PHOTOVOLTAICS AS MAJOR ELECTRICITY SOURCE

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REPOWERING EUROPE

PV European Technology & Innovation Platform

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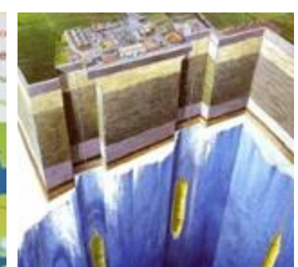
Cornerstones for the Transformation of our Energy System
to efficient use of finally 100% renewable energy –

- **Energy efficiency**: buildings, production, transport
- Massive increase in **renewable energies**: photovoltaics, solar and geo thermal, wind, hydro, biomass...
- Fast development of the **electric grid**: transmission and distribution grid, bidirectional
- Small and large scale energy **storage systems**: electricity, hydrogen, methane, methanol, biogas, solar heat, hydro.....
- **Sustainable mobility** as integral part of the energy system: electric mobility with batteries and hydrogen/fuel cells

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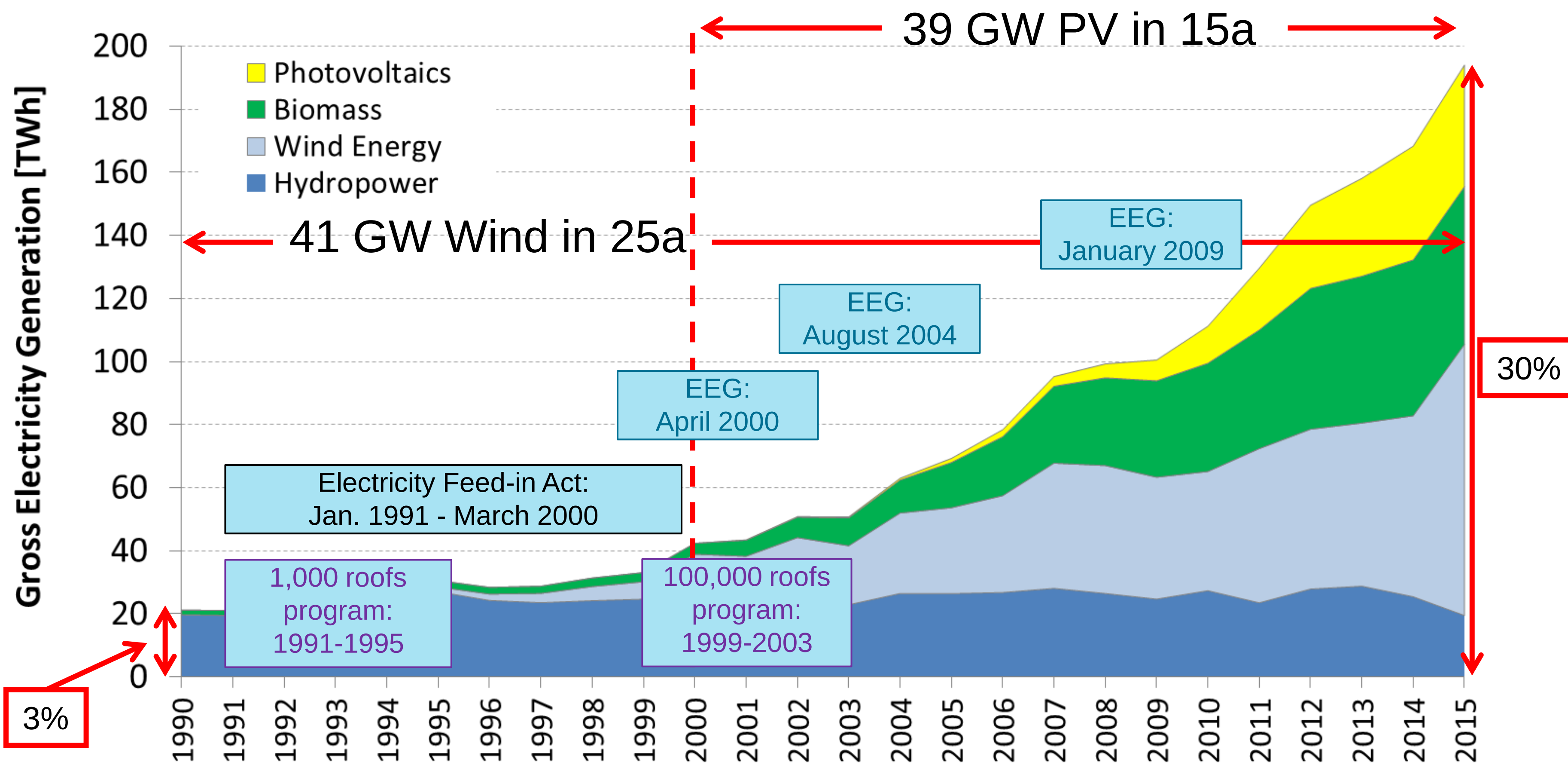
Contribution of RES to Electricity Supply in Germany
Historical Development



Data: BMWi

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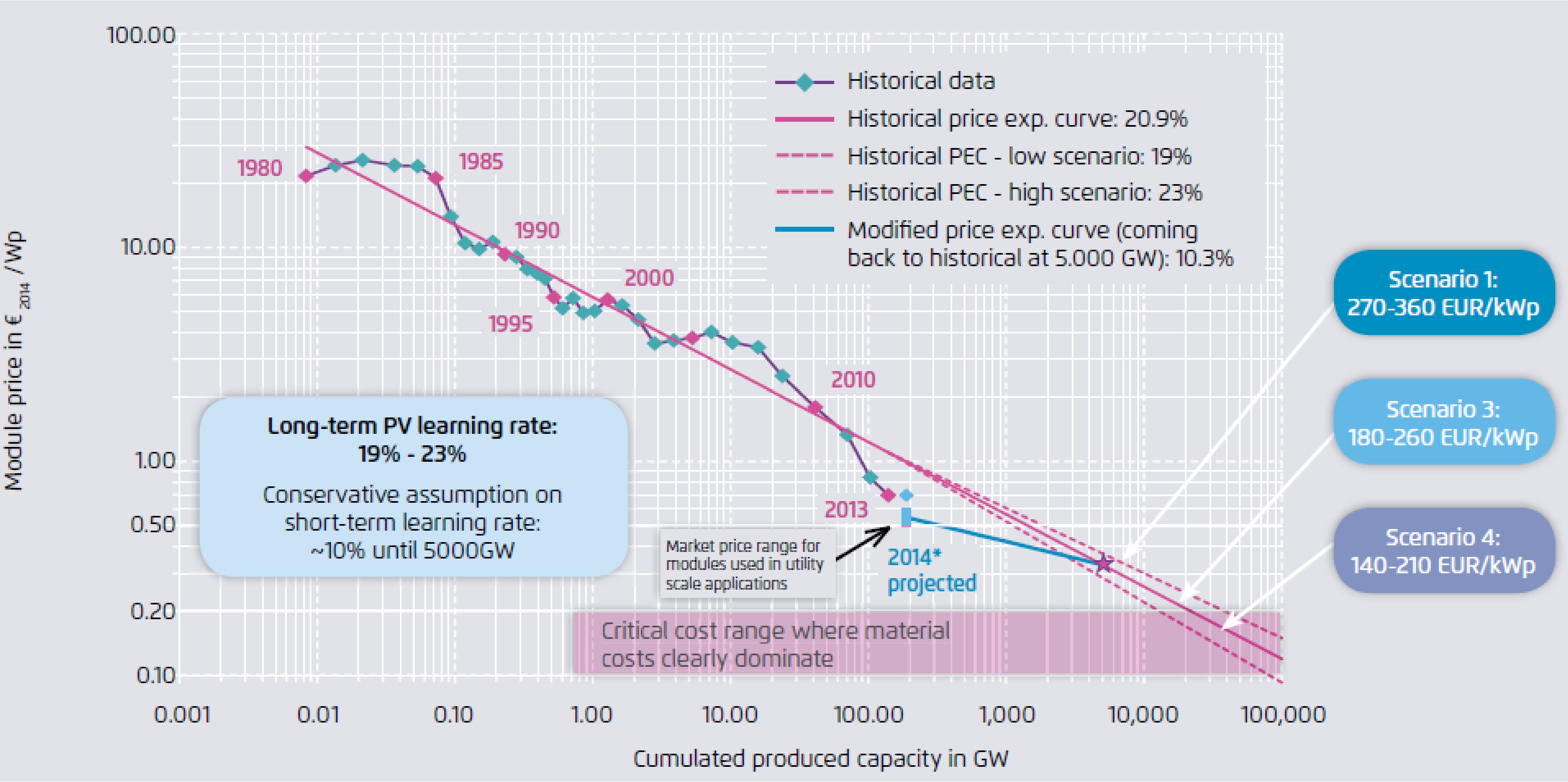
Long-term utility-scale PV system price scenarios

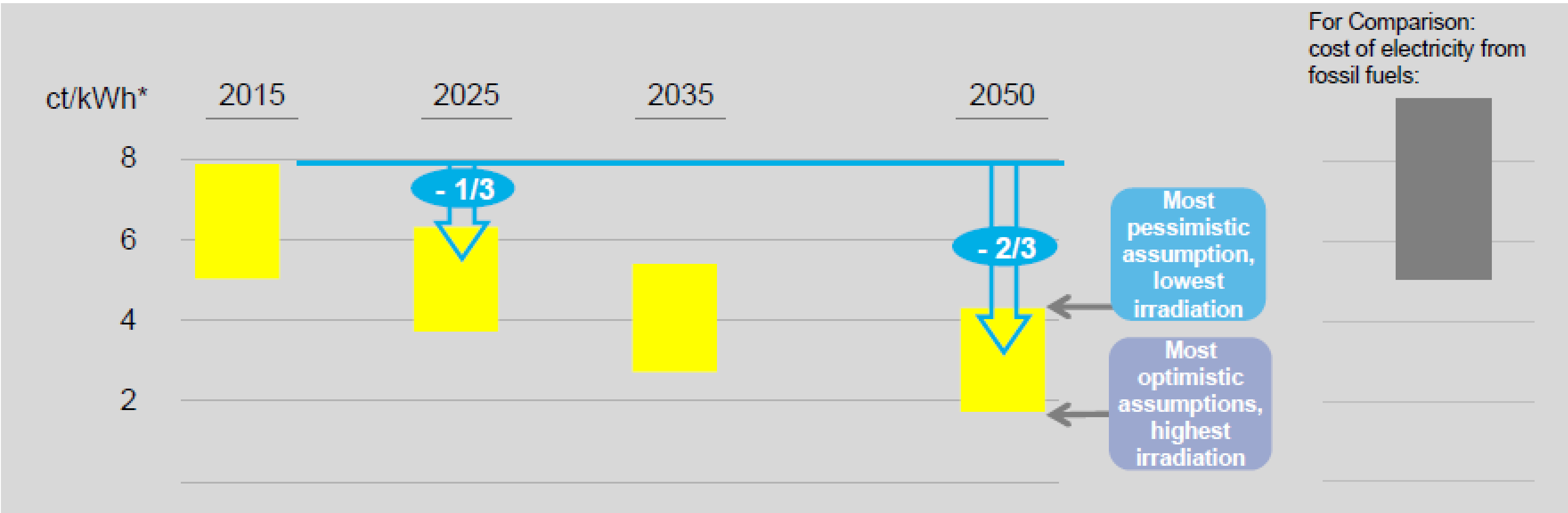


Source: Fraunhofer ISE (2015): Current and Future Cost of Photovoltaics. Study on behalf of Agora Energiewende

Levelized Cost of Electricity

Solar Power will soon be the Cheapest Form of Electricity in Many Regions of the World

Cost of electricity from new solar power plants in Southern and Central Europe

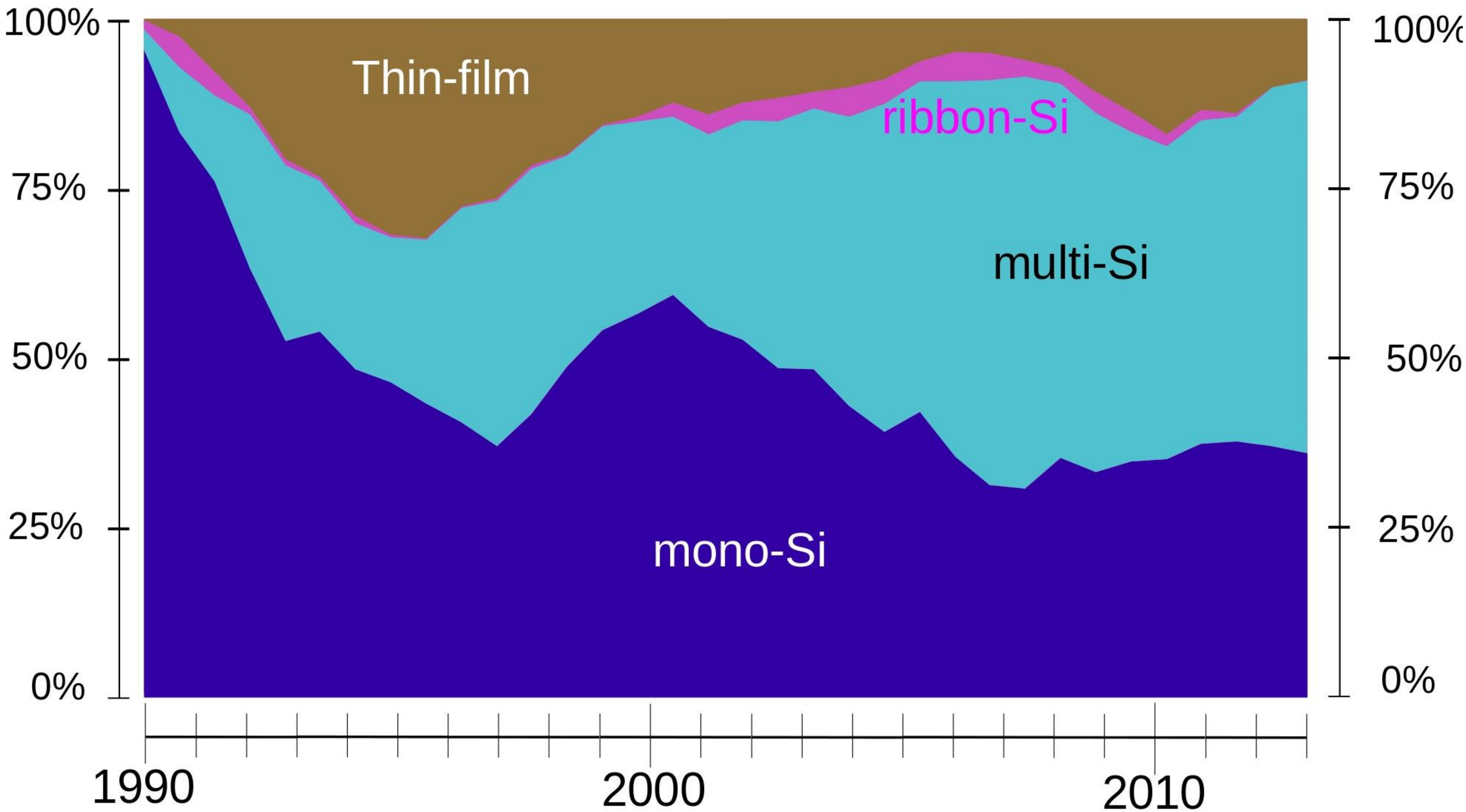


*Real values in EUR 2014; bandwidth represent different scenarios of market, technology and cost development, as well as power plant location between south of Germany (1190 kWh/kWp/y) and south of Spain (1680 kWh/kWp/y). Source: Own illustration

Source: Fraunhofer ISE (2015): Current and Future Cost of Photovoltaics. Study on behalf of Agora Energiewende

Global Market Share by PV Technology

from 1990 to 2013



Source: Solarbuzz 2014

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Crystalline Silicon Technology Portfolio
c-Si PV is not a Commodity, but a High-Tech Product!

material quality

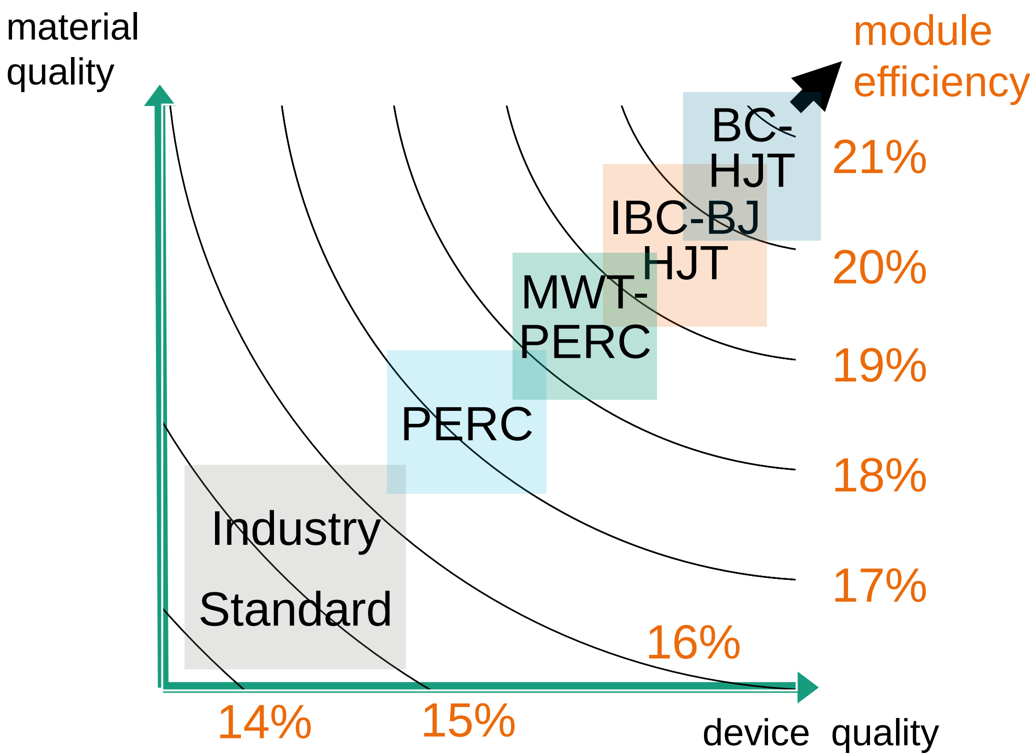
- diffusion length
- base conductivity

device quality

- passivation of surfaces
- low series resistance
- light confinement

cell structures

- PERC: Passivated Emitter and Rear Cell
- MWT: Metal Wrap Through
- IBC-BJ: Interdigitated Back Contact – Back Junction
- HJT: Hetero Junction Technology



Adapted from Preu et al., EU-PVSEC 2009

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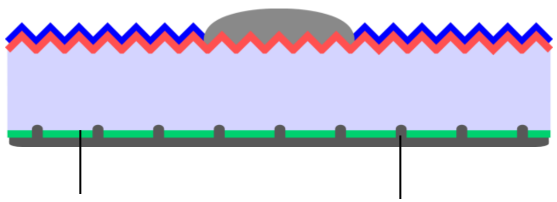
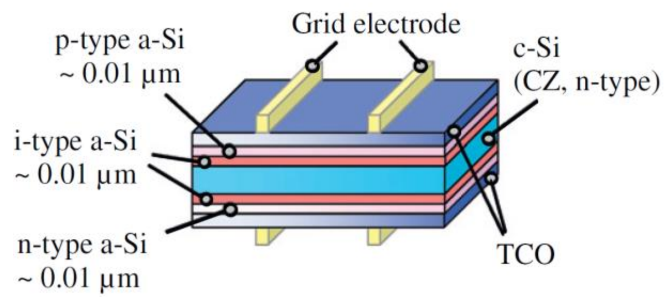
Advanced Cell Technologies

Passivated Emitter and Rear PERC[1]

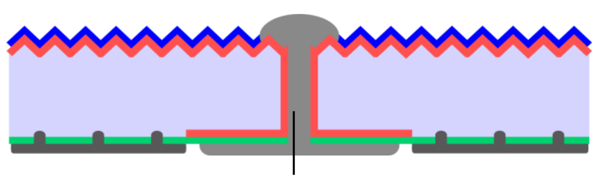


Passivating Layer Local Contacts

Heterojunction on Intrinsic layer HIT[3]



Metal Wrap-Through MWT-PERC[2]

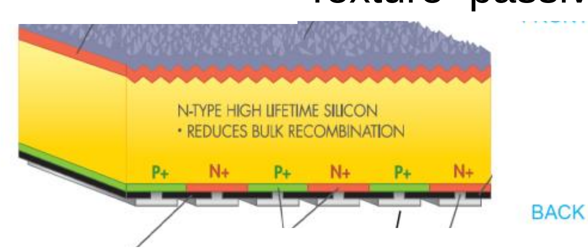


Metal Wrap Through Contact

Interdigitated Back Contact/Junction IBC-BJ[4]

Lightly Doped Front Diffusion

Texture+passivation Layer



Passivating Layer Local Contacts

[1]Blakers et al., Appl. Phys. Lett. 55, pp. 1363-5, 1989

[2]Dross et al., Proc. 4th WCPEC, 2006, pp. 1291-4

[3] Sanyo/Panasonic [4] Sunpower

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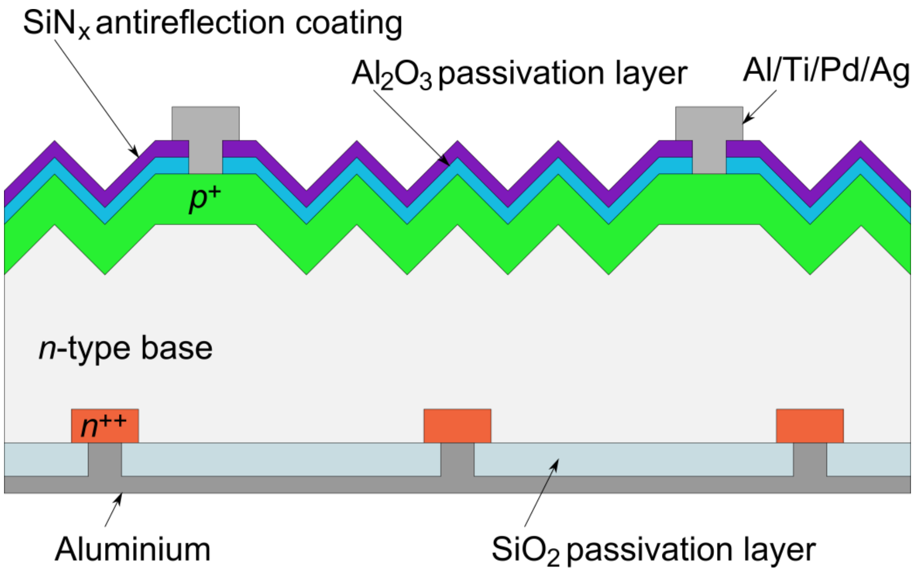
High-efficiency n-type PERL Cells
Lab Results

- Excellent performance at cell level
- Only very thin ALD layer necessary

	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Best cell	**705**	**41.1**	**82.5**	**23.9***



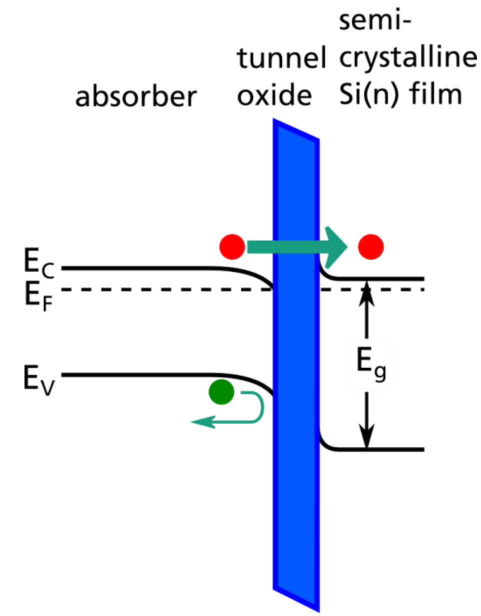
*Confirmed at Fraunhofer ISE CalLab

ap = aperture area
(= bus bar included in illuminated area)

Benick et al., APL 92 (2008)
Glunz et al., IEEE-PVSC (2010)

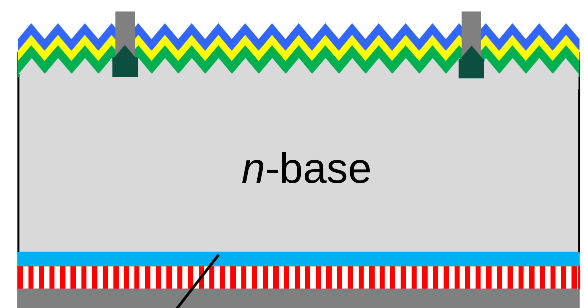
Advanced Cell Technologies
Tunnel Oxide Passivated Contact (*TOPCon*)

- TOPCon enables:
  - Excellent carrier-selectivity
  - High tolerance to high-temperature processes
- Very high V_{oc} and *FF* achieved due to
  - Excellent surface passivation
  - 1D carrier flow pattern in base



	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
Champion	**719**	**41.5**	**83.4**	**24.9**[*]

[*]FZ-Si, *n*-type, 2x2 cm², aperture area, confirmed by Fraunhofer ISE Callab



TOPCon: $J_{0,rear}$ □ 7 fA/cm²

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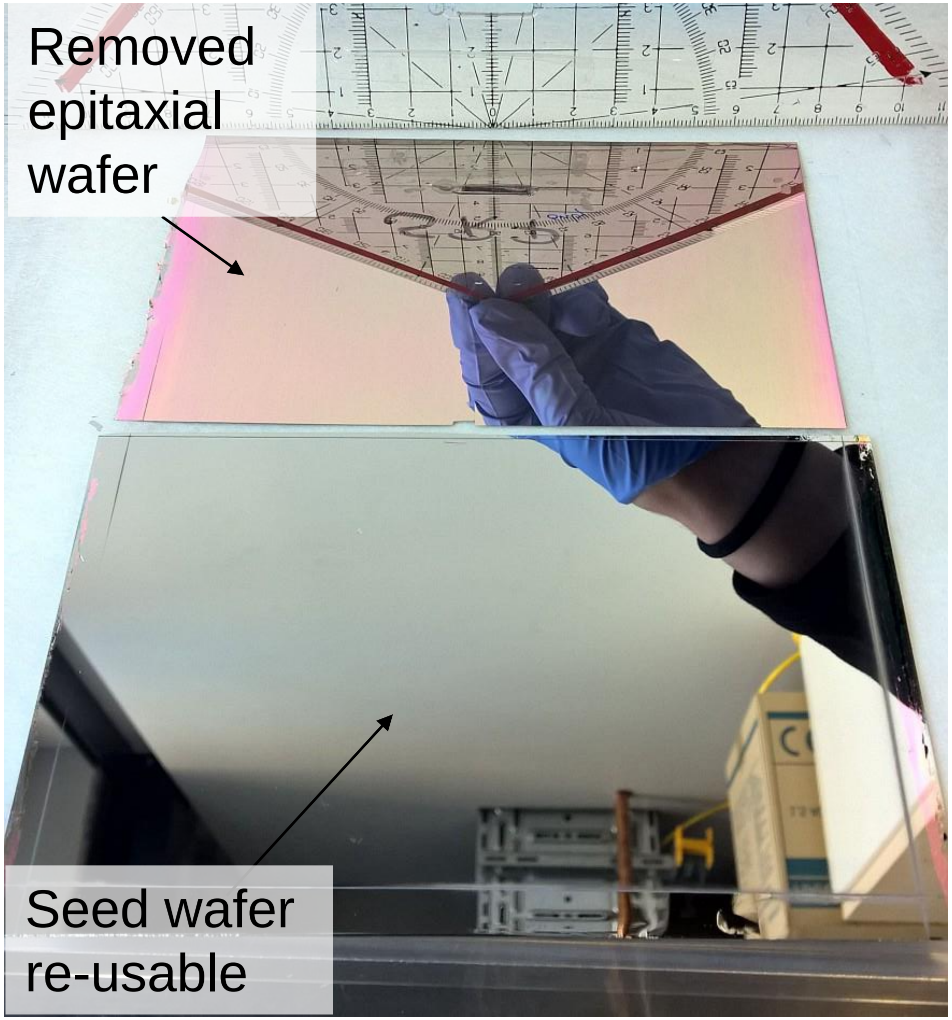
NexWafe:
Kerfless Wafer Production for High-Efficiency PV

- Product: n-type wafer for high-efficiency solar cells
- ISE high-throughput ProConCVD to grow the epitaxial layer
- Wafer thickness 150 µm → “drop-in” replacement for Cz-wafer
- Proof-of-concept verified on small scale, upscaling under way!
- Wafers available 2017!



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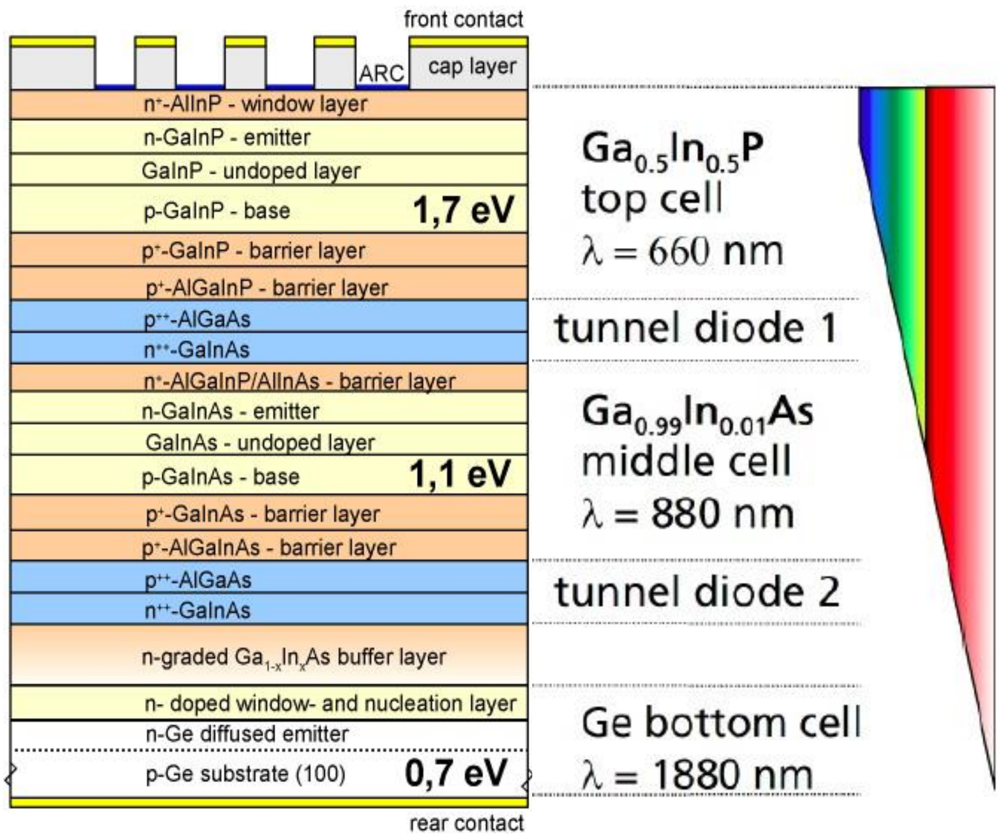
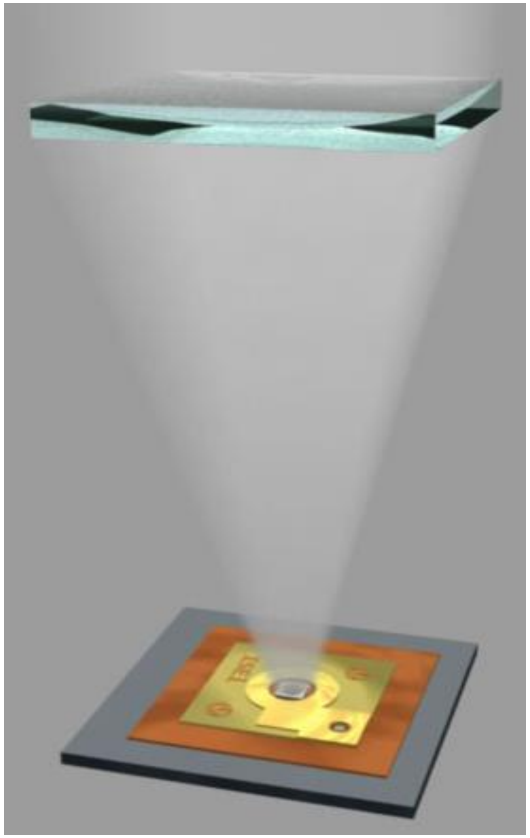
High-Efficiency III/V Based Triple-Junction Solar Cells





Slide: courtesy of F. Dimroth

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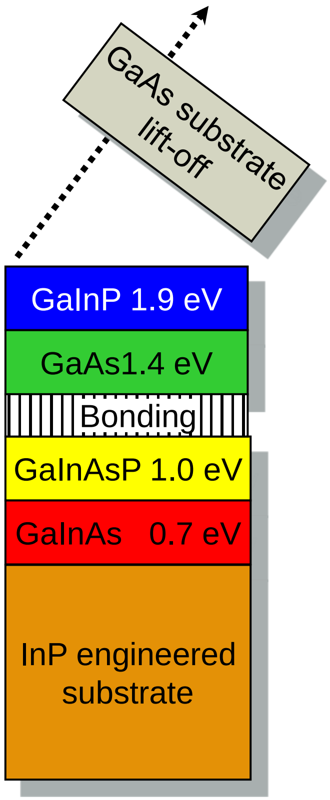
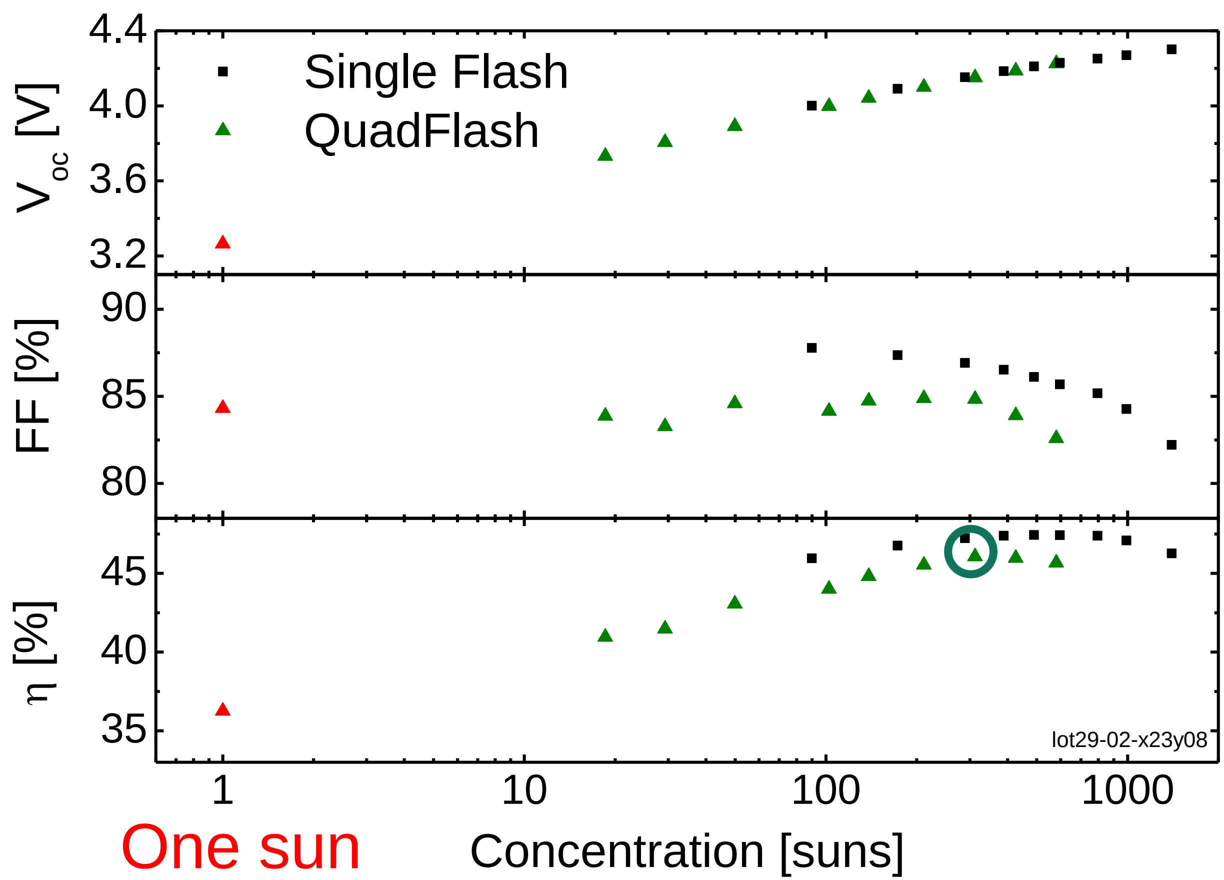
InP based 4-Junction Solar Cell Results on Engineered Substrate

QuadFlash: η = **46.1 %** C = 312





Nanowire Array Solar Cells

- may bring to the market single-Xtal III-V solar cells to the cost of Thin Films

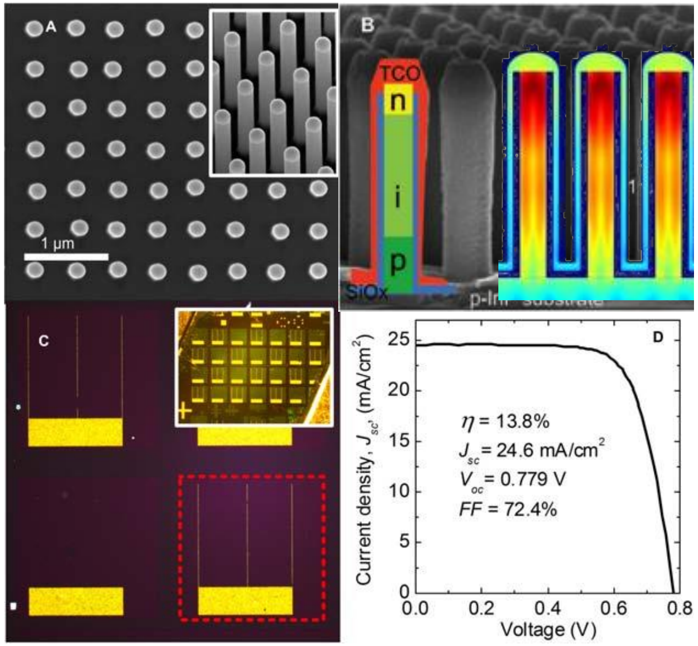
BUT - how will this be achieved?

- Nanowire arrays from EPITAXY
- Nanowire arrays from AEROTAXY

InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit

Jesper Wallentin,[1] Nicklas Anttu,[1] Damir Asoli,[2] Maria Huffman,[2] Ingvar Åberg,[2] Martin H. Magnusson,[2] Gerald Siefer,[3] Peter Fuss-Kailuweit,[3] Frank Dimroth,[3] Bernd Witzigmann,[4] H. Q. Xu,[1,5] Lars Samuelson,[1] Knut Deppert,[1] Magnus T. Borgström[1]*

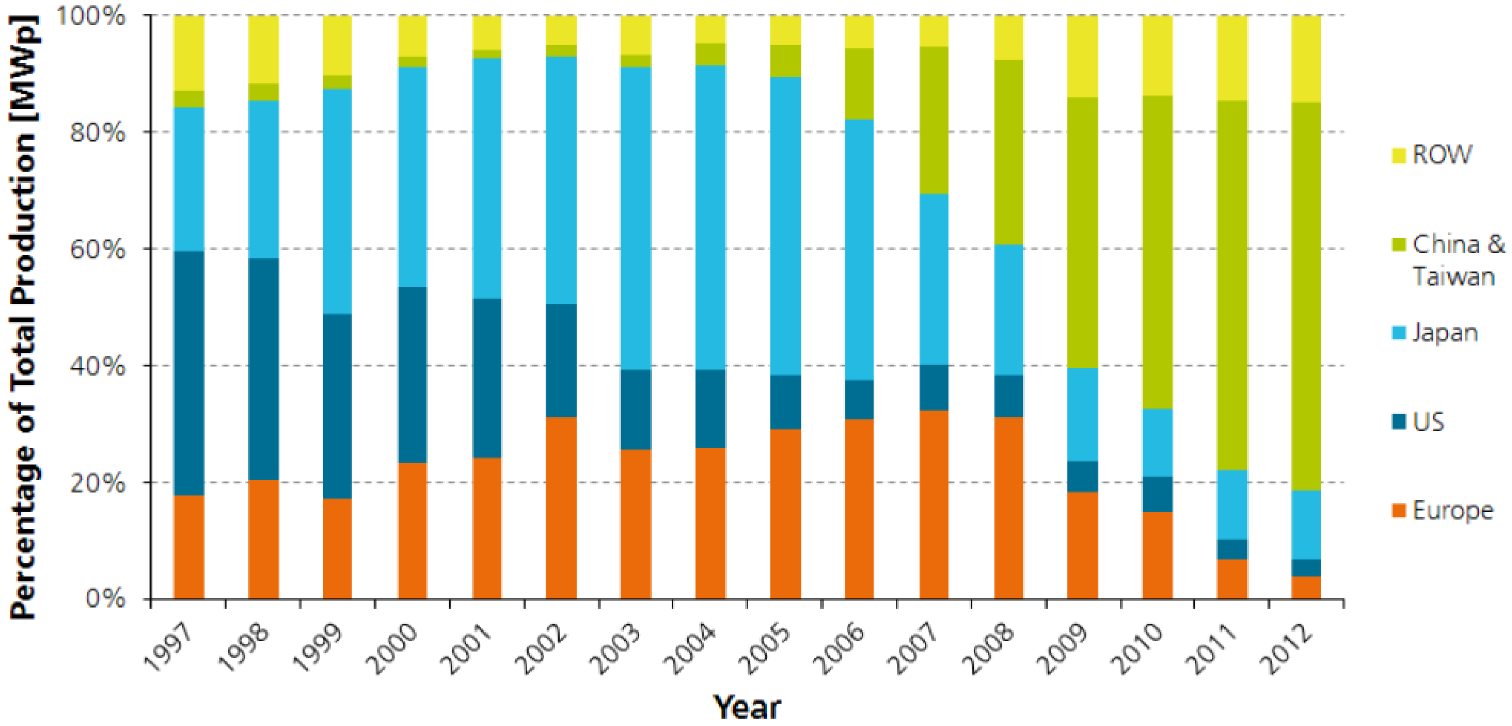
Photovoltaics based on nanowire arrays could reduce cost and materials consumption compared with planar devices but have exhibited low efficiency of light absorption and carrier collection. We fabricated a variety of millimeter-sized arrays of p-type/intrinsic/n-type (p-i-n) doped InP nanowires and found that the nanowire diameter and the length of the top n-segment were critical for cell performance. Efficiencies up to 13.8% (comparable to the record planar InP cell) were achieved by using resonant light trapping in 180-nanometer-diameter nanowires that only covered 12% of the surface. The share of sunlight converted into photocurrent (71%) was six times the limit in a simple ray optics description. Furthermore, the highest open-circuit voltage of 0.906 volt exceeds that of its planar counterpart, despite about 30 times higher surface-to-volume ratio of the nanowire cell.



www.sciencemag.org SCIENCE VOL 339 1 MARCH 2013 1057

PV-Production Capacity by Global Regions 1997-2012

Will China dominate the 100 GW/a World Market 2020?



Source: Navigant Consulting, Grafics: PSE AG 2013

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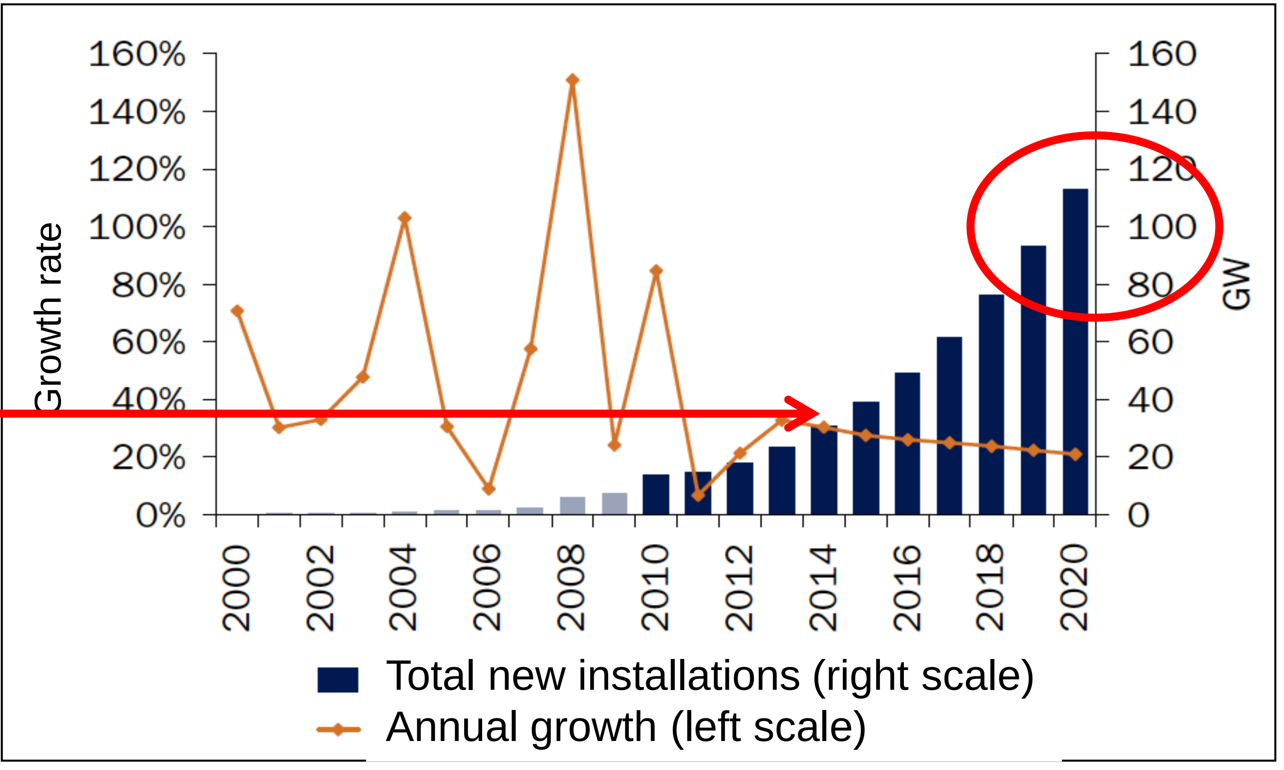
World Market Outlook: Experts are Optimistic
Example Sarasin Bank, November 2010

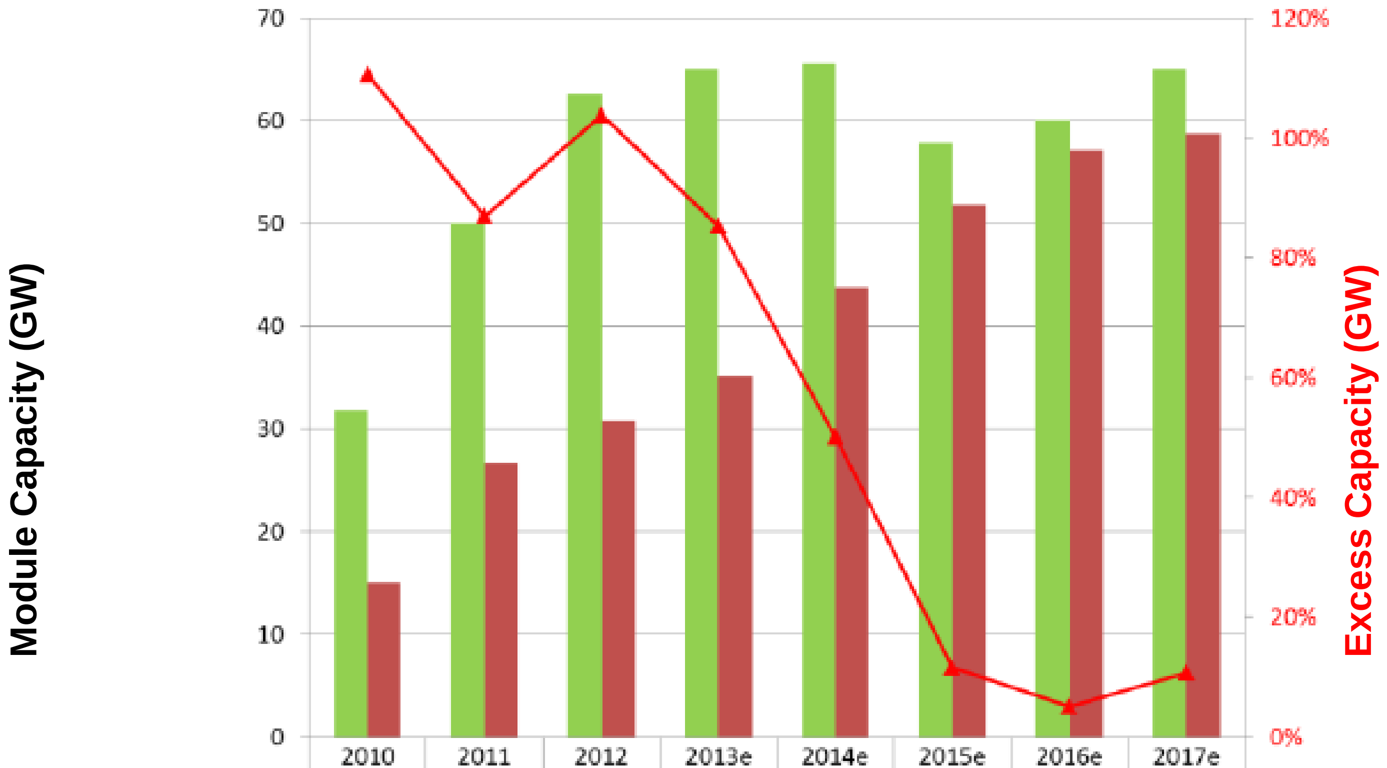
- **market forecast (2010): 30 GW_p in 2014, 110 GW_p in 2020**
  annual growth rate: in the range of 20 % and 30 %

2014:
ca. 40 GW_p,
1/3 above
forecast!



Source: Sarasin, Solar Study, Nov 2010

Global PV Production Capacity and Installations

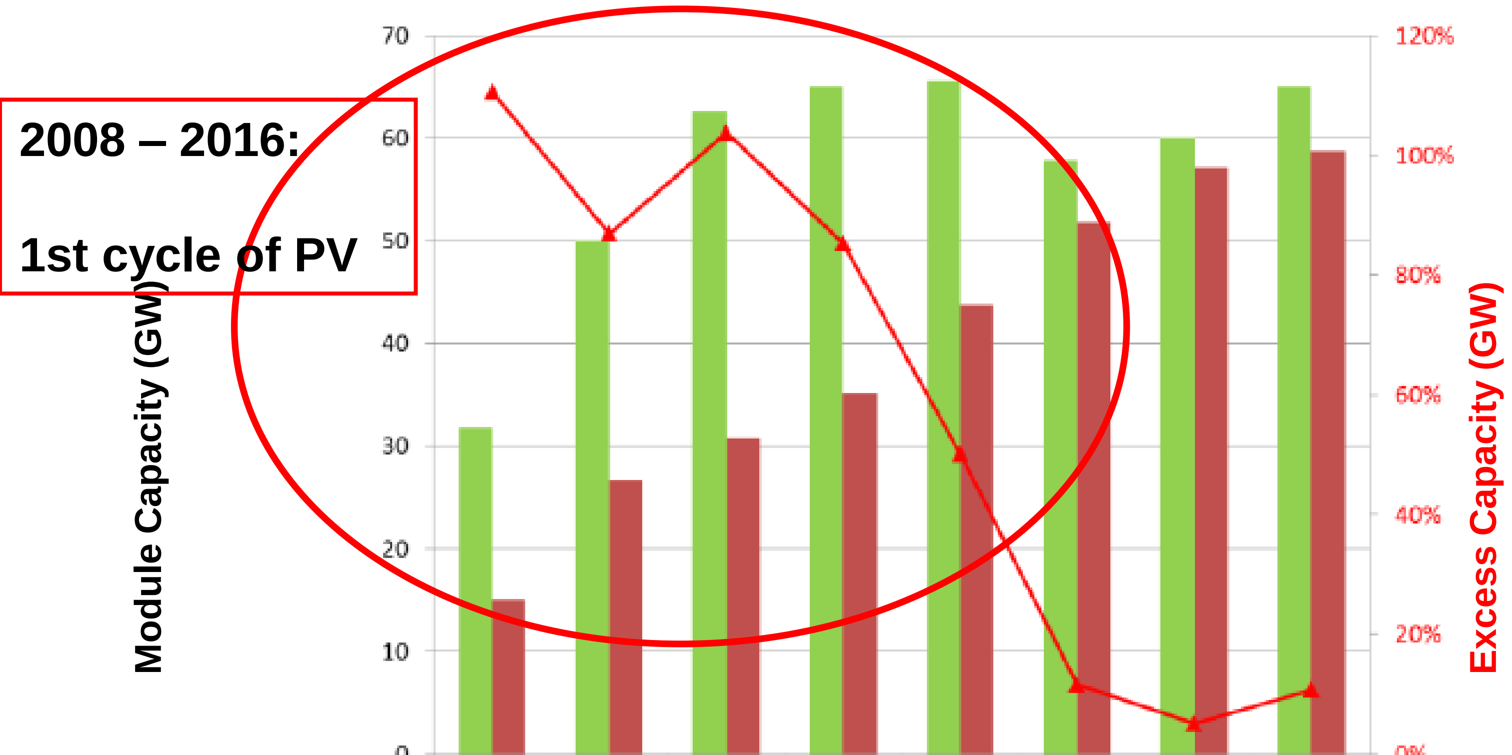


	2010	2011	2012	2013e	2014e	2015e	2016e	2017e
Production Capacity	31,8	50,1	62,7	65,1	65,6	57,9	60,0	65,1
Installations	15,1	26,8	30,8	35,1	43,7	51,9	57,1	58,8
Excess Capacity	110,6%	86,9%	103,8%	85,3%	50,1%	11,6%	5,1%	10,7%

Outlook for the development of supply and demand in the global PV market.

Source: Lux Research Inc., Grafik: PSE AG

Global PV Production Capacity and Installations



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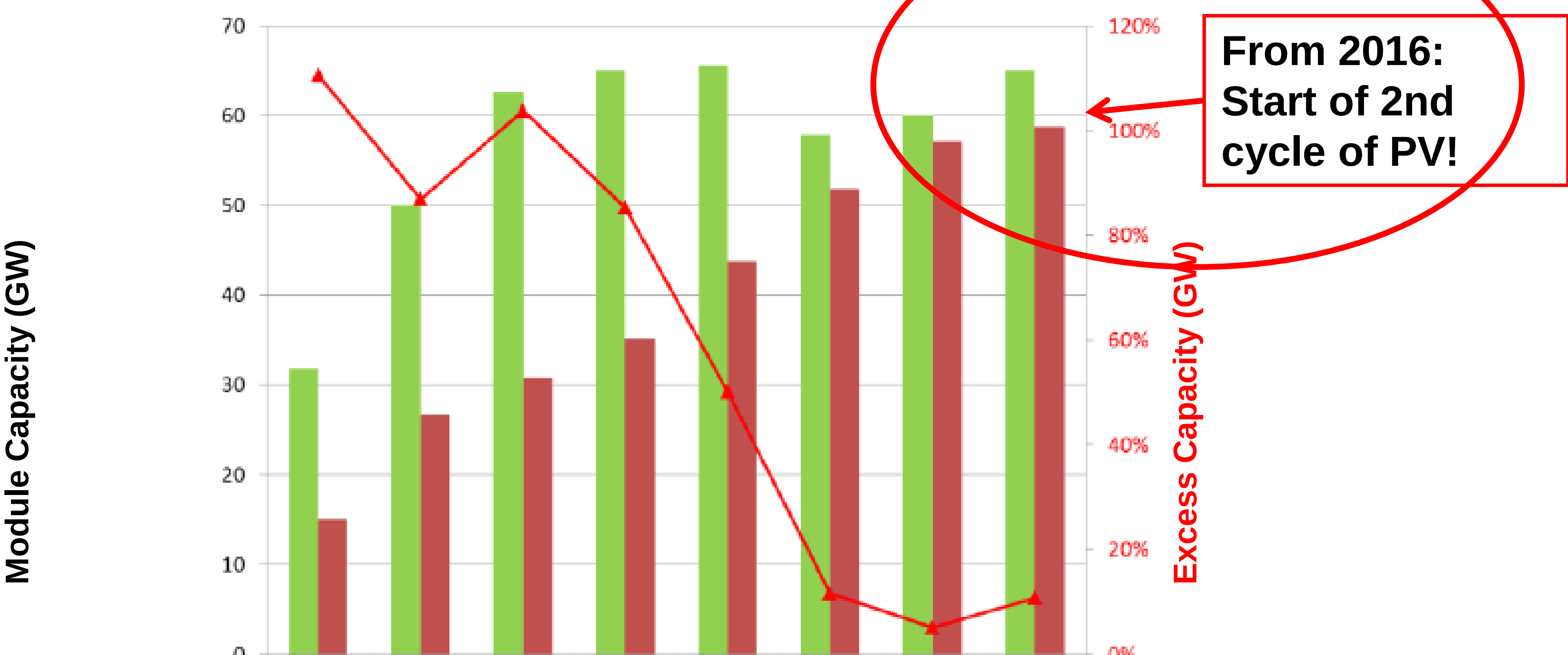

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Source: Lux Research Inc., Grafik: PSE AG

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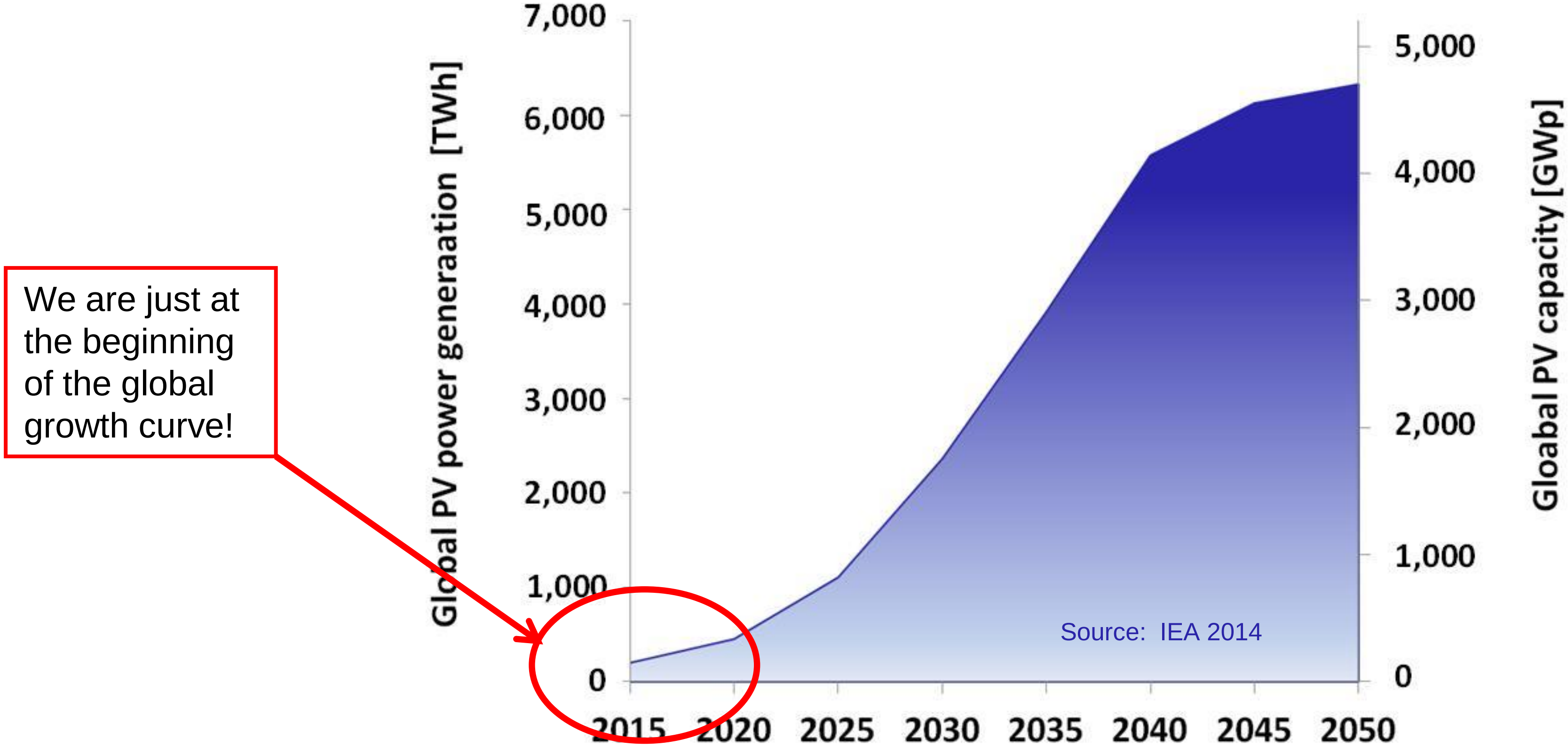
PV Market Growth: PV heading into the Terawatt Range!

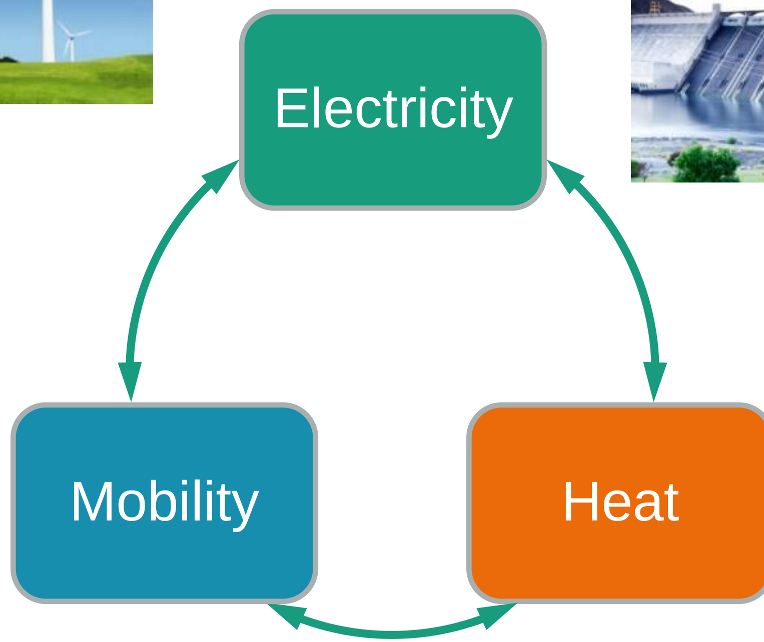
- Rapid introduction of PV globally is fueled by availability of cost-competitive, distributed energy
- In 2050 between 4.000 and 30.000 GW_p PV will be installed!
- By 2015, less than 300 GW_p have been installed!



How Will the Energy System Look Like in 2050?







→ Develop a model to simulate the transformation of the energy system

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Optimization of Germany's future energy system based on hourly modeling

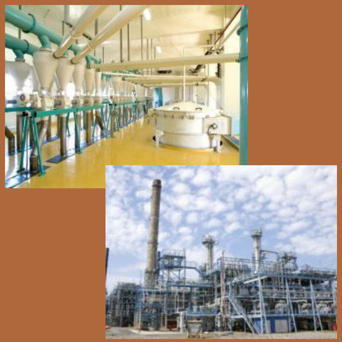
Comprehensive analysis of the overall system

Electricity generation, storage and end-use

Fuels (including biomass and synthetic fuels from RE)

Mobility (battery-electric, hydrogen, conv. fuel mix)

Heat (buildings, incl. storage and heating networks)



Processes in industry and tertiary sector

REMod-D

Renewable Energy Model – Deutschland

Slide courtesy Hans-Martin Henning 2014

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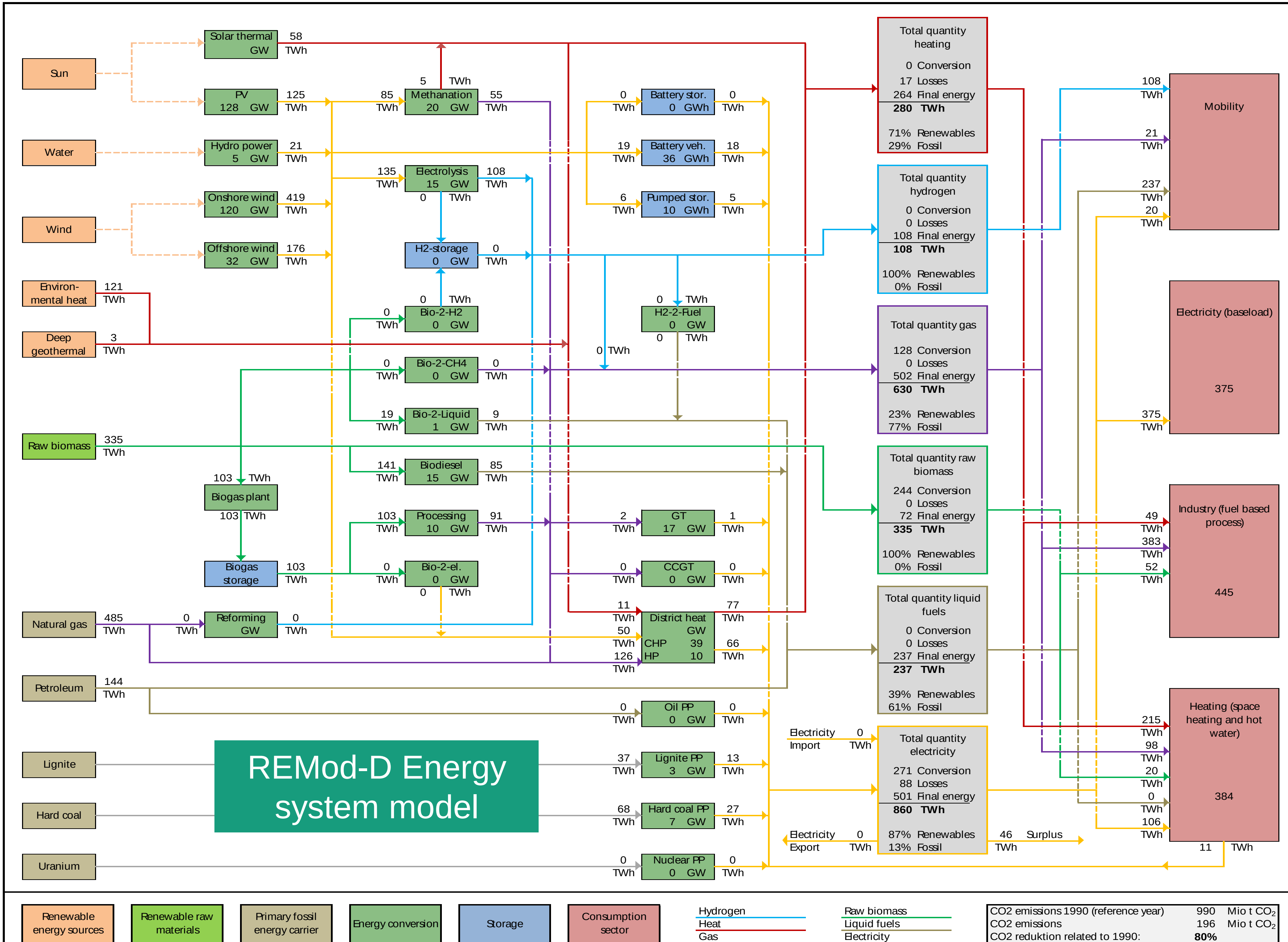
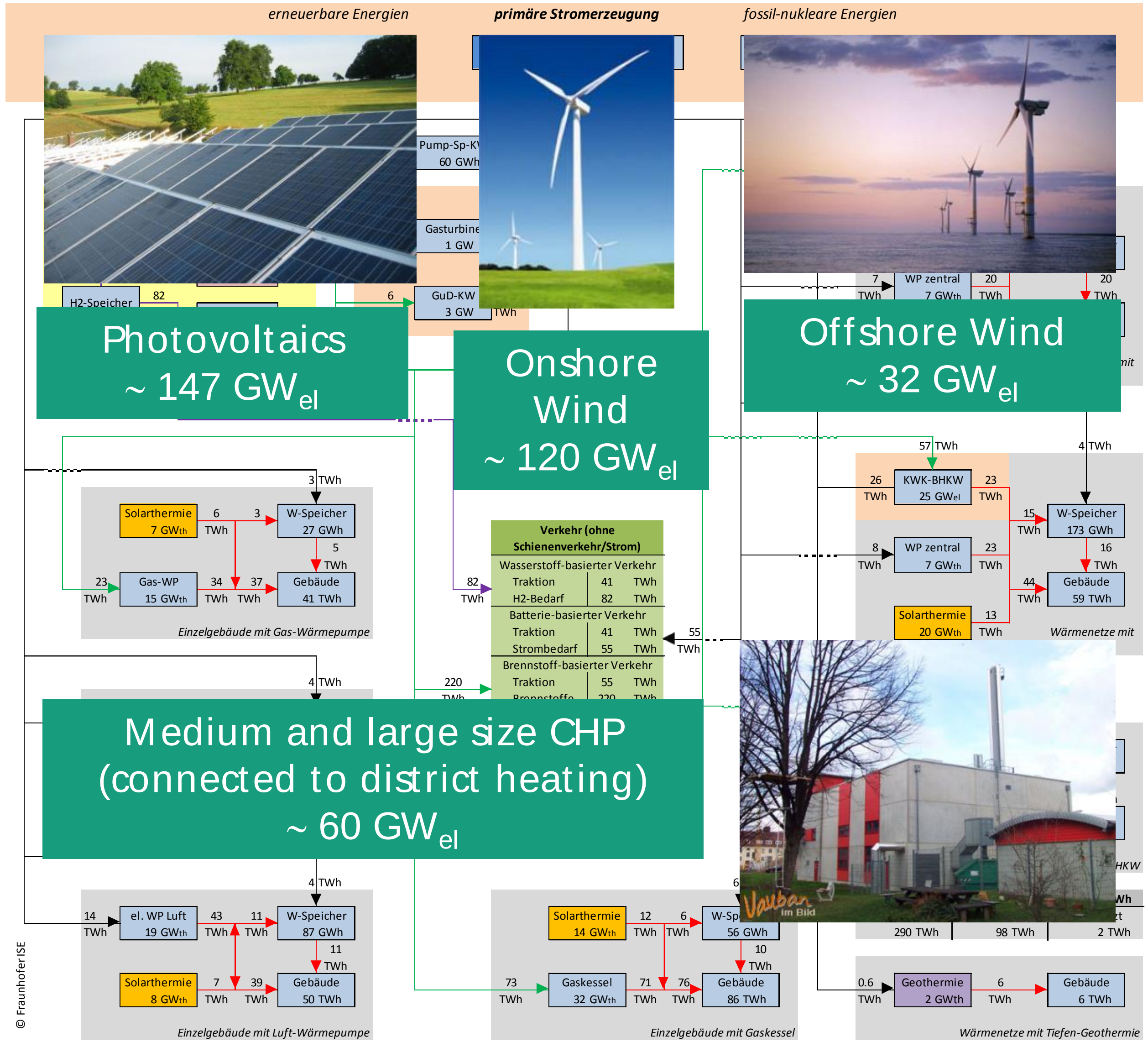


REMod-D Energy system model
Sun
Water
Wind
Environmental heat 121 TWh
Deep geothermal 3 TWh
Raw biomass 335 TWh
Natural gas 485 TWh
Petroleum 144 TWh
Lignite
Hard coal
Uranium
Solar thermal GW 58 TWh
PV 128 GW 125 TWh
Hydro power 5 GW 21 TWh
Onshore wind 120 GW 419 TWh
Offshore wind 32 GW 176 TWh
Methanation 20 GW 85 TWh 55 TWh 5 TWh
Electrolysis 15 GW 135 TWh 108 TWh 0 TWh
H2-storage 0 GW 0 TWh
Bio-2-H2 0 GW 0 TWh 0 TWh
Bio-2-CH4 0 GW 0 TWh 0 TWh
Bio-2-Liquid 1 GW 19 TWh 9 TWh
Biodiesel 15 GW 141 TWh 85 TWh
Biogas plant 103 TWh 103 TWh
Processing 10 GW 103 TWh 91 TWh
Biogas storage 103 TWh
Bio-2-el. 0 GW 0 TWh 0 TWh
Reforming GW 0 TWh 0 TWh
Battery stor. 0 GWh 0 TWh 0 TWh
Battery veh. 36 GWh 19 TWh 18 TWh
Pumped stor. 10 GWh 6 TWh 5 TWh
H2-2-Fuel 0 GW 0 TWh 0 TWh
0 TWh
GT 17 GW 2 TWh 1 TWh
CCGT 0 GW 0 TWh 0 TWh
District heat GW CHP 39 HP 10 11 TWh 50 TWh 126 TWh 77 TWh 66 TWh
Oil PP 0 GW 0 TWh 0 TWh
Lignite PP 3 GW 37 TWh 13 TWh
Hard coal PP 7 GW 68 TWh 27 TWh
Nuclear PP 0 GW 0 TWh 0 TWh
Total quantity heating: 0 Conversion, 17 Losses, 264 Final energy, 280 TWh, 71% Renewables, 29% Fossil
Total quantity hydrogen: 0 Conversion, 0 Losses, 108 Final energy, 108 TWh, 100% Renewables, 0% Fossil
Total quantity gas: 128 Conversion, 0 Losses, 502 Final energy, 630 TWh, 23% Renewables, 77% Fossil
Total quantity raw biomass: 244 Conversion, 0 Losses, 72 Final energy, 335 TWh, 100% Renewables, 0% Fossil
Total quantity liquid fuels: 0 Conversion, 0 Losses, 237 Final energy, 237 TWh, 39% Renewables, 61% Fossil
Total quantity electricity: 271 Conversion, 88 Losses, 501 Final energy, 860 TWh, 87% Renewables, 13% Fossil
Electricity Import 0 TWh
Electricity Export 0 TWh
46 TWh Surplus
Mobility: 108 TWh, 21 TWh, 237 TWh, 20 TWh
Electricity (baseload) 375; 375 TWh
Industry (fuel based process) 445; 49 TWh, 383 TWh, 52 TWh
Heating (space heating and hot water) 384; 215 TWh, 98 TWh, 20 TWh, 0 TWh, 106 TWh; 11 TWh
Renewable energy sources
Renewable raw materials
Primary fossil energy carrier
Energy conversion
Storage
Consumption sector
Hydrogen
Heat
Gas
Raw biomass
Liquid fuels
Electricity
CO2 emissions 1990 (reference year) 990 Mio t CO2
CO2 emissions 196 Mio t CO2
CO2 reduktion related to 1990: 80%

Electricity generation



Slide courtesy Hans-Martin Henning 2014

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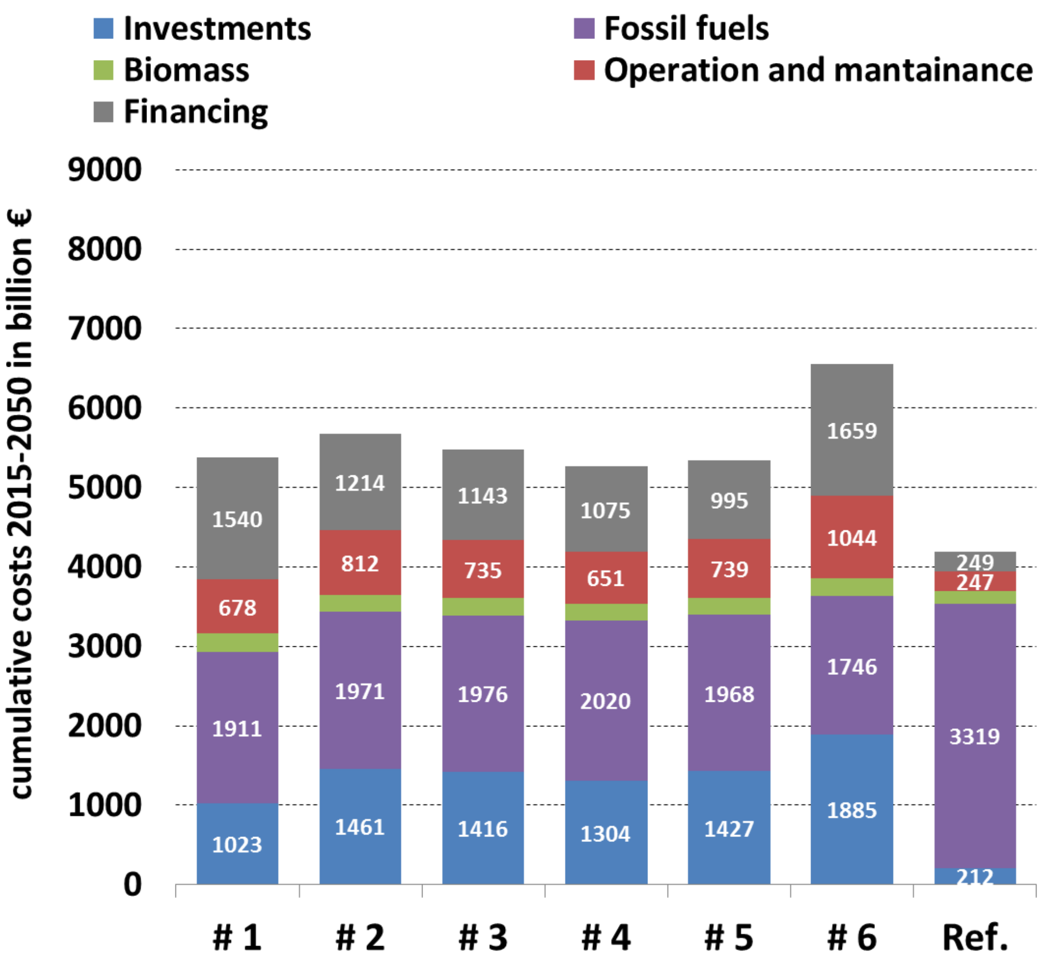
Scenario results hourly modeling 2014-2050
Cumulative total cost

- No penalty on CO_2 emissions
- Stable fossil fuel prices



#1 -80 % CO_2, low rate building energy retrofit, electric vehicles dominant, coal until 2050

#2 -80 % CO_2, low rate building energy retrofit, mix of vehicles, coal until 2050

#3 -80 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2050

#4 -80 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

#5 -85 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

#6 -90 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

Ref today‘s system; no change

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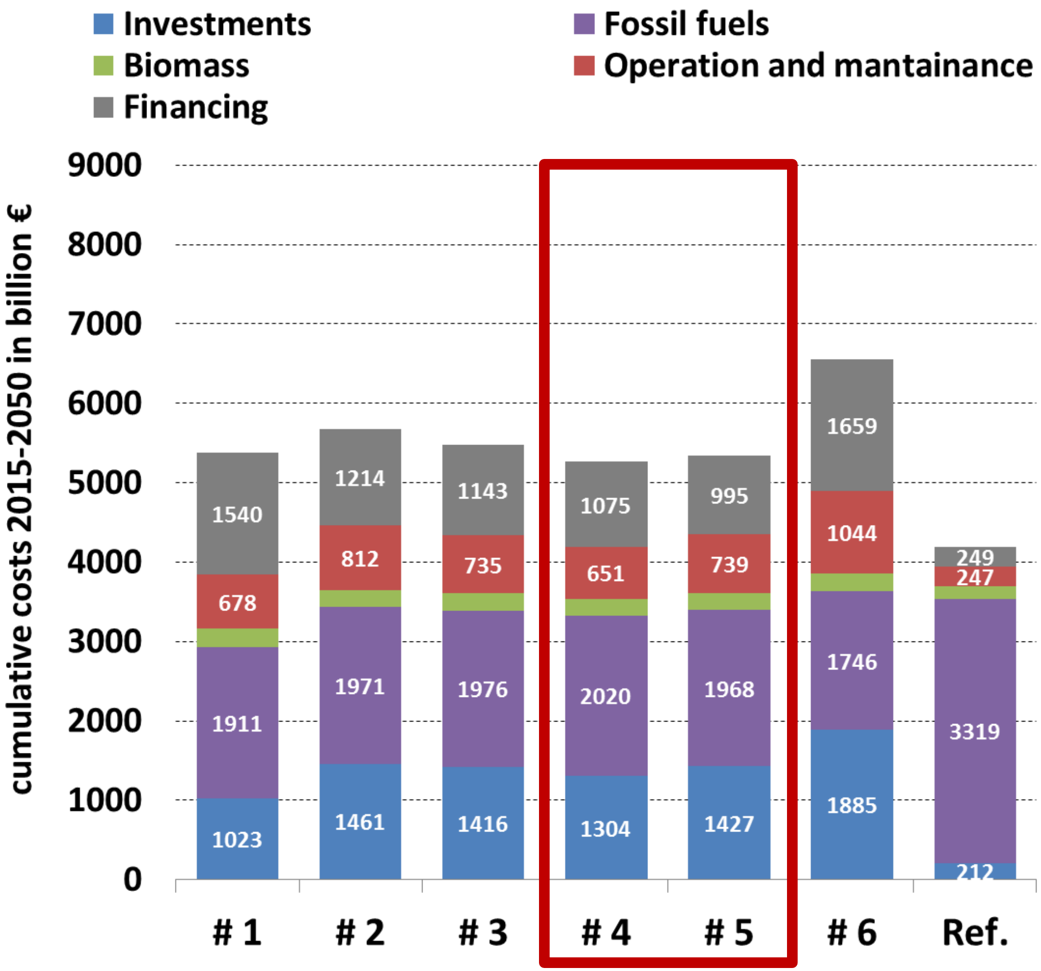
Scenario results
Cumulative total cost

- No penalty on CO_2 emissions
- Stable fossil fuel prices



Cumulative cost of scenarios # 4 und # 5 approx. 1100 bn € higher than reference for the total time 2014 – 2050 (about 0.8 % of German GDP)

#4 -80 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

#5 -85 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

Ref today‘s system; no change

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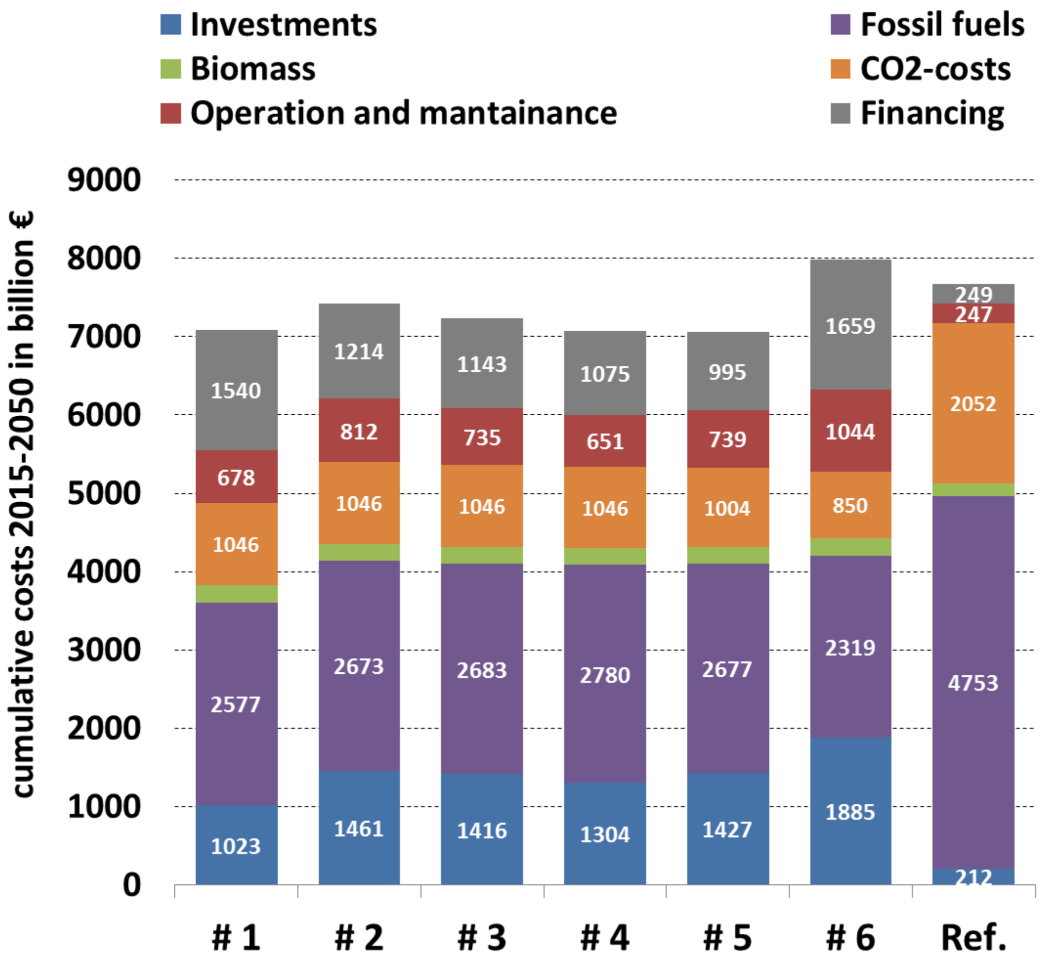
Scenario results
Cumulative total cost

- Rising penalty cost for CO_2 emissions up to 100 € per ton in 2030; then stable
- Price increase for fossil fuels 2 % p.a.



#1 -80 % CO_2, low rate building energy retrofit, electric vehicles dominant, coal until 2050

With CO_2 pricing, the total cost of business-as-usual till 20150 will be even higher than for the transformed system!

#4 -80 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

#5 -85 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

#6 -90 % CO_2, high rate building energy retrofit, mix of vehicles, coal until 2040

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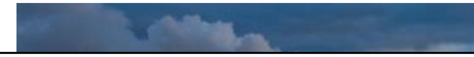
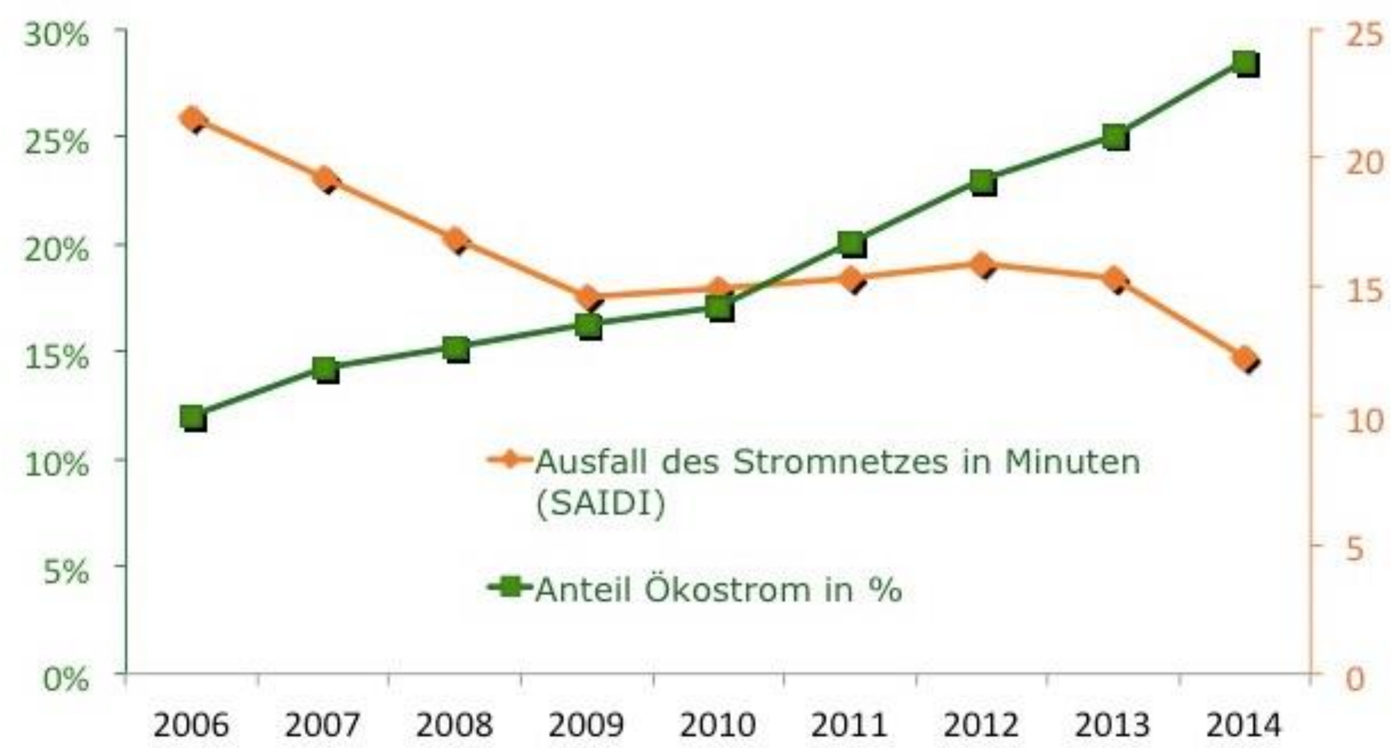


Essential messages out of the model:

The cost of the new Energy System is not higher than the cost for the current system!

The cost for transformation is in the same order as maintaining the current system!


Grid stability with growing amounts of fluctuating RE:
Grid in Germany today more stable than in 2006!



Quelle: Bundesnetzagentur (2015); http://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Stromnetze/Versorgungsqualität/Versorgungsqualität-node.html ; BMU, BEE, bdew

Hans-Josef Fell – MdB (1998-2013)
Präsident der Energy Watch Group

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Photovoltaics as Major Electricity Source

- Technology development combined with rapid growth of production volumes resulted in an unprecedented reduction in PV production cost and prices, by more than an order of magnitude in the last decades!
- The market is dominated by crystalline-Si technologies; a multitude of further technology advances, allowing higher efficiencies at lower production costs, are ready to be implemented in c-Si PV cells and modules.
- The cost of PV systems will decrease further, driven by technology developments, accompanied by supportive financial and regulatory environments.
- PV will grow soon into the Terawatt range, making it the cheapest form of electricity in many regions of the world → 2-4 ct/kWh.
- The key for a stable energy system based on RE is to link the electricity, heat and transport sectors.
- The challenge for the EU will be to maintain the current technological leadership position, by keeping a stable market, combined with local PV production along the whole food chain, from research to deployment!

Thank you
For your attention!

AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST) NREL NATIONAL RENEWABLE ENERGY LABORATORY Fraunhofer ISE