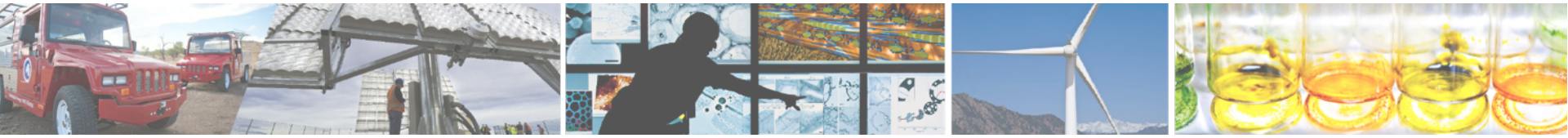
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY



Building on 35 Years of Progress – The Next 10 Years of Photovoltaic Research at NREL

Pioneers in Energy Lecture
Purdue University

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

17 July, 2013

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

The National Center for Photovoltaics (NCPV) is the nation'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

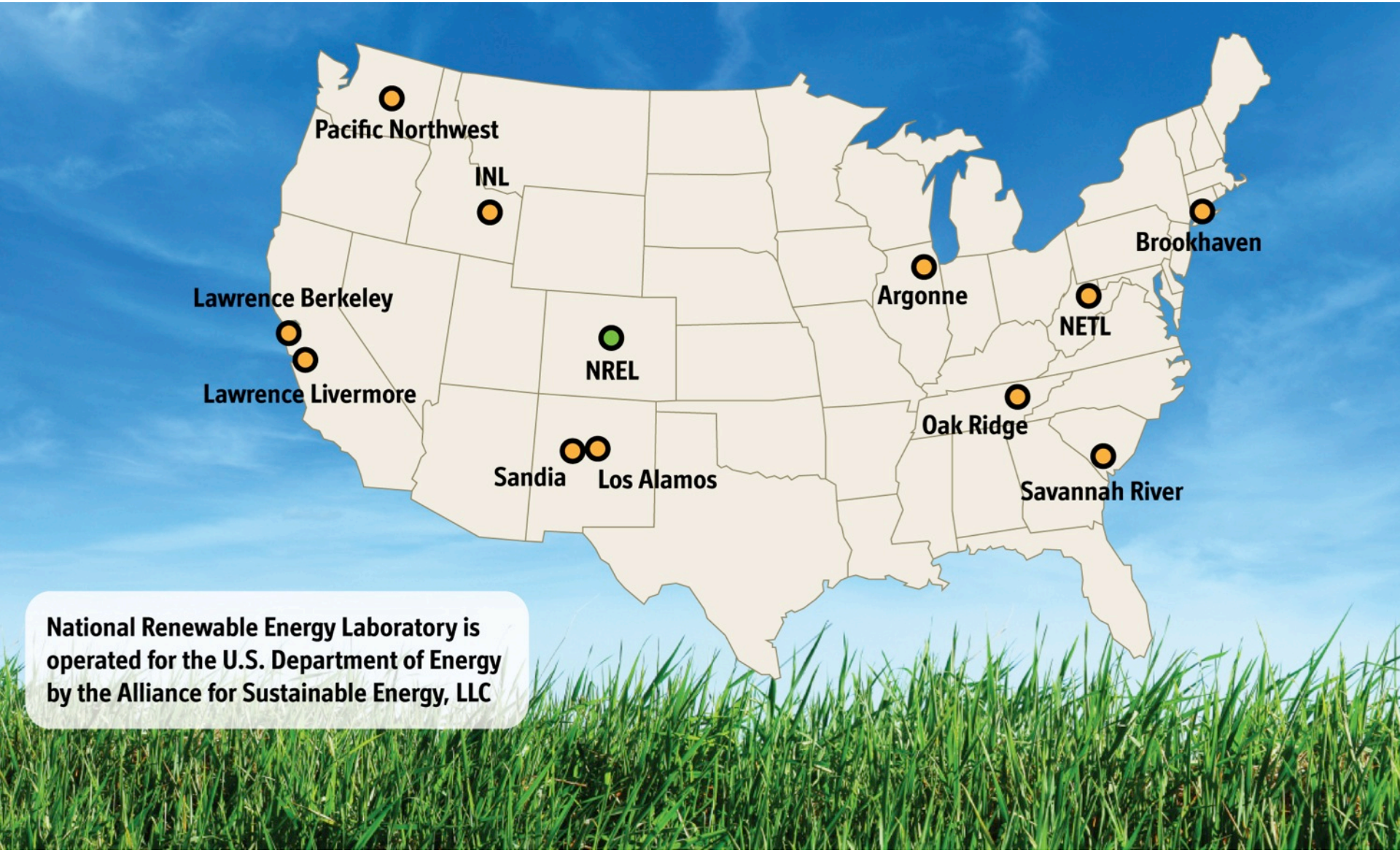
SunShot
U.S. Department of Energy

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.

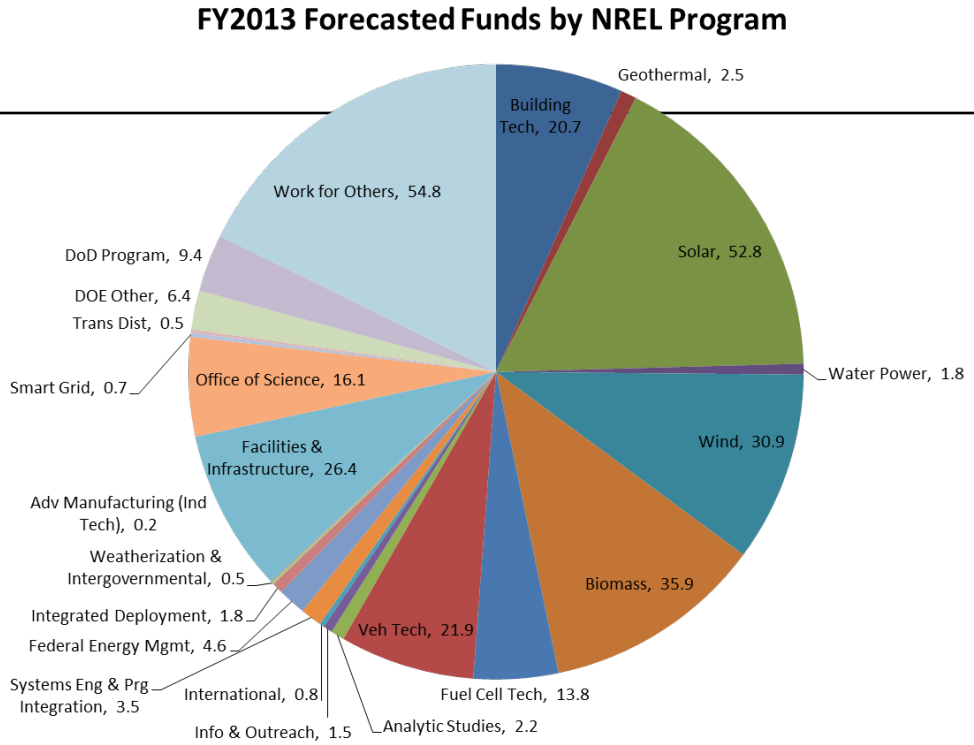
National Renewable Energy Laboratory

NREL - Part of DOE's National Lab Complex



NREL Snapshot

- 35+ years of accomplishments and market impact in energy efficiency and renewable energy technology R&D
- 2,419 staff (as of 12/2012)
  - 1,634 employees
  - 785 non-payroll
- $329.5M total funding in FY12
- $309M projected for FY13
- More than 350 partnerships
- International benchmark for sustainability



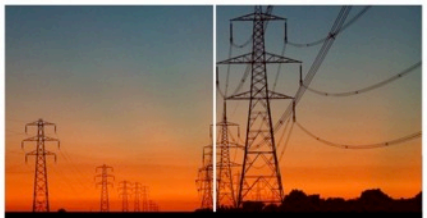
Scope of Mission

Energy Efficiency

- Residential Buildings
- Commercial Buildings
- Personal and Commercial Vehicles

Renewable Energy

- Solar
- Wind and Water
- Biomass
- Hydrogen
- Geothermal



Systems Integration

- Grid Infrastructure
- Distributed Energy Interconnection
- Battery and Thermal Storage
- Transportation

Market Focus

- Private Industry
- Federal Agencies
- Defense Dept.
- State/Local Govt.
- International

NCPV: Helping Seed the PV Technologies of Tomorrow

SERI begins operation

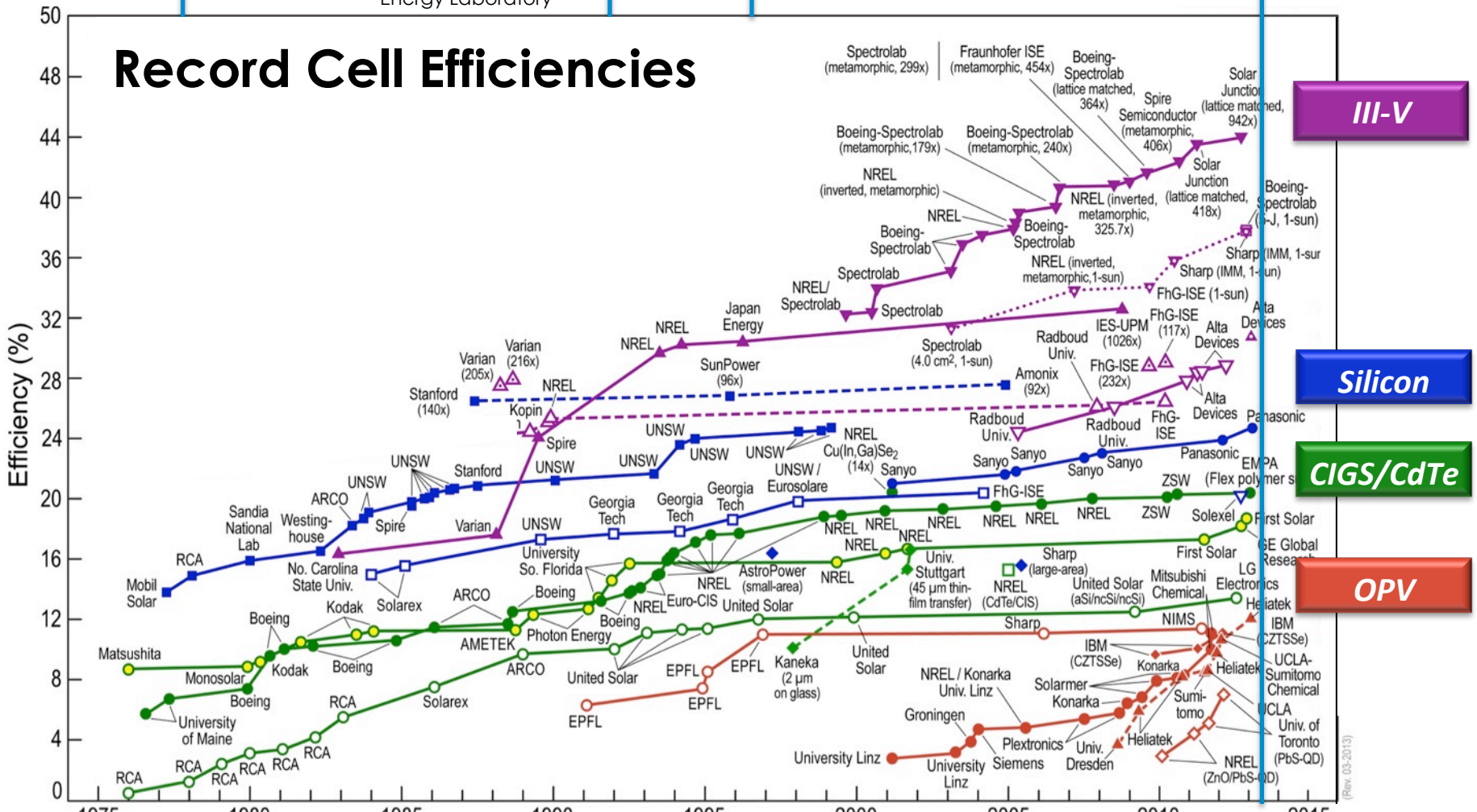
SERI becomes the National Renewable Energy Laboratory

NCPV

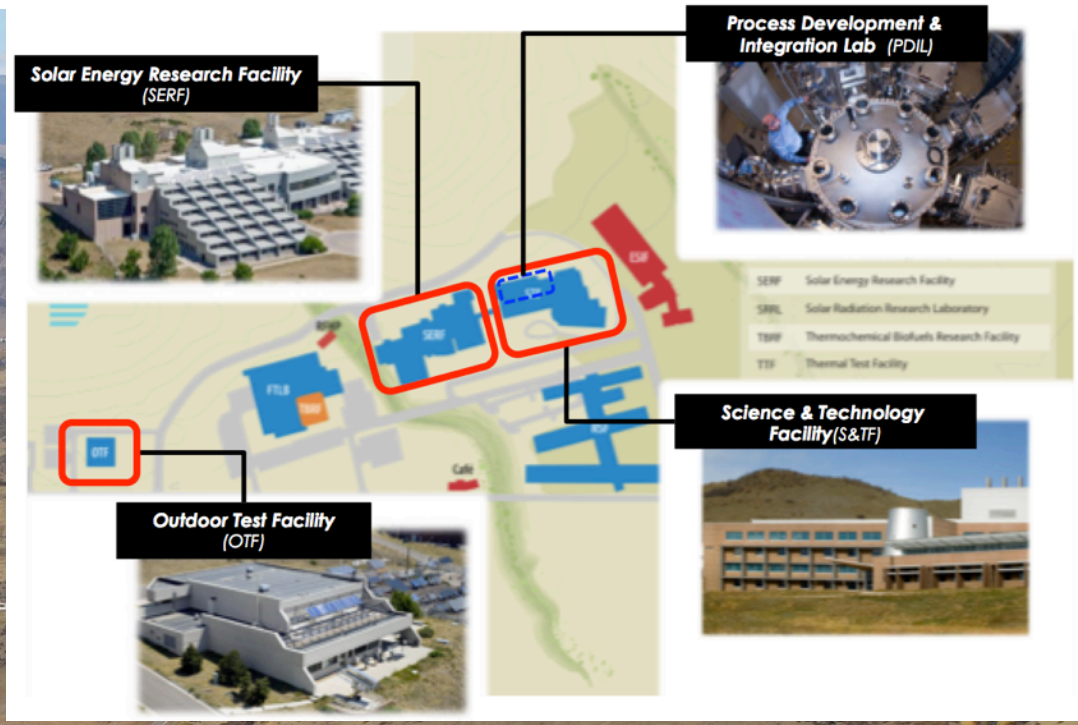
National Center for Photovoltaics (NCPV) is established

Today

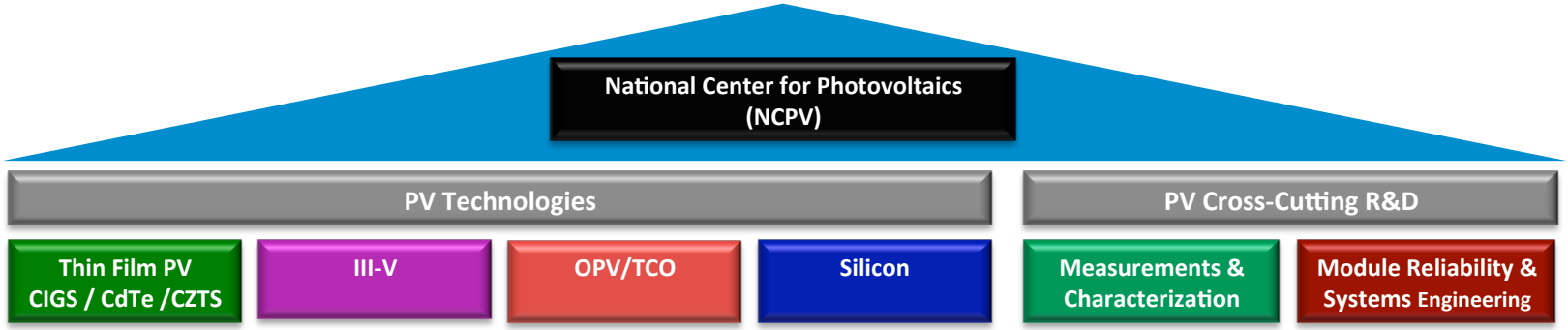
2013



The NCPV Today

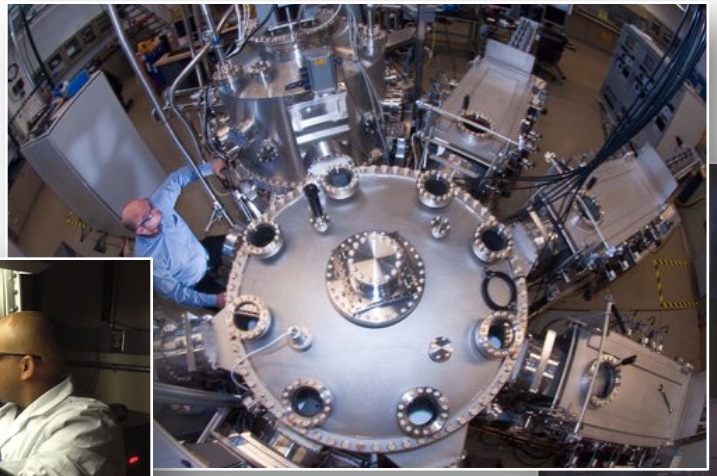


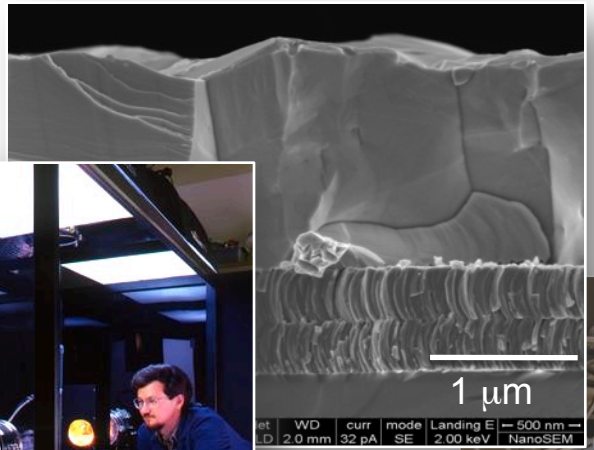
NCPV Competencies

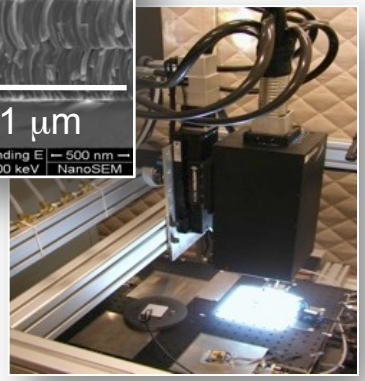


Extensive Capabilities and PV Experience Under One Roof

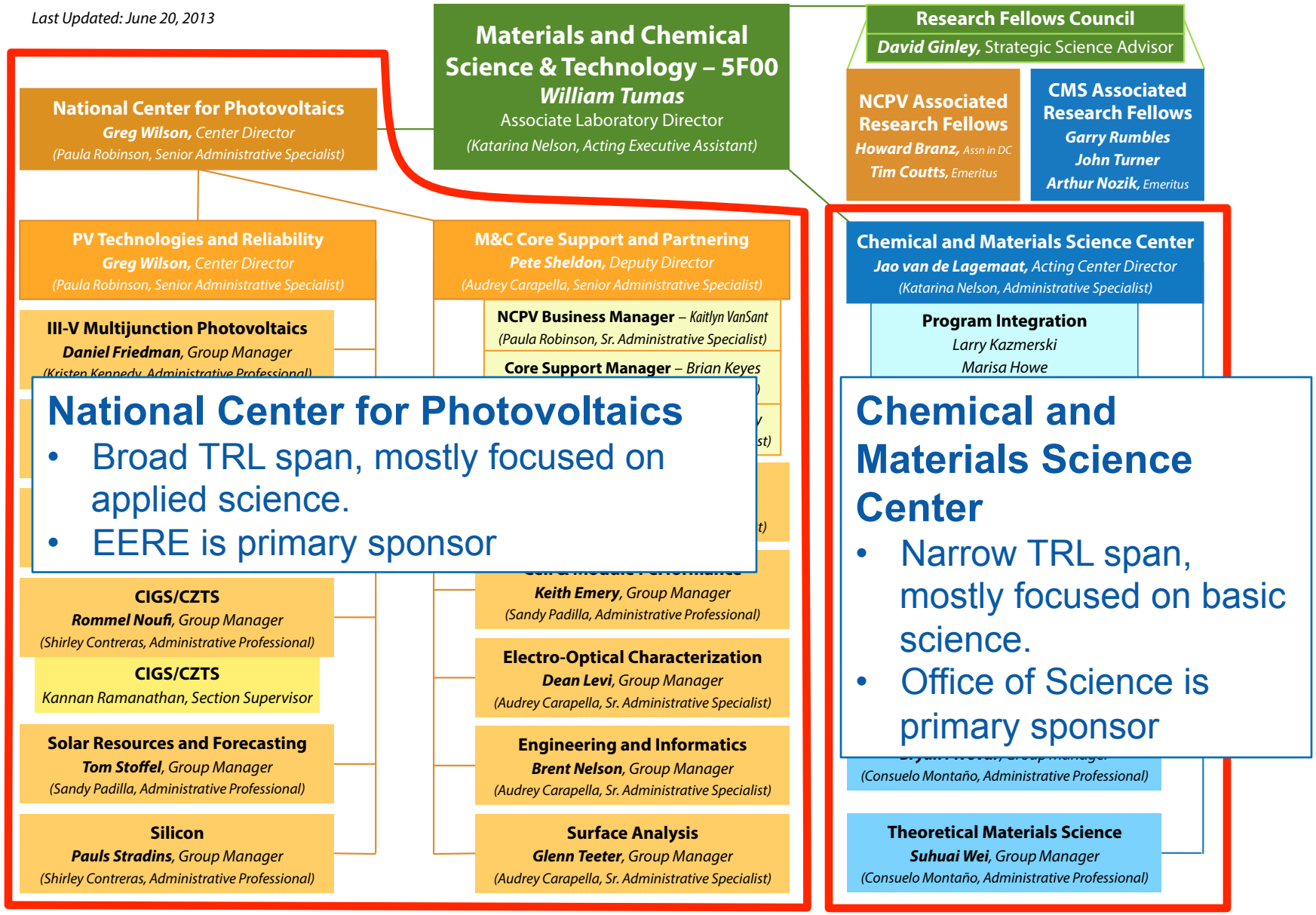
Material Synthesis • Device Processing • Device Design • Device Modeling • Measurements & Characterization • A Highly Trained Technical Staff





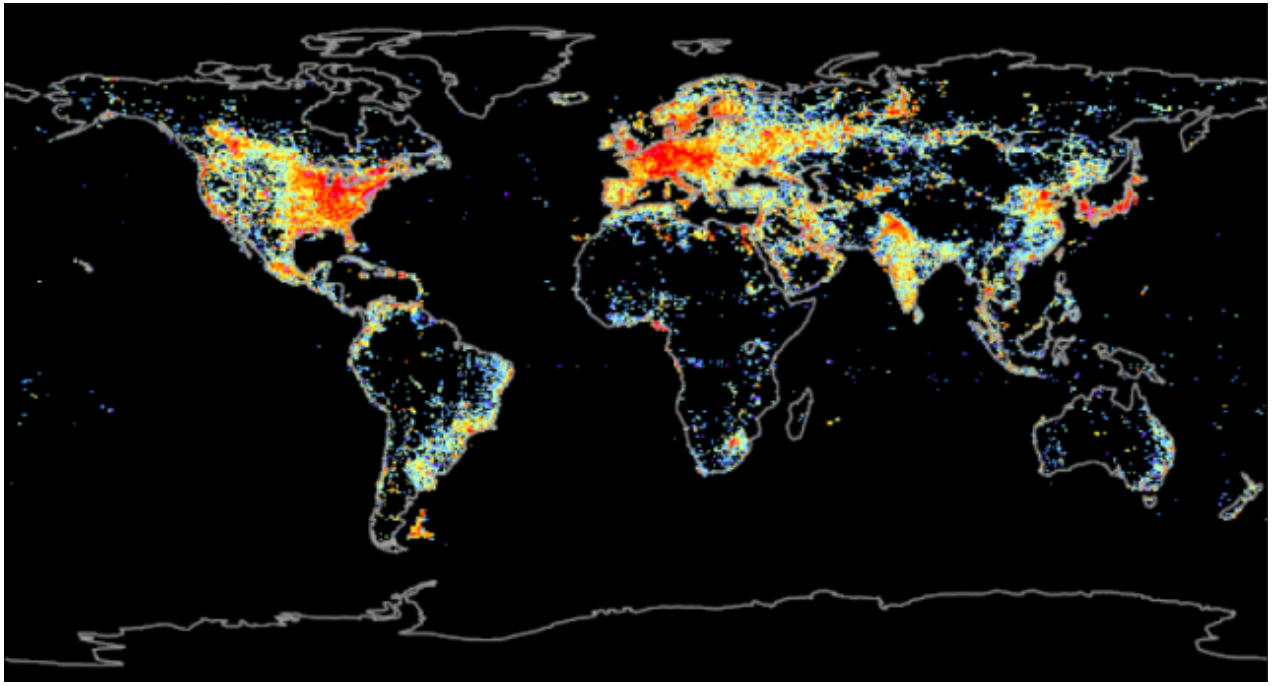


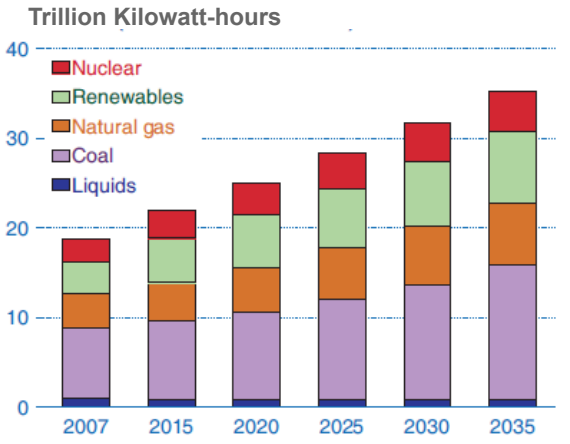
Organization Structure – Directorate Level



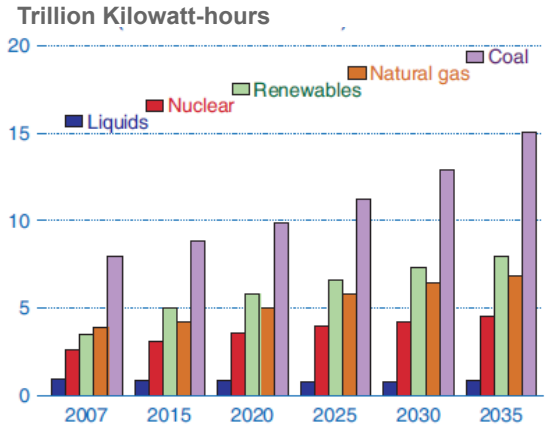
World Energy Consumption

The earth's population currently consumes ~21 trillion kWhrs of electricity, with ~2/3 generated using fossil fuels.

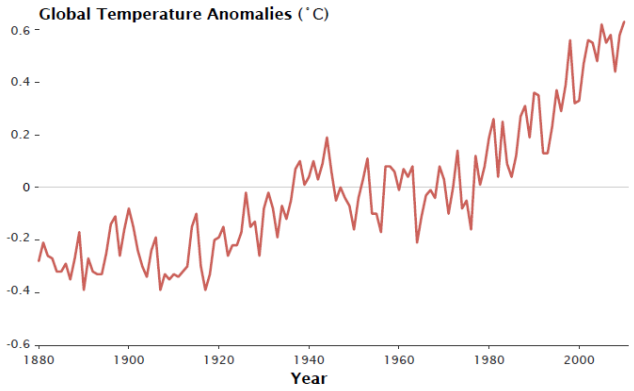




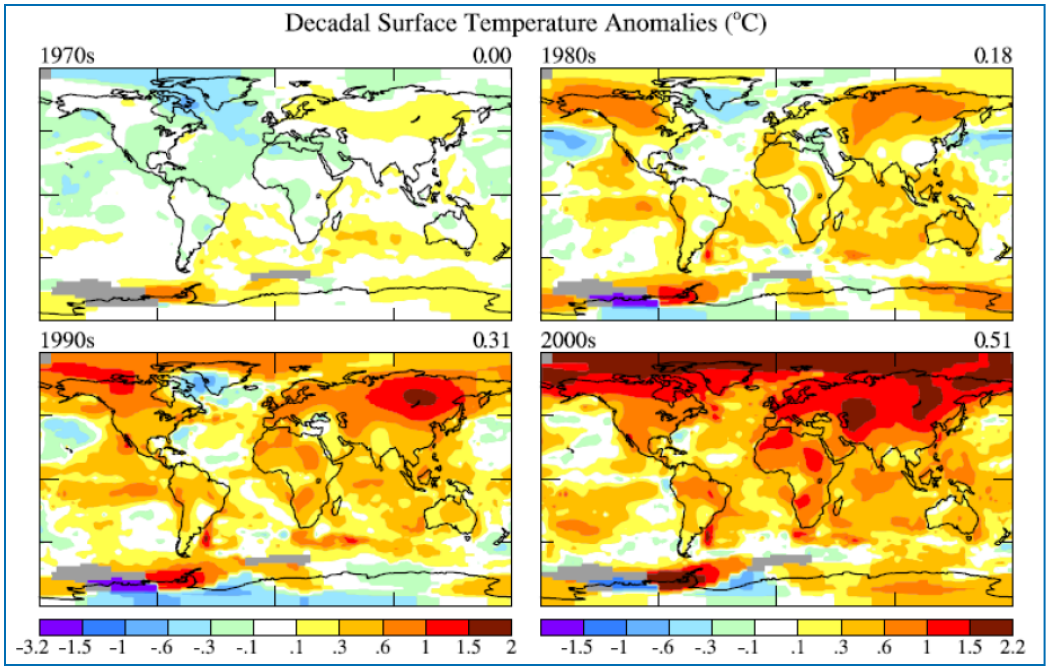
Source: 2010 DOE-EIA International Energy Outlook



Energy & CO_2 - 21st Century Grand Challenges

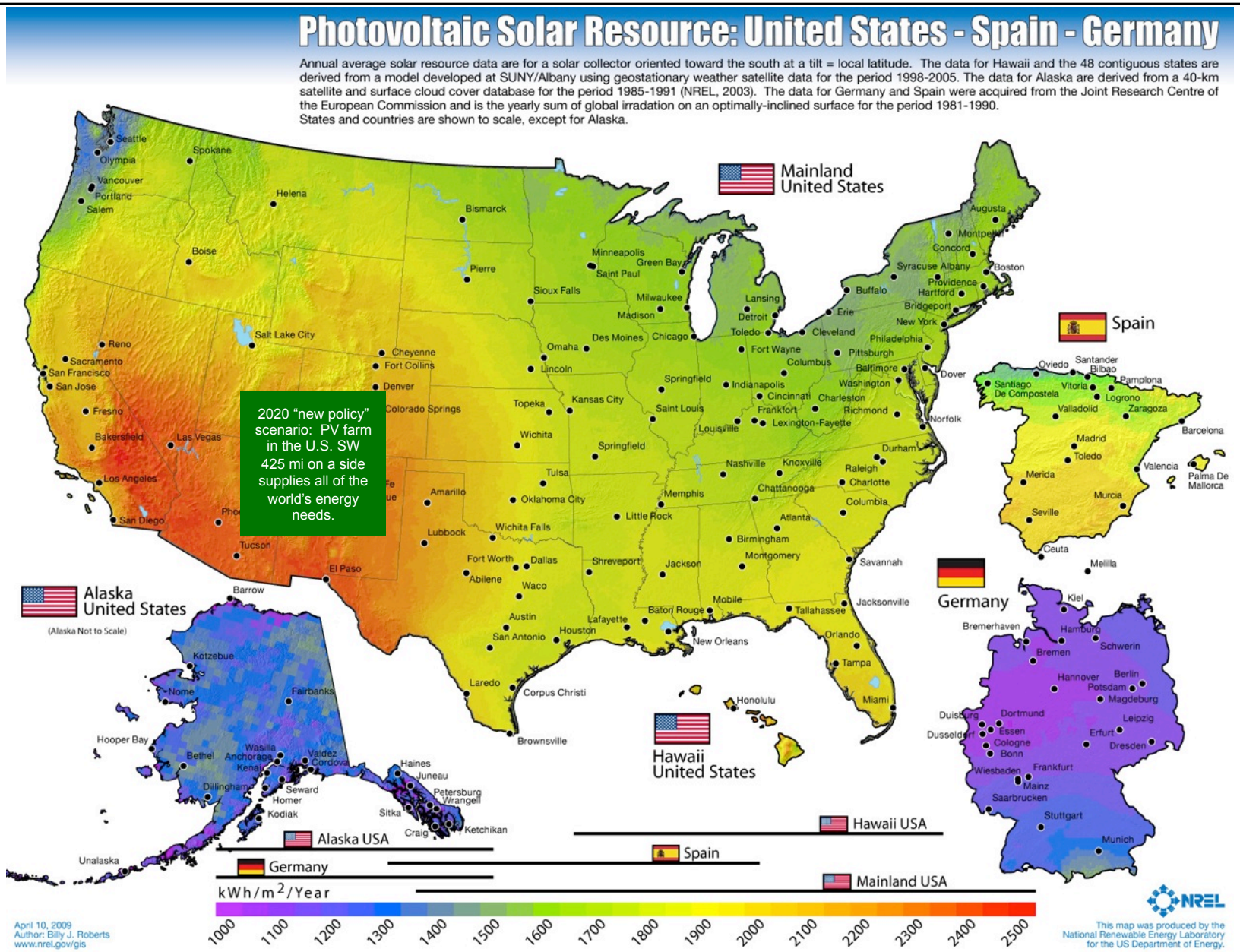


Source: NASA-GISS

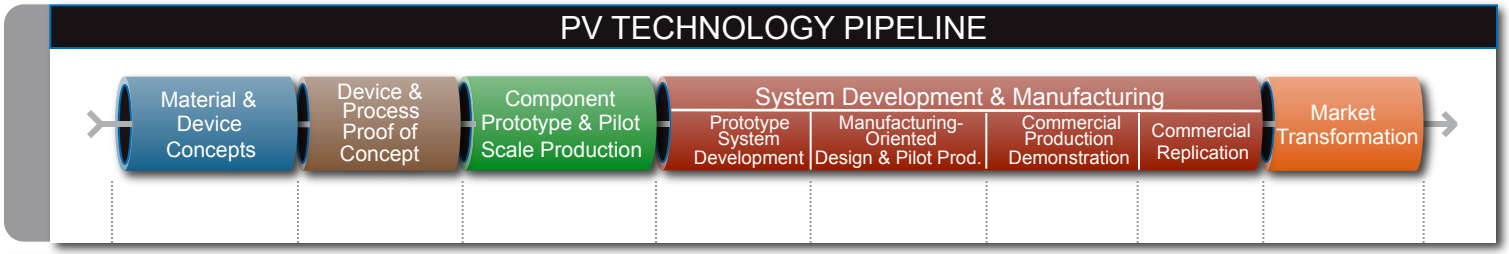


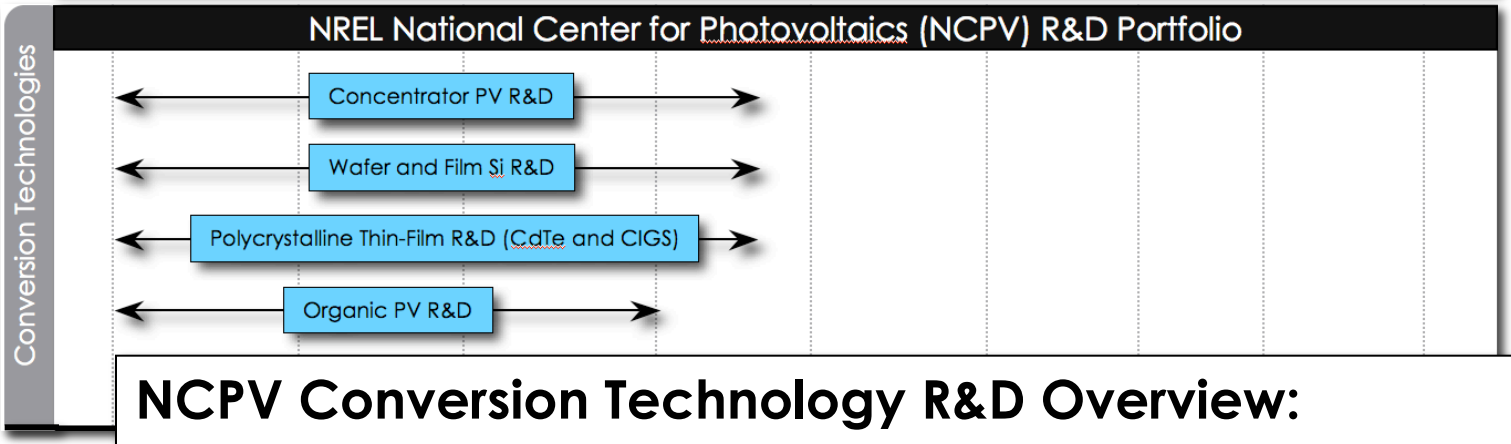
- The CO_2 emissions from fossil fuel combustion have resulted in unprecedented new problems:
  - Global climate change with associated changes in rainfall patterns, average surface temperatures and polar ice cover.
  - Increased ocean CO_2 content with a corresponding increase in acidity.
- Photovoltaic energy production is a rapidly scalable, non-nuclear alternative that is large enough to address the problems we are facing.

PV Energy for Planet Earth in 2020



NCPV Conversion Technology R&D Portfolio

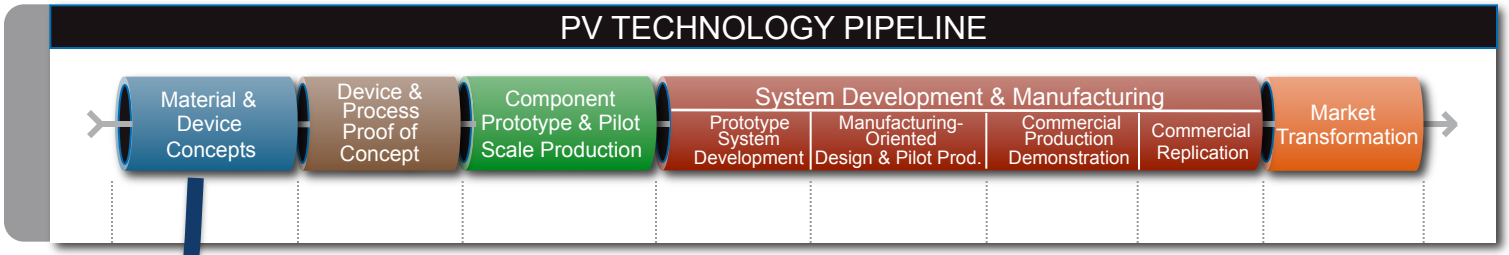




NCPV Conversion Technology R&D Overview:

- III-V Multijunction — Highest potential η , > 50%
- Wafer Si — Most common technology, ~25% 1-J η today
- Thin Si — ** Potential for low cost and > 20% η
- CdTe — Lowest cost in HVM today, potential for > 20% η
- CIGS — Can be flexible, potential for > 20% η
- Organic PV (OPV) — Flexible, potentially very low cost

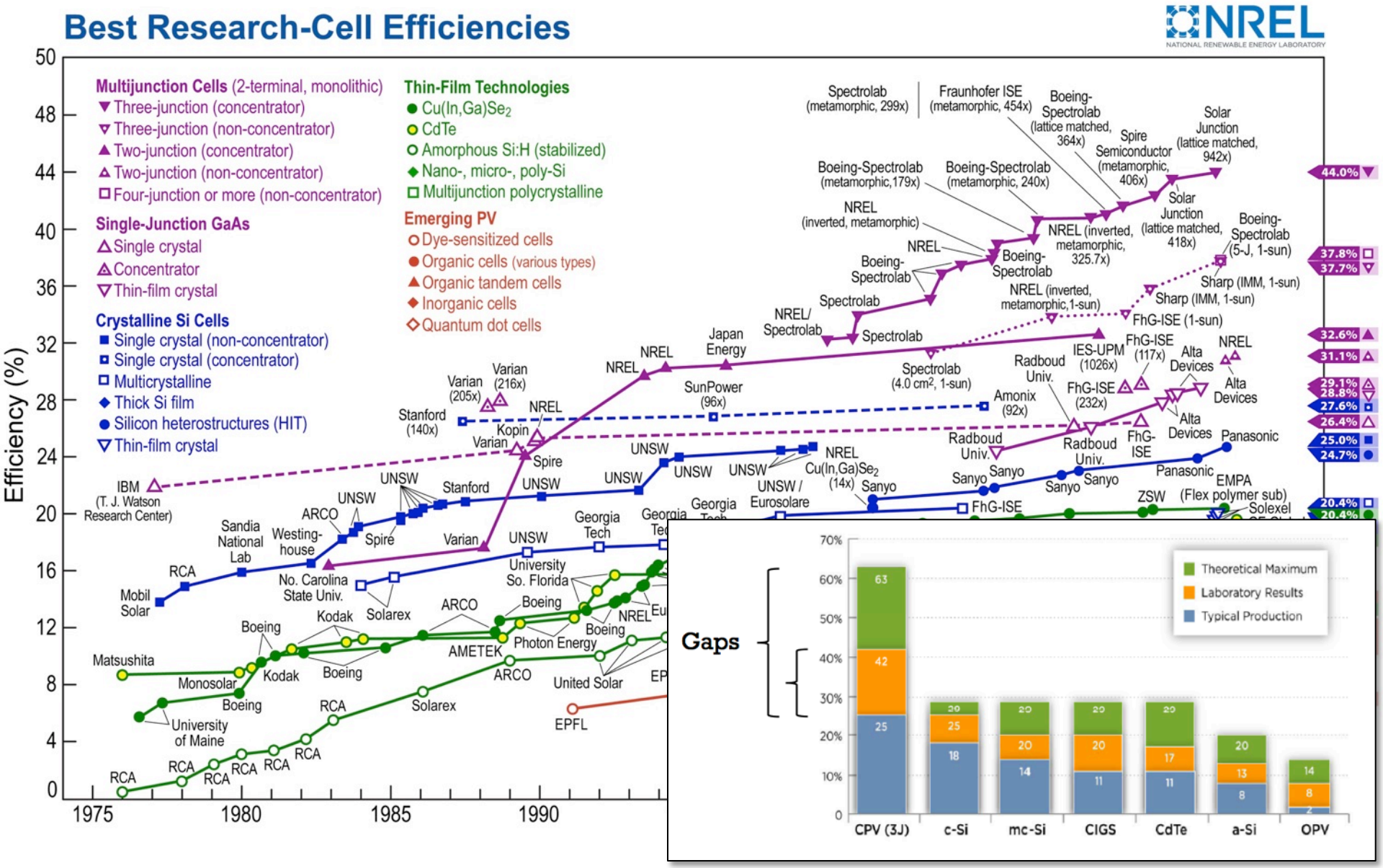
NCPV Research Portfolio



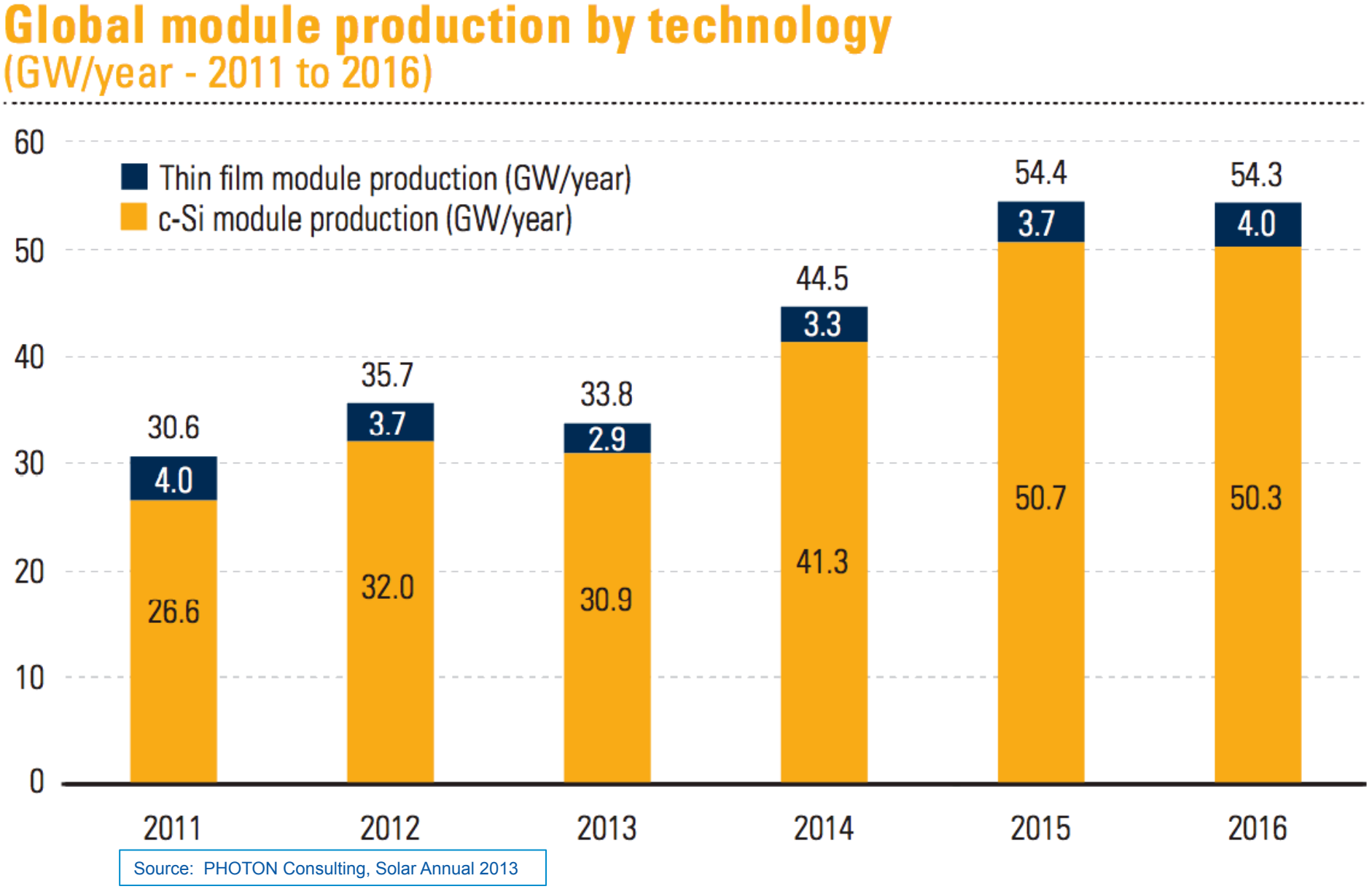
Other NCPV Research Areas:

- CZTS — Earth abundant replacement for CIGS
- III-V 1J via HVPE — Potential path to low-cost, 1-sun III-V cells
- Novel PV Absorbers — Search via Inverse Design
- Novel TCO — Search for better TCO materials

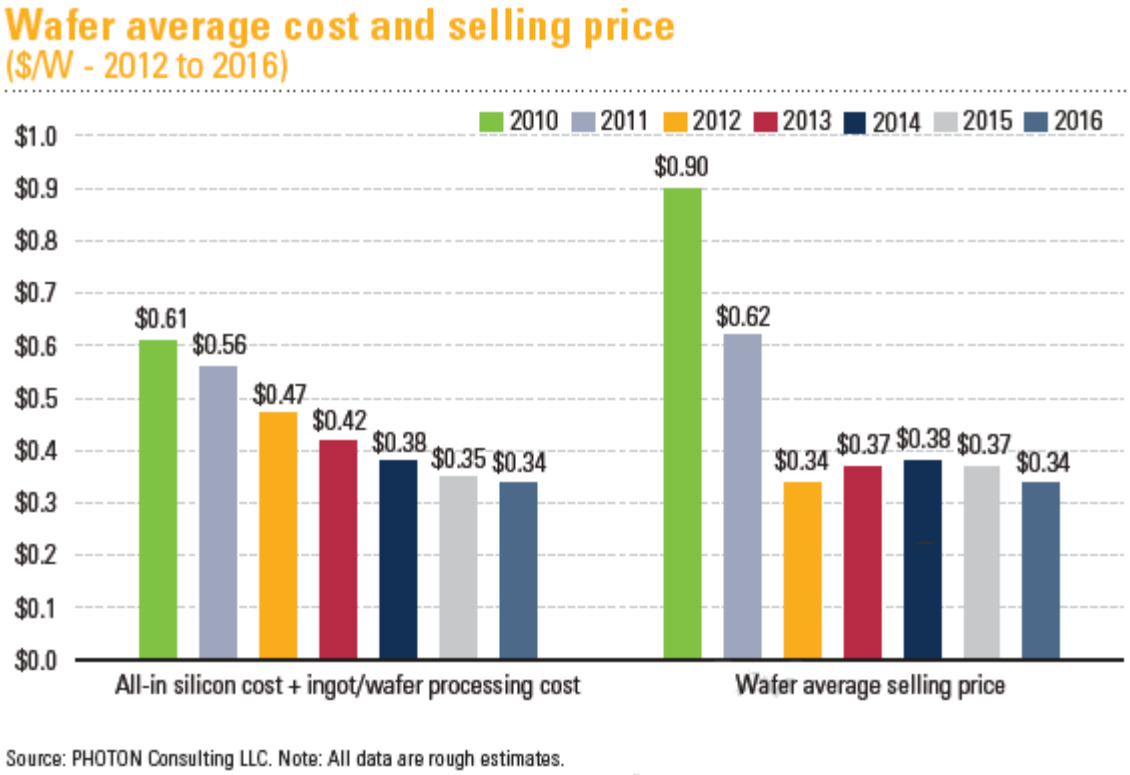
Best Research Cell Efficiencies



PV Market: cSi now with 91%



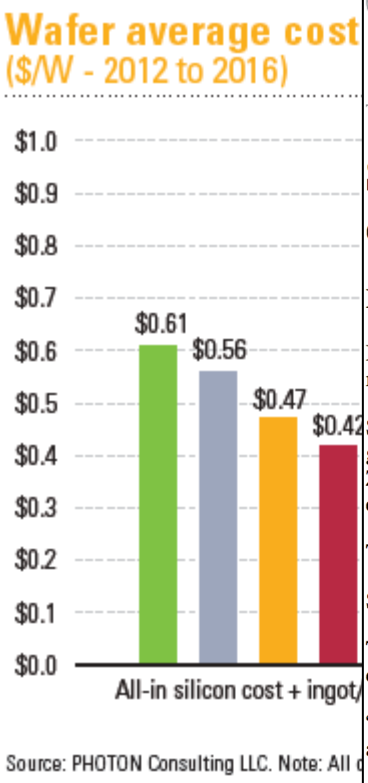
The cSi PV Business Problem



Source: PHOTON Consulting LLC. Note: All data are rough estimates.

- Prices at or below cost across the entire cSi PV value chain. Situation not predicted to improve in meaningful timeframe.
- Required capital investment is high but returns too low to attract investment from capital markets.
- Once strong cSi cell and module companies in China are beginning to experience problems.

The cSi PV Business Problem



The Washington Post

Solar giant Suntech announces $541 million bond default, search for financing

By Associated Press, Published: March 18

BEIJING — Suntech, one of the world's biggest solar panel manufacturers, said Monday it has defaulted on a $541 million bond payment in the latest sign of the financial squeeze on the struggling global solar industry.

Suntech Power Holdings Ltd.'s announcement was a severe setback for a company lauded by China's Communist government as a leader of efforts to make the country a center of the renewable energy industry. Its founder, Shi Zhengrong, became one of the industry's most prominent entrepreneurs and a billionaire, only to see most of his fortune evaporate as the company's share price plummeted.

The company is "exploring strategic alternatives with lenders and potential investors," David King, who replaced Shi as a CEO last year, said in a statement.

Suntech was due to make a $541 million bond payment on Friday but ran short of cash following heavy losses over the past year.

The company said it reached agreement with holders of 60 percent of the bonds to postpone payment but Monday's announcement said the bonds' trustee had declared a default. It said that triggered defaults on other debts to the International Finance Corp. and Chinese lenders.

"It is currently a very difficult time for our company and our industry, but the management and board of Suntech are committed to finding a way forward that will take into account the rights and interests of all of its constituents, including shareholders, note holders, lenders, customers, suppliers and employees," King said.

A sharp drop in solar panel prices over the last several years has erased the profits of solar panel makers around the world.

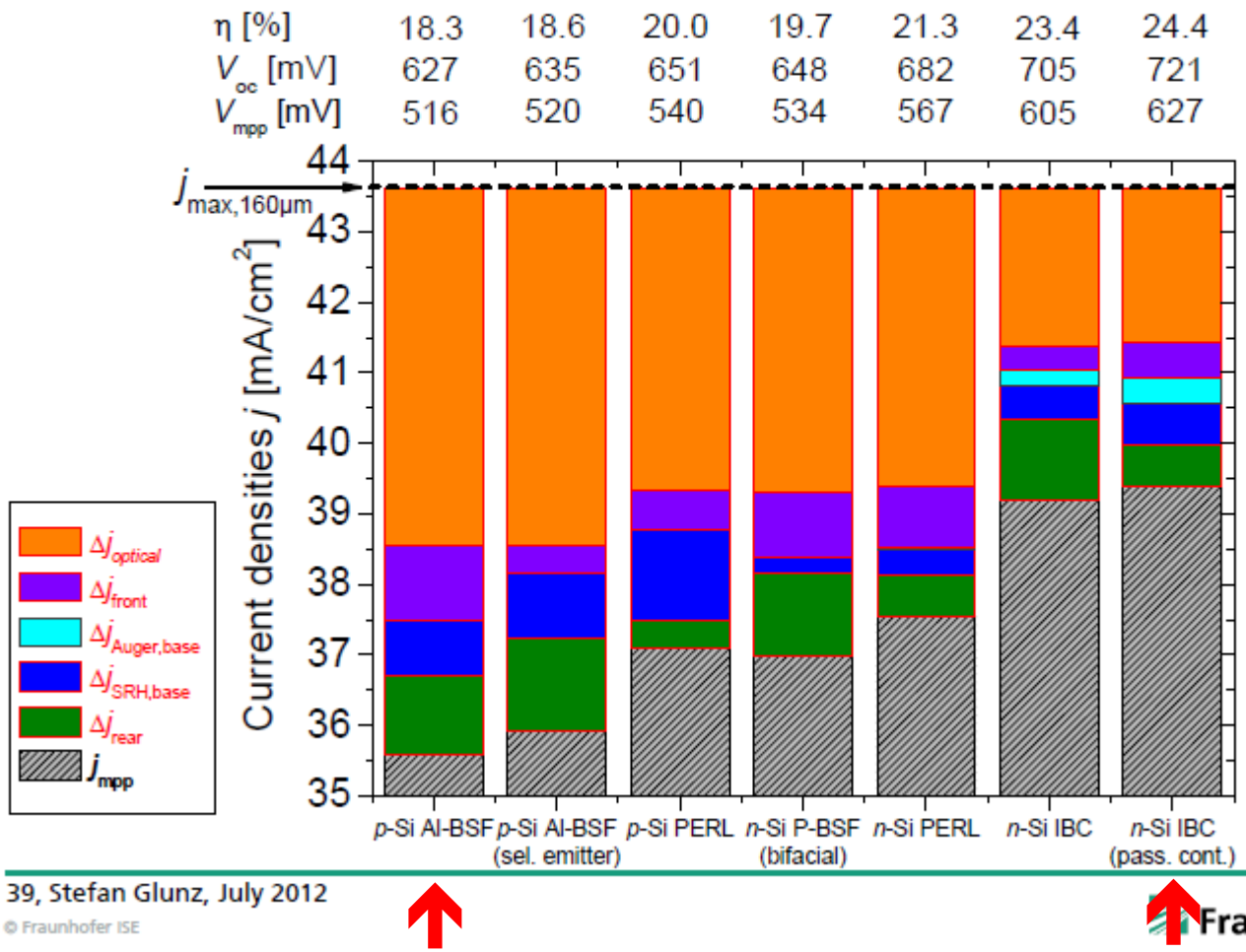
Suntech has also been hurt by a revelation in July that a business partner faked $680 million in collateral for a loan Suntech had guaranteed.

Suntech's U.S. shares tumbled in the days leading up to the debt deadline as fears rose that the company could be forced into bankruptcy. The stock, down nearly 80 percent in the past 12 months, dipped another 6 cents to close at 64 cents Monday.

➔ Prices across the cSi PV supply chain will eventually rise to reflect real manufacturing costs.

PV Workhorse – 1J Silicon

IBC cell with passivated contacts on n-type silicon



39, Stefan Glunz, July 2012

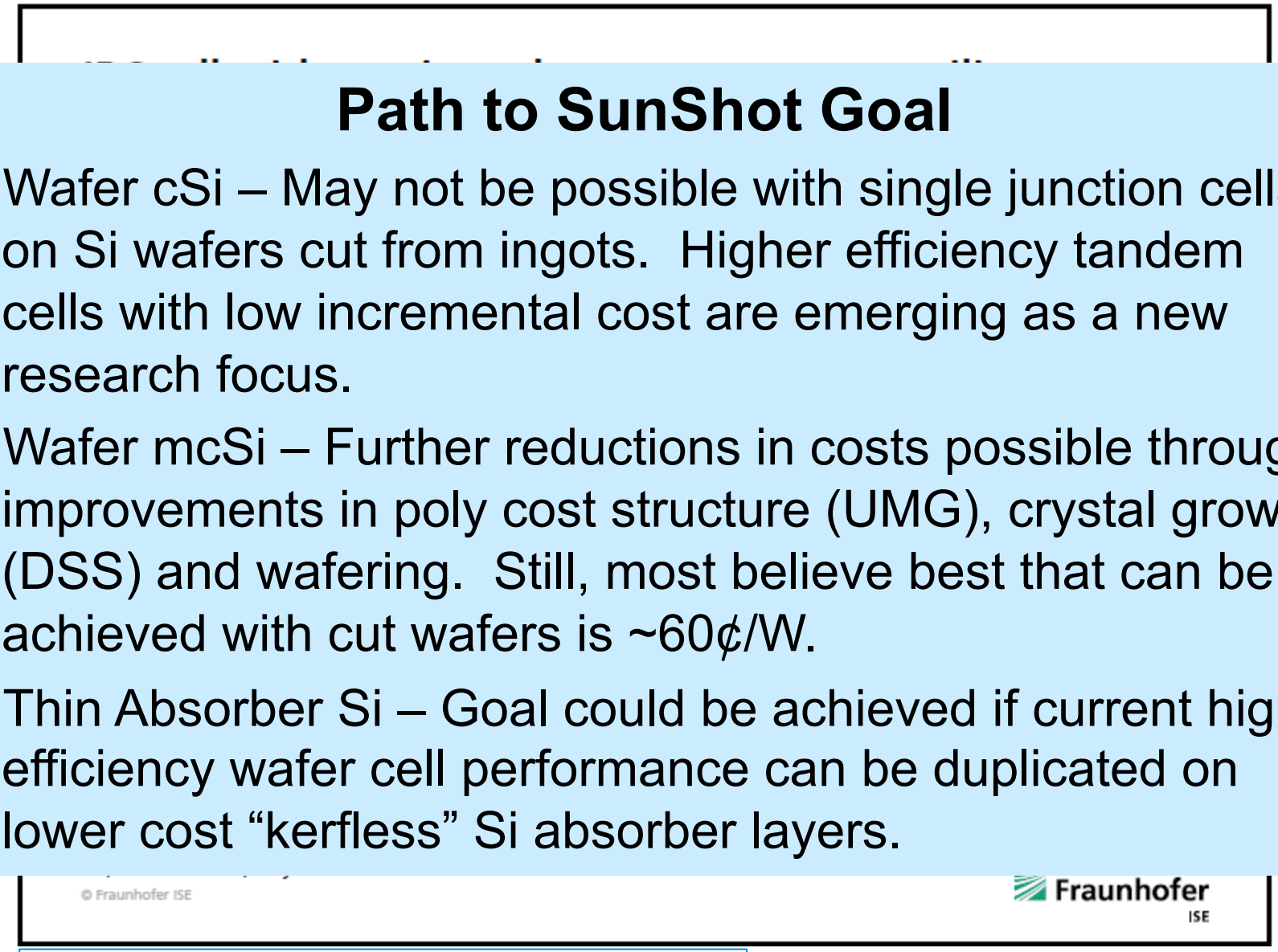
© Fraunhofer ISE

Fraunhofer ISE

- Typical Chinese cSi cells today are p-type CZ Si diffused junction cells with Al BSF with η ≈ 18% resulting in roughly 16% modules.
- SunPower's best production IBC cell has η > 24%.
- Panasonic recently announced a new record cSi 24.7% cell based on their heterojunction technology.

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

Cost Potential - Silicon PV

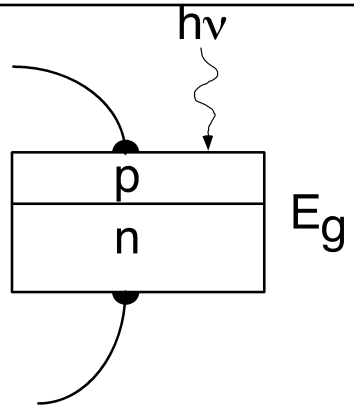


Path to SunShot Goal

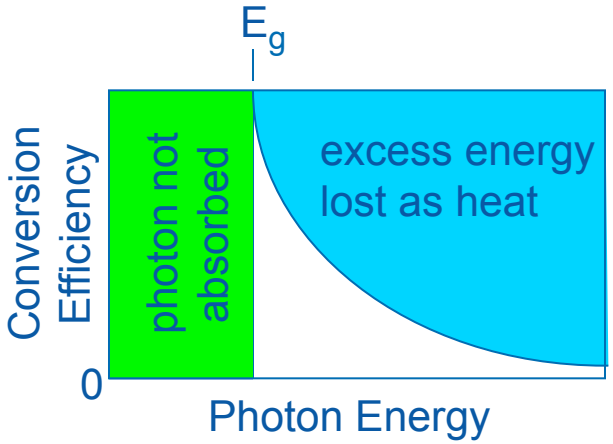
- Wafer cSi – May not be possible with single junction cells on Si wafers cut from ingots. Higher efficiency tandem cells with low incremental cost are emerging as a new research focus.
- Wafer mcSi – Further reductions in costs possible through improvements in poly cost structure (UMG), crystal growth (DSS) and wafering. Still, most believe best that can be achieved with cut wafers is ~60¢/W.
- Thin Absorber Si – Goal could be achieved if current high efficiency wafer cell performance can be duplicated on lower cost "kerfless" Si absorber layers.

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

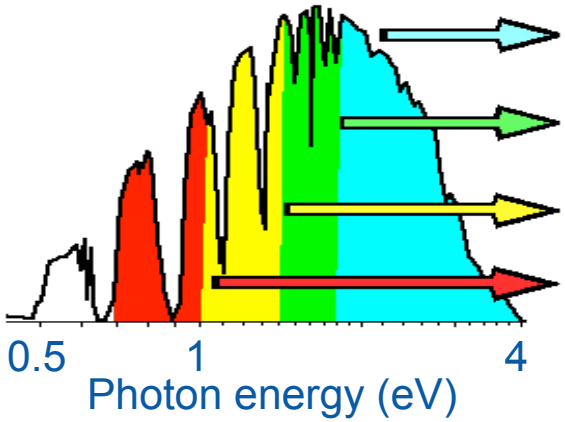
Limitation of Conventional Solar Cells



Conventional (single-junction) Cell, e.g. silicon…



…has unavoidable losses which put a fundamental ceiling on cell efficiency…

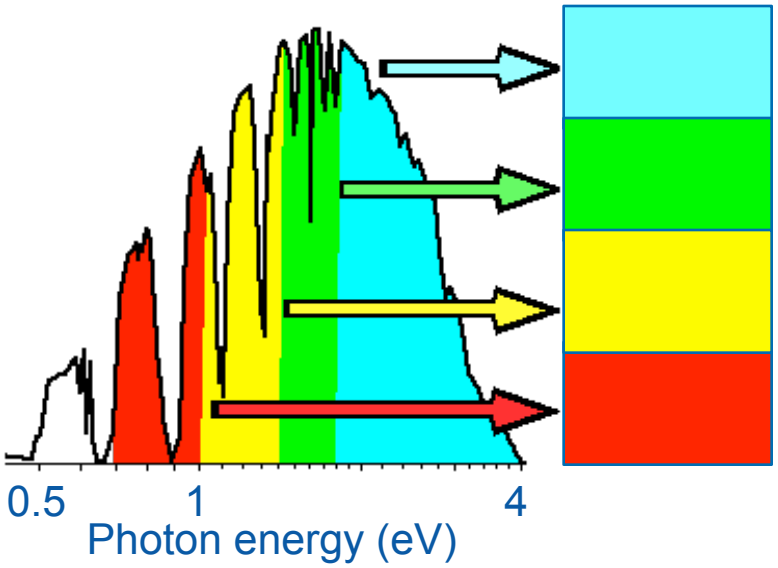


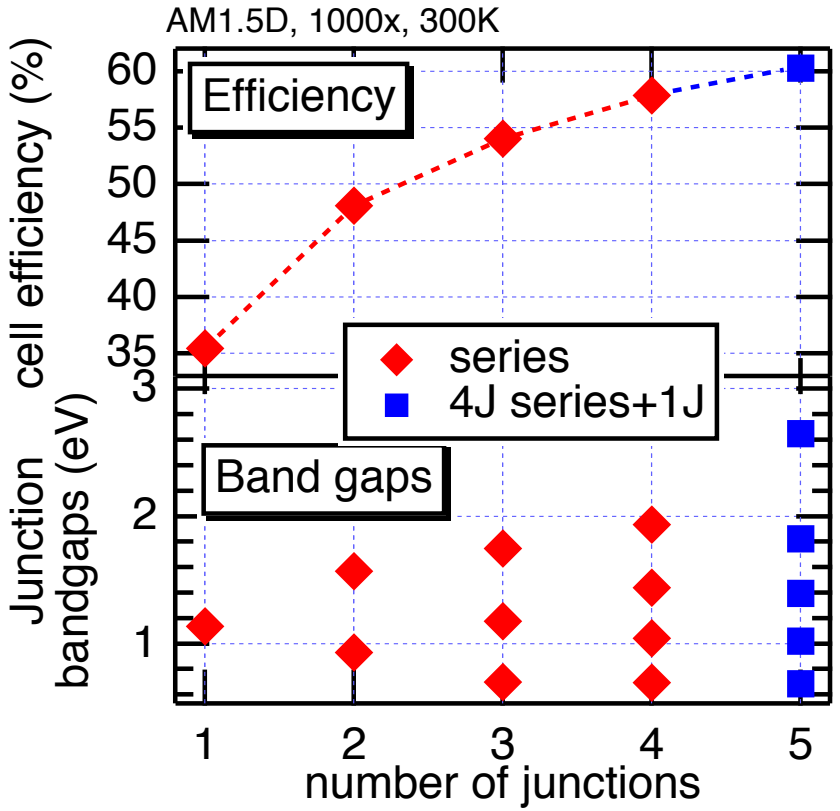
…when applied to the sun's broad spectrum

the sun is not a laser!

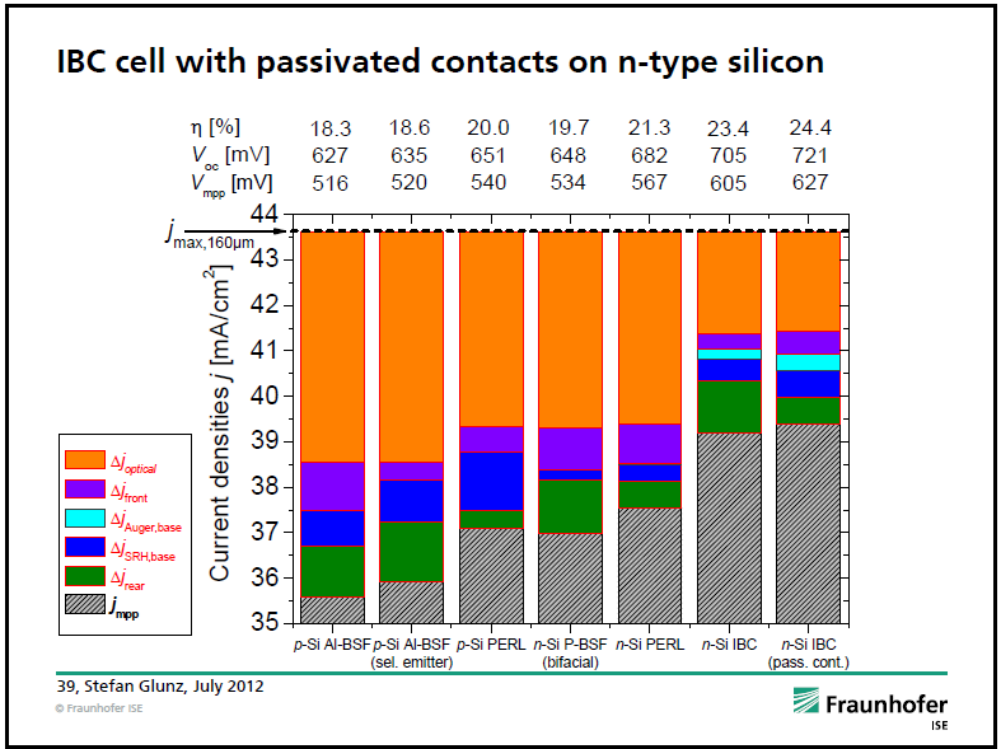
Capturing More Photons - Multijunctions

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

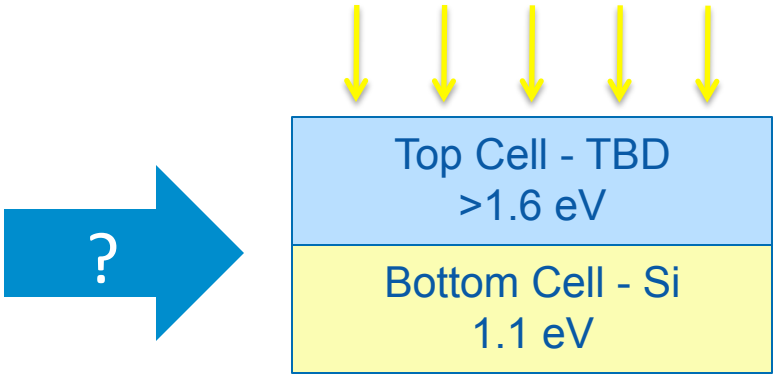




Next Gen Si PV - Tandem Cells



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

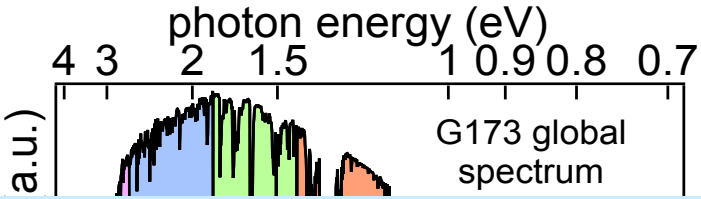


- Path to > 30% efficiency for Si wafer based cells.
- Top cell requirements:
  - Lattice match to Si
  - CTE match to Si
  - Target band gap
  - Top cell optical properties

III-V Multijunctions – Future Plans

48% in 2014

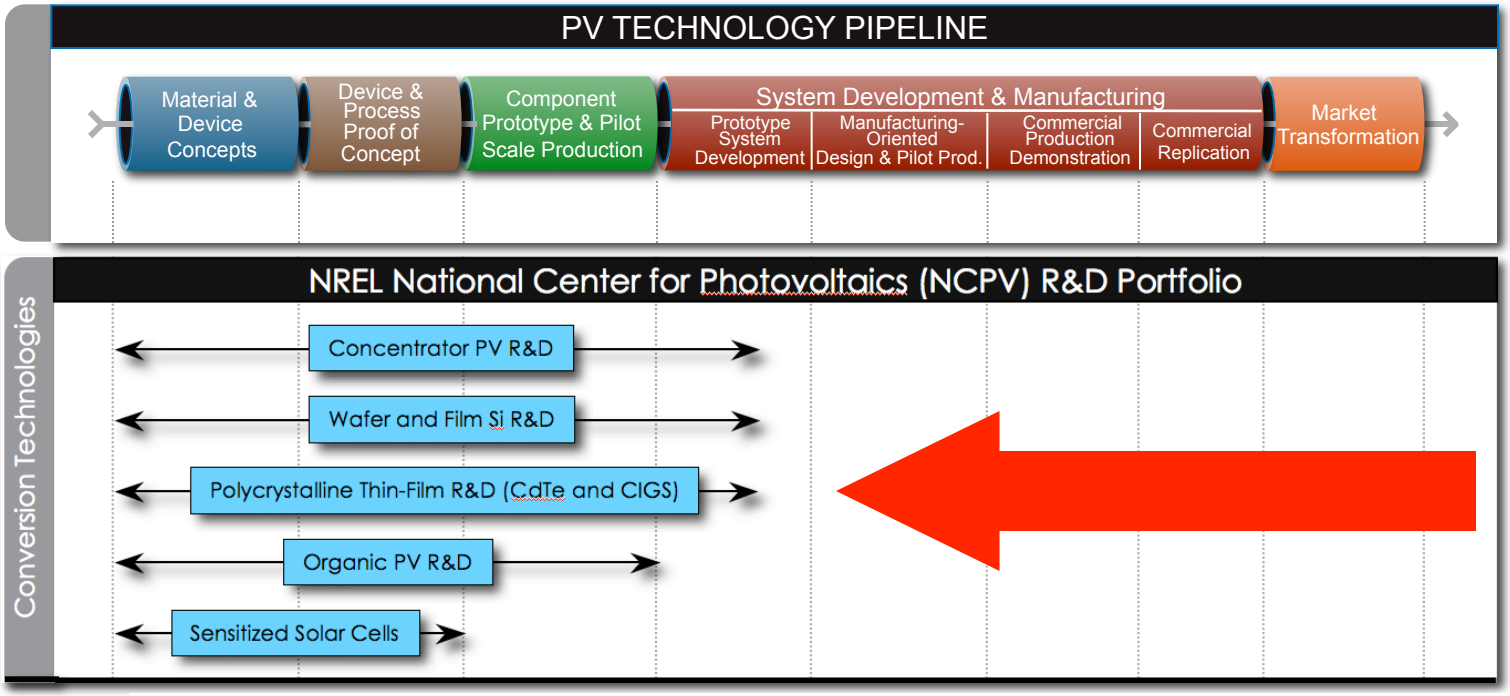
52% in 2016



Path to SunShot Goal

- III-V multijunctions cells will continue to be expensive given the very sophisticated process and expensive materials required.
- Still, system cost potential for CPV probably $1.25/W in high DNI areas.
- Cost will be low enough to grow CPV market in spite of missing $1/W target.

What About Thin Films?



CdTe PV Research: GBs, Defects & Doping

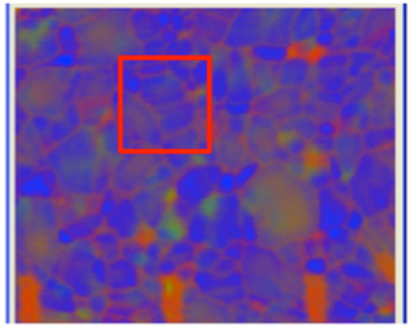
Objective:

Identify the path to a 20% production cell. To get there we need to significantly increase CdTe carrier concentration (10^{14} cm^{-3}) and lifetime (1-2 ns).

EBSD indicates grain structure

Cathodoluminescence spectra

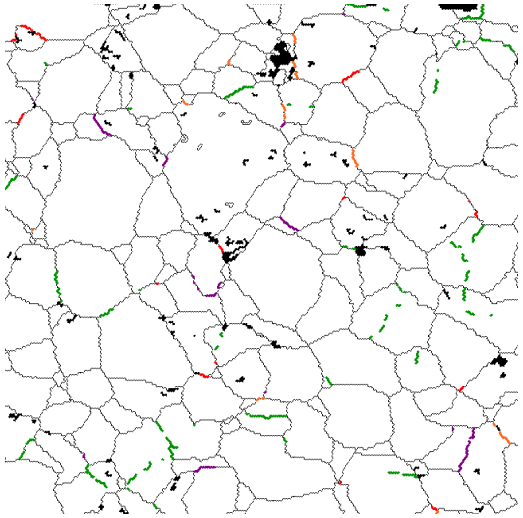
Blue = excitonic emission, Red = donor-acceptor pair

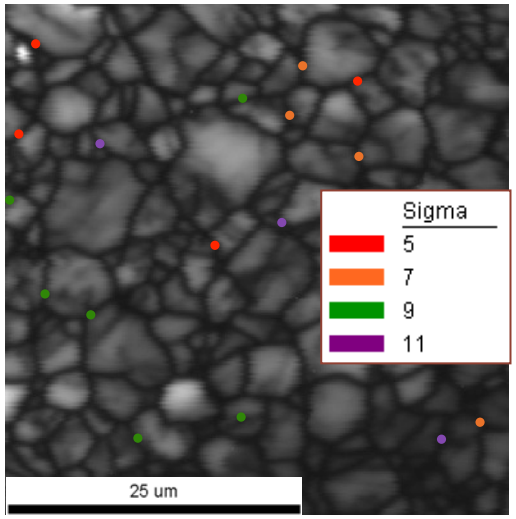


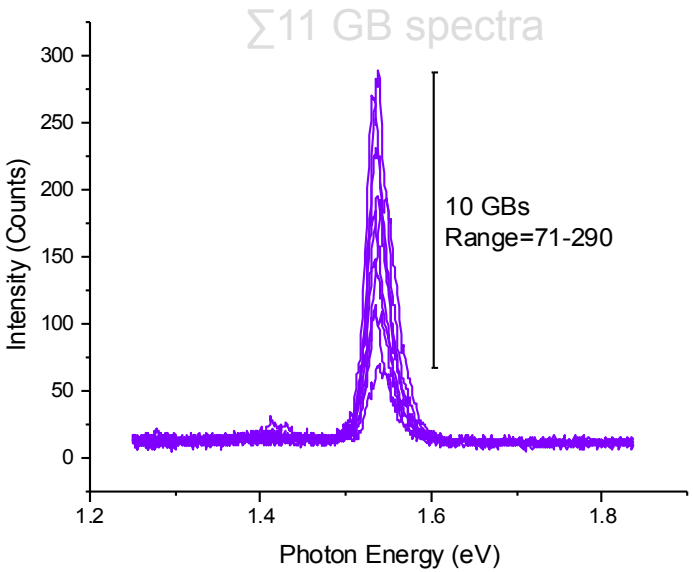
Approach:

- Learn how to dope >1x10^{16} with single crystals – MBE and novel post-deposition treatments.
- Improve lifetime to >10 ns - Deconvolute surface, bulk, and grain-boundary recombination. Work backwards from high lifetime material.
- Understand GBs - Deposit films with large grain size. Characterize how potential, lifetime, chemistry changes at GB.
- Answer fundamental questions – Does $CdCl_2$ create a Voc limit?

CdTe: GBs and Recombination

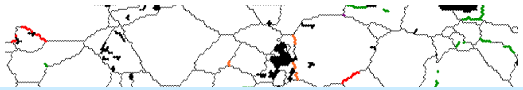






- Currently working to catalog hundreds of GBs in EBSD, then collecting CL spectra from each of these GBs to statistically evaluate the role of GBs on recombination.
- ∑3 GBs are preferable to other GBs.
- Statistics will be required to distinguish differences between ∑5, ∑7, ∑9, and ∑11 GBs.
- Work on non CSL GBs is in progress.

CdTe: GBs and Recombination

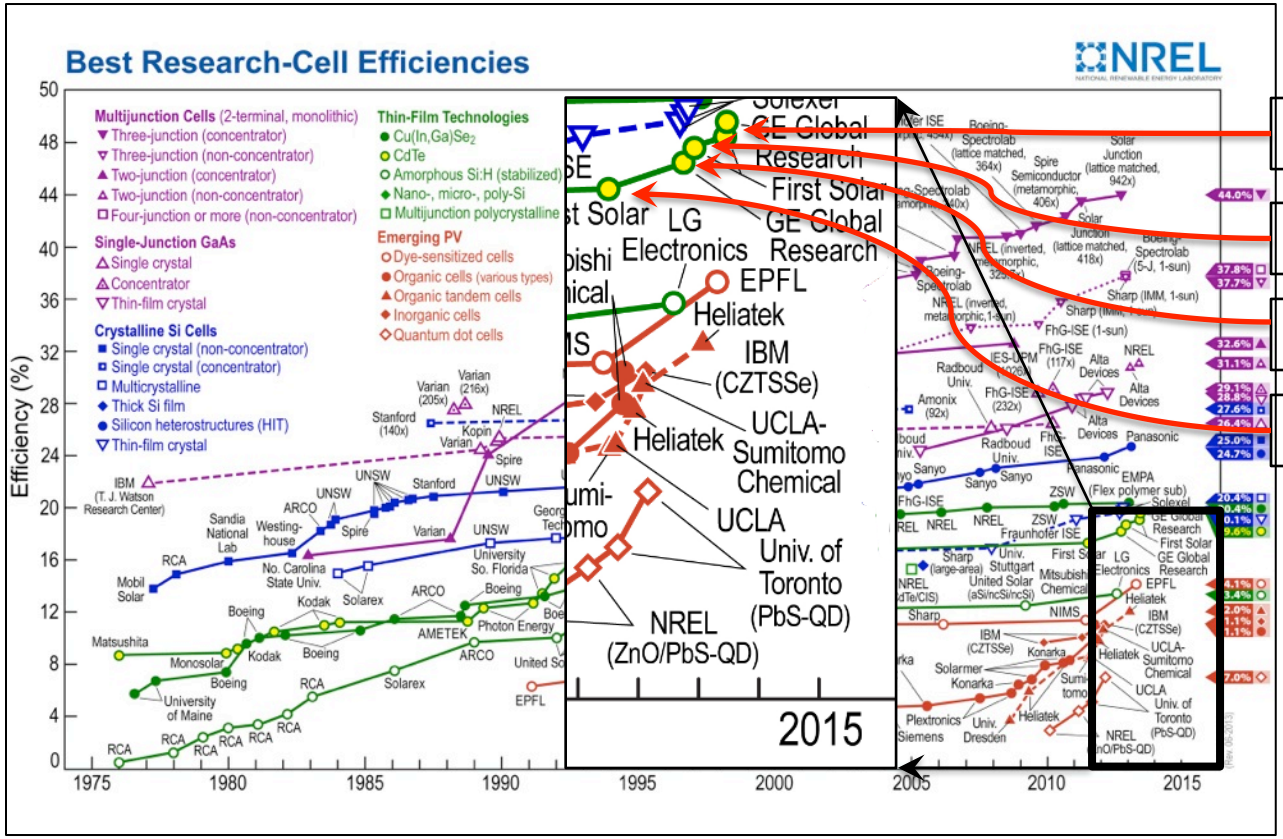


Path to SunShot Goal

- Current CdTe HVM production costs probably around 75¢/W with average panel efficiencies around 12%.
- Increasing panel efficiency to 18% with minimal increase in unit manufacturing cost is possible and would move panel cost to <40¢/W.

- Currently working to catalog hundreds of GBs in EBSD, then collecting CL spectra from each of these GBs to statistically evaluate the role of GBs on recombination.
- ∑3 GBs are preferable to other GBs.
- Statistics will be required to distinguish differences between ∑5, ∑7, ∑9, and ∑11 GBs.
- Work on non CSL GBs is in progress.

CdTe: Recent Progress



June, 2013 - GE, 19.6%

February, 2013 - FSLR, 18.7%

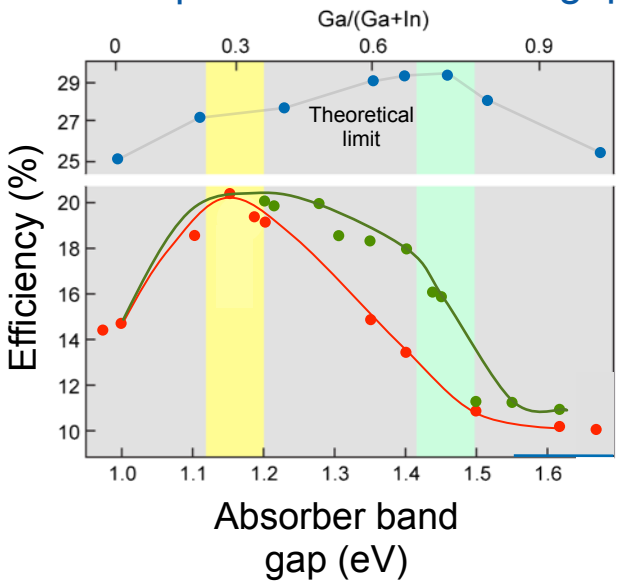
October, 2012 - GE, 18.3%

June, 2011 - FSLR, 17.3%

Major progress in champion cell efficiencies at both First Solar and GE over the last 2 years provides strong evidence that CdTe production module efficiencies have the potential to reach 18%.

CIGS PV Research: Enable Low Cost HVM

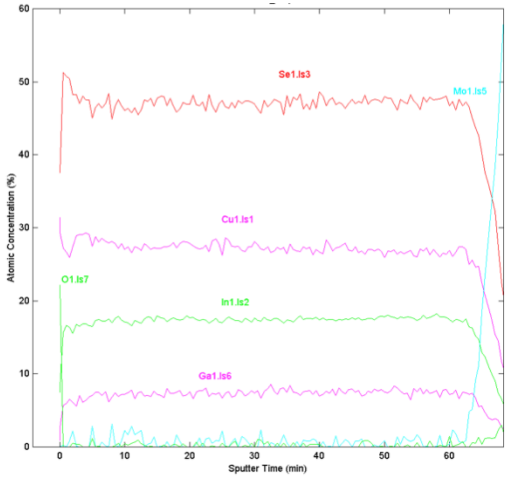
Increase η across CIGS band-gap range

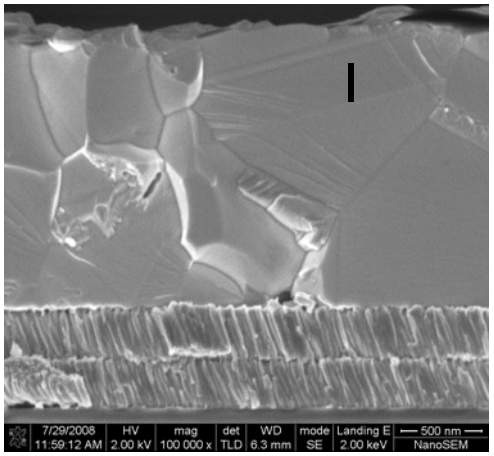


Approach

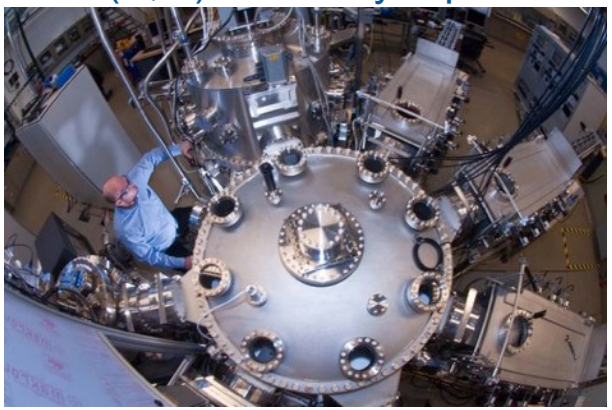
- Demonstrate higher η device (23%) and larger process window (higher evap process T, reduced Ga content).
- Optimize layer stack enabling much faster selenization process (Se vapor).
- Optimize emitter layer and process (CBD vs. sputter ZnS:O).
- Continue to investigate impact of CIGS defects on Voc and FF.

Fast, 2-step selenization process (10X faster than state of the art)



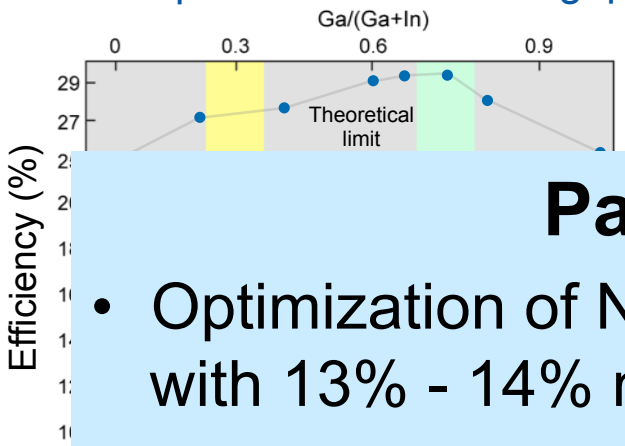


Fast Zn(S,O) buffer layer processes



CIGS PV Research: Enable Low Cost HVM

Increase η across CIGS band-gap range



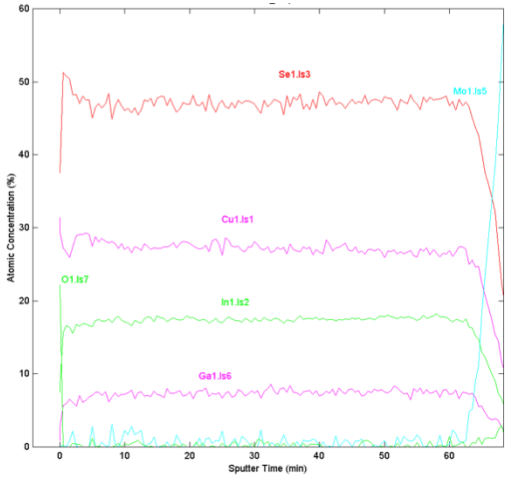
Approach

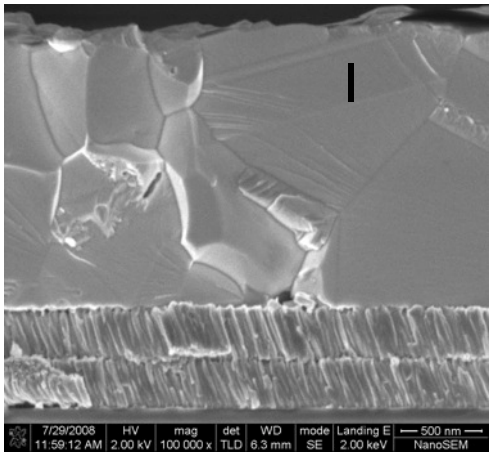
- Demonstrate higher η device (23%)

Path to SunShot Goal

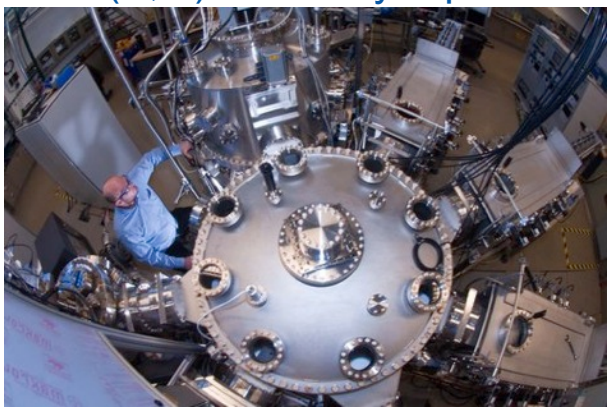
- Optimization of NREL CIGS process leads to ~50¢/W with 13% - 14% module efficiencies.
- Improvements in production cell efficiency with low to zero incremental cost is likely and should drive panel cost to 40¢ - 50¢ per Watt.

(10X faster than state of the art)

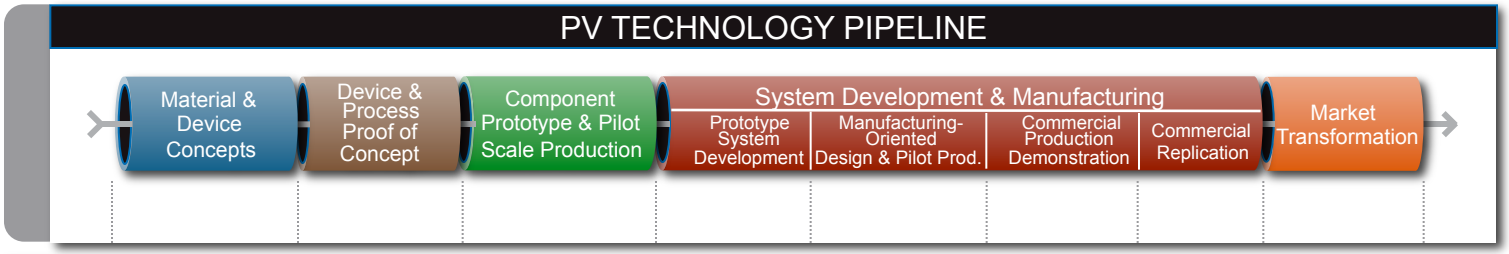


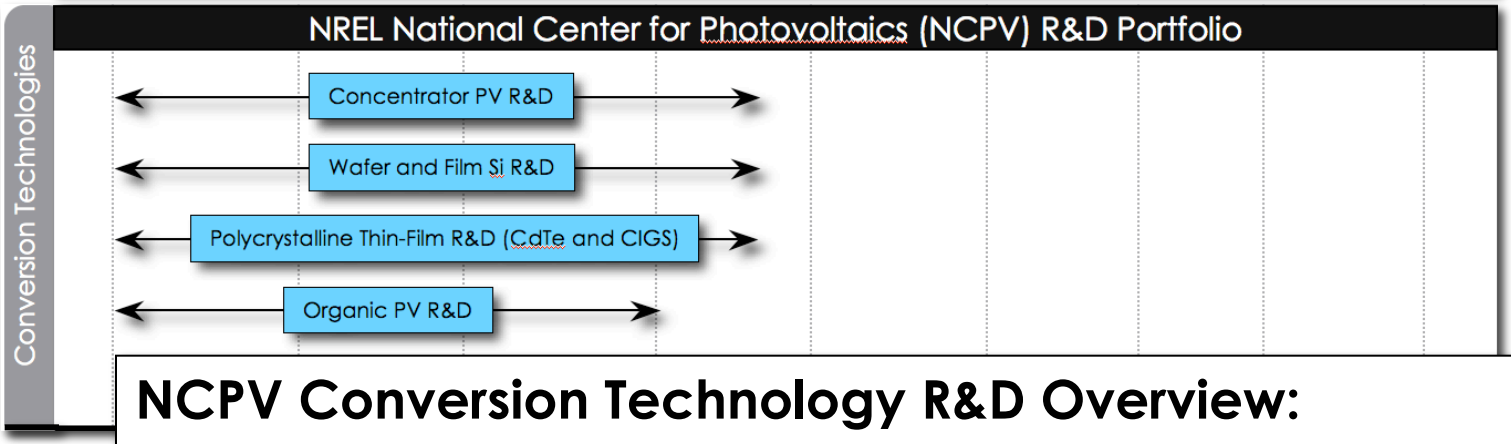


Fast Zn(S,O) buffer layer processes



NCPV Conversion Technology R&D Portfolio





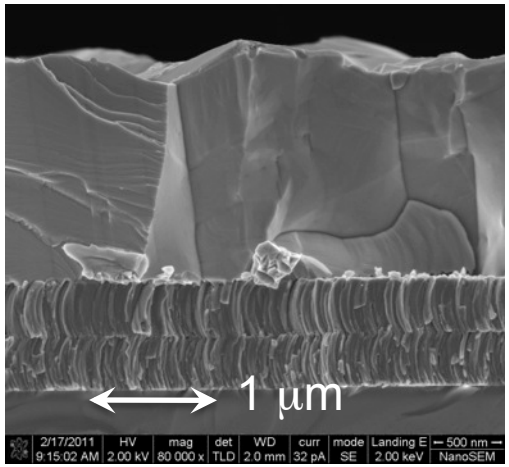
NCPV Conversion Technology R&D Overview:

- CIGS
  - Can be flexible, potential for > 20% η
- CZTS

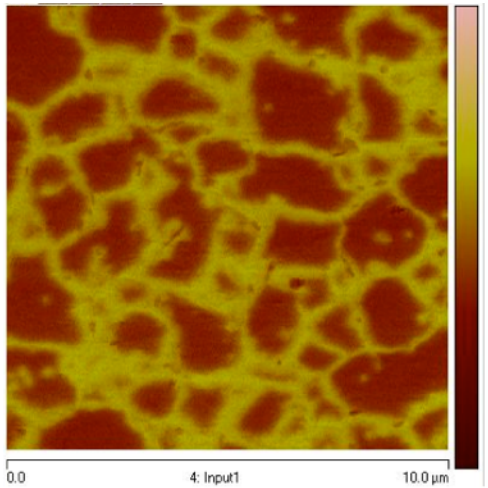
CZTS Thin Film Solar Cells

Achieved **9.2% cell efficiency**

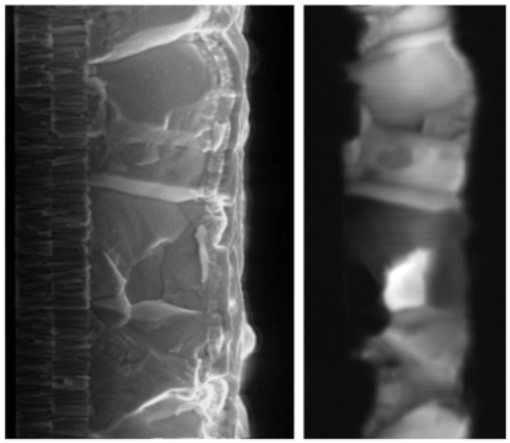
Project started in FY11 made rapid progress in less than two years



Large grains, Compact film, like CIGS.

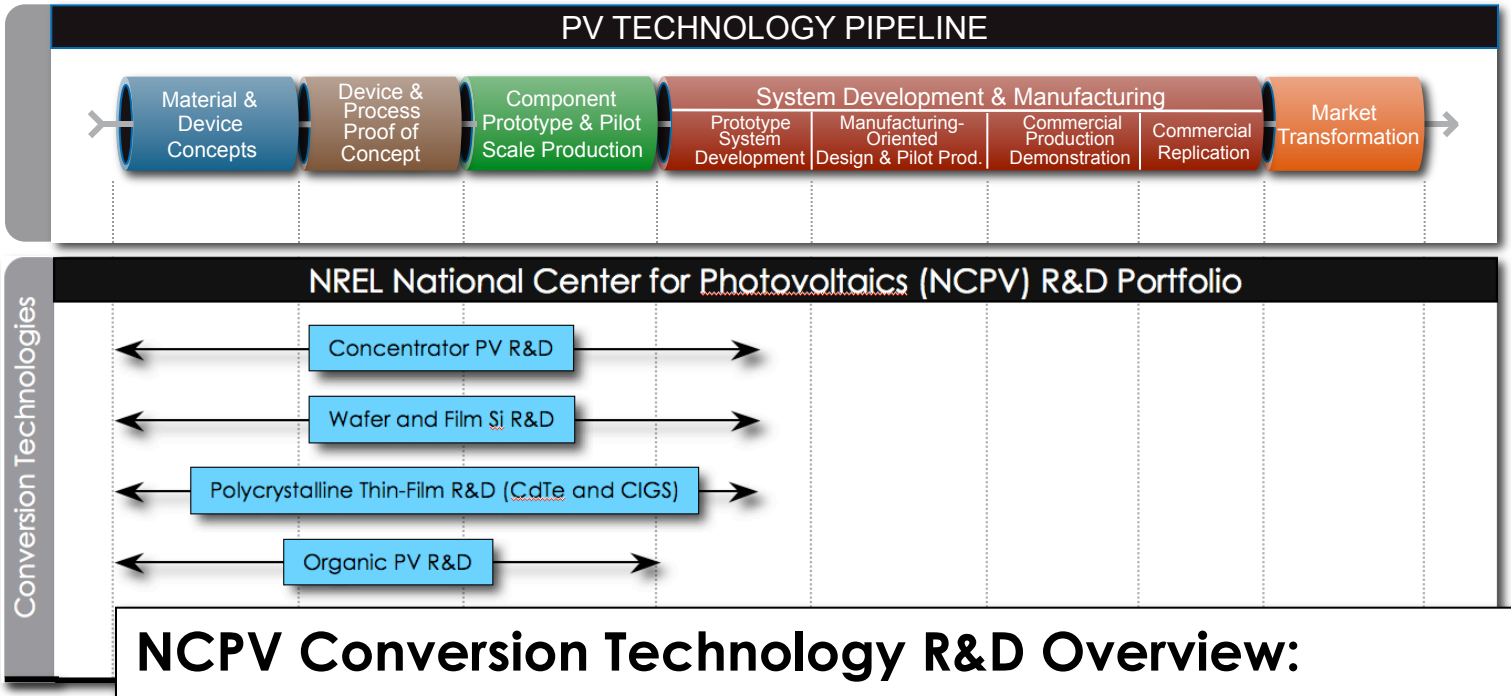


100's meV potential barrier at grain boundaries, like CIGS.



- **Some grains show high collection and flat response.**
- **Some grains nearly inactive.**
- **TEM studies in literature also indicate some grain-to-grain nonuniformity.**

NCPV Conversion Technology R&D Portfolio



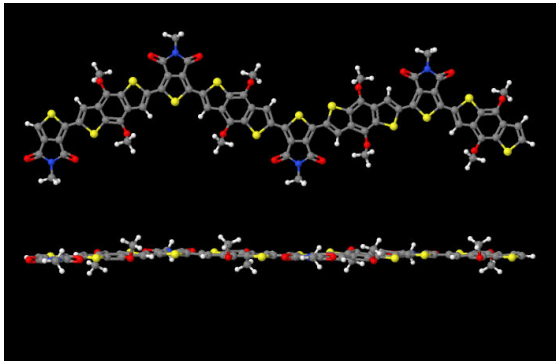
NCPV Conversion Technology R&D Overview:

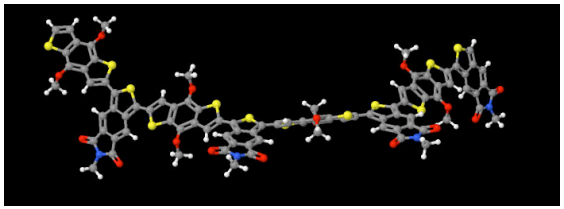
- Organic PV (OPV) — Flexible, potentially very low cost

OPV Materials Design and Characterization

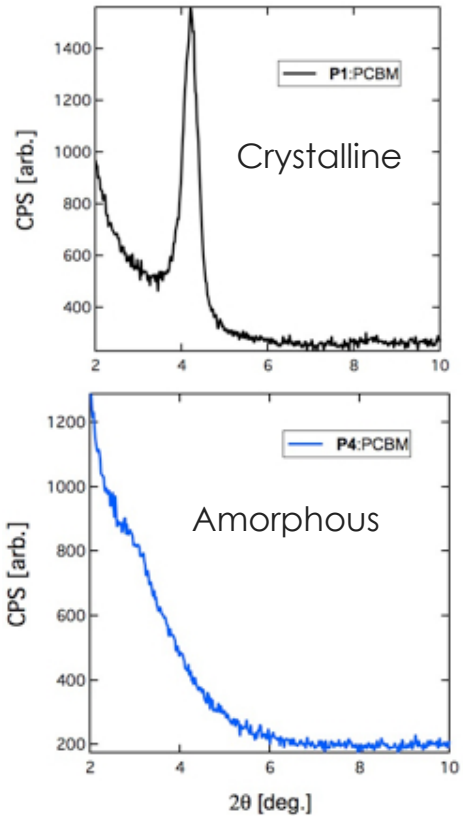
Combinatorial Computation & Theory → Synthesis → Characterization → Device optimization

Theory - DFT



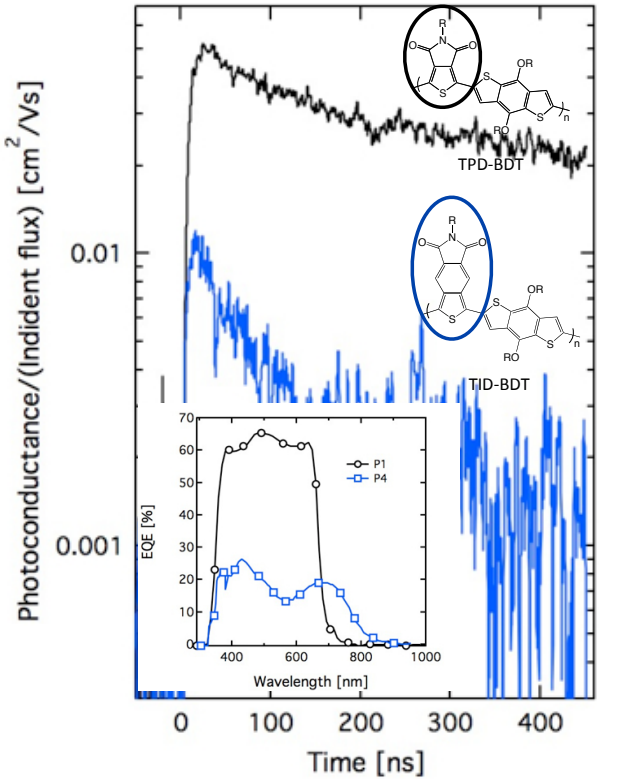


Structure - XRD



Charge Generation

Time Resolved Microwave Conductivity (TRMC)



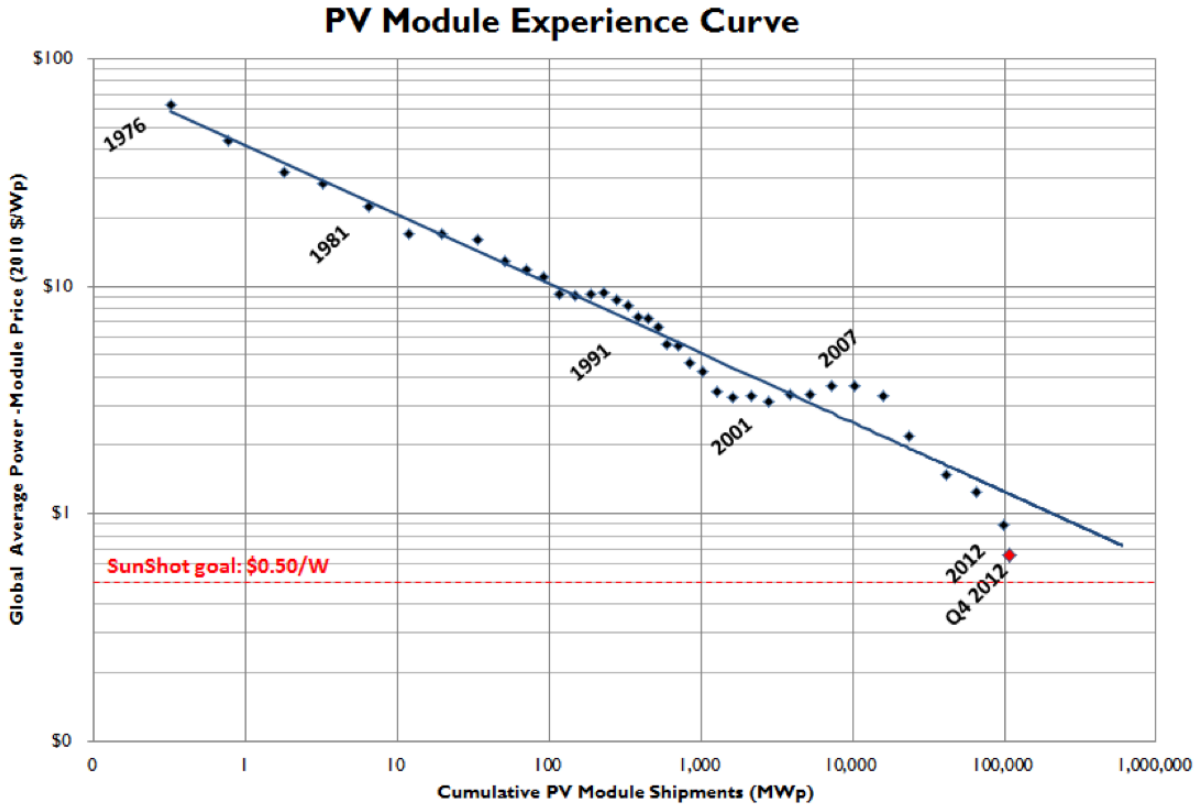
- Planar structure of **BDT-TPD** leads to ordered films and longer photocarrier lifetimes
- **BDT-CID** shows an amorphous structure consistent with calculations

W. Braunecker, *Chem. Mater*. DOI:10.1021/cm2038427

Review - SunShot Goal

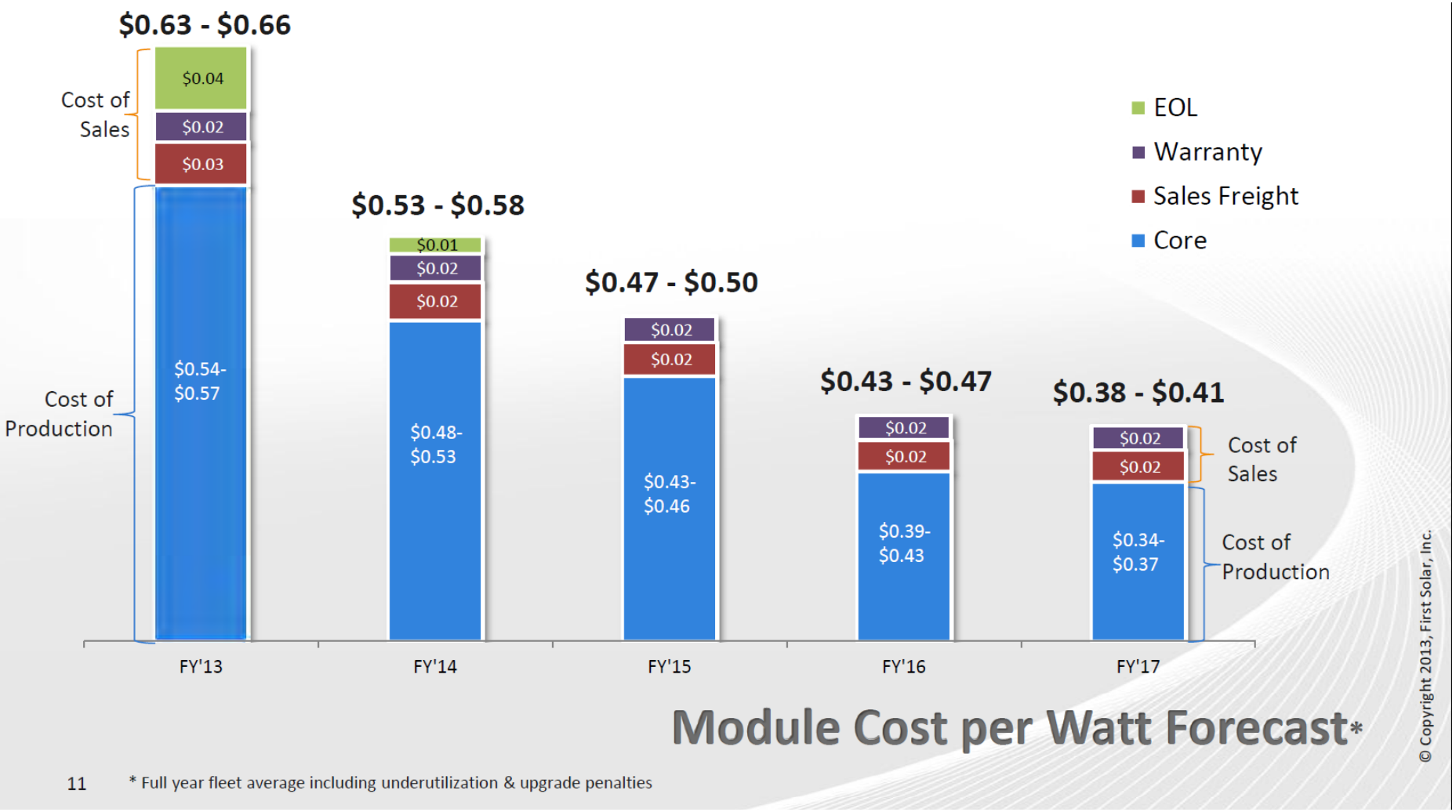
- Grid Parity by 2020.
- $1/Watt installed PV (5MW scale), 50¢/Watt module price.
  - Equivalent to 5-6 cents per kilowatt hour.
  - Competitive with fossil energy.
  - Rapid growth without incentives.

Towards SunShot



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).

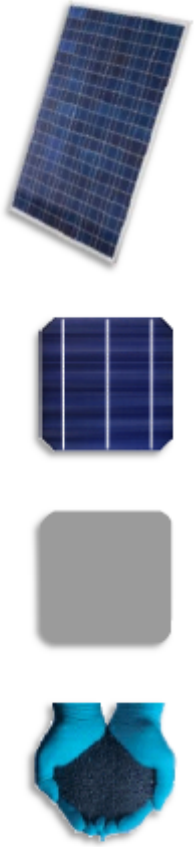
Cost Forecast – First Solar



11 * Full year fleet average including underutilization & upgrade penalties

FSLR plans to cut their costs nearly in half over the next 4 years, <u>again</u>.

Cost Forecast - SunEdison



“440 Goal”

- 400Wp Module
- at $0.40/Wp
- by 2016

Note : Cost includes opex, silicon, son-silicon, depreciation, warranty and inbound freight and excludes corporate general & admin. expenses)

Capital Markets Day | March 13, 2013

51

SunEdison

SunEdison has a cost roadmap similar to FSLR’s.

Beyond SunShot

So what will be the impact of 1 or more PV conversion technologies achieving the SunShot goal?

- Utilities can and will continue to limit PV penetration around the world until the PV business model works for them…
  - ➔ PV market growth will continue to be constrained without breakthroughs related to **cost effective energy storage**.
- **PV system reliability** will continue to be closely watched by the project finance investment community…
  - ➔ Module failures above some critical threshold could severely limit willingness to raise capital for new projects.
- If the above problems are managed then **PV terawatt scalability** will become the next major challenge…
  - ➔ Earth abundant materials and energy payback time will determine which PV conversion technologies win market share.

Summary

- Great world-wide progress over the last 10 years in demonstrating multiple PV conversion technologies.
- Crystalline Si PV based on both cSi and mcSi wafers will continue to dominate the industry for a number of years but more efficient use of high purity Si must be part of Si PV's terawatt scale future.
- In spite of current headwinds, polycrystalline thin film technologies continue to have the potential to compete effectively with mcSi PV technology over the longer term.
- Module efficiency, energy payback and earth abundance of materials will become increasingly important as PV moves "beyond SunShot" towards the terawatt scale.

Thank You