Applied Solar Expertise

PV as a Major Contributor to the Global Future Energy Needs

MPI

Garching, 4th November, 2014

Dr. Winfried Hoffmann – ASE

Chairman of Supervisory Board Solarfabrik AG
Member of Supervisory Board SMA Solar Technology AG and ISFH
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Outline

What are the future energy needs?

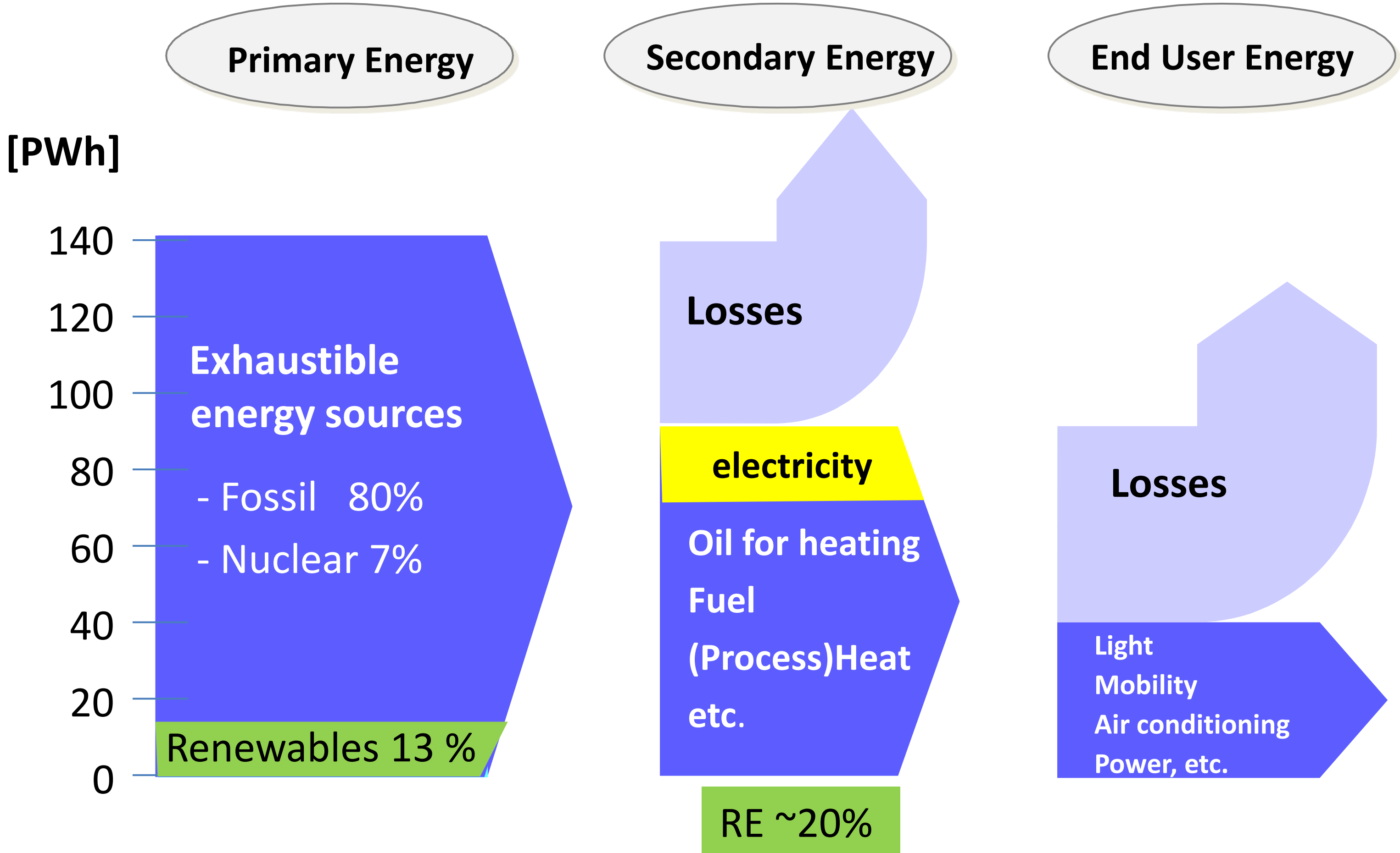
The importance of energy efficiency

Historic and further development of PV

The importance of electricity storage for variable RE sources

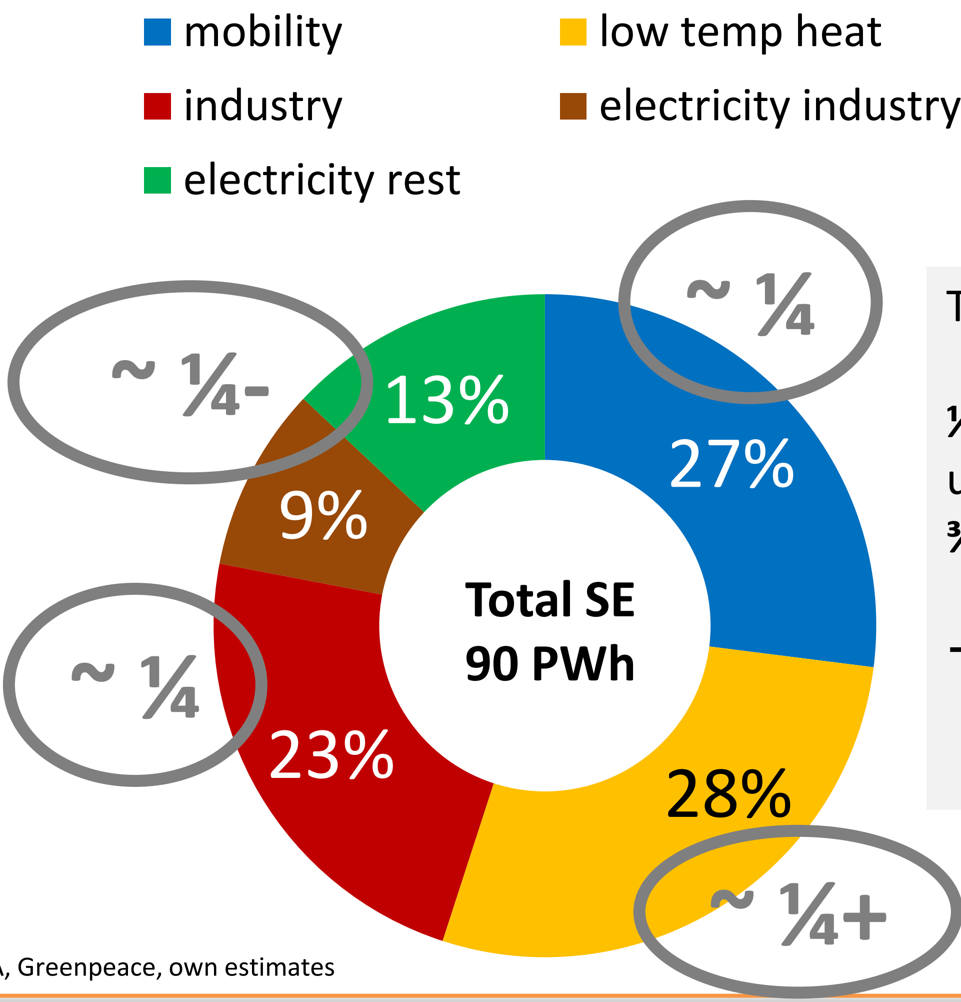
The development towards a 100% renewably powered world

Primary, secondary and end energy usage (~2010)



Source: World Energy Council, Greenpeace, IEA, own estimates

Energy sectors (~2010)



Today's inequity (simplified):

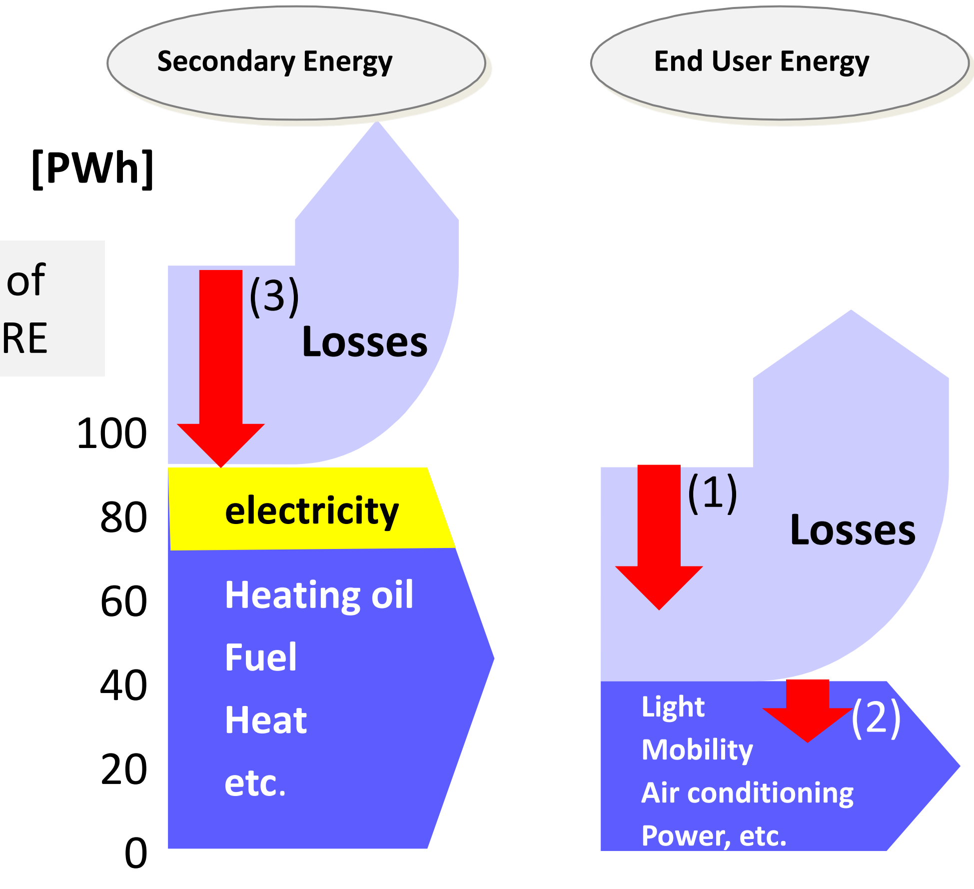
¼ of ~6bn people (=1.5bn)
use
¾ of 90 PWh (=67.5 PWh)

→ today's „high quality **‚HQ' life**"
needs **45 PWh / 1bn people**

Source: IEA, Greenpeace, own estimates

Energy efficiency measures & avoiding (PE → SE) - losses

(3): use of 100% RE

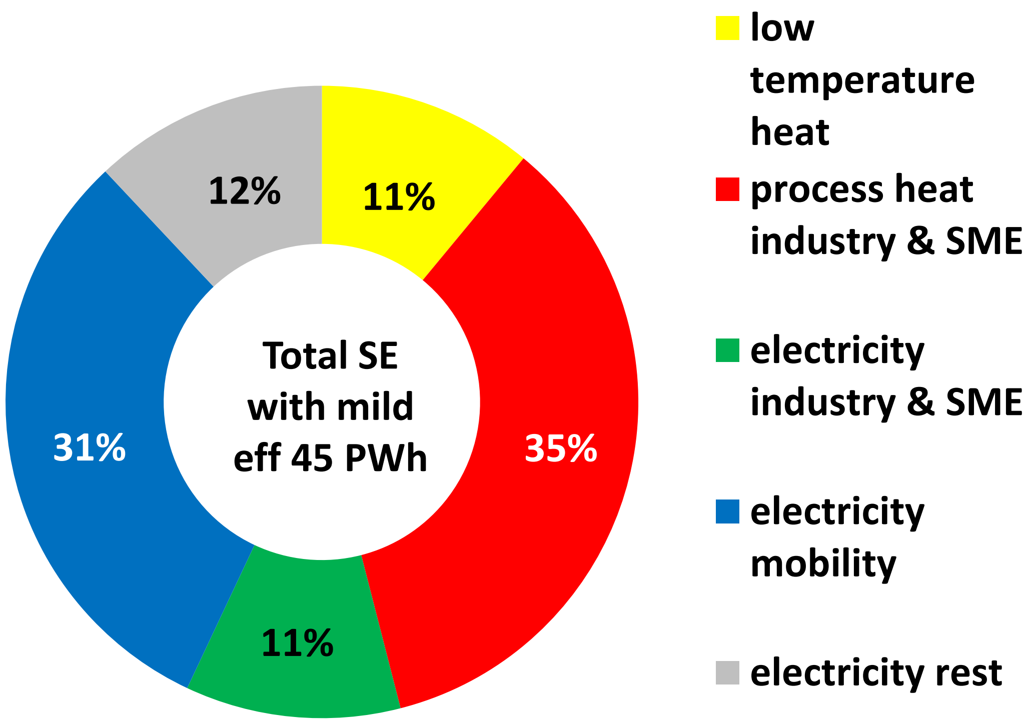


(1) examples:
- light bulbs → (O)LED‘s
- petrol cars → e-mobility
- … and many more

(2) examples:
- house insulation
- urban traffic optimization
- … and many more

Source: World Energy Council, Greenpeace, IEA, own estimates

Today‘s SE with „mild“ and „agressive“ efficiency measures



SE from 90 PWh → ~45 PWh
^= productivity increase of 2

Relative share of electricity from 22% → 54%

„High quality life“ would need: ~22.5 PWh / 1 bn people

Von Weizsäcker et al:
Factor 4 and even 5 productivity increase „agressive“ efficiency measure

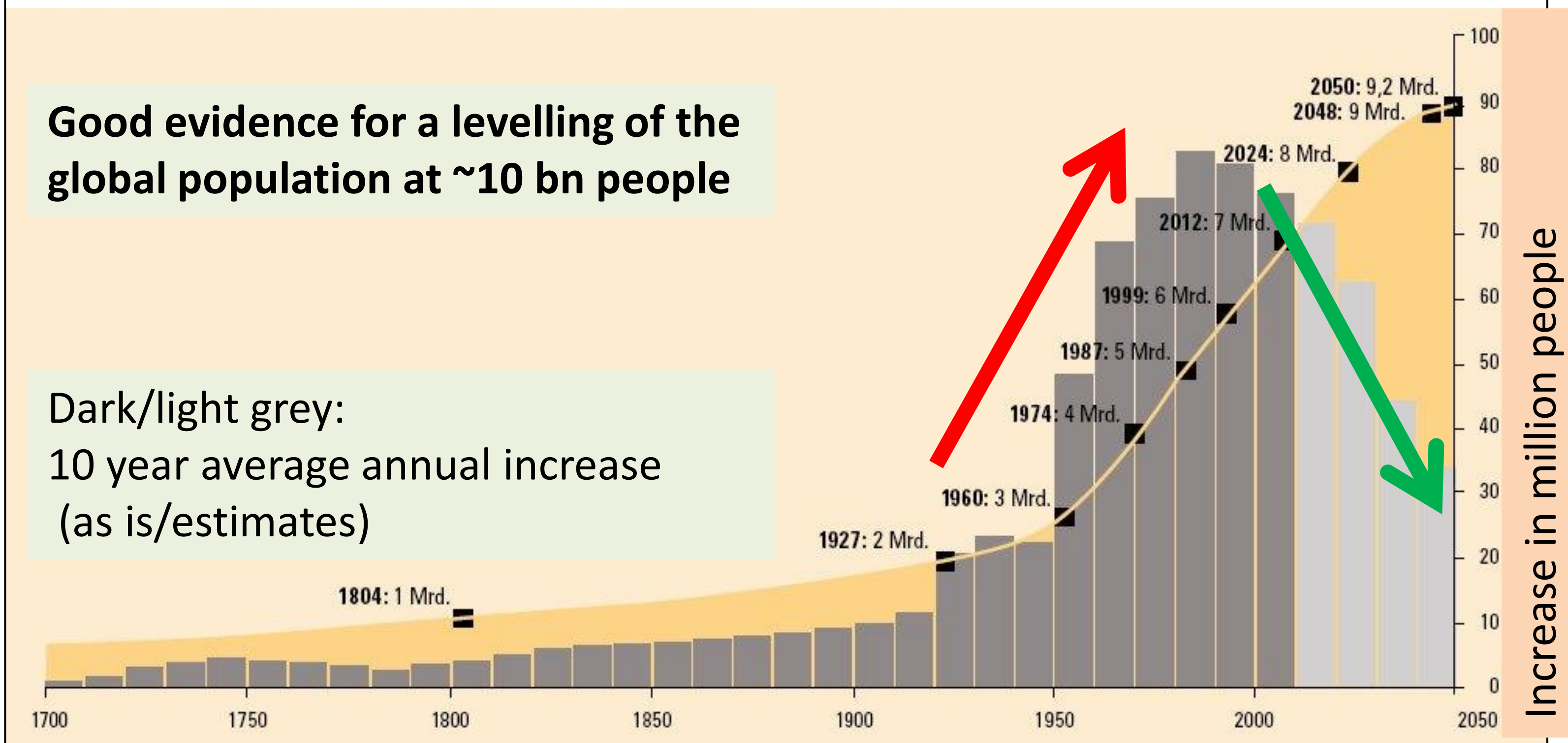
→ ~9 PWh / 1 bn people only for „high quality life“

Source: Own estimates

History and future estimate of global population

Good evidence for a levelling of the global population at ~10 bn people

Dark/light grey:
10 year average annual increase
(as is/estimates)



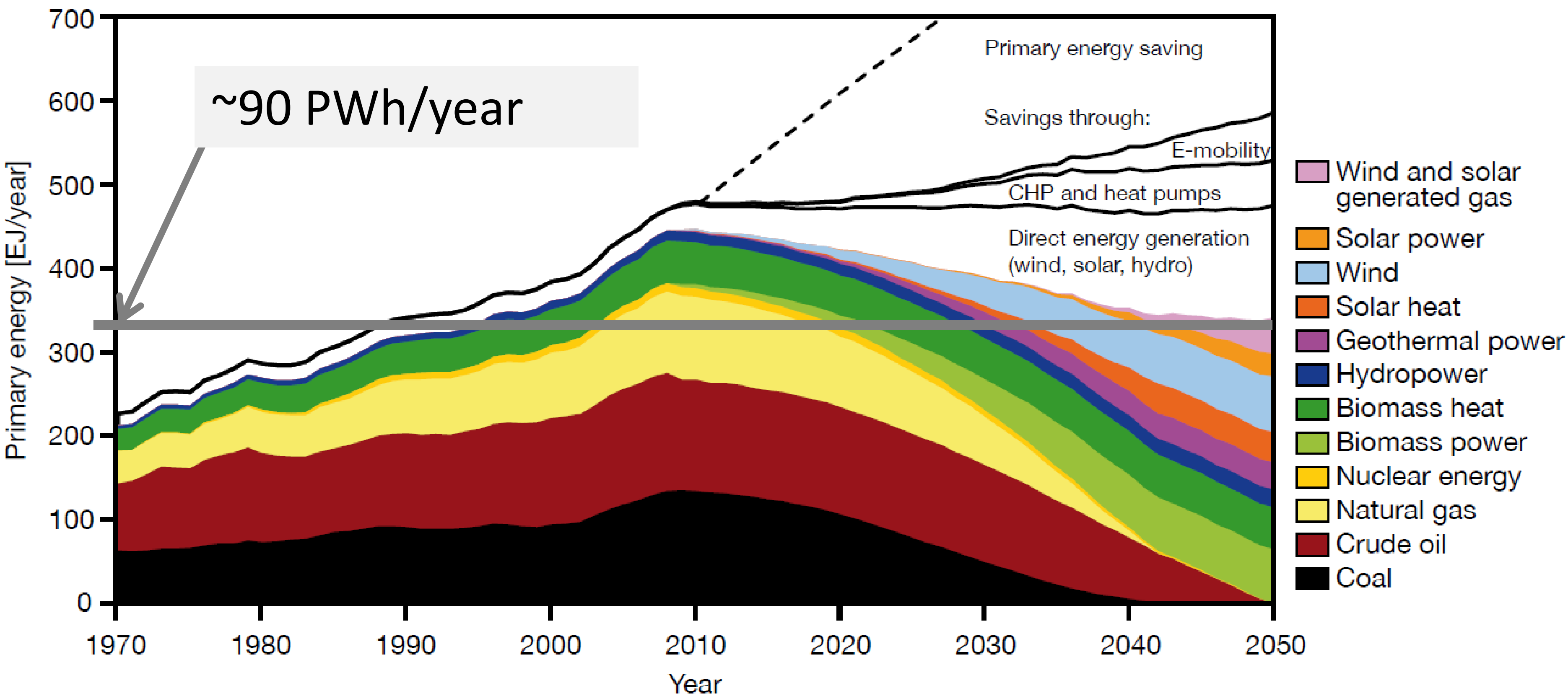
Source: UN, World Population Prospects: The 2006 revision

Future Secondary Energy needs for expected 10 bn people in 2100+

	Productivity increase	SE for ALL 10 bn people
Today (@ HQ for ALL)	-	450 PWh
„mild“ efficiency measure	2	225 PWh
„agressive“ efficiency measure	5	90 PWh
„realistic“ efficiency measure	3	150 PWh

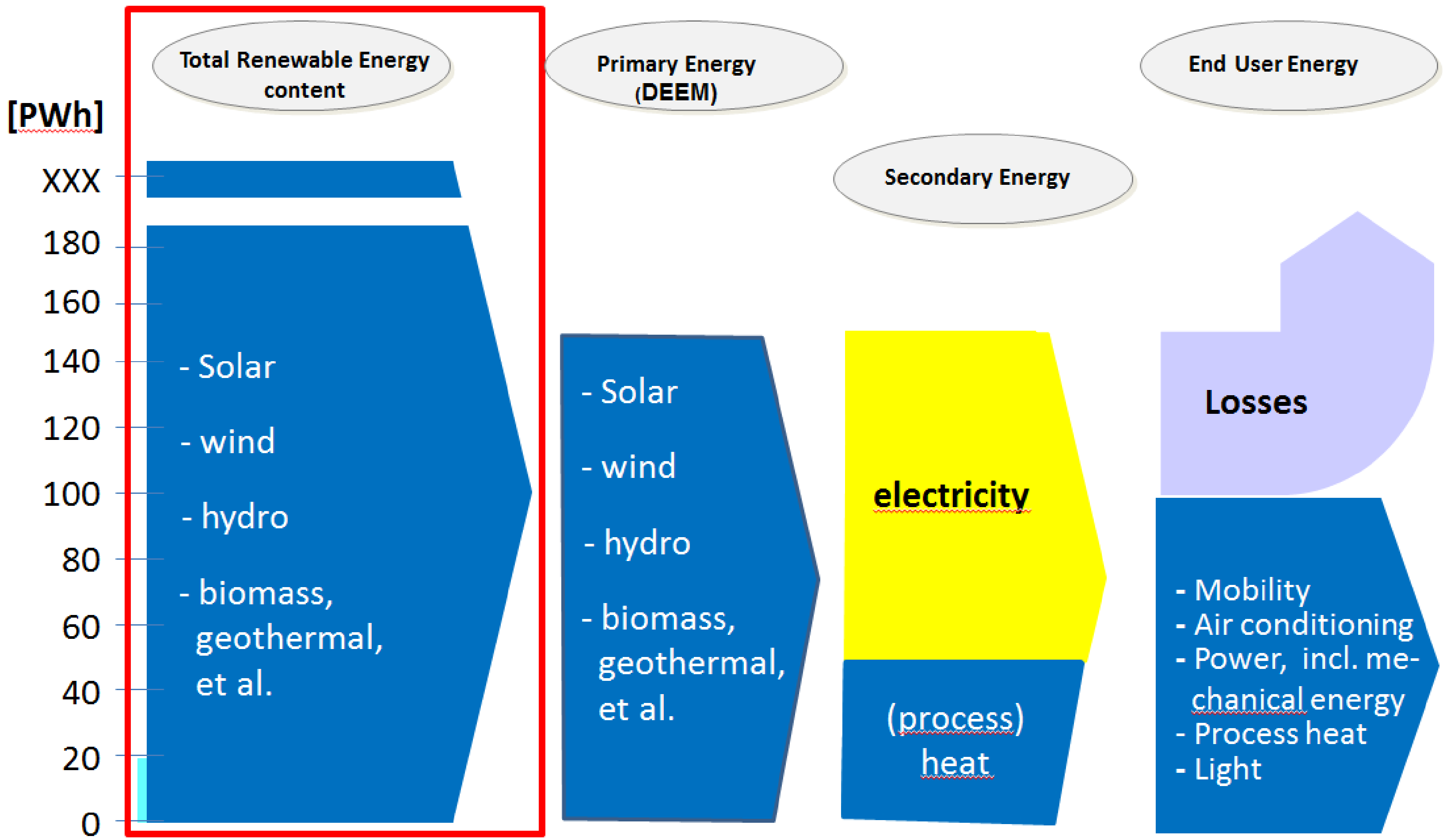
Source: Own estimates, von Weizsäcker et al.

One of the WBGU models for a global „2°C - scenario“



Source: WBGU (Scientific Board for Global Environmental Changes to the German parliament) 2011 Flagship report

Future „realistic“ Secondary and End Energy needs and supply



Source: own estimates, DEEM: Direct Energy Equivalent Method

Variety of customer needs served by PV products

on-grid | **off-grid** | **consumer** | **high efficiency**




€/kWh | €/hr light | W/m² | g/W




Source: Fraunhofer ISE

Source: Own data

€/m² / aesthetics | €/W | flexibility | W/mm²

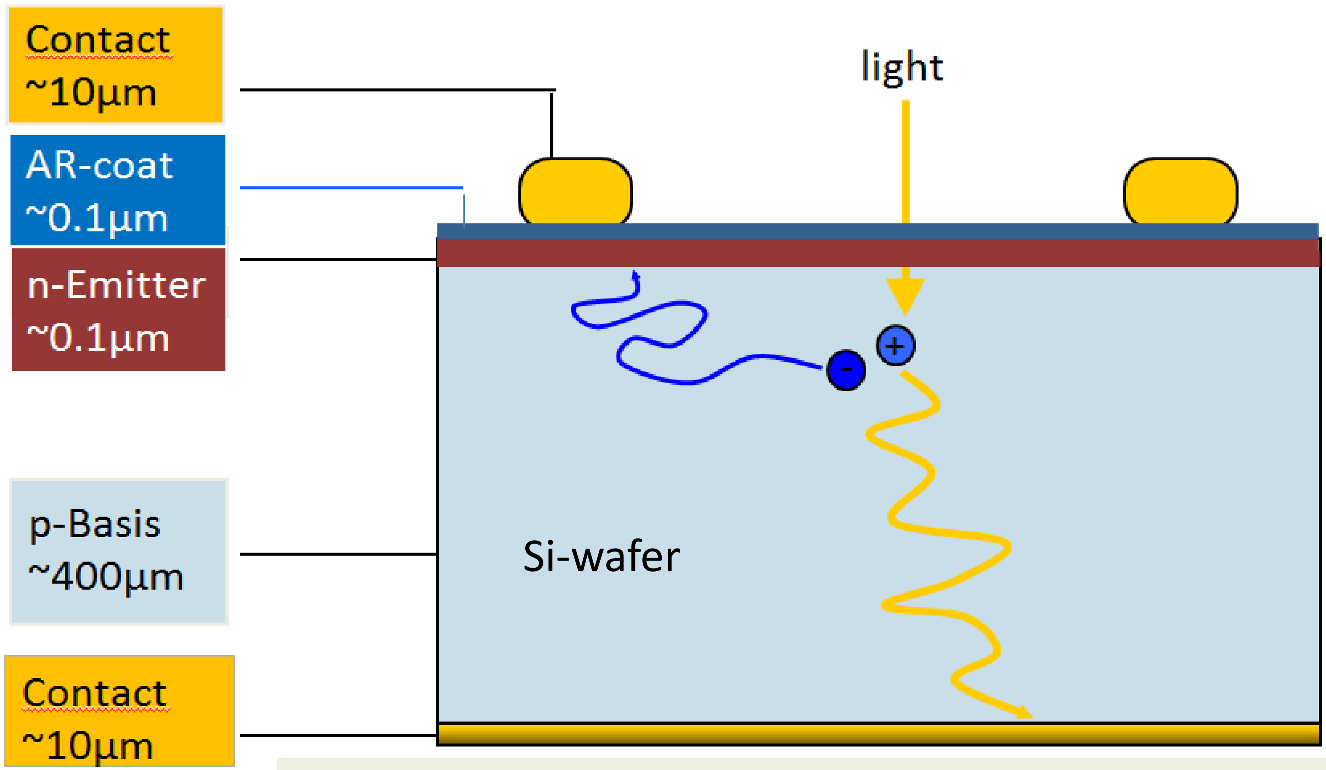
1980s

- **~10 MW annual market at the start of decade (17% p.a. av. growth this decade)**
- satellites, off-grid and consumer applications

1990s

2000s

Early standard c-Si solar cell



…April 25, 1954 by Bell Labs, just 60 years ago, where the first Si-solar cell developed by Chapin, Fuller & Pearson was disclosed, which won the race with RCA on atomic batteries (John Perlin, NREL, 2004)

Source: Winfried Hoffmann

1980s

- ~10 MW annual market at the start of decade (17% p.a. av. growth this decade)

1990s

- **~50 MW (20% p.a.)**
- 1991 GER StrEG & 1.000 roof (Feed-in tariff & priority access of RE)
- Japan‘s 70,000 roof, Germany‘s 100,000 roof & municipality initiatives

2000s

1980s

- ~10 MW annual market at the start of decade (17% p.a. av. growth this decade)

1990s

- ~50 MW (20% p.a.)

2000s

- **~300 MW (52% p.a.)**
- 2000 GER EEG & many FiT‘s to follow (EU) … PPA‘s , FTC‘s & REPS‘s (mainly USA)
- Decade with highest growth ever … product & material limitation

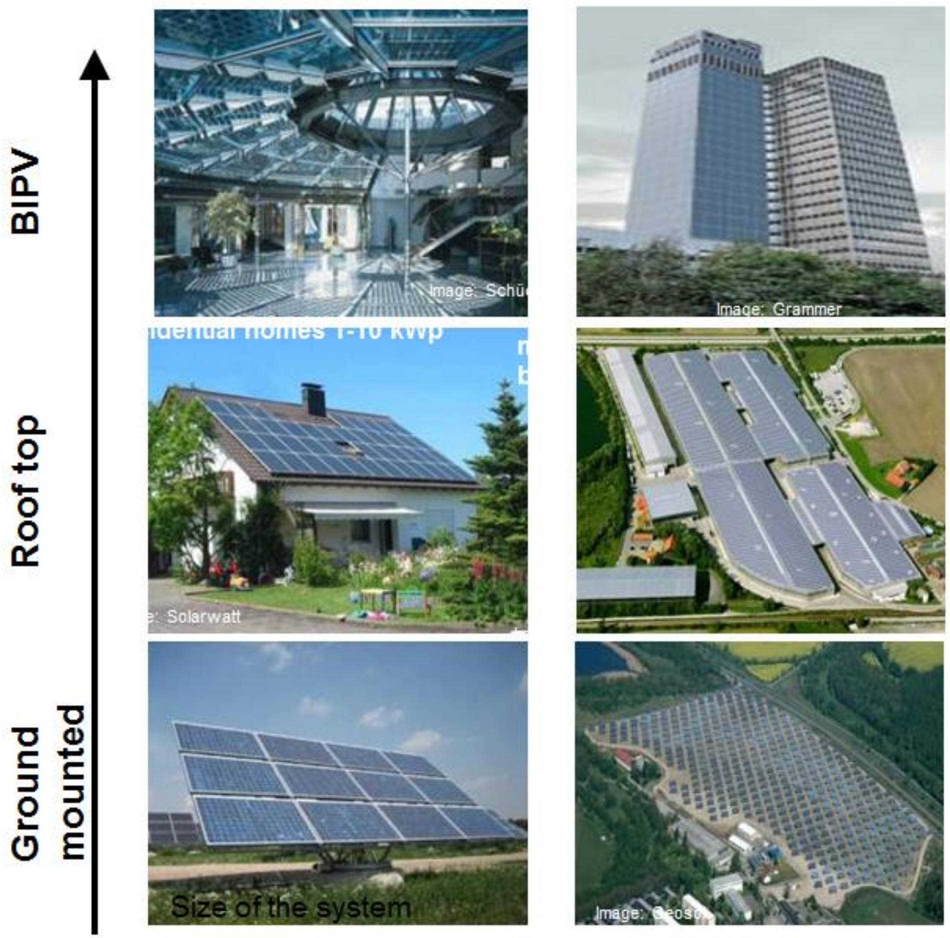
2010s

- **~20 GW (20% pa)**
- FiT in Japan, market support in China, India etc
- PV-Diesel fuel save → PV+storage (+Diesel back up)

…some highlights:

- … increasing number of countries with „Grid Parity“
- PV industry consolidates after years of undersupply & strong market demand resulting in build-up of 100% capacity oversupply
- Self consumption at local level (households, multi family houses and SME‘s/offices) assisted by increasing economic storage solutions
- Introduction of new market models for the integration of increasing levels of variable renewable sources (solar&wind) assisted by the future „Smart Grid“
- PV increasingly „lowest cost solution“

Major PV market segments today



BIPV	kW ... MW **Private & commercial**
Roof top	kW ... MW **Private & commercial**
Ground mounted	100 kW ... GW **Commercial & industrial**

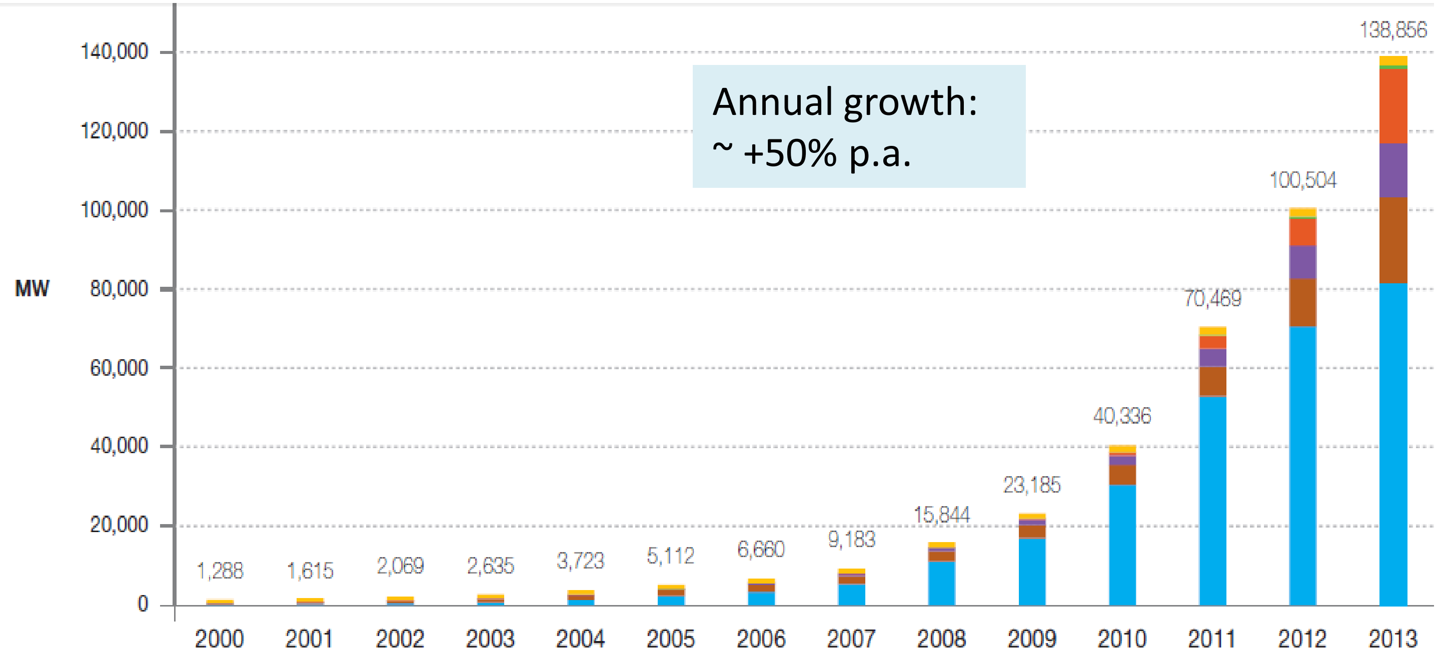
Source: BSW Solar, Stryi-Hipp

Bird‘s eye view to the largest (as of 2013: 290 MW AC) PV plant Agua Caliente in Arizona (2014 ~400 MW)

Area ~ 2 x 3 km²
@ 13% eta and FF 50%

Source: First Solar

EPIA's historic market analysis in cumulative numbers

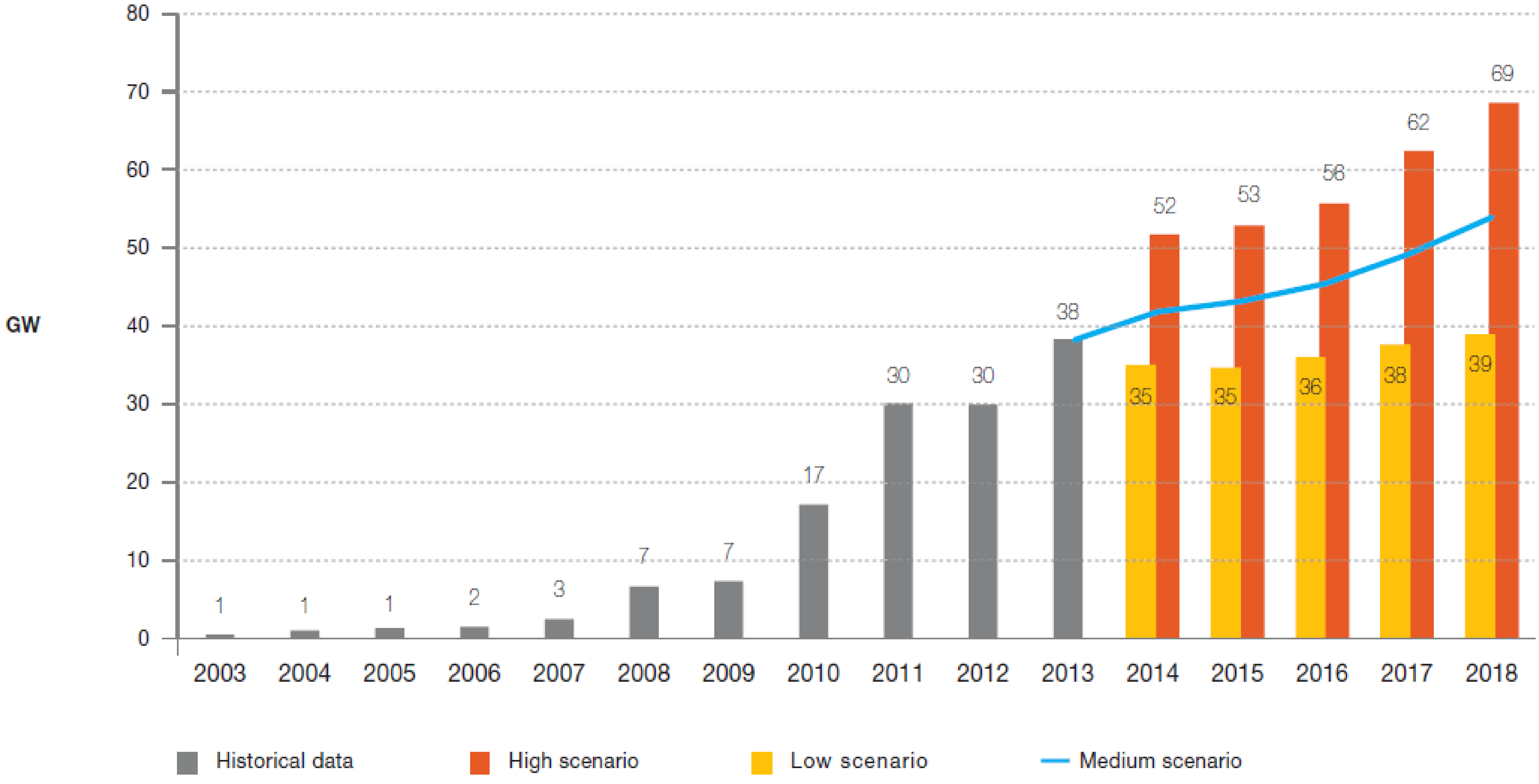


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	**1,288**	**1,615**	**2,069**	**2,635**	**3,723**	**5,112**	**6,660**	**9,183**	**15,844**	**23,185**	**40,336**	**70,469**	**100,504**	**138,856**

100 GW(peak) PV power
= ~
85 GW power
= ~
65 full size 1.3 GW nuclear reactors

100 GW (peak) PV
x
1.3 kWh/W(peak)
= ~
130 TWh p.a. electricity =~
13 f.s. 1.3 GW nuclear reactors

EPIA's global market forecast 2014 - 2018

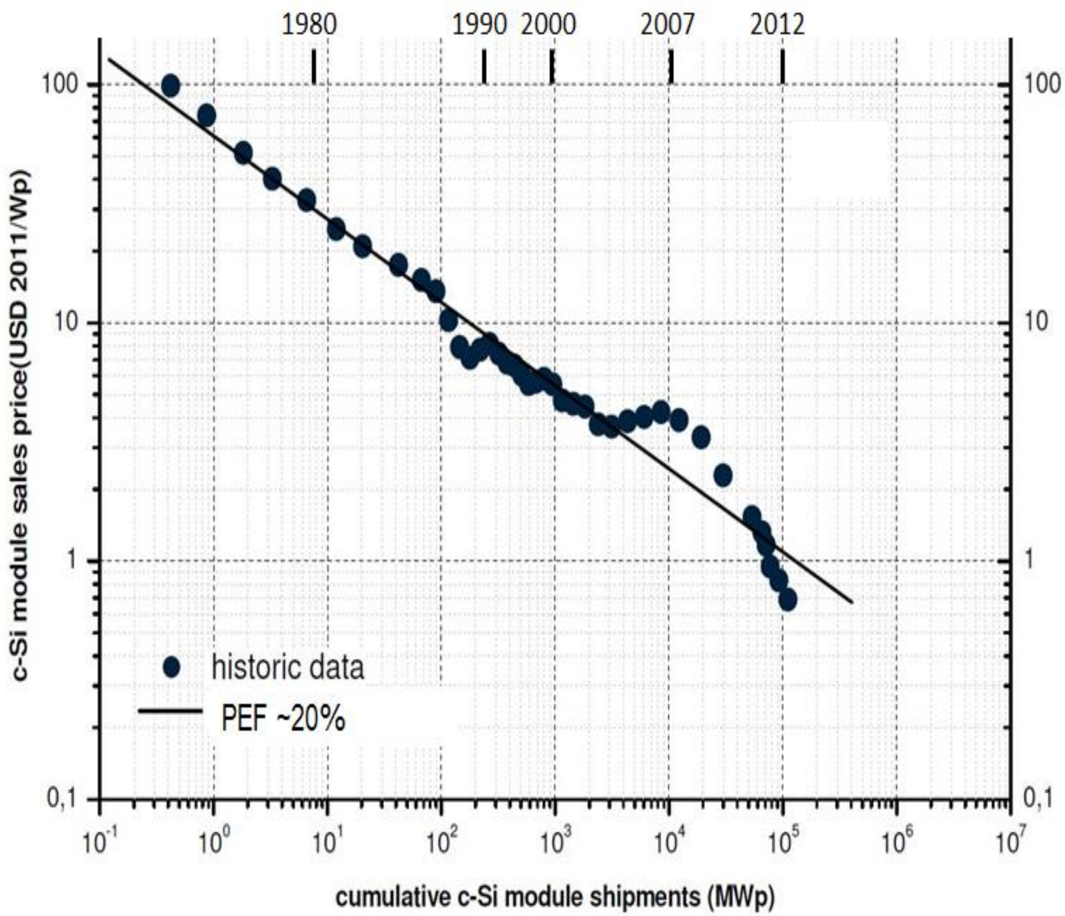


Major drivers for future growth: no longer Europe, but …

- China (government targets: 35GW in 2015, 50-75 in 2020)
- US (Renewable Portfolio Standards)
- India (PV-Diesel hybrid systems - ~10 GW Diesel Gensets each year)
- Japan
- South Africa
- South America
- Middle East (PV electricity cheaper than burning oil at 3.5 $/barrel instead of selling at 100$)
- Australia (decentralized systems)
- … fight poverty with pico-, SHS- and village powering …

Source: EPIA, own estimates

Price Experience Curve for PV



Source: ITRPV 2013

Specific material cost:

- Wafer thickness 700 → 150µm
- Kerf loss 500 → 100µm

  → weight 28 → 6 g/dm(2)
- Poly Si 60 → 20 $/kg

  → material cost 1.68→ 0.12 $/dm(2)
- Efficiency 8 → 20%

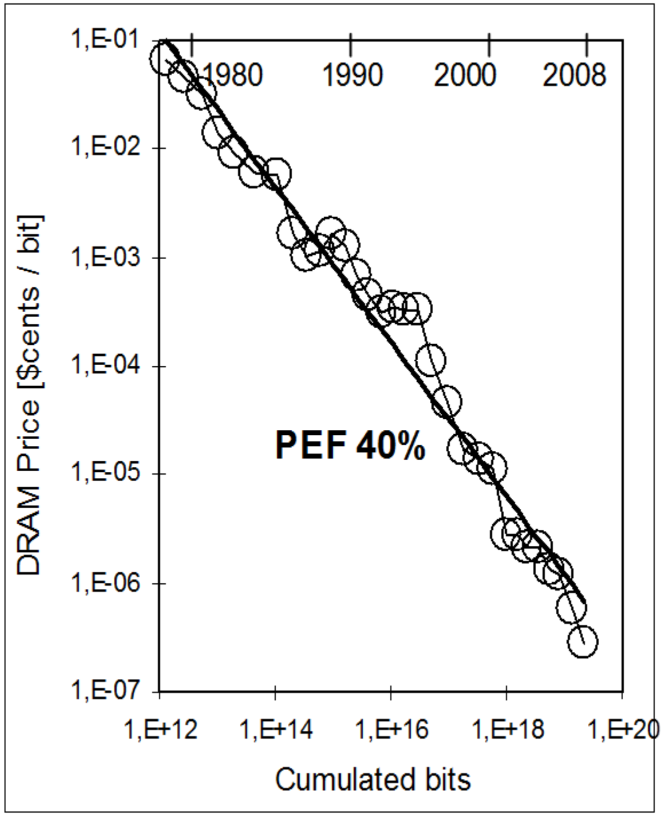
  →**spec. Cost** 2,10 → 0.06 $/W

  reduction by factor 35!

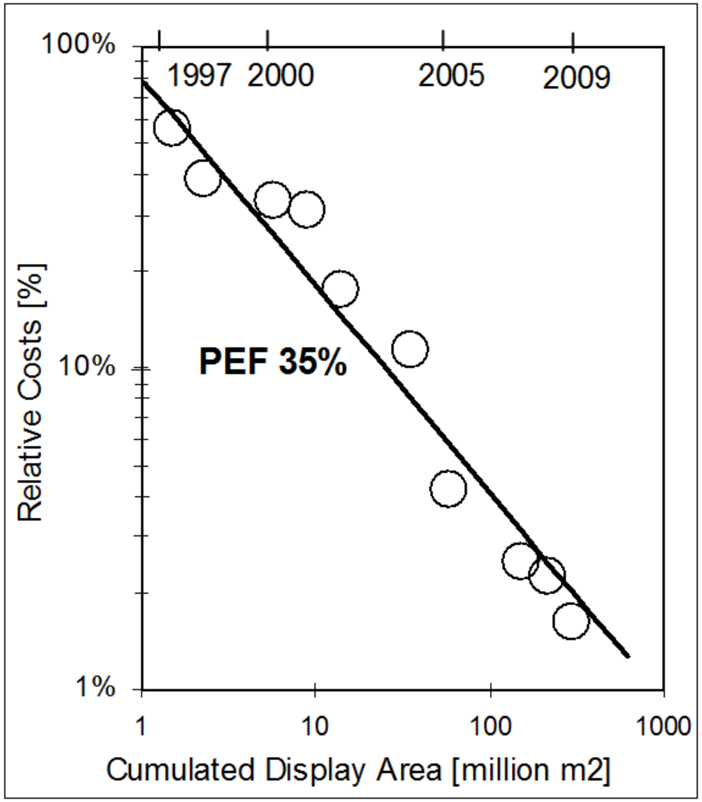
Economy of scale & industrial manufacturing

- **Production line** 1 MW → 200 MW
- **Automation & high yield**
- **Production processes with low specific cost for high volume**

Other "Price Experience Curves"



Semiconductor DRAM

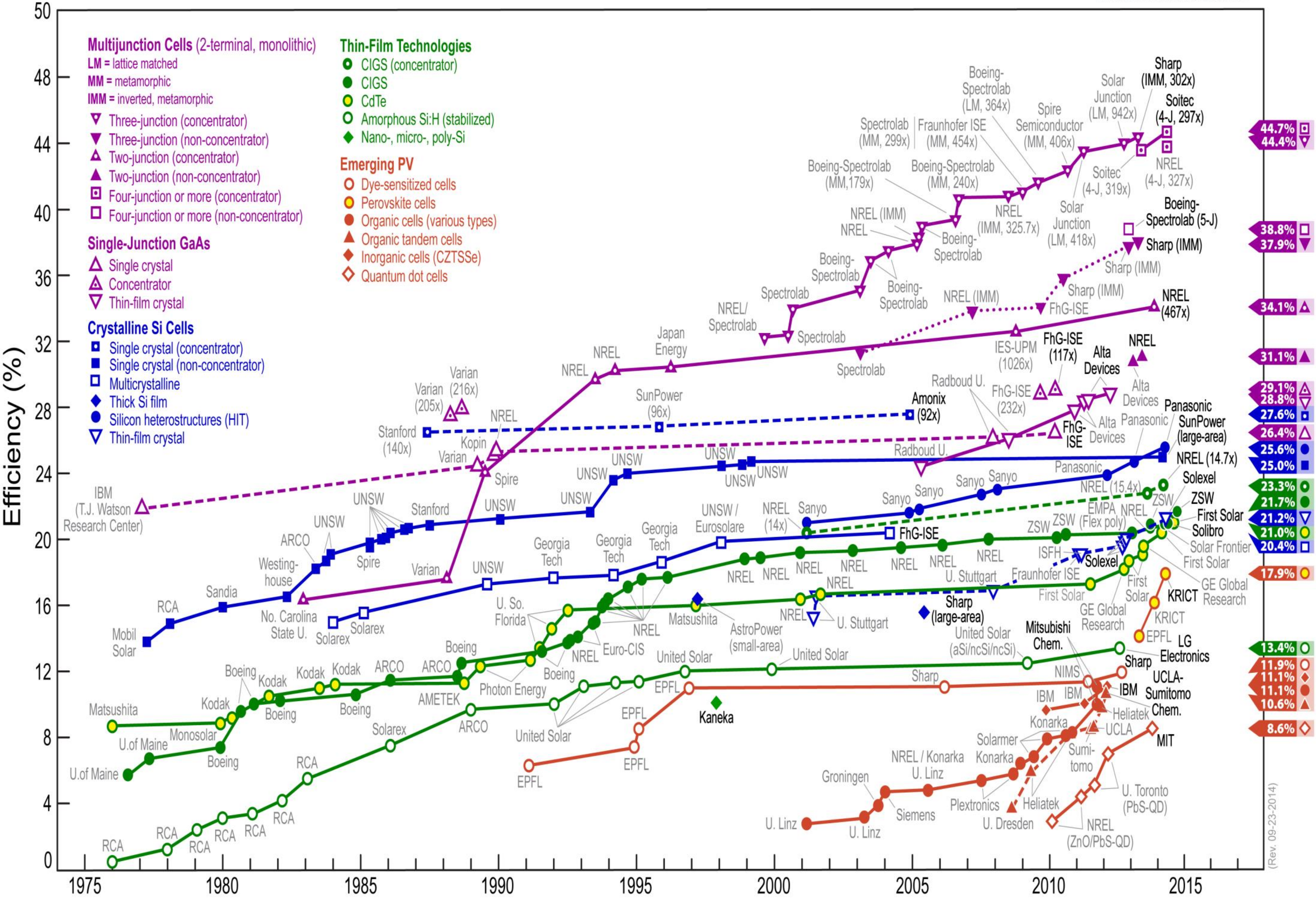


Flat Panel Display

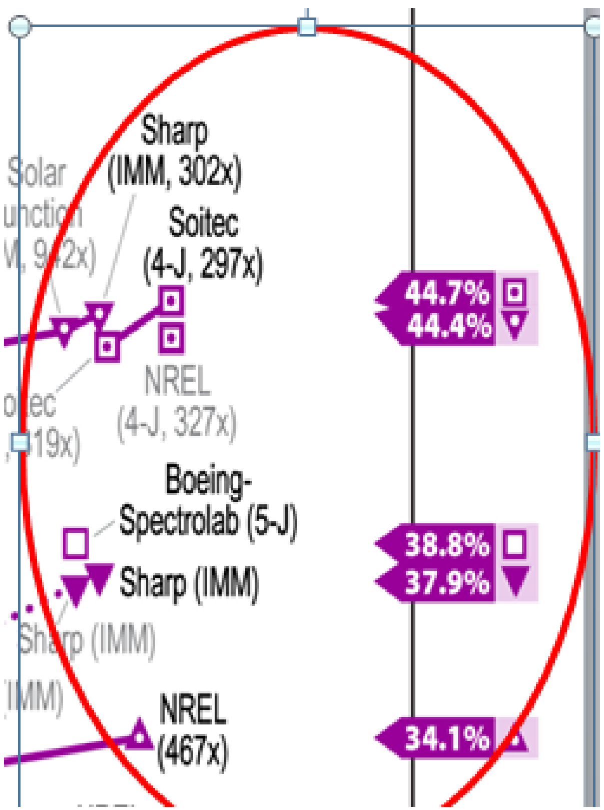
Source: Applied Materials, own data

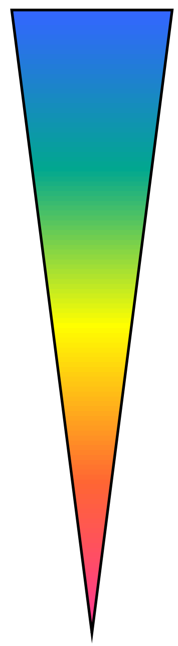
Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



III-V solar cells





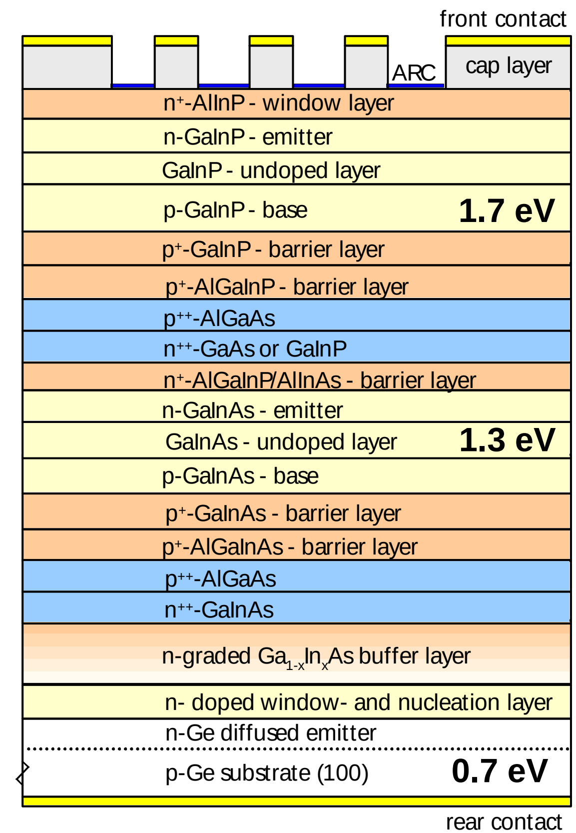
$Ga_{0.65}In_{0.35}P$

Tunnel diode

$Ga_{0.83}In_{0.17}As$

Tunnel diode

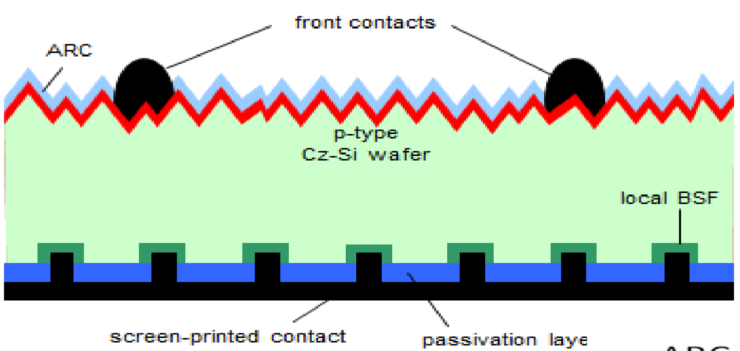
Ge

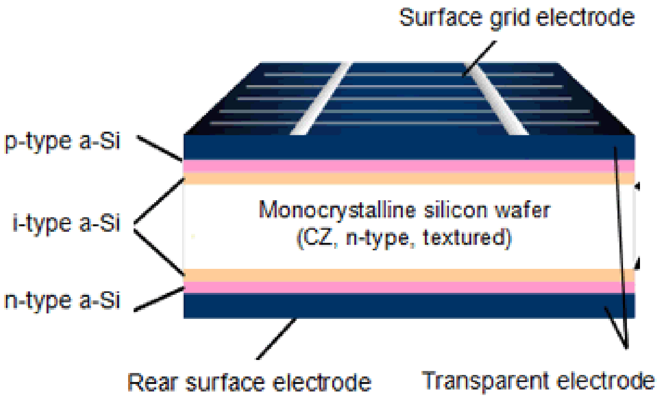


Source: NREL

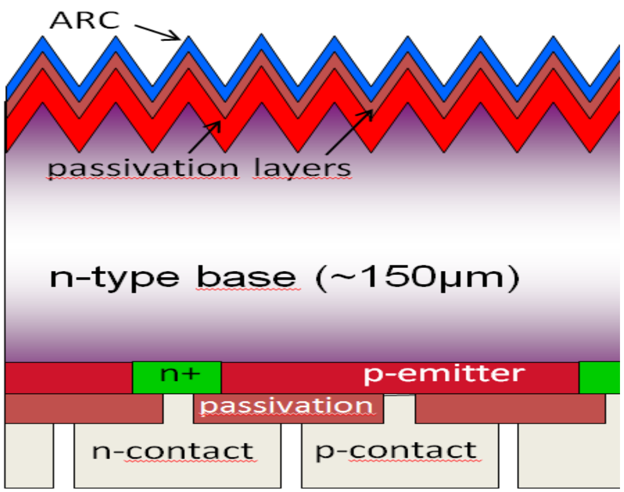
Today's state of the art c-Si wafer technology

All-screen-printed solar cell with eta >21% with standard 156 mm Cz-wafers





„Honey moon" HJ cell
World record Panasonic 25,6%

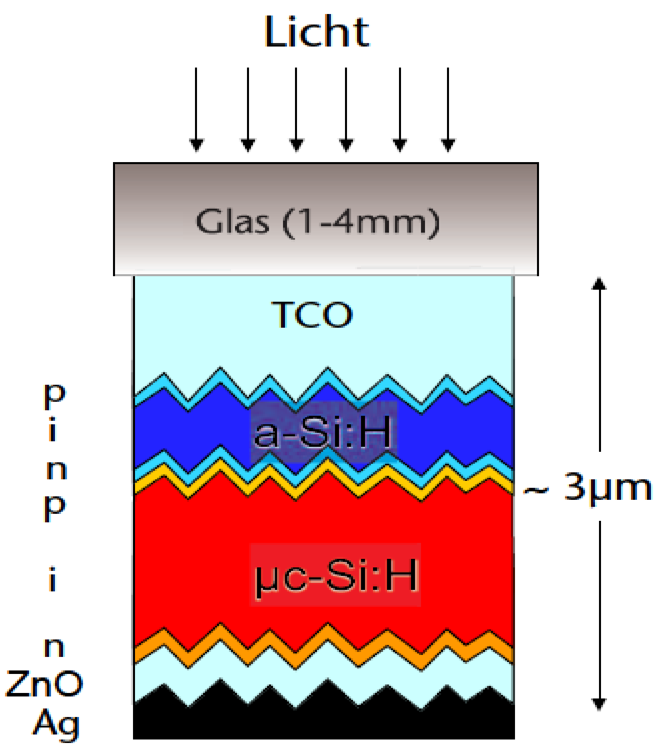


IBC (interdigitated back contact) Sun Power (Total) 25%

Source: A. Metz et al., SCHOTT Solar

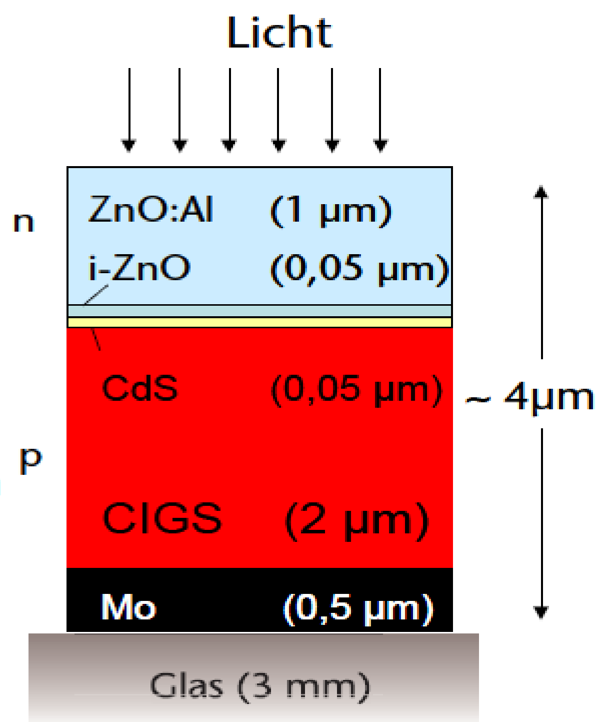
Thin-Film Solar Cells

a-Si/µc-Si Tandemzelle („Micromorph“)



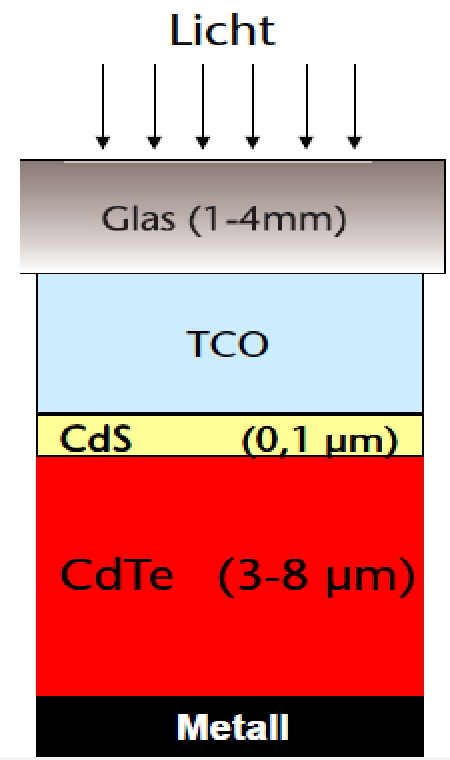
Best cell: sj 10.2% (AIST) [13.4% tjSi (LG)]
Modules: ~(10 -11)%

CIGS-Solarzellen: $CuIn_{1-x}Ga_xSe_{1-y}S_y$



Best cell: 21,7 % (ZSW)
Modules: ~15% (Solar Frontier, MANZ, …)

CdTe-Solarzellen: CdTe



Best cell: >20% (First Solar)
Modules: ~13%

Emerging technologies

Organic PV (OPV) – potentially suited very well for many consumer products

Dye solar cells (‚Grätzel cell') – solid state devices with eff up to 14.1%, BUT from my point of view **different dyes** offer various **true colours** for many applications, even at the **expense of efficiency**

Perovskites – the „shooting star" for lab record cells:

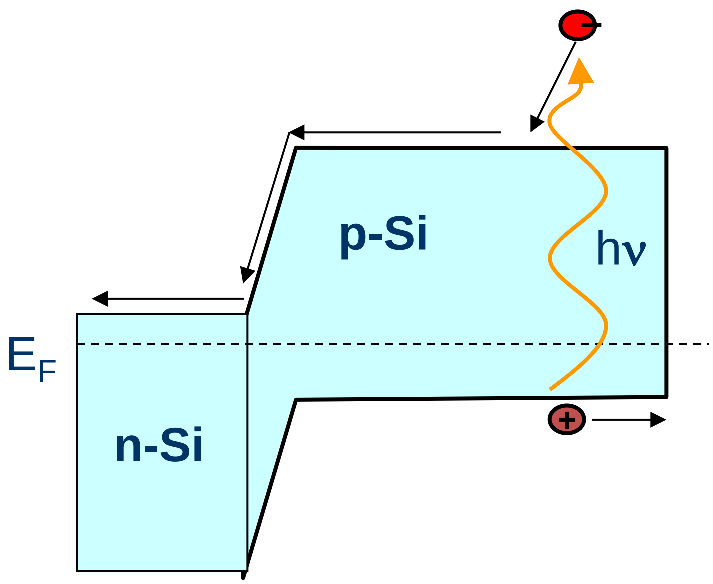
- From 0 → ~18% in very short period of time …!
- BUT: still a long way to go for a customer product:
  # lab cells are << $1cm^2$
  # marked hysteresis for I-V curve measurement
  # contain today ~33% toxic Pb (…not RoHS compliant)

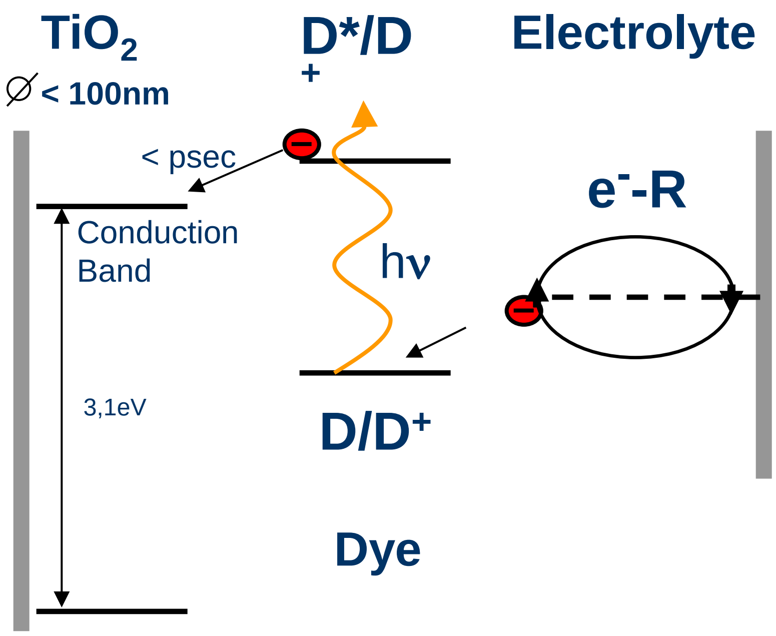
Quantum dot cells, up-converters, down-converters …

Source: PVSEC 2014, NREL

Dye Solar Cell
(Michael Grätzel (1980er))

Photovoltaic-Solar Cells	Dye Solar Cells

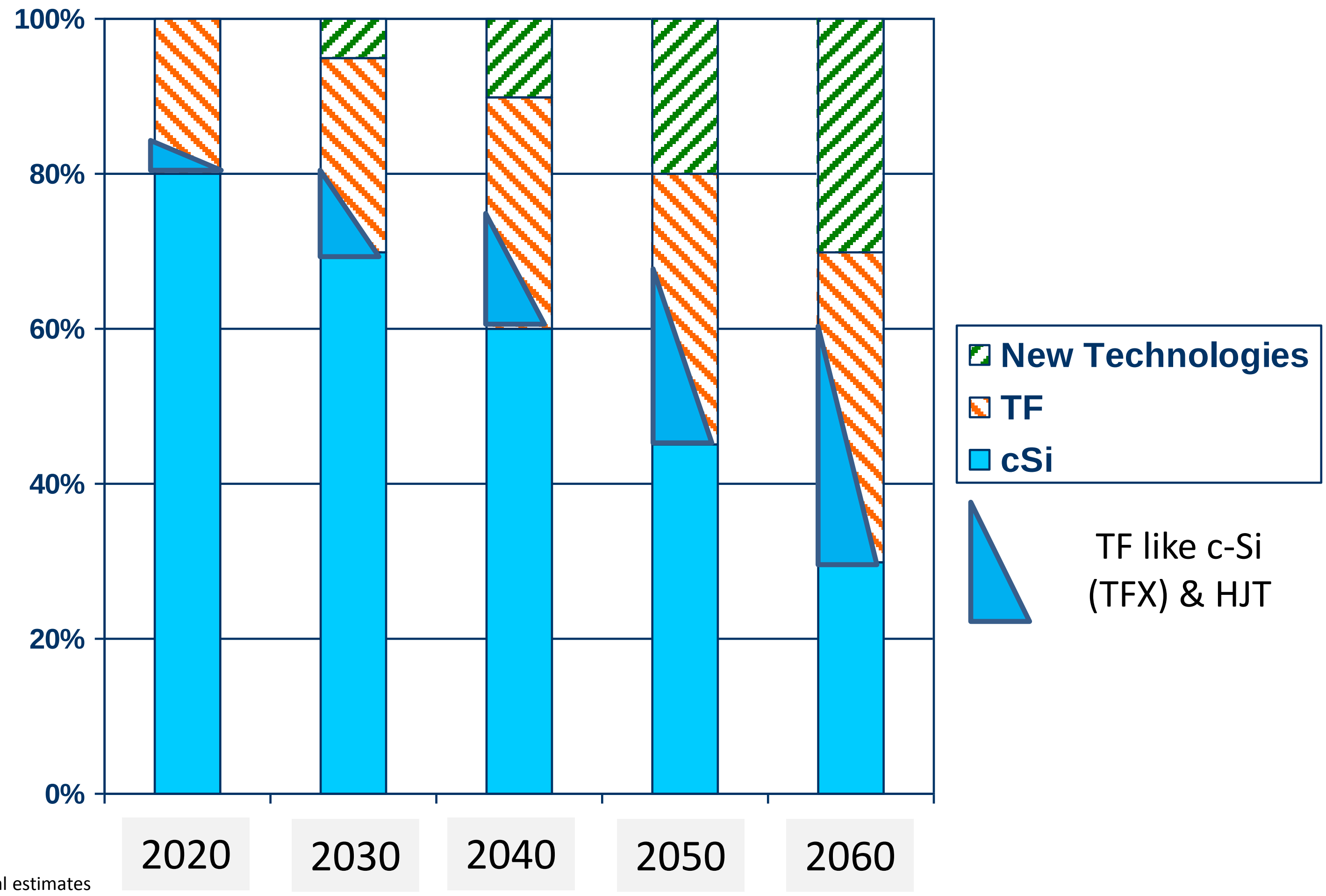




Charge separation by asymmetry created by p- and n-doped semiconductor materials

Charge separation by kinetic competition like in photosynthesis

Share of PV Technologies – NEW time line as of 2014



Ref: W. Hoffmann personal estimates

2020s

- **~120 GW (14% pa)**
- Decade of transition from nuclear & fossil → RE
- PV & storage fully competitive

2030s

- **~450 GW (8% pa)**
- Many municipalities demonstrate 100% autarchy
- Energy efficiency & RE‘s become standard globally

2040s

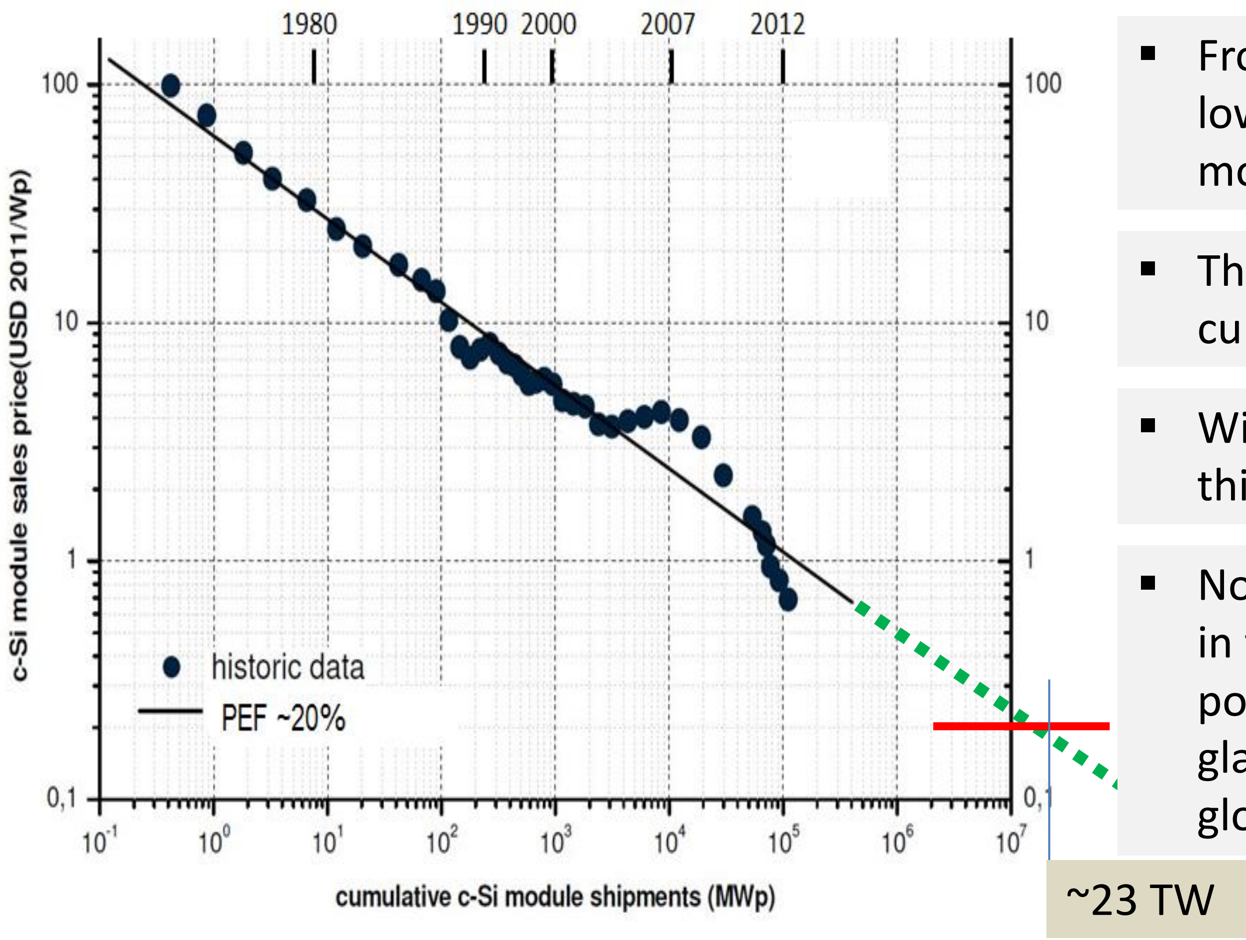
- **~990 GW (4% pa)**
- More & more countries demonstrate superiority of RE
- Portfolio of RE & storage from kWh to TWh

… how realistic is a 20% PV share for the future annual SE with 100% RE ?

	V 1
Decade	% growth
1990 - 2000	*20*
2000 - 2010	*50*
2010 - 2020	20
2020 - 2030	14
2030 – 2040	8
2040 – 2050	4
cumulative PV power in 2050 [TW]	**23**
Annually produced energy [PWh] in 2050 at 1.3 kWh/W (average)	**30**

Source: Winfried Hoffmann, own data

Extrapolation for PV Price Experience Curve



Source: ITRPV 2013

- From today's perspective the lower price limit for sj-Si-wafer modules is ~0.2$/W
- This limit is reached at a cumulative volume of ~23TW
- With realistic growth numbers this is reached in ~2050
- No material limitation at 1TW/a in the 2040s:
  poly-Si: 1.7 Mt (20kt→0.3 Mt)
  glass: 8 bn m² (today ~4 bn m² global production)

Potential price development for c-Si small PV systems at „fair prices“

year	Module-efficien-cy	Price reduction with PEF		Price reduction with efficiency factor	Sum
	[%]	module [$/W]	inverter [$/W]	BoS & installation [$/W]	[$/W]
2010	15	1.5	0.2	0.8	2.5
2020	20	0.6	0.1	0.6	1.3
2030	25	0.35	0.05	0.5	0.9
~2050	25(+)	0.20	0.03	0.37	0.6

Source: Own data

Potential development for global annual PV industry turnover

year	market [GW/year]	modules [bn $]	inverters [bn $]	BoS&inst [bn $]	total [bn $]
2020	120	72	12	72	156
2030	450	161	23	230	410

In **2040** the total turnover according to the later discussed growth could be **~800 bn$** and in **2050 ~1,100 bn$,** becoming comparable to the automotive industry (which was in Germany in 2011 ~450 bn$, worldwide ~3-4 times as large)

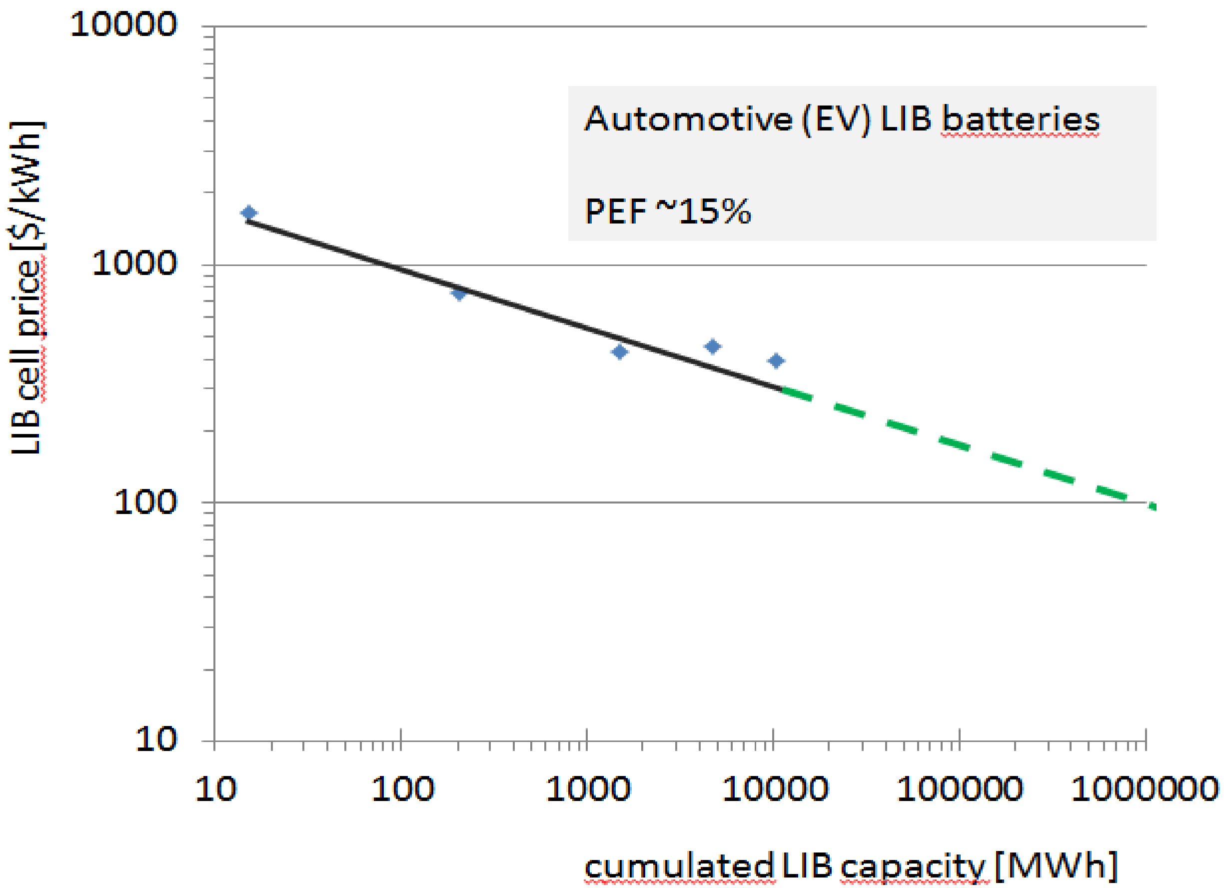
Source: Own data

Longer term electricity price development

Own	Technology	LCOE in today's currency [$ct/kWh]
Traditional	Clean coal with CSS	~10
	Nuclear fission	>~10
Photovoltaics	Southern areas (~2 kWh/W_{PV})	3 – 4
	Northern areas (~1 kWh/W_{PV})	6 – 8
Wind	On-shore (~2 kWh/W_{wind})	3 – 4
	Off-shore (~4 kWh/W_{wind})	4 – 5
Storage	Small (~kWh+)	>~5
	Large (~MWh)	< 5

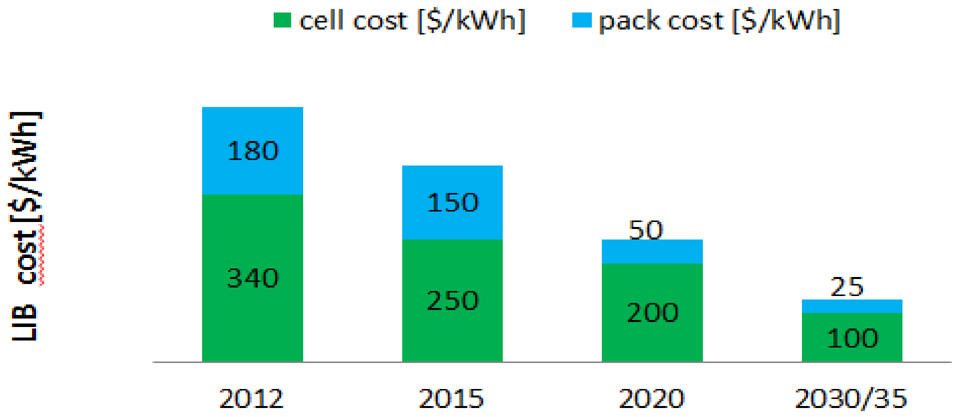
Source: Own data

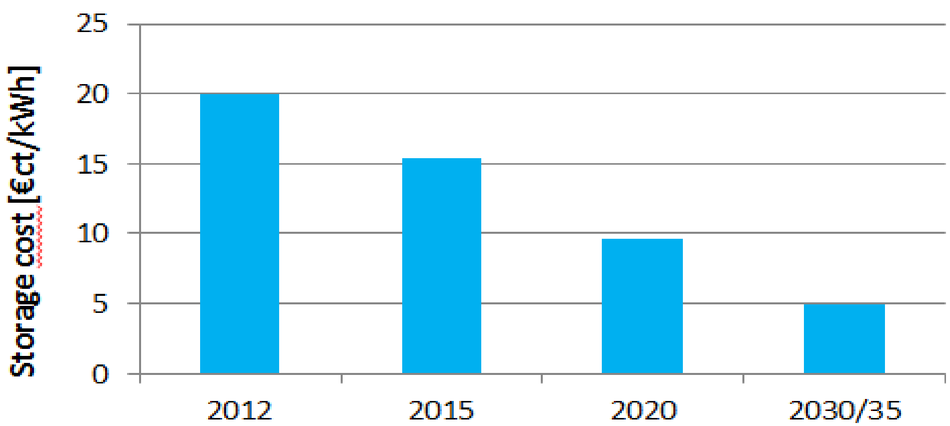
PEC for LIB batteries for automotive applications



Source: Raw data from personal communication C. Pillot (2014), avicenne; PEC curve constructed by author

LIB cell- and battery cost and resulting storage cost





In the late 2020s we have:

Petrol driven car:
@ 4l/100km and (1.50-2.50)€/l →
(6-10)€/100km

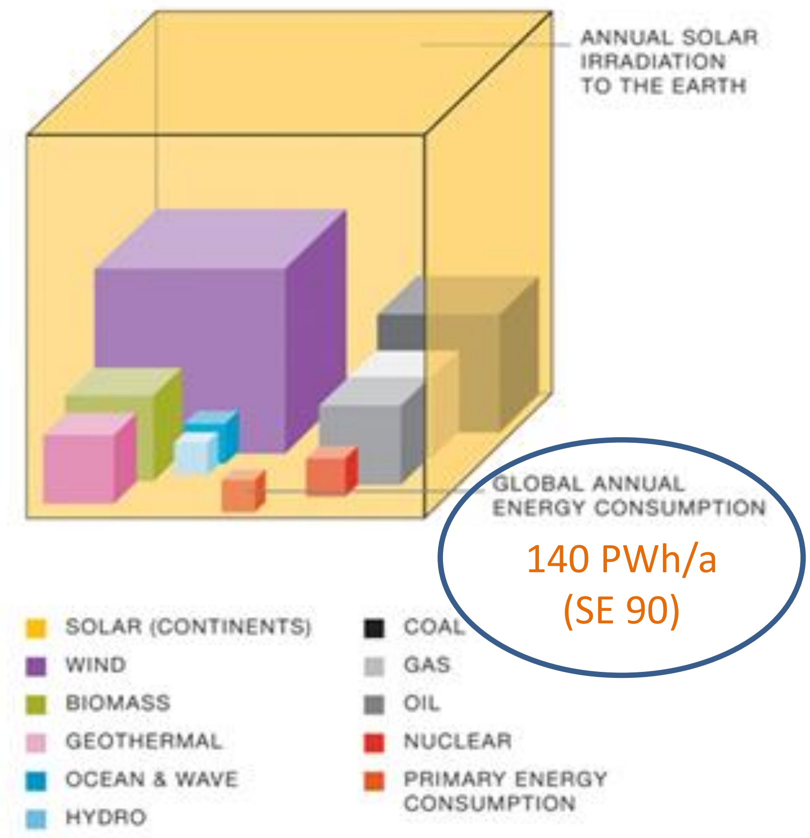
e-car:
@20 kWh/100km ,
5€ct/kWh storage cost and
(5-10)€ct/kWh electricity from PV
→
(2-3)€/100km

… which is (2-5) times less!!

Source: LIB cost 2012, 2015 and 2020 from C. Pillot (2014), avicenne; 2030/35 LIB cost, storage cost and conclusions are own estimates

Potential Renewable Resources per Year

and comparison to known exhaustible (conventional) sources & annual primary energy consumption

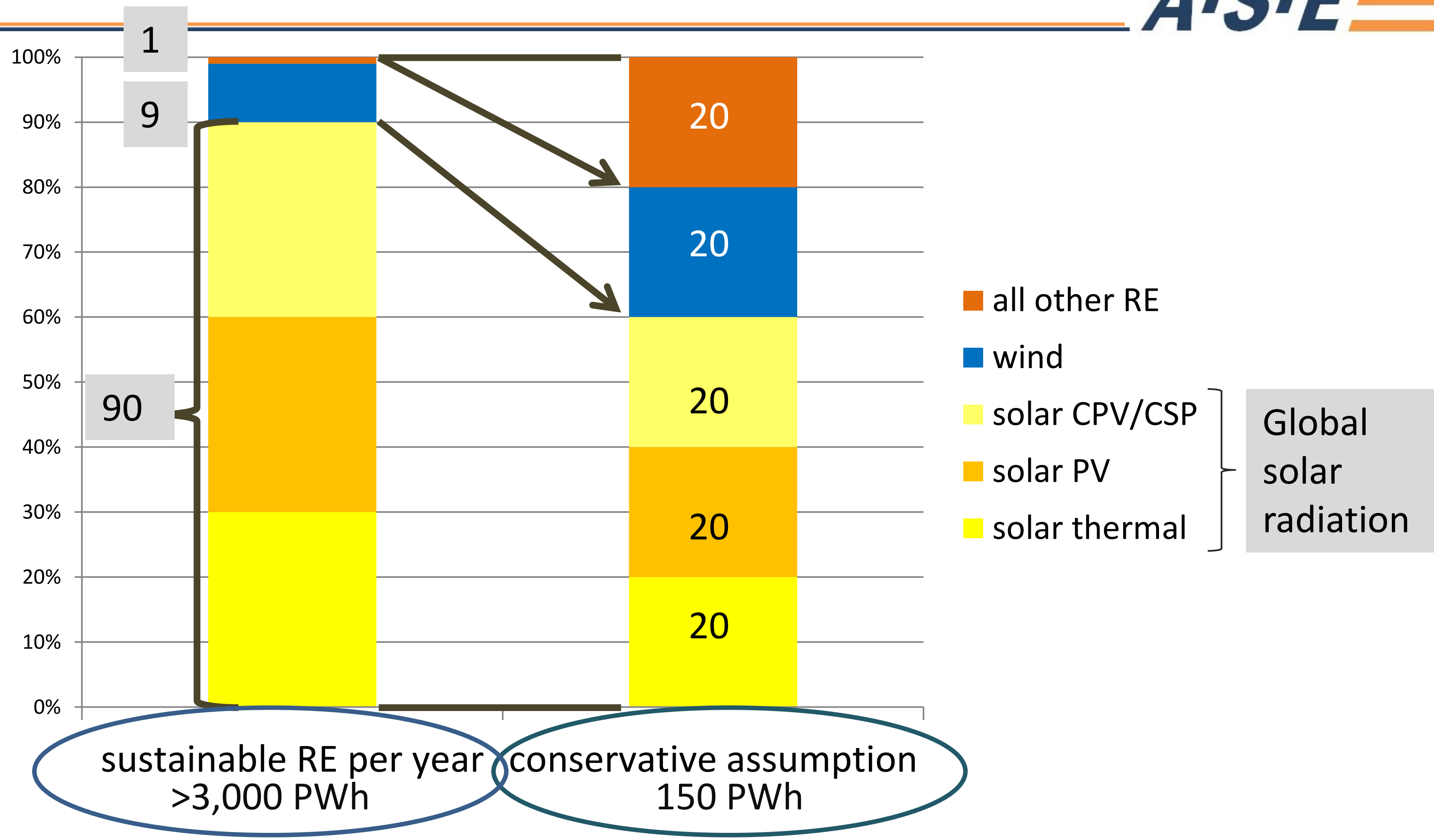


	Technical potential [PWh/year]	Sustainable potential [PWh/year]	
Biomass	224	28.0	~1%
Geother	202	6.2	
Hydro	45	3.4	
Solar	78,400	2,800.0	~90%
Wind	476	280 .0	~9%
total	79,347	3,117.6	~100%

=~ 20 x SE of future (~= 150 PWh)

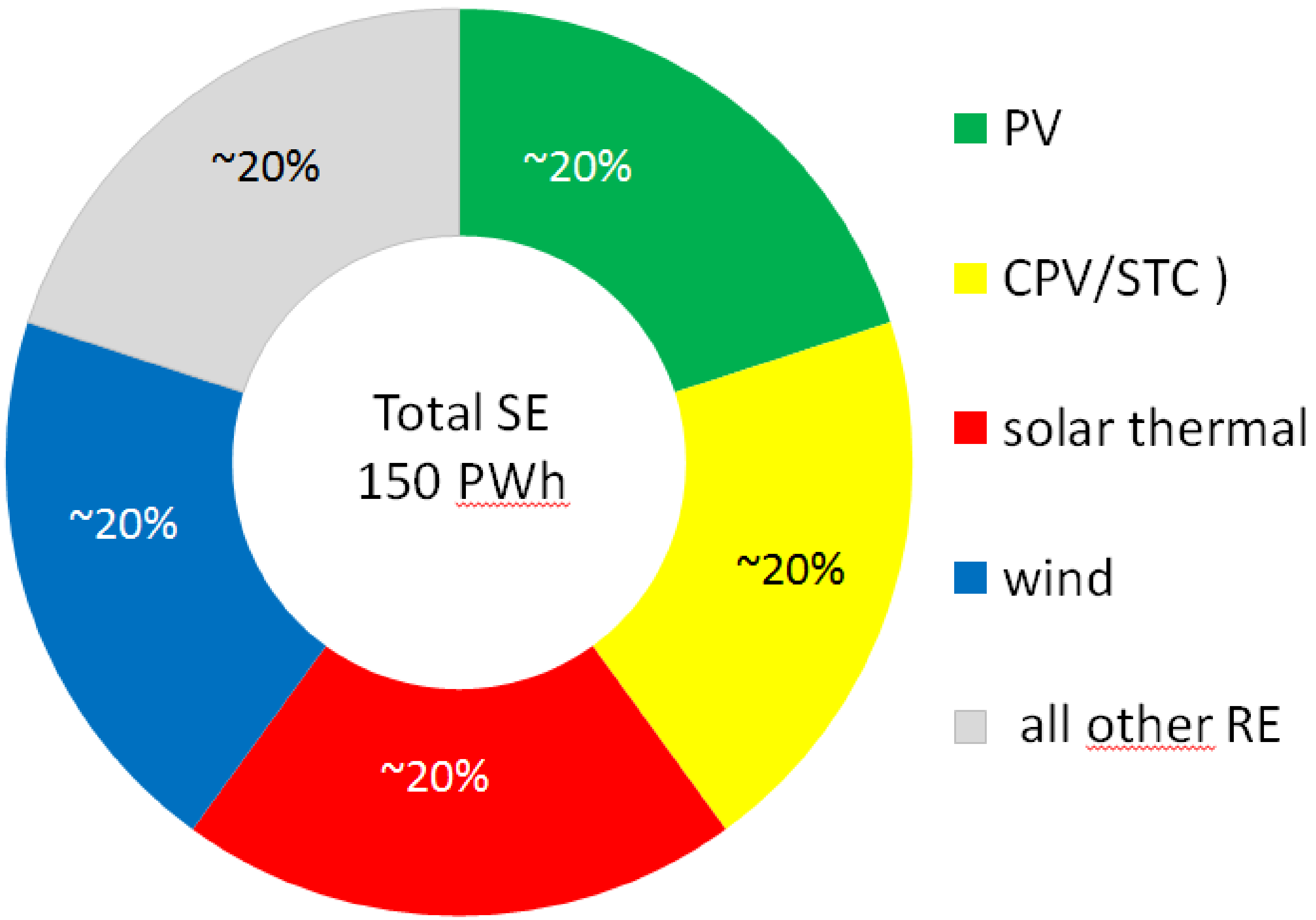
Source: EPIA, DLR (cube data), WBGU (technical and sustainable potentials), own data (future SE)

Annual sustainable potential for RE and conservative assumption



Source: WBGU, 2011 (left column);Winfried Hoffmann, own estimates (right column)

Secondary Energy Needs in 2050+



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… and for those who want to read more:

- Physik Journal, February 2014, W. Hoffmann „Perspektiven der Photovoltaik“
- Book by Wiley (author Winfried Hoffmann) „The Economic Competitiveness of Renewable Energy – Pathways to 100% Global Coverage“ (ISBN: 978-1-118-23790-8)

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… an old Chinese saw goes like

„if the wind of change blows up,
some are building shelters,
others install windmills“

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