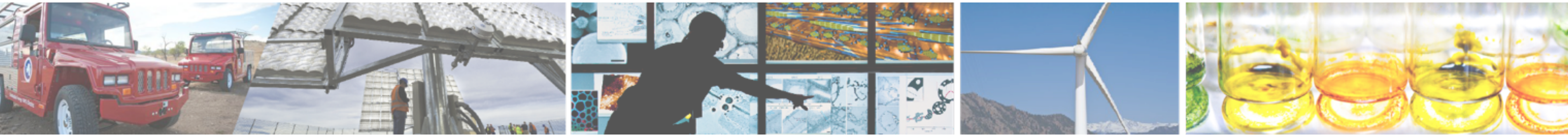


Building on 37 Years of Progress: The Next 10 Years of PV Research

University of New South Wales

Dr. Gregory M. Wilson
Director, National Center for Photovoltaics
National Renewable Energy Laboratory
Golden, Colorado - USA

15 April, 2014

The National Center for Photovoltaics (NCPV) is America's largest PV research institute focused on the scientific research and technology developments needed by industry to rapidly move PV forward as a mainstream source of low cost, reliable energy.

"That's one small step for man, one giant leap for mankind."
Neil Armstrong, July 20, 1969

SunShot
U.S. Department of Energy

Our Mission:

- Grid Parity by 2020.
- $1/Watt installed PV (5MW scale), 50¢/Watt module price.
  - Equivalent to 5-6 cents per kilowatt hour.
  - Competitive with fossil energy.
  - Rapid growth without incentives.

NCPV: Helping Seed the PV Technologies of Tomorrow

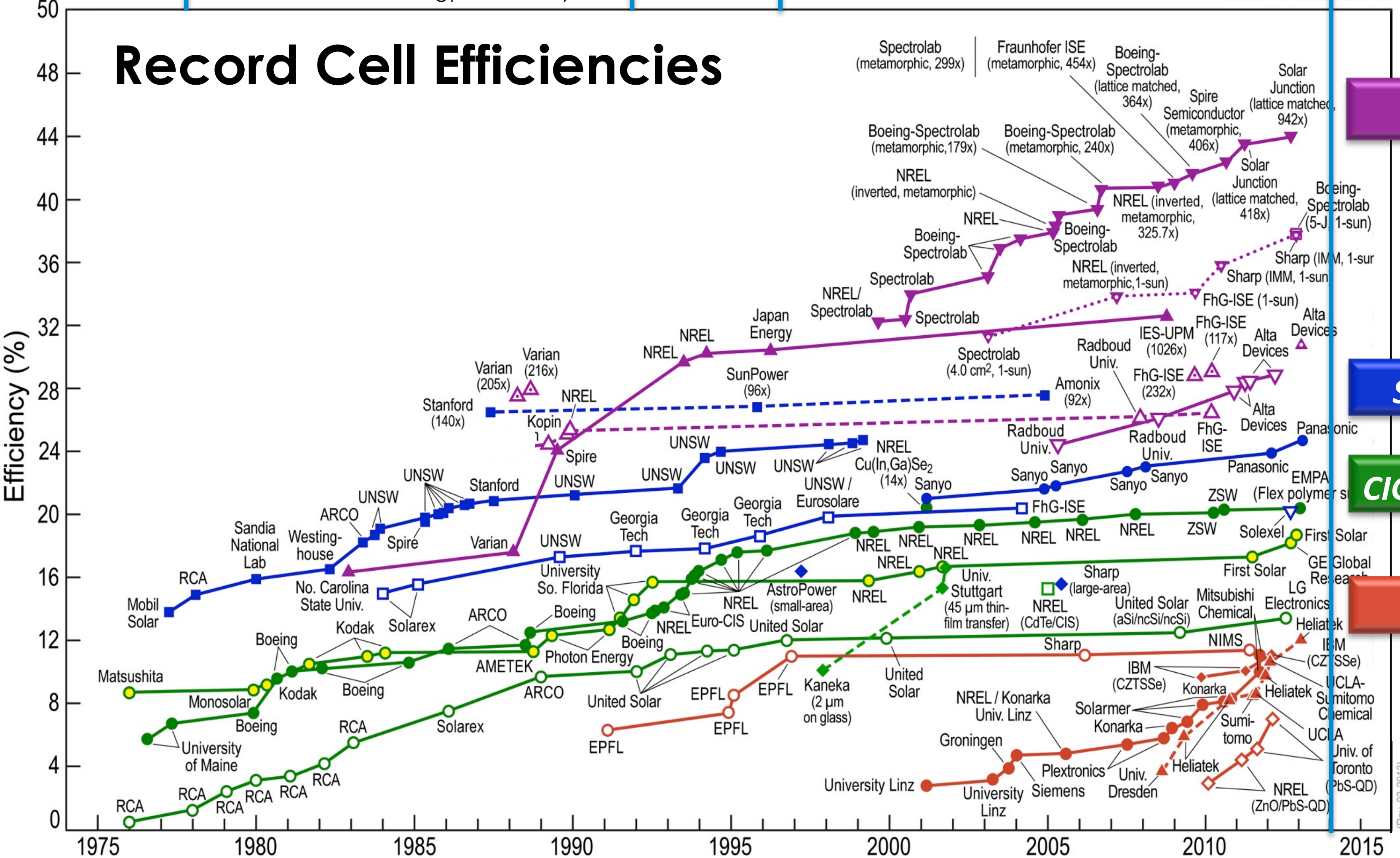
SERI → NREL (NATIONAL RENEWABLE ENERGY LABORATORY) → NCPV → Today

SERI begins operation

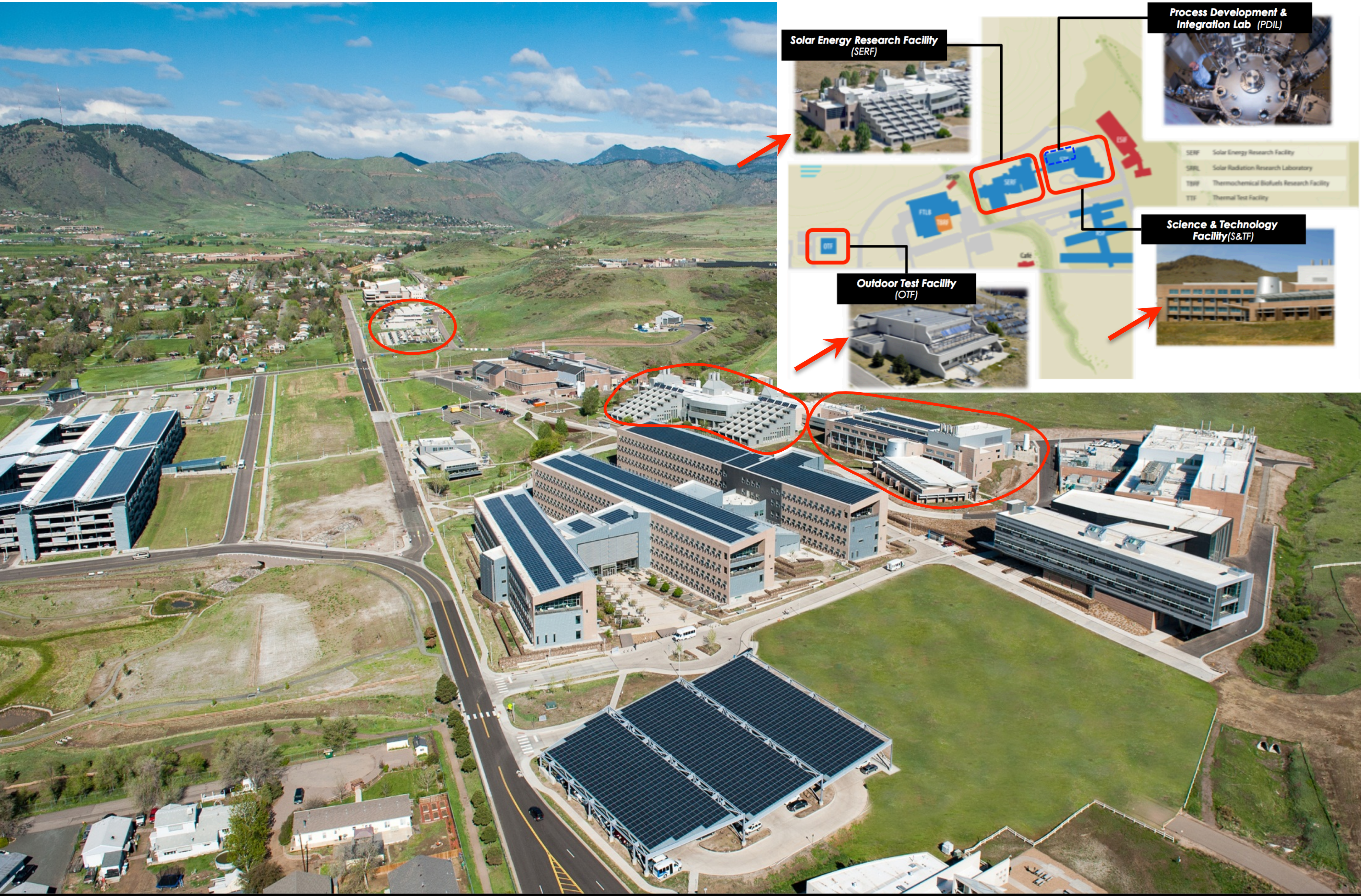
SERI becomes the National Renewable Energy Laboratory

National Center for Photovoltaics (NCPV) is established

2014



NREL and the NCPV Today



NCPV Competencies

National Center for Photovoltaics (NCPV)

PV Technologies

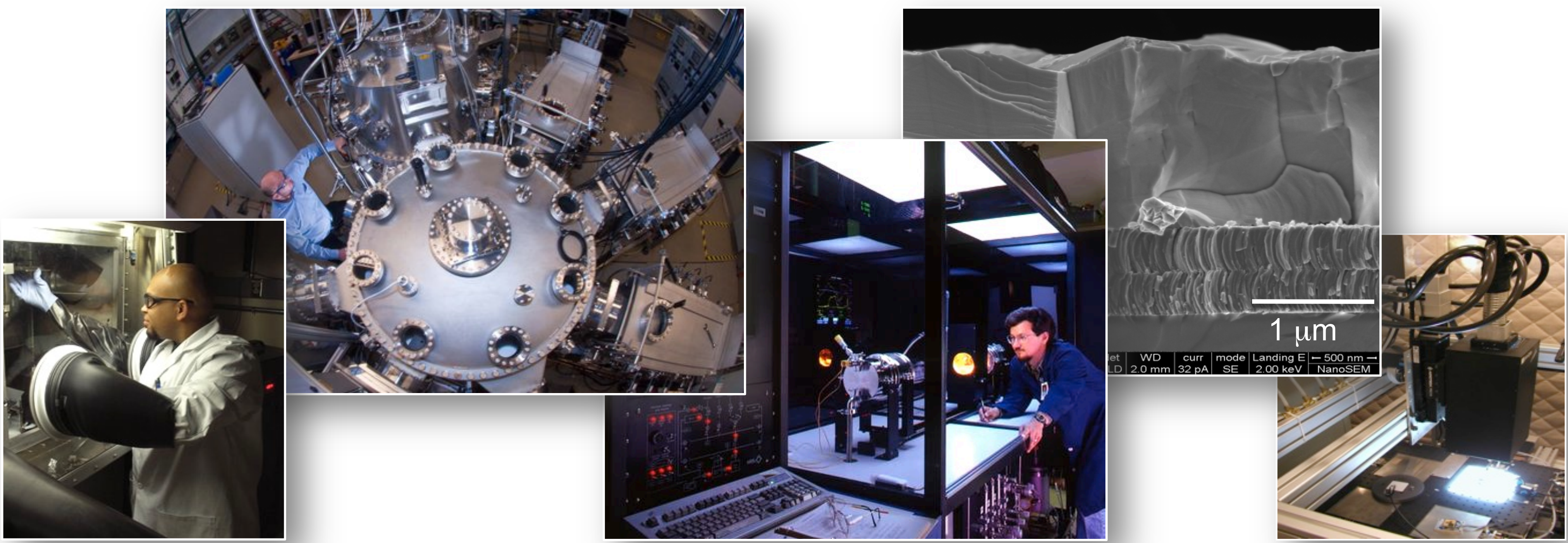
- Thin Film PV — CIGS / CdTe /CZTS/Novel
- III-V — MJ & 1J
- Silicon
- OPV/TCO

PV Cross-Cutting R&D

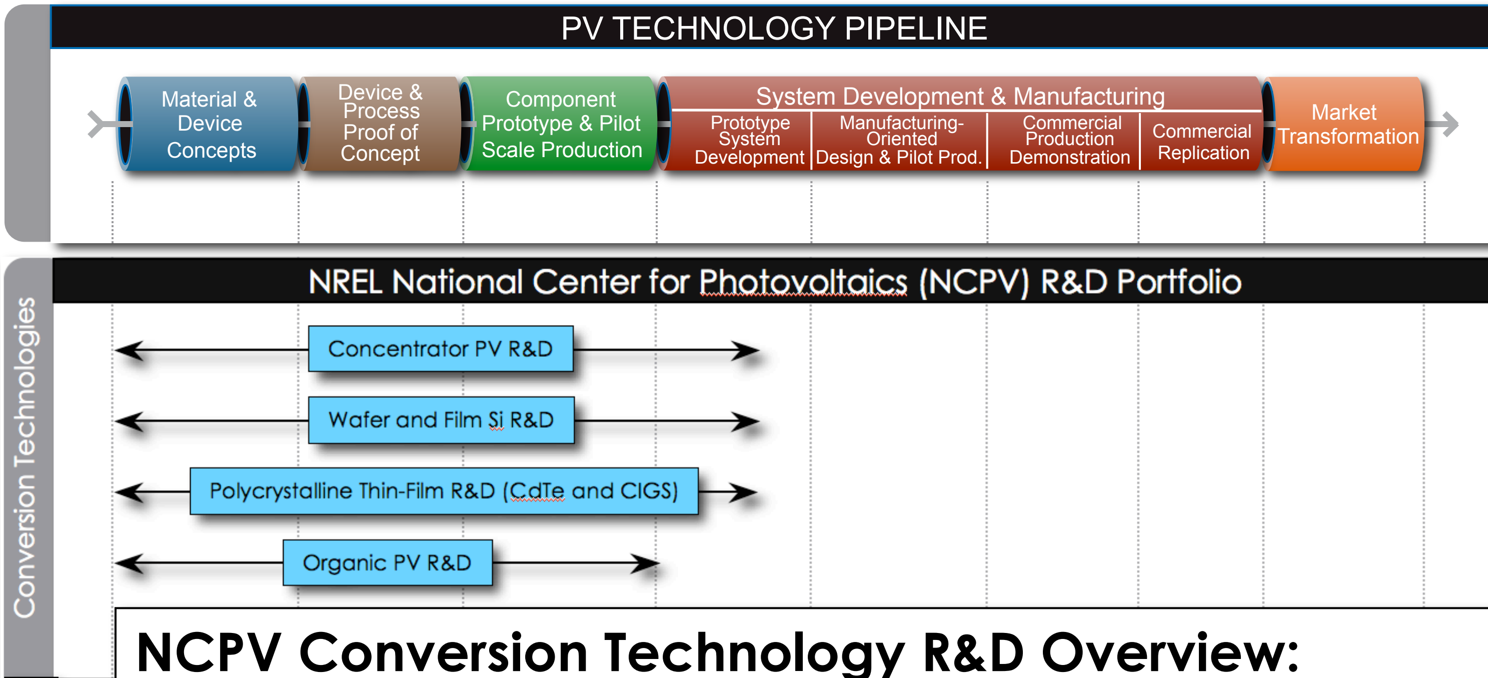
- Measurements & Characterization
- Module Reliability & Systems Engineering

Extensive Capabilities and PV Experience Under One Roof

Material Synthesis • Device Processing • Device Design • Device Modeling • Measurements & Characterization • A Highly Trained Technical Staff



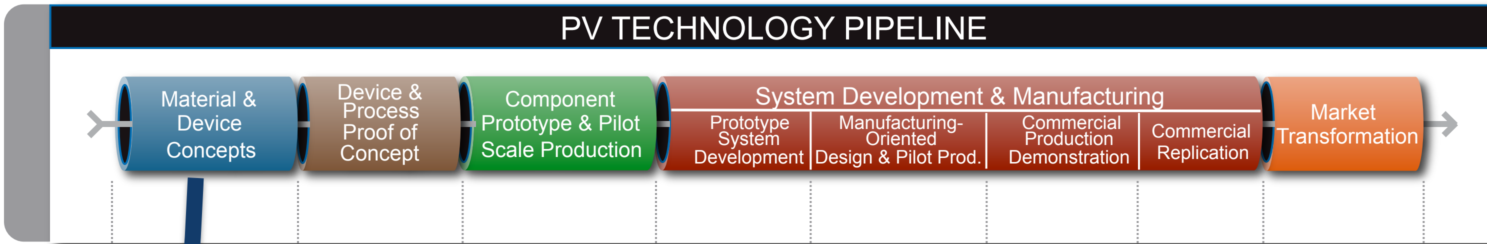
NCPV Conversion Technology R&D Portfolio



NCPV Conversion Technology R&D Overview:

- III-V Multijunction — Demonstrate > 50% 4J device
- Wafer Si Tandem — Demonstrate > 30% 2J device on cSi wafer
- CdTe — Fundamental CdTe materials questions ⇒ Enable >16% HVM module
- CIGS — Fundamental CIS materials questions ⇒ Enable >16% HVM module
- Organic PV (OPV) — Build on BES program, demonstrate commercial viability

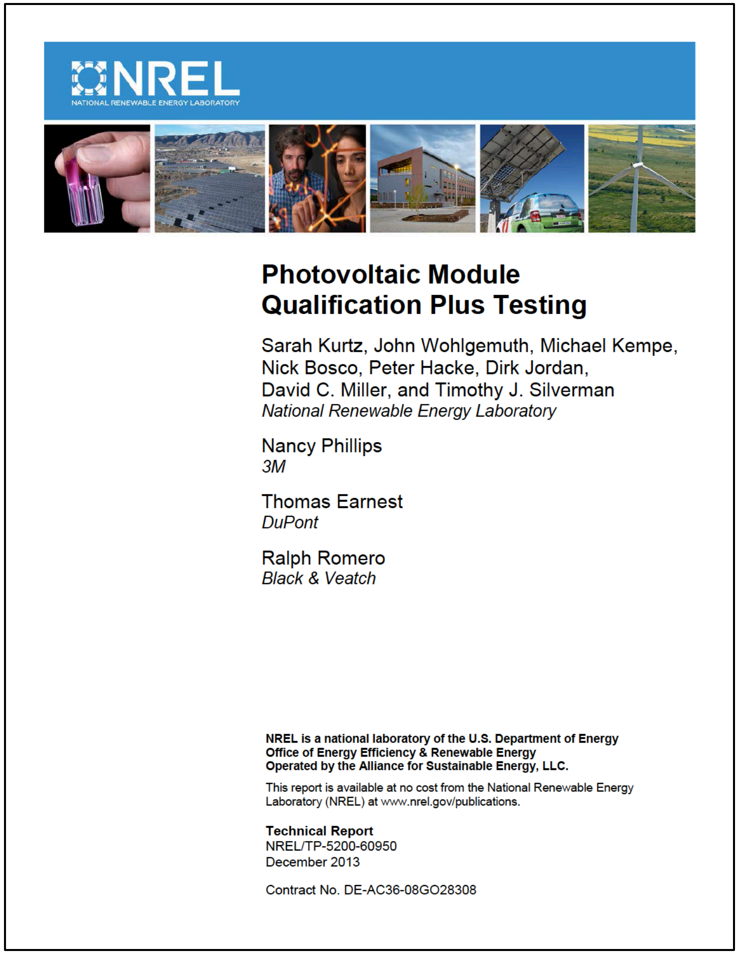
NCPV Research Portfolio



Other NCPV Research Areas:

- CZTS — More fundamental materials questions, demonstrate commercial viability
- III-V 1J via HVPE — Develop route to low-cost, 1-sun III-V cells
- Novel PV Absorbers — Build on Inverse Design EFRC, identify new PV absorbers
- Novel TCOs — Build on Inverse Design EFRC, identify new TCOs

PV Reliability


NATIONAL RENEWABLE ENERGY LABORATORY

Photovoltaic Module Qualification Plus Testing

Sarah Kurtz, John Wohlgemuth, Michael Kempe, Nick Bosco, Peter Hacke, Dirk Jordan, David C. Miller, and Timothy J. Silverman
National Renewable Energy Laboratory

Nancy Phillips
3M

Thomas Earnest
DuPont

Ralph Romero
Black & Veatch

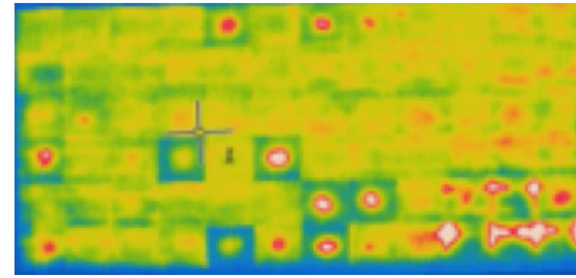
NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

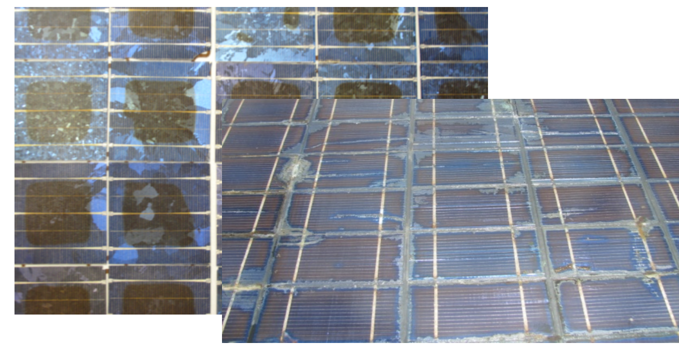
Technical Report
NREL/TP-5200-60950
December 2013

Contract No. DE-AC36-08GO28308

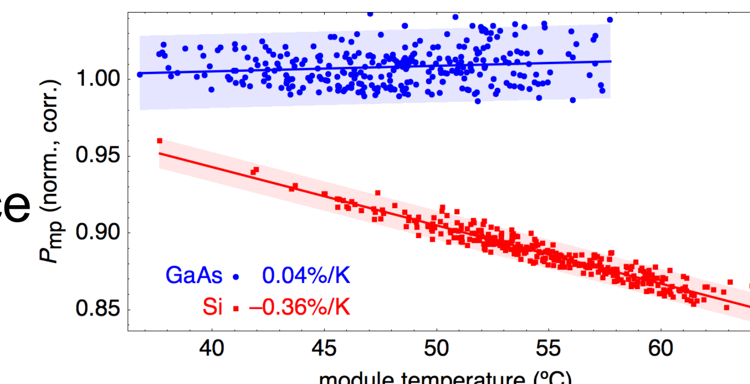
Potential Induced Degradation



Encapsulant & Edge Seal Durability



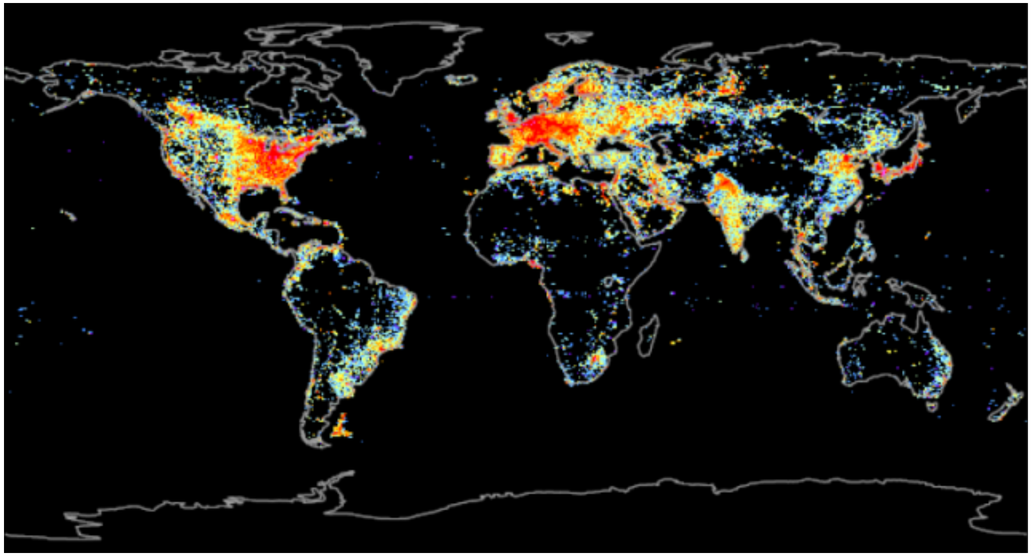
Module Performance

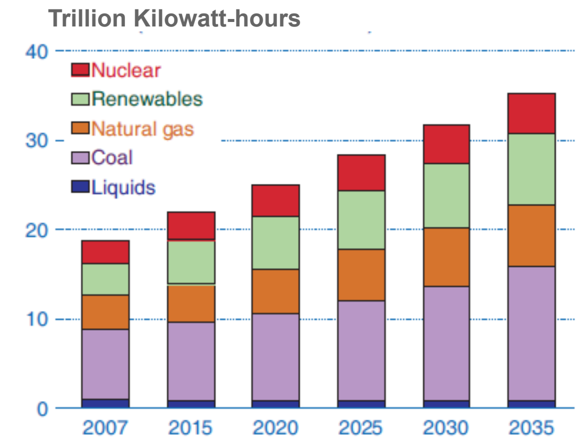


Many other projects:

http://www.nrel.gov/pv/performance_reliability/publications.html

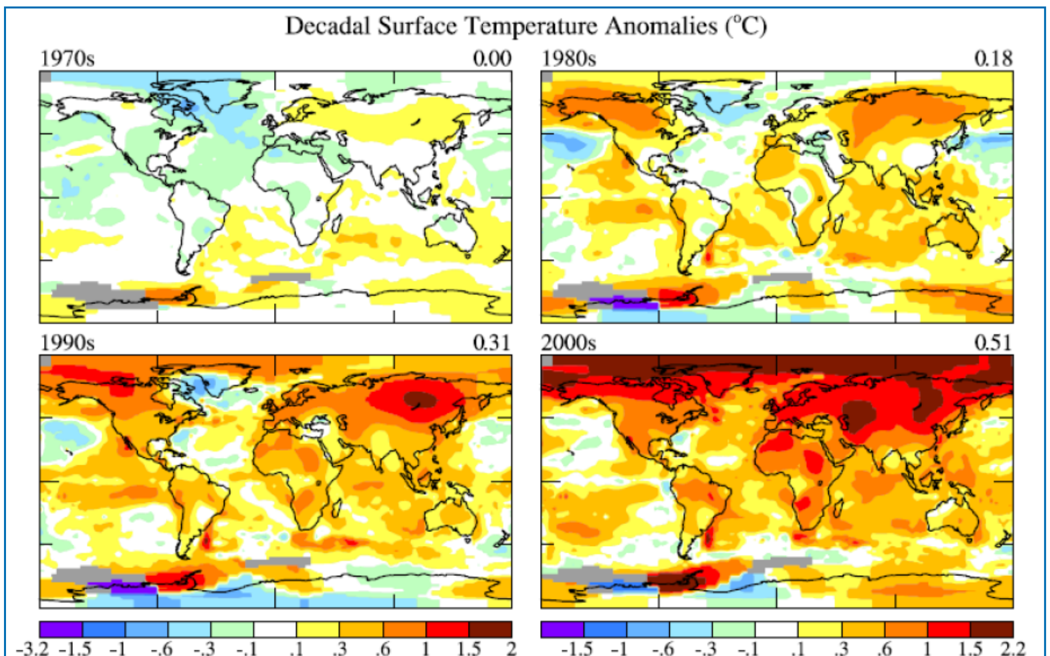
Motivation is Clear – Energy Needs vs. CO_2

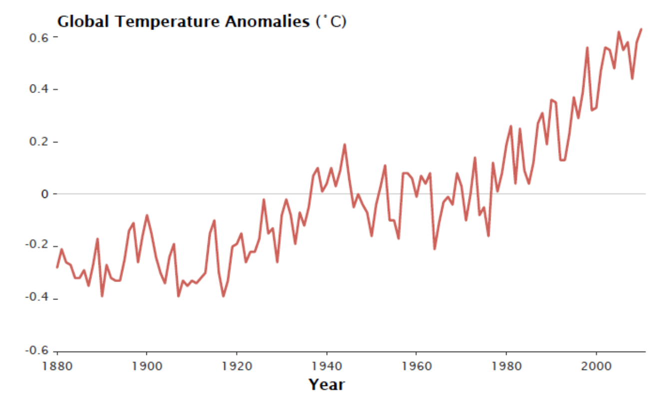




Source: 2010 DOE-EIA International Energy Outlook

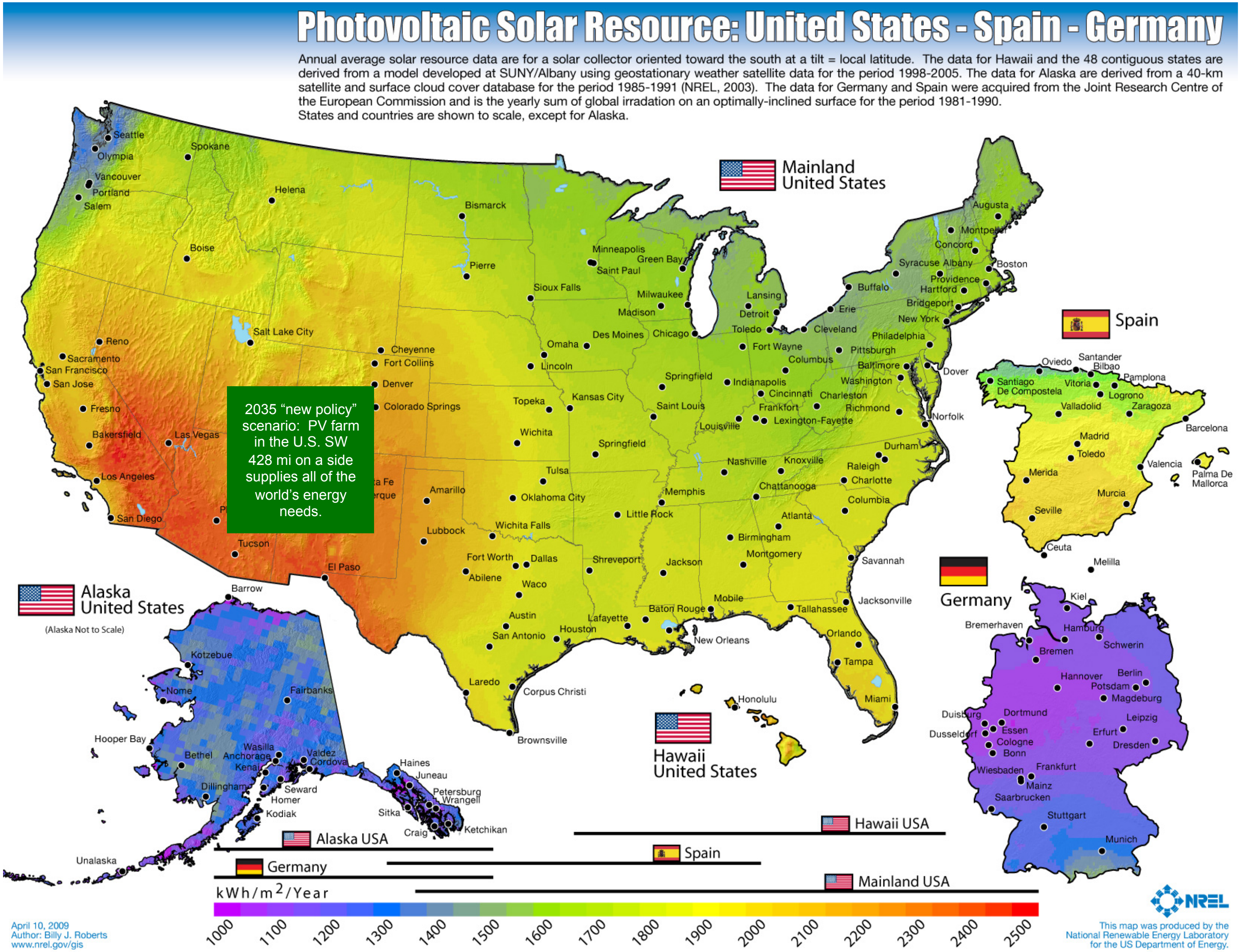
- ~21 trillion kWhrs of electricity, ~2/3 from fossil fuels.
- Earth at 400ppm CO_2.



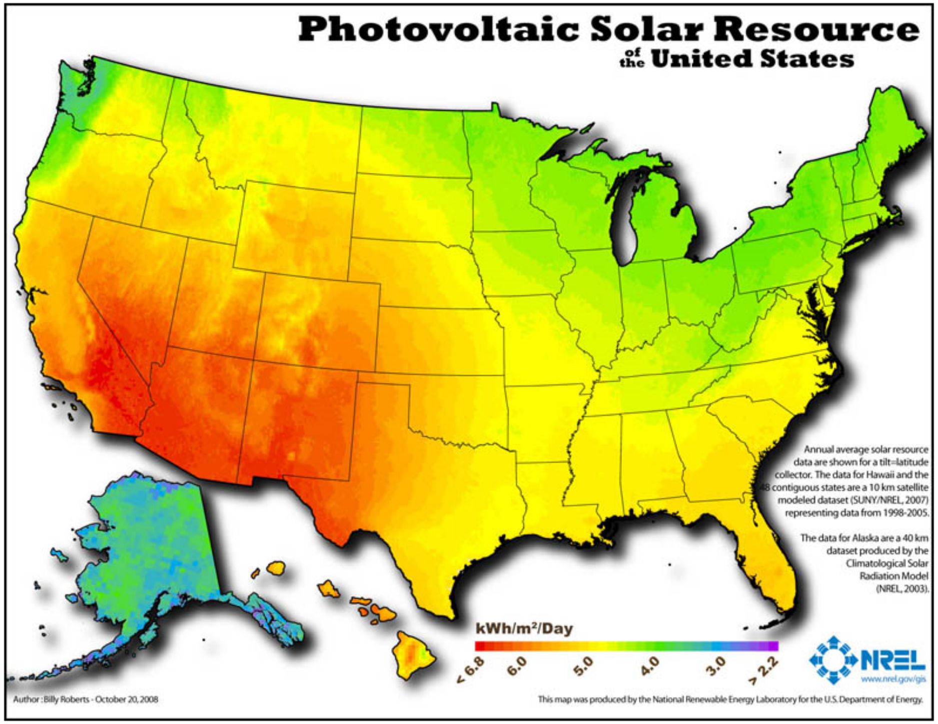


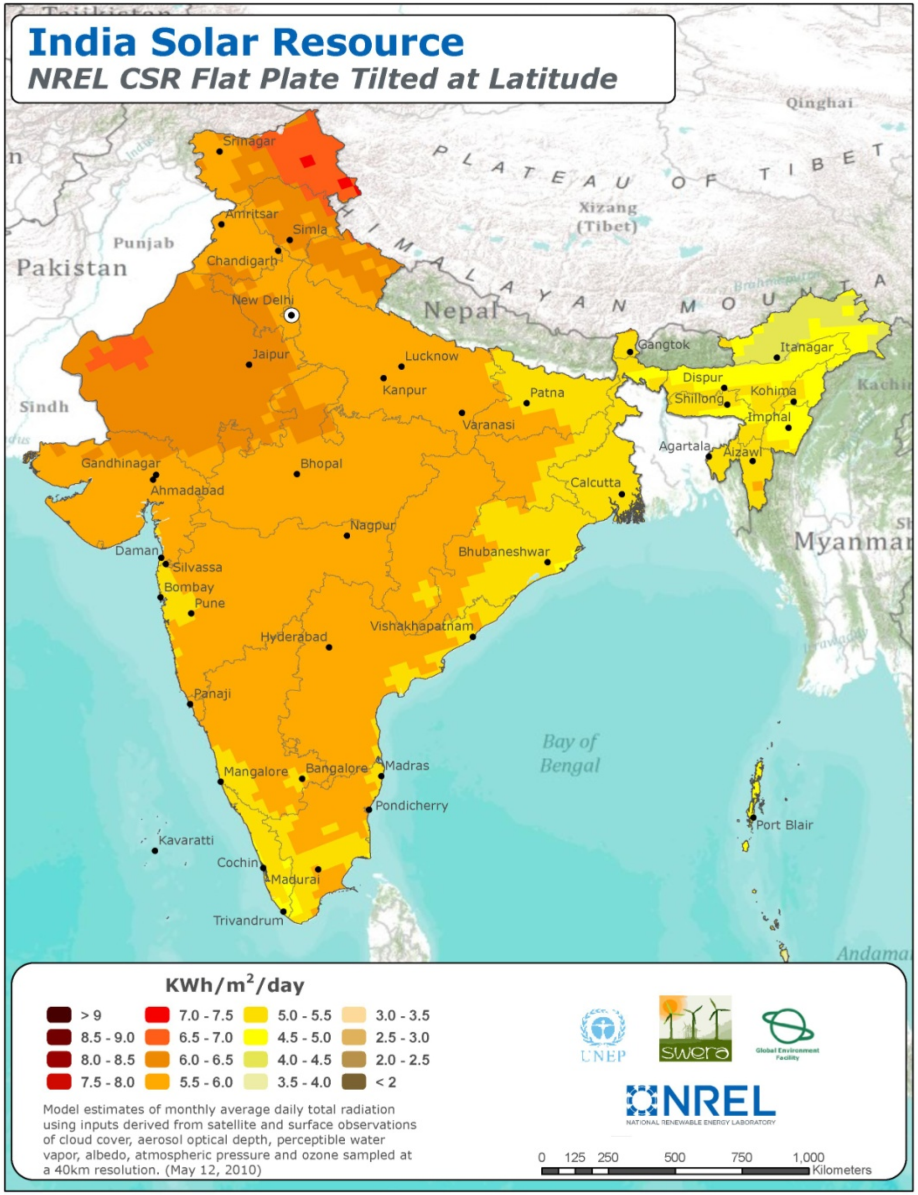
Source: NASA-GISS

PV Energy for Planet Earth in 2035

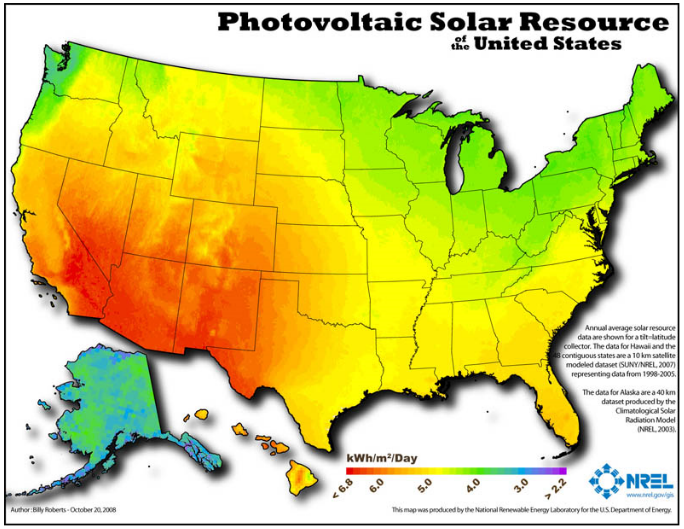


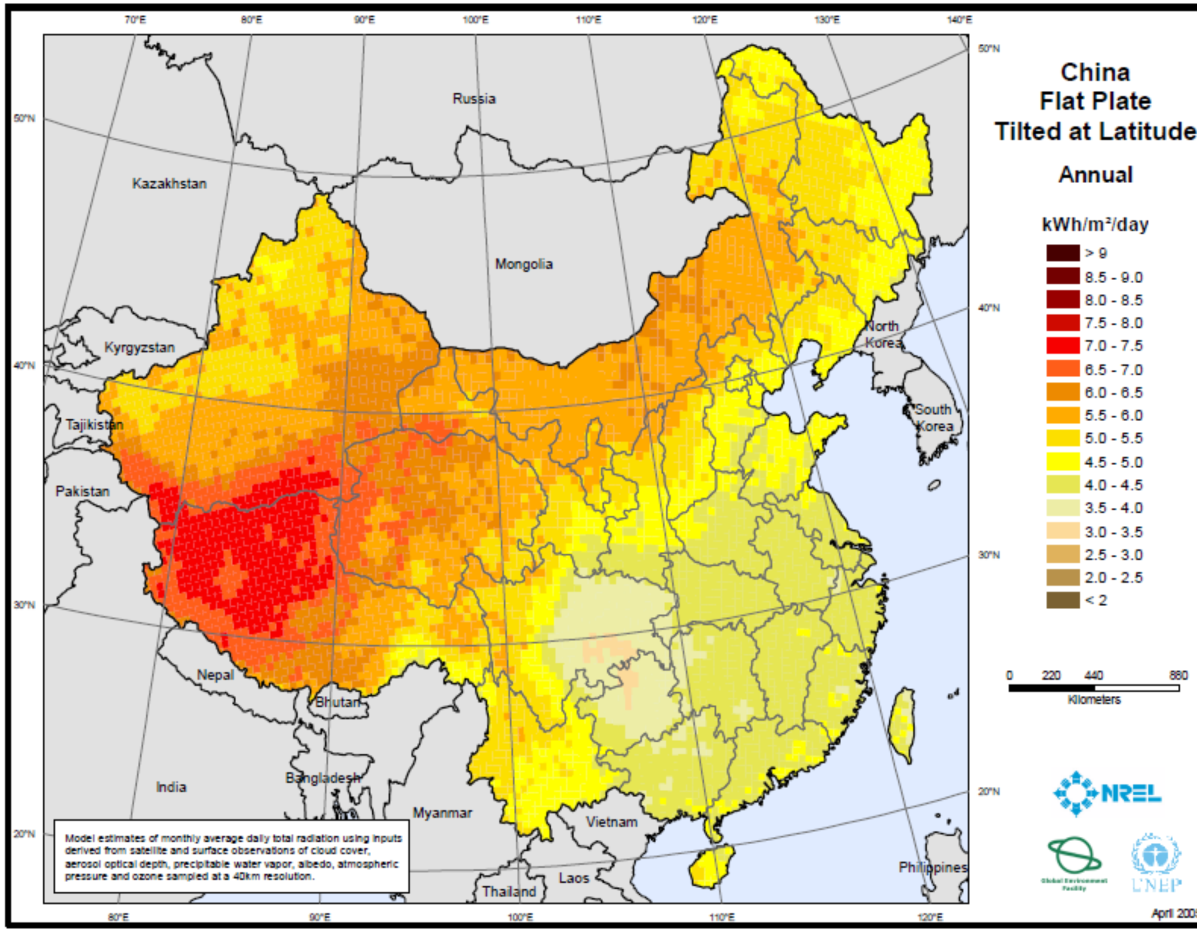
Solar Insolation – U.S. vs. India



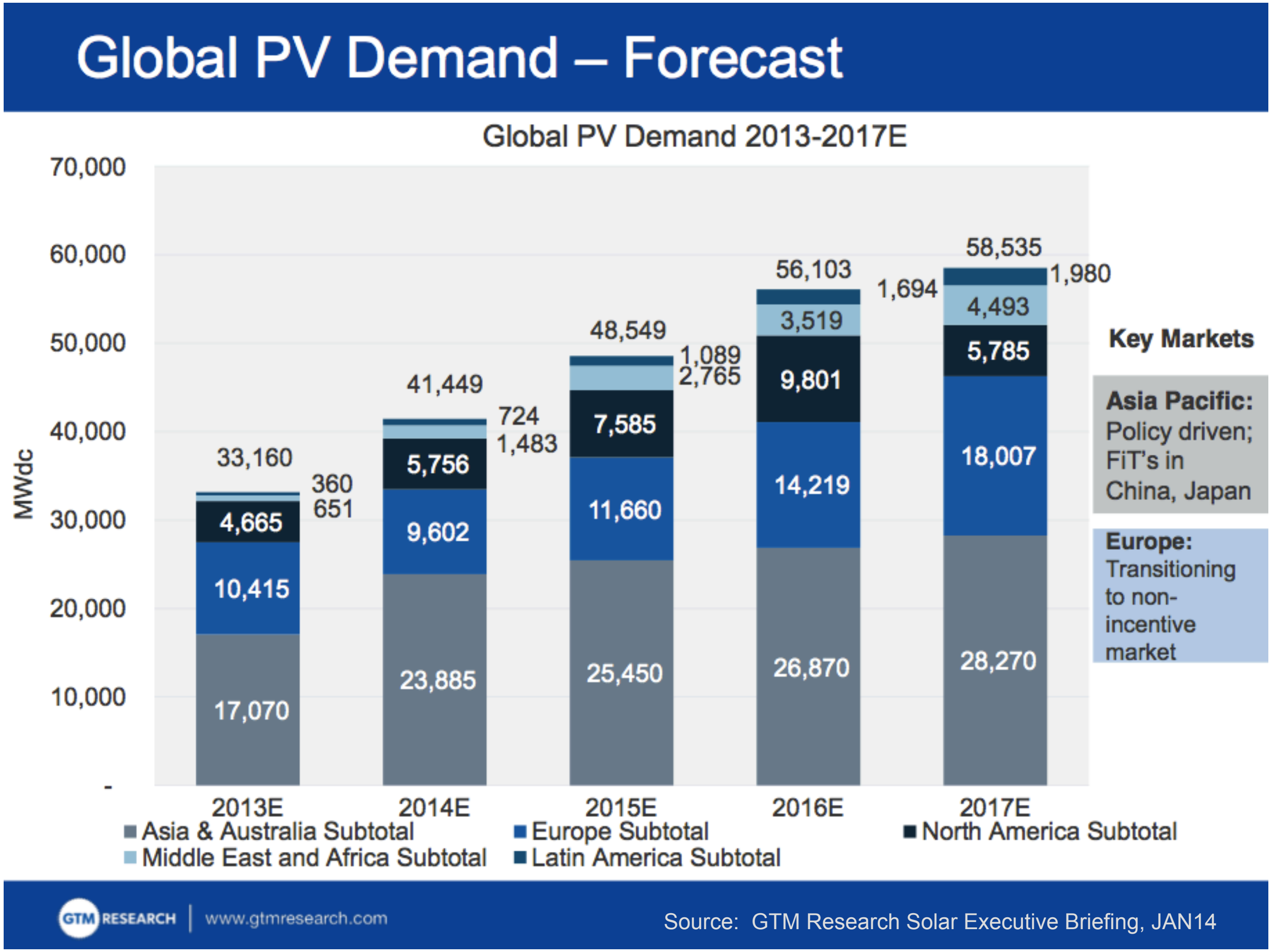


Solar Insolation – U.S. vs. China





Global PV Demand Forecast



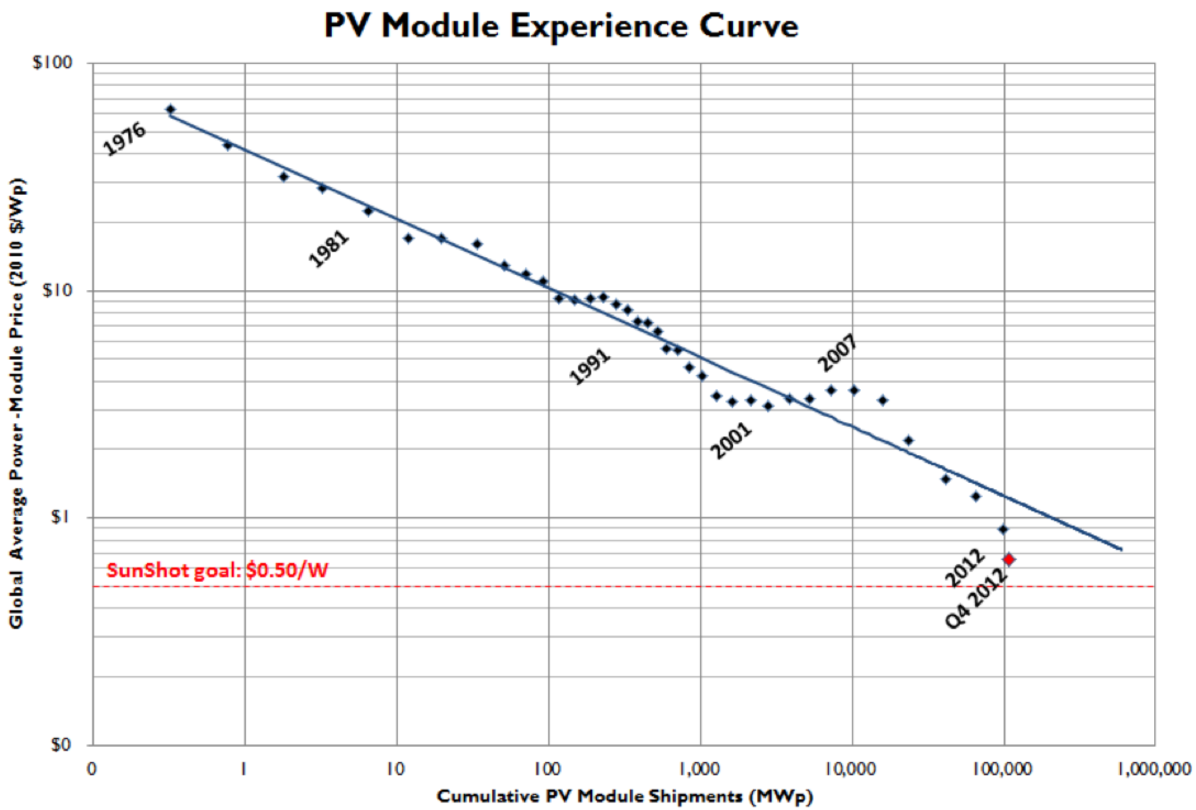
Reality – Small PV Contribution in 2035

	Electrical capacity (GW)					Shares (%)		CAAGR (%)
	2011	2020	2025	2030	2035	2011	2035	2011-2035
	New Policies Scenario					NPS	NPS	NPS
Total capacity	**5 456**	**7 308**	**8 121**	**8 922**	**9 760**	**100**	**100**	**2.5**
Coal	1 739	2 147	2 264	2 393	2 503	32	26	1.5
Oil	439	362	317	288	274	8	3	-1.9
Gas	1 414	1 854	2 058	2 247	2 462	26	25	2.3
Nuclear	391	471	512	545	578	7	6	1.6
Hydro	1 060	1 361	1 493	1 617	1 731	19	18	2.1
Bioenergy	93	154	190	226	266	2	3	4.5
Wind	238	612	797	960	1 130	4	12	6.7
Geothermal	11	19	27	35	43	0	0	5.9
Solar PV	69	312	437	564	690	1	7	10.1
CSP	2	14	23	40	70	0	1	16.7
Marine	1	1	3	6	14	0	0	14.7

Source: IEA WEO 2013

- Although PV growth rate will remain high, it is projected to only be 7% of global electrical generating capacity under the IEA's New Policies Scenario.
- To reach its potential as the "biggest renewable energy generator", several problems still need to be solved…
    - Total system cost – Need SunShot target, LCOE of 6¢/kWh
    - Intermittency – Both storage and optimized PV grid integration
    - TW Scaling Barriers – Capital, materials availability, energy payback time

History – Module Cost



Learning curve factors from 1980-2001 (Nemet 2006):

- Plant size
- Efficiency
- Silicon cost

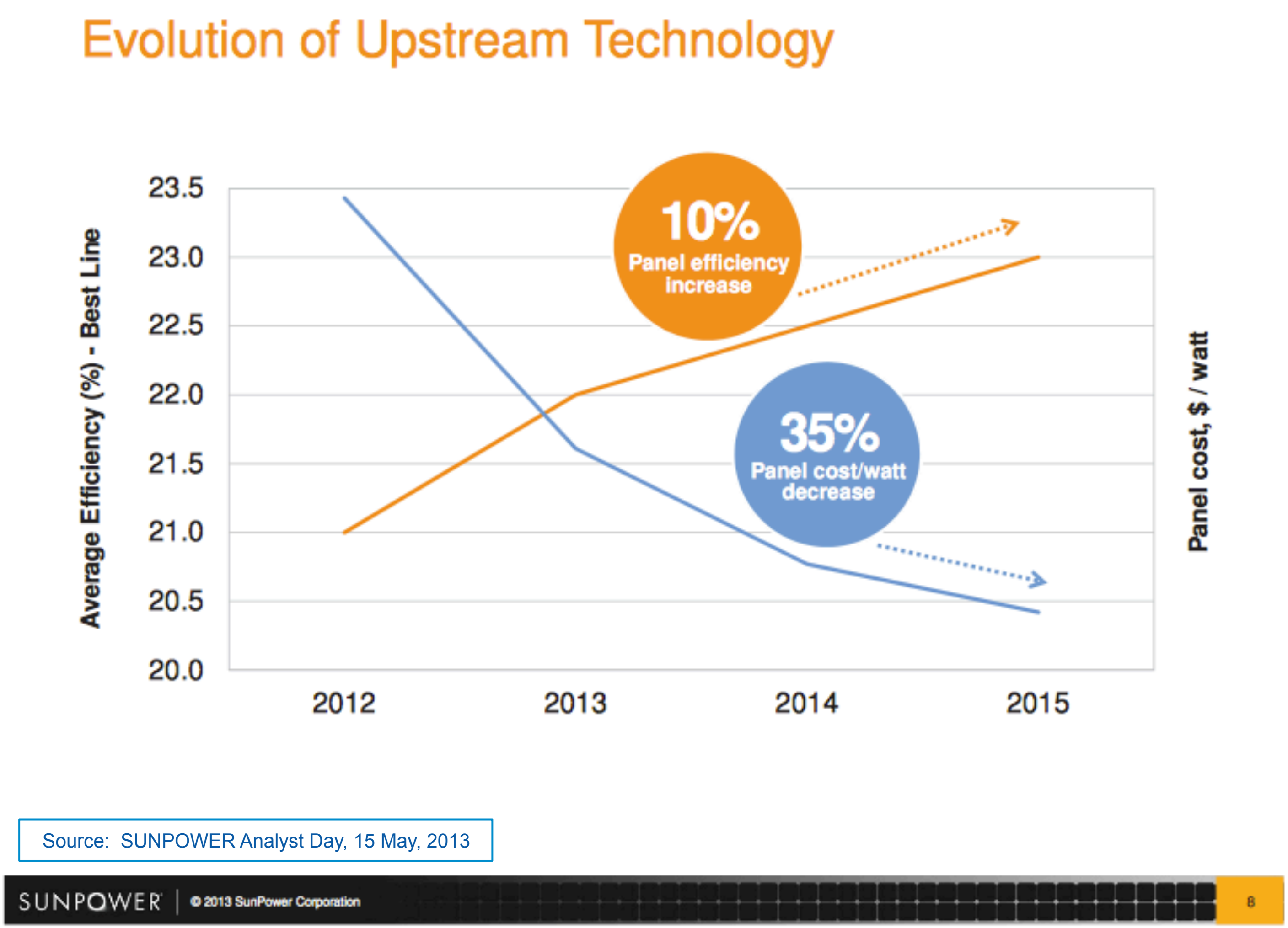
Proposed LC factors since 2006:

- Plant size
- Regionalization
- Silicon cost
- Margin compression
- Conversion efficiency

Are future gains of diminishing returns?

Sources: For 2012:SPV Market Research, Q4 2012 PV Technology Price Update (Dec. 2012). For 2011: Navigant Consulting (2012), Photovoltaic Manufacturer Shipments, Capacity & Competitive Analysis 2011/2012, Report NPS-Supply7 (April 2012). For 1984-2009: Navigant Consulting (2010), Photovoltaic Manufacturer Shipments, Capacity & Competitive Analysis 2009/2010, Report NPS-Supply5 (April 2010). For 1980-1984: Navigant Consulting (2006), Photovoltaic Manufacturer Shipments 2005/2006, Report NPS-Supply1 (August 2006). For 1976-1980: Strategies Unlimited (2003), Photovoltaic Manufacture Shipments and Profiles, 2001-2003, Report SUMPM 53 (September 2003).

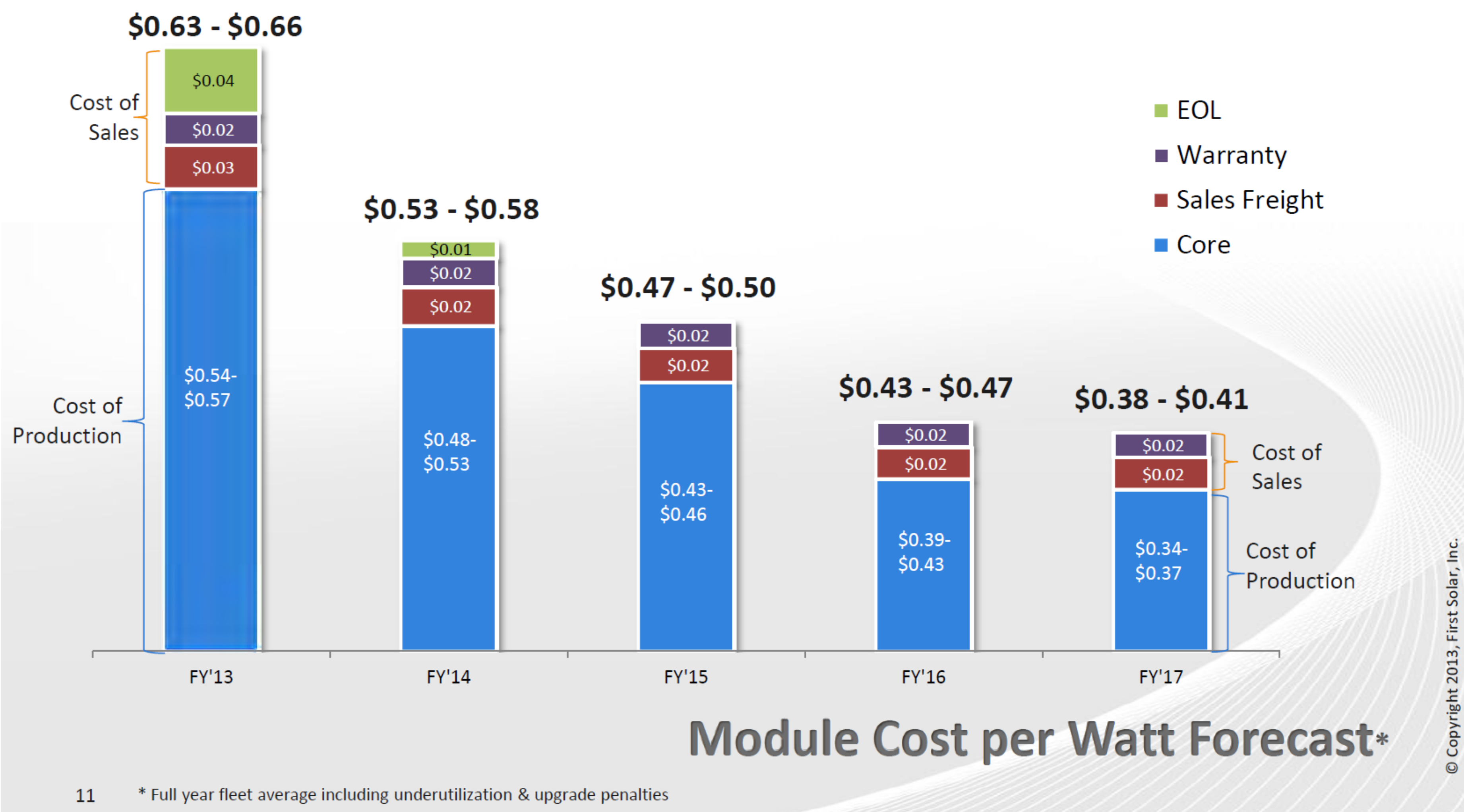
Highest η cSi – SUNPOWER's Roadmap



Source: SUNPOWER Analyst Day, 15 May, 2013

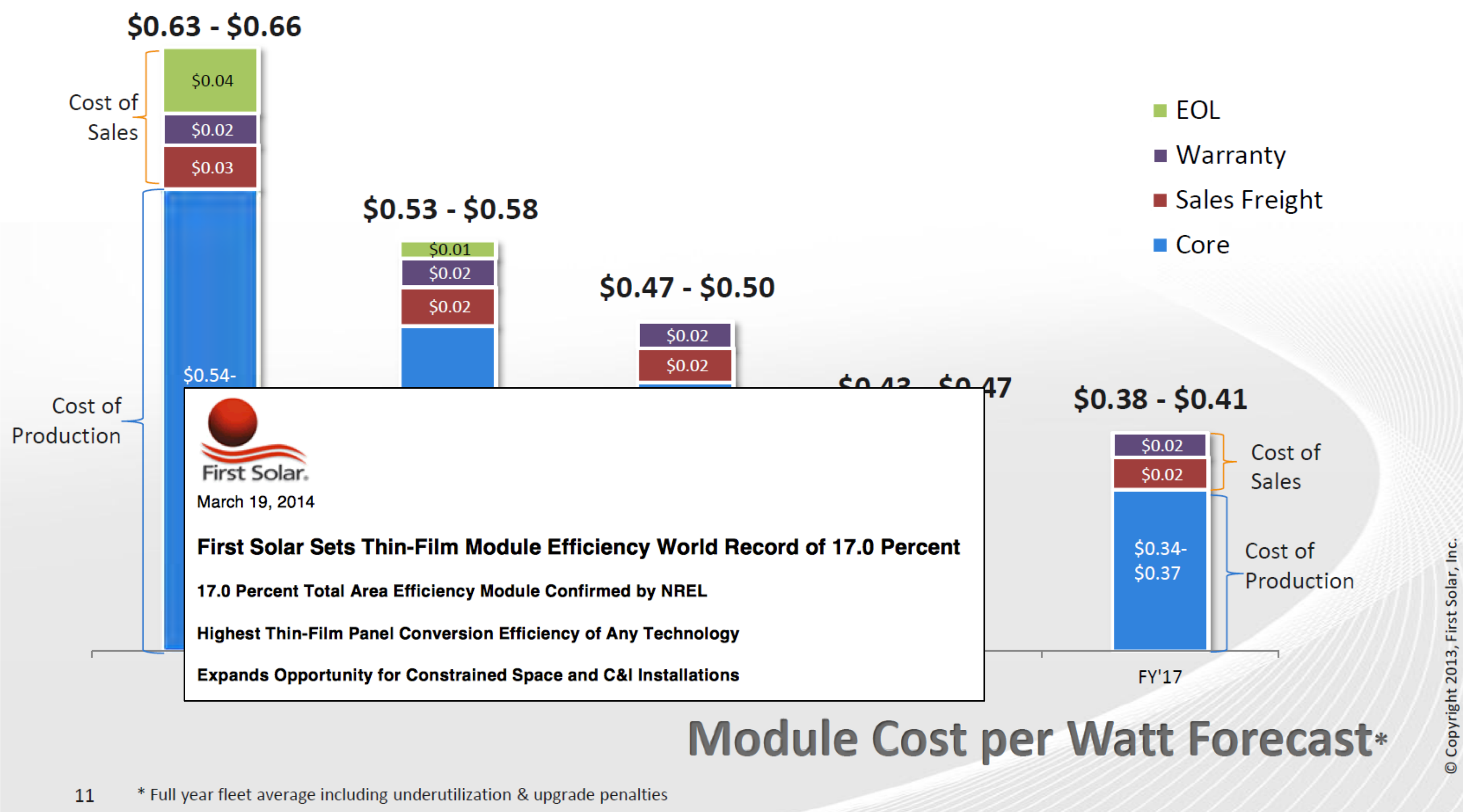
Silicon modules already dominate the PV market with >90% share, upside potential for c-Si cell efficiency remains high.

High η CdTe - First Solar's Roadmap



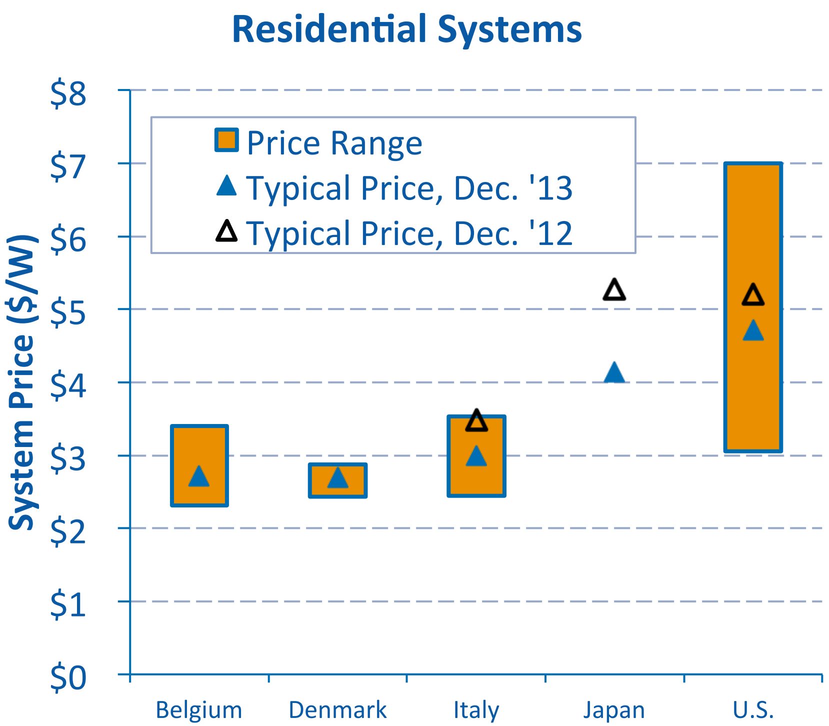
16% modules at SunShot panel cost targets will allow CdTe and CIGS to penetrate traditional mc-Si PV markets.

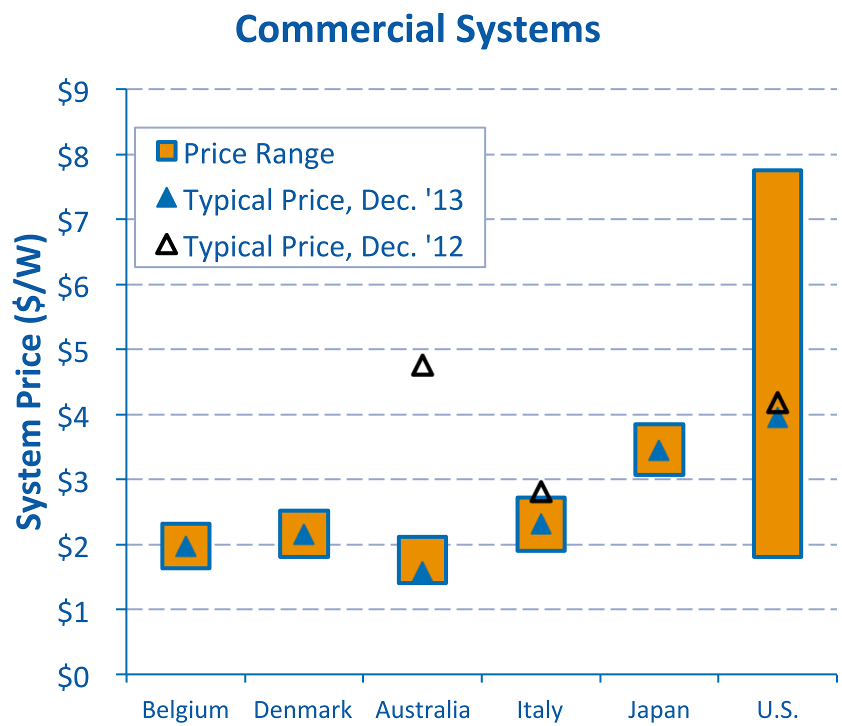
High η CdTe - First Solar's Roadmap



16% modules at SunShot panel cost targets will allow CdTe and CIGS to penetrate traditional mc-Si PV markets.

PV System Price by Country

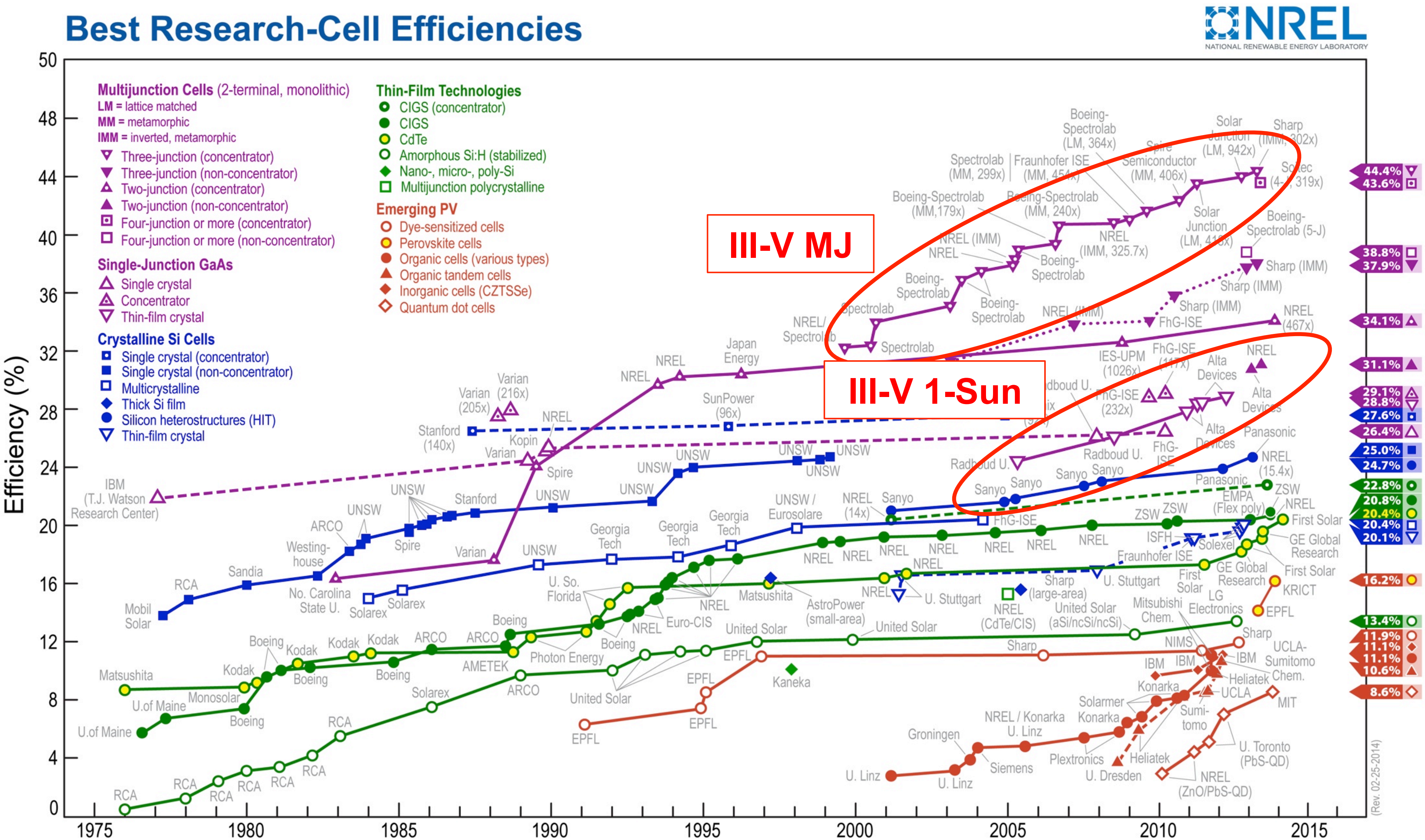




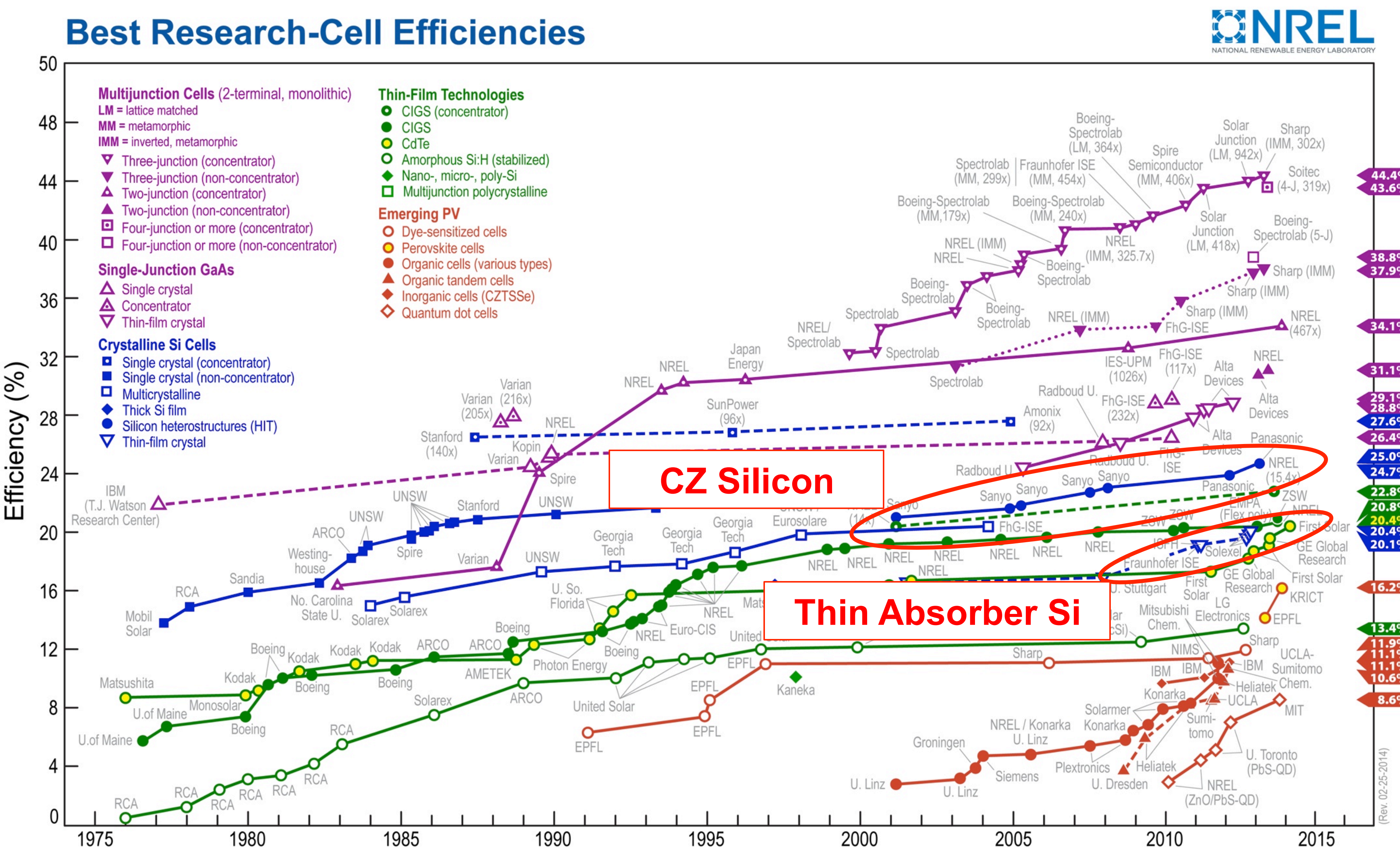
Sources: 2013 (IEA reporting by country, Jan. '14); 2012 (IEA PVPS (01/18/13)).

- Module prices in multiple conversion technologies are on track to hit 2020 targets yet US system costs are substantially higher than other countries.
- Problem is "soft" and BOS costs unique to US market – US DOE now focusing more effort in these areas.
- **PV cell research now becoming more focused on <u>high efficiency</u> plus <u>new processes & materials with still lower cost potential</u>.**

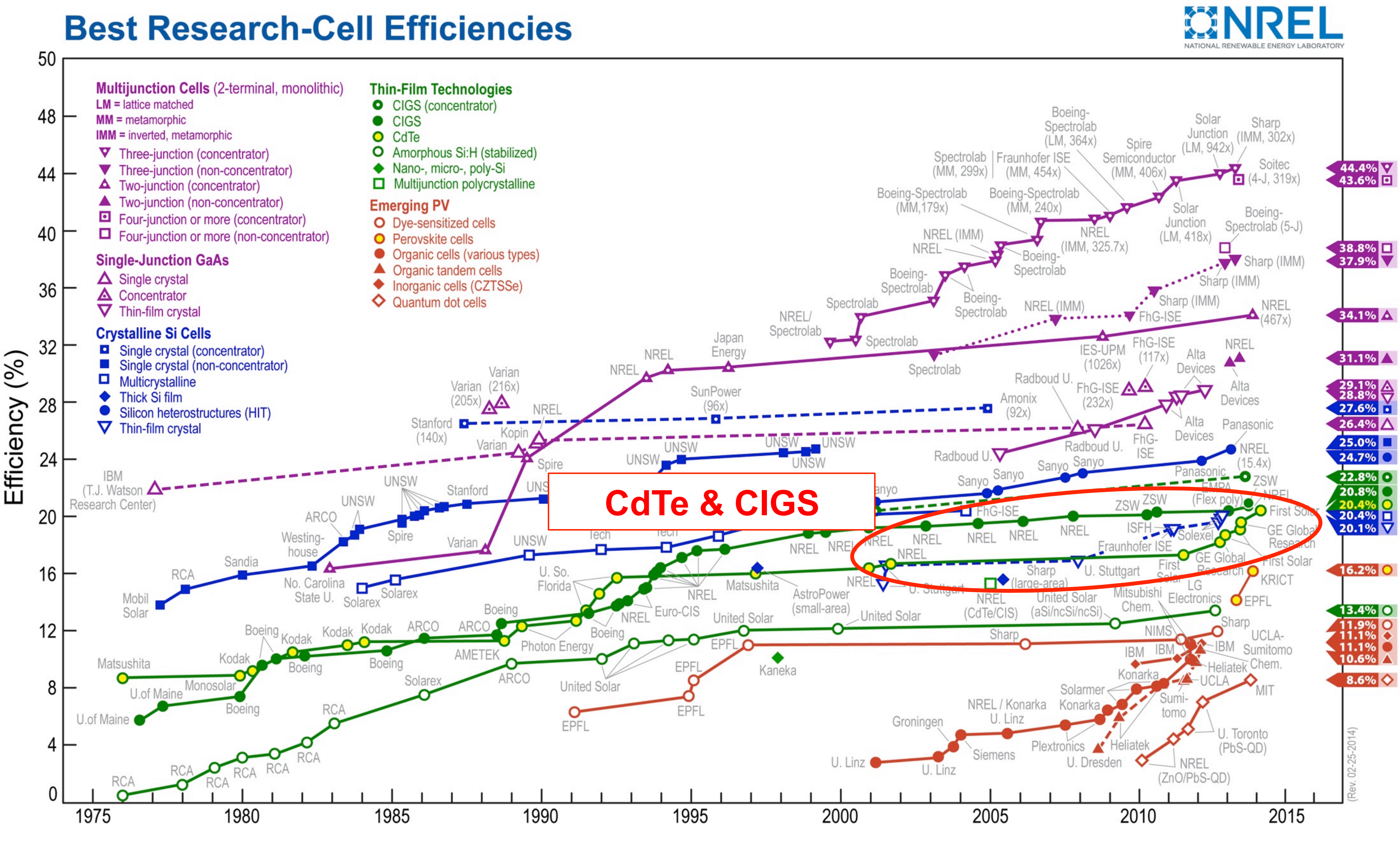
History – Research Cell Efficiency



History – Research Cell Efficiency



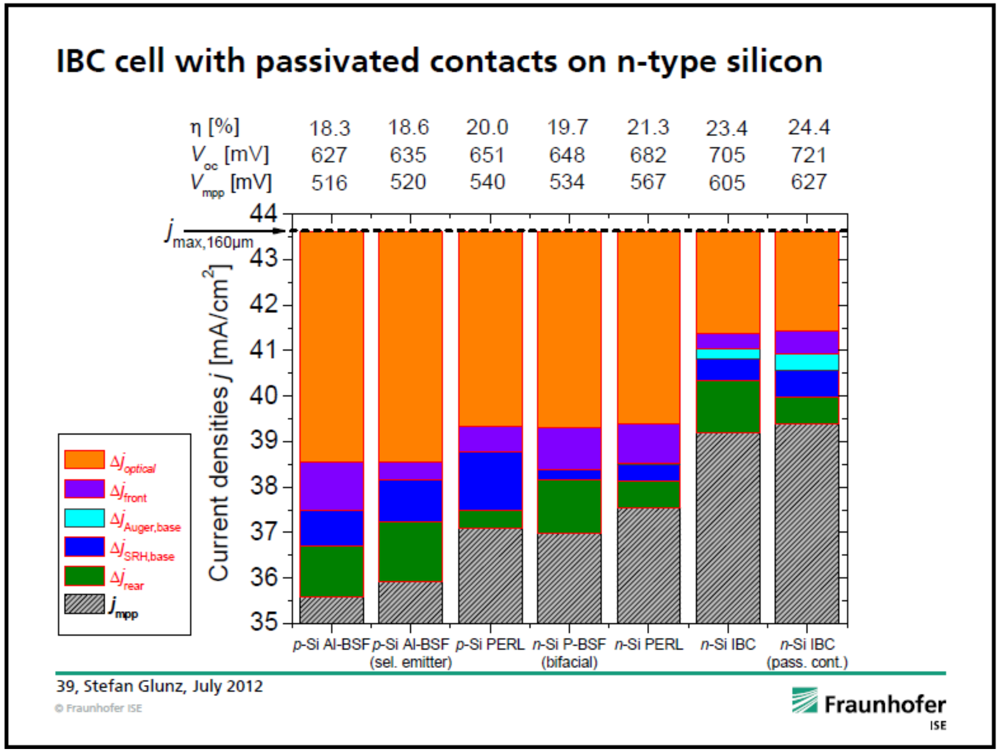
History – Research Cell Efficiency



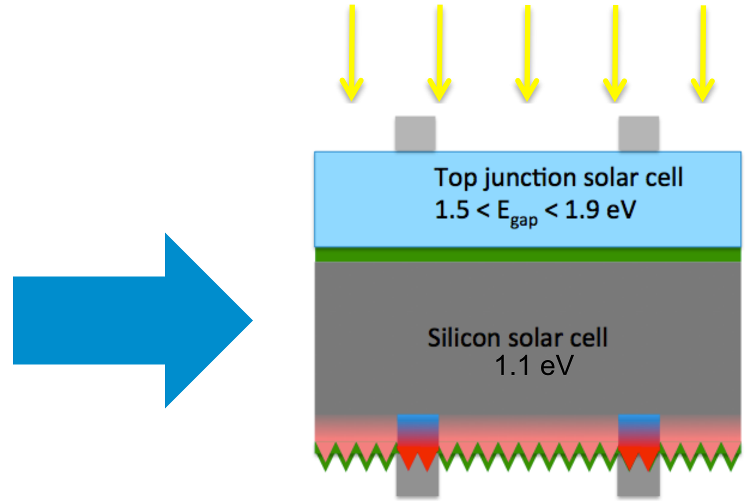
Important PV Research Fronts

- High Efficiency Thin Films – Improved carrier lifetime and development of doping techniques will boost commercial module efficiency to 16%.
- Si Tandem Cells – Potential to increase the best cell efficiencies by 10%, to over 30%.
- Low Cost III-V 1J & 2J Cells – Potential to lower III-V growth cost by 1 – 2 orders of magnitude.
- "Kerfless Si" Wafers & Cells – Potential to cut supply chain capital investment by 50% with comparable cell performance.
- Perovskites – Very new polycrystalline thin film technology that has already demonstrated $\eta > 16\%$.

Si Tandem Cells



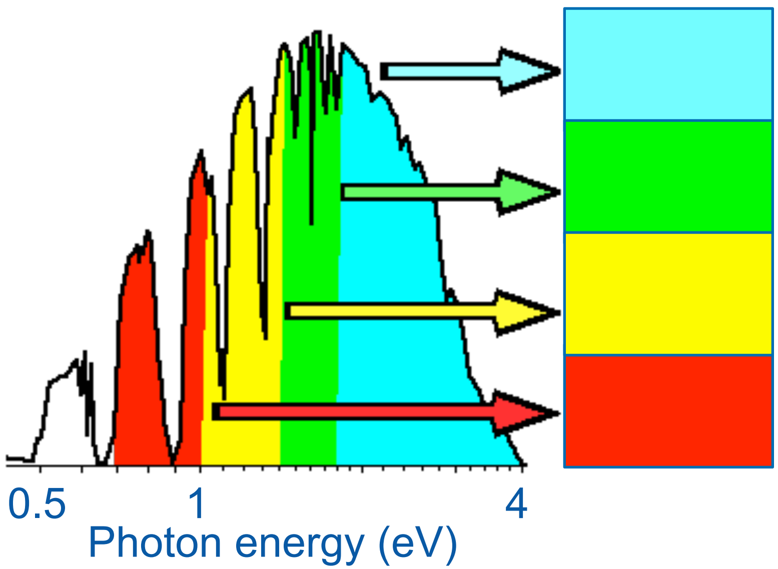
Source: Stefan Glunz presentation, NREL Si Workshop in Vail, CO, July, 2012

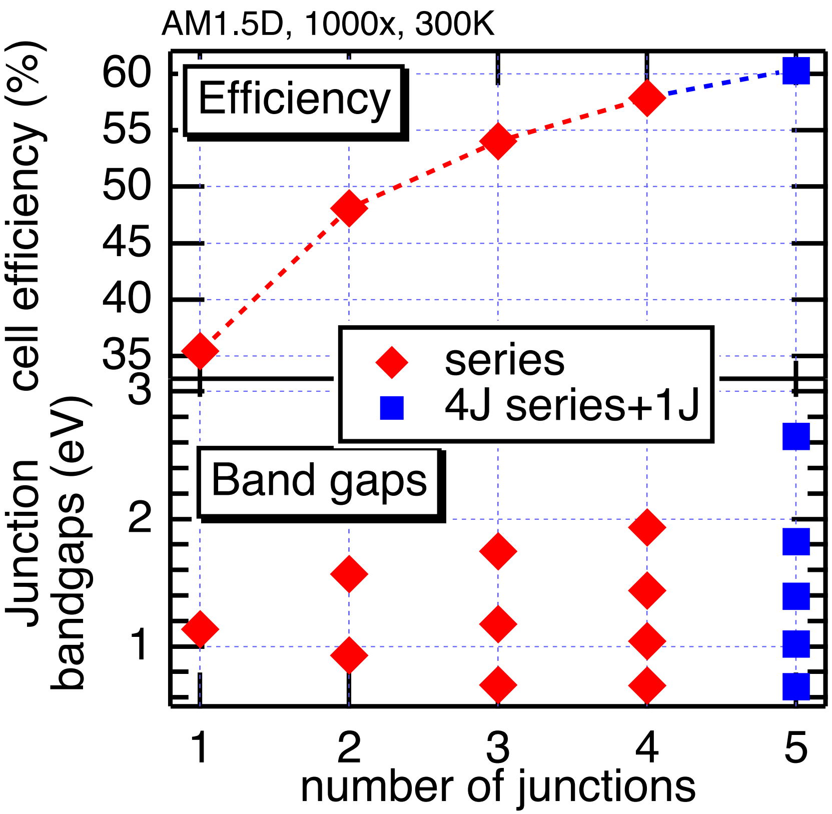


- Path to > 30% efficiency for Si wafer based cells.
- Top cell requirements:
  - Lattice & CTE match to Si
  - Target band gap
  - Top cell optical properties
- Perovskites may evolve into good polycrystalline choice.

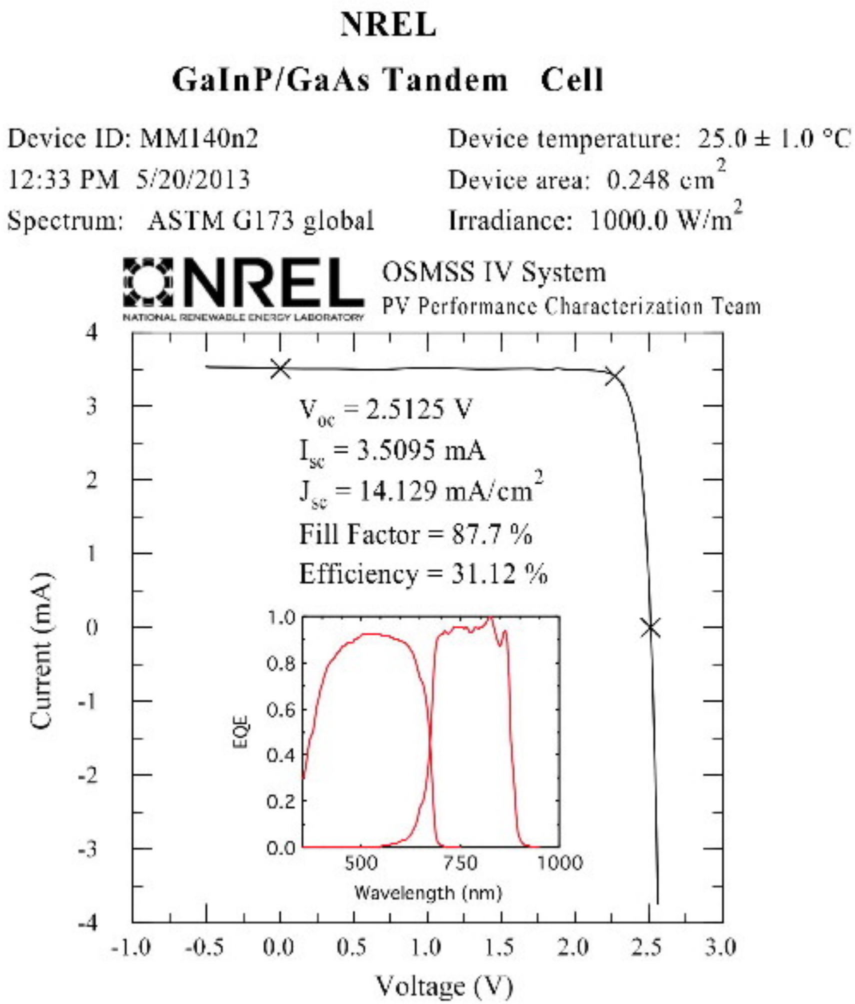
Capturing More Photons - Multijunctions

Multijunctions provide **much** higher efficiencies than conventional cells





GaInP/GaAs Tandem Solar Cell Record



Scientific Achievement

- High internal luminescent efficiency in both junction (GaInP~80% and GaAs ~97%)
- Enhanced photon recycling in GaAs junction due to metal reflector

Significance and Impact

World record efficiency for two-junction cell at one-sun: 31.1%

M.A. Steiner, J.F. Geisz, I. García, D.J. Friedman, A. Duda, W.J. Olavarria, M. Young, D. Kuciauskas, S.R. Kurtz, "Effects of Internal Luminescence and Internal Optics on Voc and Jsc of III-V Solar cells", IEEE J. of Photovoltaics, **3**, 1437 (2013)

Low Cost III-V Absorbers

- MOCVD remains too expensive for high volume 1-sun PV cell/ module production...
  - > Metal-organic precursors are too expensive.
  - > MOCVD growth rates are too low.
- NREL's new reactor…
  - > 100x higher growth rate.
  - > No metal-organic precursors.

⇒ In addition to developing a better III-V deposition technology for PV, the community must also develop a low-cost route for separating epitaxially grown III-V absorbers and re-using the starting wafer.

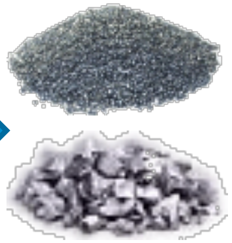
Conventional vs. "Kerfless" Si Cells

Step 1

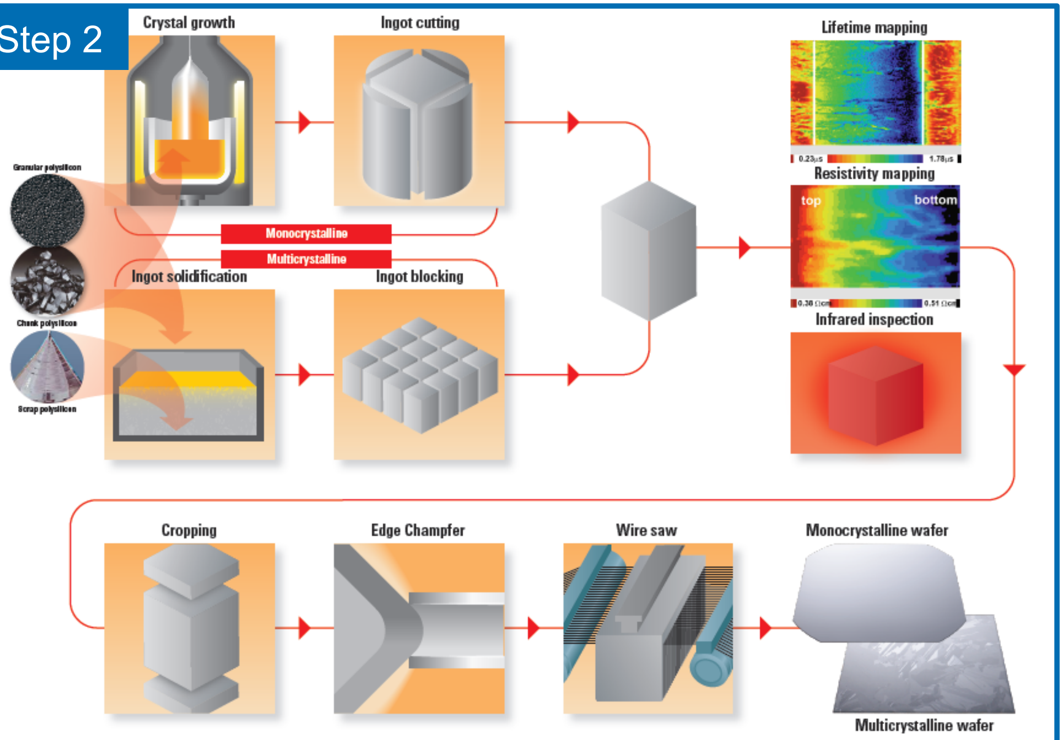
mgSi → HCl →

Conversion of mgSi to chlorosilanes → Purification of desired Si containing gas → Production of ultra pure polysilicon via CVD →

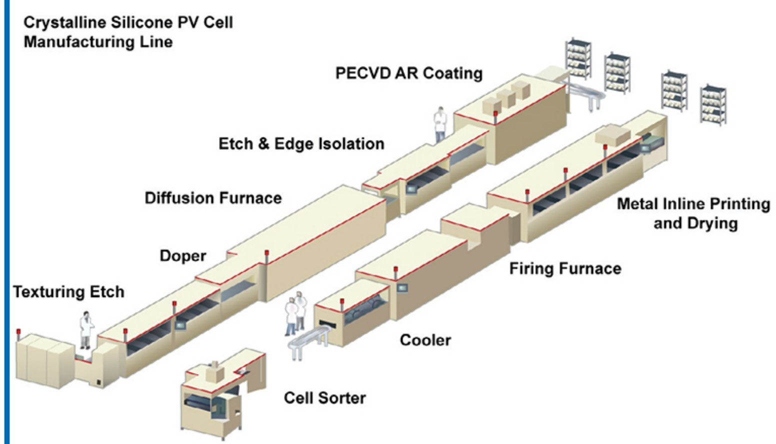
Impurities



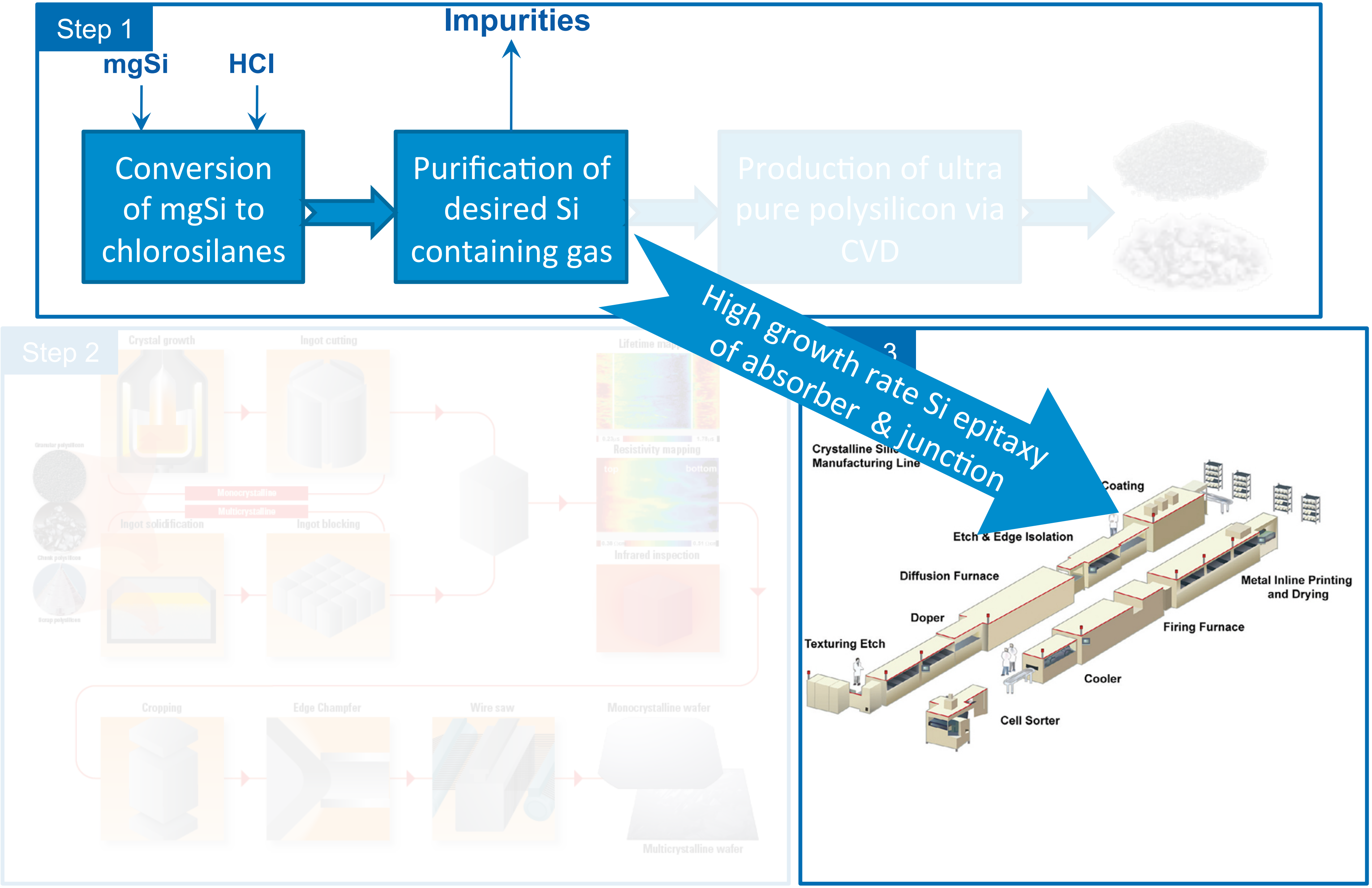
Step 2



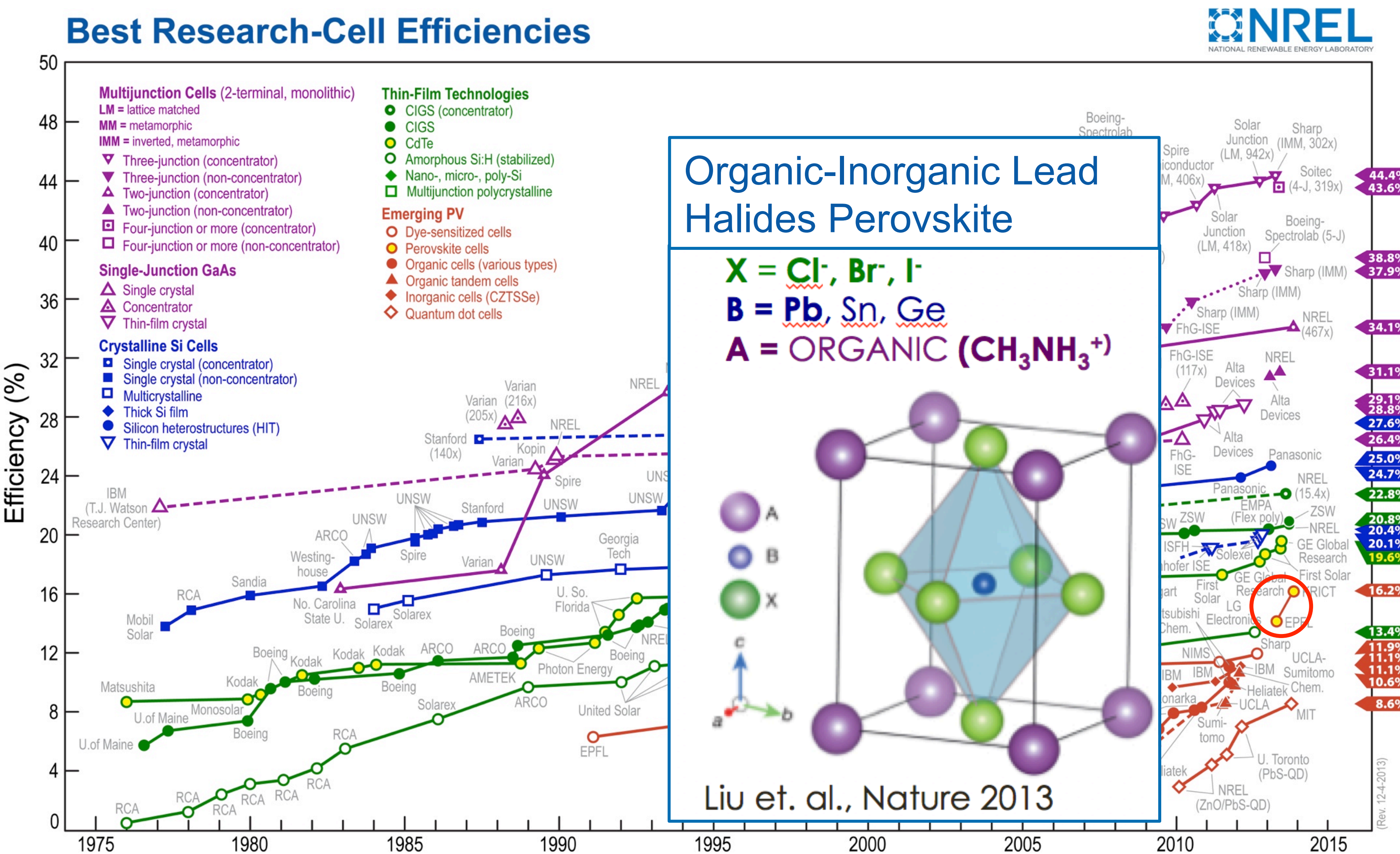
Step 3



Conventional vs. "Kerfless" Si Cells

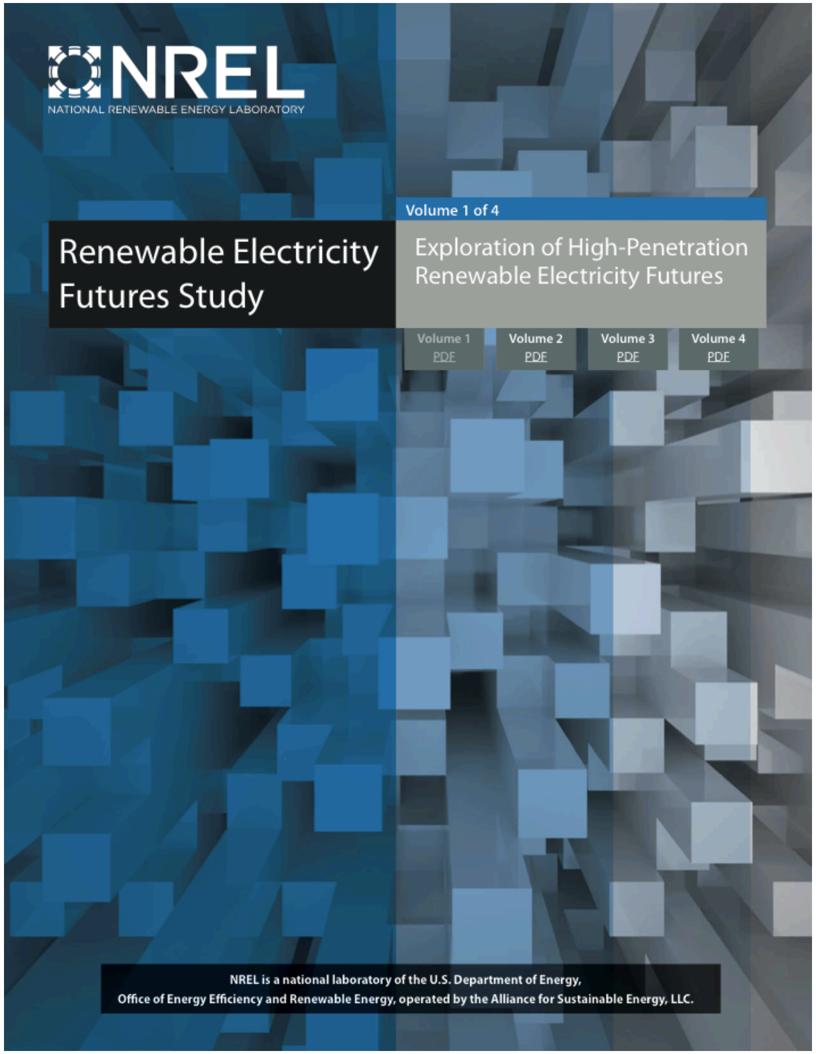


Perovskite PV Cells



Renewable Intermittency?

- Much can be done with existing electricity distribution & management systems.
- NREL's 2012 Renewable Electricity Futures Study discussed how 80% RE penetration could be achieved by 2050.



Summary

- Great world-wide progress over the last 20 years in advancing multiple PV conversion technologies.
- Si PV based on both c-Si and mc-Si wafers will continue to dominate the industry but more efficient use of high purity Si must be part of Si PV's terawatt scale future.
- Polycrystalline thin film technologies have made substantial progress and now have the potential to compete effectively with mc-Si PV.
- PV will become increasingly relevant in a world troubled by climate change – high efficiency, system cost, reliability and building integration will all matter as we move towards the terawatt scale.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Thank You