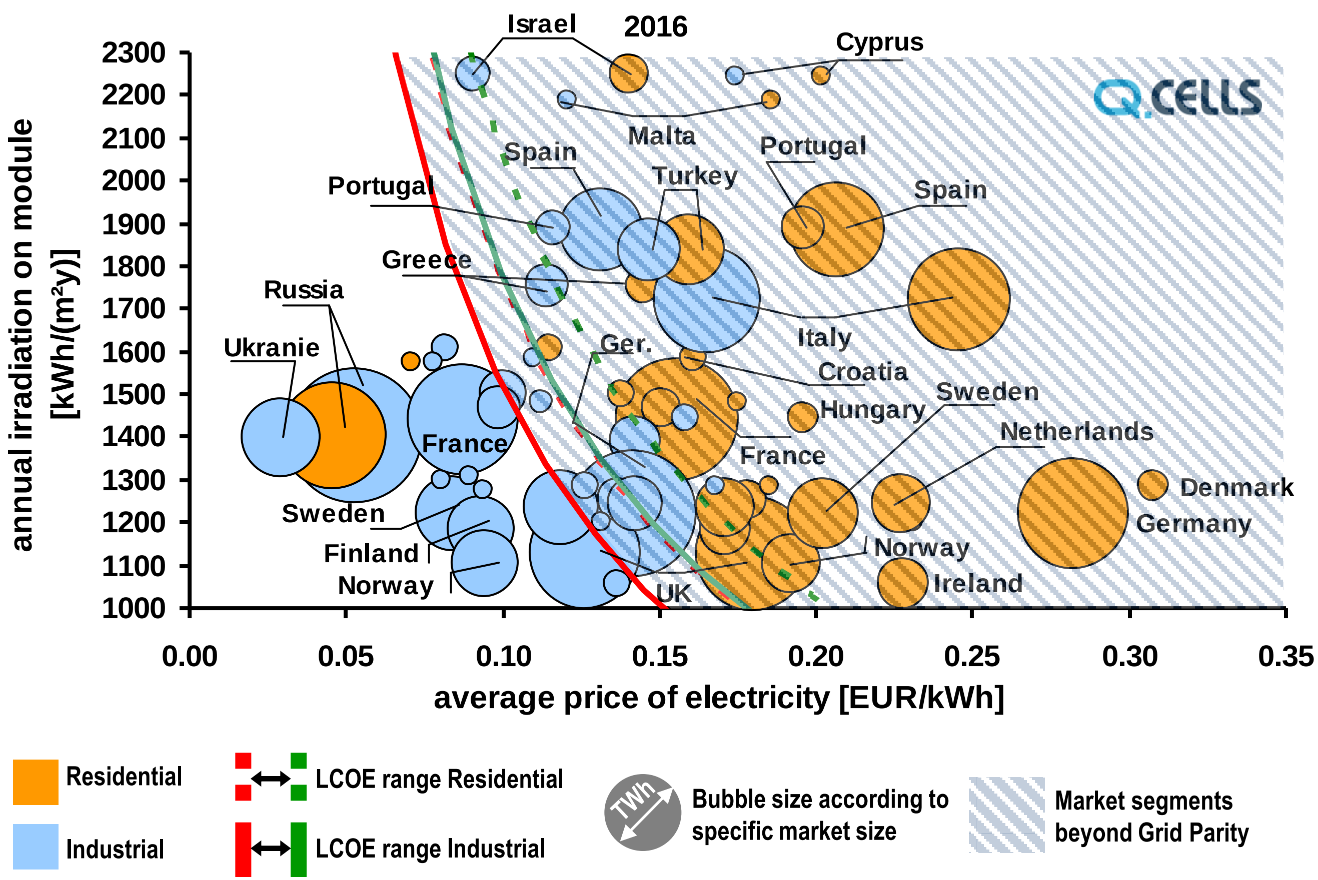
2013 Europe



Residential
Industrial
LCOE range Residential
LCOE range Industrial
Bubble size according to specific market size
Market segments beyond Grid Parity

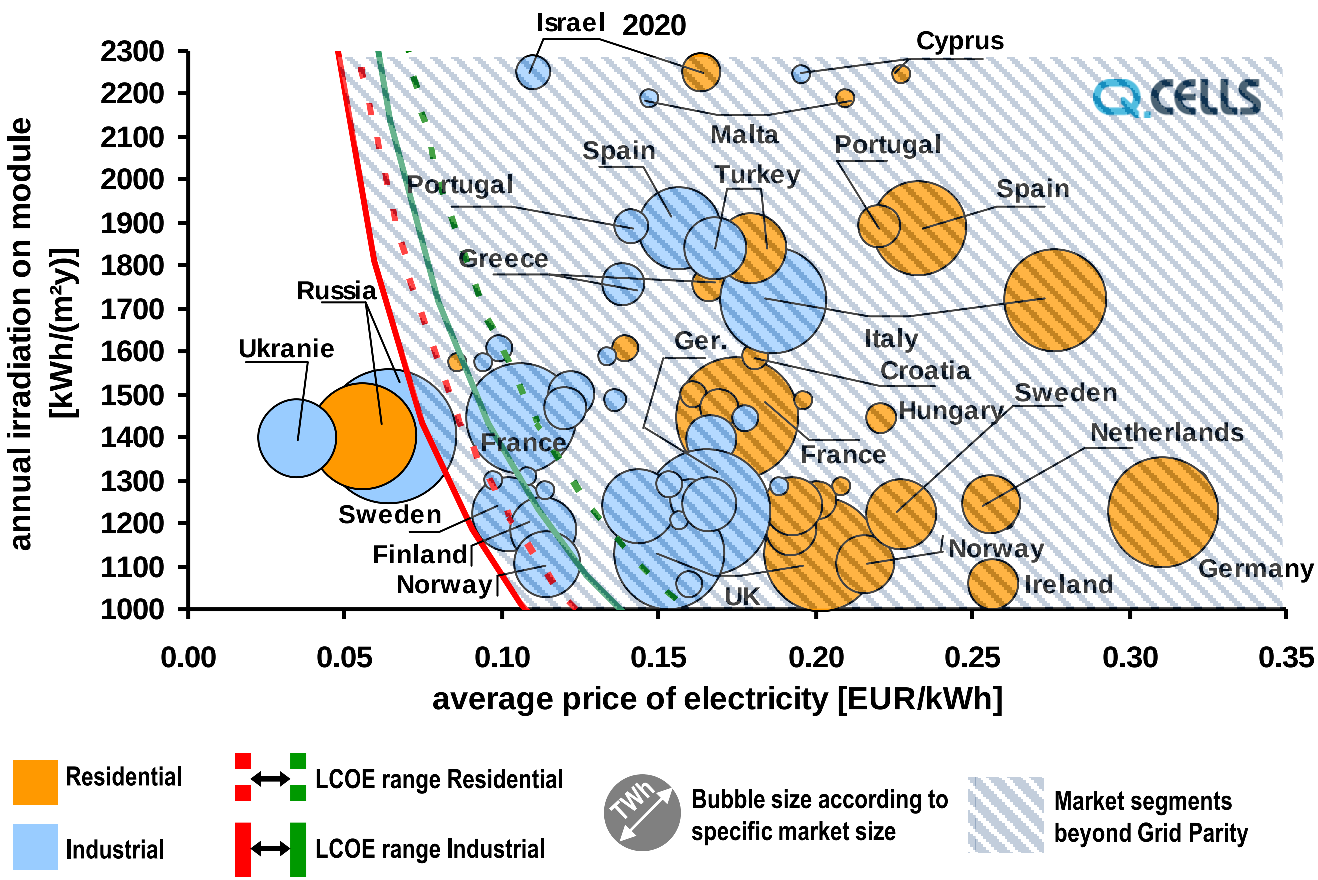
source: Ch. Breyer and A. Gerlach, Global Overview on Grid-Parity Event Dynamics , 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6–10

2016 Europe



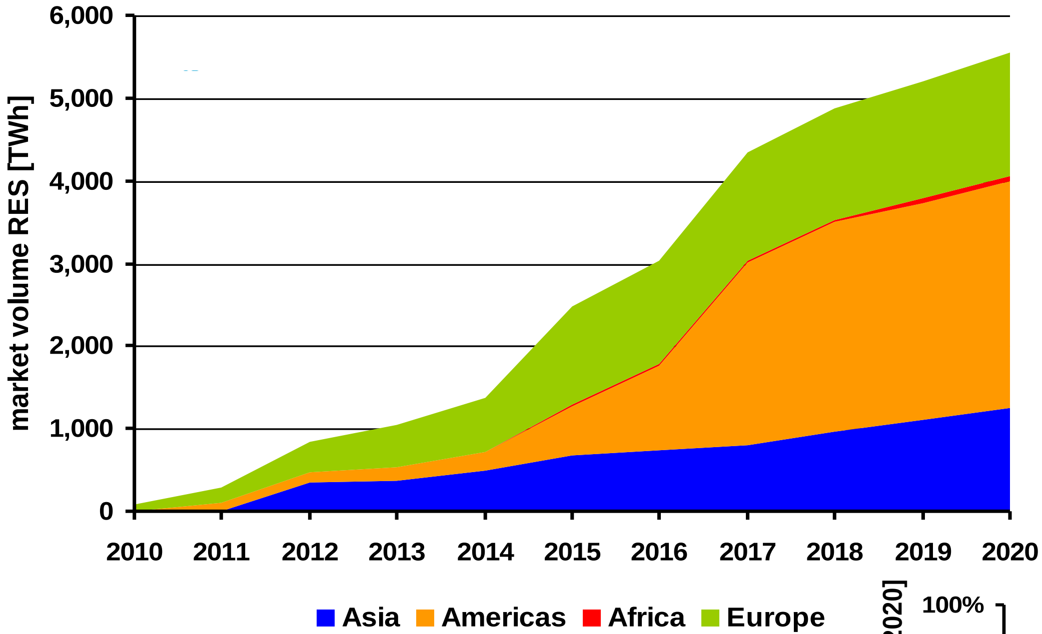
source: Ch. Breyer and A. Gerlach, Global Overview on Grid-Parity Event Dynamics , 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6–10

2020 Europe



source: Ch. Breyer and A. Gerlach, Global Overview on Grid-Parity Event Dynamics , 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6–10

Grid-Parity: Global Trends



Assumptions: Capex 2010: ~2.7 €/Wp residential, ~2.4 €/Wp industrial; Opex: 1.5% of Capex; system lifetime 25 years; performance ratio 80%; WACC 6.4%; growth rate: ~30%/y; learning rate: 15-20%

source:

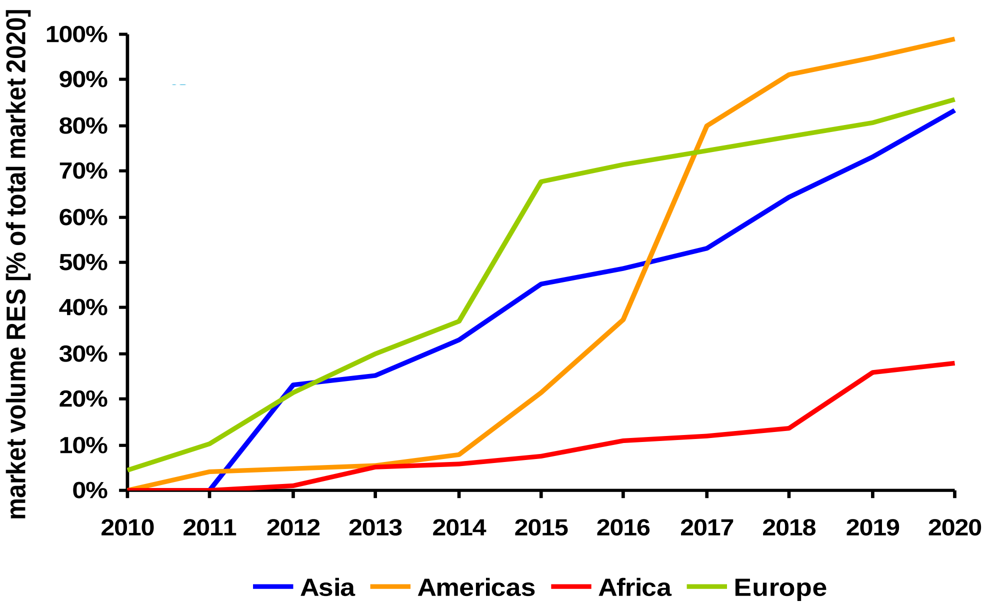
Breyer Ch. and Gerlach A., 2010. Global Overview on Grid-Parity Event Dynamics, 25th EU PVSEC/ WCPEC-5, Valencia, September 6–10

Breyer Ch., 2011. The Photovoltaic Reality Ahead: Terawatt Scale Market Potential Powered by Pico to Gigawatt PV Systems and Enabled by High Learning and Growth Rates, 26th EU PVSEC, Hamburg, September 5–9

regarded countries for residential markets represent:

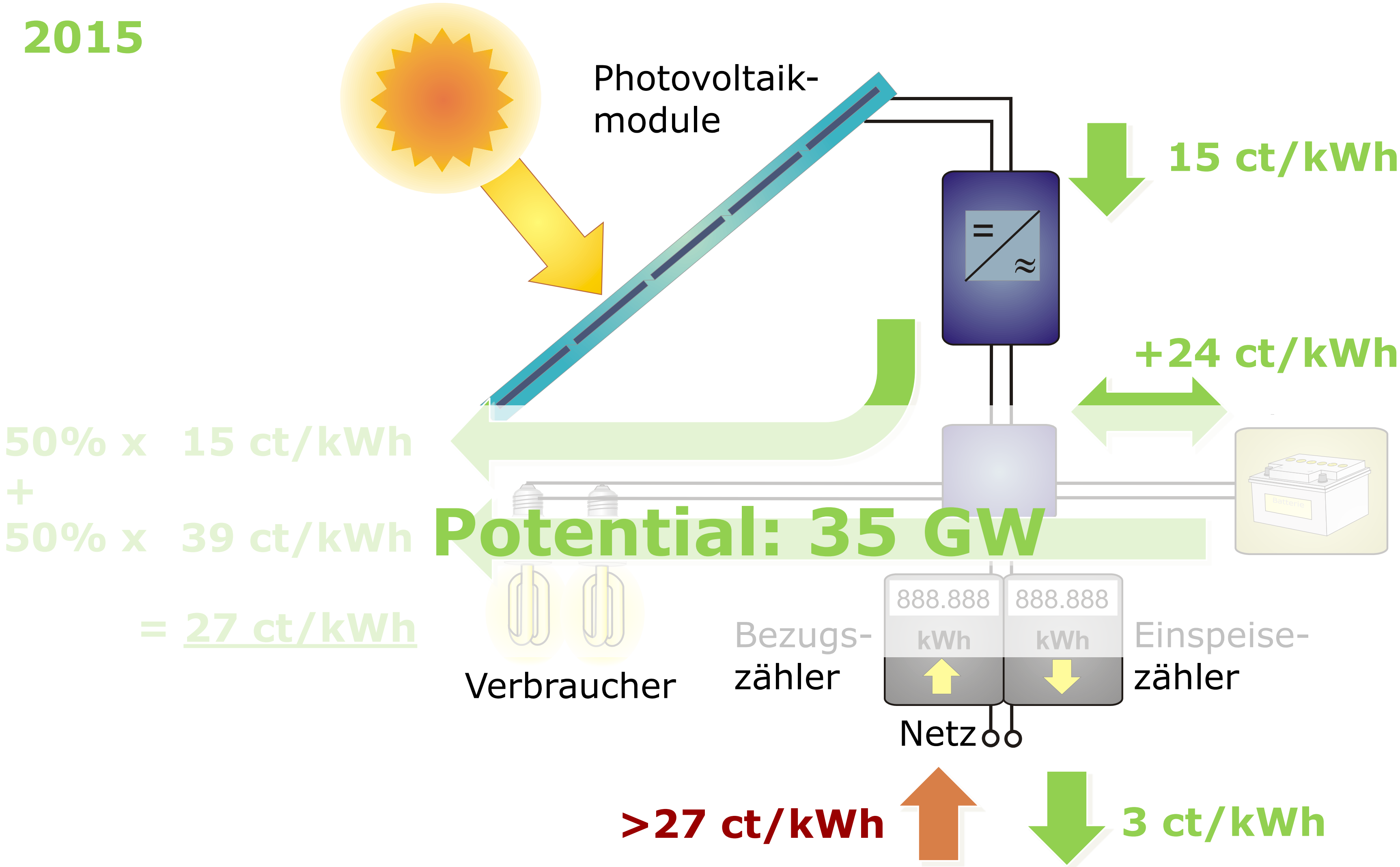
- 98.0% of world population
- 99.7% of global GDP
- 99.2% of global energy related CO_2 emissions
- 99.5% of global residential electricity consumption

total Grid-Parity translates to 2,000 - 3,900 GWp Market Potential in 2020



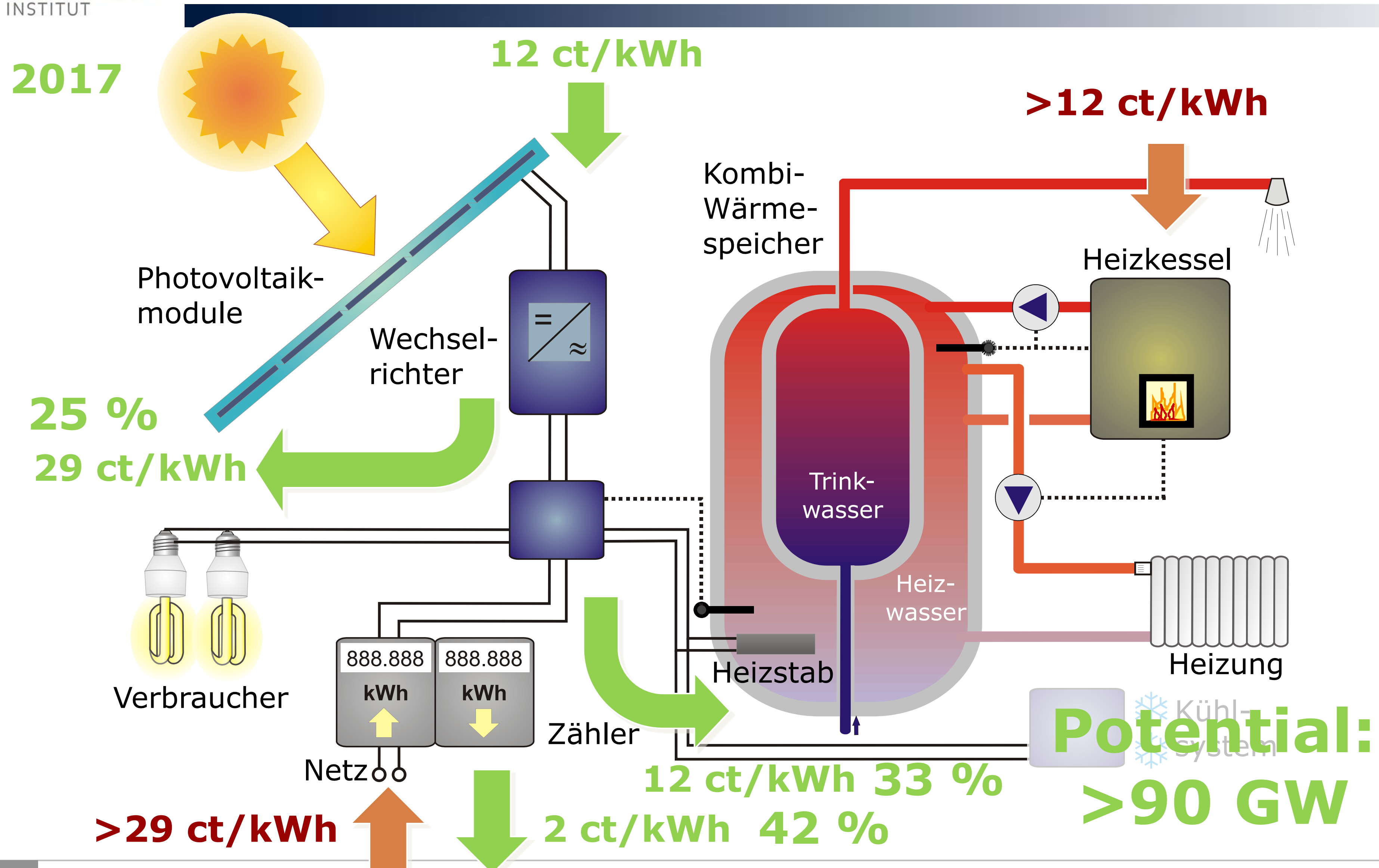
Netzgekoppeltes Batteriesystem

2015



Quelle: Quaschning V., 2012. Einsatzmöglichkeiten und Potenziale der Photovoltaik ohne erhöhte EEG-Vergütung, 27. Symposium Photovoltaische Solarenergie, Staffelstein, 29.2.2012

Photovoltaische Heizungsunterstützung



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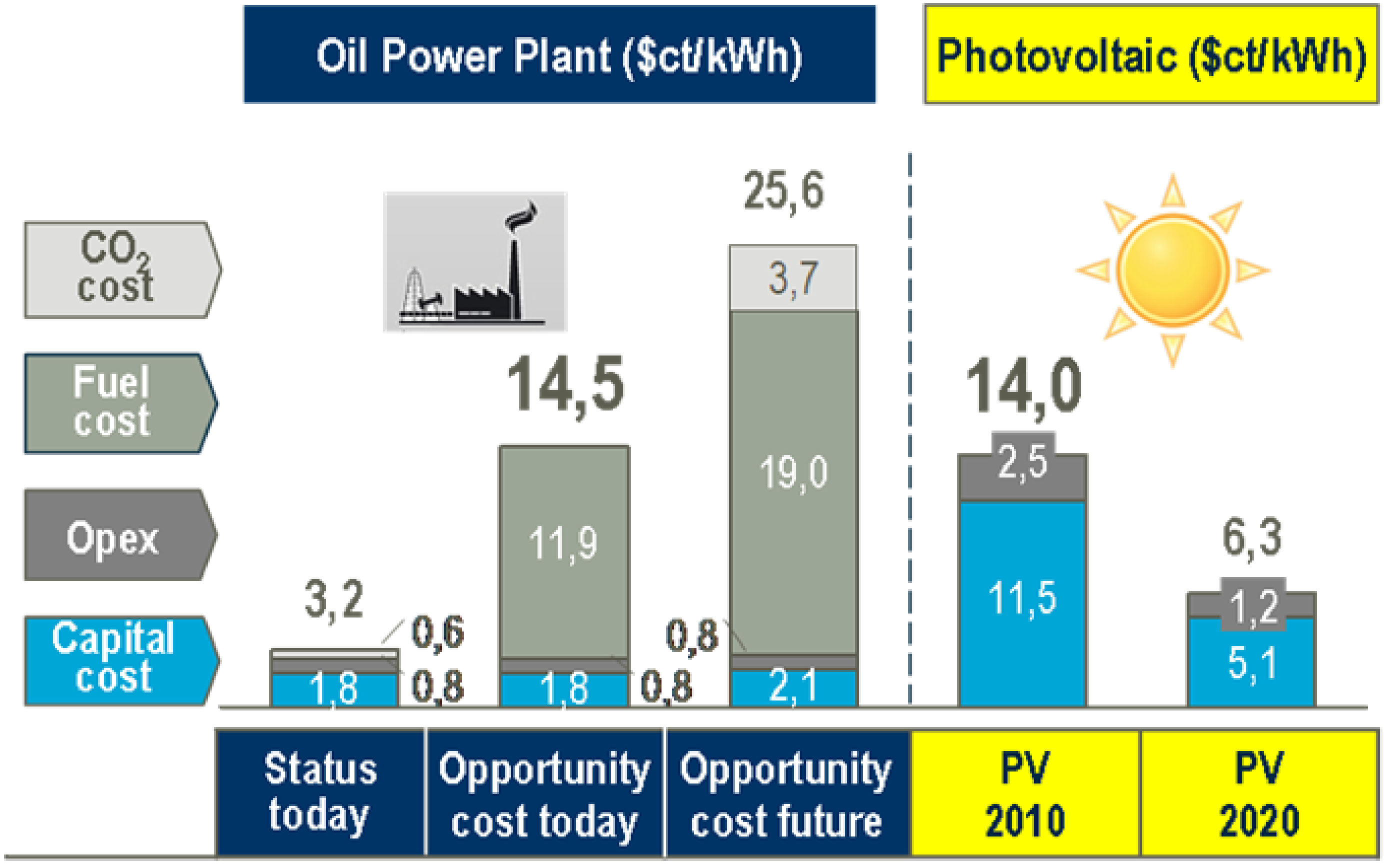
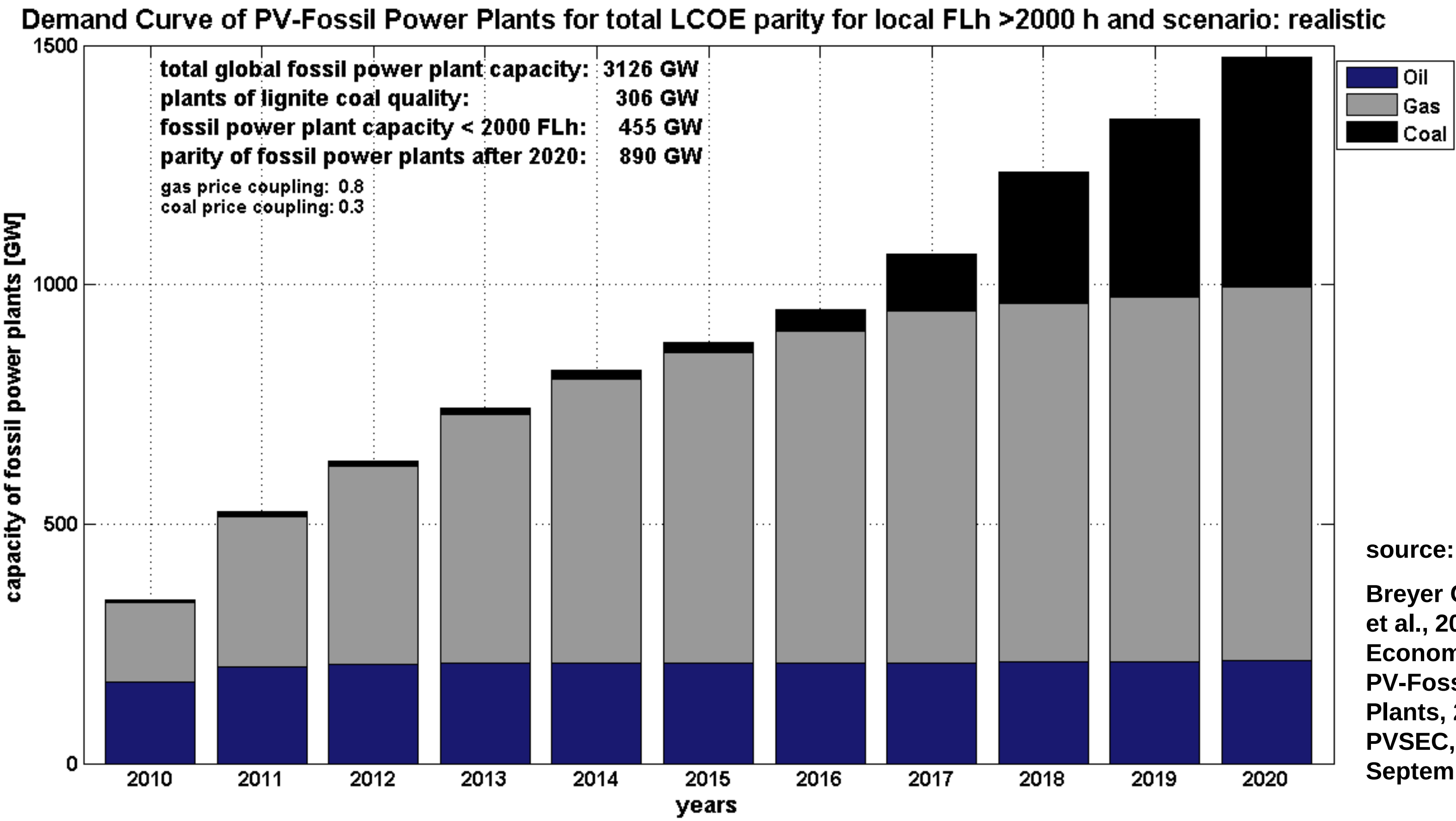
PV Oil Fuel-Parity in Sunny Regions



* oil production cost 4 $/barrel, world market price for opportunity cost today 80 $/barrel and in future 160 $/barrel, PV Capex 2,000 €/kWp (2010) and 1000 €/kWp (2020), 5% WACC

source: Breyer Ch., Görig M., et al., 2011. Economics of Hybrid PV-Fossil Power Plants, 26th EU PVSEC, Hamburg, September 5–9

Hybrid PV-Fossil: Global Demand for the 2010s



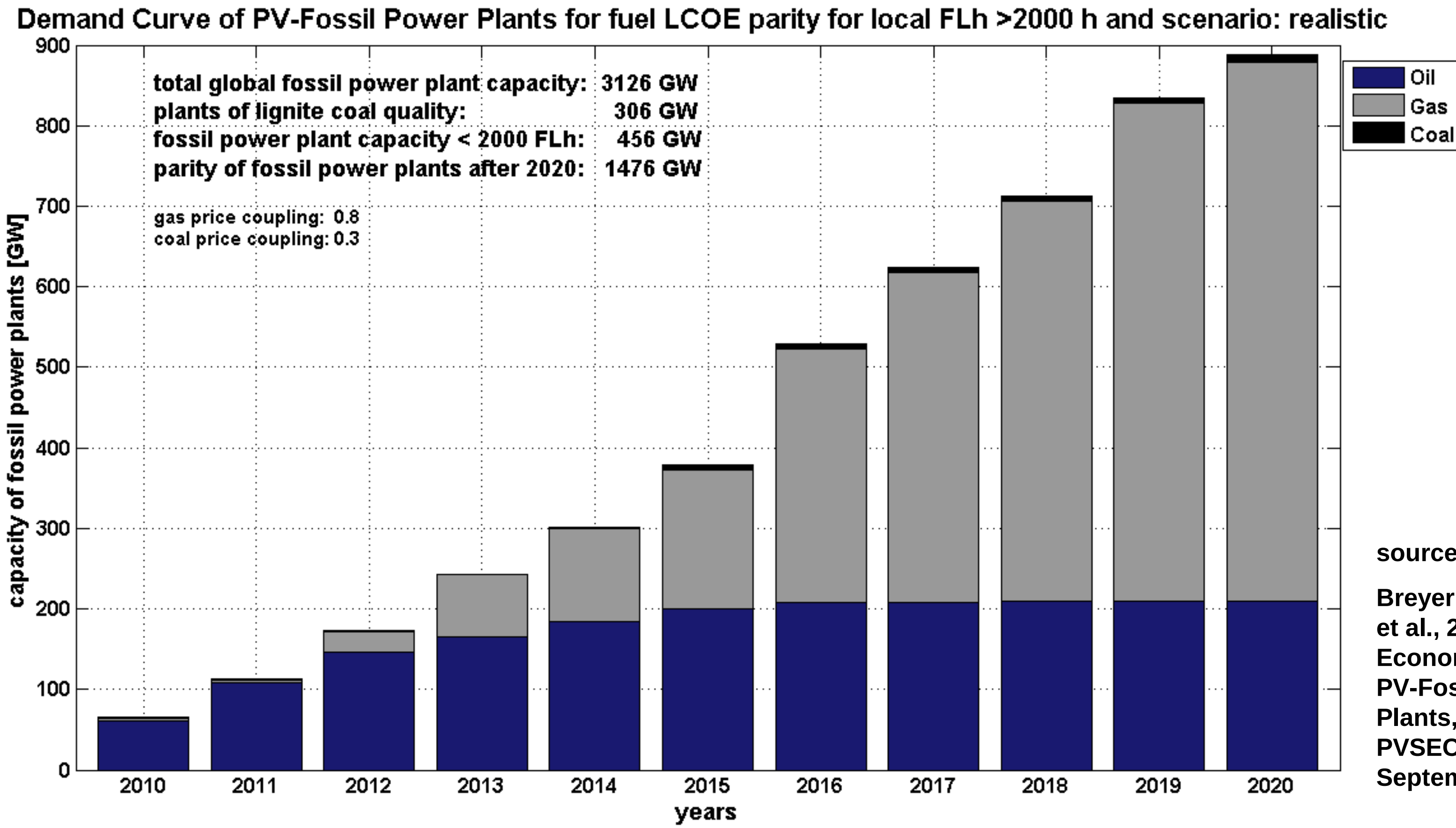
source:

Breyer Ch., Görig M., et al., 2011. Economics of Hybrid PV-Fossil Power Plants, 26th EU PVSEC, Hamburg, September 5–9

total $LCOE_{fossil}$ > total $LCOE_{PV}$ + FLh-$effect_{fossil}$

more optimistic assumptions would lead to up to 2,300 GW economic upgrading potential

Hybrid PV-Fossil: Global Demand for the 2010s



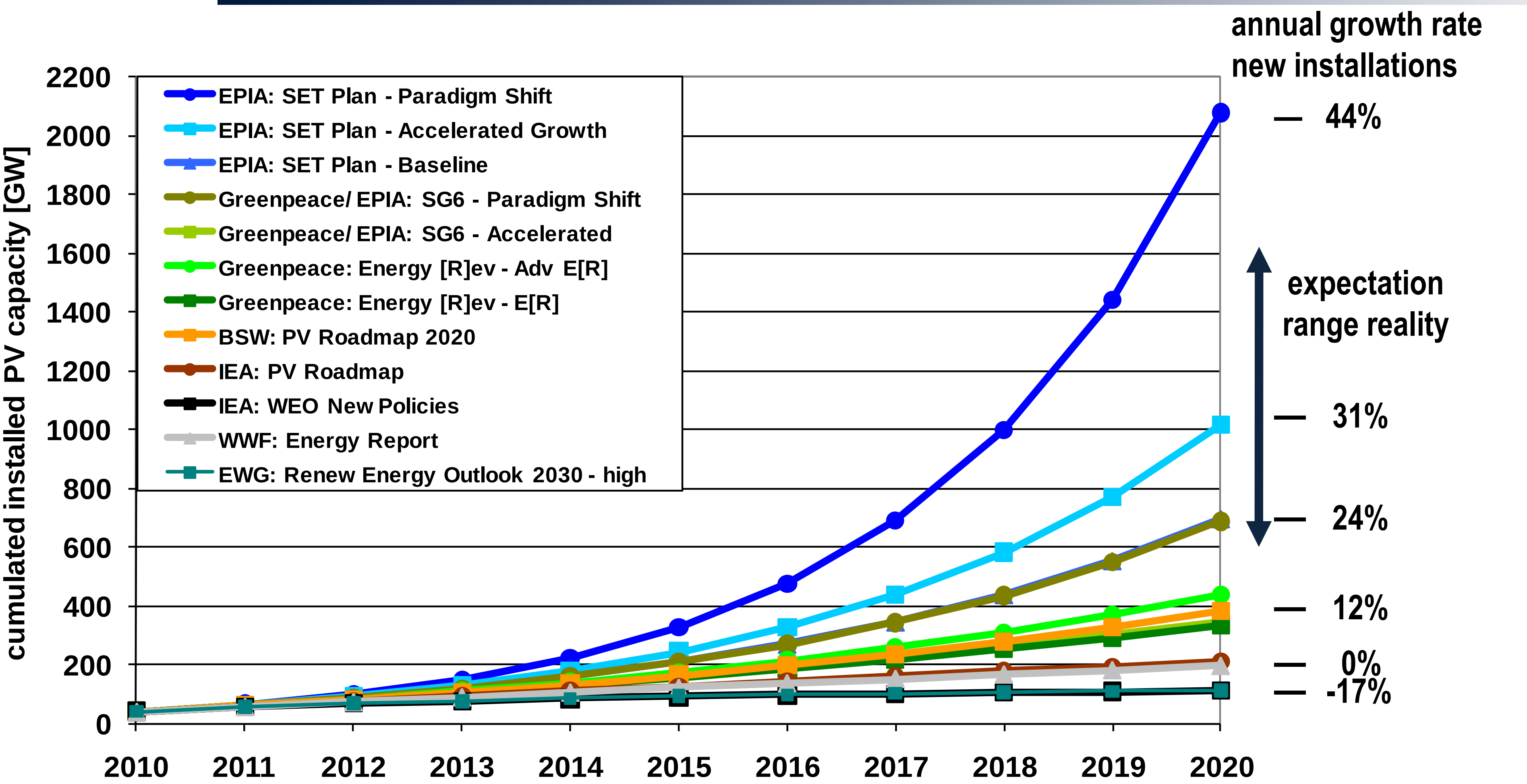
source:

Breyer Ch., Görig M., et al., 2011. Economics of Hybrid PV-Fossil Power Plants, 26th EU PVSEC, Hamburg, September 5–9

fuel $LCOE_{fossil}$ > total $LCOE_{PV}$ + FLh-$effect_{fossil}$

more pessimistic assumptions would lead to at least 700 GW economic upgrading potential

Cumulated Installed PV Capacity - World



source: Breyer Ch., 2011. The Photovoltaic Reality Ahead: Terawatt Scale Market Potential Powered by Pico to Gigawatt PV Systems and Enabled by High Learning and Growth Rates, 26th EU PVSEC, Hamburg, September 5–9

Grid-Parity Analysis		2,000 – 3,900 GWp
Fuel-Parity Analysis		1,200 – 2,000 GWp
Economic Market Potential (on-grid)		2,700 – 4,200 GWp
Economic Market Potential (off-grid)		100 GWp
Pessimistic Case	~20% of Potential:	~600 GWp
Realistic Case	~35% of Potential:	~1,000 GWp
Optimistic Case	~50% of Potential:	~1,600 GWp

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PV and Wind: Ressouce Availability

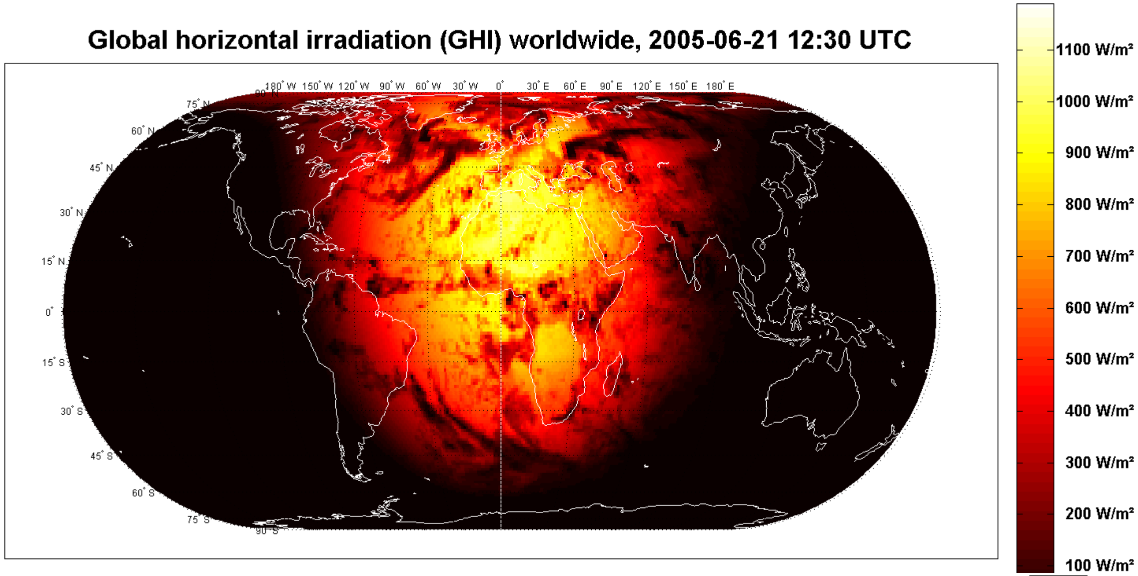
Data: NASA Surface Meteorology and Solar Energy SSE Release 6.0

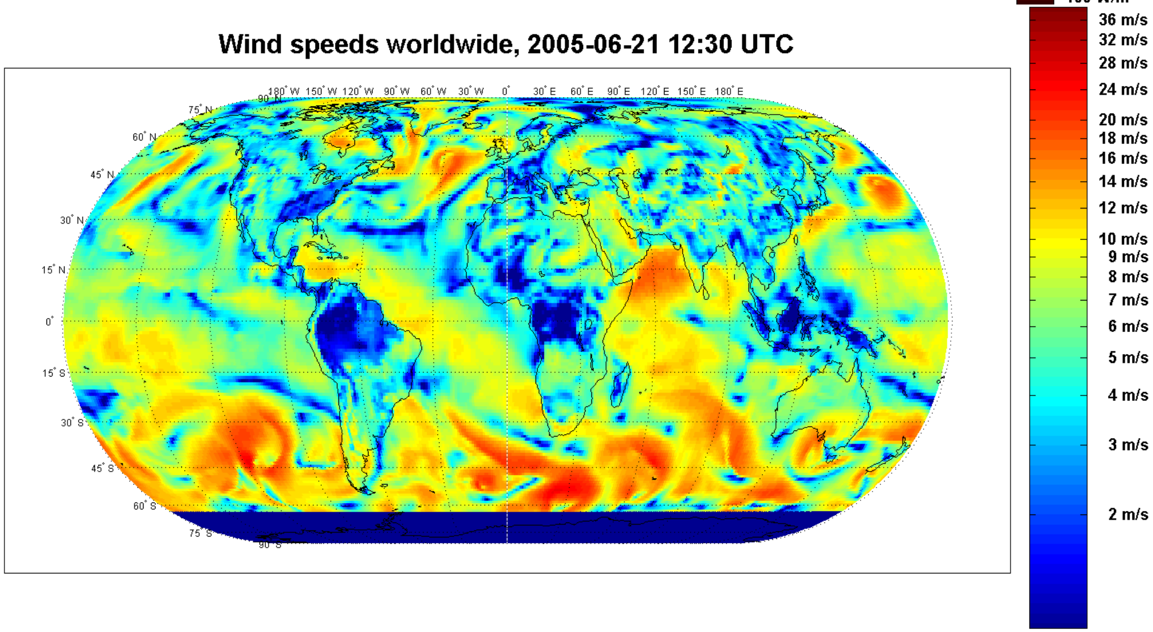
22 years, 1 h time-resolved and 1° spatially-resolved

PV: modeling of 1 GW power plant (optimally tilted, dependent on temperatur and irradiation , c-Si Module, central inverter)

Wind: modeling of 1 GW power plant (7.5 MW E-126 with 150 m hub height)

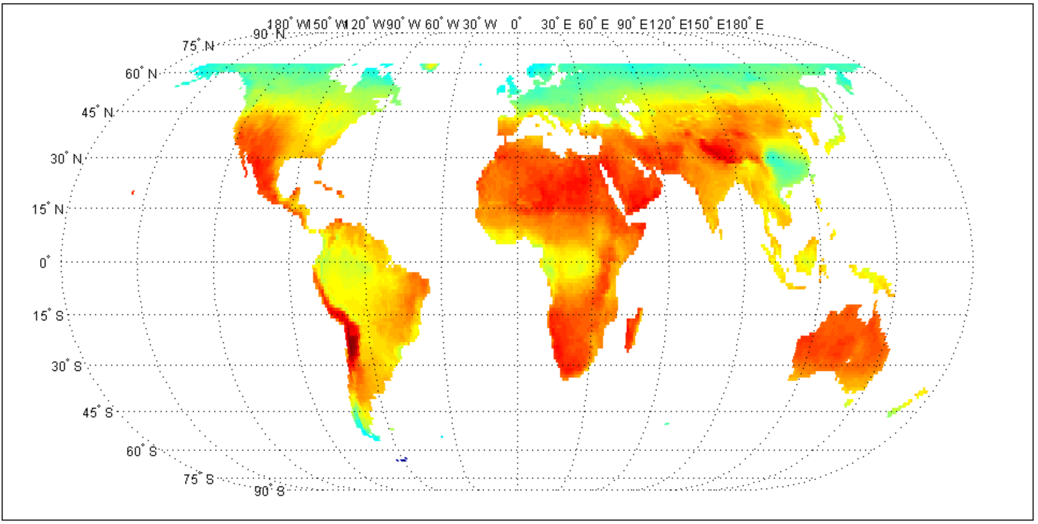
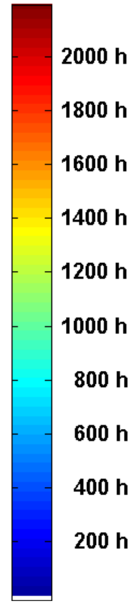
source:
Gerlach A.-K., Diploma Thesis, 2011
Gerlach A.-K., Stetter D., Breyer Ch., et al., PV and Wind Power – Complementary Technologies, 26th EU PVSEC, Hamburg 2011, September 5–9





Full Load Hours of PV and Wind Power

Full load hours PV worldwide, 2005

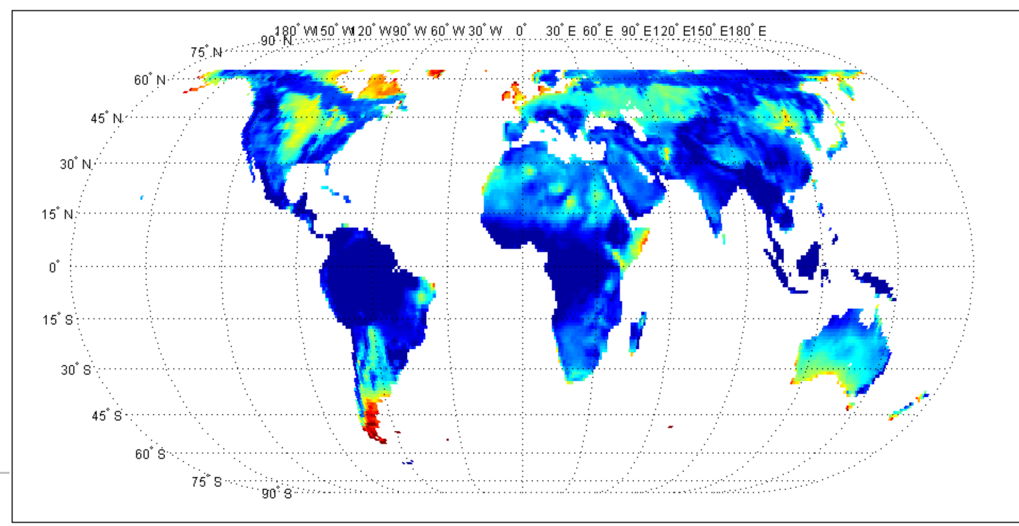
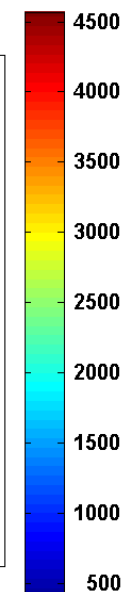



Technical Potential		PV [TW]	Wind [TW]
Weingart	1978	> 100	-
WBGU	2003	infinite	90
Greenpeace	2008	150	35
Sawin and Moomaw	2008	145	55
Lu et al.	2009	-	80 - 150
Jacobson and Delucchi	2009	580	40 - 85
WBGU	2011	8900	54
IPCC SRREN	2011	120000	190
Current Global Energy Demand			
including waste of heat	[TW]	17.0	
direct energy demand	[TW]	11.5	

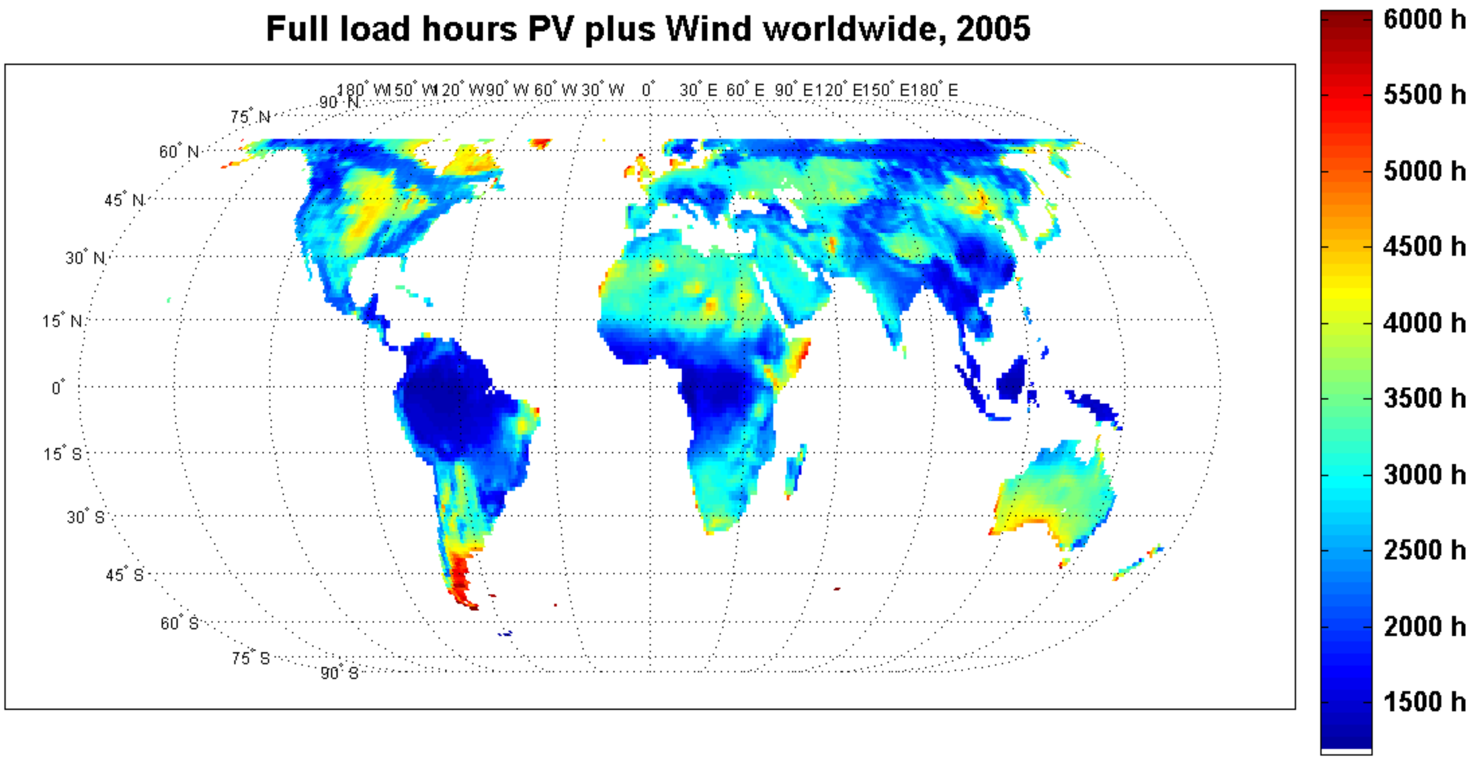
$$FLh_{PV} = \left(\sum_{i=1}^{8760}\left(P_{PV,i}\right)\right)\cdot 1GW^{-1}$$

$$FLh_{Wind} = \left(\sum_{i=1}^{8760}\left(P_{Wind,i}\right)\right)\cdot 1GW^{-1}$$

Full load hours Wind worldwide, 2005

Full Load Hours of PV and Wind Power



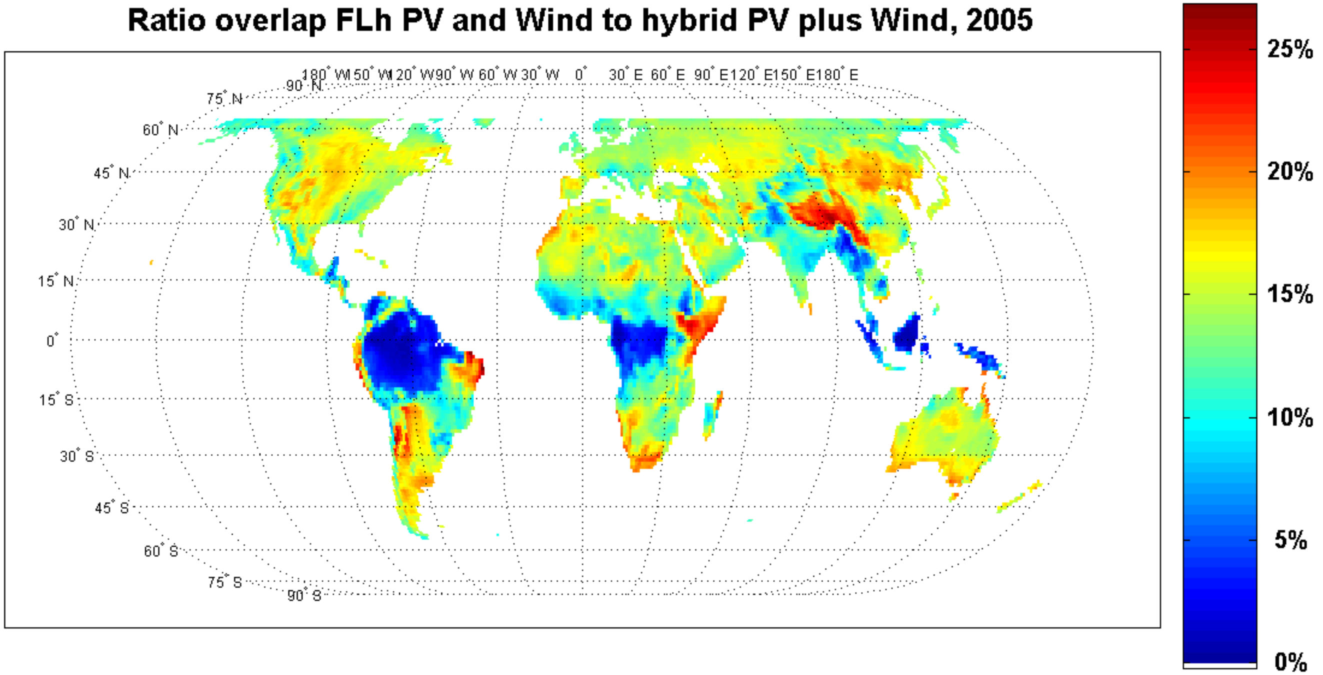
$$FLh_{PV,Wind} = FLh_{PV} + FLh_{Wind}$$

Question: How much of PV and Wind energy has been produced at the same time?

Overlap of PV and Wind Power

Overlap
ranging between
5 ... 25 %
of total energy

Ratio overlap FLh PV and Wind to hybrid PV plus Wind, 2005

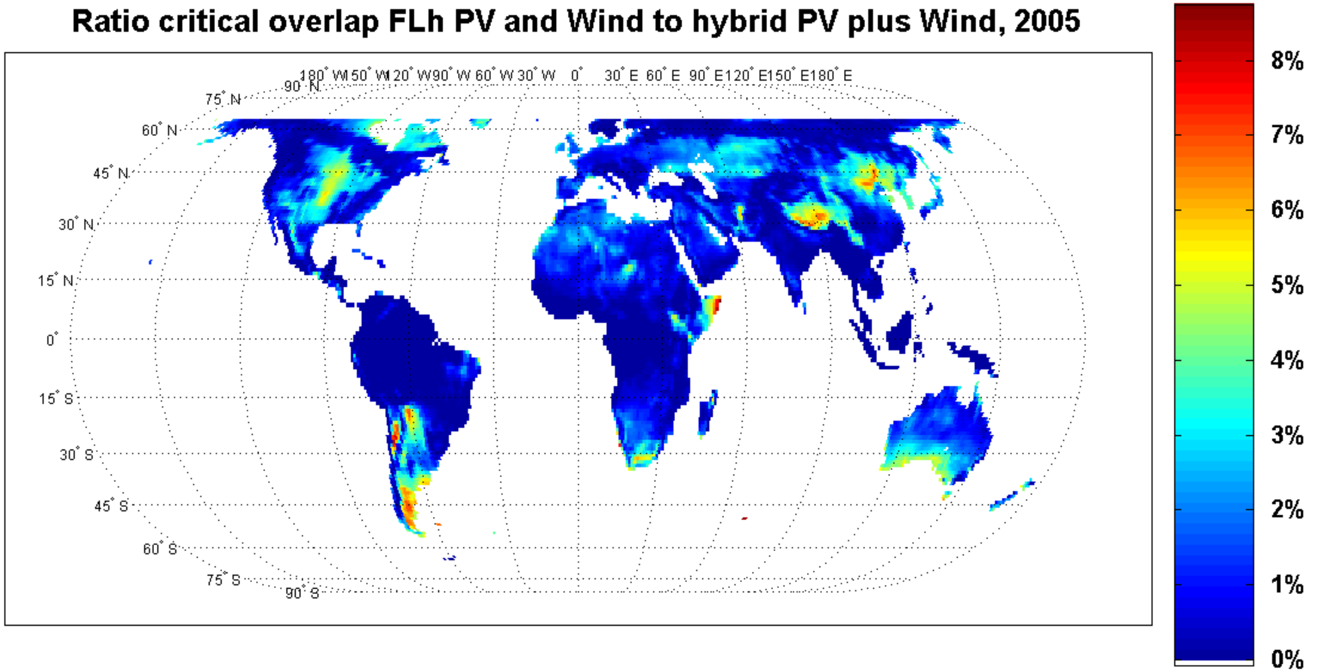


$$FLh_{OL} = \left(\sum_{i=1}^{8760} min(P_{PV,i}, P_{Wind,i}) \right) \cdot 1GW^{-1}$$

Question: How much of the overlap energy is critical?

Critical Overlap of PV and Wind Power

Ratio critical overlap FLh PV and Wind to hybrid PV plus Wind, 2005



Critical Overlap < 9 %

of total energy

critical due to limitations in
- grid capacity,
- storage capacity,
- balancing systems,
- etc.

$$FLh_{COL} = \left(\sum_{\forall i \in \{(P_{PV,i} + P_{Wind,i}) > 1GW\}} P_{PV,i} + P_{Wind,i} - 1GW \right) \cdot 1GW^{-1}$$

→ in most parts of the world **only 1 – 3 %** of total energy production would be critical

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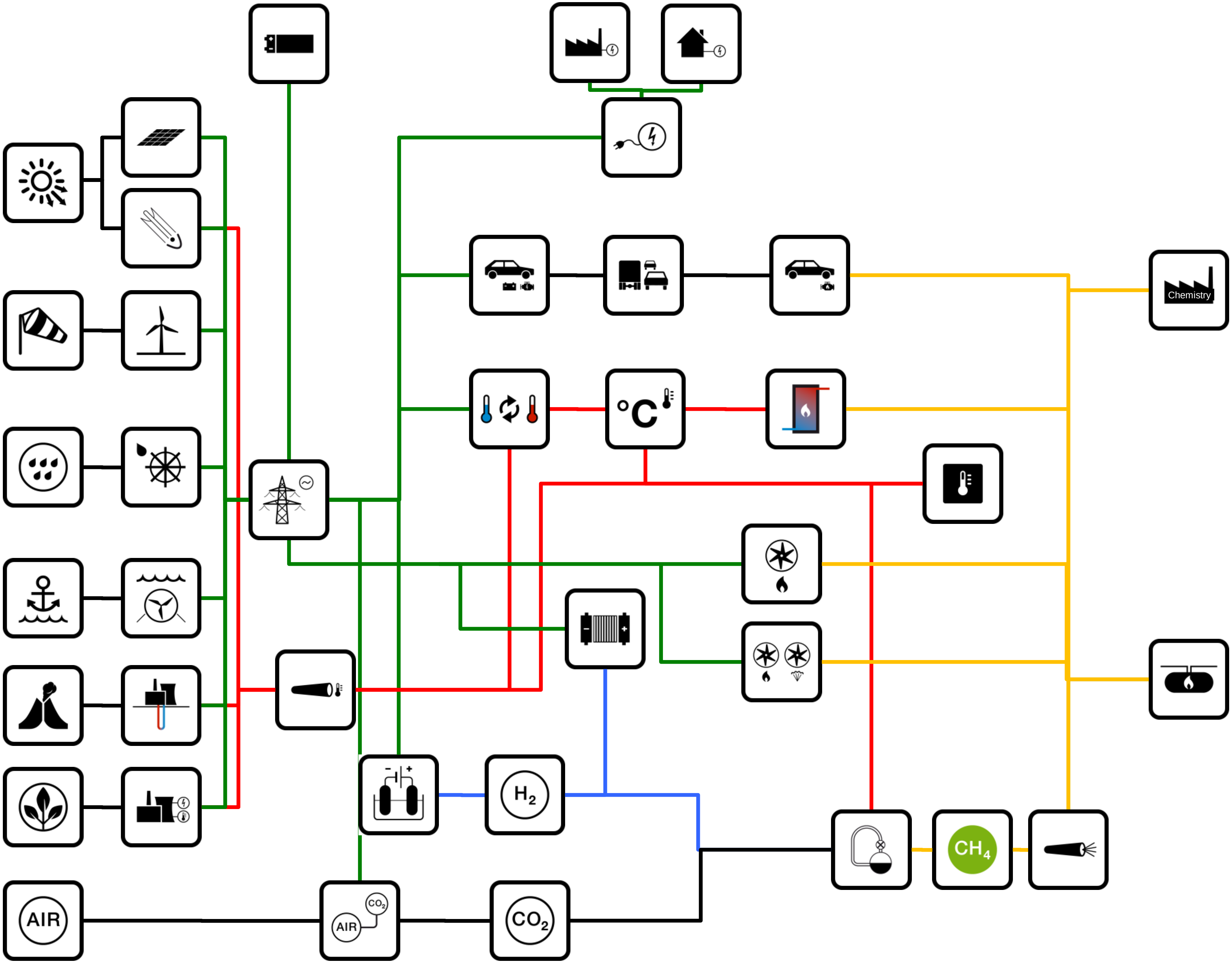
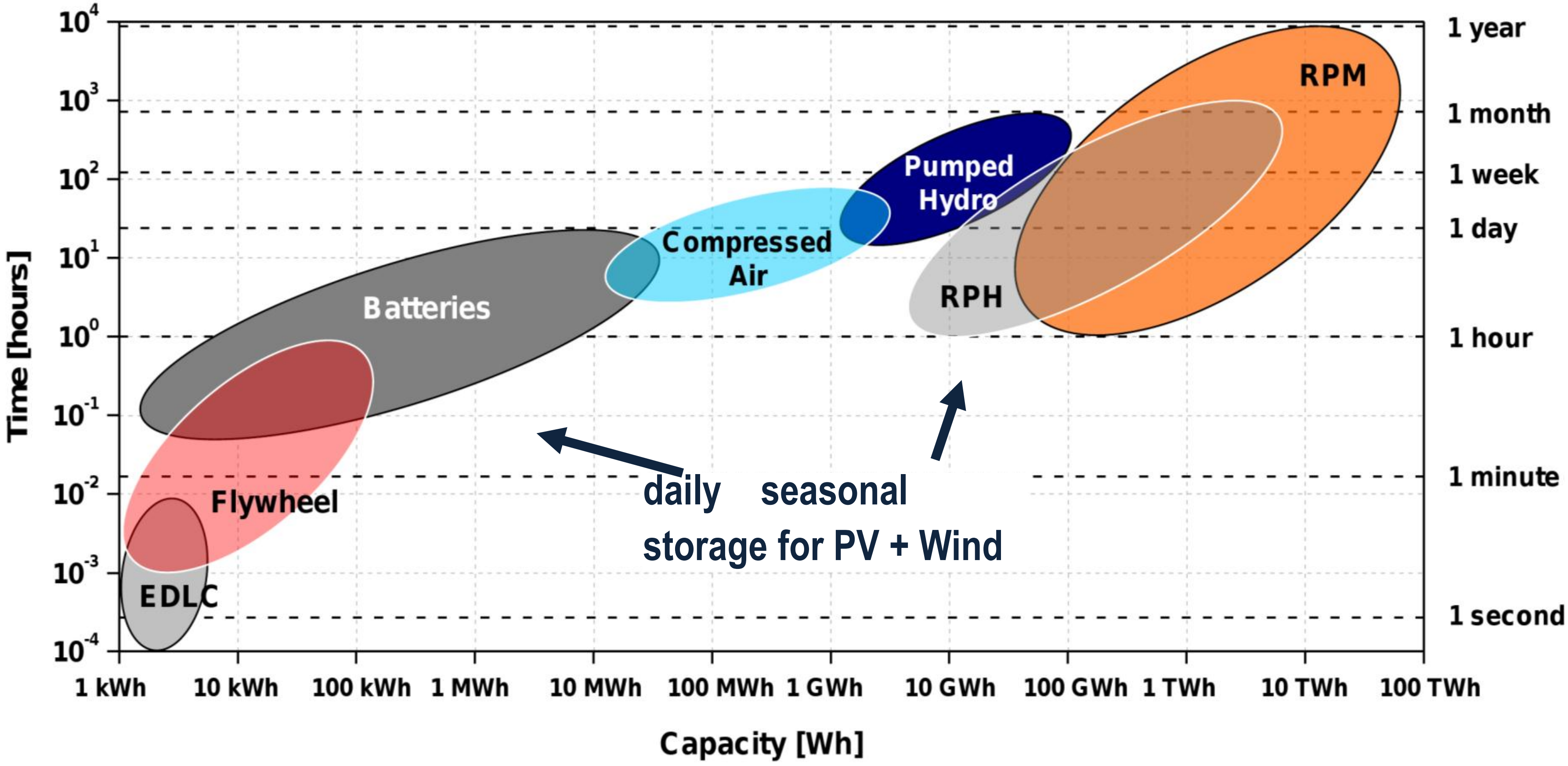

Chemistry
AIR
AIR
CO_2
CO_2
H_2
CH_4

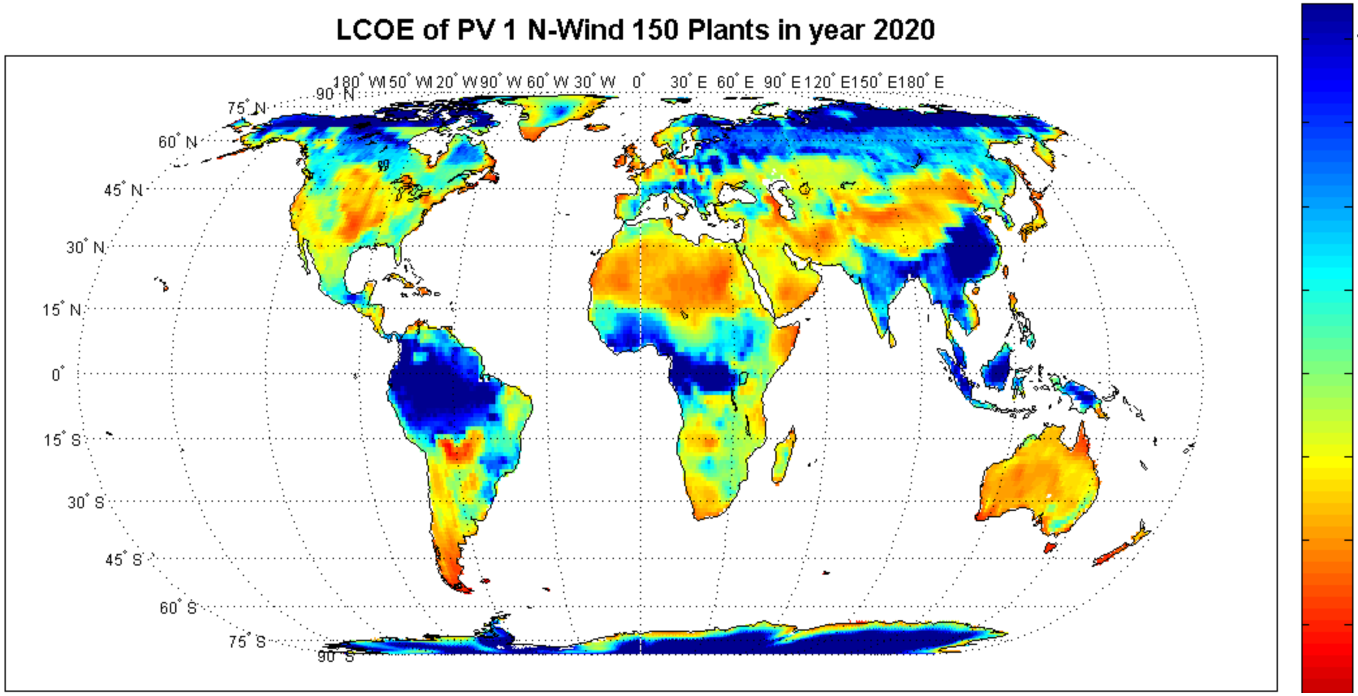
Overview on storage options

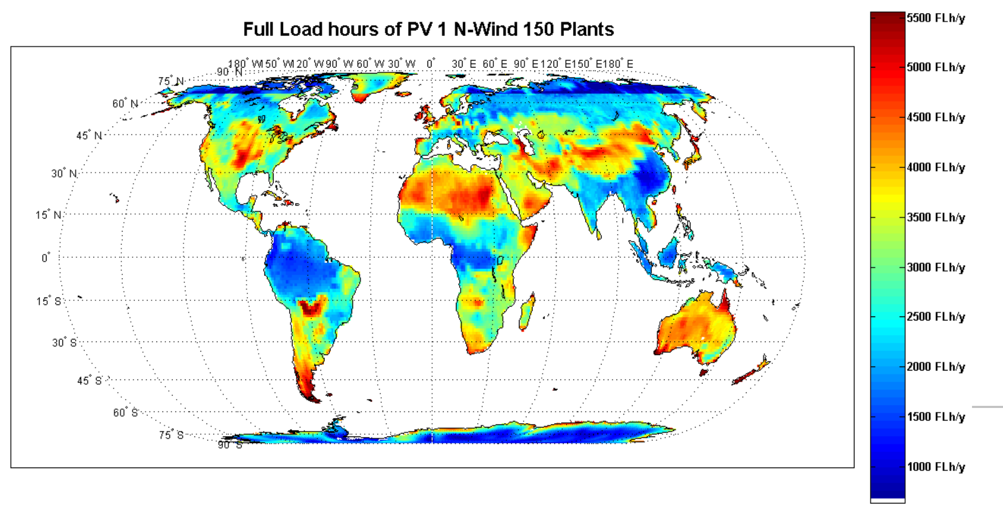


source: Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5-9

RPM: most relevant TWh seasonal storage (Capex, Opex, efficiency, infrastructure)

RPM: hybrid PV-Wind power plant basis

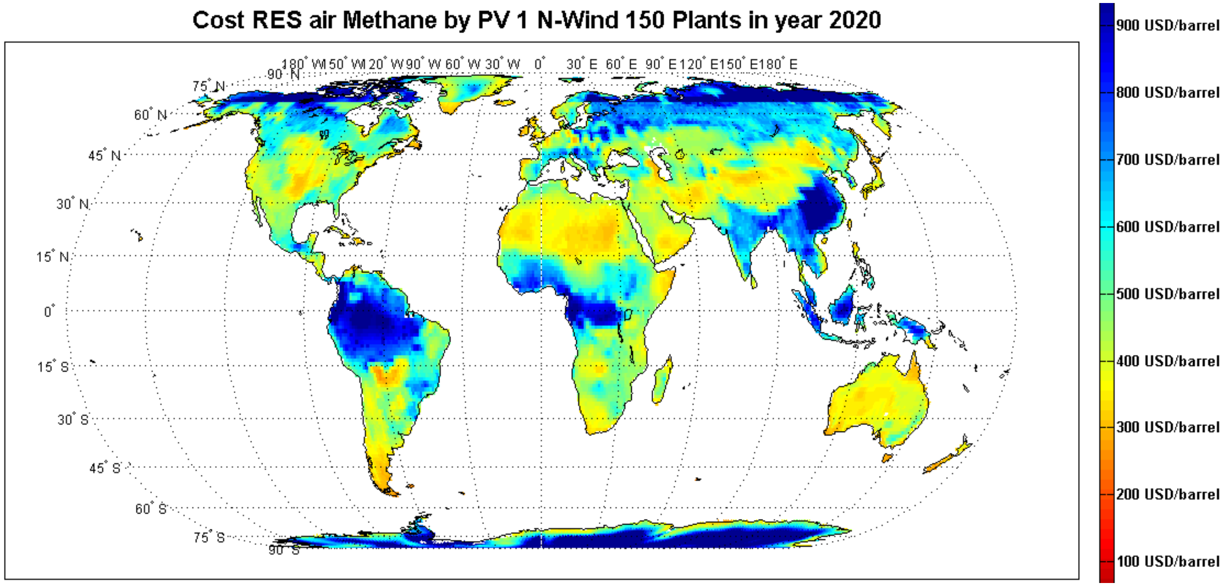




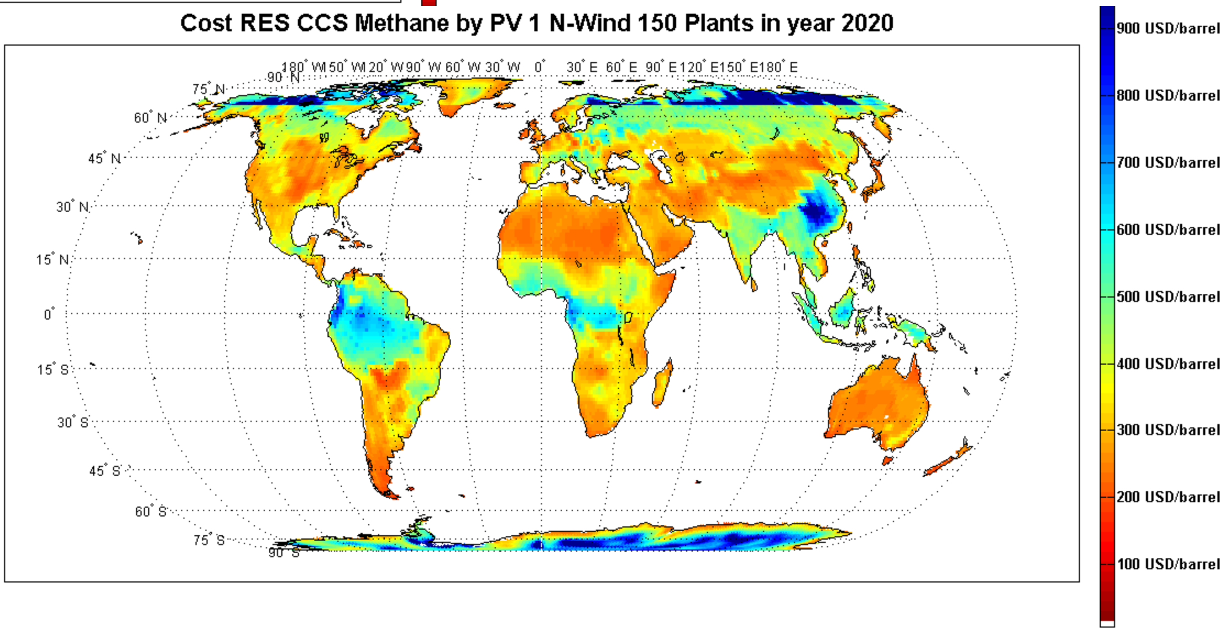
source:
Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5–9

RPM: hybrid PV-Wind power plant basis

Cost RES air Methane by PV 1 N-Wind 150 Plants in year 2020

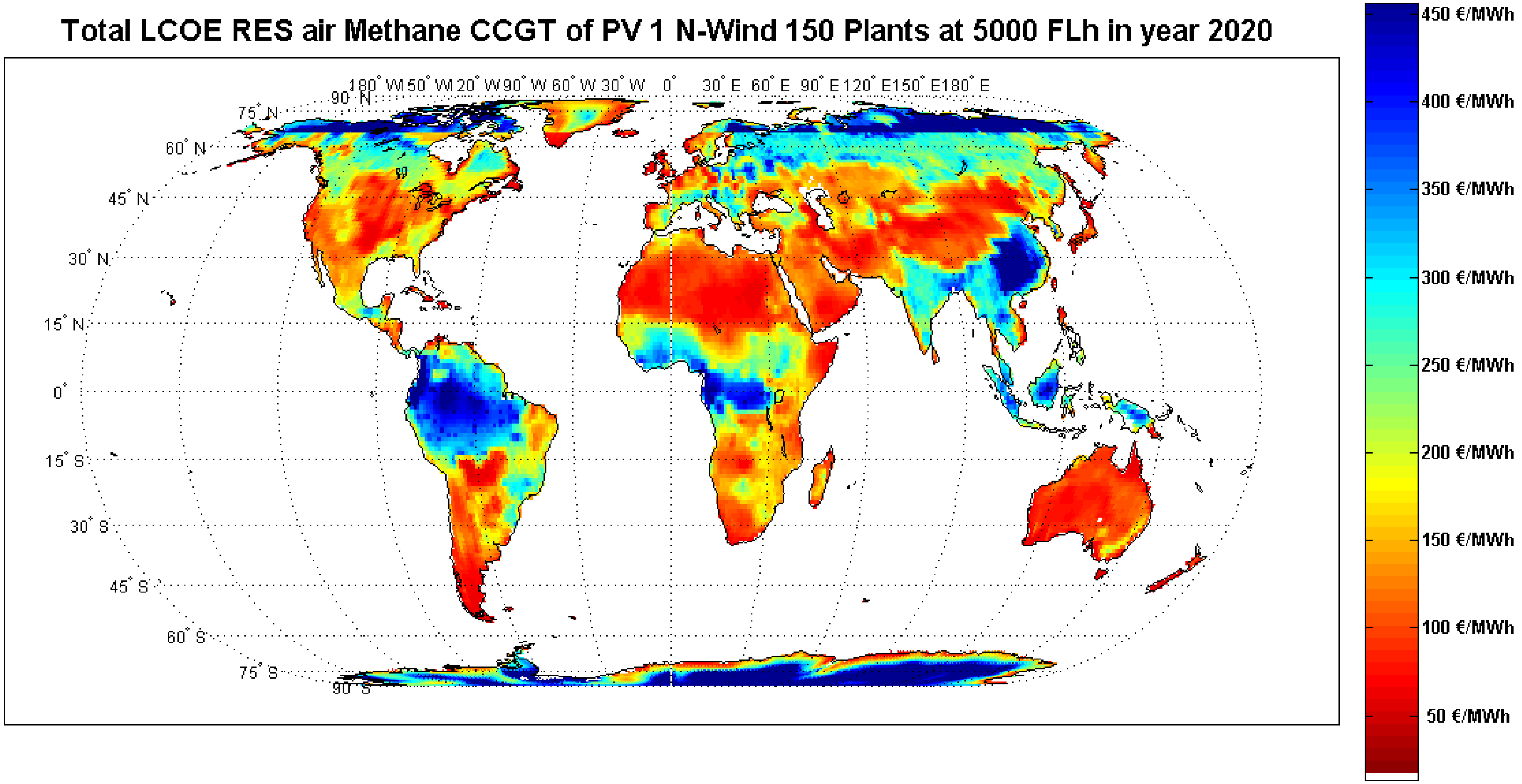


Cost RES CCS Methane by PV 1 N-Wind 150 Plants in year 2020



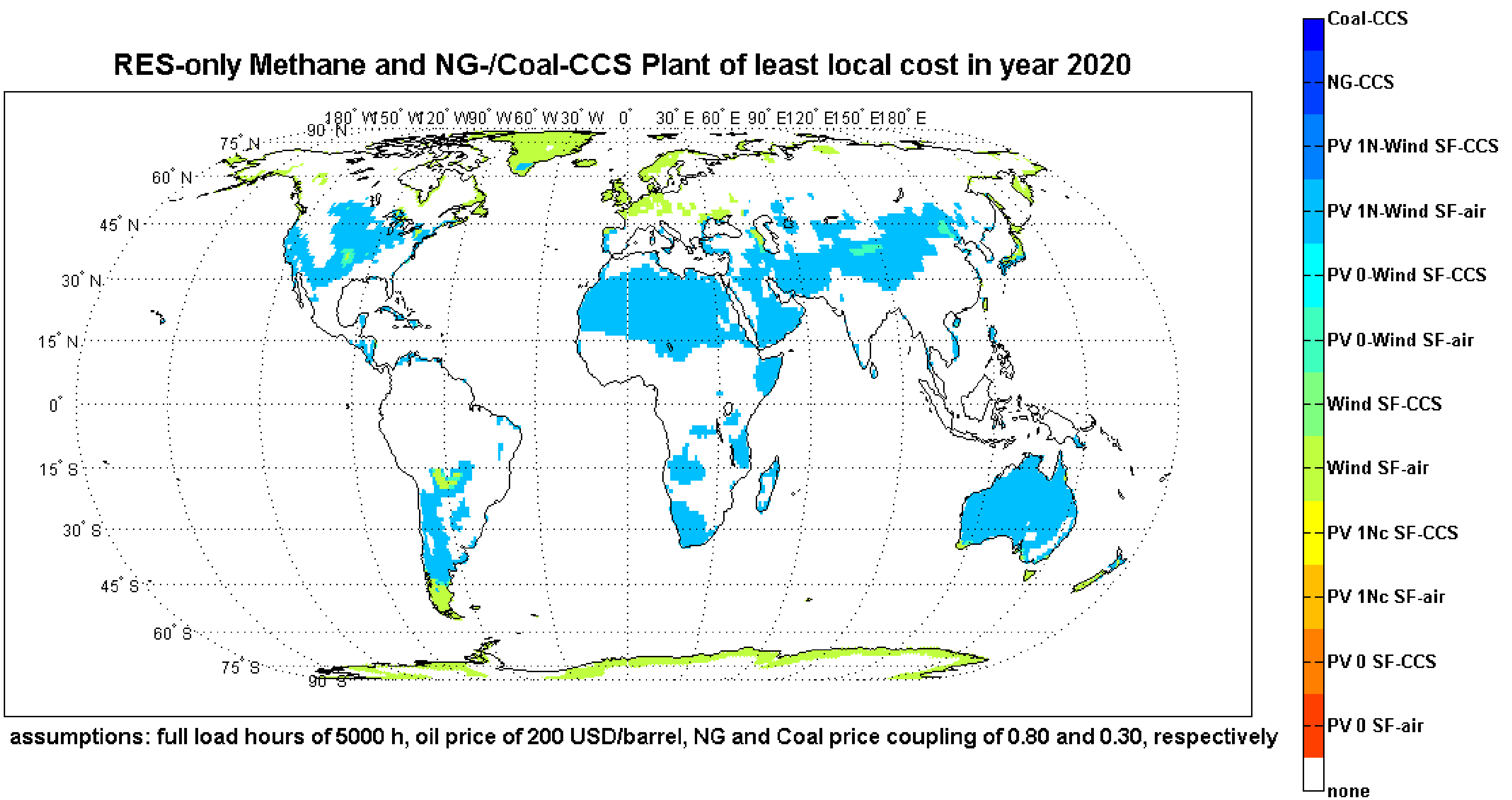
source:
Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5–9

RPM: hybrid PV-Wind power plant basis



source:
Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5–9

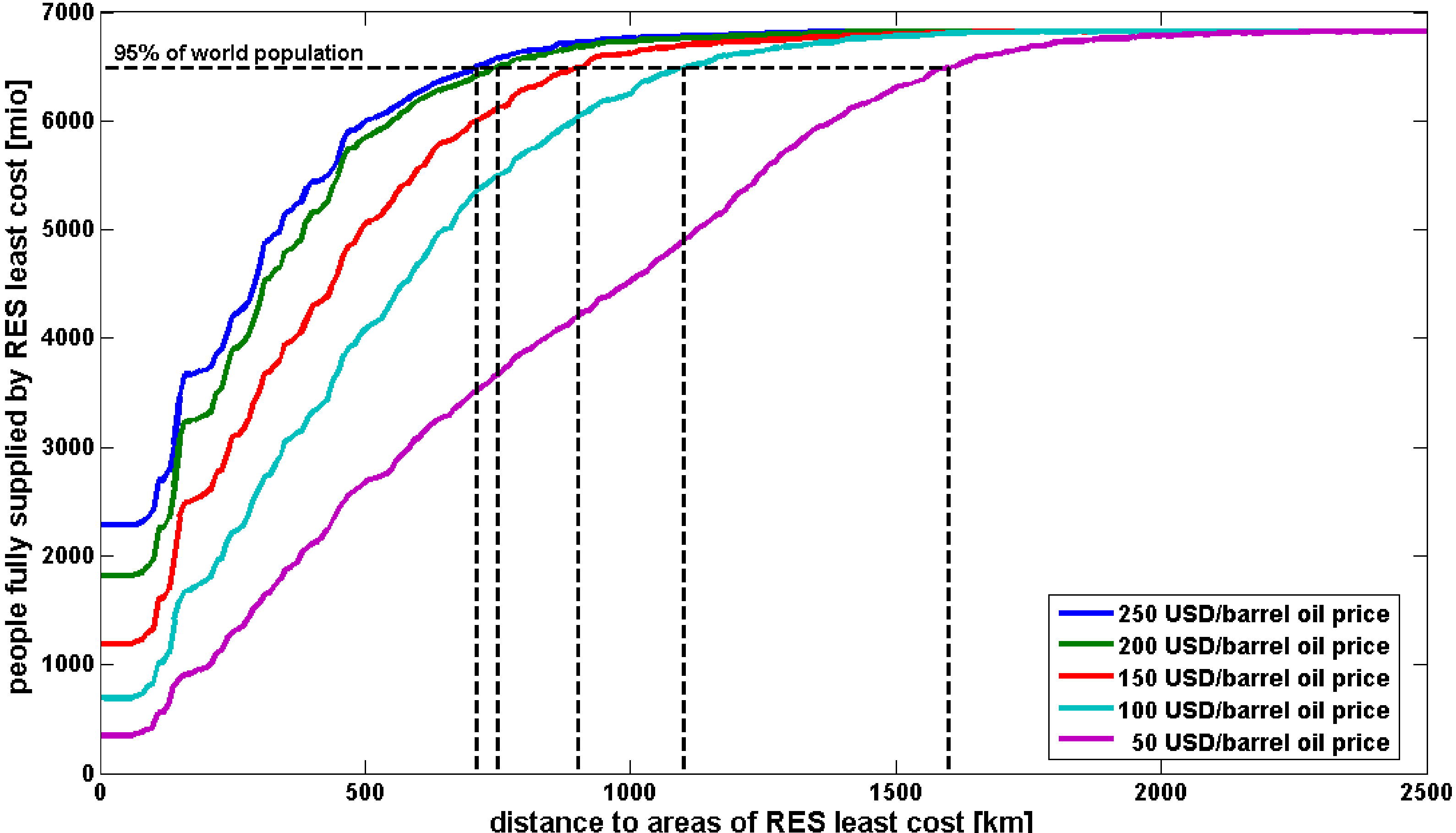
Least LCOE systems as basis for global supply



source:
Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5–9

RPM: hybrid PV-Wind power plant basis

RES least cost supply potential in distance to population at 5000 FLh and various oil price levels



source:
Breyer Ch. et al., 2011. Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg, September 5–9

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Energiewende: 100% EE – Autarkie (Mitteldeutschland)

Speicher, täglich, dezentral

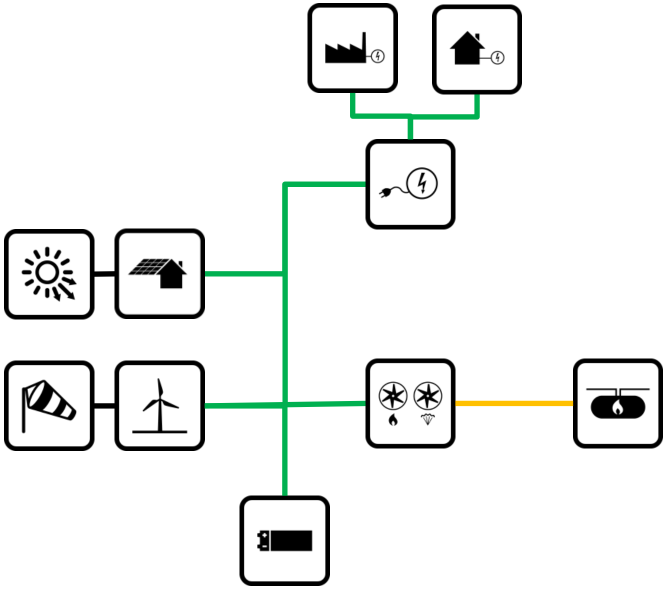
Speicher, täglich, zentral

Methan (Erdgas) GuD-Kraftwerk

Photovoltaik

Windkraft

0% EE
100% Erdgas → 100% EE
0% Erdgas



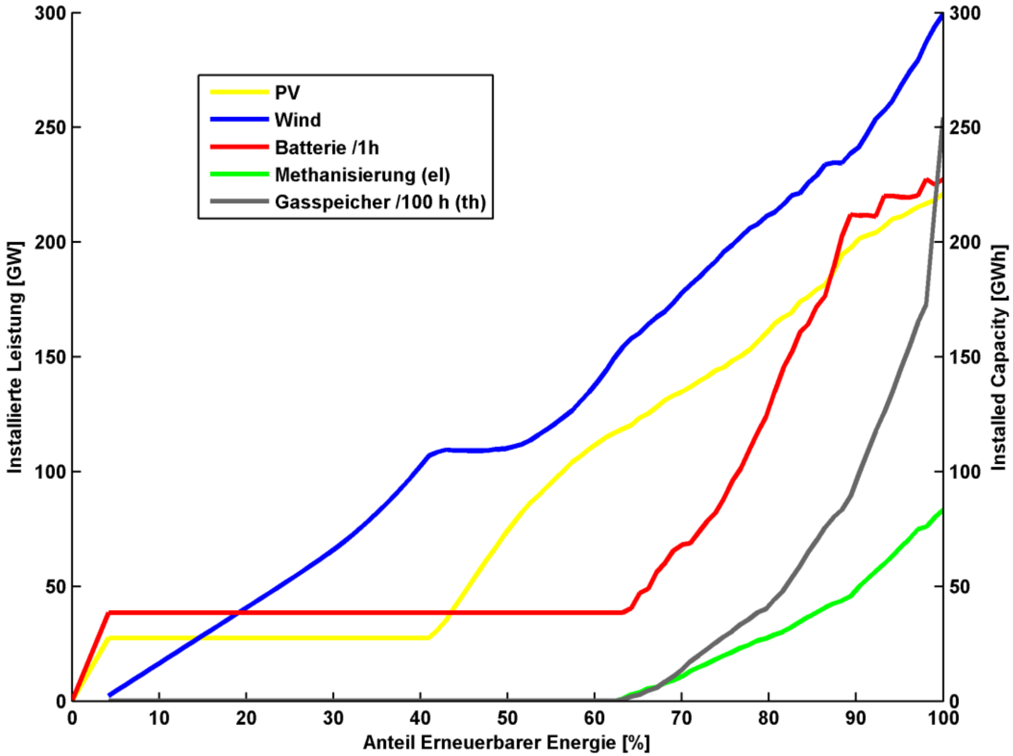
Speicher, saisonal, zentral
EE-Methan Anlage

es fehlen (noch):

- Biogas dezentral/ Biomethan zentral
- Wasserkraft
- Kopplung Wärme
- Kopplung Mobilität
- Kopplung Verbundnetz

Quelle: Gerlach A.-K. und Breyer Ch., 2012. PV und Windkraft: sich ergänzende Technologien, 27. Symposium PV, Staffelstein

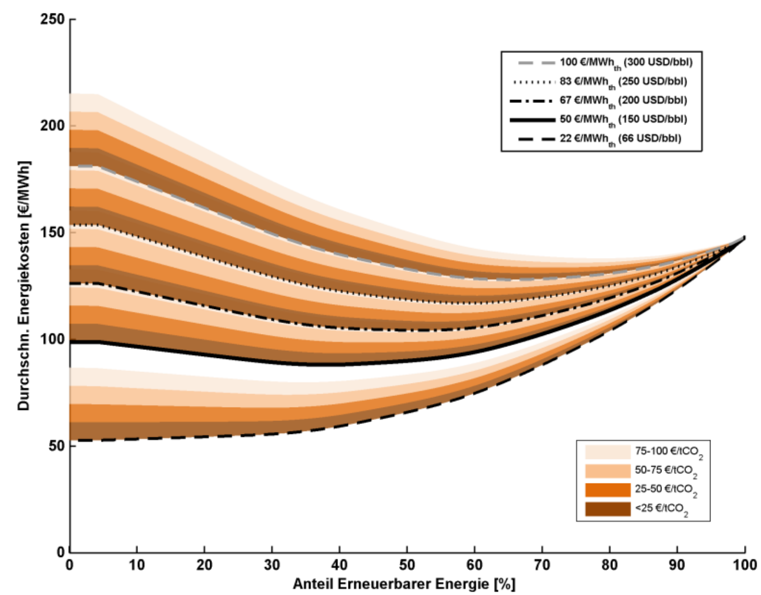
Energiewende 2020: 100% EE - Autarkie



Annahmen:

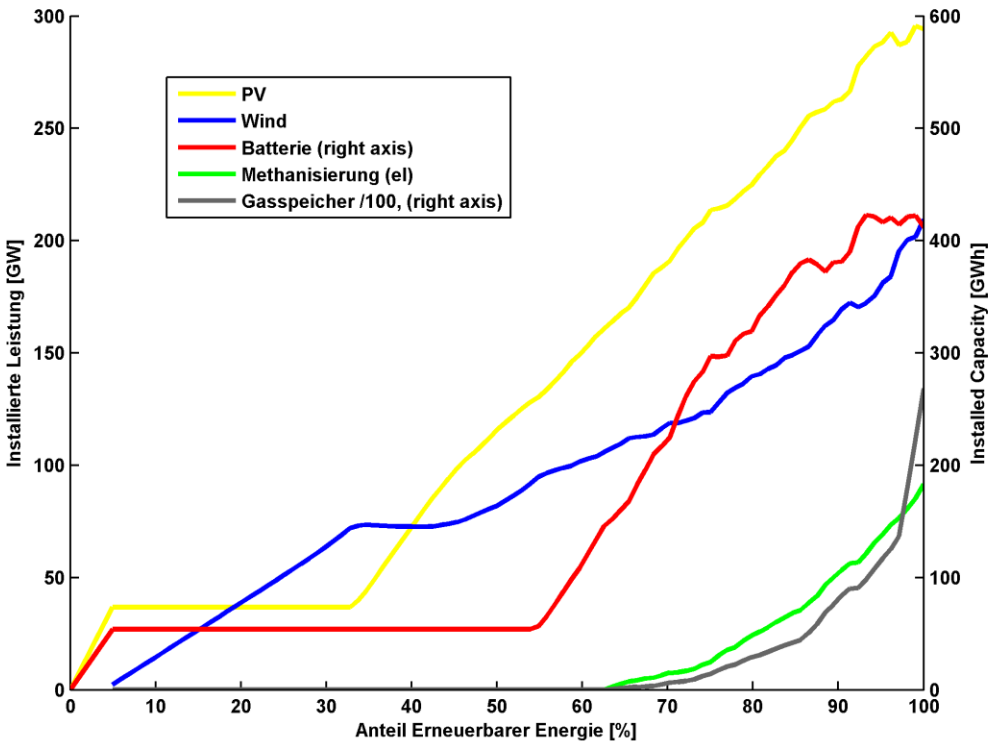
- PV plus Speicher Netzparität
- Rest kostenoptimiert Netzebene
- Referenzjahre: 2020 (Kosten EE), 2005 (Wetter), 2010 (Lastgang)
- Capex: PV (1000 €/kW), Wind (1000 €/kW), Batterie (175 €/kWh)
- WACC: 6,4 %
- VLh: PV (~ 1000), Wind (~ 2000)

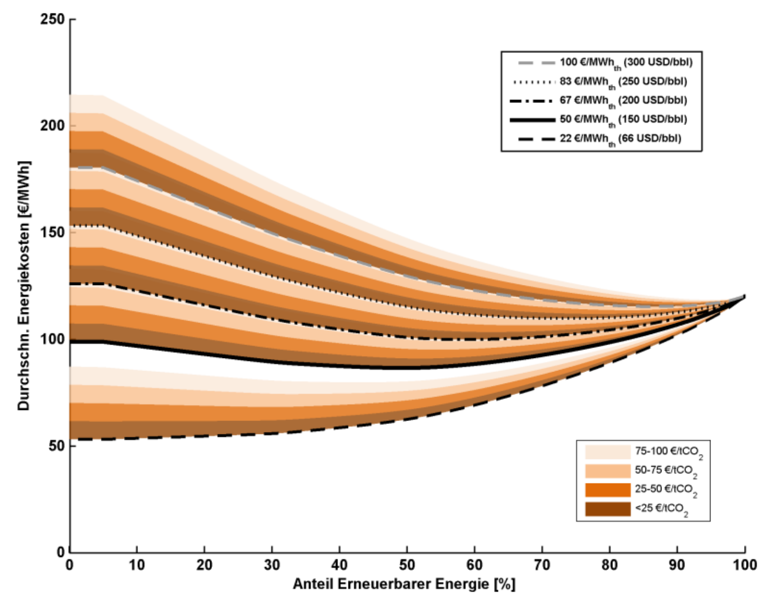
- PV und Windkraft mit vergleichbarer Leistung
- Stundenspeicher erst dezentral dann zentral
- saisonaler Speicher ab 60 - 70 % EE
- die ersten 40 – 50 % EE senken sicher die Kosten



Energiewende 2030: 100% EE - Autarkie

Annahmen:
- PV plus Speicher Netzparität
- Rest kostenoptimiert Netzebene
- Referenzjahre: 2020 (Kosten EE), 2005 (Wetter), 2010 (Lastgang)
- Capex: PV (730 €/kW), Wind (1000 €/kW), Batterie (100 €/kWh)
- WACC: 6,4 %
- VLh: PV (~ 1000), Wind (~ 2000)





- PV und Windkraft mit vergleichbarer Leistung
- Stundenspeicher erst dezentral dann zentral
- saisonaler Speicher ab 60 - 70 % EE
- die ersten 80 % EE sind kostenneutral

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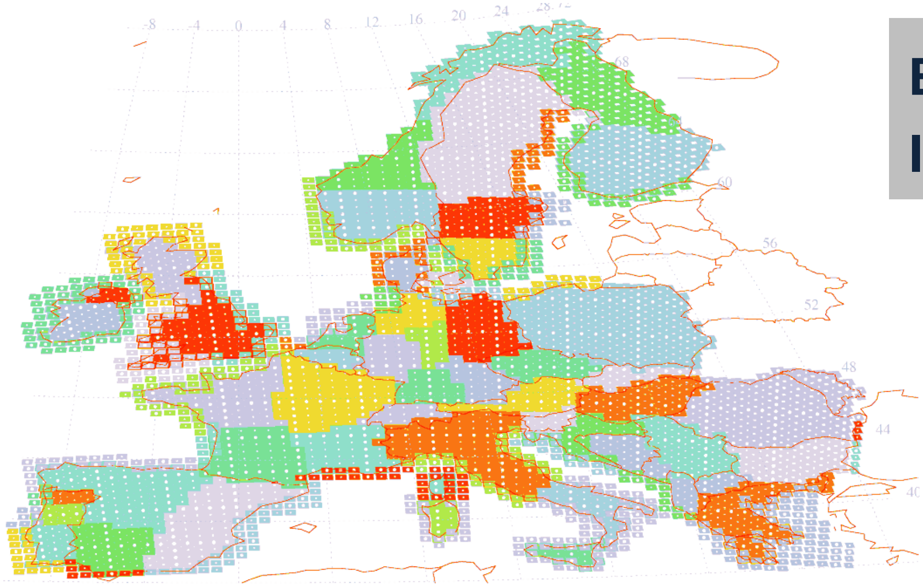
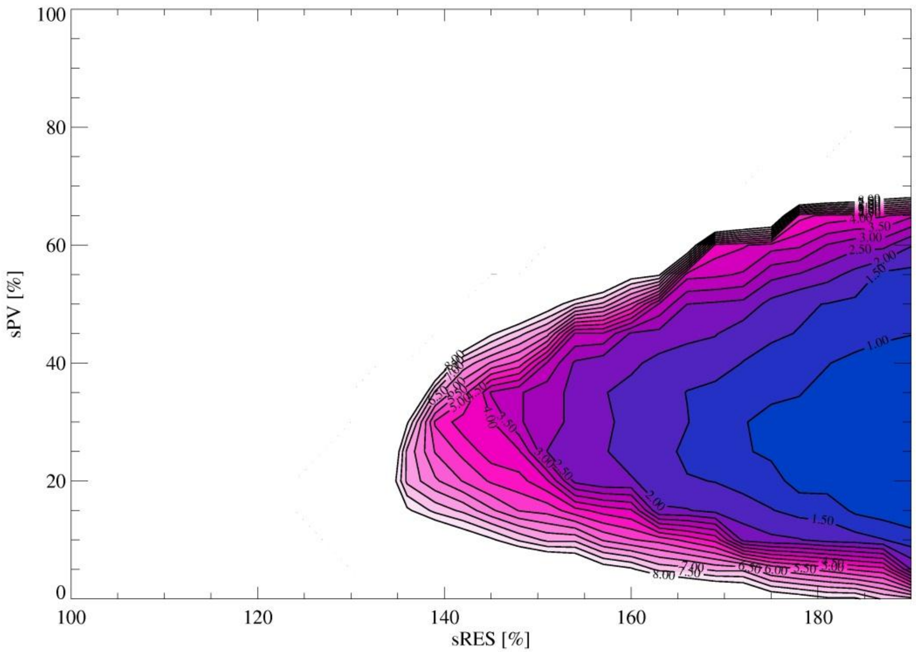
Europe: Growth limits for PV

PV potential in Europe assuming excellent grids and substantial storage



EPIA PV target 2020: 12% of supply
It might be too conservative!



20 - 50% PV supply in the European electricity system might be possible

source: Hoffmann C., 2008. IRES-III Berlin
(study by Siemens and FhG-IWES)

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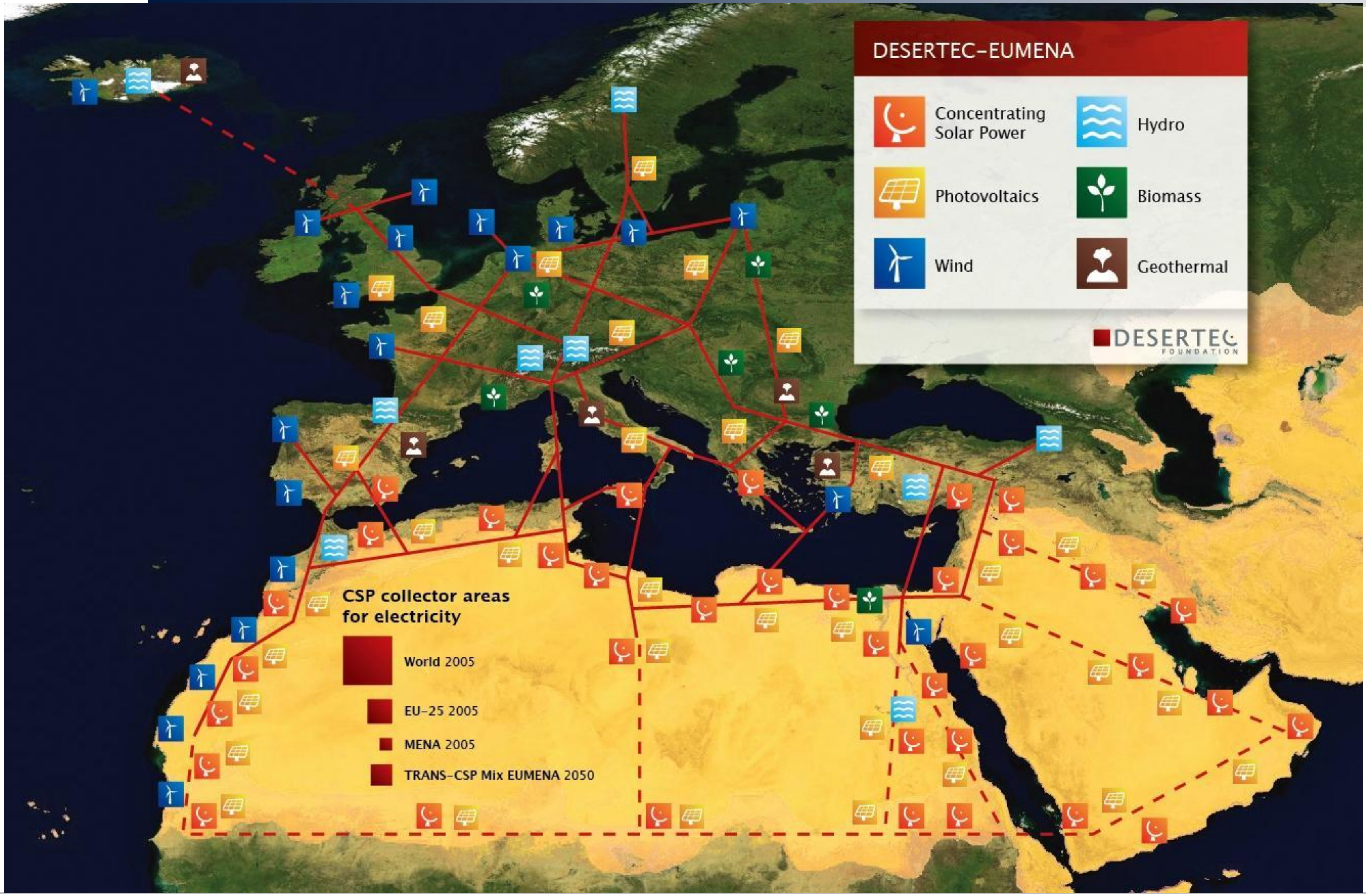
DESERTEC concept: Major Technologies

DESERTEC concept for EU-MENA



source: DESERTEC, 2009

Grand Solar Plan for the US

50% solar electricity supply target
(25% by PV and 25% by solar thermal)

source: Fthenakis V., 2008. 25th PVSEC Valencia

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Summary

- ongoing fast PV cost reduction is very likely
- high (economic) demand for adapted off-grid PV solutions
- 30-40% more tracking yield equals 5-10% lower LCOE
- economic PV market potential by 2020 roughly 2,800 – 4,300 GWp
- cumulative installed capacity by 2020 roughly 600 – 1,600 GWp
- PV and wind power complement each other perfectly
- renewable power methane may become an attractive storage option
- >95% of mankind live <1,000 km to least cost PV-Wind-RPM-CCGT sites

Thanks for your attention.

… and in particular to Alexander Gerlach, Marzella Görig, Ann-Katrin Gerlach, Chris Werner, Friederike Kersten, Achim Reiß, Till Utermöhlen and Ina von Spies for contribution and support.

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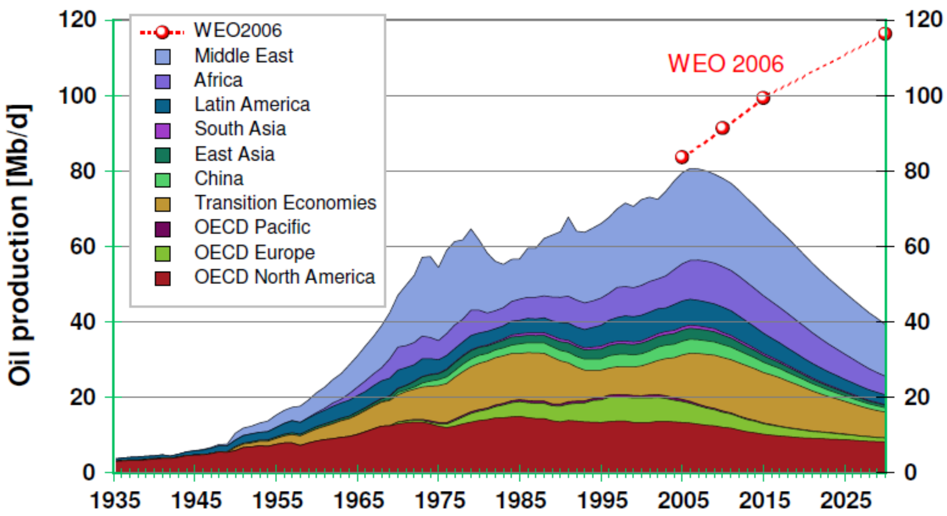
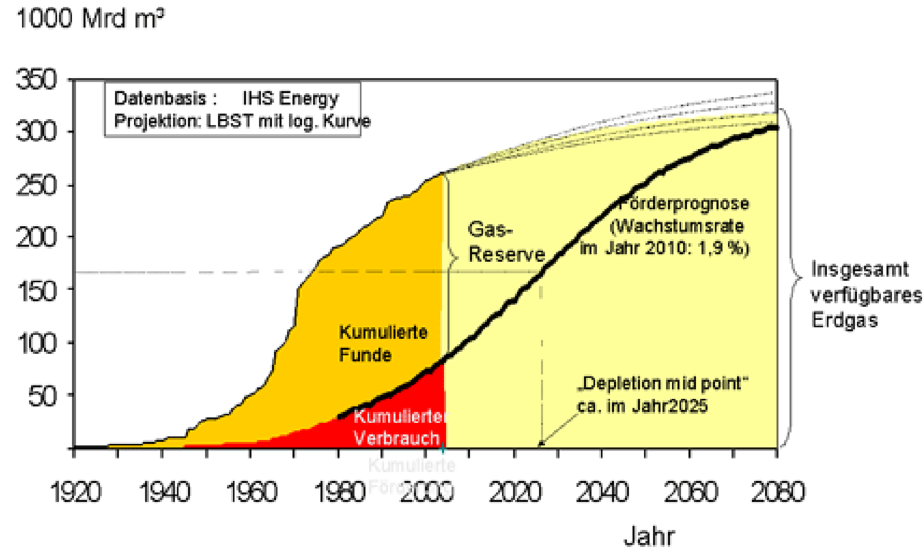
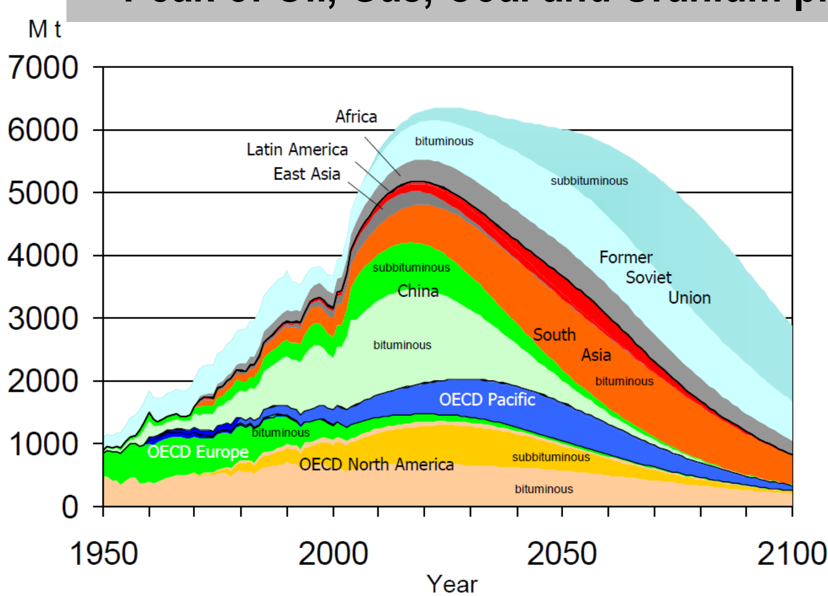
Backup

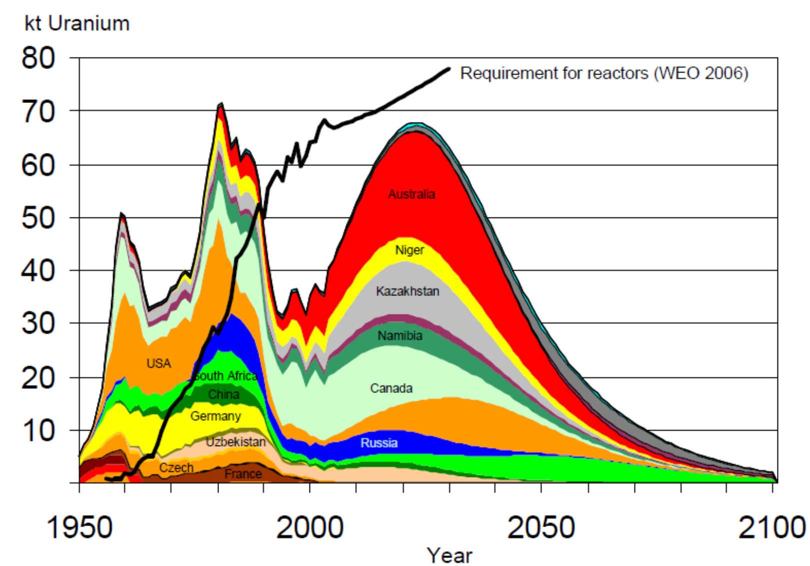
Electricity Constraints: Diminishing Energy Fuels



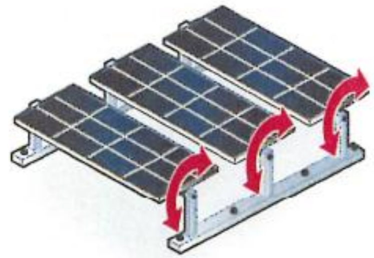


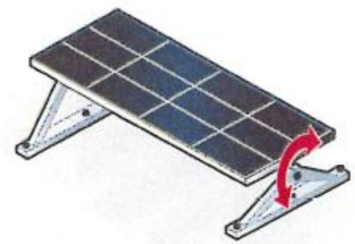
Peak of Oil, Gas, Coal and Uranium production within next 5 – 25 years (very likely)





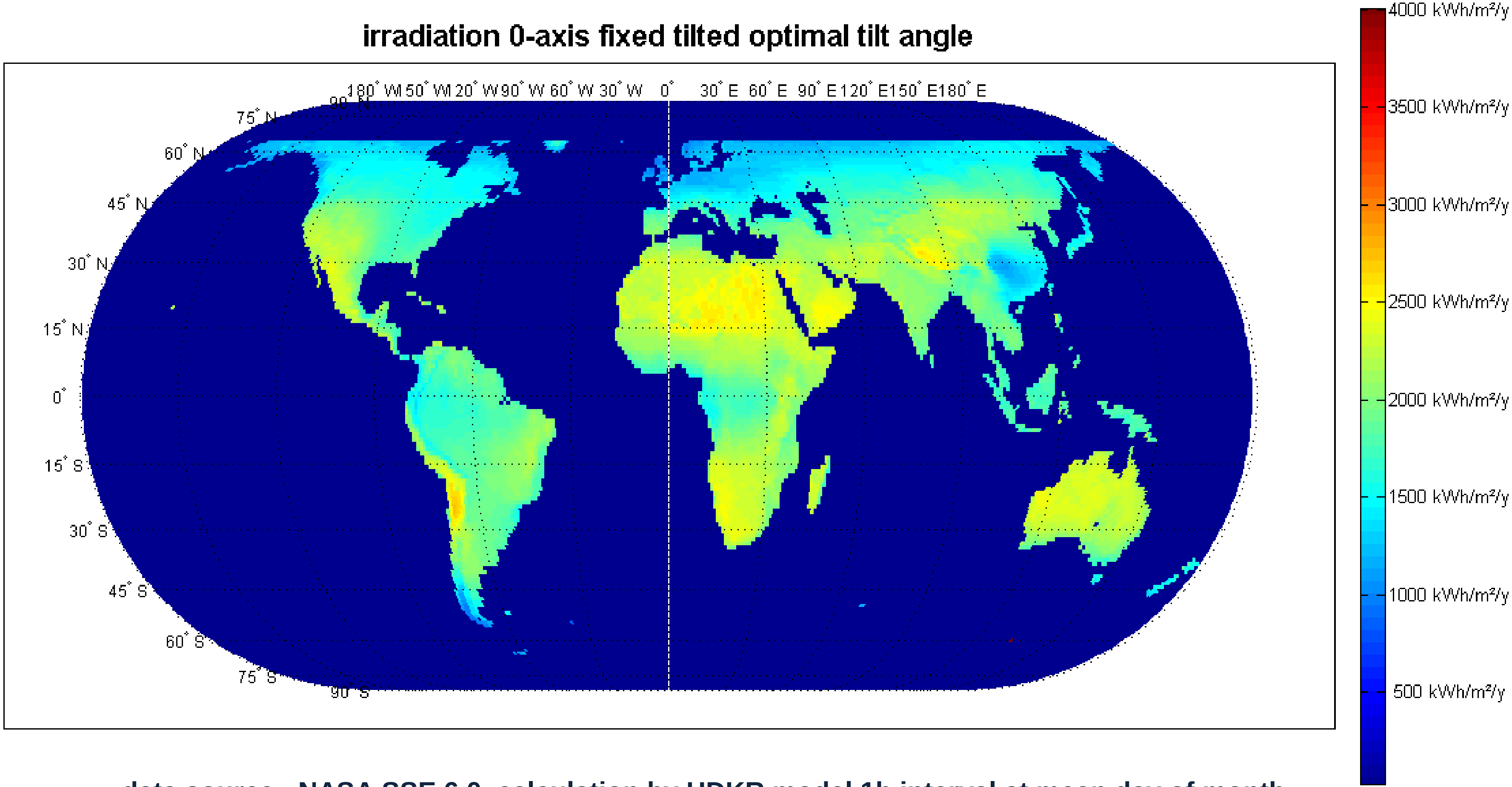
Major Tracking Systems





0-axis fixed tilted
1-axis horizontal
1-axis tilted
1-axis vertical
2-axes

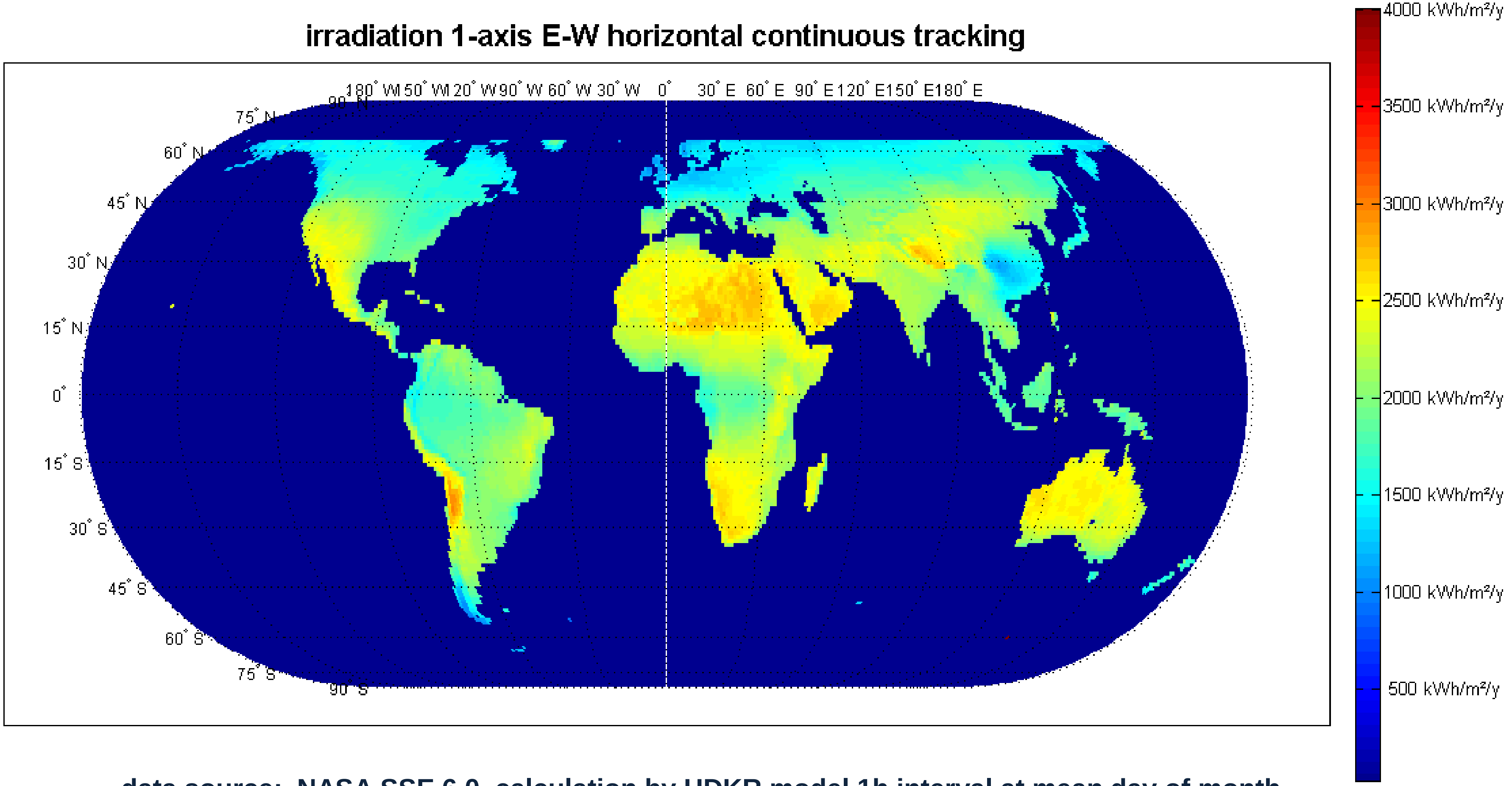
Irradiation: Fixed Tilted at Optimal Tilt Angle



data source: NASA SSE 6.0, calculation by HDKR model 1h interval at mean day of month for all months of the year

source: Breyer Ch. and Schmid J., 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 PVSEC/ WCPEC-5, Valencia, September 6–10

Irradiation: 1-axis E-W Horizontal Continuous



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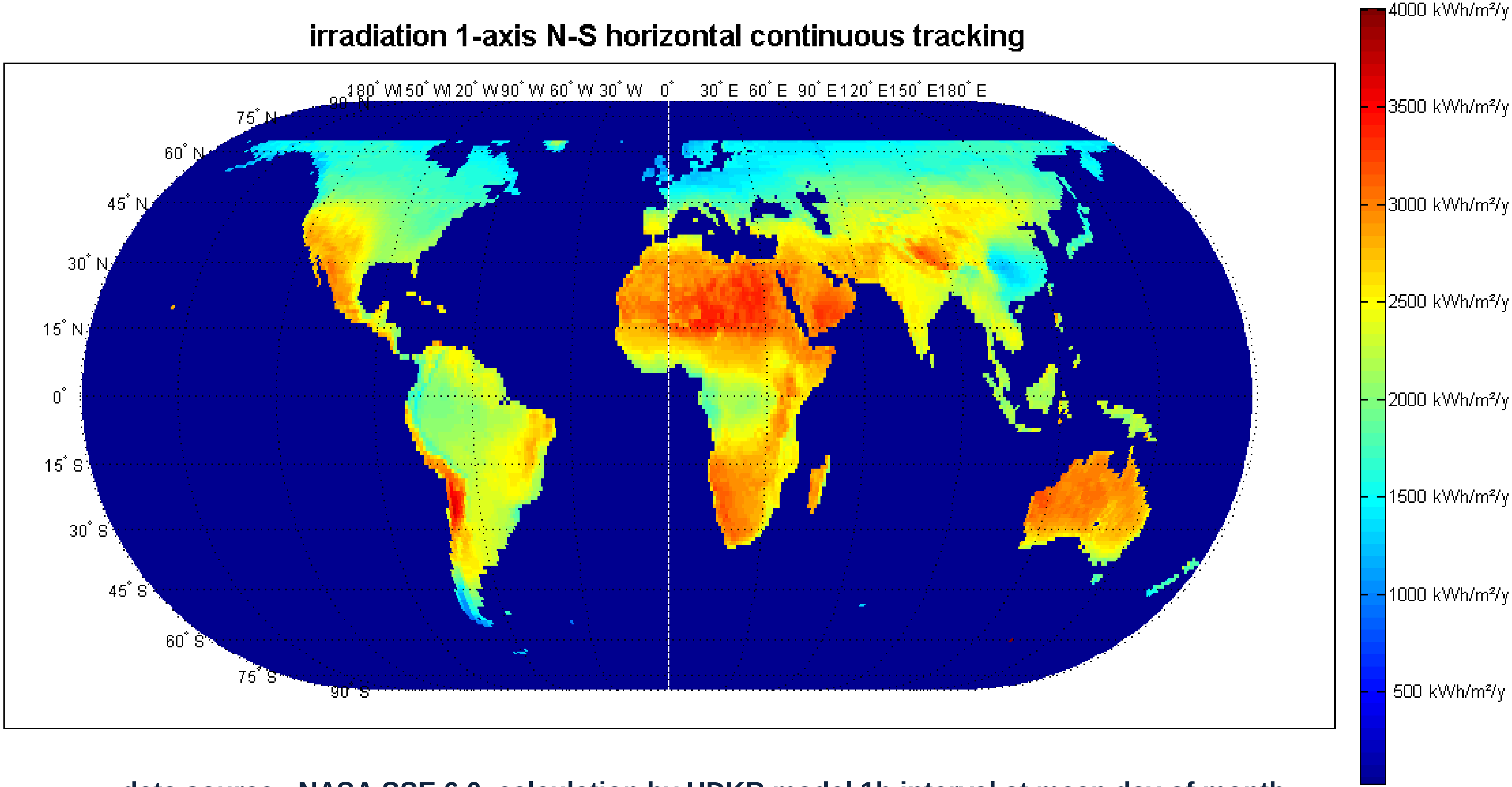
source: Breyer Ch. and Schmid J., 2010. Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, 25th PVSEC/ WCPEC-5, Valencia, September 6–10

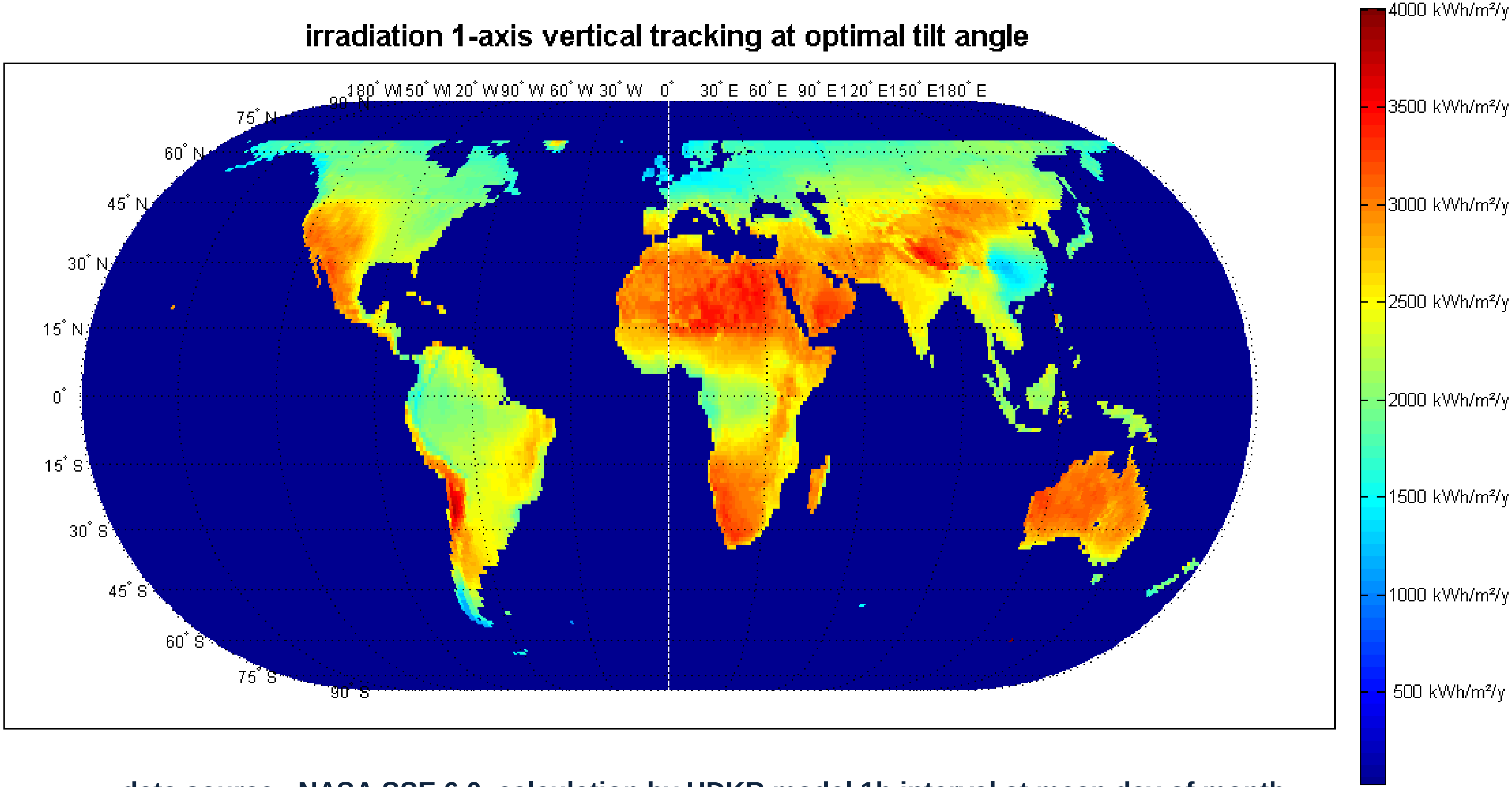
Irradiation: 1-axis N-S Horizontal Continuous



data source: **NASA SSE 6.0, calculation by HDKR model 1h interval at mean day of month for all months of the year**

source: **Breyer Ch. and Schmid J., 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 PVSEC/ WCPEC-5, Valencia, September 6–10**

Irradiation: 1-axis Vertical at Optimal Tilt Angle



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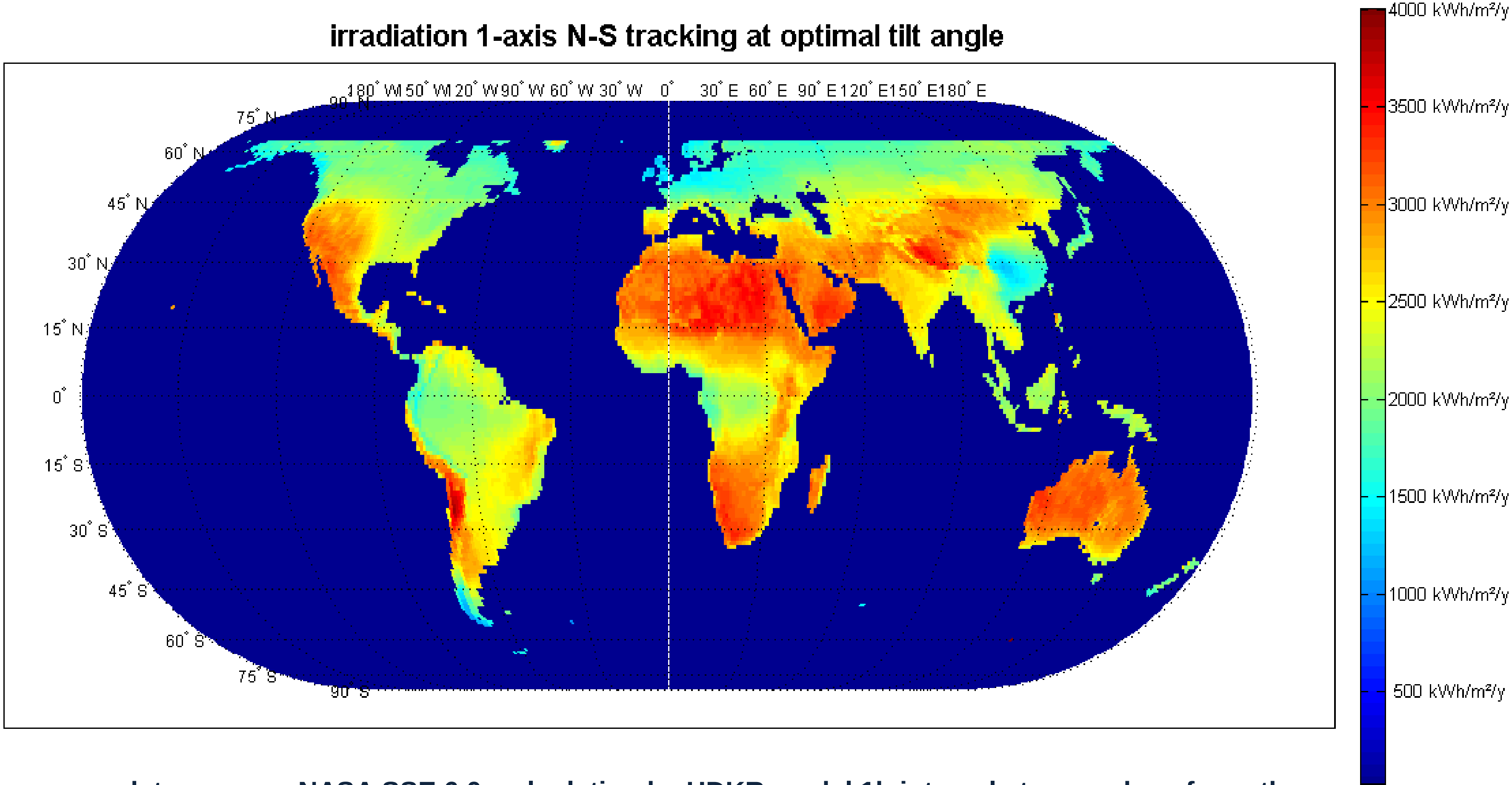
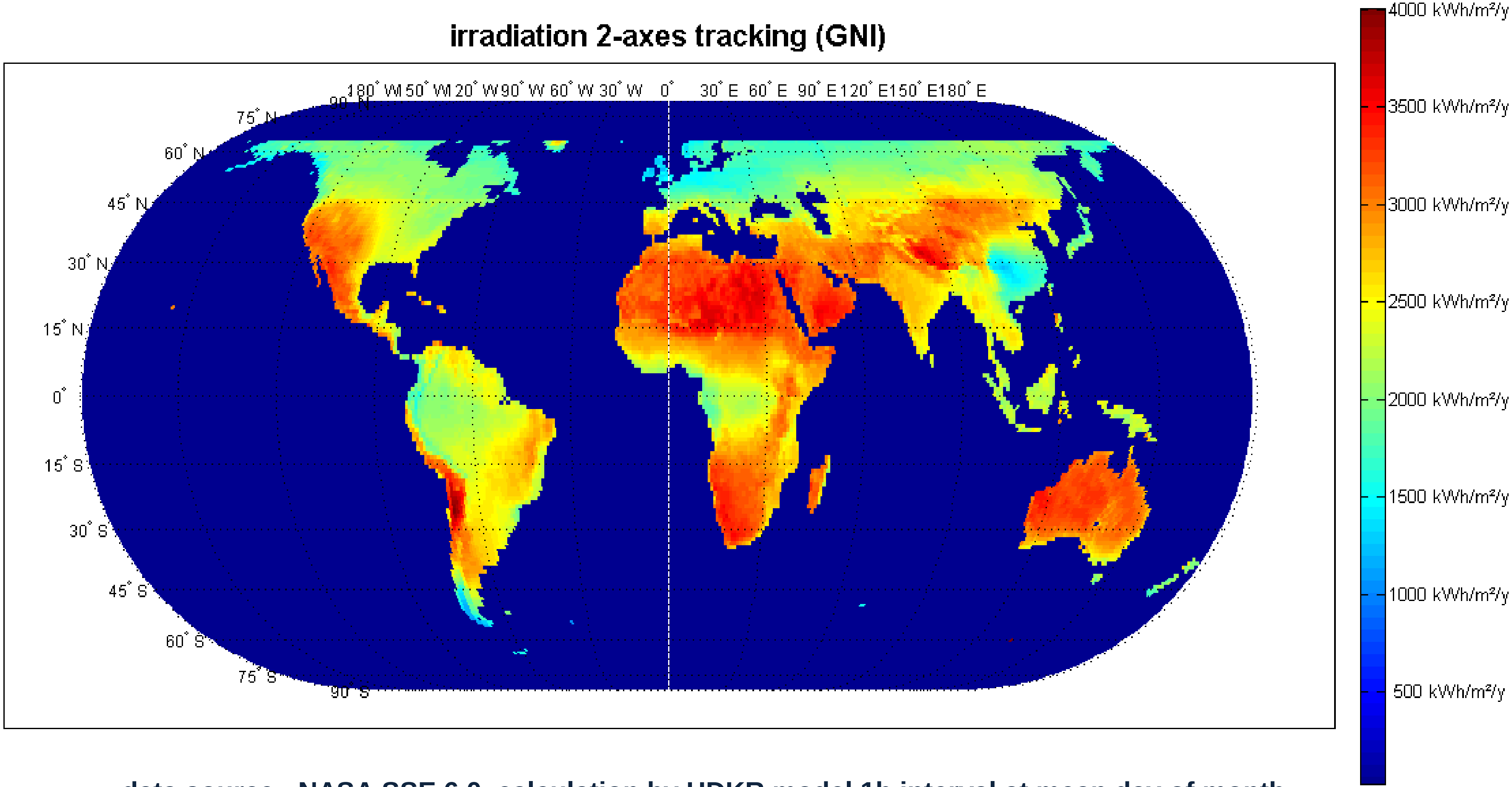
Irradiation: 1-axis N-S at Optimal Tilt Angle



data source: NASA SSE 6.0, calculation by HDKR model 1h interval at mean day of month for all months of the year

source: Breyer Ch. and Schmid J., 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 PVSEC/ WCPEC-5, Valencia, September 6–10

Irradiation: 2-axes (Global Normal Irradiation)



data source: **NASA SSE 6.0, calculation by HDKR model 1h interval at mean day of month for all months of the year**

source: **Breyer Ch. and Schmid J., 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 PVSEC/ WCPEC-5, Valencia, September 6–10**

LCOE Modell

- generation costs have to be compared to other electricity generation technologies in cost per energy [€/kWh]
- transformation of €/kW in €/kWh: Capex, capital cost, annual cost, full load hours at site

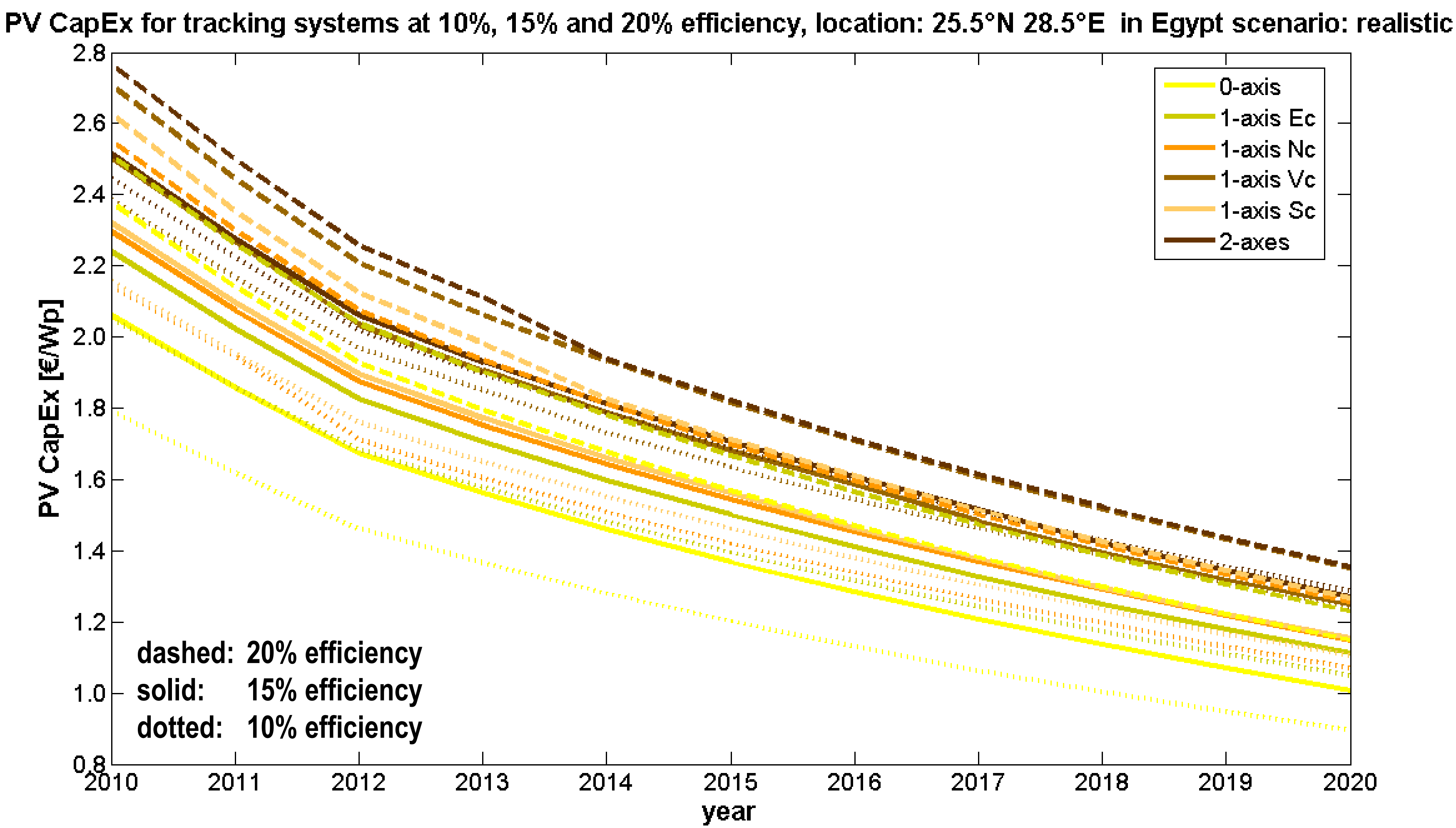
$$\mathrm{LCOE} = \frac{Capex \cdot crf + Opex}{FLh} = \frac{Capex \cdot crf + Opex}{Yref \cdot PR}$$

$$crf = \frac{\mathrm{WACC} \cdot (1 + \mathrm{WACC})^{\mathrm{N}}}{(1 + \mathrm{WACC})^{\mathrm{N}} - 1}$$

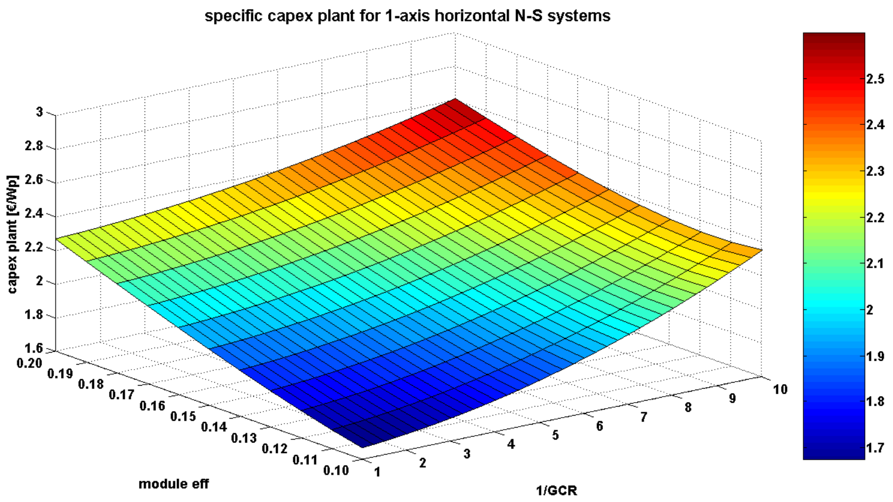
- calculation of LCOE is simplified by
  - neglecting tax rates
  - neglecting system residual value
  - treating annual cost as fixed over lifetime
- abbreviations in formulas
  - crf: capital recovery factor
  - FLh: full load hours
  - Yref: reference yield
  - PR: performance ratio
  - N: lifetime

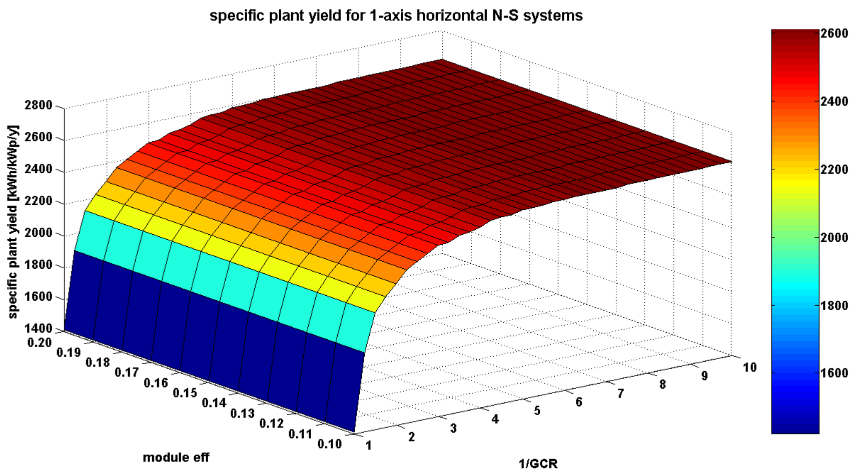
source: NREL, 1995

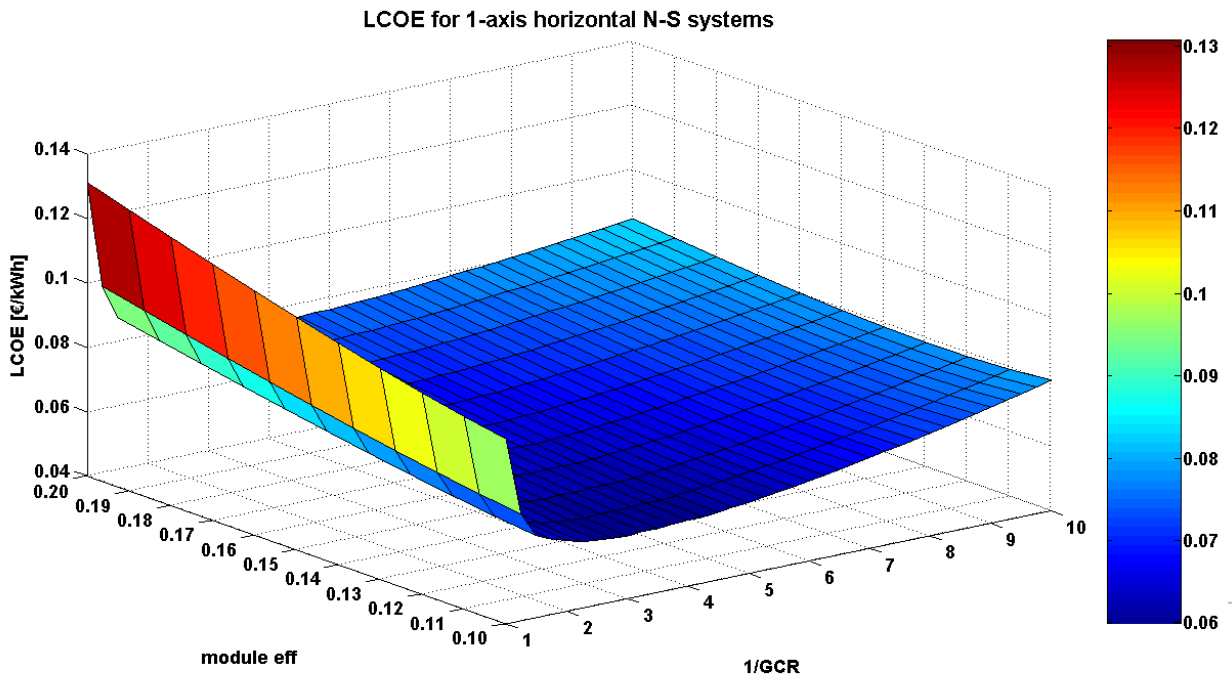
Capex of PV Power Plants in 2010s (realistic)



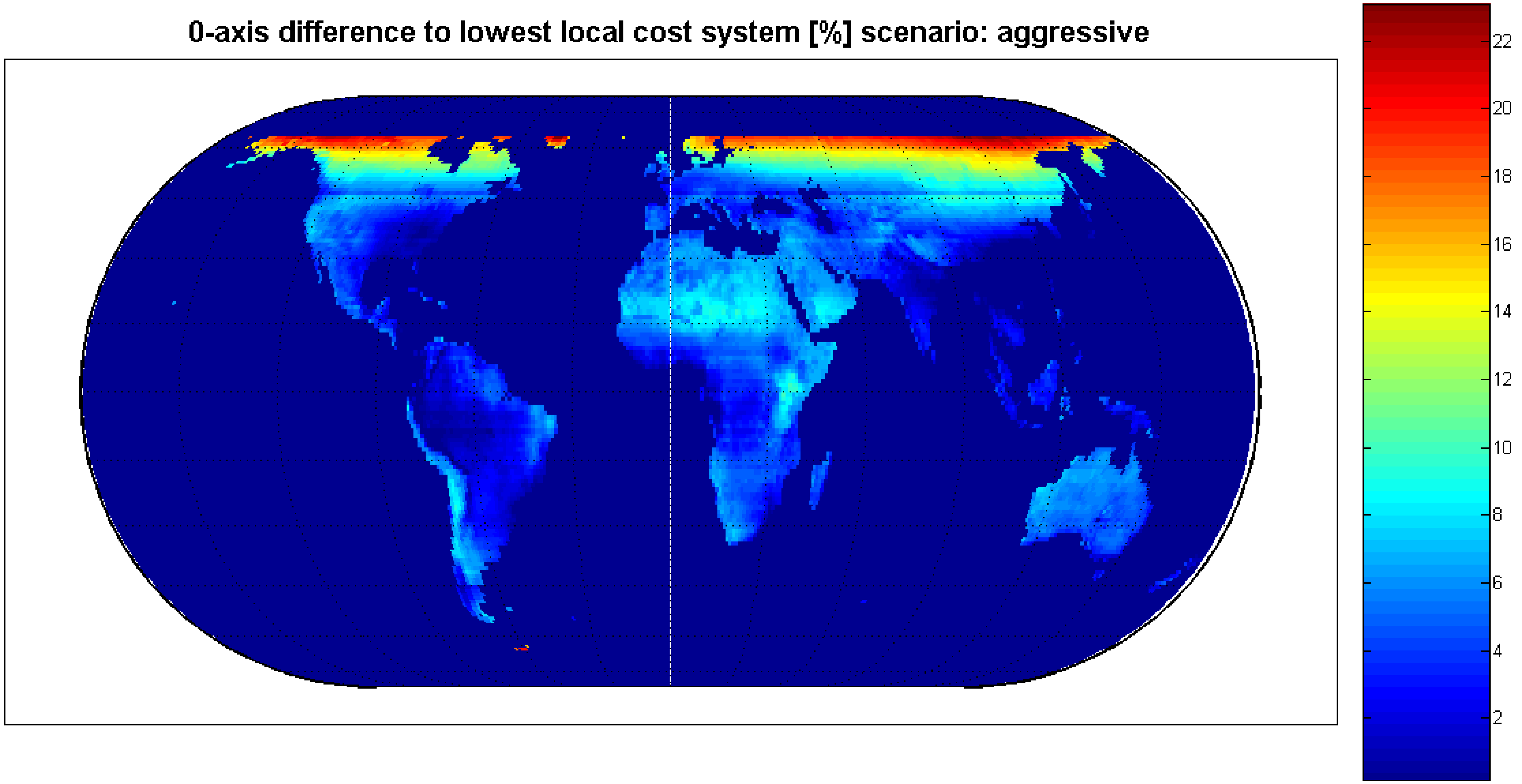
LCOE: Niger/ Sahara – 1-axis N-S (aggressive)



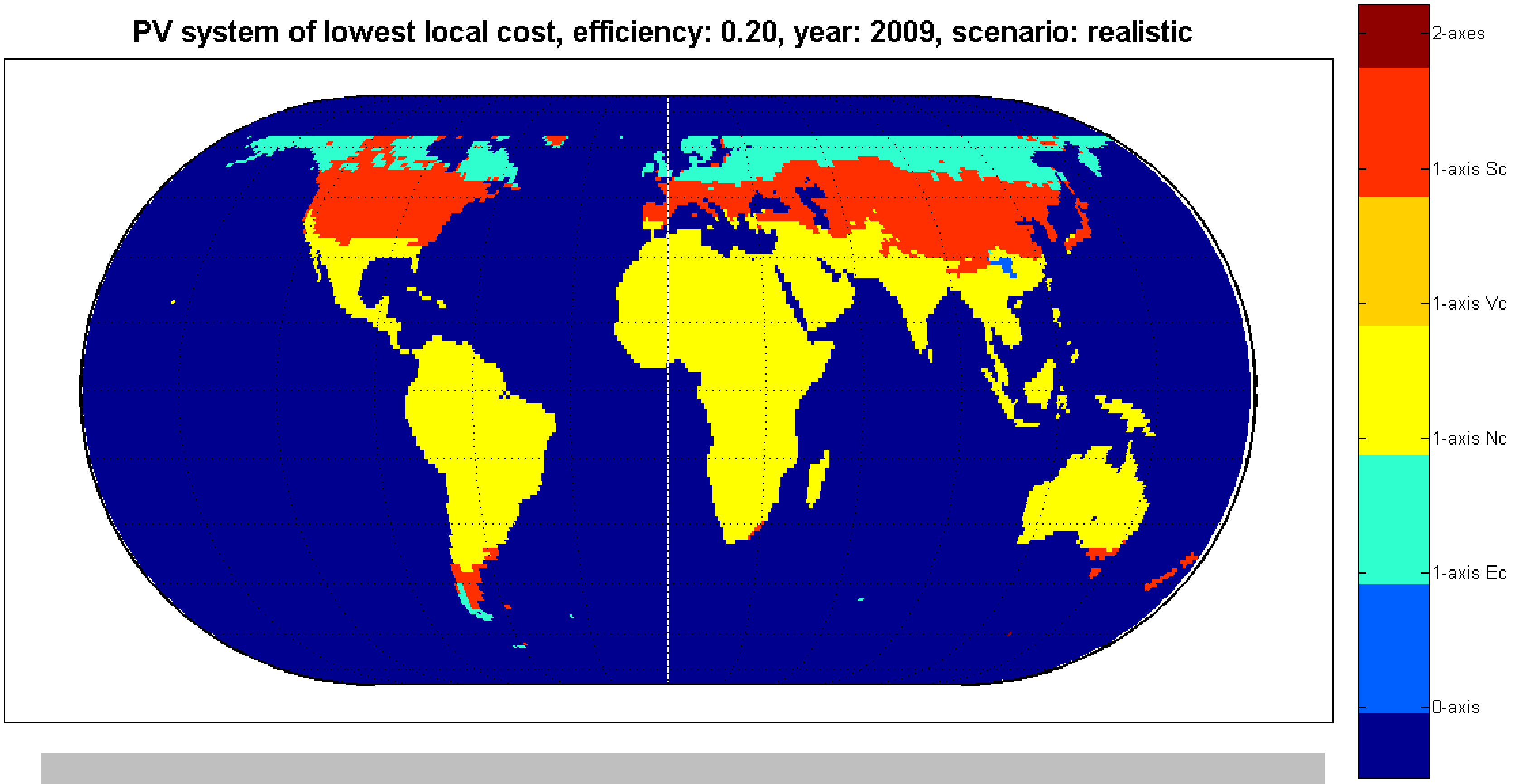




LCOE: Global View 2010 0-axis (aggressive)

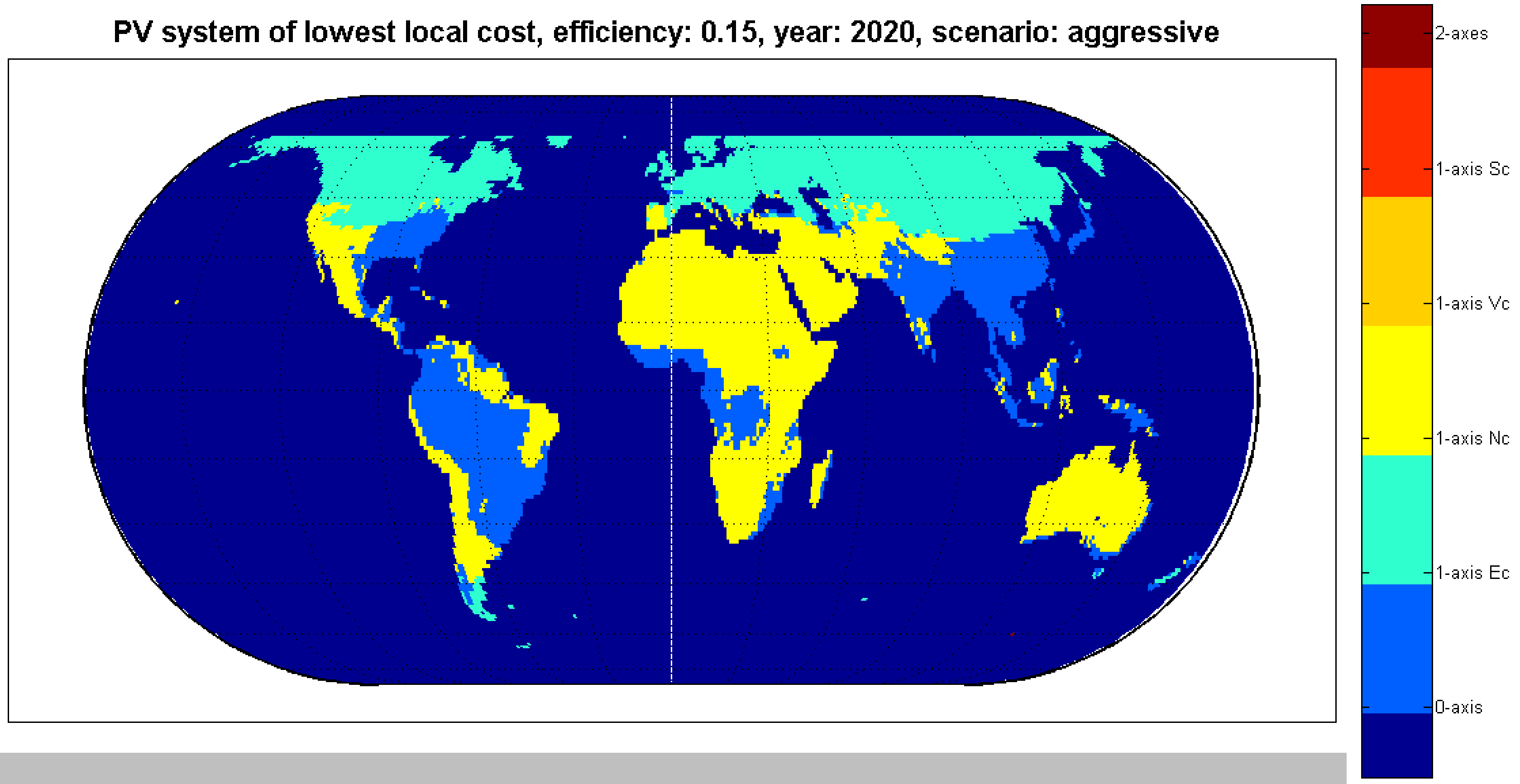


System Dependence on Efficiency: realistic



the higher module efficiency the more least cost sites via tracking

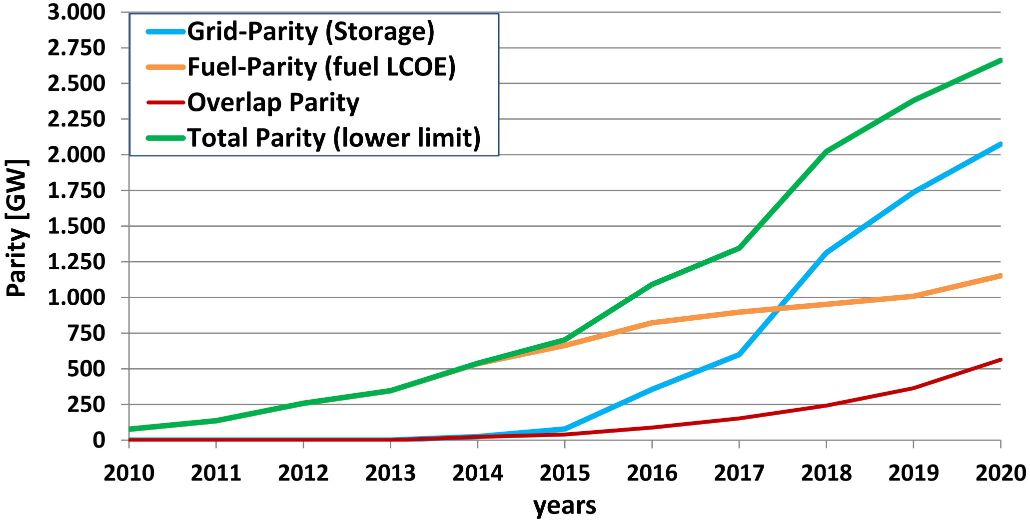
System Dependence on Time: aggressive



cost reduction module > tracking leads to fewer least cost sites via tracking

Total Parity: Grid-Parity and Fuel-Parity

Total Parity Economic Market Potential lower realistic limit
(sceanrio: realistic, LR 20%/15%, storage, fuel LCOE)



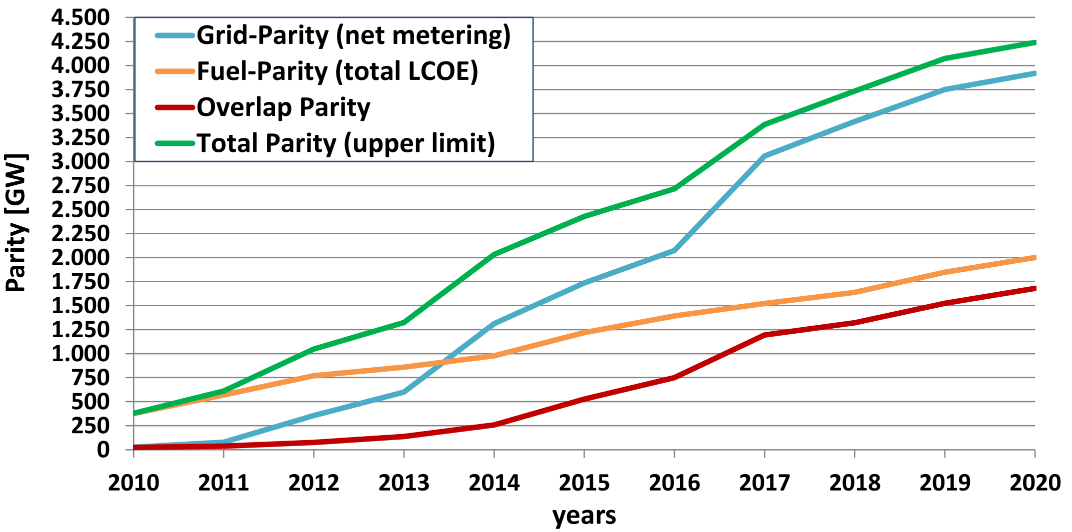
source:

Breyer Ch., 2011. The Photovoltaic Reality Ahead: Terawatt Scale Market Potential Powered by Pico to Gigawatt PV Systems and Enabled by High Learning and Growth Rates, 26th EU PVSEC, Hamburg, September 5–9

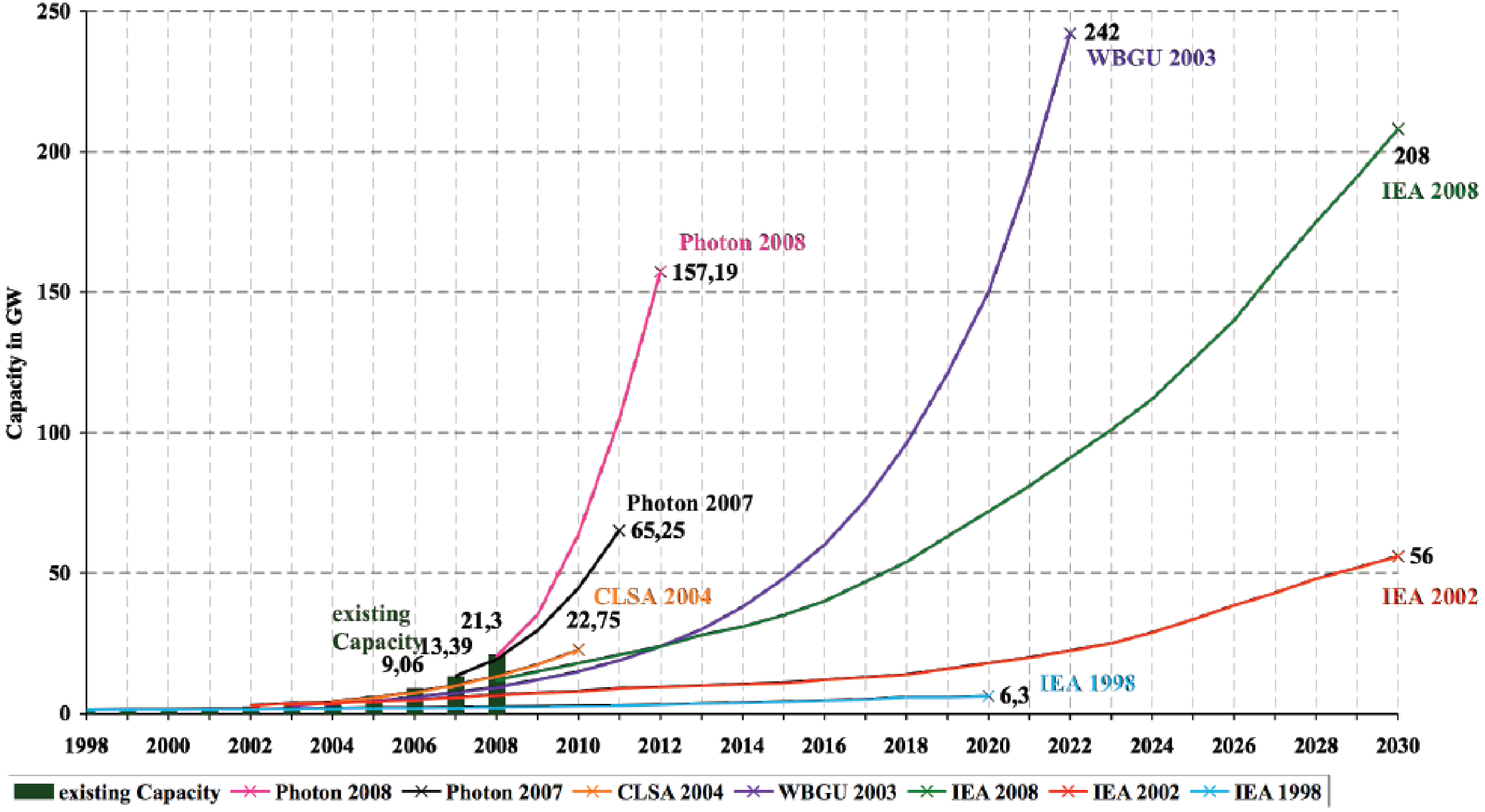
Grid-Parity Analysis	2,000 – 3,900 GWp
Fuel-Parity Analysis	1,200 – 2,000 GWp
Economic Market Potential (on-grid)	2,700 – 4,200 GWp
Economic Market Potential (off-grid)	100 GWp

Pessimistic Case	~20% of Potential:	~600 GWp
Realistic Case	~35% of Potential:	~1,000 GWp
Optimistic Case	~50% of Potential:	~1,600 GWp

Parity Economic Market Potential upper realistic limit
(sceanrio: realistic, LR 20%/15%, net metering, total LCOE)



Scenarios vs Reality: in Last Decade



source: Gredler C., 2008. Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure

Scenarios Covering PV Market Growth