Status of PV technology development and perspectives

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Solar Energy Systems ISE

European Summer Campus 2013,
Energy on All Scales,
University of Strasbourg /
Fraunhofer ISE
Freiburg, 02.09.2013

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Program

09:00-10:00	G. Willeke, Welcome, Basics of photovoltaic solar energy conversion
10:00-11:00	S. Rogalla, Basics of inverter technology and grid integration
11:00-12:00	J. Mayer, Impact of PV and wind energy generation on the German electricity market
12:00-12:45	lunch break (A-108)
12:45-13:00	S. Rogalla, Visit Megawatt laboratory
13:00-14:30	G. Willeke, Status of PV technology development and perspectives
14:30-16:00	A. Schaadt, Hydrogen production and storage
16:00-17:00	G. Willeke / C. Schmitz, Guided tour of Fraunhofer ISE including hydrogen fuel station

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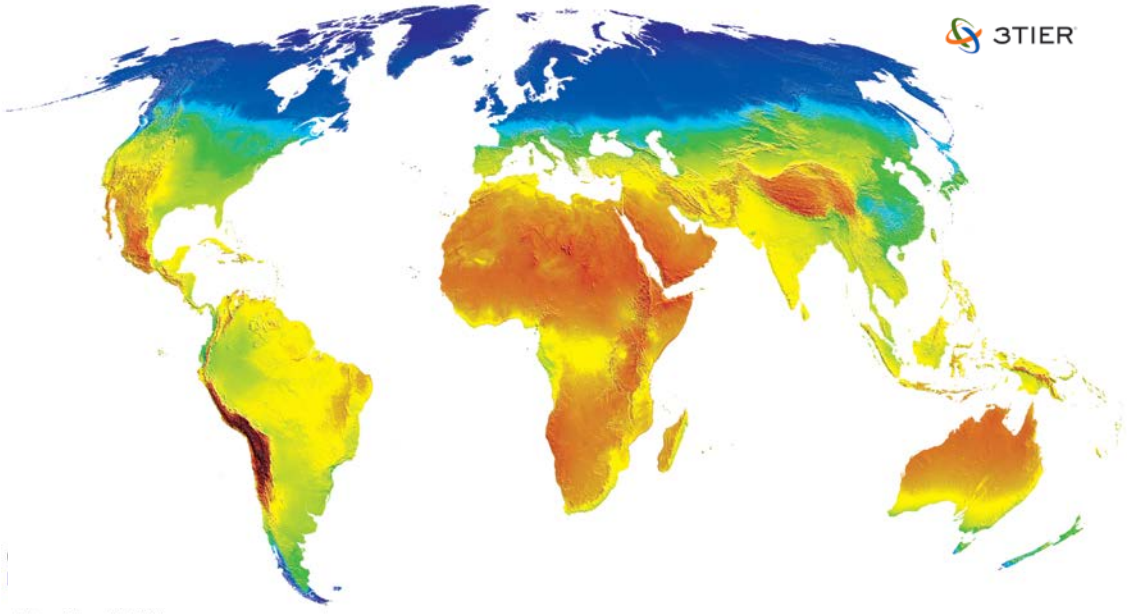
Overview



Quelle: www.3tier.com, 2011

- PV system price development and levelized cost of electricity LCOE
- Leading PV module and inverter producers
- The c-Si value chain: from quartzite rock to silicon wafers
- PV market development in Germany: status and potential
- Outlook: global PV market development

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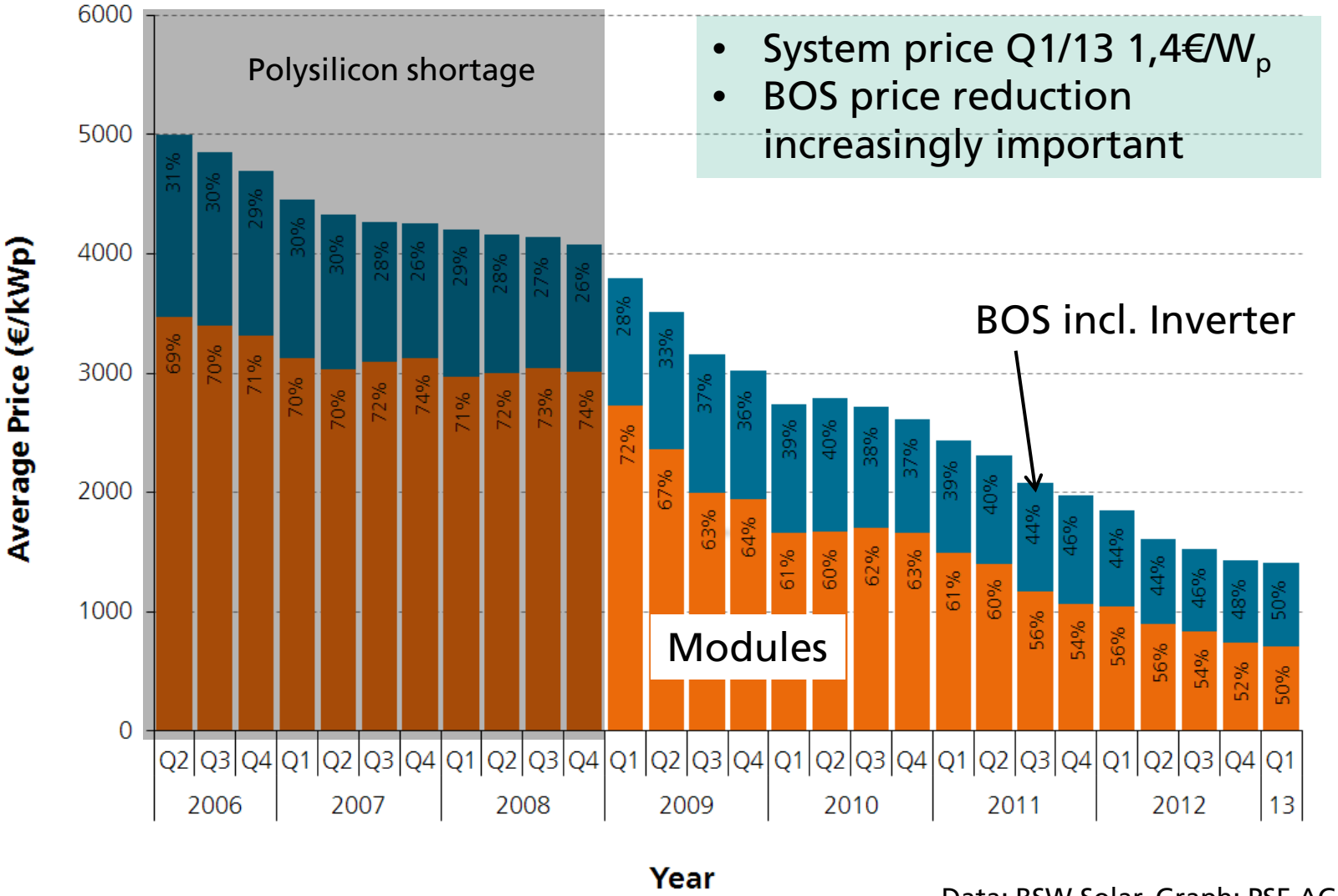
Average Price for PV Rooftop Systems in D (10kWp - 100kWp)



Data: BSW-Solar. Graph: PSE AG 2013

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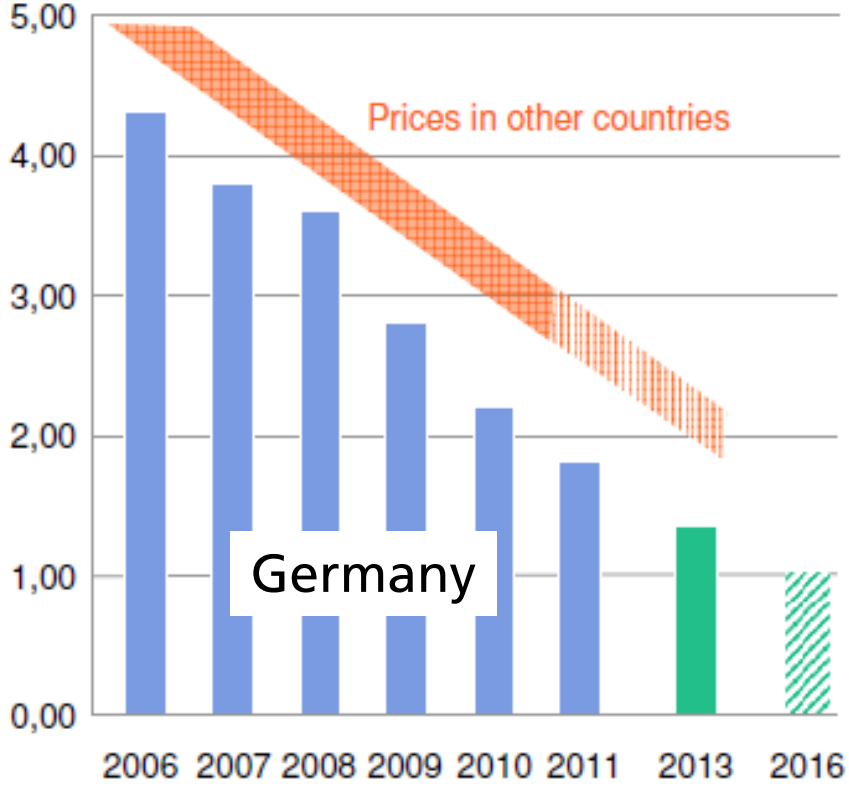
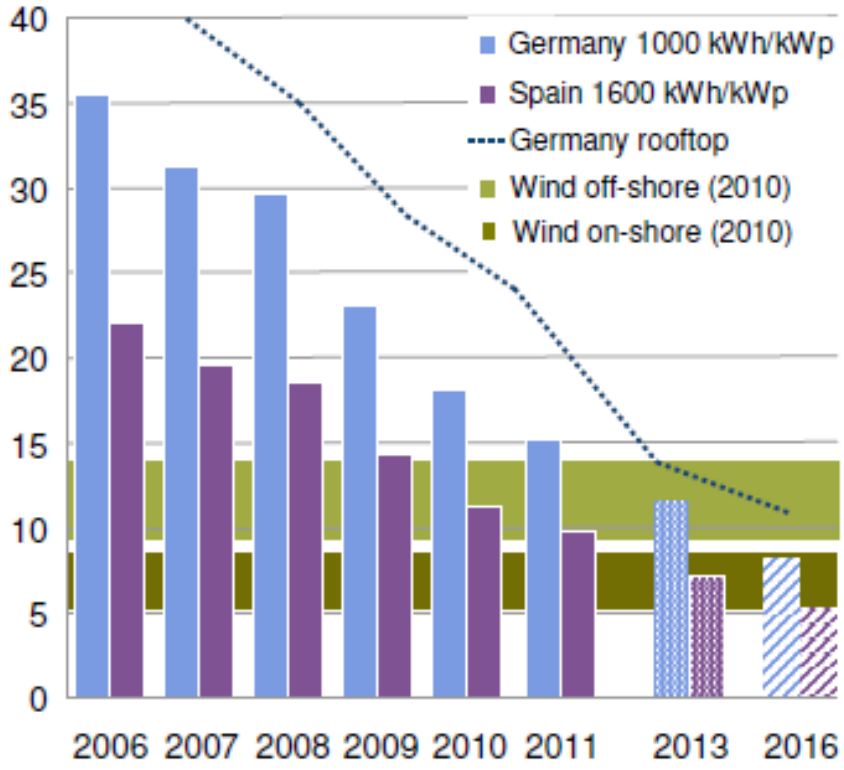
PV System Price and Levelized Cost of Electricity (ground mounted)

PV system price [€/Wp]



LCOE [€cents/kWh]



Source: LBBW 02/2009, Industry announcements, WACKER Analysis

→ PV LCOE will soon be competitive with wind in Germany

Source: Photon 09/2011, E. Schindlbeck, Wacker Polysilicon, 26th EUPVSEC, Hamburg Sept. 2011

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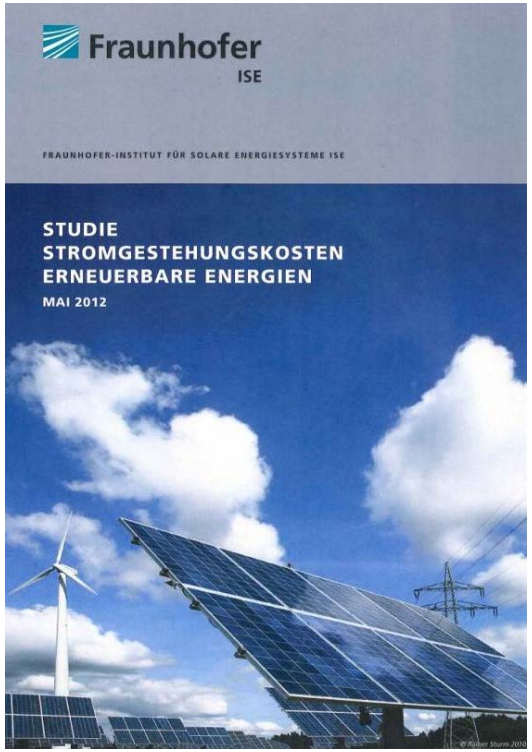
Stromgestehungskosten Erneuerbare Energien

Levelized Cost of Electricity LCOE



$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}}$$

LCOE	Stromgestehungskosten in Euro/kWh
I_0	Investitionsausgaben in Euro
A_t	Jährliche Gesamtkosten in Euro im Jahr t
M_{el}	Produzierte Strommenge im jeweiligen Jahr in kWh
i	realer kalkulatorischer Zinssatz in %
n	wirtschaftliche Nutzungsdauer in Jahren
t	Jahr der Nutzungsperiode (1, 2, ...n)

- Assumption: equal investment cost for all countries

Source: C. Kost, T. Schlegl, J. Thomsen, S. Nold, J. Mayer, Renewable Energy Innovation Policy RENIP, Mai 2012; http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-stromgestehungskosten-erneuerbare-energien.pdf

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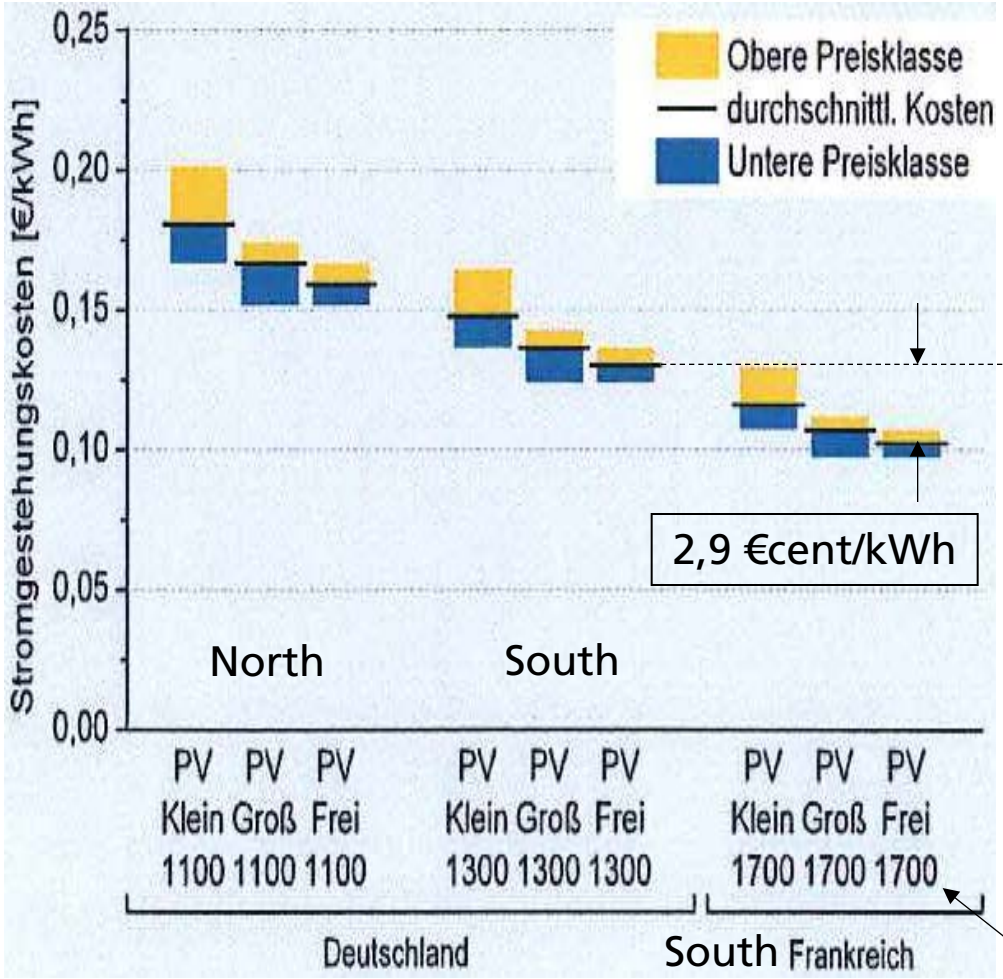
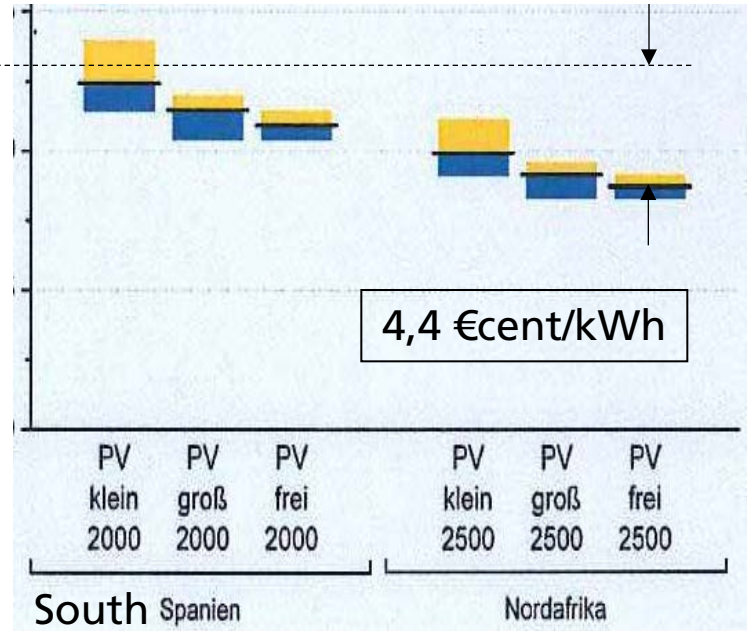
Results PV 2012

I_0	small	large	ground
[€/Wp]	2,20	1,80	1,70
[€/Wp]	1,90	1,70	1,60
[€/Wp]	1,70	1,50	1,50
	<10kW$_p$	<1MW$_p$	>1MW$_p$





kWh/m²a

- LCOE PV ground mounted [€cent/kWh]: S-D 13.1; S-F 10.2; N-Africa 8.7

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Results PV 2012

1,00 €/Wp (2013)

I_0	small	large	ground
[€/Wp]	2,20	1,80	1,70
[€/Wp]	1,90	1,70	1,60
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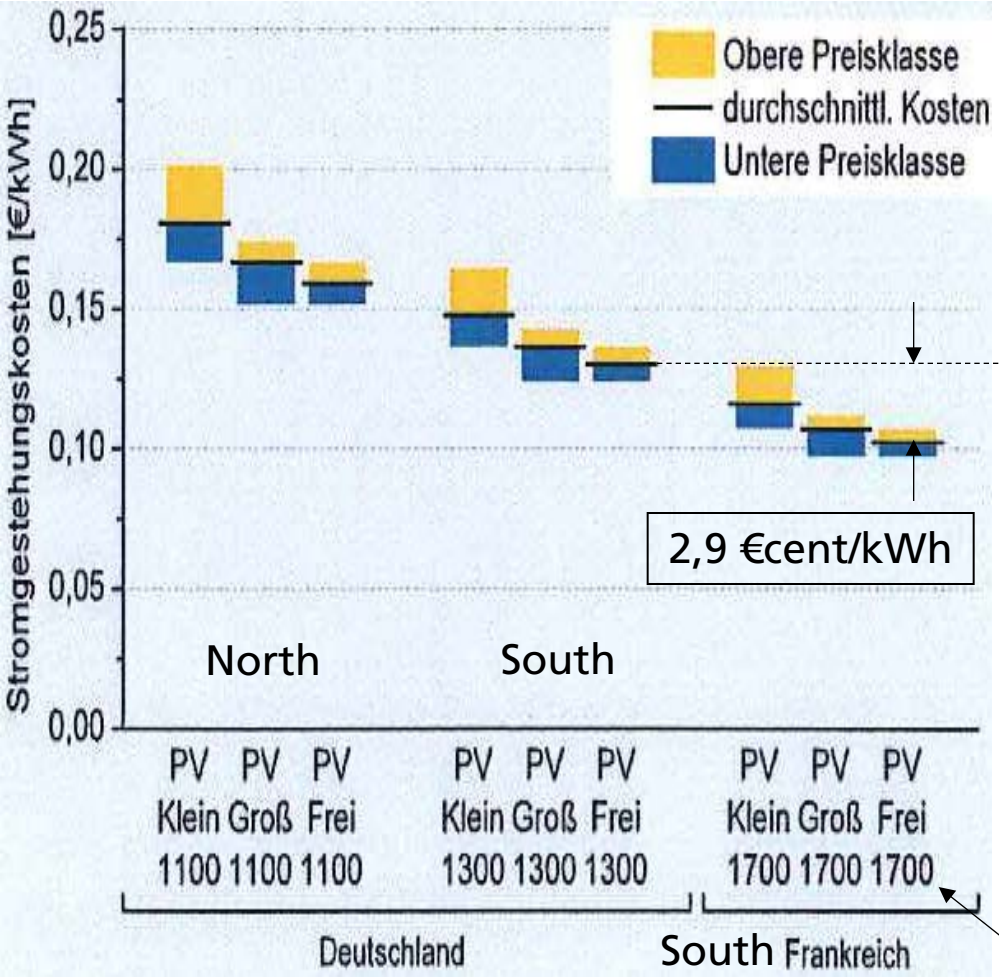

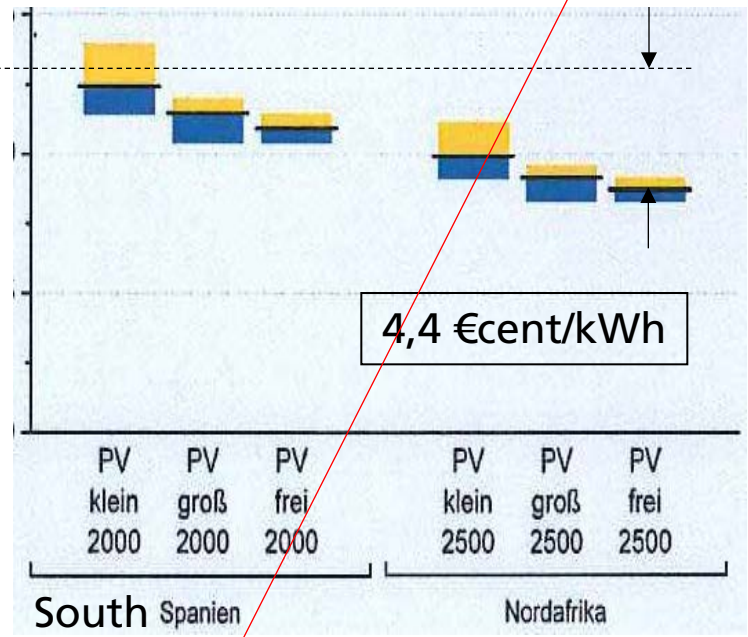

kWh/m²a

- LCOE PV ground mounted [€cent/kWh]: S-D 13.1; S-F 10.2; N-Africa 8.7

S-D 8.2 €cent/kWh (2013)

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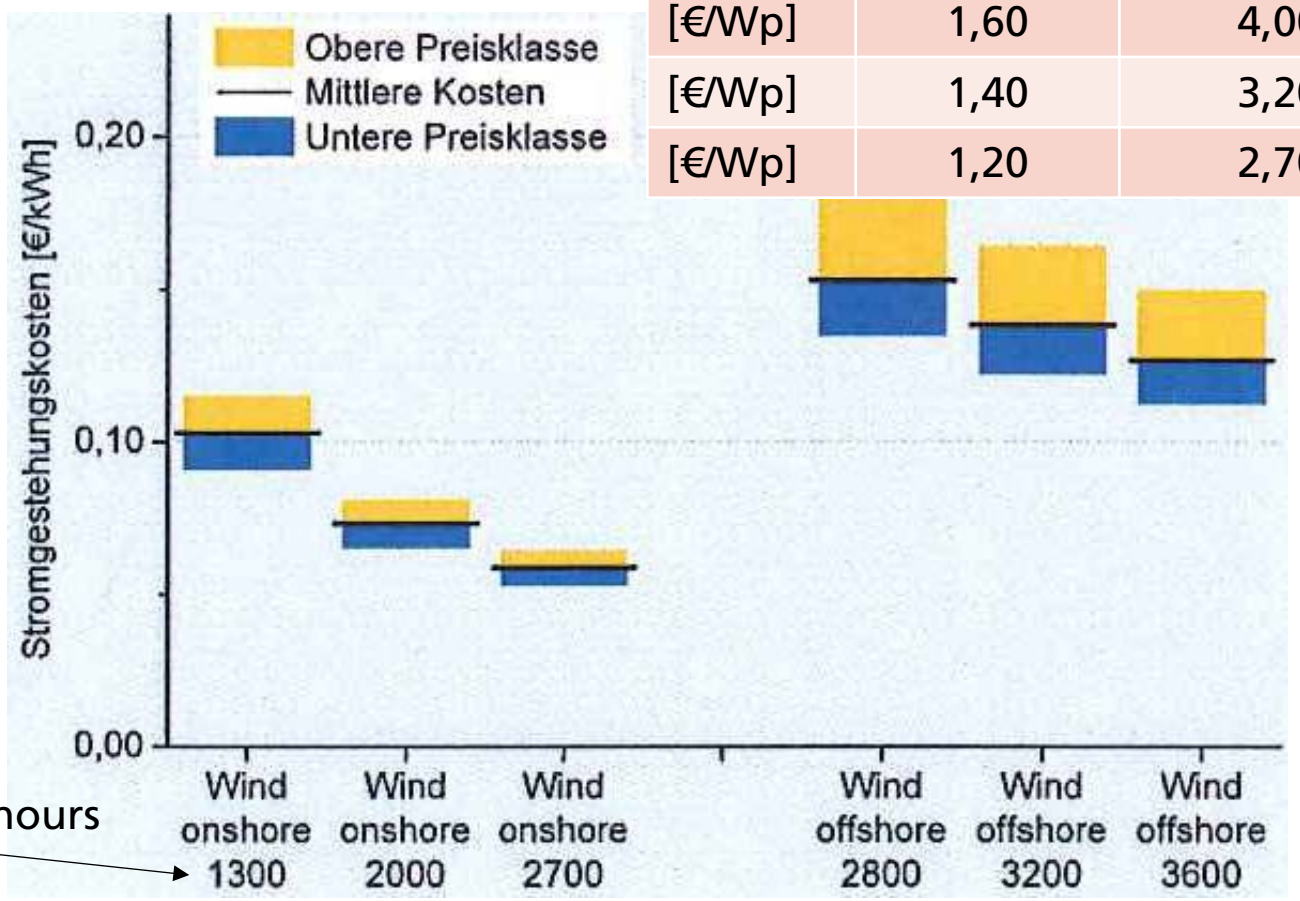
Results Wind 2012

I_0	Onshore (2-3MW$_p$)	Offshore (3-5MW$_p$)
[€/Wp]	1,60	4,00
[€/Wp]	1,40	3,20
[€/Wp]	1,20	2,70



Full load hours

Schwachwind windreich Atlantik-UK geringere mittlere höhere Küstenentfernung

- LCOE Wind [€cent/kWh]: Onshore 1300 (BaWü) 10.3; Offshore 3200 13.8

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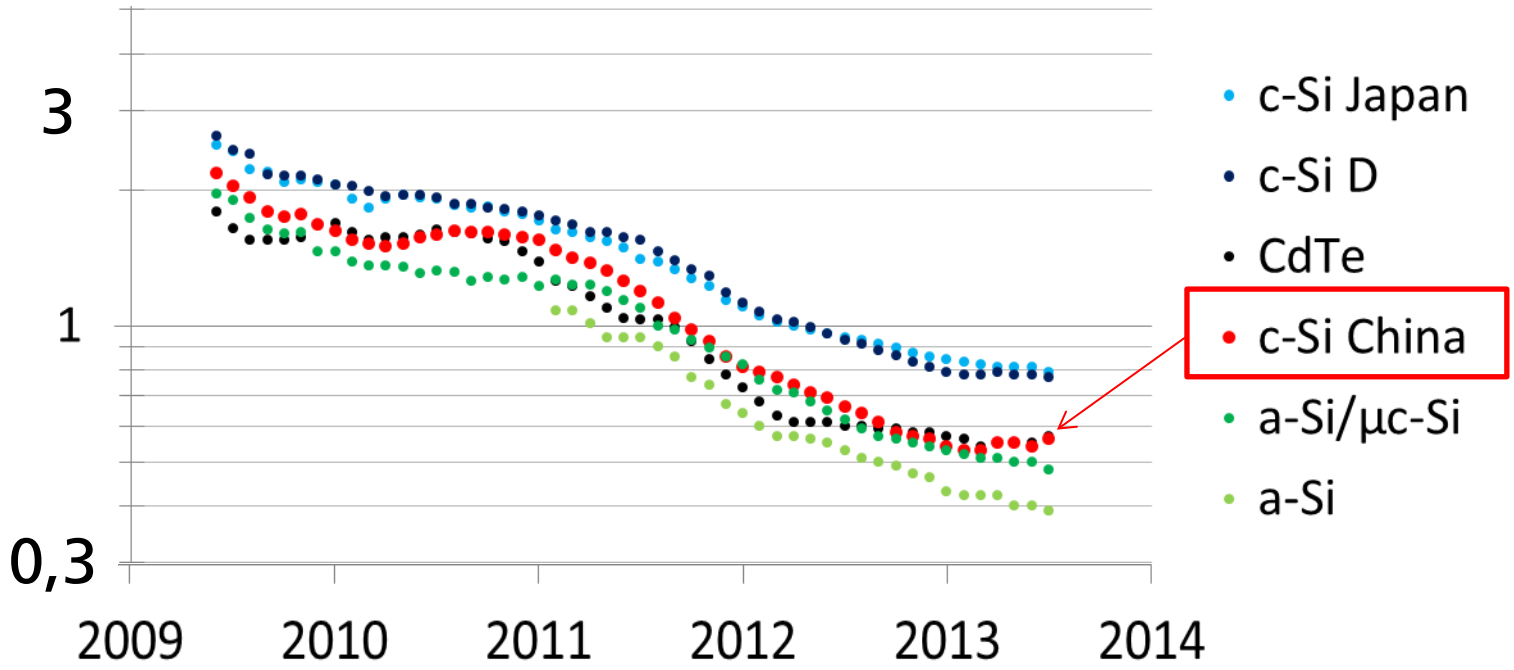
Modul Prices International Spot Market (retail, net)



- **Overcapacities are leading to a ‚buyer's market'**
- **Chinese module prices lead to consolidation: Schott and Bosch exit PV**
- **Prognosis 2020: c-Si module prices of 0,4-0,5€/Wp**

Quelle Daten: http://www.solarserver.de/service-tools/photovoltaik-preisindex.html; abgerufen am 05.08. 2013

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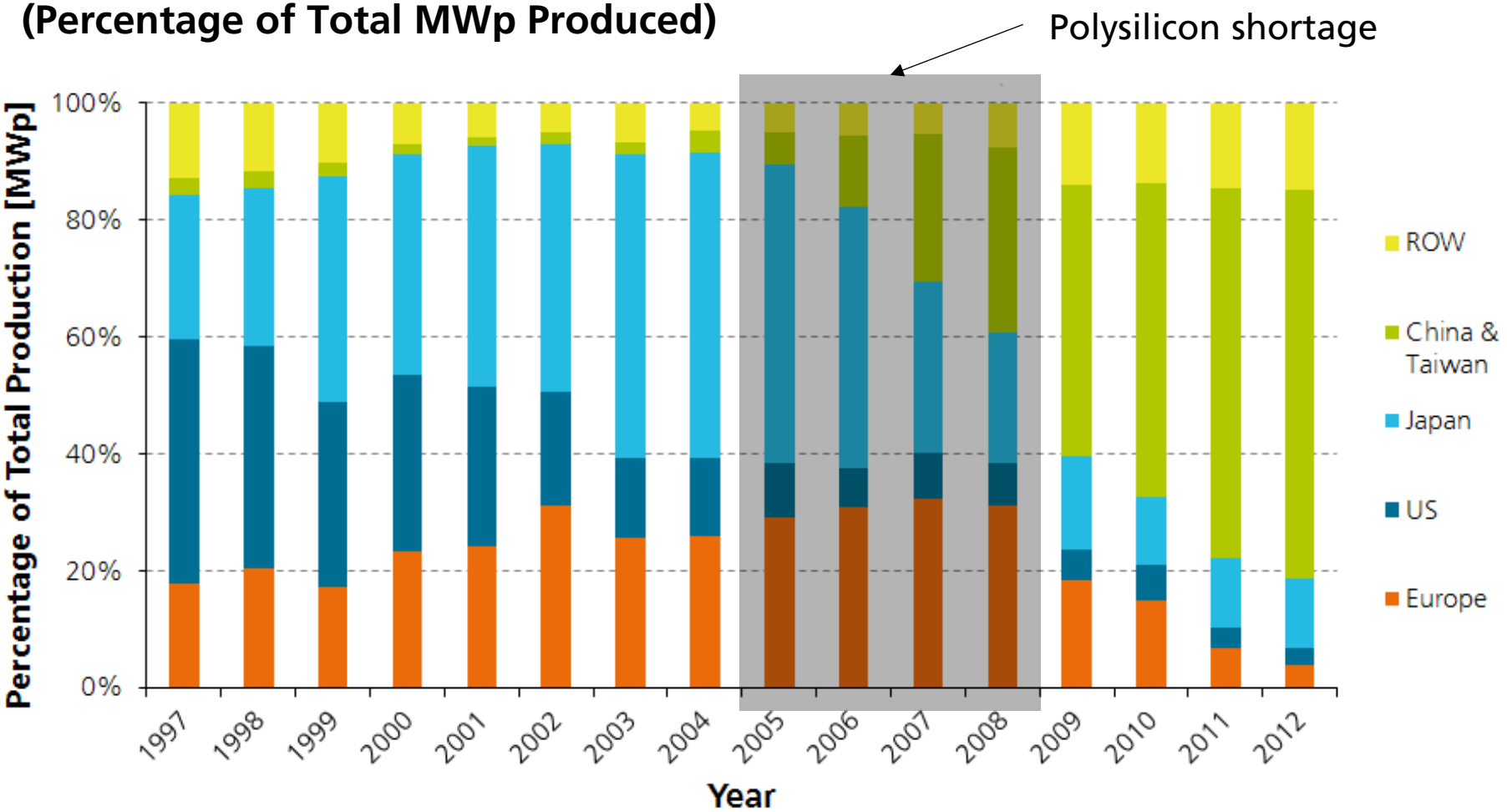
PV Cells/Modules Production by Region 1997-2012

(Percentage of Total MWp Produced)



PV module production domination: USA -> Japan -> Europe -> China

Data: Navigant Consulting. Graph: PSE AG 2013

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2012 TOP 20 PV module producers (mostly c-Si) [MWp/a]

CdTe

	Firma	Zentrale	2011		2012
1	First Solar	USA	1981	↘	1875
2	Yingli	China	1395	↗	1850
3	Trina Solar	China	1560	↗	1700
4	Suntech	China	2022	↘	1505
5	Canadian Solar	Kanada	1355	↗	1485
6	Sharp	Japan	1110	→	1077
7	Hanwha/Qcells	Südkorea	909	↗	1066
8	JA Solar	China	487	↗	953
9	Flextronics	Singapur		↗	885
10	Jinko Solar	China	781	↗	860

19% a-Si

CIGS

	Firma	Zentrale	2011		2012
11	Sunpower	USA	640	↗	848
12	Hareon Solar	China	428	↗	818
13	Jabil	China		↗	800
14	REC Group	N	607	↗	722
15	Solar Frontier	Japan	380	↗	655
16	Solarworld	D	550	↗	608
17	Renesola	China	285	↗	590
18	Kyocera	Japan	255	↗	545
19	Astronergy	China	298	↗	480
20	LG	Südkorea	281	↗	471

- **Mostly Asean companies invest in PV module production**
- **Most of the production takes place in Asia!**
- **TOP 10: 1-2GWp annual production; TOP 20: > 0,5GWp/a**
- **Prognosis TOP 10 2013: 2-3GWp/a**

Quelle: IHS, Integrated PV Market Tracker Q1 2013, PV Module Supplier Data, PSE AG

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Quelle: IHS, Integrated PV Market Tracker Q1 2013, PV Module Supplier Data, PSE AG

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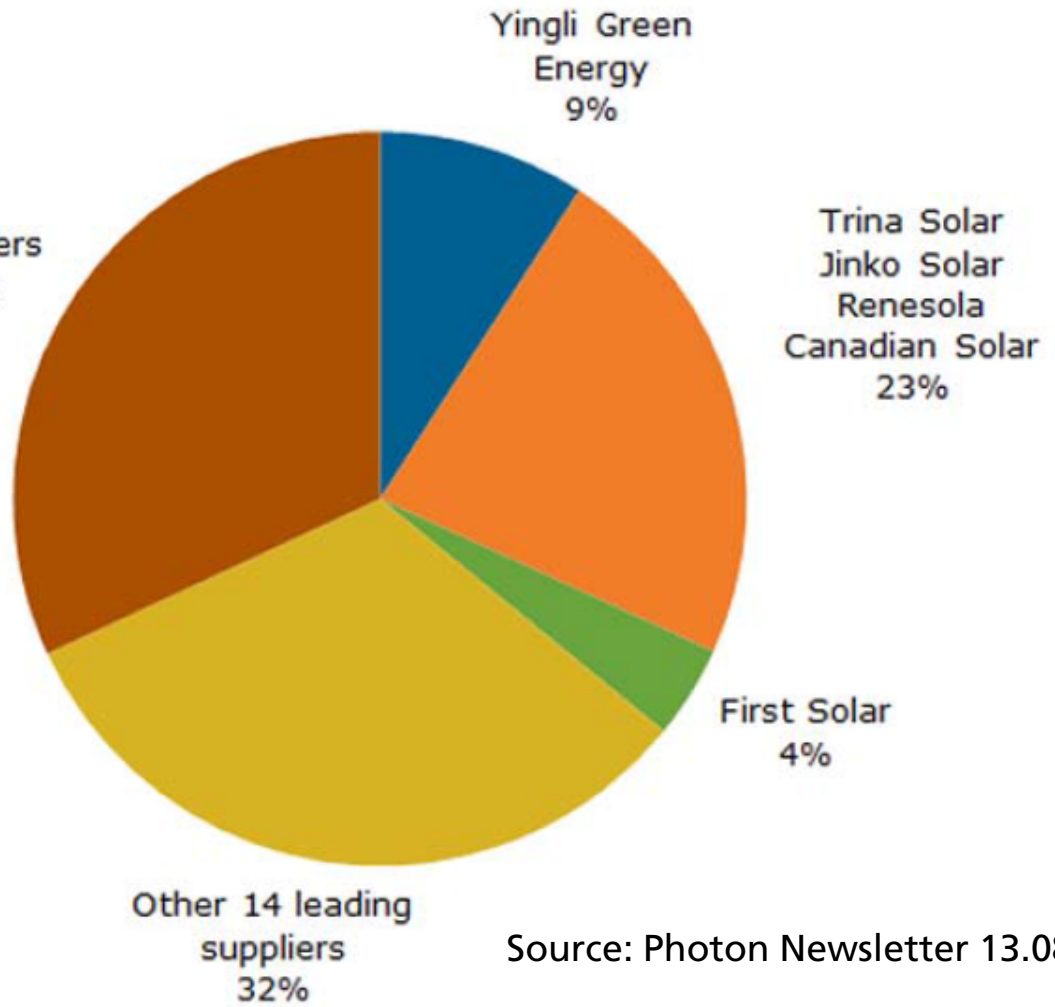
Q2'13 Global PV Module Shipment

Total shipment:
Q2'13: 5.8GW
(Q2'12: 4.8GW)



Source: NPD Solarbuzz *Module Tracker Quarterly*

Source: Photon Newsletter 13.08.2013

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TOP 10 Q4 2012 PV Inverter Manufacturers (global revenue share)

		HQ	2011	Q1'12	Q2'12	Q3'12	Q4'12	2012
1.	SMA	D	27,4%	32,0%	26,9%	23,6%	18,9%	25,2%
2.	ABB/Power-One	CH/USA	10,1%	8,7%	12,8%	11,0%	6,8%	10,0%
3.	Omron Corp.	Japan	<2%	<2%	<2%	2,5%	3,8%	2,4%
4.	Sungrow	China	<2%	<2%	<2%	<2%	3,3%	<2%
5.	Advanced Energy	USA	2,7%	2,8%	2,7%	3,3%	3,3%	3,0%
6.	Kaco	D	4,3%	3,8%	4,0%	3,5%	3,1%	3,6%
7.	Tabuchi	Japan	<2%	<2%	<2%	2,0%	3,1%	<2%
8.	Enphase Energy	USA	2,1%	2,3%	2,5%	2,6%	2,6%	2,5%
9.	SolarEdge	Israel	<2%	2,1%	<2%	<2%	2,4%	<2%
10.	Fronius	Austria	3,8%	3,4%	3,0%	2,4%	2,4%	2,8%

- **SMA dominates the market (but decreasing market share)**
- **ABB (Power-One) establishes itself as number 2 (turnover)**

Quelle: IHS, Integrated PV Market Tracker Q1 2013, PV Module Supplier Data, PSE AG

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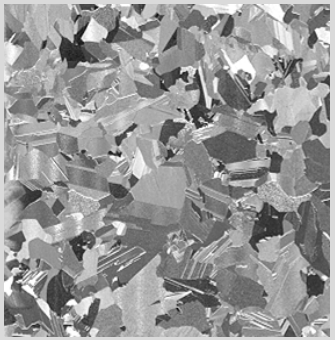
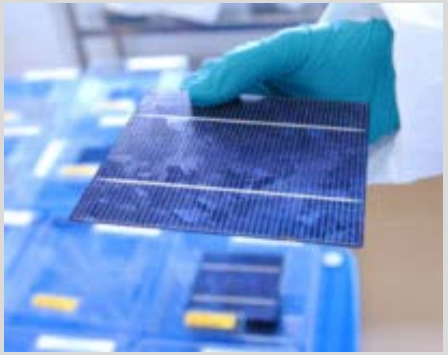
Value Chain of c-Si Photovoltaics

Si-Rohstoff -> Kristall



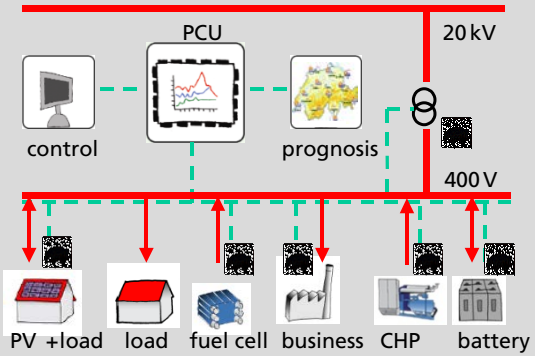
Si-Scheibe



Solarzelle

Module & System

Wechselrichter



Stromnetz

Quelle: Dr. G. Ebert, Fraunhofer ISE, 2012

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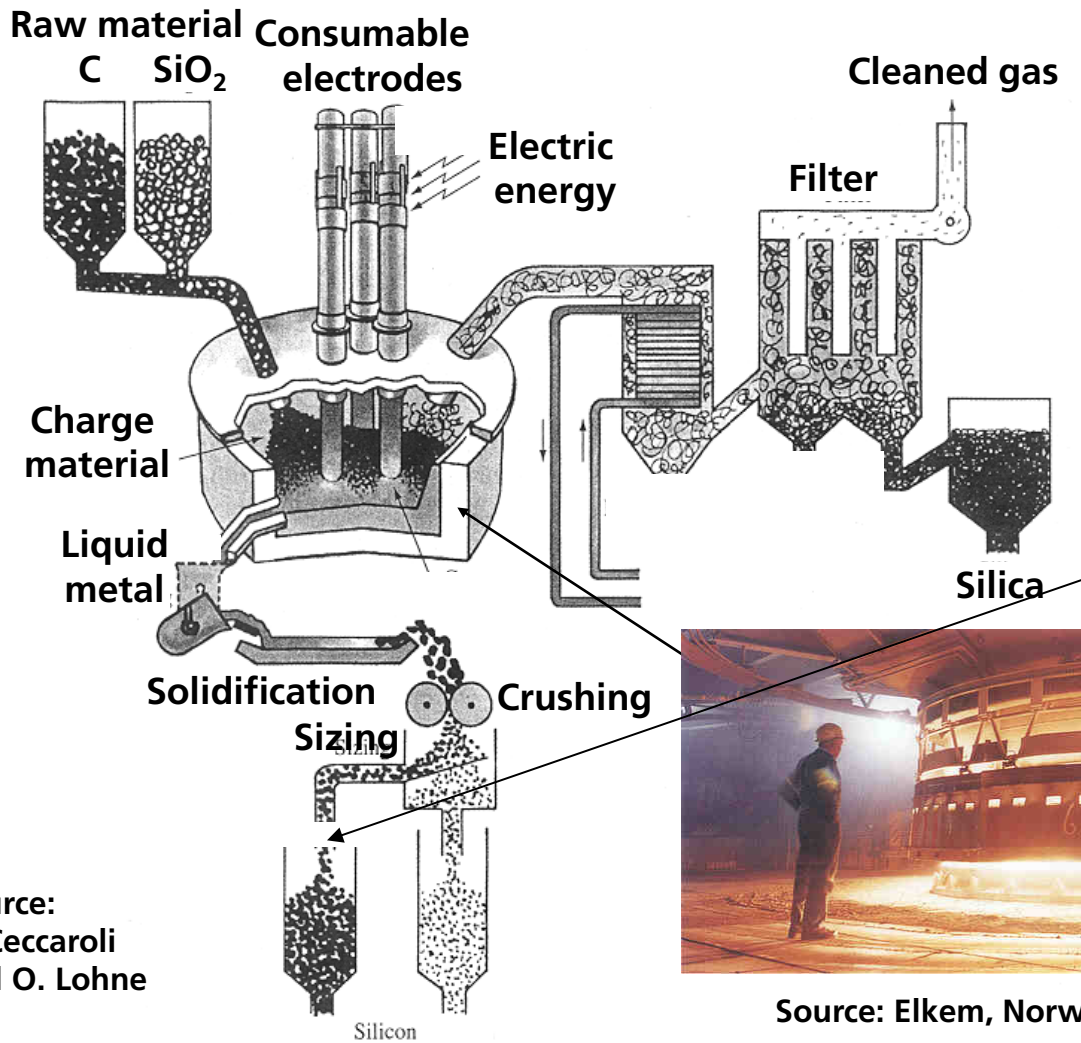
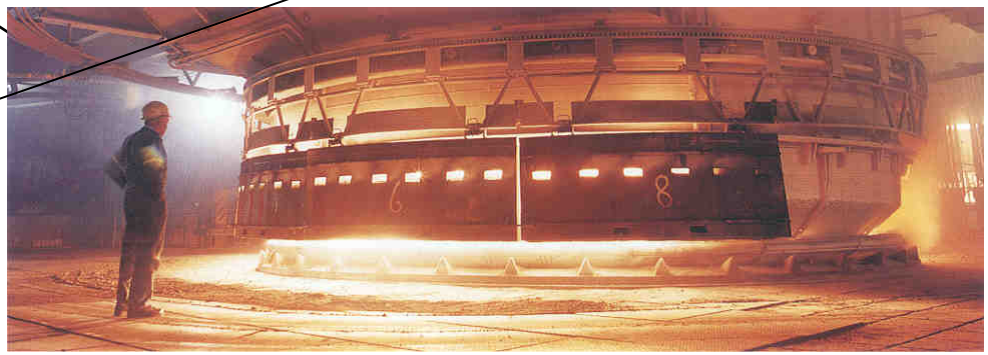
From Quartzite Rock to Crystalline Silicon Wafers

Generation of metallurgical grade silicon (mg-Si)



- 2 Mio. t/a @ 1.5 - 2 $/kg
- 10 kWh/kg
- 5 t CO_2 per 1 t Si
- China (50%), Brazil, Norway, Canada

Source: RW Silicium



Source: Elkem, Norway

Source:
B. Ceccaroli
and O. Lohne

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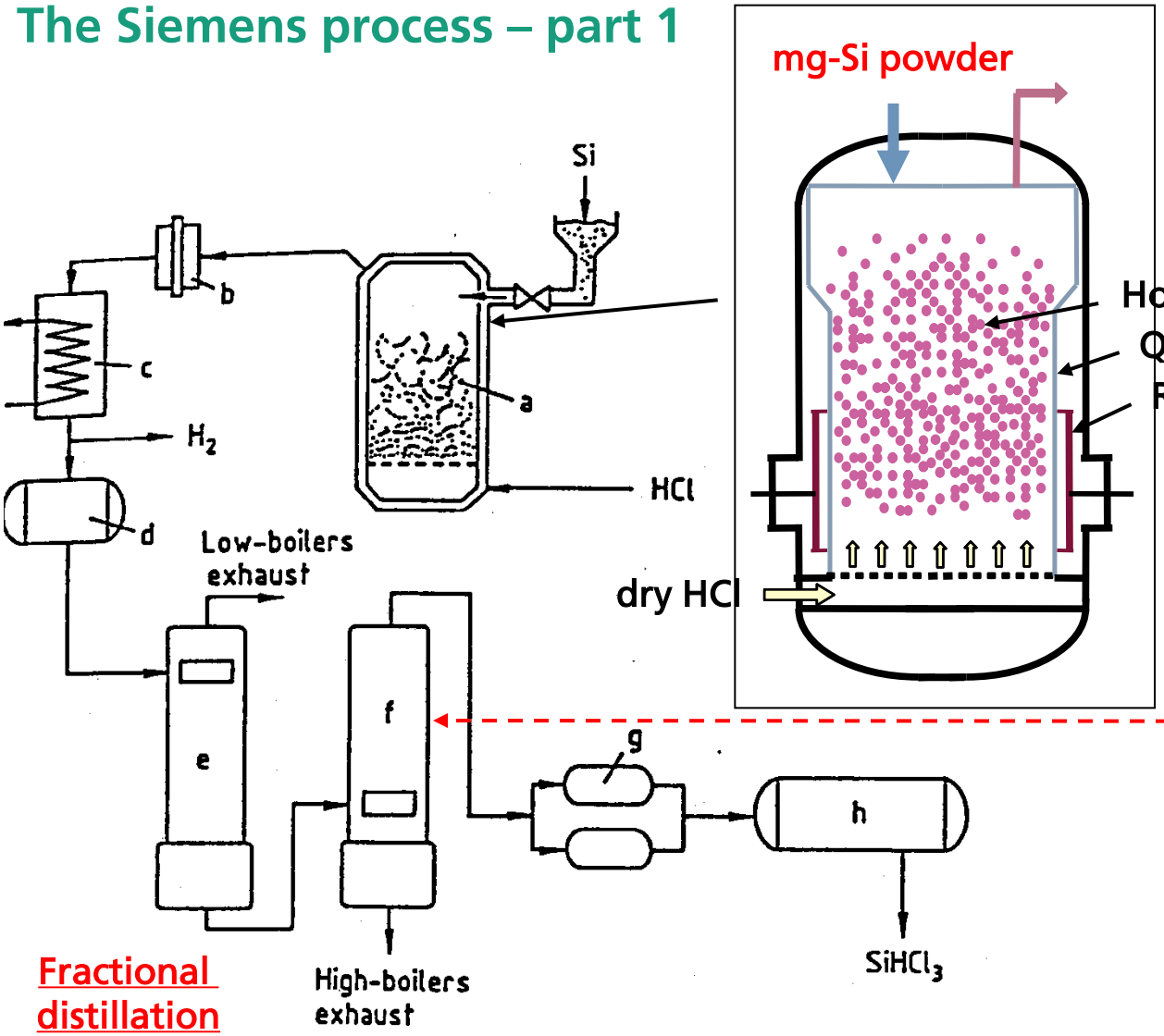
From Quartzite Rock to Crystalline Silicon Wafers

The Siemens process – part 1

recycling

Exhaust gas
(85% $SiHCl_3$, 15% $SiCL_4$, H_2, metal chlorides)



Fluidised Bed Reactor

Hot silicon dust (300 – 350°C)
Quartz tube
Resistive heater

Fractional distillation

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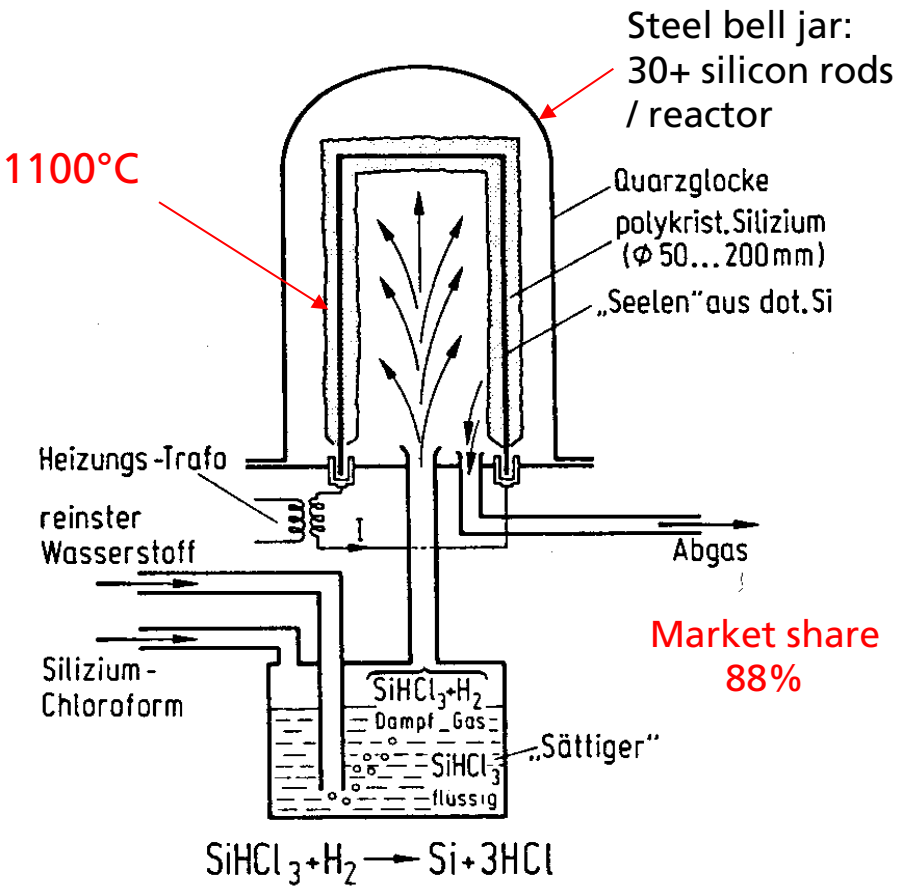
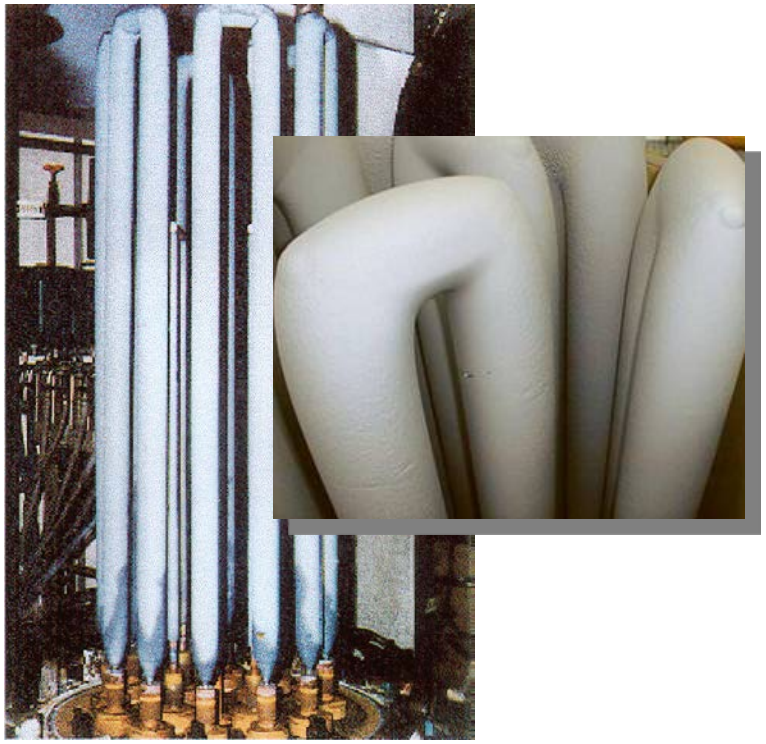
From Quartzite Rock to Crystalline Silicon Wafers

The Siemens process – part 2



Market share
88%



Specific energy consumption
(Siemens process): 65 – 115 kWh/kg

Wacker version: $4SiHCl_3 \rightarrow Si + 3SiCl_4 + 2H_2$; $3SiCl_4 + 3H_2 \rightarrow 3SiHCl_3 + 3HCl$

[Alternative (market share 3%): SiH_4 (370-450°C) -> Si + $2H_2$ (REC)]

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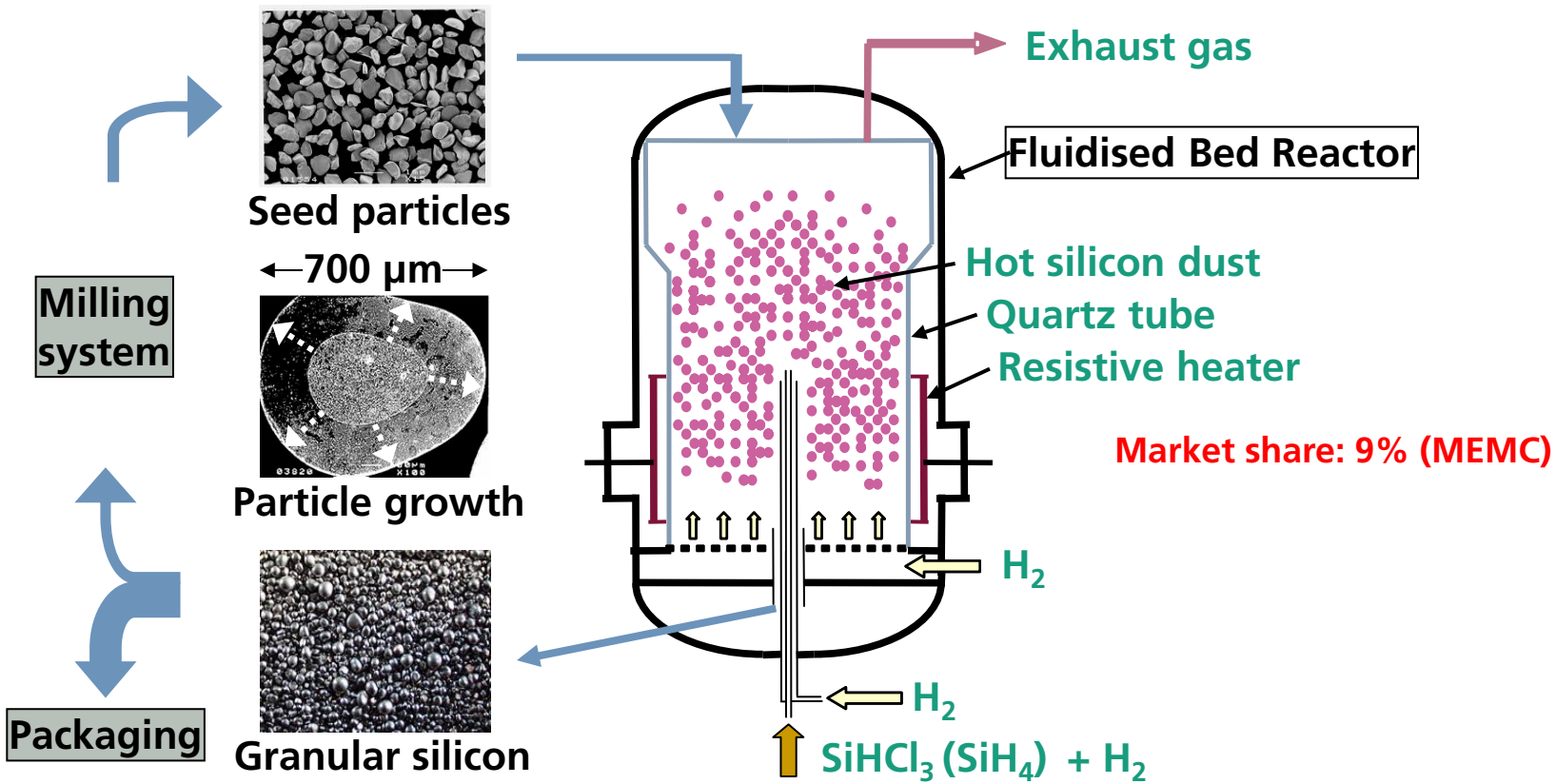
From Quartzite Rock to Crystalline Silicon Wafers

Fluid bed deposition



Source: after Dr. K. Hesse, Wacker Polysilicon

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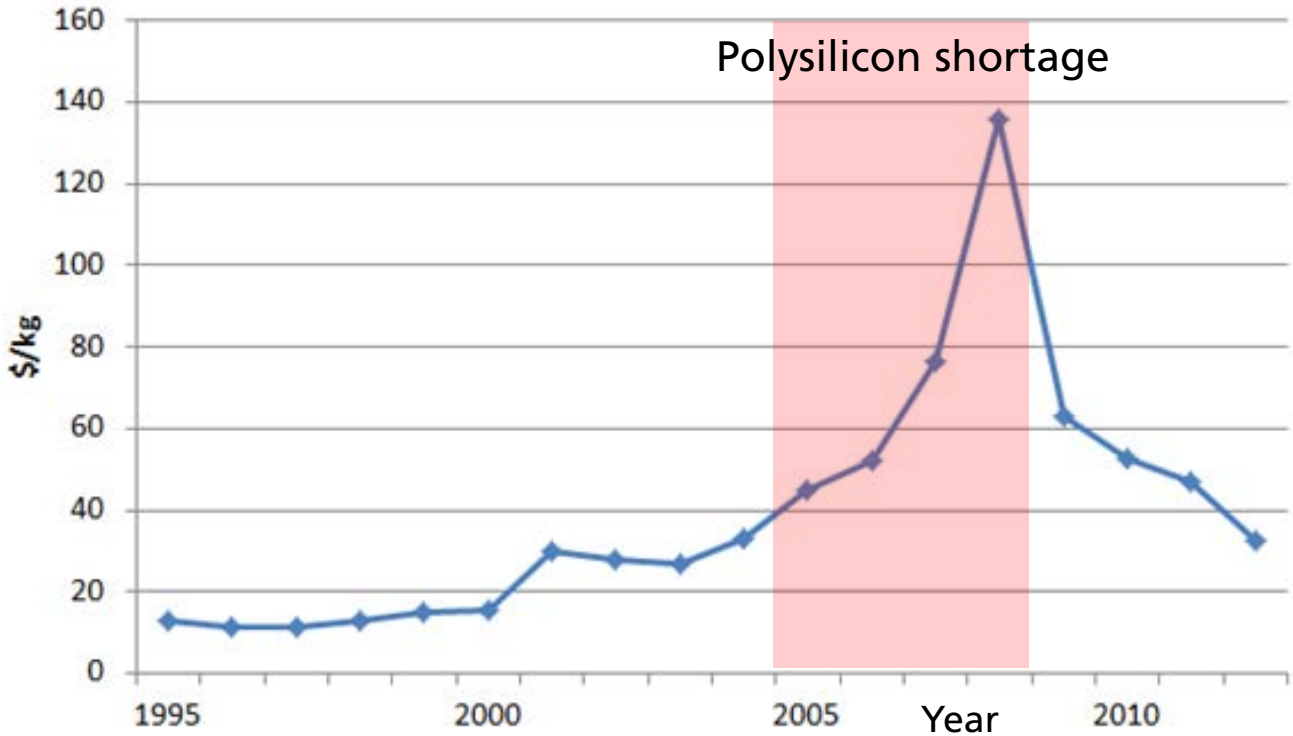
From Quartzite Rock to Crystalline Silicon Wafers

Polysilicon feedstock price development



- Price is weighted average between contract (80%) and spot market (20%)
- Silicon shortage 2005-2008 because of missing Siemens capacity
- 30GW PV added capacity 2012 (85% c-Si, 7g/W_p): 180 000 t/a
- Outlook 2020: 100GW PV added (3-5g/W_p) -> 300 – 500 000 t/a

Source: G. Willeke and A. Räuber, On the History of Terrestrial PV Development: With a Focus on Germany, G. Willeke and E.R. Weber (Eds.), Semiconductors and Semimetals, vol. 87, Elsevier, Oxford, UK, (2012)

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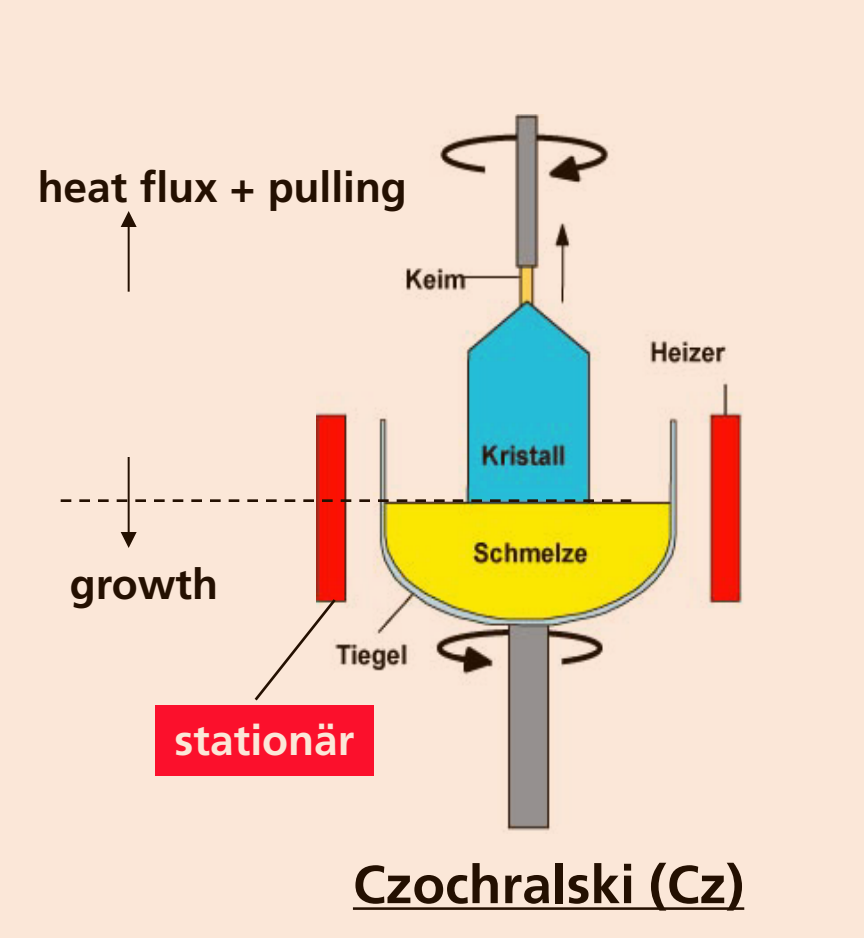
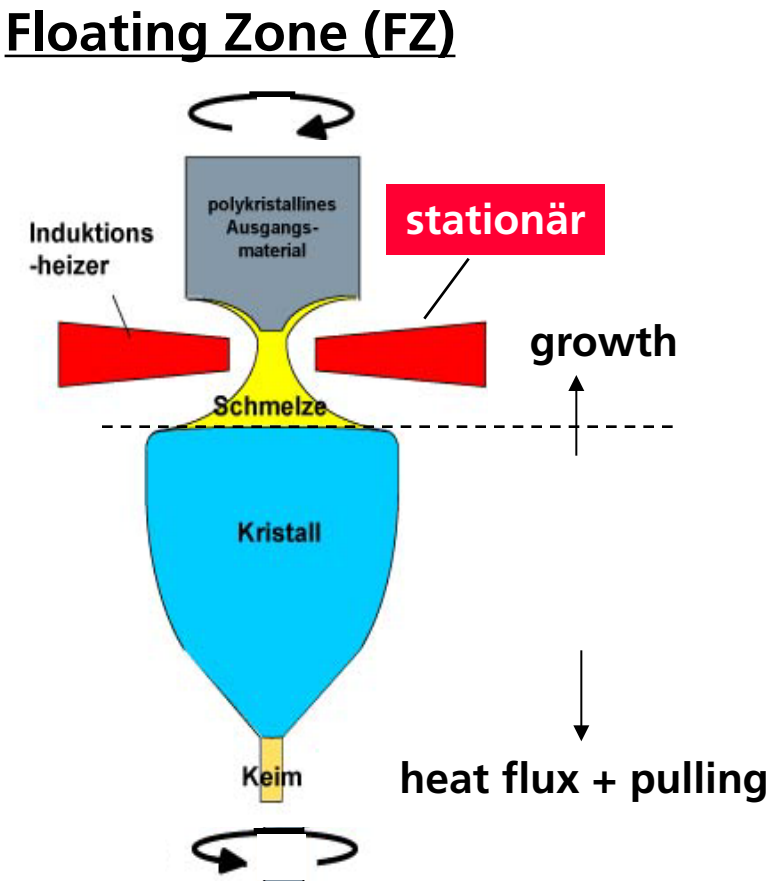
From Quartzite Rock to Crystalline Silicon Wafers

Single crystal growth techniques





- PV market share 2011: 40%

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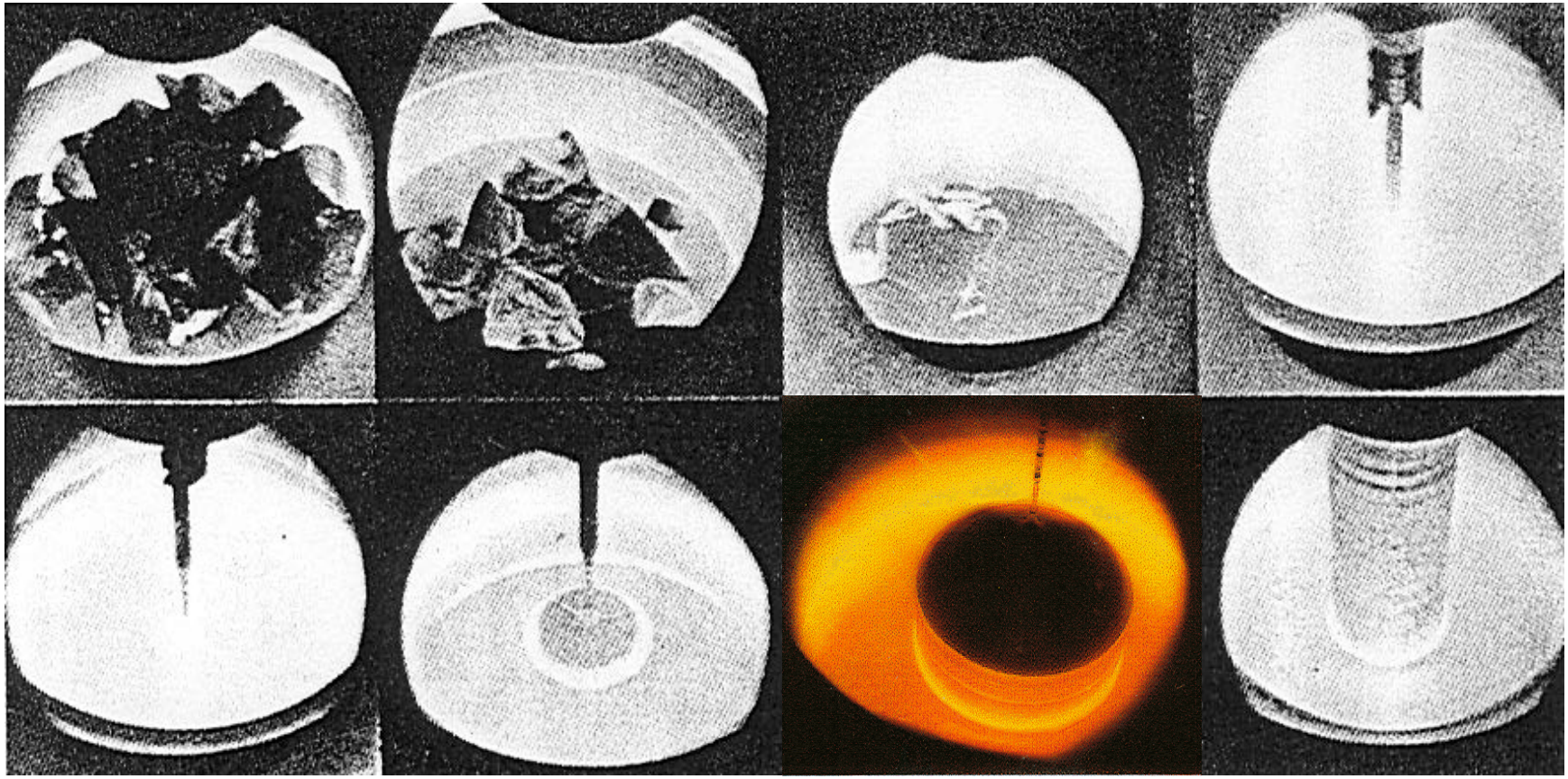
From Quartzite Rock to Crystalline Silicon Wafers

Czochralski monocrystalline silicon growth



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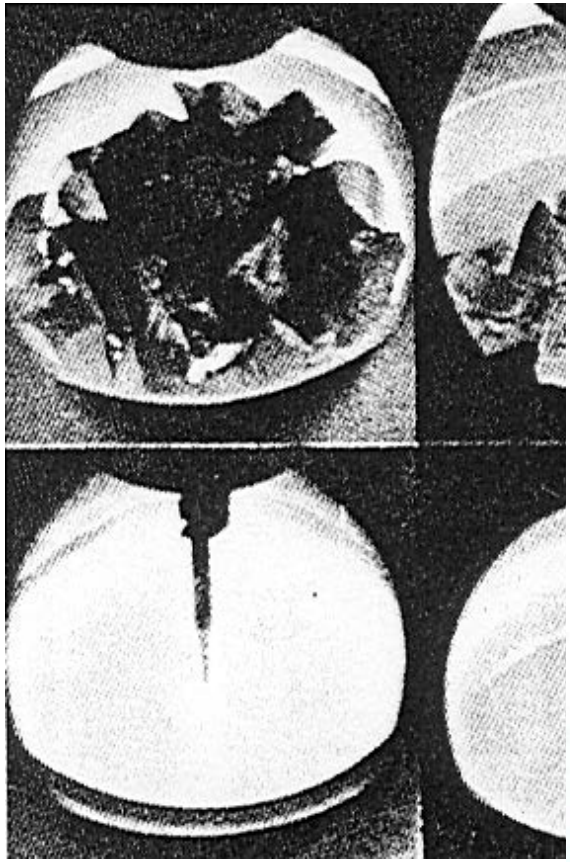
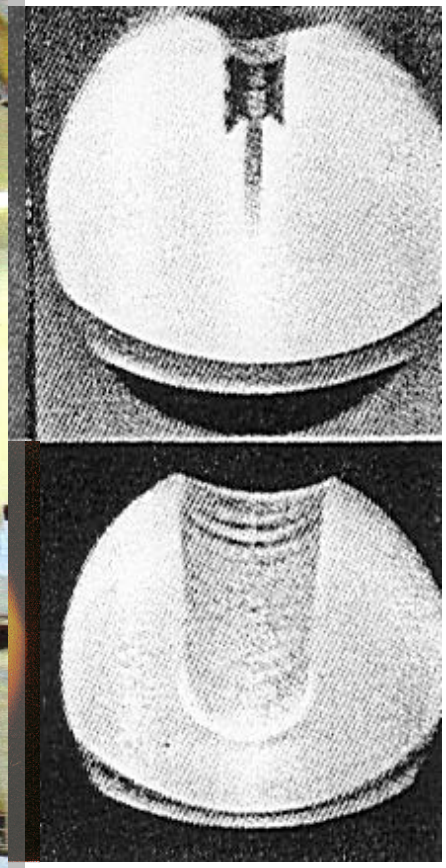
From Quartzite Rock to Crystalline Silicon Wafers

Czochralski monocrystalline silicon growth





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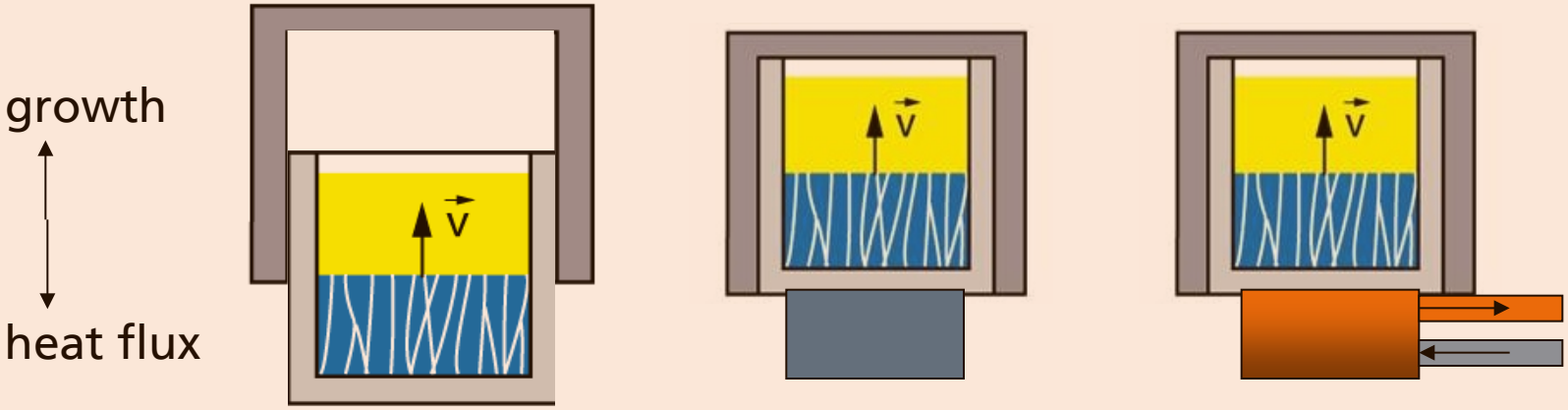
From Quartzite Rock to Crystalline Silicon Wafers

Multicrystalline silicon crystal growth by directional solidification

Melting and crystallisation in the same crucible



Source: Dr. T. Bähr, Access, 2007

Bridgman: Remove crucible from hot zone

HEM: docking on heat exchange block

TCVP: switch on active cooling block

- PV market share 2011: 45%

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From Quartzite Rock to Crystalline Silicon Wafers

Multicrystalline silicon crystal growth by directional solidification

Source: H. Aulich, PV Crystalox Solar, 2007

1995: 150 kg

2004: 330 kg

2010: 1000 kg

Dr. A. Müller, Deutsche Solar, 2007

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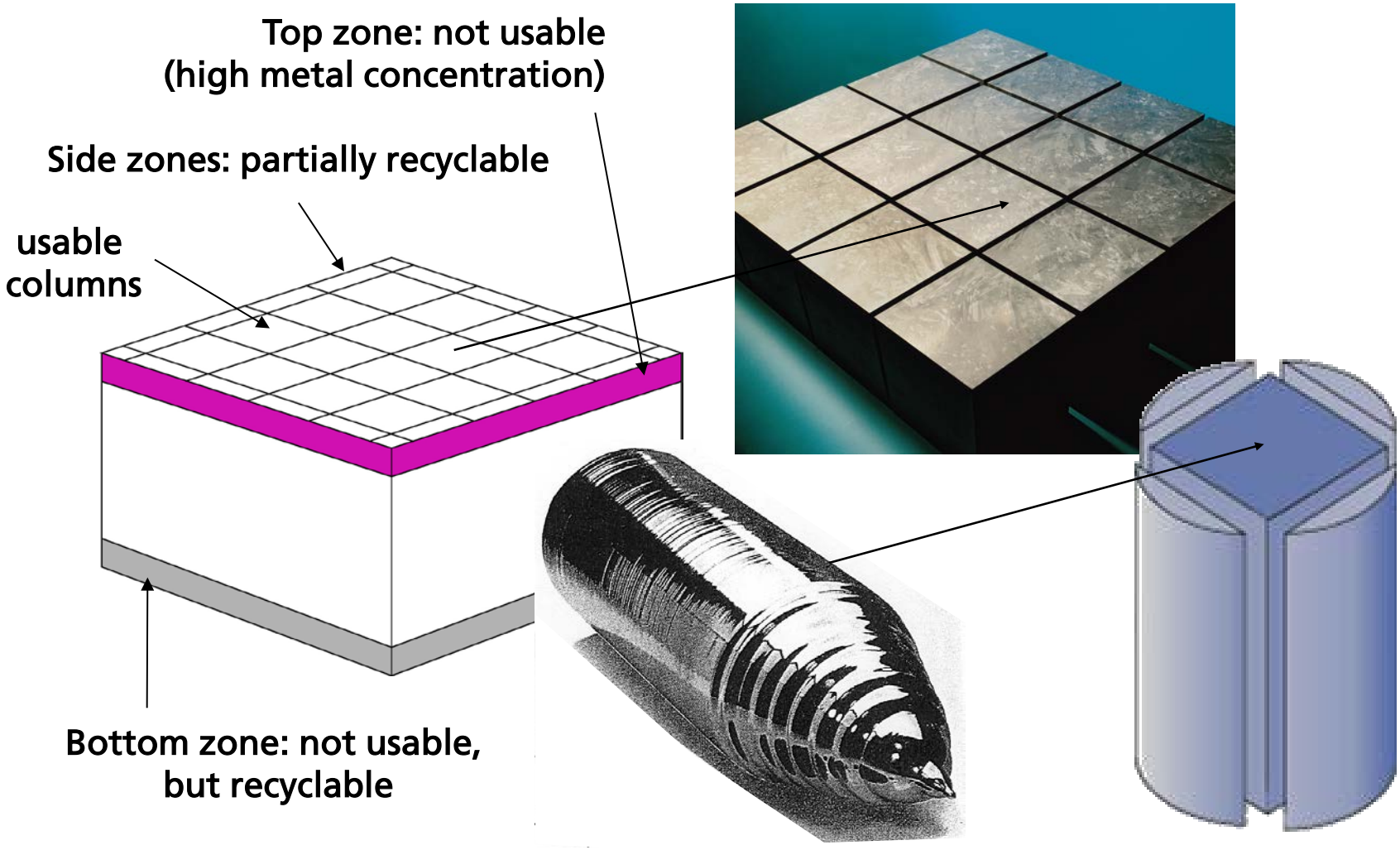
From Quartzite Rock to Crystalline Silicon Wafers

Silicon brick formation

Overall mass yield ingot to column: 70%



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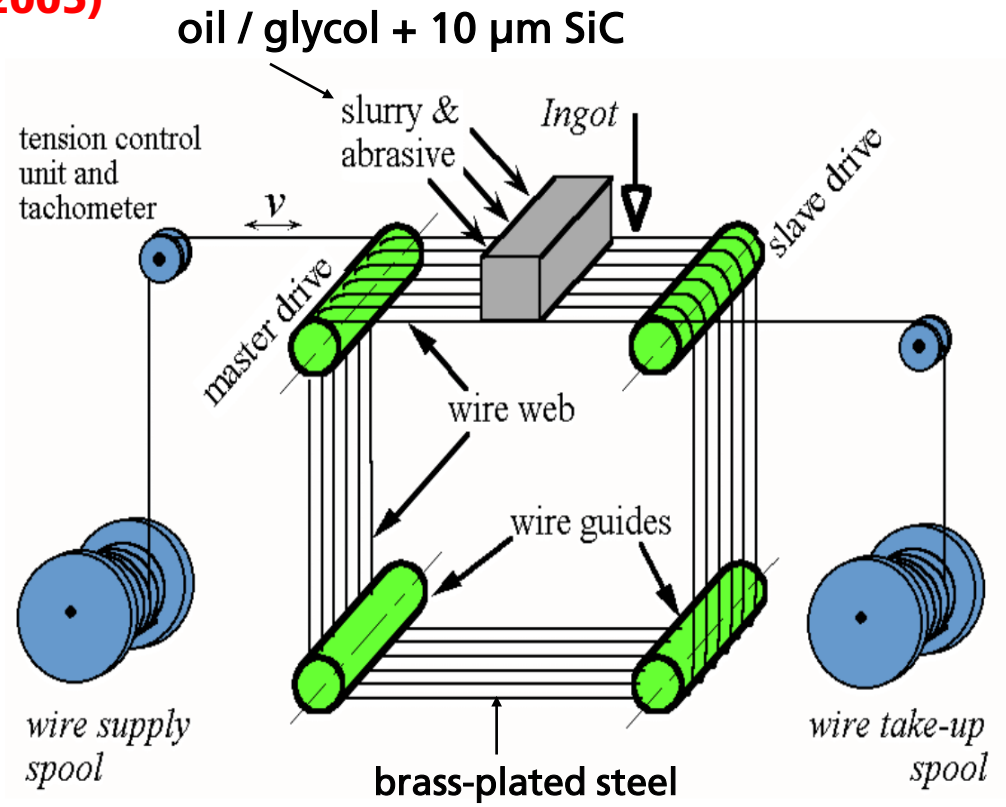
From Quartzite Rock to Crystalline Silicon Wafers

Wafering by multi-wire slurry saw MWSS

	Data 2004	goal 2020 (2005)
Wire		
diameter:	**180 µm**	**120 µm**
length:	**500 km**	
speed:	**15 m/sec**	
spacing:	**500 µm**	**250 µm**
Wafer		
thickness:	**295 µm**	**100 µm**
kerf loss:	**205 µm**	**150 µm**



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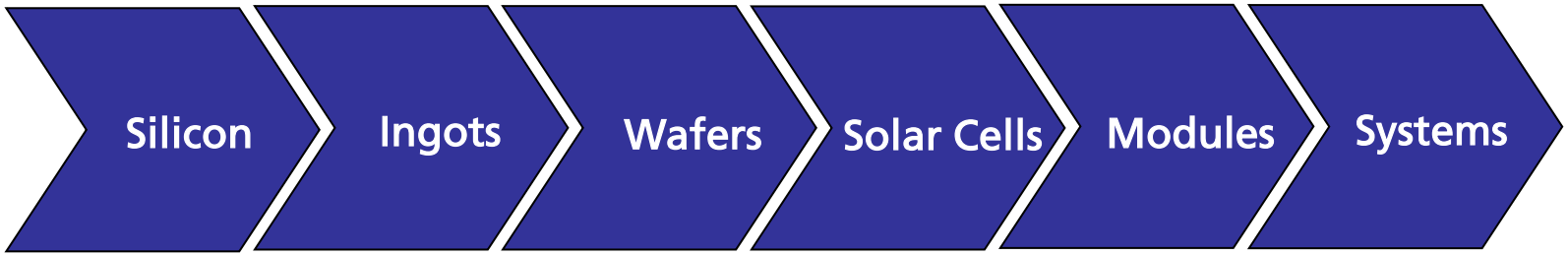
C-Si PV Value Chain and Cost Structure (2013)



€/W	0.08	0.11	0.09	0.20	0.22	0.70
Σ	0.08	0.19	0.28	0.48	0.70	1.40
[%]	6	8	6	14	16	50
[%Σ]	6	14	20	34	50	100

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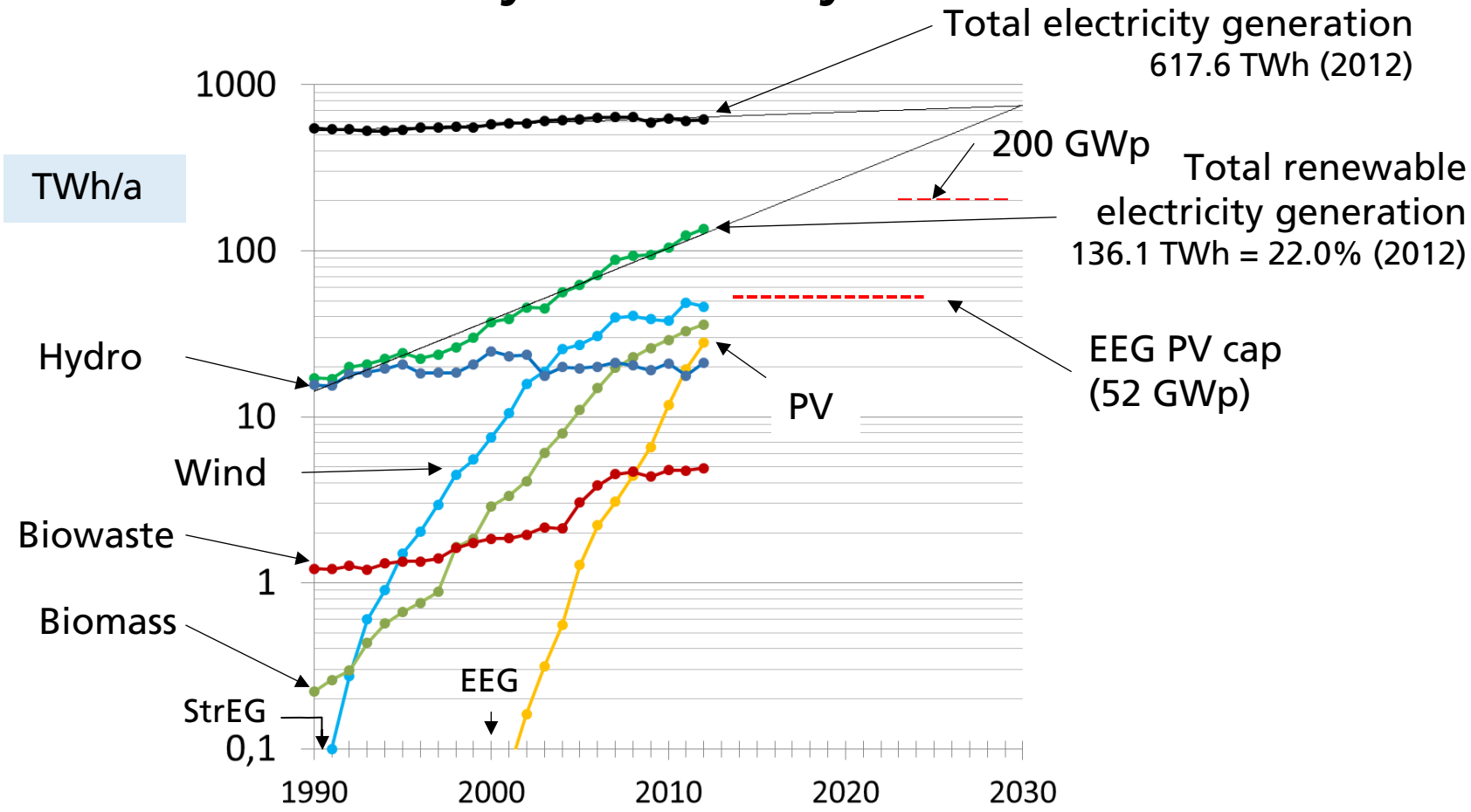
Renewable Electricity in Germany



- **Decreasing dynamics with wind and biomass electricity**
- **Strongest dynamics with PV, but: Renewable energy law EEG PV cap at 52 GWp**

Source: Zahlen und Fakten Energiedaten, Nationale und Internationale Entwicklung, Stand 21.05.2013
http://www.bmwi.de/DE/Themen/Energie/Energiedaten/gesamtausgabe.html

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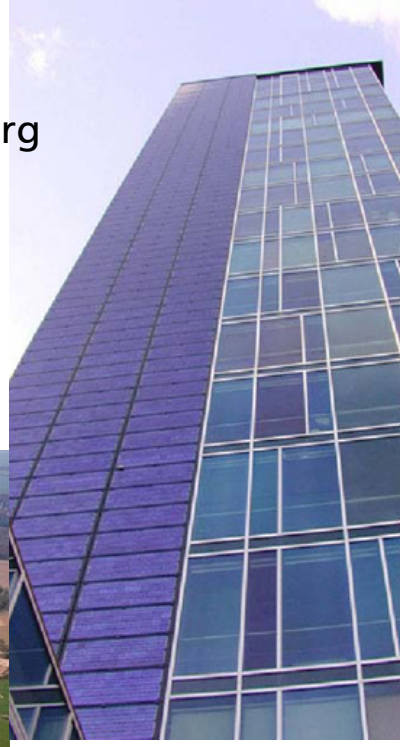
2012: 1 Million PV-Systems in Germany (30GWp)

Kleine Aufdachanlage

Bahnhof Freiburg



1MW Neue Messe München

40MW Brandis nähe Leipzig

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Technical-ecological Potential in D (conservative estimate)

Technically usable:
800 km² roofs,
150 km² facades,
670 km² sealed settlement area,
19% η_m, 900kWh/kW$_p$*a

	Status (2012) [GWp]	Potential Peak power [GWp]	Pot. Annual Electricity [TWh/a]	Status (2012) [TWh/a]
PV	32,6	275	**248**	28,0
Wind on-shore **(IWES 03/2011²)**	31,0	60 **(198*)**	**180** **(390*)**	45,3
Wind off-shore (91% N, 9% O)	0,28	45	**180**	0,7
Hydro	4,4	5,2	**24**	21,2
Geothermal	0,012	6,4	**50**	0,025
Waste biomass (only Biogas)		On demand	**23**	
Bioelectr. total	13,6			40,9
Total	81,9		**705**	136,1

Quelle: Potenzial: Umweltbundesamt UBA, Juli 2010, *Fraunhofer IWES Onshore Study, March 2011,
Status: Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland, Stand Februar 2013, www.bmu.de

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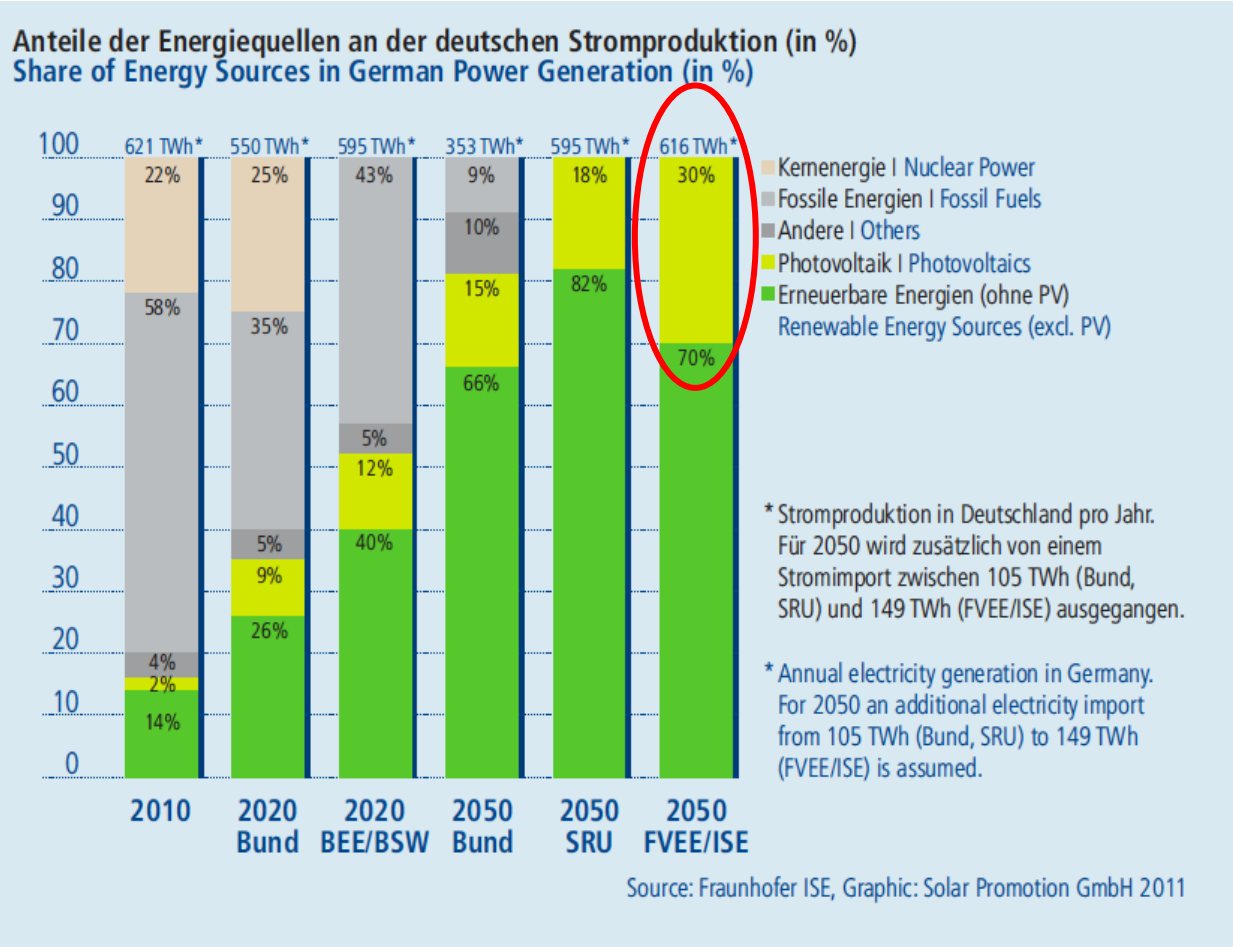
The Fraunhofer ISE Renewable Energy Scenario 2050



Source: G. Stryi-Hipp, Fh-ISE, 2011

Reasons for increased PV share:

- Popularity
- Local generation
- Price reductions

30% PV share represents 185 TWh or 200 GWp

Quellen | Sources:
2020 Bund, 2050 Bund: Szenario IIA mit 52 GW PV | energy scenario IIA with 52 GW PV, ewi/gws/prognos, 8/2010
2050 SRU: Gutachten 100 % erneuerbare Stromversorgung | Report 100 % renewable electricity supply, Sachverständigenrat für Umweltfragen, 1/2011
2050 ISE: ISE-Szenario auf Basis des FVEE-Energiekonzepts 2050 | ISE-Scenario based on the FVEE-energy concept 2050, Fraunhofer ISE, 5/2011

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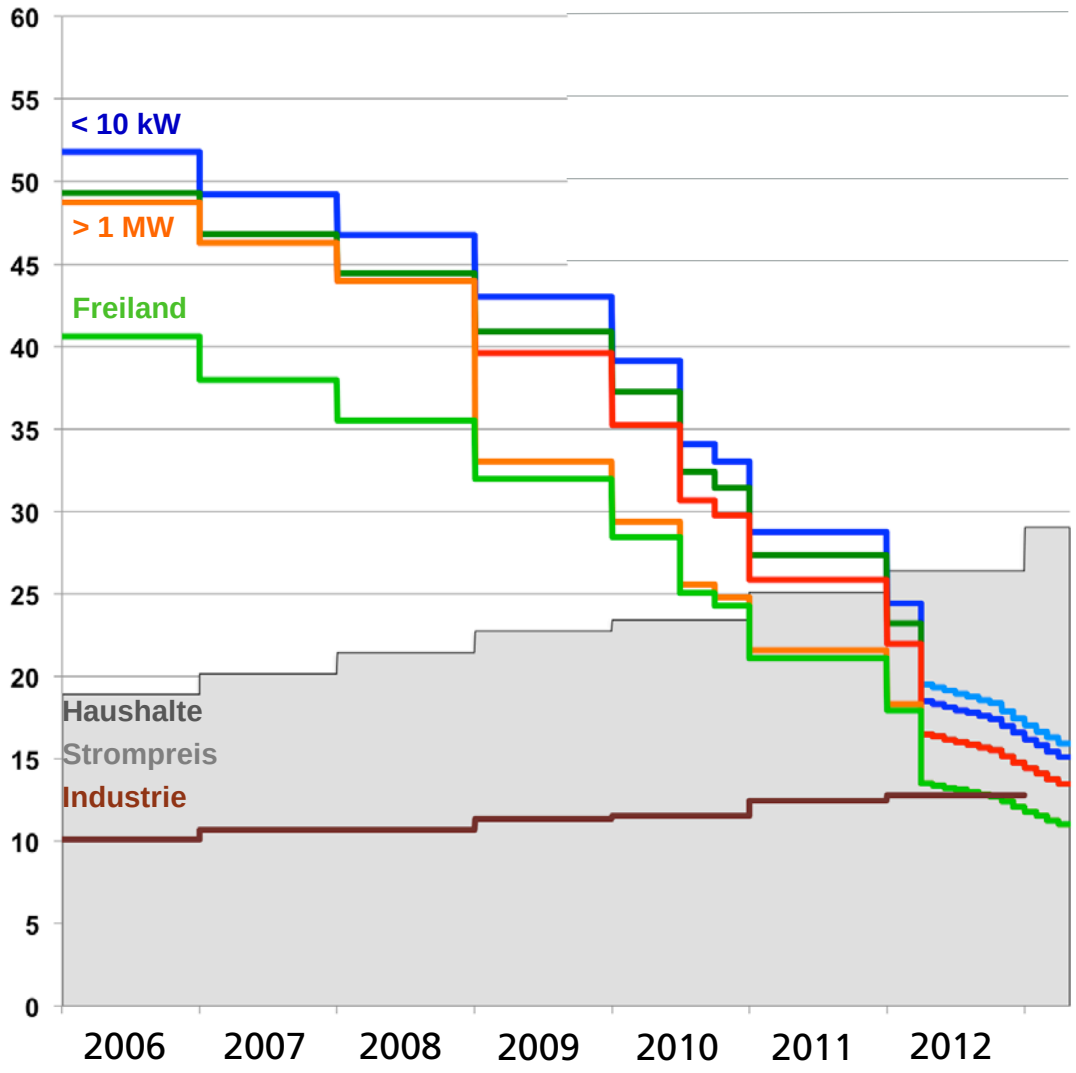
German Feed-in Tariff Development

Feed-in tariff in ct/kWh for 20 years at the moment of installation

Vergütung Solarstrom	Januar 2006	01.07. 2013
Aufdach		
< 10 kW	51,80	15,07
< 40 kW	51,80	14,30
< 100 kW	49,28	12,75
< 1000 kW	48,74	
< 10 MW	48,74	10,44
Freiland	40,60	



Quelle: Dr. G. Stryi-Hipp, Fraunhofer ISE

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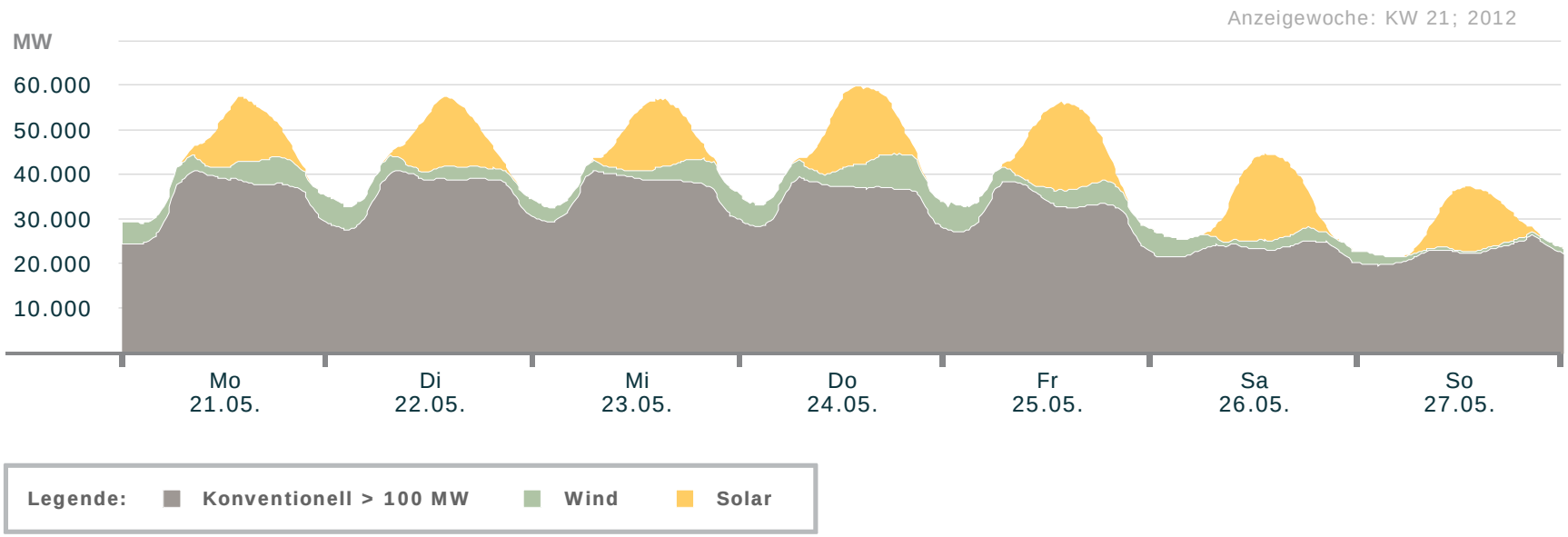
German Electricity Consumpt: Week 21, 21.-27. Mai 2012

Tatsächliche Produktion



- Solar: max. 22,4 GW
- Summe Mai: > 4 TWh entspr. 10% des mtl. Stromverbrauchs (BDEW)
- Steigerung um 40% ggü. Vorjahr

Grafik: B. Burger, Fraunhofer ISE; Daten: Leipziger Strombörse EEX

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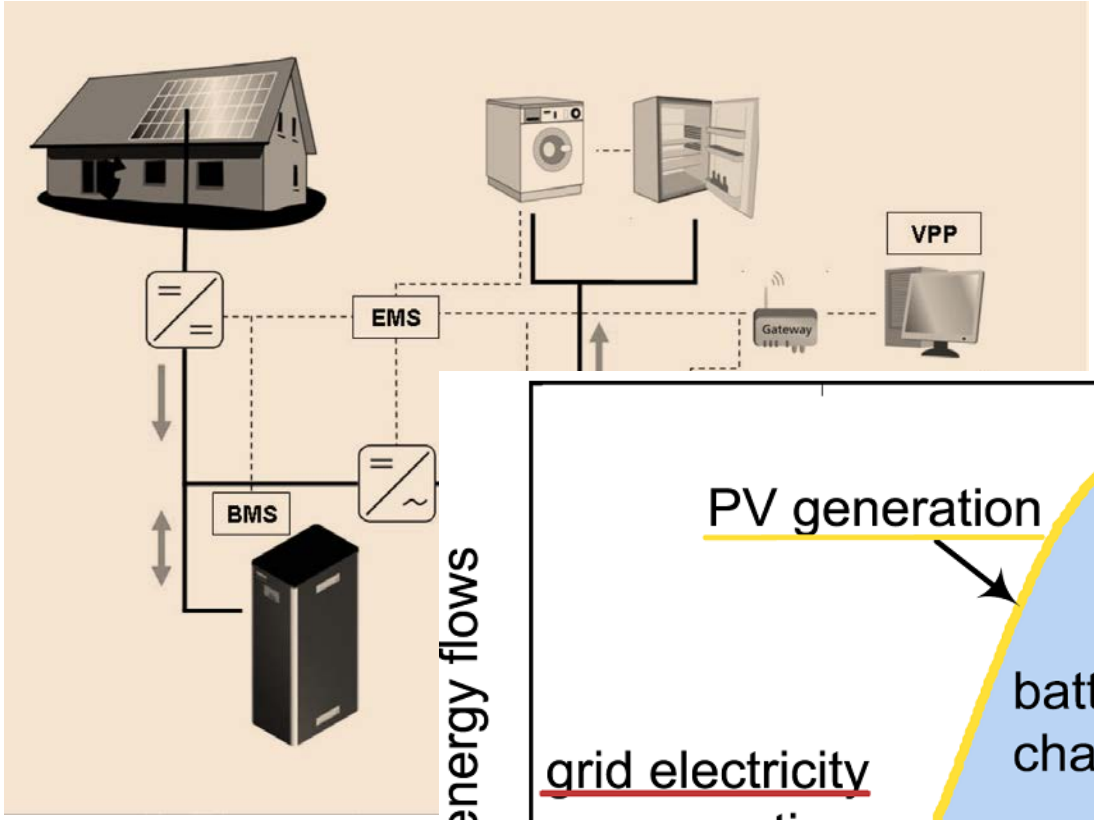
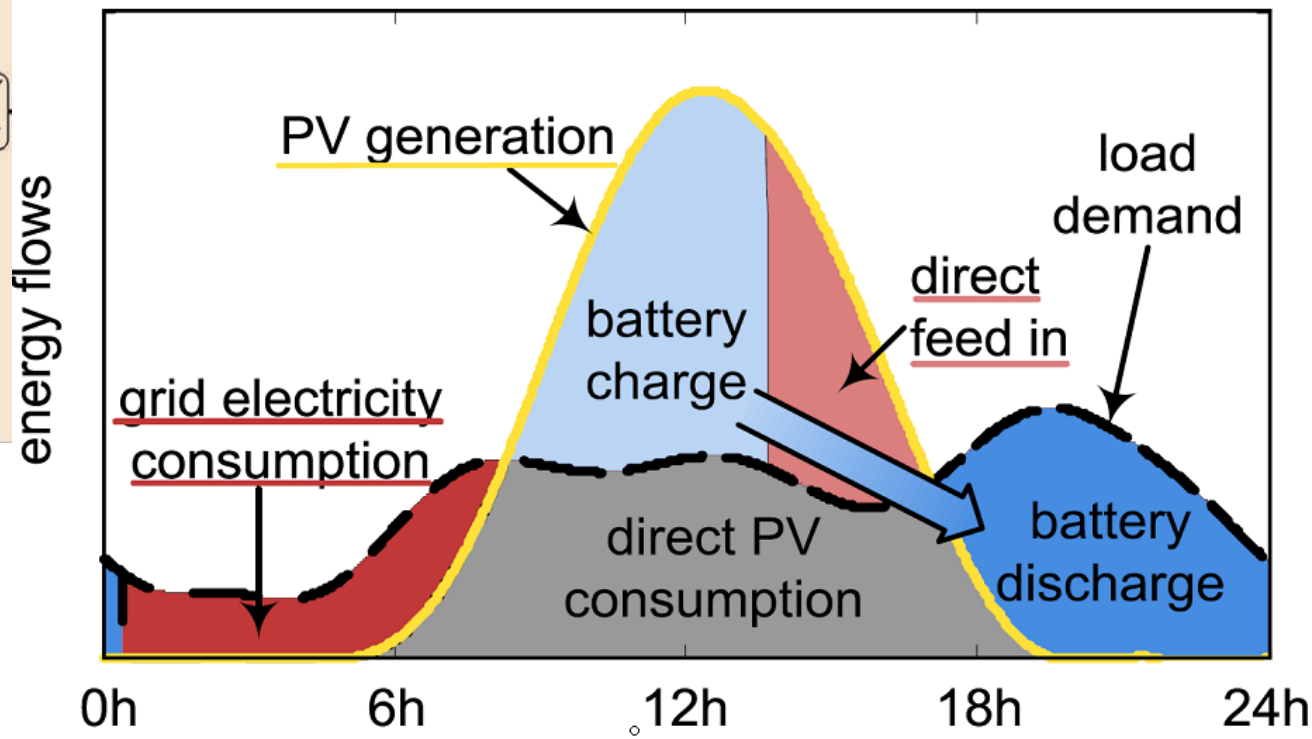
PV Electricity Storage in Houses





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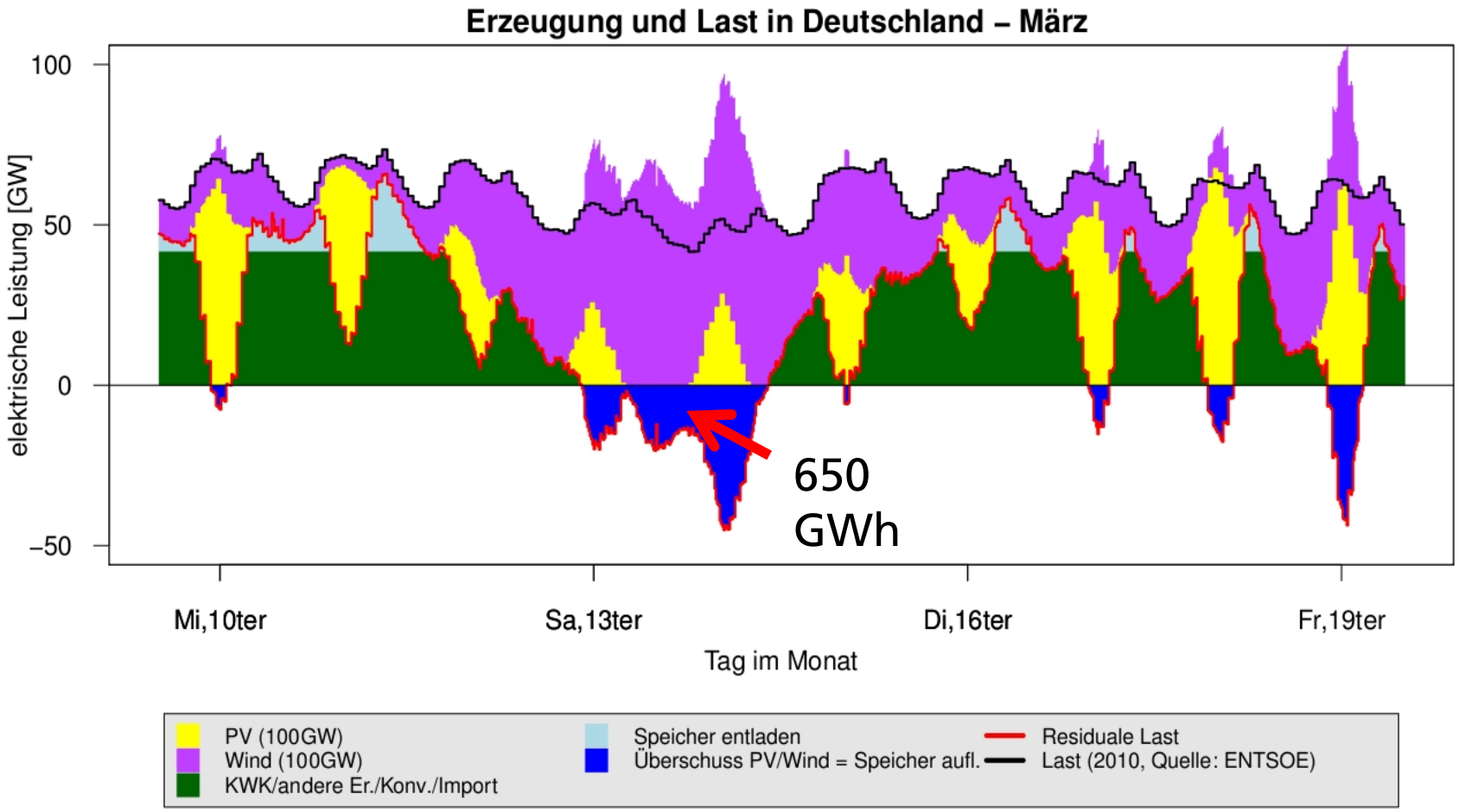
Future Renewable Scenario: Storage Needed



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Most attractive Storage Technologies for Grid Support

mechanical

- Pumped storage hydroelectricity
- Compressed air energy storage; CAES

electrochemical

- Batteries PB/ NiCd/NIMH/Li-Ion
- HT Batteries NaS/ NaNiCl
- Flow batteries Redox or Hybrid flow

chemical

- Hydrogen Fuel Cell
- Methane from Hydrogen & CO2

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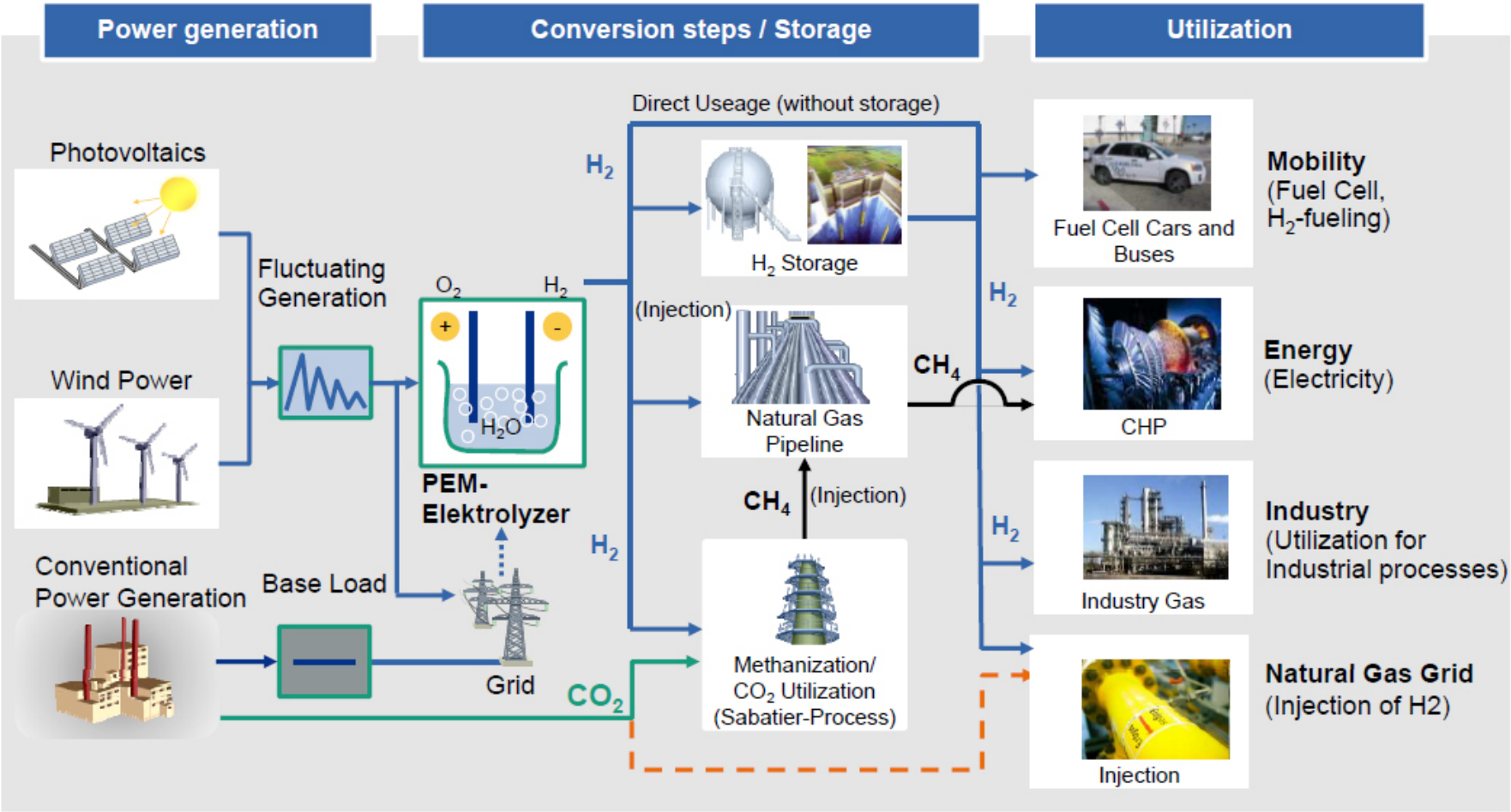
Seasonal Storage (Power-to-gas)



- **Technologien zur Integration fluktuierender erneuerbarer Stromquellen werden immer wichtiger!**

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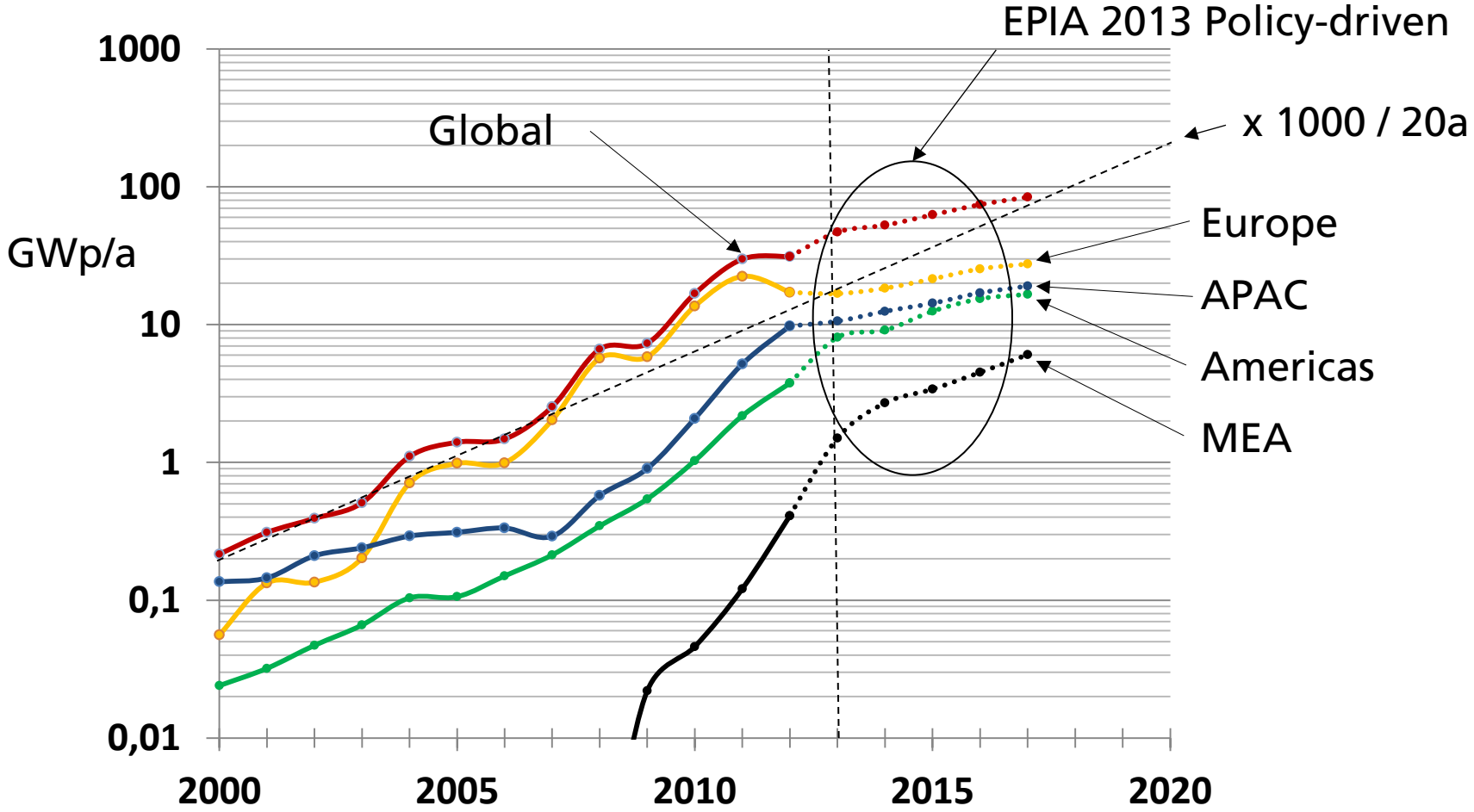
Global Annual PV Market Development



- **1GW/a: Europe 2005, APAC 2009, Americas 2010, MEA 2013**
- **Most dynamic markets: MEA, APAC**

Source: EPIA Global Market Outlook for Photovoltaics 2013-2017, http://www.epia.org/home/; download 07.06.2013

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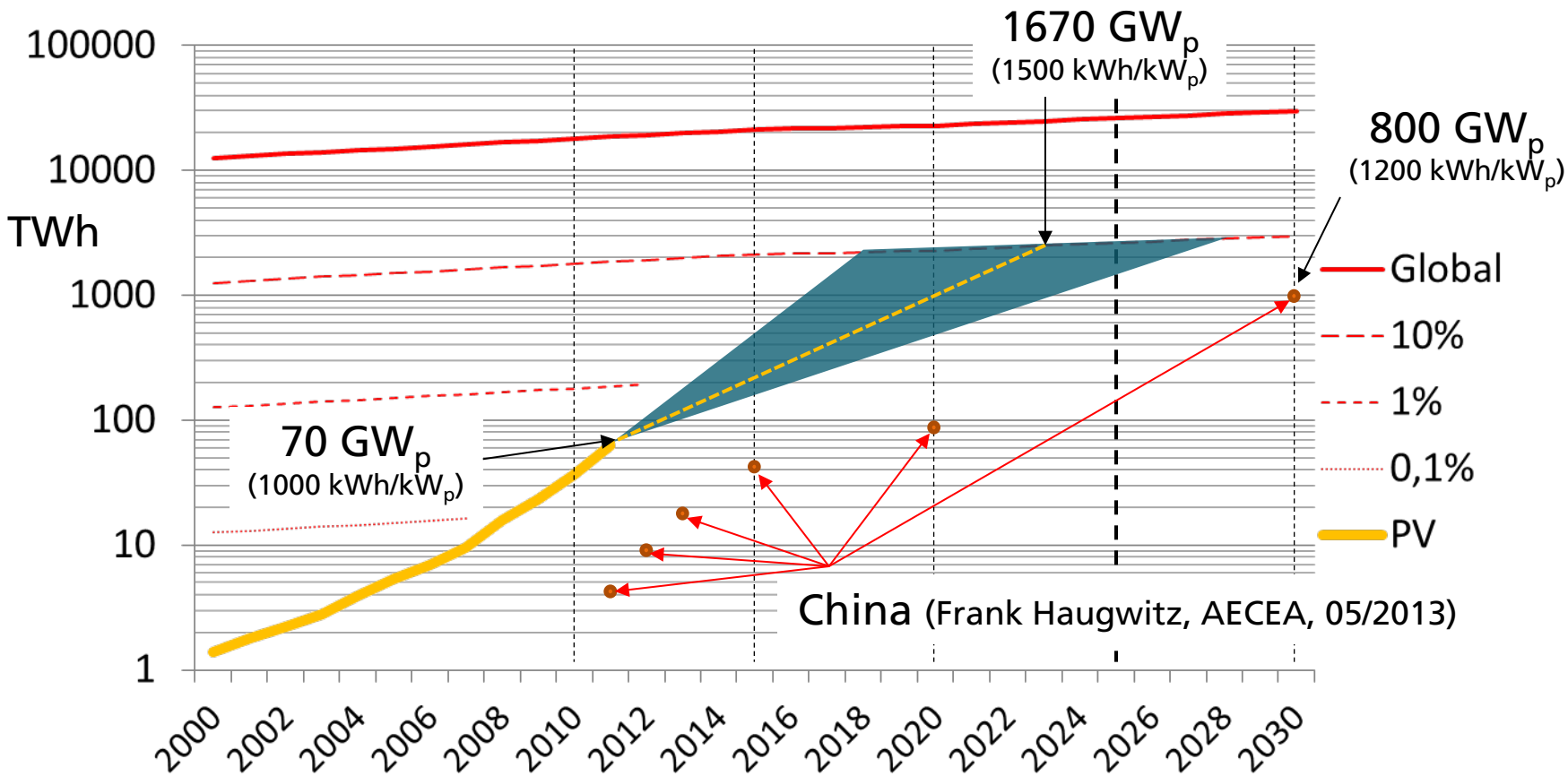
PV Share of Global Electricity Consumption



- 10% global solar PV electricity by 2030 possible!

Source: world electricity demand: http://www.iea.org/textbase/nppdf/free/2007/weo_2007.pdf, reference scenario, Tab. 1.8, p. 95; PV cumulative installation: EPIA Solar Generation 6 2011; conversion: 1000 kWh/kWp

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Summary

- Ground mounted PV system price 1€/W (LCOE 8€cents/kWh) -> PV starts to become competitive with wind electricity in southern Germany
- Prognosis 2020: c-Si module prices 0.4-0.5€/W
- Top 5 module producers 2013: all Chinese (2-3GW/a each)
- Quartzite rock, carbothermic reduction mg-Si, Siemens solar Si purification, directional solidification mc / Czochralski sc-Si and MWSS wafering strongly dominate
- c-Si market share 2012: 86% (8% CdTe, 4% CIGS, 2% a-Si)
- 2012: 1Mio. PV systems in Germany (33GW, 28TWh = 5% of total)
- Conservative technical-oecological potential in D: 275GW
- Storage and grid integration become more and more important

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Outlook

- **The European market lost its dynamics**
- **The Asia/Pacific APAC and Americas markets are about to overtake the European market (strongest dynamics in MEA)**
  -> PV goes global!
- **Possible: 100-200GW market in 2020, 10% global PV electricity before 2030**
- **c-Si will continue to dominate**

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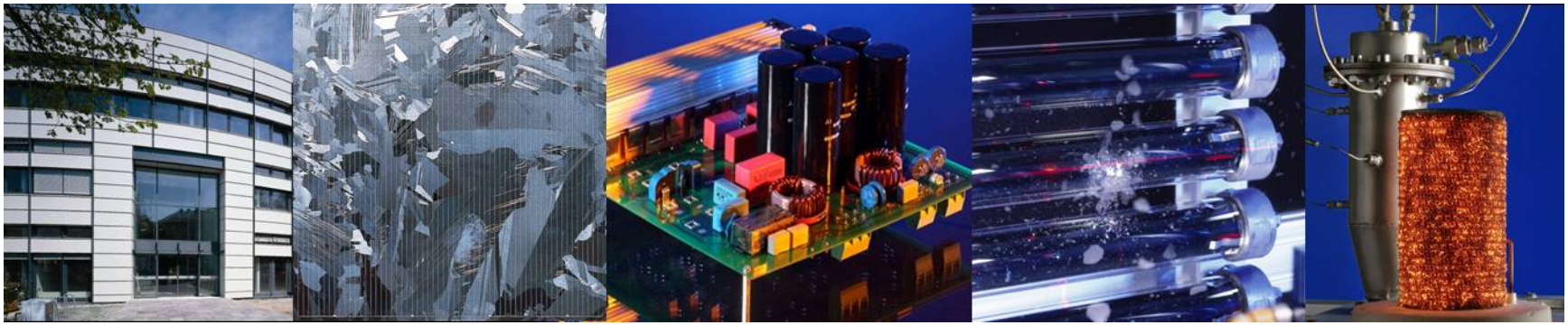
Thank you for you attention!



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