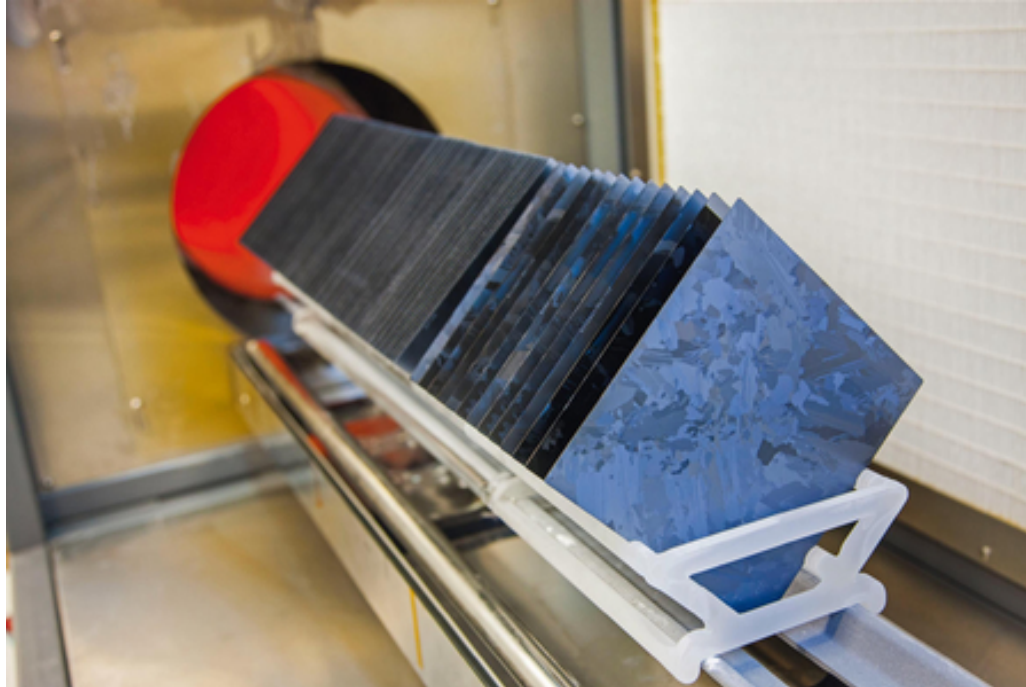


Photovoltaics – Silicon Solar Cells



Andy Greenspon
Harvard Energy Journal Club
October 21, 2015

Outline

- Solar PV production and distribution
- Silicon-based solar PV and silicon wafer production

Outline

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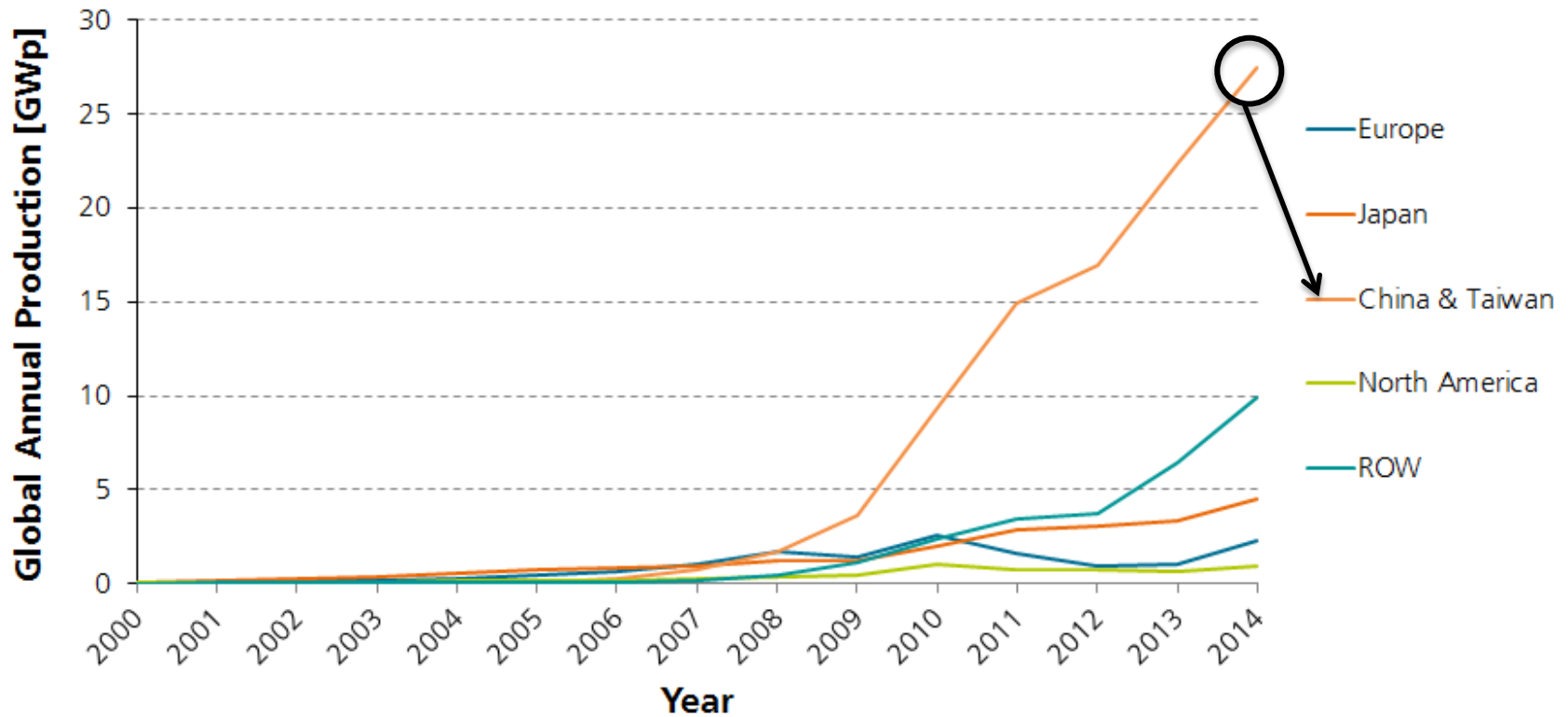
Table 1: Progress in solar PV markets and installation since 2009

	<i>End of 2009</i>	<i>End of 2013</i>
Total installed capacity	23 GW	135 GW
Annual installed capacity	7 GW	37 GW
Annual investment	USD 48 billion	USD 96 billion
Number of countries with >1 GW installed	5	17
Number of countries with >100 MW yearly market	9	23
PV electricity generated during the year	20 TWh	139 TWh
PV penetration levels	% of yearly electricity consumption	
Europe		2.6%
● Germany		5.3%
● Italy		7%

- New systems were installed in 2013 at a rate of 100 megawatts (MW) of capacity per day.
- Total installed capacity by early 2014: > 150 GW
- Total installed capacity by end of 2014: ~183 GW
- Since 2010, the world has added more solar PV capacity than in the previous four decades.

PV Industry Production by Region (2000-2014)

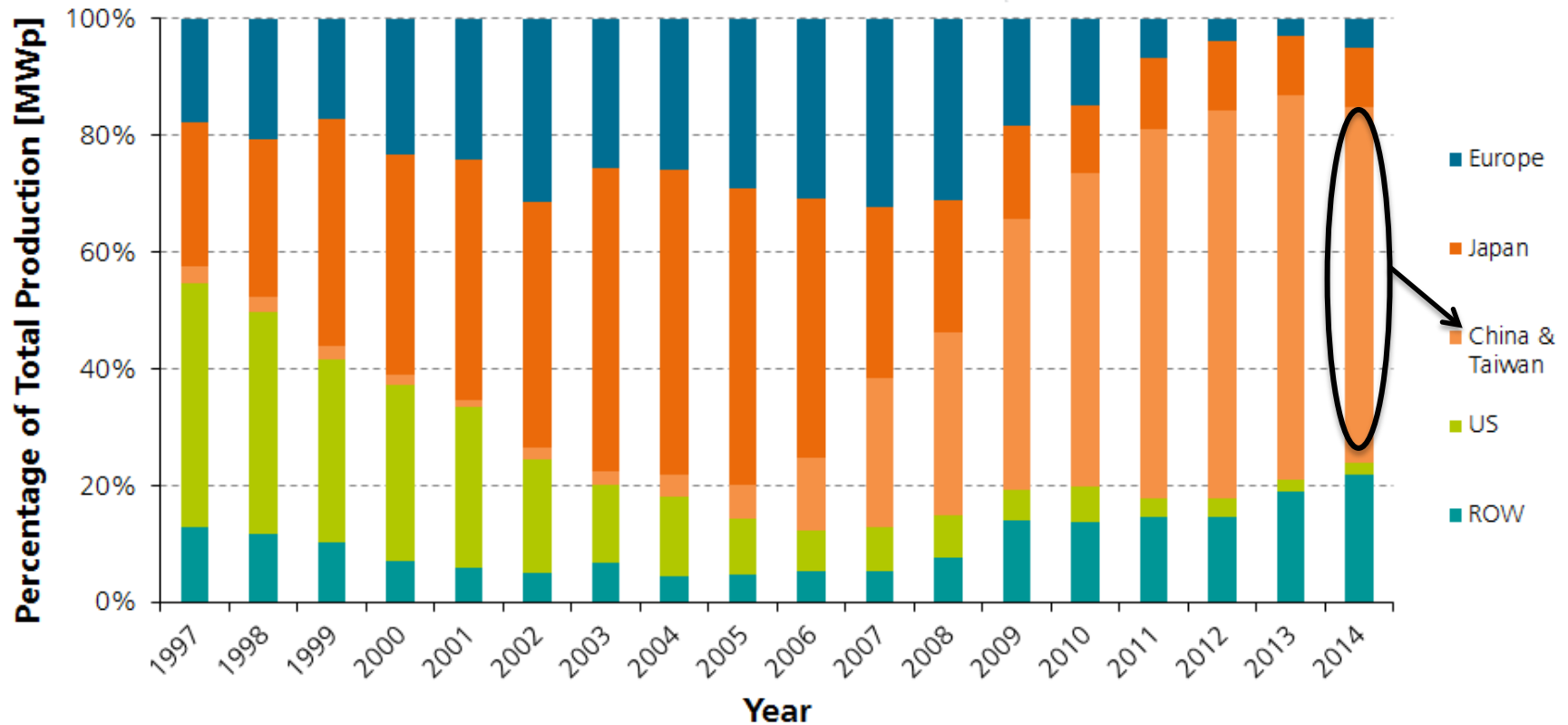
Global Annual Production



Data: Navigant Consulting and Paula Mints. Graph. PSE AG 2015

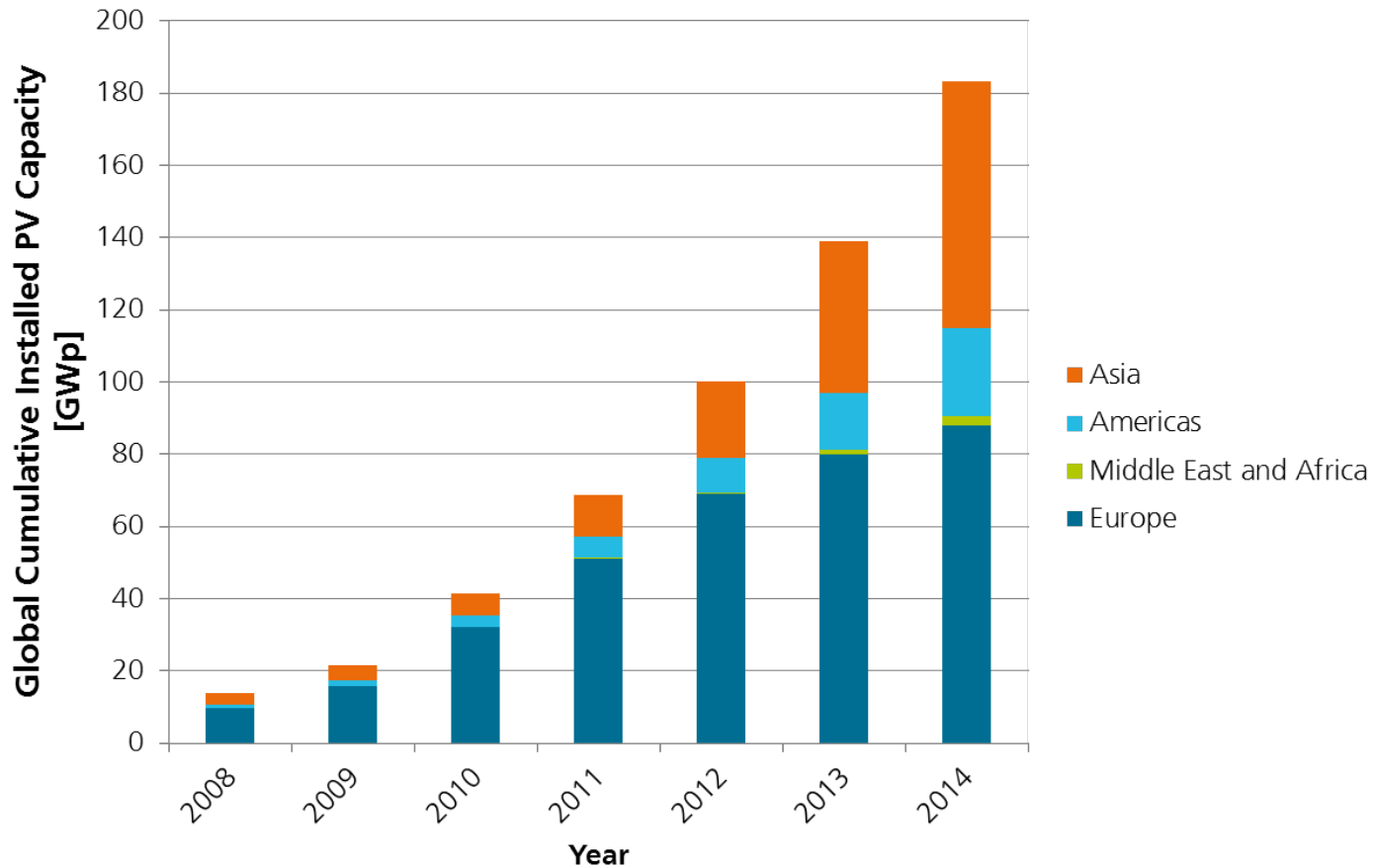
PV Cell/Module Production by Region 1997-2014

Percentage of Total MWp Produced



Data: Navigant Consulting and Paula Mints. Graph: PSE AG 2015

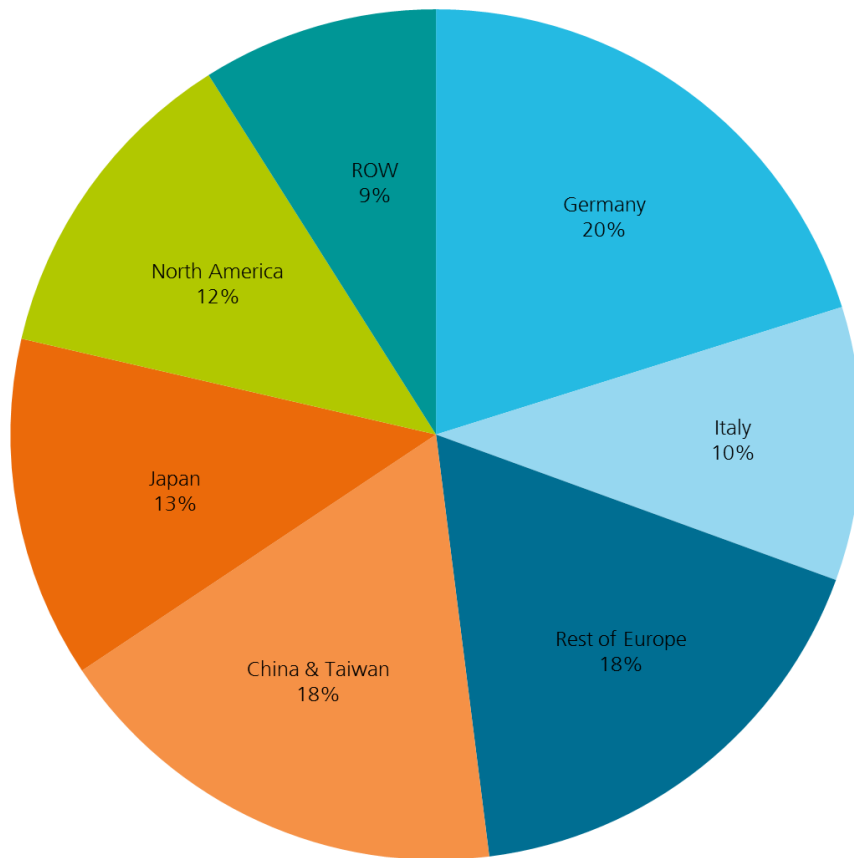
Global Cumulative PV Installation until 2014



Data: IHS. Graph: PSE AG 2015

Global Cumulative PV Installation by Region

Status 2014

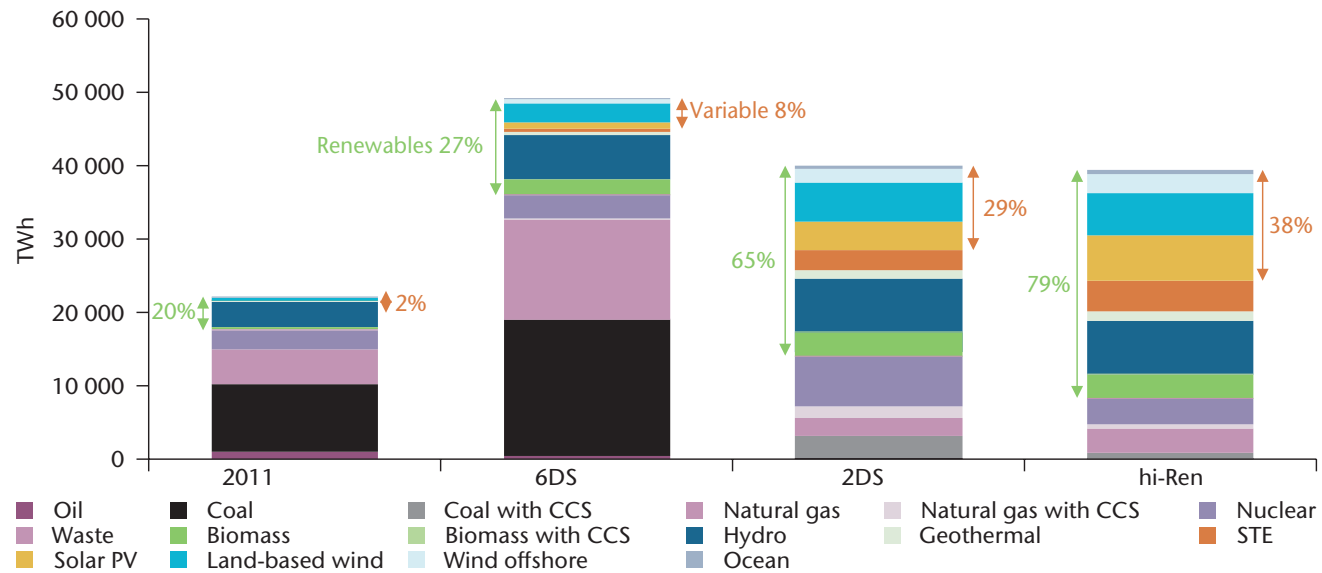


The total cumulative installations amounted to 183 GWp at the end 2014.

All percentages are related to total global installations, including off-grid systems.

Data: IHS. Graph: PSE AG 2015

Figure 5: Global electricity mix in 2011 and in 2050 in three ETP 2014 scenarios



KEY POINT: in the hi-Ren Scenario, renewables provide 79% of global electricity by 2050, variable renewables provide 38%, and PV provides 16%.

Table 3: PV capacities by region in 2030 and 2050 in the hi-Ren Scenario (GW)

Year	US	Other OECD Americas	EU	Other OECD	China	India	Africa	Middle East	Other developing Asia	Eastern Europe and former Soviet Union	Non-OECD Americas	World
2013	12.5	1.3	78	18	18	2.3	0.3	0.1	1.4	3	0.2	135
2030	246	29	192	157	634	142	85	94	93	12	38	1721
2050	599	62	229	292	1738	575	169	268	526	67	149	4674

PV Costs

Table 4: Projections for LCOE for new-built utility-scale PV plants to 2050 (USD/MWh) in the hi-Ren Scenario

<i>USD/MWh</i>	<i>2013</i>	<i>2020</i>	<i>2025</i>	<i>2030</i>	<i>2035</i>	<i>2040</i>	<i>2045</i>	<i>2050</i>
Minimum	119	96	71	56	48	45	42	40
Average	177	133	96	81	72	68	59	56
Maximum	318	250	180	139	119	109	104	97

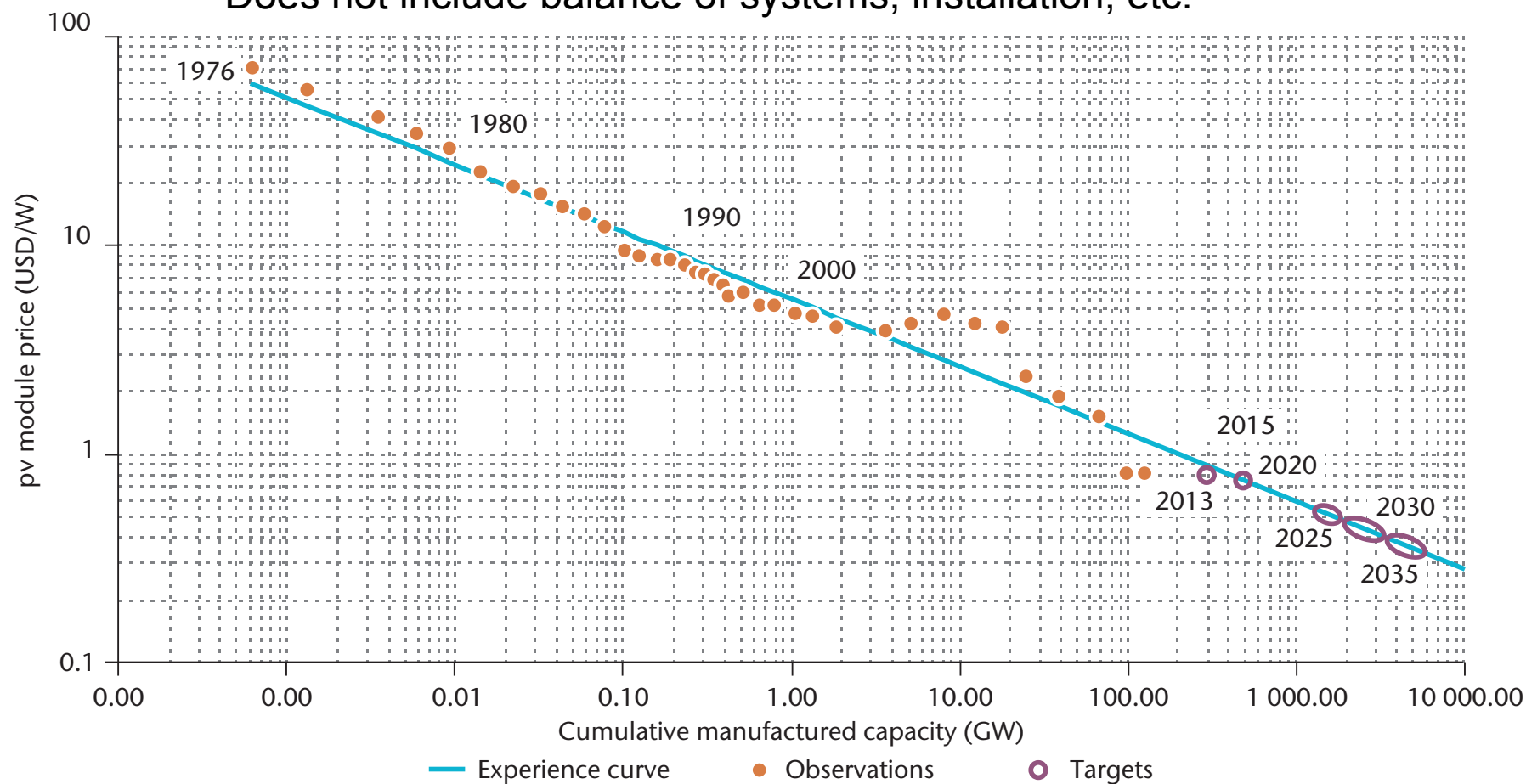
Note: All LCOE calculations in this table rest on 8% real discount rates as in *ETP 2014* (IEA, 2014b). Actual LCOE might be lower with lower WACC.

Table 5: Projections for LCOE for new-built rooftop PV systems to 2050 (USD/MWh) in the hi-Ren Scenario

<i>USD/MWh</i>	<i>2013</i>	<i>2020</i>	<i>2025</i>	<i>2030</i>	<i>2035</i>	<i>2040</i>	<i>2045</i>	<i>2050</i>
Minimum	135	108	80	63	55	51	48	45
Average	201	157	121	102	96	91	82	78
Maximum	539	422	301	231	197	180	171	159

Note: All LCOE calculations in this table rest on 8% real discount rates as in *ETP 2014* (IEA, 2014b).

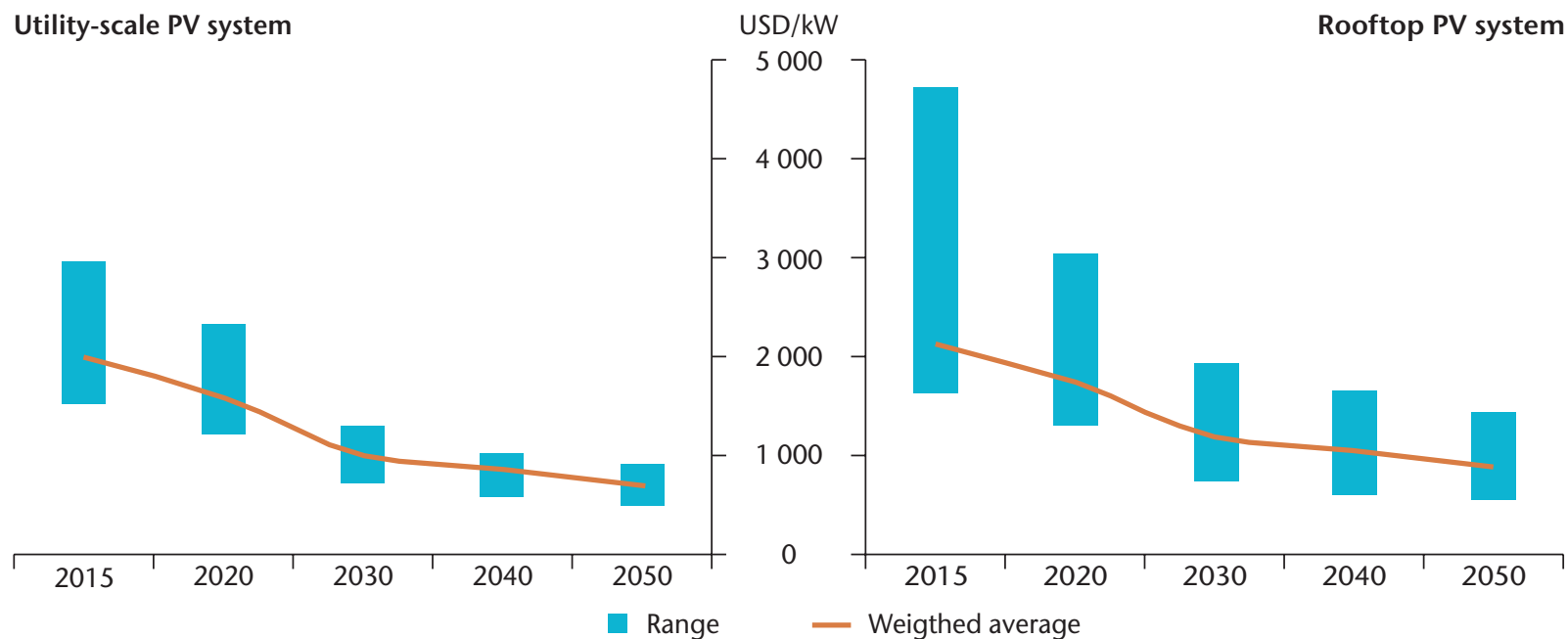
Figure 10: Past modules prices and projection to 2035 based on learning curve
Does not include balance of systems, installation, etc.



Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

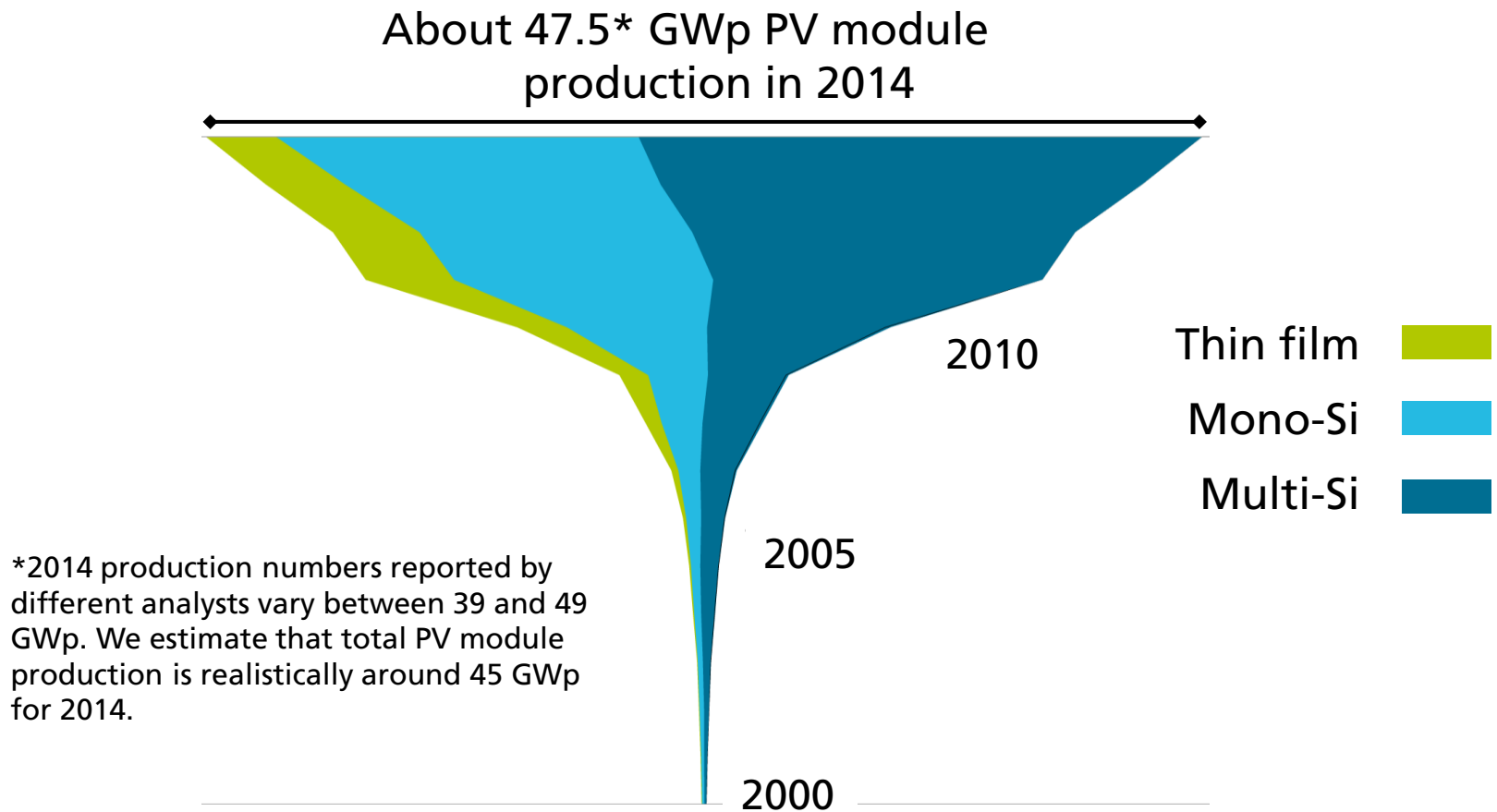
KEY POINT: This roadmap expects the cost of modules to halve in the next 20 years.

Figure 11: PV investments cost projections in the hi-Ren Scenario



KEY POINT: The price ranges of PV systems will narrow, and the average cost will be halved by 2040 or before.

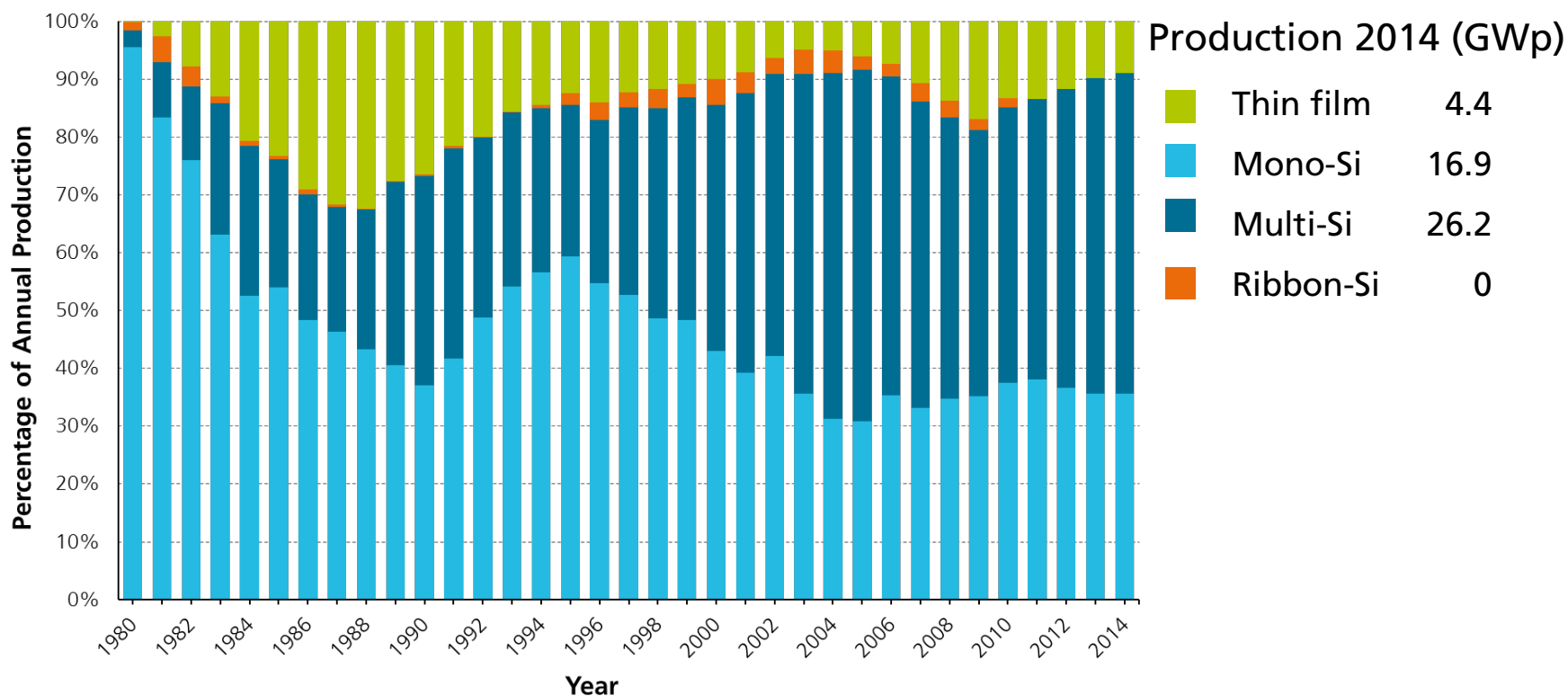
Annual PV Production by Technology Worldwide (in GWp)



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion: Paula Mints). Graph: PSE AG 2015

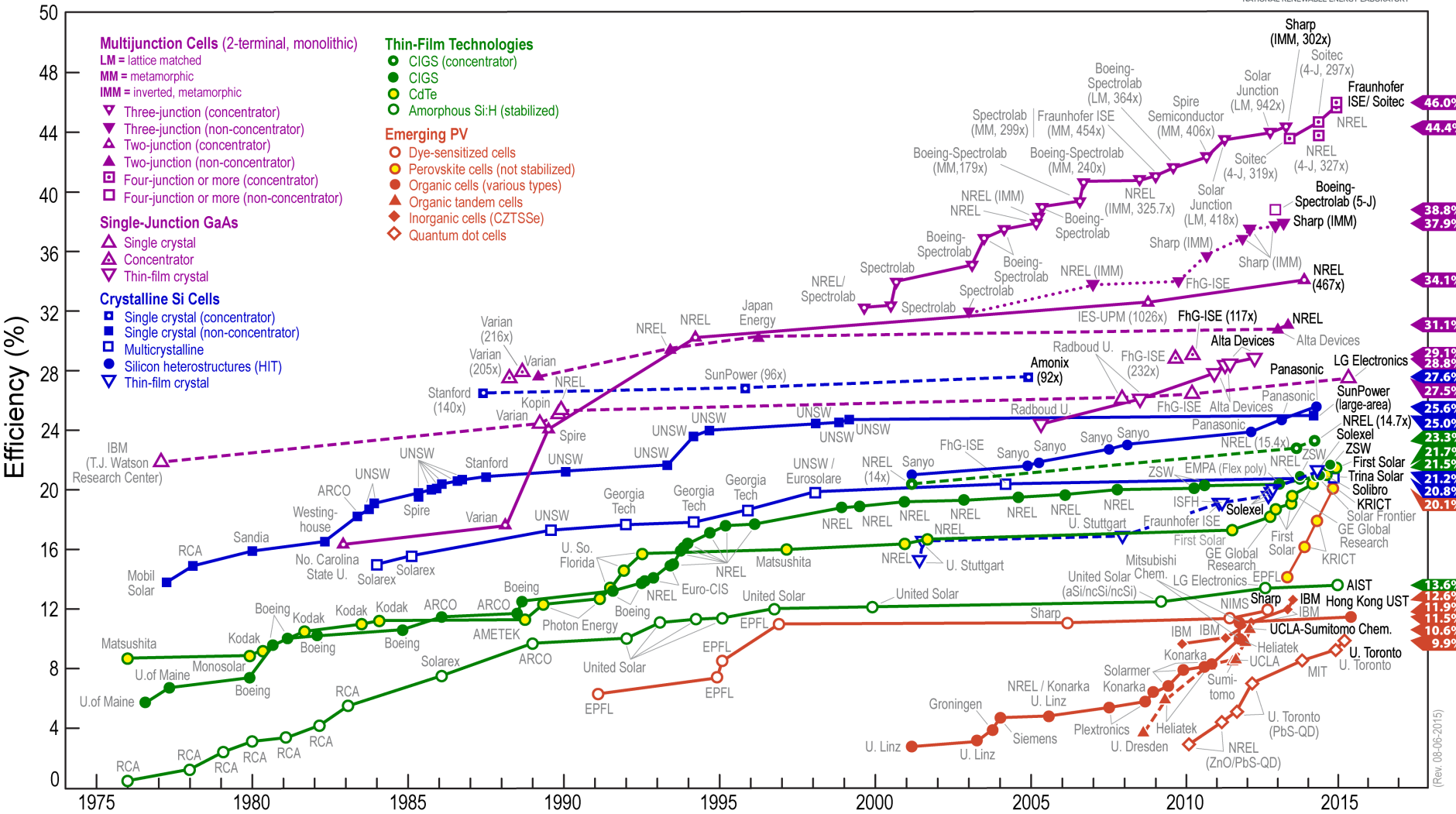
PV Production by Technology

Percentage of Global Annual Production



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion by Paula Mints). Graph: PSE AG 2015

Best Research-Cell Efficiencies



(Rev. 08-06-2015)

Multijunction Cells (2-terminal, monolithic)

LM = lattice matched

MM = metamorphic

IMM = inverted, metamorphic

▼ Three-junction (concentrator)

▼ Three-junction (non-concentrator)

▲ Two-junction (concentrator)

▲ Two-junction (non-concentrator)

□ Four-junction or more (concentrator)

□ Four-junction or more (non-concentrator)

Single-Junction GaAs

▲ Single crystal

▲ Concentrator

▼ Thin-film crystal

Crystalline Si Cells

■ Single crystal (concentrator)

■ Single crystal (non-concentrator)

□ Multicrystalline

● Silicon heterostructures (HIT)

▼ Thin-film crystal

Thin-Film Technologies

● CIGS (concentrator)

● CIGS

● CdTe

○ Amorphous Si:H (stabilized)

Emerging PV

○ Dye-sensitized cells

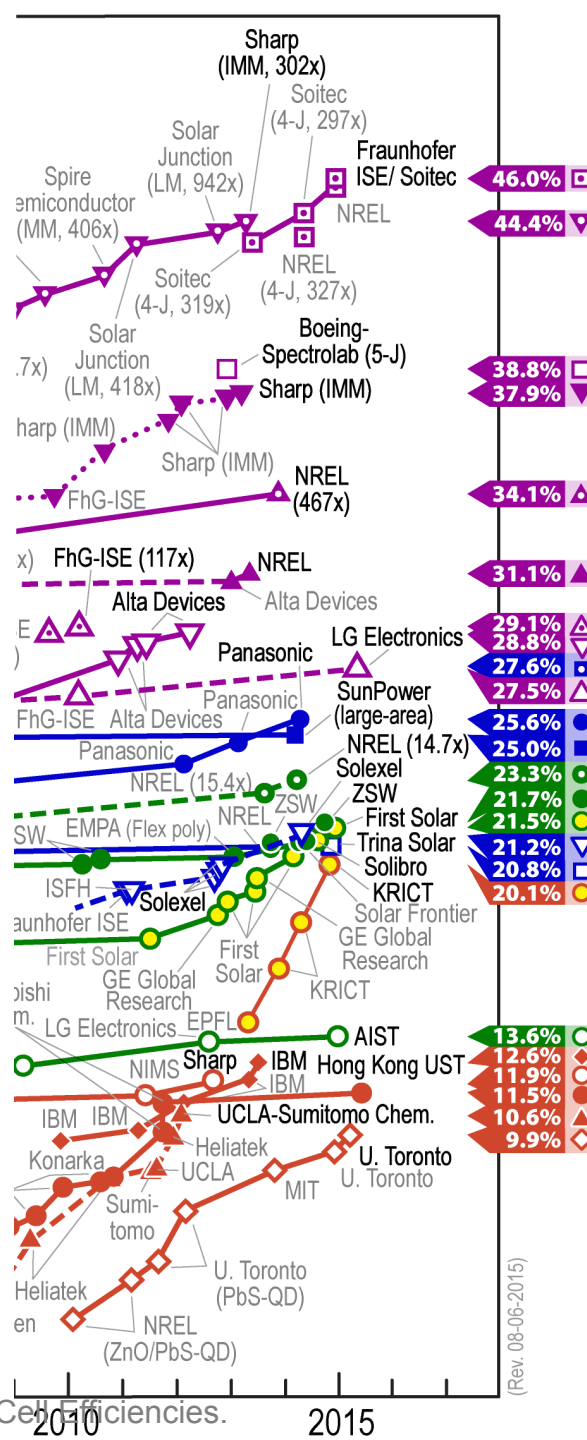
● Perovskite cells (not stabilized)

● Organic cells (various types)

▲ Organic tandem cells

◆ Inorganic cells (CZTSSe)

◆ Quantum dot cells

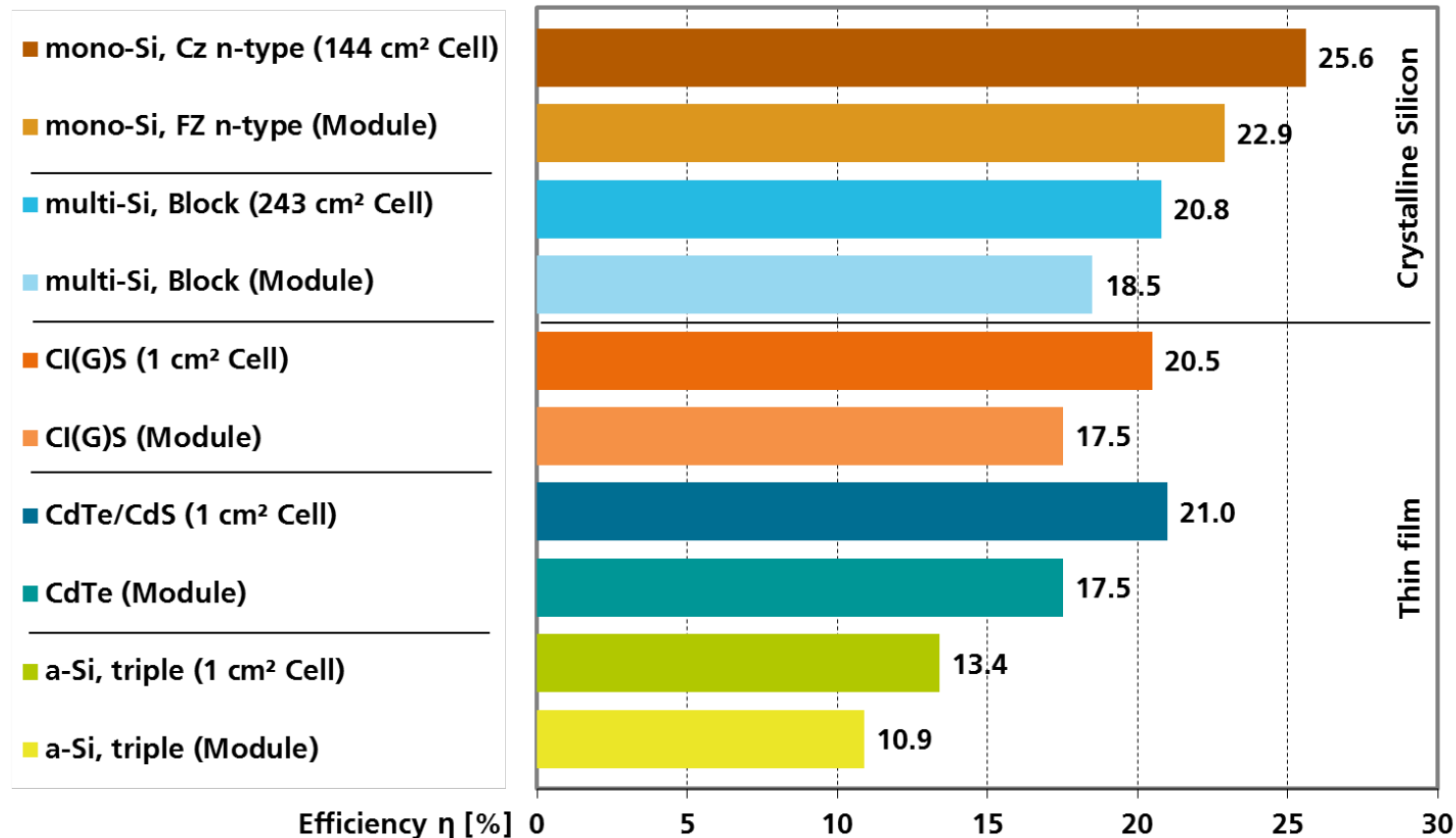


Single crystal Si
(sc-Si)

Multicrystalline Si
(mc-Si)

Amorphous Si
(a-Si)

Efficiency Comparison of Technologies: Best Lab Cells vs. Best Lab Modules



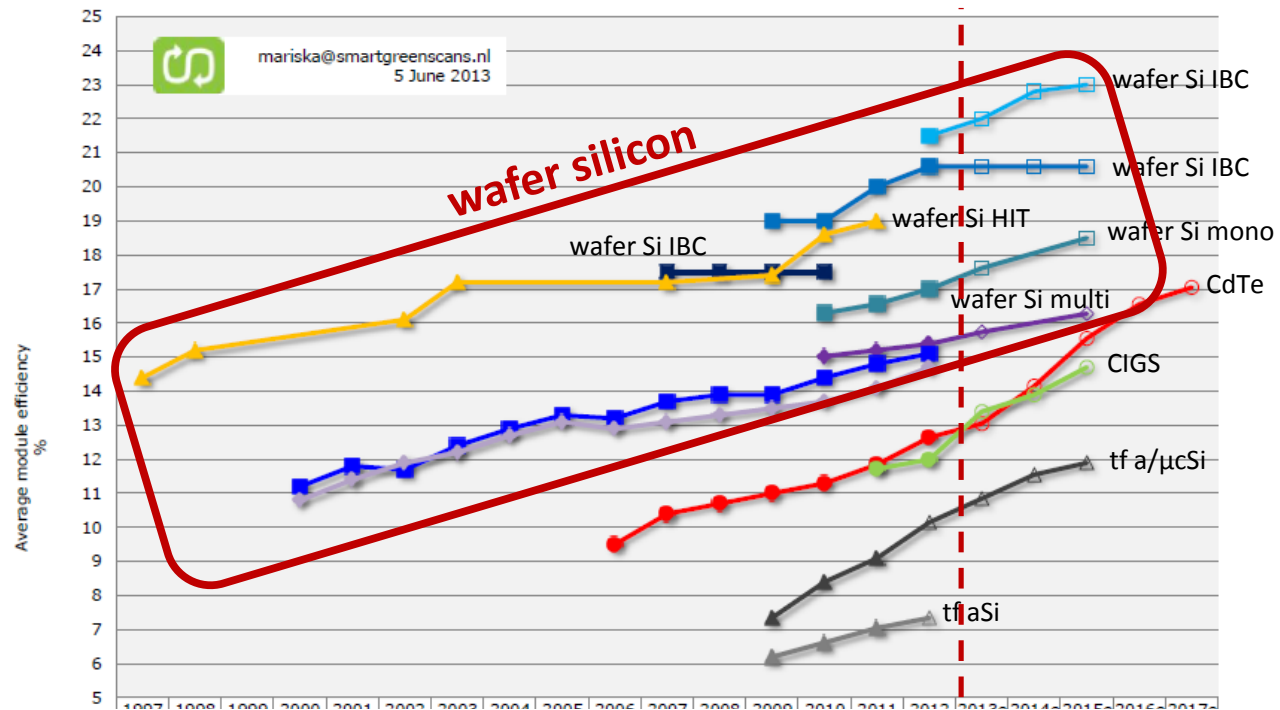
Data: Green et al.: Solar Cell Efficiency Tables, (Version 45), Progress in PV: Research and Applications 2015. Graph: PSE AG 2015

Commercial module efficiencies (selection) ECN

History + short-term projections (announced)

Cost-effective high-efficiency 1-sun PV modules, Wim Sinke, ECN Solar Energy, IEA PV Roadmap Workshop, Paris, 04-02-2014.

M.J. de Wild-Scholten
SmartGreenScans
(June 2013)



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013e	2014e	2015e	2016e	2017e
— Sunpower, X-series																21.5	22.0	22.8	23.0		
— Sunpower, E-series													19.0	19.0	20.0	20.6	20.6	20.6	20.6		
— Sunpower, 1st generation											17.5	17.5	17.5	17.5							
— HIT, Sanyo/Panasonic	14.4	15.2				16.1	17.2				17.2		17.4	18.6	19.0			25.6 (claimed)			
— Mono-Si n-type PANDA, Yingli, CN														16.3	16.6	17.0	17.6		18.5		
— Multi-Si, Yingli, CN														15.0	15.2	15.4	15.7		16.3		
— Mono-Si (Photon Int Feb 2013)				11.2	11.8	11.7	12.4	12.9	13.3	13.2	13.7	13.9	13.9	14.4	14.8	15.1					
— Multi-Si (Photon Int Feb 2013)				10.8	11.4	11.9	12.2	12.7	13.1	12.9	13.1	13.3	13.5	13.7	14.1	14.7					
— CdTe, First Solar										9.5	10.4	10.7	11.0	11.3	11.9	12.7	13.1	14.2	15.6	16.6	17.1
— CIGS, Solar Frontier, JP															11.7	12.0	13.4	13.9	14.7		
— μc/a-Si, Oerlikon Solar Fabs													7.4	8.4	9.1	10.2	10.9	11.6	11.9		
— a-Si, TSolar, ES													6.20	6.63	7.05	7.35					

Outline

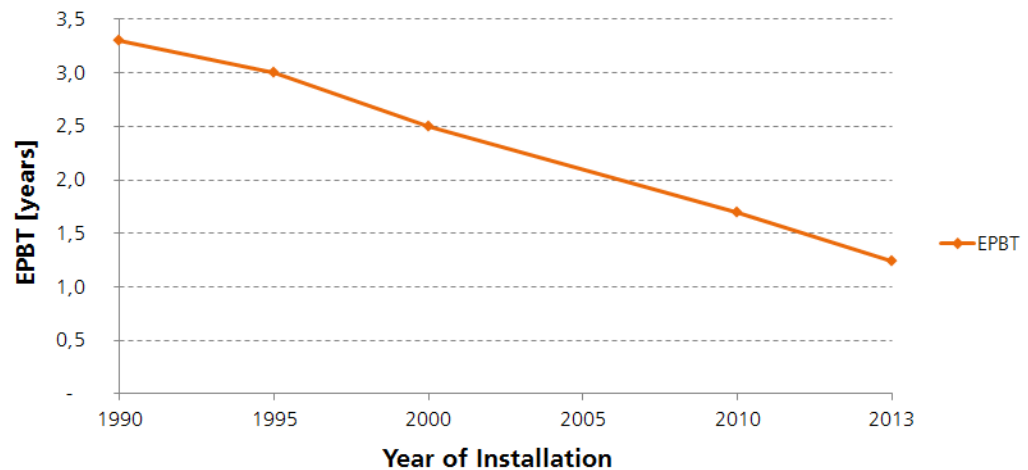
- Solar PV production and distribution
- Silicon-based solar PV and silicon wafer production

Historic Trend in Energy Payback Time of Crystalline Silicon PV Modules

Depending on the technology and location of the PV system, the EPBT today ranges from 0.7 to 2 years.

Rooftop PV systems produce net clean electricity for approx. 95 % of their lifetime, assuming a life span of 30 years or more.

EPBT of multicrystalline PV rooftop systems installed in Southern Europe*



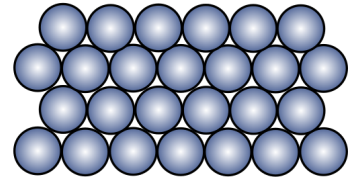
*Irradiation: 1700 kWh/m²/a at an optimized tilt angle

Data: EPIA Sustainability Working Group Fact Sheet 2011; since 2010: M.J. de Wild-Scholten 2013. Graph: PSE AG 2014

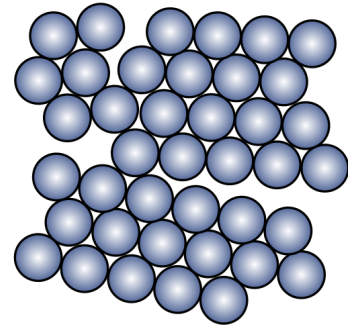
Silicon Solar PV

- Crystalline and multi-crystalline Si: ~90% of the market
- Some thin film PV is Si-based as well (a-Si)
- Avg. efficiency of commercial silicon modules has improved in the last ten years by about **0.3% per year, reaching 16% in 2013**
- **Best commercial efficiency of c-Si: ~22% (SolarCity)**

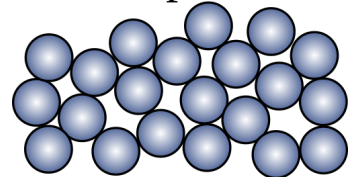
Monocrystalline



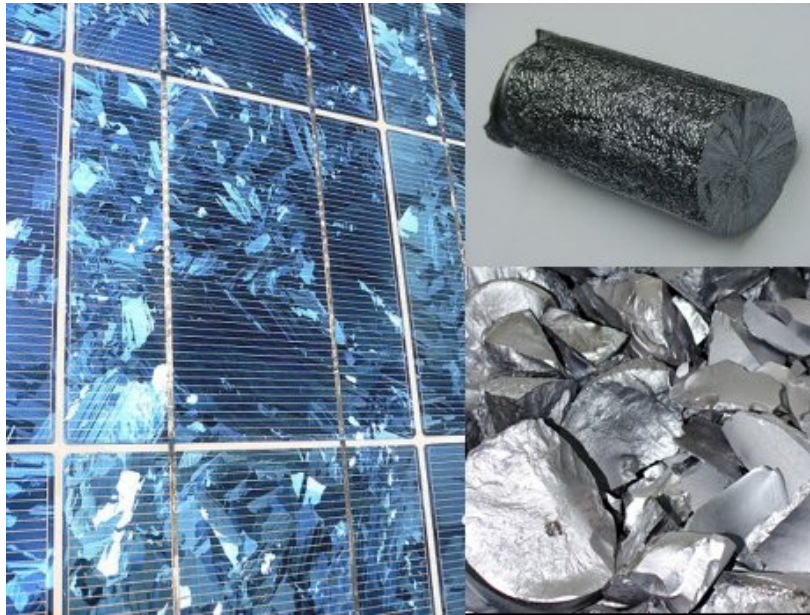
Polycrystalline



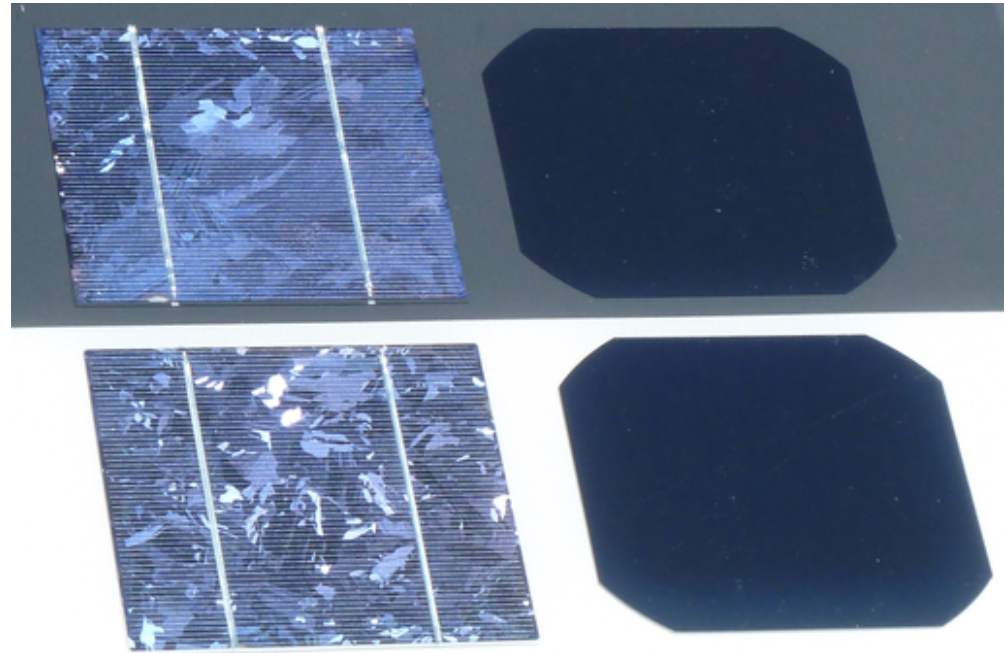
Amorphous



Polycrystalline



Polycrystalline



Single crystal

Si Wafer Production

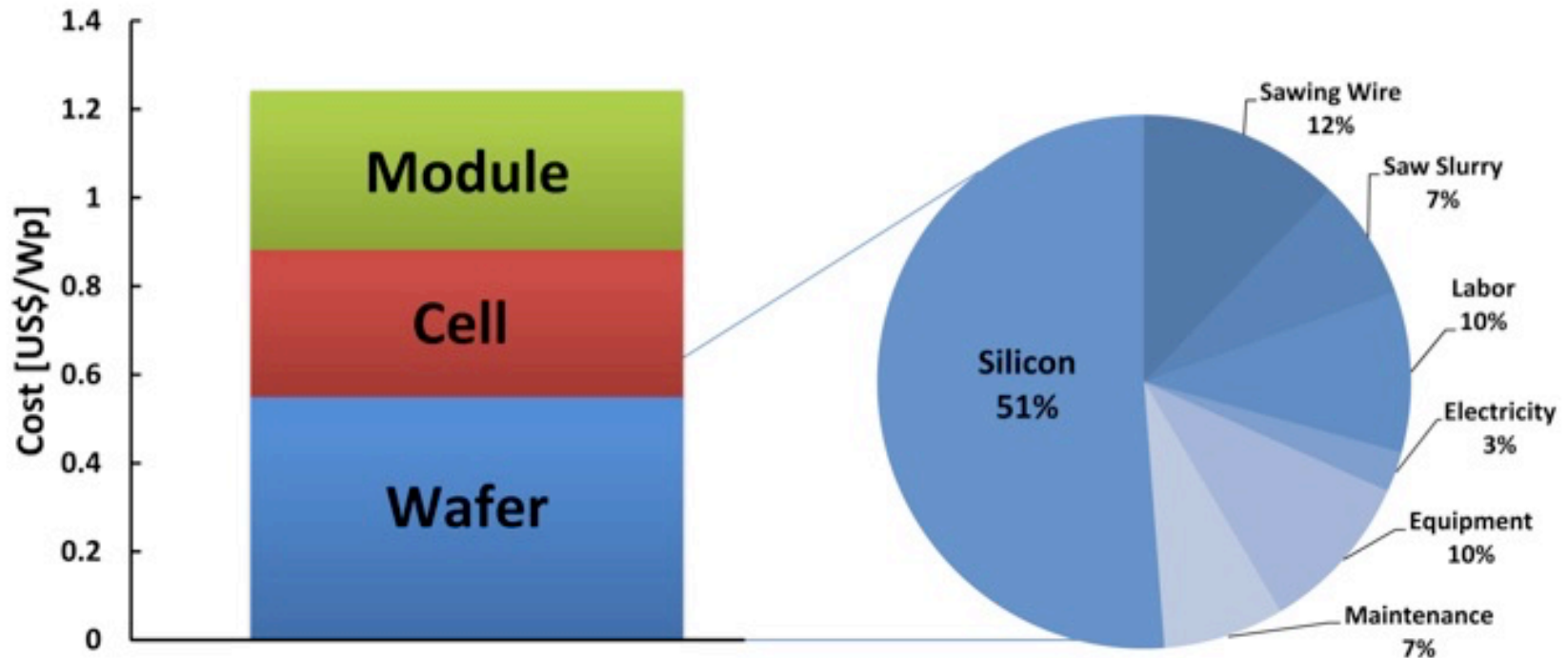
- Poly-Si feedstock: \$67/kg in 2010 to \$20/kg in 2012 (currently ~\$17/kg)

Methods to produce Si wafers:

- Crystal Ingots + sawing thin wafers.
 - Lots of waste (kerf)
 - Standard process for most solar PV cells
- Kerf-less technology:
 - Create wafers directly from molten silicon
 - Grow thin wafers with a template
 - Start-ups and research labs exploring this technology (1366 Technologies, Solexel, Crystal Solar, Fraunhofer Institute for Solar Energy Research).

US Module Cost Breakdown 2011

Does not include balance of systems, installation, etc.

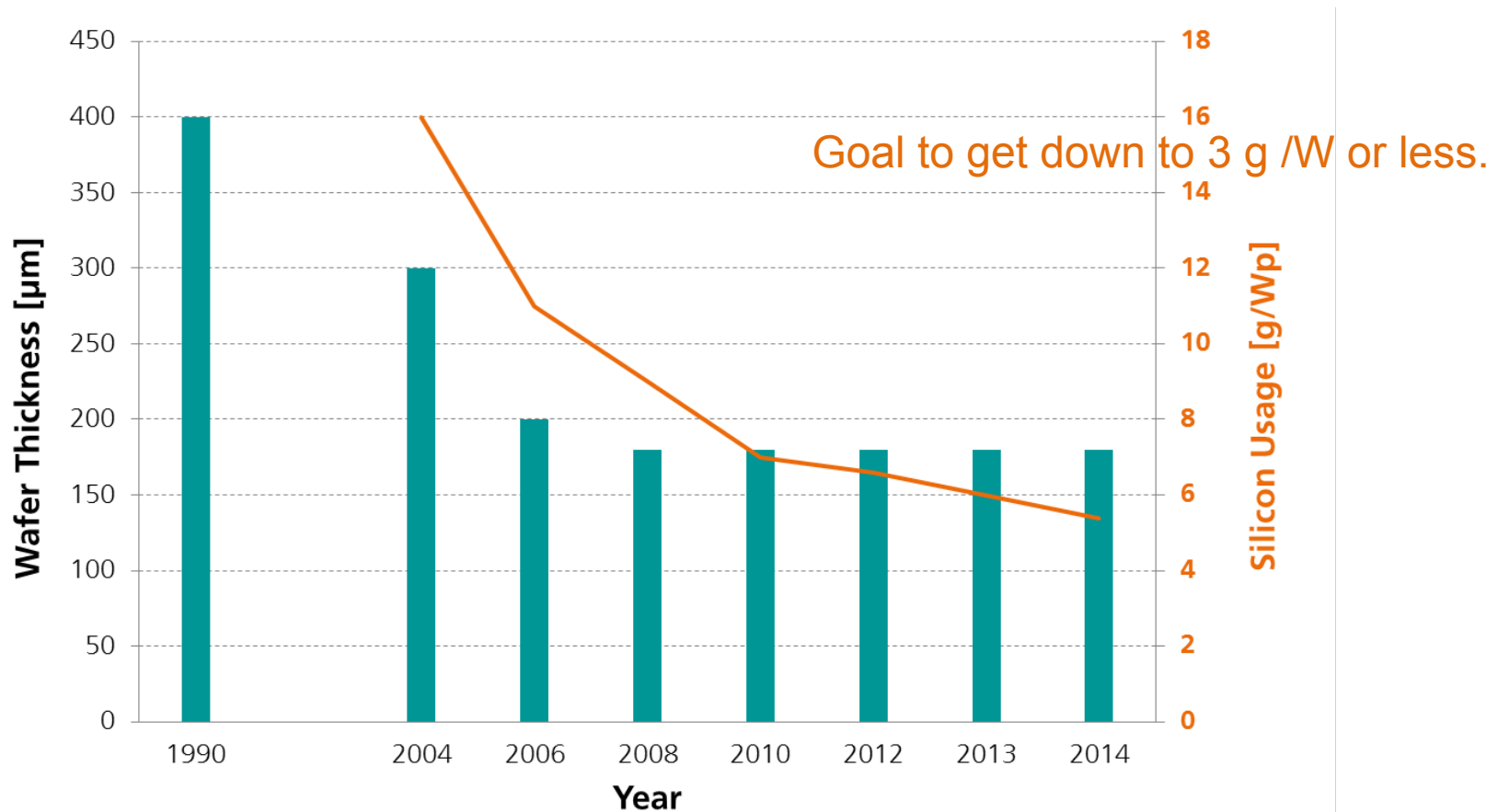


Crystalline silicon photovoltaic module costs and detailed cost breakdown of silicon wafer costs. The crystalline silicon wafer comprises about half of the final module costs. In the silicon wafer wire sawing and silicon feed stock are the main cost drivers.

Adapted from Solar PV Manufacturing Cost Analysis: U.S. Competitiveness in a Global Industry; Alan Goodrich, Ted James, and Michael Woodhouse October 10, 2011; NREL/PR-6A20-53938

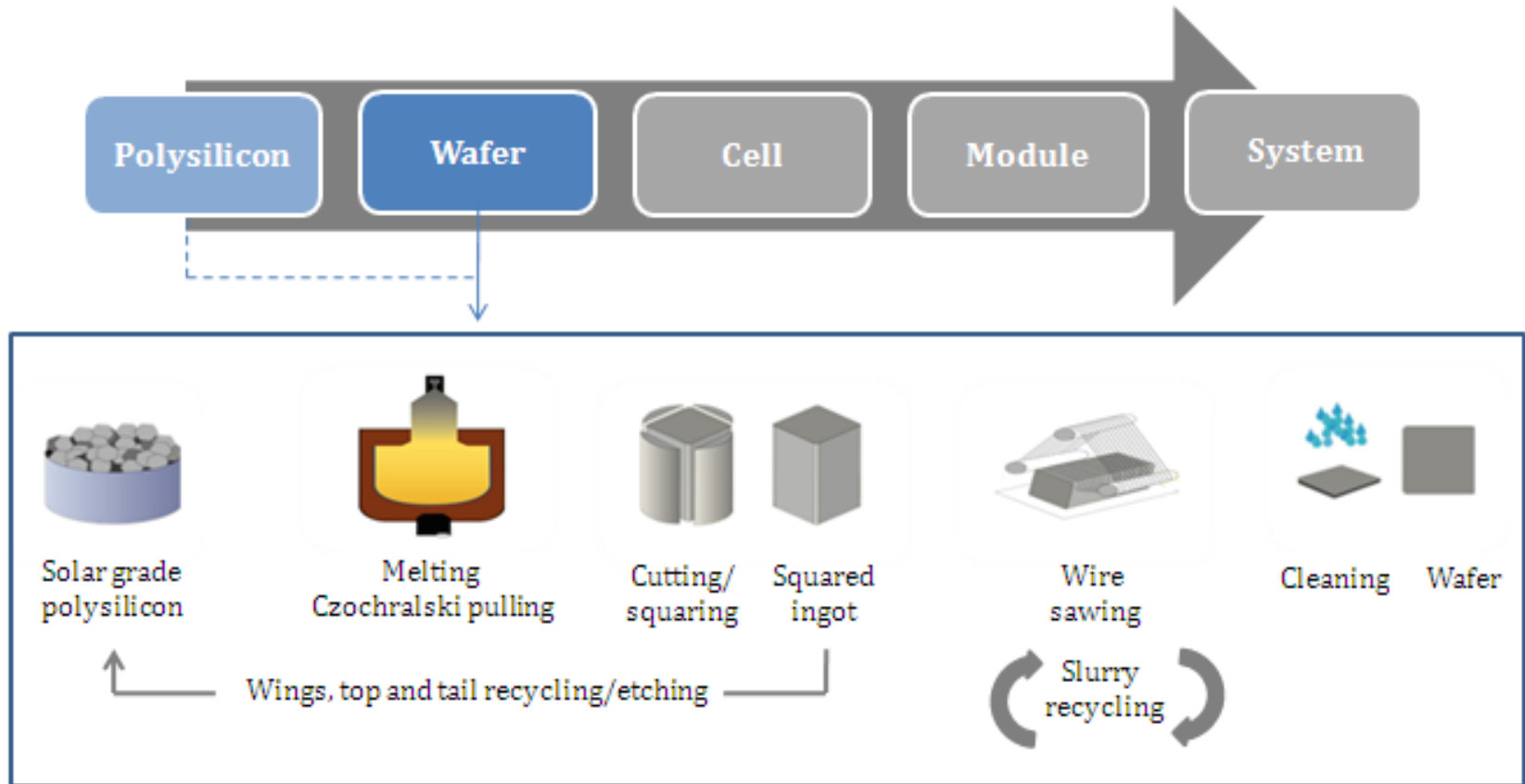
c-Si Solar Cell Development

Wafer Thickness [μm] & Silicon Usage [g/Wp]



Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: c-Si Roadmap ITRPV; 2015. Graph: PSE AG 2015

Silicon wafer processing



- Polysilicon melted down at temps $>2600^{\circ}\text{F}$, then let cool to form amorphous, poly, or single crystal silicon
- Sawing wafers generates a lot of waste Si dust
- **~50% of silicon is lost during production**

Kerf-less wafers: basic research

- Fraunhofer Institute for Solar Energy Research
- Reduce material losses by 50 percent while using 80 percent less energy
 - Lower heat (less energy) – 1800°F
- Si vapor Si vapor, flown past a crystalline template wafer to orient the Si vapor to become crystalline
 - Gives wafers their final thin shape – no sawing needed!
 - Wafers can be half as thin, reducing the cost of a solar cell by 20 percent.

Kerf-less wafers: Commercial

- Solexel:
 - 21.2% cell efficiency with 35 micron wafer
 - 19% module efficiency
 - Goal: \$0.40/W for modules by 2017.
 - Negatives – changed entire production line to handle thin wafers
- 1366 Technologies:
 - Cast wafers with conventional thickness from molten Si.
 - ‘Drop-in’ replacement for 60% of photovoltaics market.
 - 17.2 % cell efficiency in customer trials.
 - Construction of facility in upstate NY to be complete in 2017.
- “While 1366 plans to initially be a wafer supplier, Solexel is attempting to replicate a larger part of the supply chain. This can be a dangerous proposition, and many analysts cite such an approach as a factor in the failure of “string ribbon” PV wafer and module maker Evergreen Solar.”

Back contacted solar cells: basic research

- Fraunhofer Institute for Solar Energy Research
- Back and front contacted solar cells.
 - Full-area passivated back contact.
 - No complex cell structures or patterns.
- TOPCon (Tunnel Oxide Passivated Contact)
 - Intermediate passivation layer of tunnel oxide of 1-2 nm thick allows the charge carriers to "tunnel" through it.
 - Then a thin coating of highly doped silicon is deposited over the entire layer of ultra-thin tunnel oxide
 - Enables majority charge carriers to pass and prevents minority carriers from recombining
 - This novel combination of layers allows electrical current to flow out of the cell with nearly zero loss
- Efficiency of 25.1%

SolarCity new commercial panels

- Rooftop solar panel, with a module efficiency ~22%.
- “The silicon-based bifacial PV cell combines n-type substrates, copper electrodes, thin-film passivation layers, and a tunneling oxide layer that yields high conversion efficiencies.”
- Production will begin this month at the firm's 100-megawatt pilot facility
- Most of the new solar panels will be produced at SolarCity's 1 -gigawatt factory in upstate New York.
- Full production will be 9,000 – 10,000 solar panels per day at full capacity.
- Plans: “tens of gigawatts per year” over the next decade.
- Goal: ~\$0.55/W for a module

Conclusions (?)

Silicon will continue to dominate the solar PV market

Question: what types of Si-based cells will dominate?

At least 5 years before we get a sense of which of these technologies may be most cost-effective for mass production

References – reports

- 1) Photovoltaics Report. Fraunhofer Institute for Solar Energy Systems ISE. Freiburg, 26 August 2015.
- 2) Technology Roadmap: Solar Photovoltaic Energy – 2014 Edition. International Energy Agency.
- 3) PV Status Report 2014, Arnulf Jäger-Waldau, Joint Research Center Science and Policy Reports. European Commission, November 2014.
- 4) Cost-effective high-efficiency 1-sun PV modules, Wim Sinke, ECN Solar Energy, IEA PV Roadmap Workshop, Paris, 04-02-2014.

References – links

Which Solar Panel Type is Best? Mono- vs. Polycrystalline vs. Thin Film

<http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/>

Which Solar Panels Are Most Efficient?

<http://cleantechnica.com/2014/02/02/which-solar-panels-most-efficient/>

The disruptive potential of thin and kerfless wafers:

http://www.pv-magazine.com/archive/articles/beitrag/the-disruptive-potential-of-thin-and-kerfless-wafers-100016427/86/?tx_ttnews%5BbackCat%5D=248&cHash=4cb9a5153dd6d10526f35c9ff676c161#axzz3p8Cavqwh

Latest Innovation Could Be A Game Changer For Solar Cell Manufacturing:

<http://oilprice.com/Latest-Energy-News/World-News/Latest-Innovation-Could-Be-A-Game-Changer-For-Solar-Cell-Manufacturing.html>

1366 Technologies to Build 250MW 'Direct' Silicon Wafer Factory in Upstate NY

<http://www.greentechmedia.com/articles/read/1366-Technologies-to-Build-250MW-Direct-Silicon-Wafer-Factory-in-Upstate>

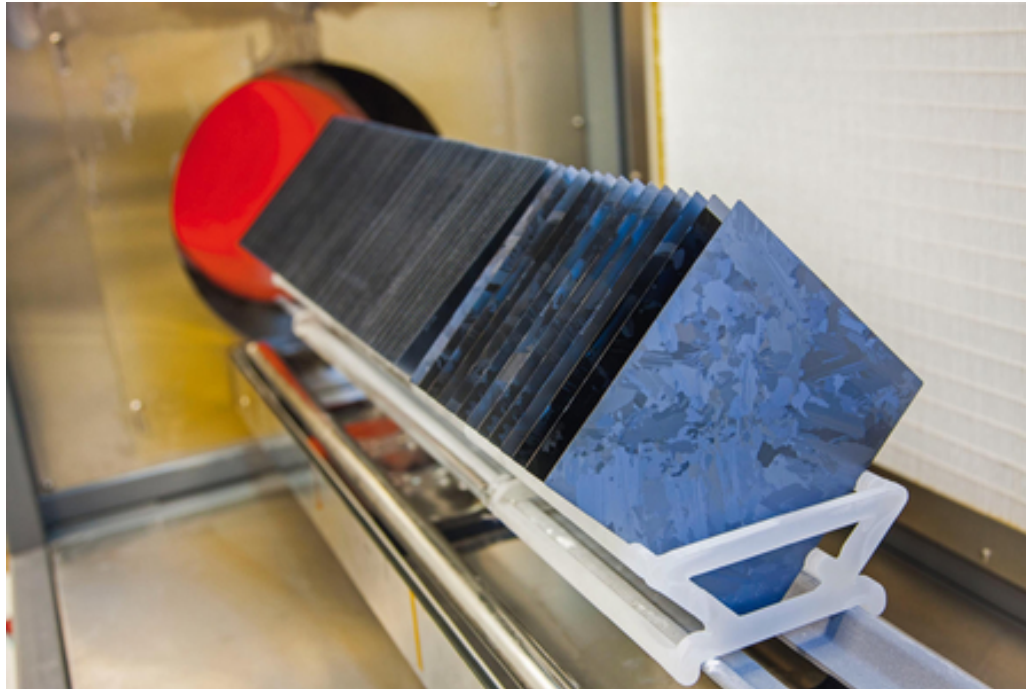
New world record for both sides-contacted silicon solar cells:

<http://www.energyharvestingjournal.com/articles/8429/new-world-record-for-both-sides-contacted-silicon-solar-cells>

Is SolarCity's New PV Module the 'World's Most Efficient Rooftop Solar Panel'?

<http://www.greentechmedia.com/articles/read/Is-SolarCitys-New-PV-Module-the-Worlds-Most-Efficient-Rooftop-Solar-Pane>

Questions?

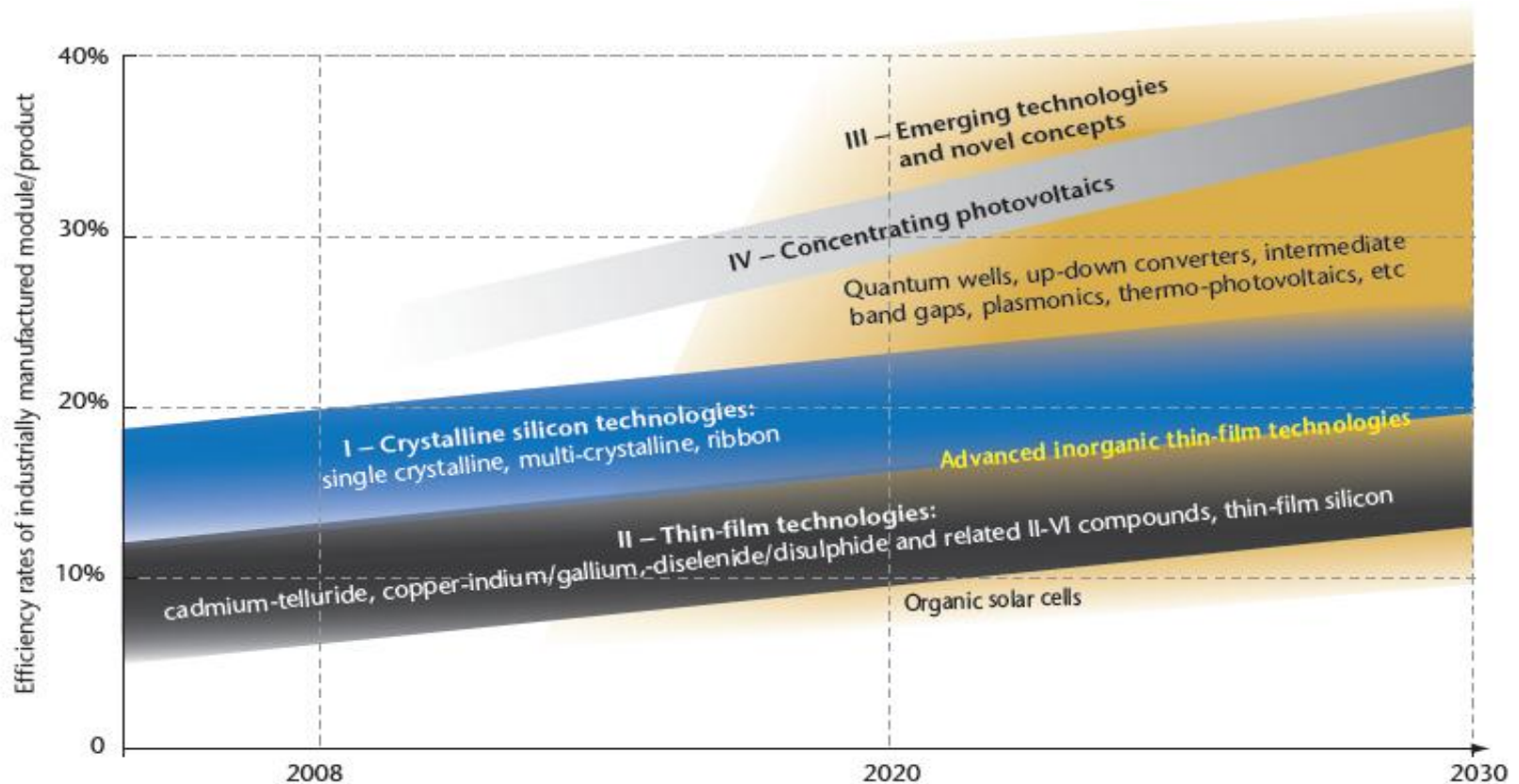


Bonus Slides

Commercial module efficiencies



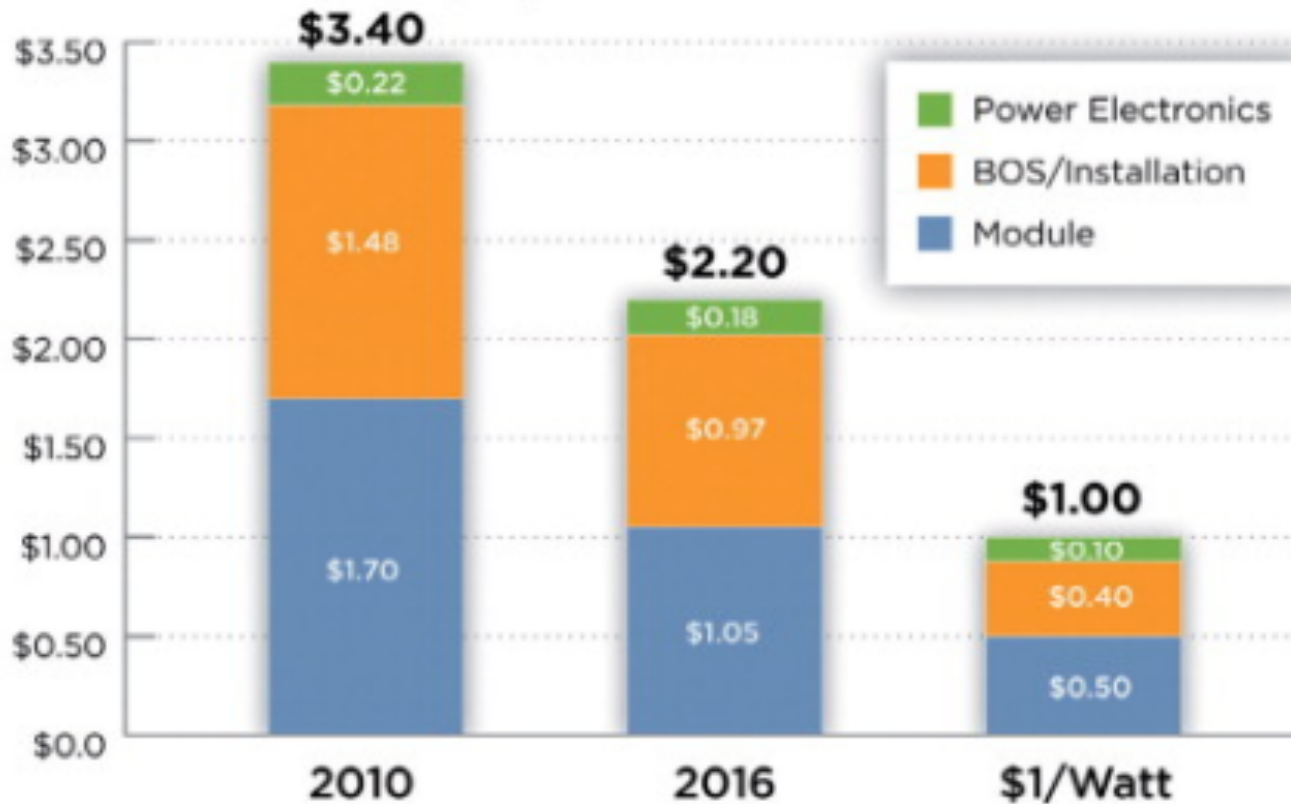
History + long-term projections (simplified estimates)



Source: IEA PVPS.

Reaching Cost Reduction Targets will require advances in all PV system components

Utility System with \$1/W Goal



Company	Phase	Name	Silicon Source	Product	Substrate Area Reported	Throughput Potential	Absorber Material Quality	Cell Efficiency	Time to Ramp
Solexel**	Gas	PSI Process licensed from ISE-Bayern	Special CVD Reactor	Film on Substrate	156mm Special Shape	Med-High	Lifetime >100us	15% Reported	Long
Crystal Solar**	Gas	CVD on silicon	Special CVD Reactor	Film on Substrate	Full Wafers	Med-High	Lifetime >15-30us	15% Reported	Long
Ampulse	Gas	Hot-wire CVD	Special CVD Reactor	Film on Substrate	Full Wafers	Med-High	Little Information Available	None Reported	Long
Evergreen Solar	Liquid	String Ribbon	Melt	Substrate	Proprietary Size 80mm 200um	High	Small Grain Multicrystalline	~15%	Closed
Solivo A.G.	Liquid	String Ribbon	Melt	Substrate	Proprietary Size 80mm 135-200um	High	Small Grain Multicrystalline	~13.5% Module Efficiency	In Production 220MW
1366	Liquid	Direct Wafering	(Melt on Ceramic Form)	Substrate	156mm Wafer 200um	High	TTV Poor No Other Information	*1.5% less than mc-Si* [6]	Short Substitutional?
Varian	Liquid	Floating Silicon Method (FSM)	Melt	Substrate	None Reported	High	None Reported	N/A	Short Substitutional?
IMEC	Solid "Thin"	SLIM-Cut	CZ	Thin Film	10cm ²	Low-Medium	TTV Poor Low Lifetime? Brittle?	10%	Long
Astrowatt	Solid "Thin"	SOM/BCSOM	CZ	Silicon on Metal	100mm Diameter	High	TTV Poor Low Lifetime? Brittle?	Est. 6-8% from Literature Data	Medium-Long
Twin Creeks	Solid "Thin"	Thin-film cleave on substrate	CZ	Film on Substrate	None Reported (Proprietary)	High	None Reported (Proprietary)	None Reported	Medium-Long
SiGen	Solid Full-Range	PolyMax	CZ	Substrate	156mm Wafer 20-120um	High	Lifetime > 200us Mechanical good TTV Good	> 16%	Short Substitutional

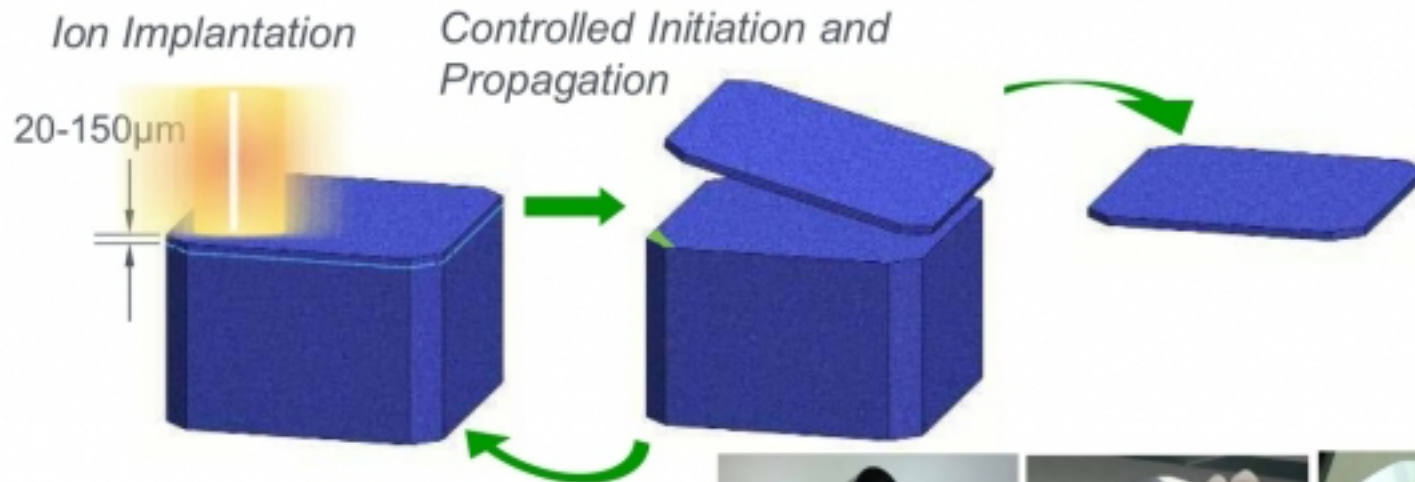
** Process Restart

Table 1: Comparison of various kerfless wafering methods

Silicon Genesis' Kerf-less Wafering (Approach)

U.S. DEPARTMENT OF
ENERGY

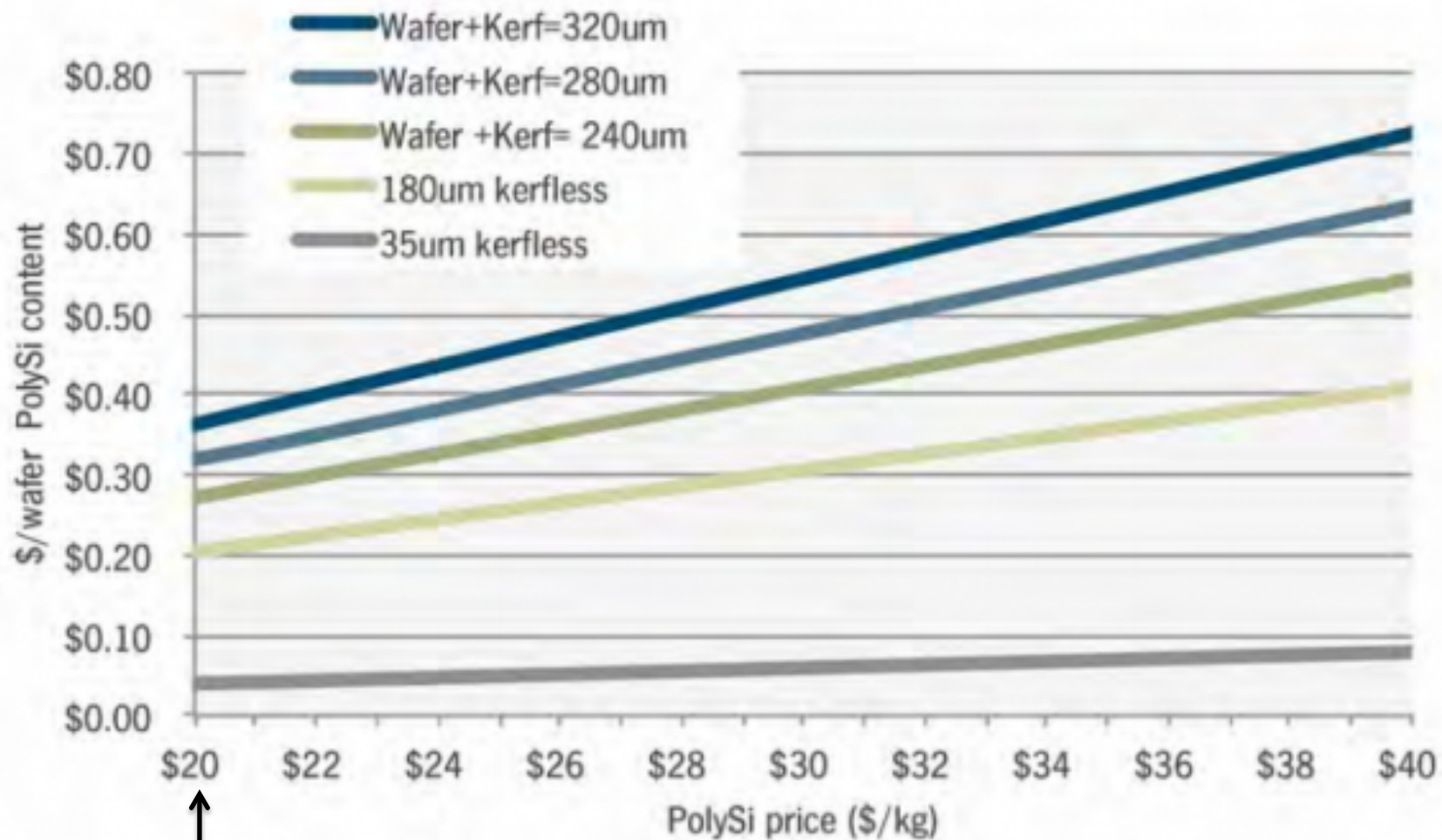
Energy Efficiency &
Renewable Energy



- PolyMax is a two-step process
- Implant light ions into c-Si
 - Forms sub-surface cleave layer
- Controlled Cleave
 - Use a small high dose area to initiate a cleave
 - Propagate cleave through the lower dose area
 - Remove wafer
- Repeat on newly exposed brick surface



- SiGen has demonstrated kerf-less wafering on its R&D tools (previous work)
- Three thickness: 20, 50, 150 micron
- 125 mm and 156 mm square form factors
- High R&D yields
- No apparent problems due to progressive slicing
- <111> crystalline silicon



~current price

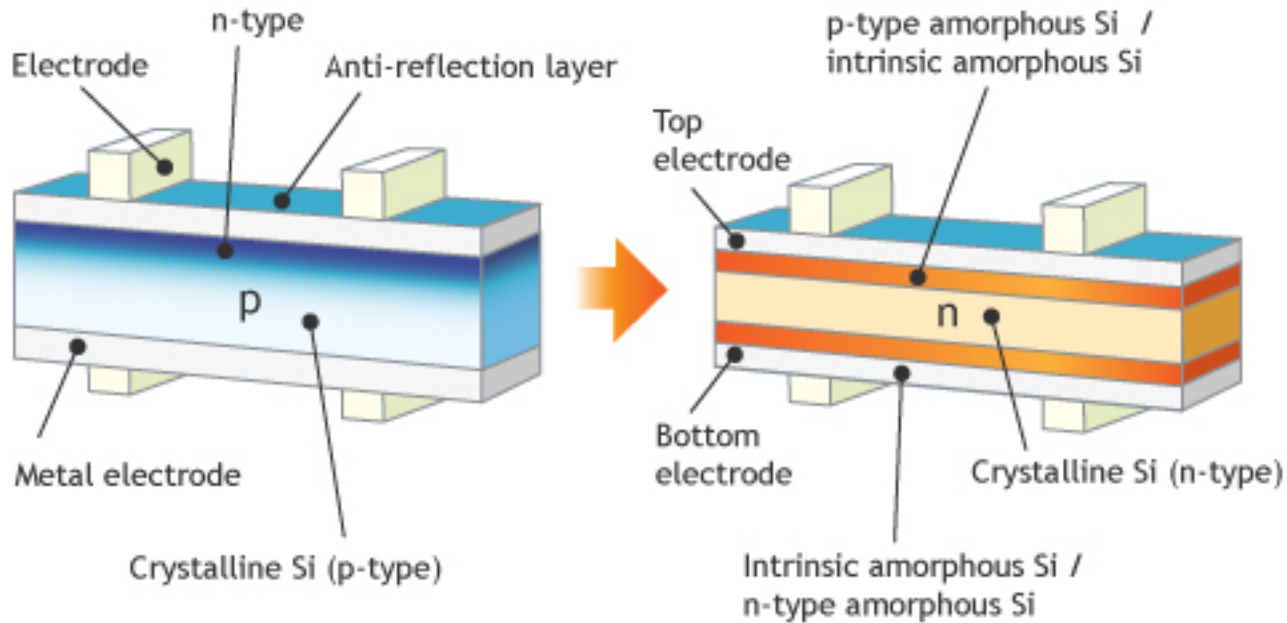


Advantages of a-Si:H over c-Si

- Technology is relatively simple and inexpensive for a-Si:H
- For a given layer thickness, a-Si:H absorbs much more energy than c-Si (about 2.5 times)
- Much less material required for a-Si:H films, lighter weight and less expensive
- Can be deposited on a wide range of substrates, including flexible, curved, and roll-away types
- Overall efficiency of around 10%, still lower than crystalline silicon but improving

25.6% efficiency as of April 2014

HIT (Heterojunction with Intrinsic Thin Layer) Solar Cell is composed of thin single crystalline Si wafer sandwiched by ultra-thin a-Si layers



Conventional c-Si solar cell

Hit solar cell

Tandem thin film cells on Si

“The rapid cost decline of c-Si, however, opens the door for mass-production of high-efficiency tandem cells, where TF would be deposited on c-Si wafers. Reviewing a broad range of material options – “III-V” alloys, chalcogenides and perovskites – and relevant production processes, Green et al. (2013) suggest that Si wafer-based tandem cells could represent a very cost-effective long- term combination. Such cells would probably be best used under 1-sun or low concentration with simplified tracking devices. “