Venture Investing in Solar - 2007/2008

Investment Theses, Market Gaps, and Opportunities

CRAIG CORNELIUS, PROGRAM MANAGER

http://www.eere.energy.gov/solar/solar_america/

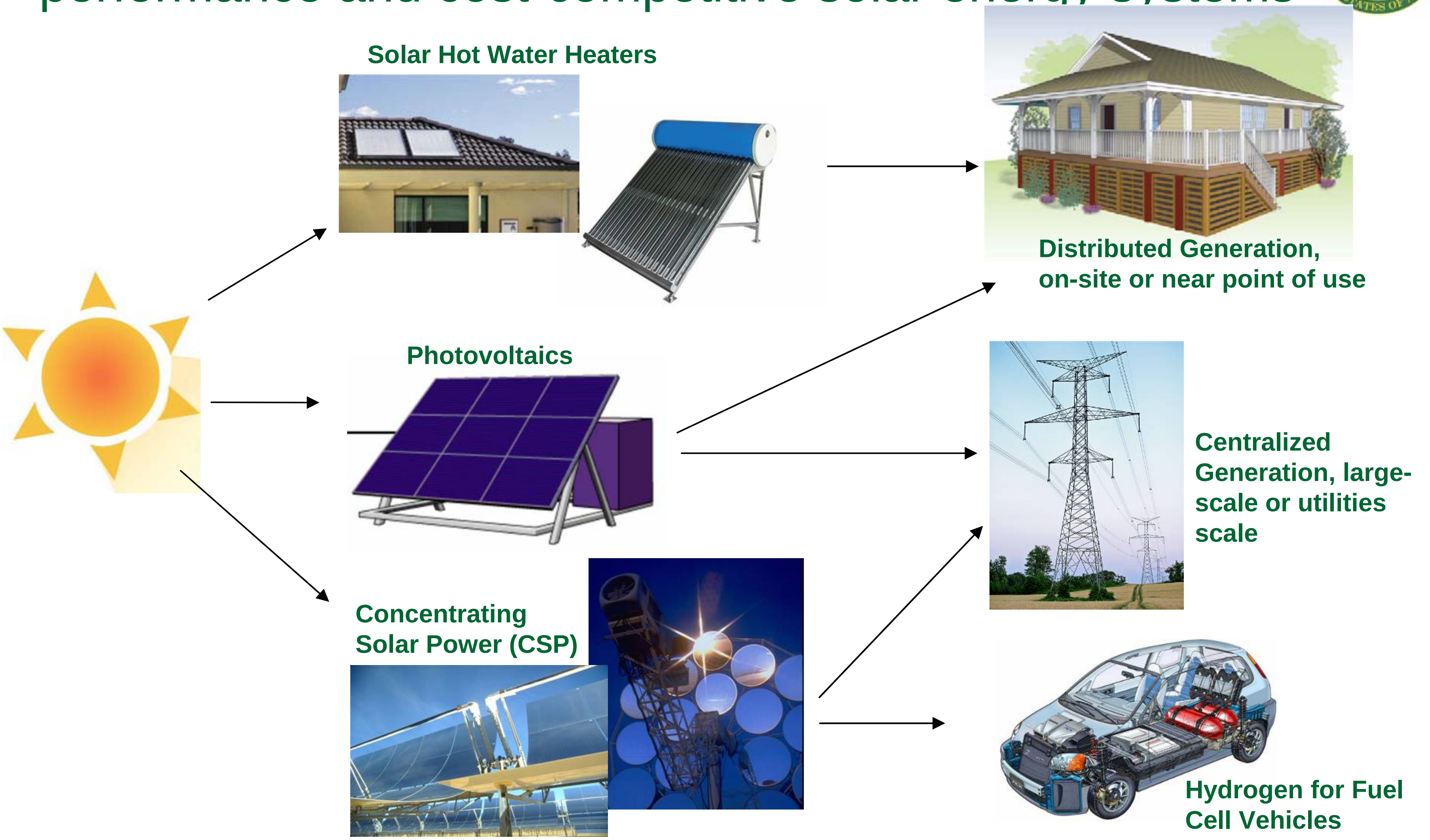
Email: craig.cornelius@ee.doe.gov

Tel: 202-586-1201

Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment “Gap” Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

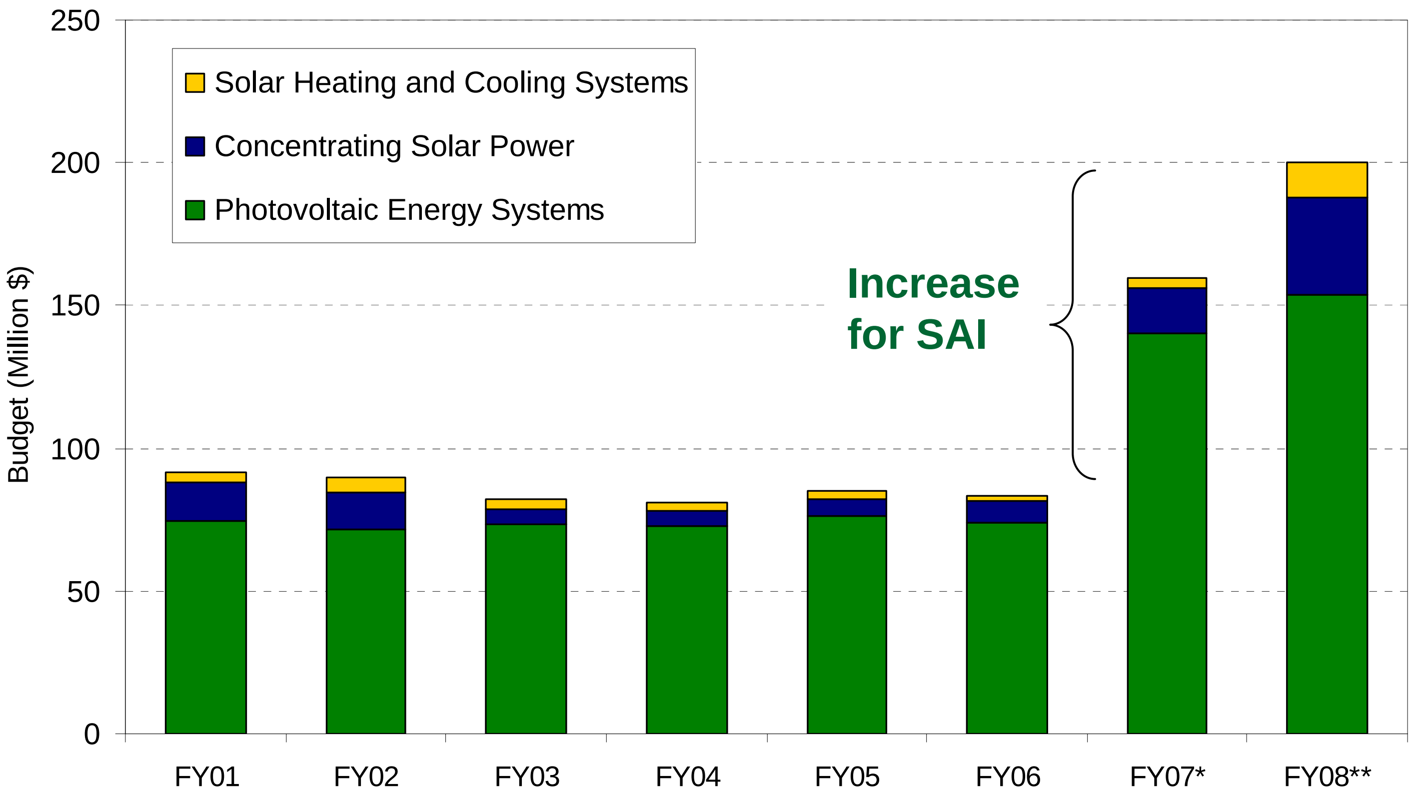
DOE's Solar Program researches and deploys high-performance and cost-competitive solar energy systems



Solar energy provides renewable and carbon-free energy to help ensure secure and affordable energy supplies and to address climate change

Funding for the Solar America Initiative will accelerate supply growth & adoption of PV/CSP technologies

Solar Energy Technologies Funding, FY01 – FY08



With one last investment push, the Federal government will realize full value of 30-years of RD&D with a major new CLEAN energy source.

* President's Request for FY07 was $148M, final FY07 CR provided $159M.
** President's Request for FY08 was $148M, current House mark for FY08 is $200M.

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Solar America Initiative Across America

Activities:

Transforming Markets and Creating Demand

Codes and Standards:
Solar America Board of Codes and Standards (NM)

Utility Technical Outreach:
Solar Electric Power Association (DC)

State Technical Outreach:
Clean Energy Group (VT)
National Assn of Regulatory Utility Commissioners (DC)
National Conference of State Legislatures (CO)

Solar America Cities:
Ann Arbor (MI)
Austin (TX)
Berkeley (CA)
Boston (MA)
Madison (WI)
New Orleans (LA)
New York (NY)
Pittsburgh (PA)
Portland (OR)
Salt Lake City (UT)
San Diego (CA)
San Francisco (CA)
Tucson (AZ)

Solar America Showcases:
City of San Jose (CA)
Forest City Military Communities (HI)
Orange County Convention Center (FL)

PV Capacity Credit Valuation Study:
State University of New York (NY)
Tucson Electric Power (AZ)

SAI Federal Projects:
Architect of the Capitol (DC)
Smithsonian Institution (DC)

The Solar America Initiative (SAI) is accelerating the development of solar technologies, including photovoltaics (PV) and concentrating solar power (CSP) systems, with the goal of making them cost-competitive across all sectors by 2015. This work could not be successful without the collaboration of all stakeholders in the solar community. This map illustrates the location of several SAI participants…from Solar America City awardees who will be developing solar projects and building awareness in their respective communities to multinational corporations who will work in strategic alliances with other companies, national laboratories, and universities to tackle solar manufacturing challenges. It is truly a nationwide effort to create a Solar America.

Developing Products and Building Supply

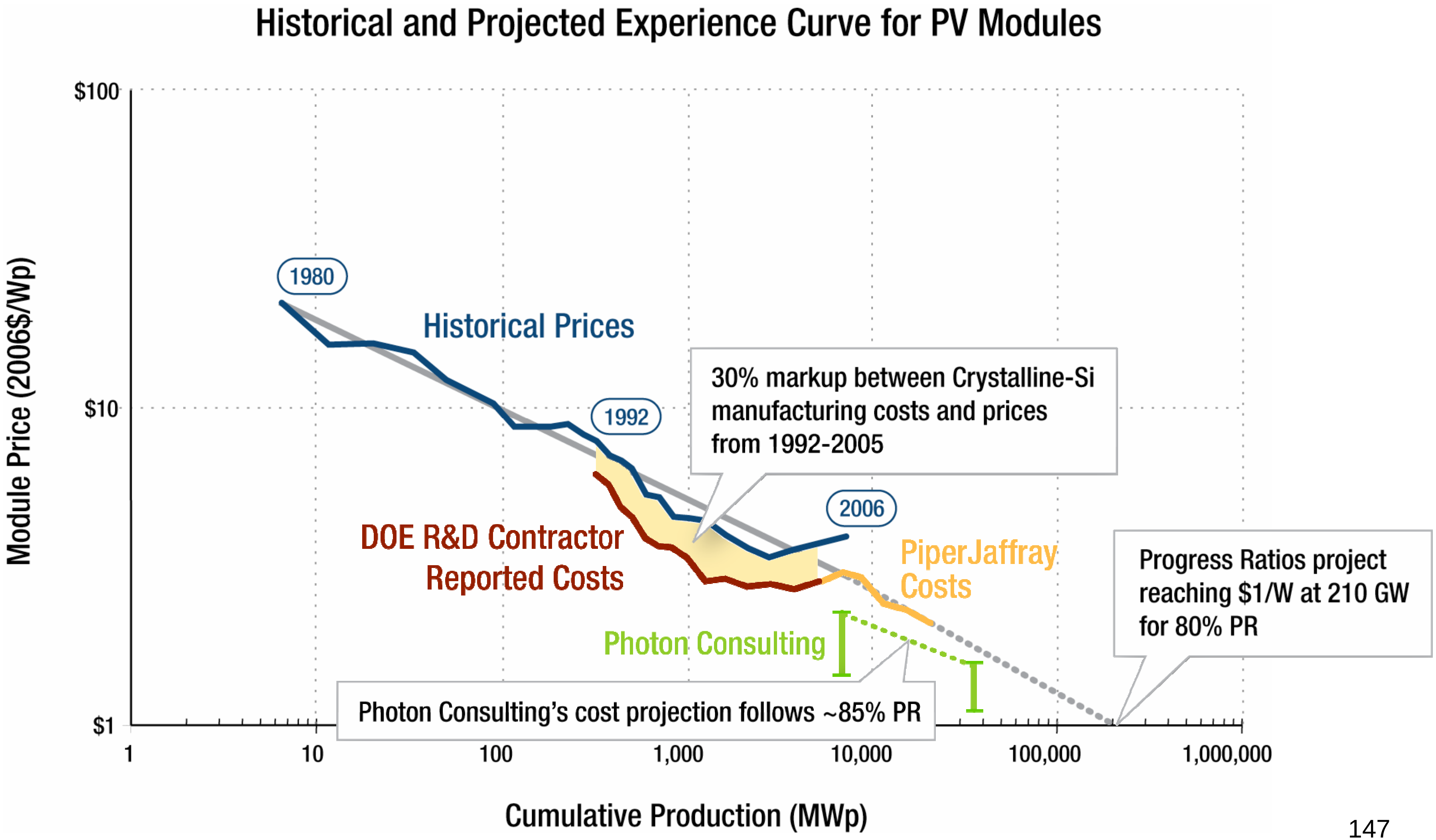
Technology Pathway Partnerships:
Amonix (CA)
Boeing (CA)
BP Solar (MD)
Dow Chemical (MI)
General Electric (DE)
GreenRay (MA)
Konarka (MA)
Miasolé (CA)
Nanosolar (CA)
Soliant (CA)
SunPower (CA)
United Solar Ovonic (MI)

PV Module Incubator:
AVA Solar (CO)
Blue Square Energy (MD)
CaliSolar (CA)
EnFocus Engineering (CA)
MicroLink Devices (IL)
Plextronics (PA)
PrimeStar Solar (CO)
Solaria (CA)
SolFocus (CA)
SoloPower (CA)

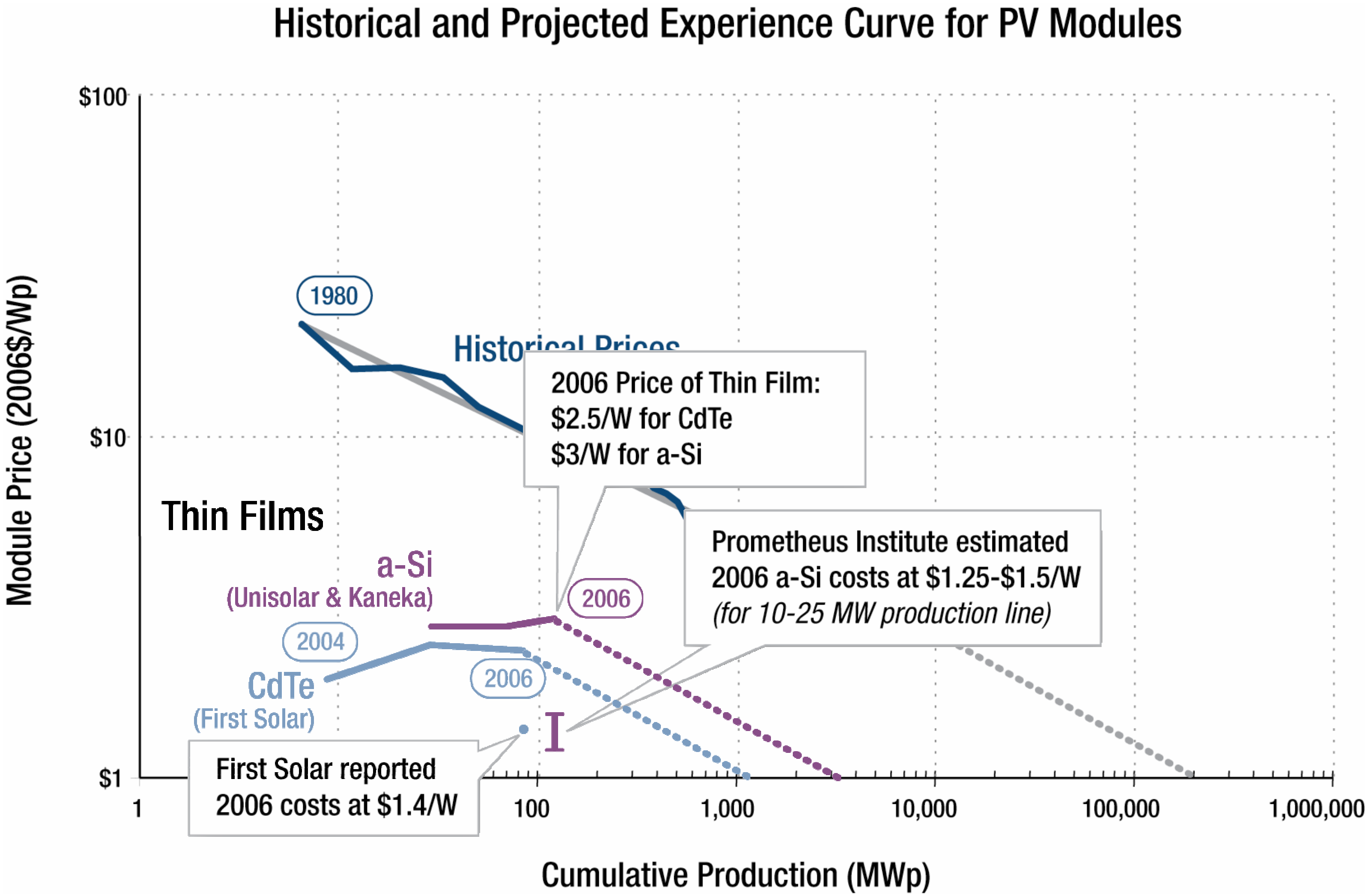
Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment "Gap" Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

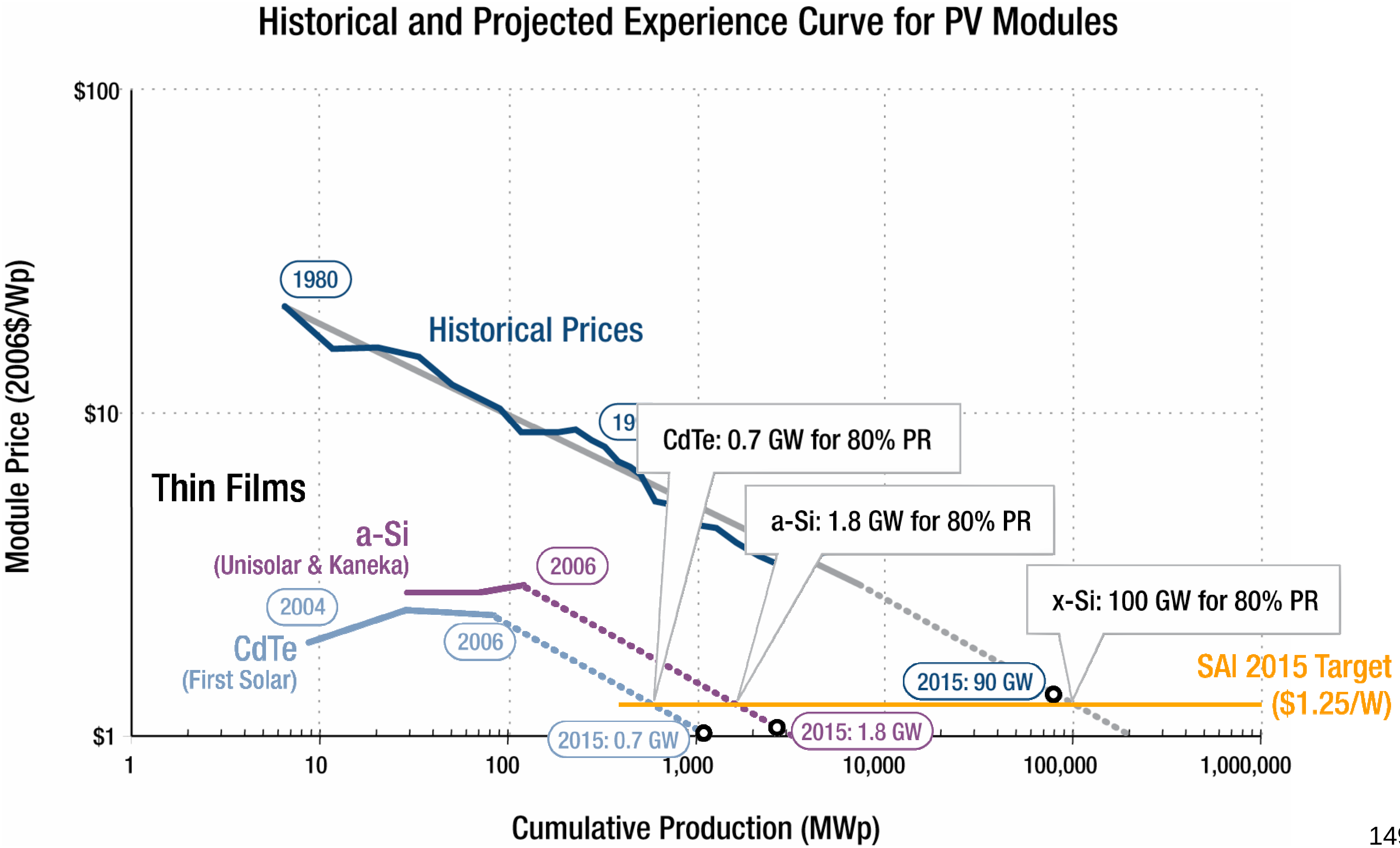
PV industry is approaching grid parity across OECD, due to virtuous cycle of policy-driven demand creation, capital investment, and production growth



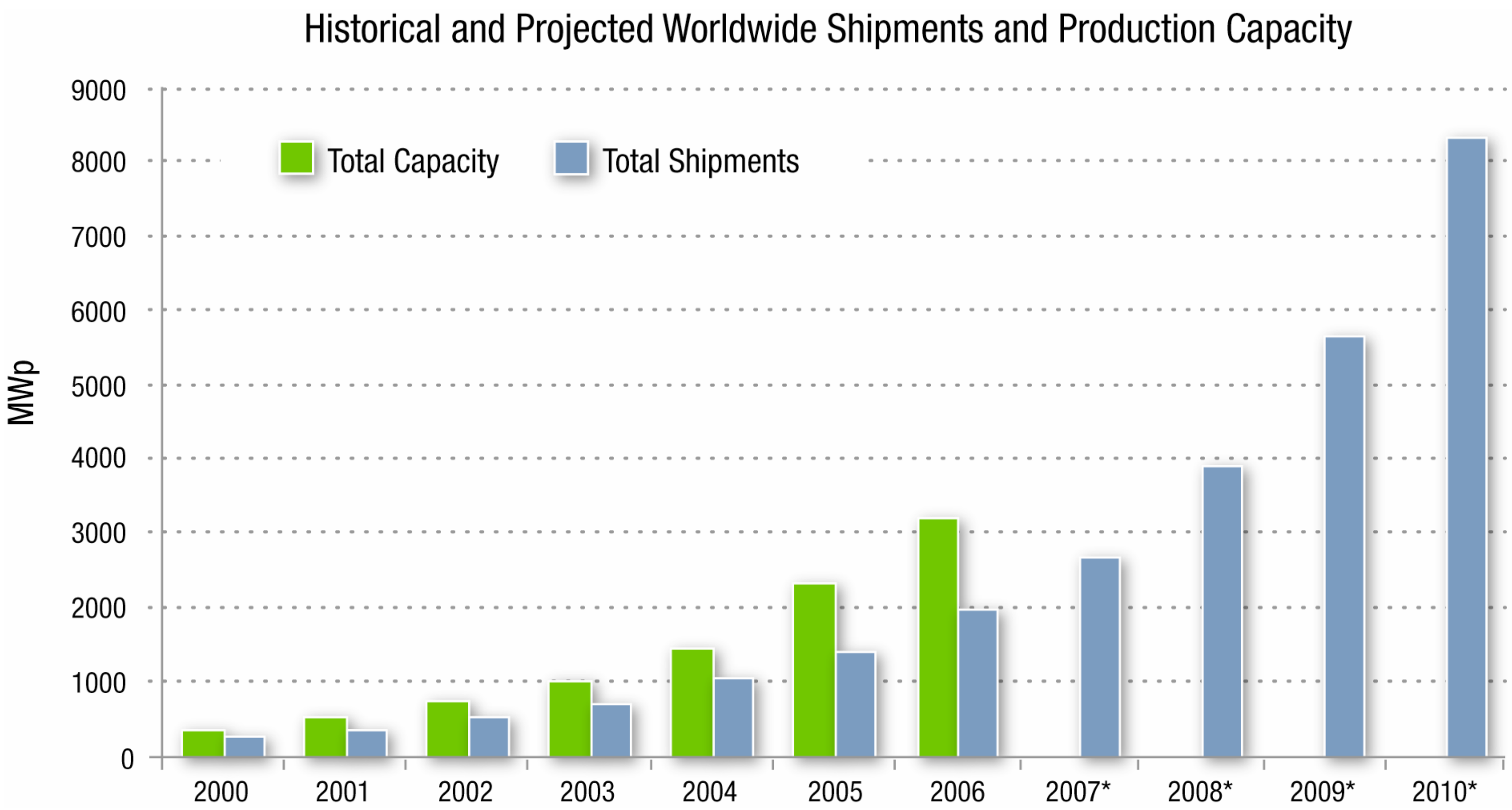
Emerging thin film suppliers exhibit initial cost advantage – but to sustain it they must deliver on learning curves and make up some share of performance disadvantage



PV industry (both c-Si and TF's) can achieve nationwide price parity by 2015 by maintaining learning curves and gradually declining CAGR in line with historical experience



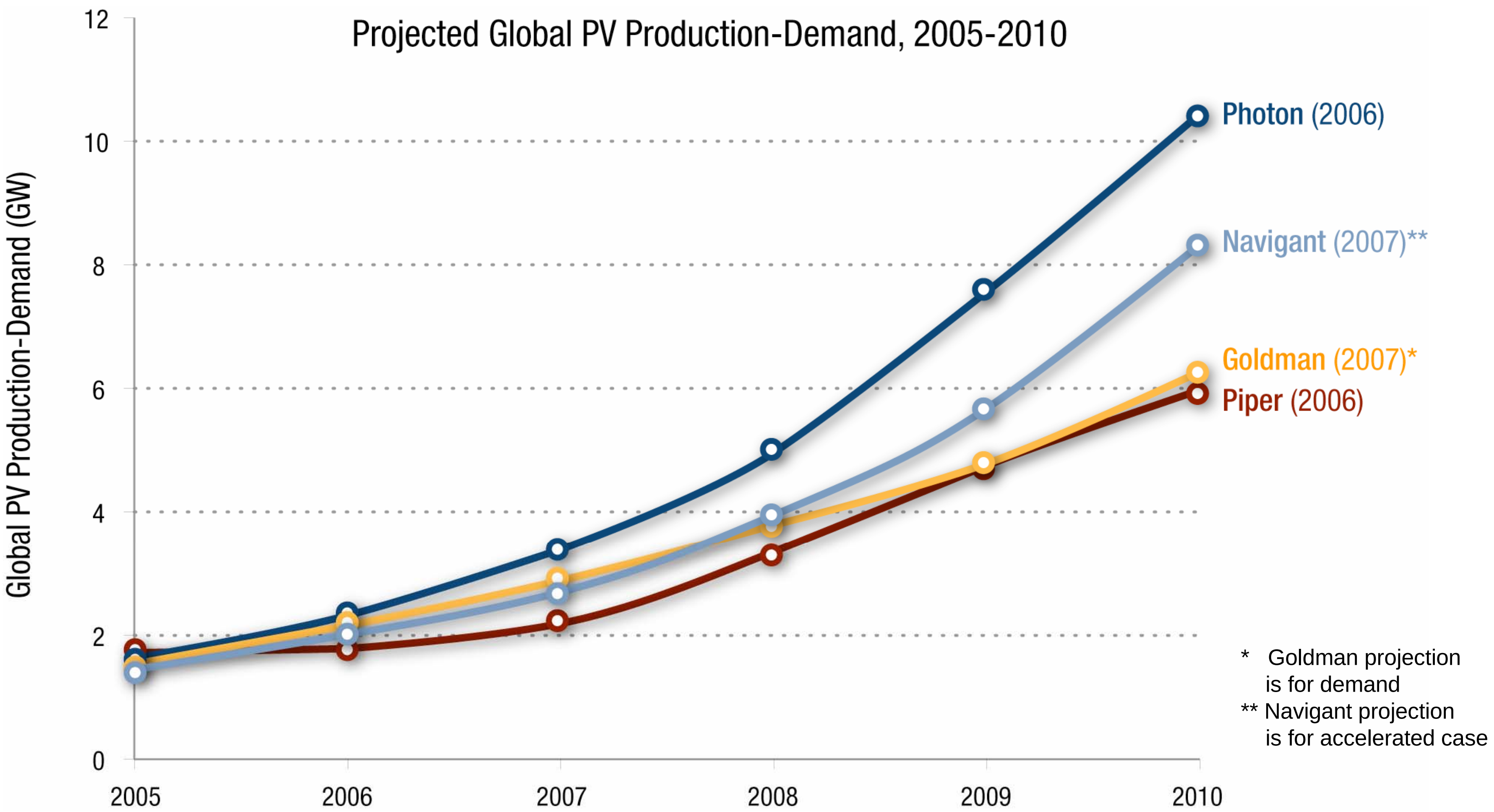
Suppliers are expanding manufacturing capacity in anticipation of production ramp in 2008-2010



* Source: Navigant Consulting 2006/2007

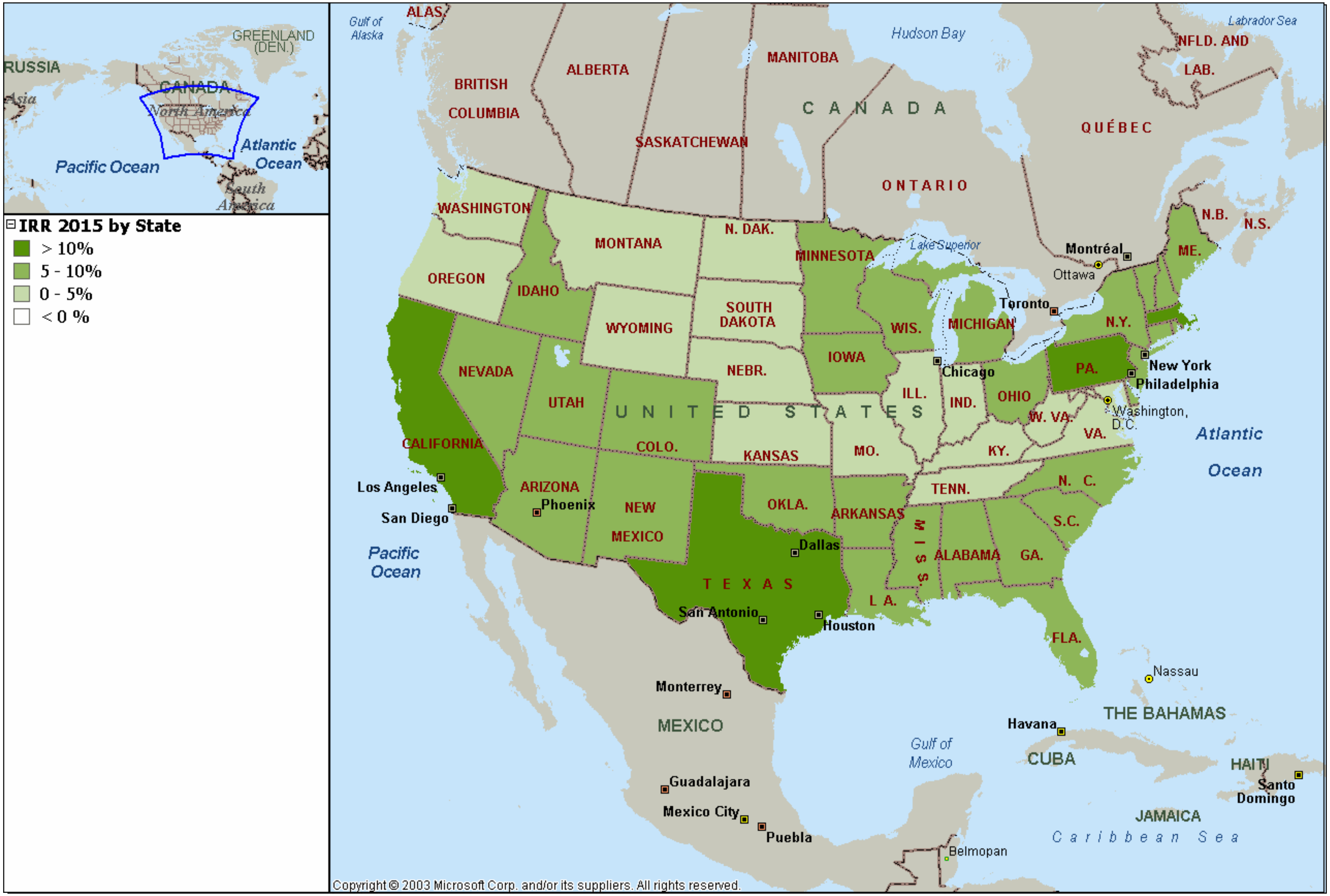
In 2008 or shortly thereafter, most of the planned additional polysilicon capacity is coming online. Along with the currently under-utilized production capacity this will allow for increased future PV shipments.

Production is expected to ramp quickly through 2010, as shipments catch up to capacity and new suppliers enter

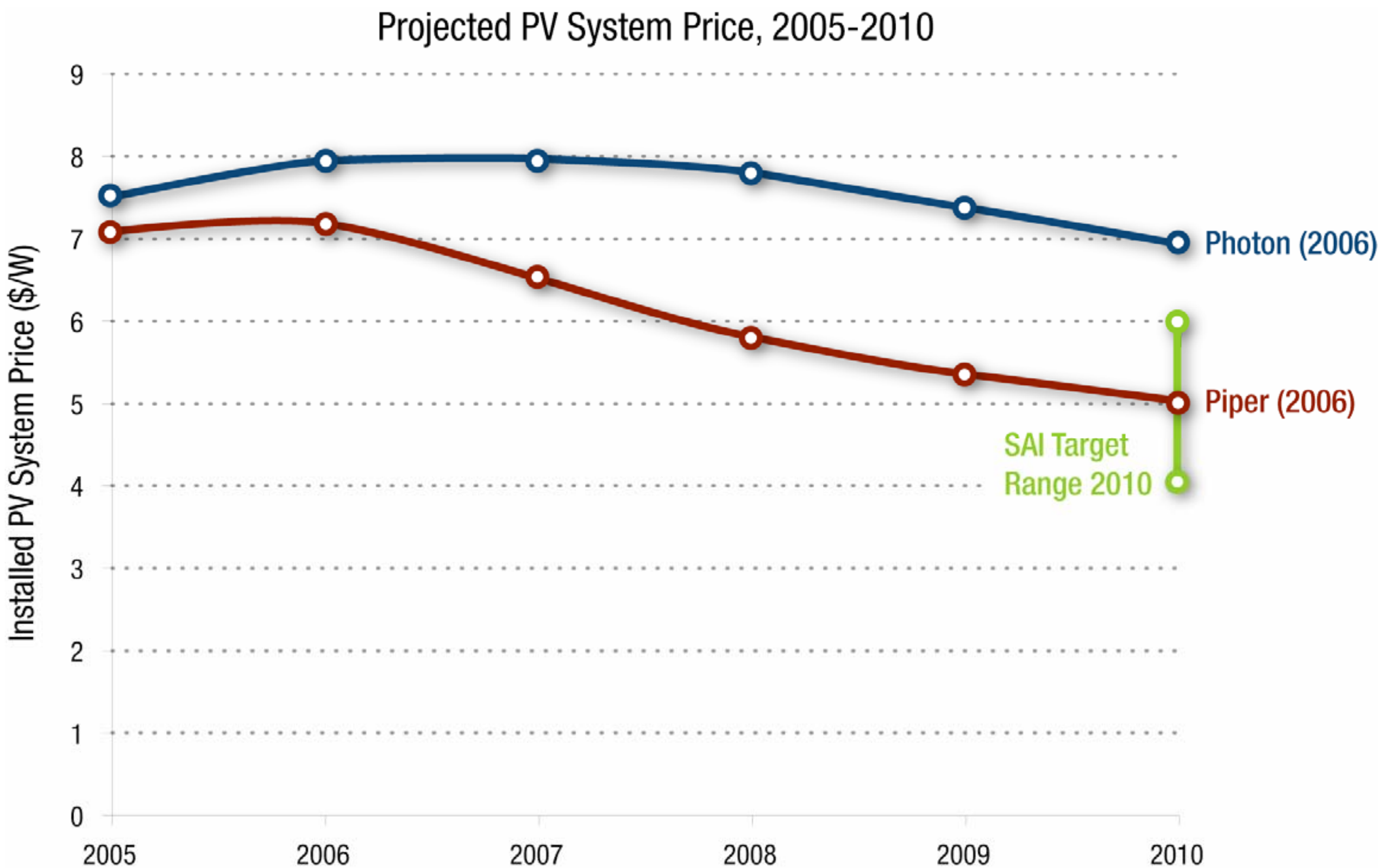


Analyst forecasts for global production/demand vary based on different expectations on ramp-rate for polysilicon, thin films, and downstream channel evolution.

Convergence of PV cost reduction, rising electricity prices, and subsidies are opening up new U.S. markets



Pricing will be stratified, cushioned by subsidies and electricity rate increases, but depressed by new capacity services markets that require lower ASP's



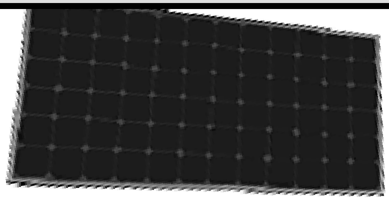
While average system ASP's are a useful indicator, ASP's will vary significantly by market – sales into Spain, Germany, California will contribute higher margins.

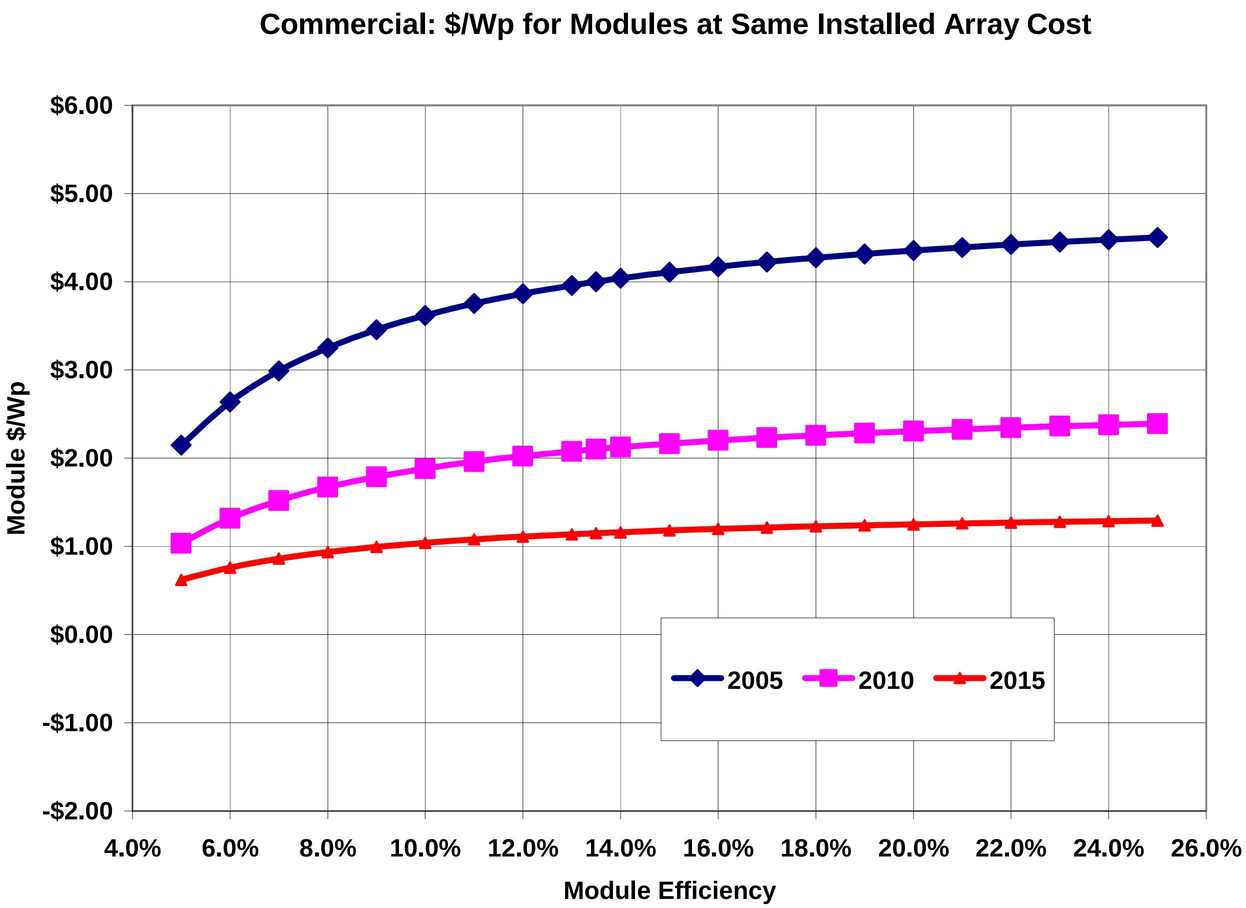
Investors and industry players rightly recognize that PV is entering a phase of commoditization, but framework still must evolve for evaluation of advantages & pricing

"3 g/W in 2010"
– Evergreen Solar

"70 ¢/W by 2012"
– First Solar

"Highest Efficiency, Smallest Footprint"
– Sunpower





Ultimately, advantages in commoditized market will be determined by combination of cost structure and product attributes that drive system-level performance/cost.

But won’t a mature commodity industry consolidate into a single winning “technology” based on lowest cost?

Aluminum – Manufacturability

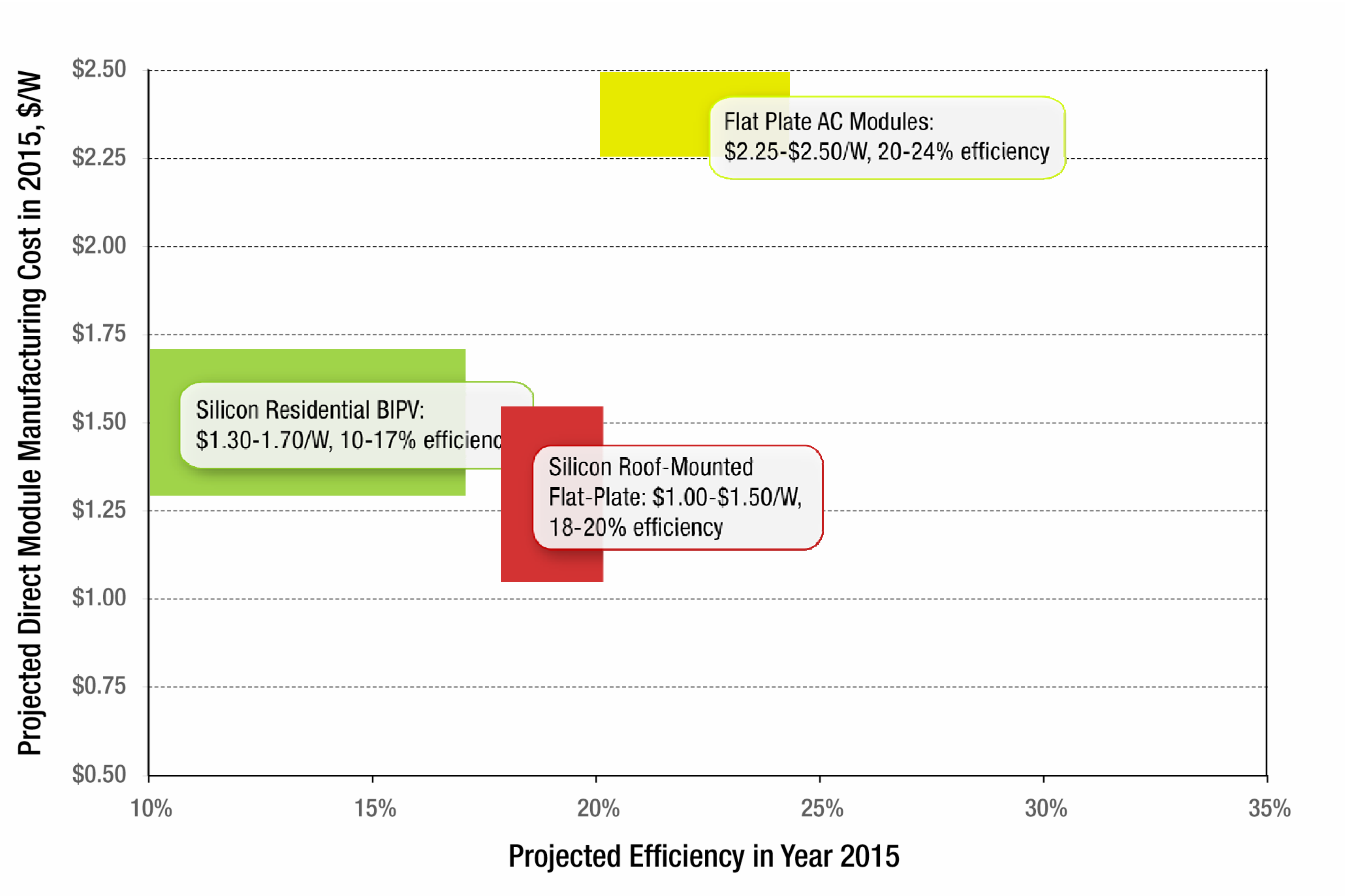
Steel – Low Price

Titanium – Durability

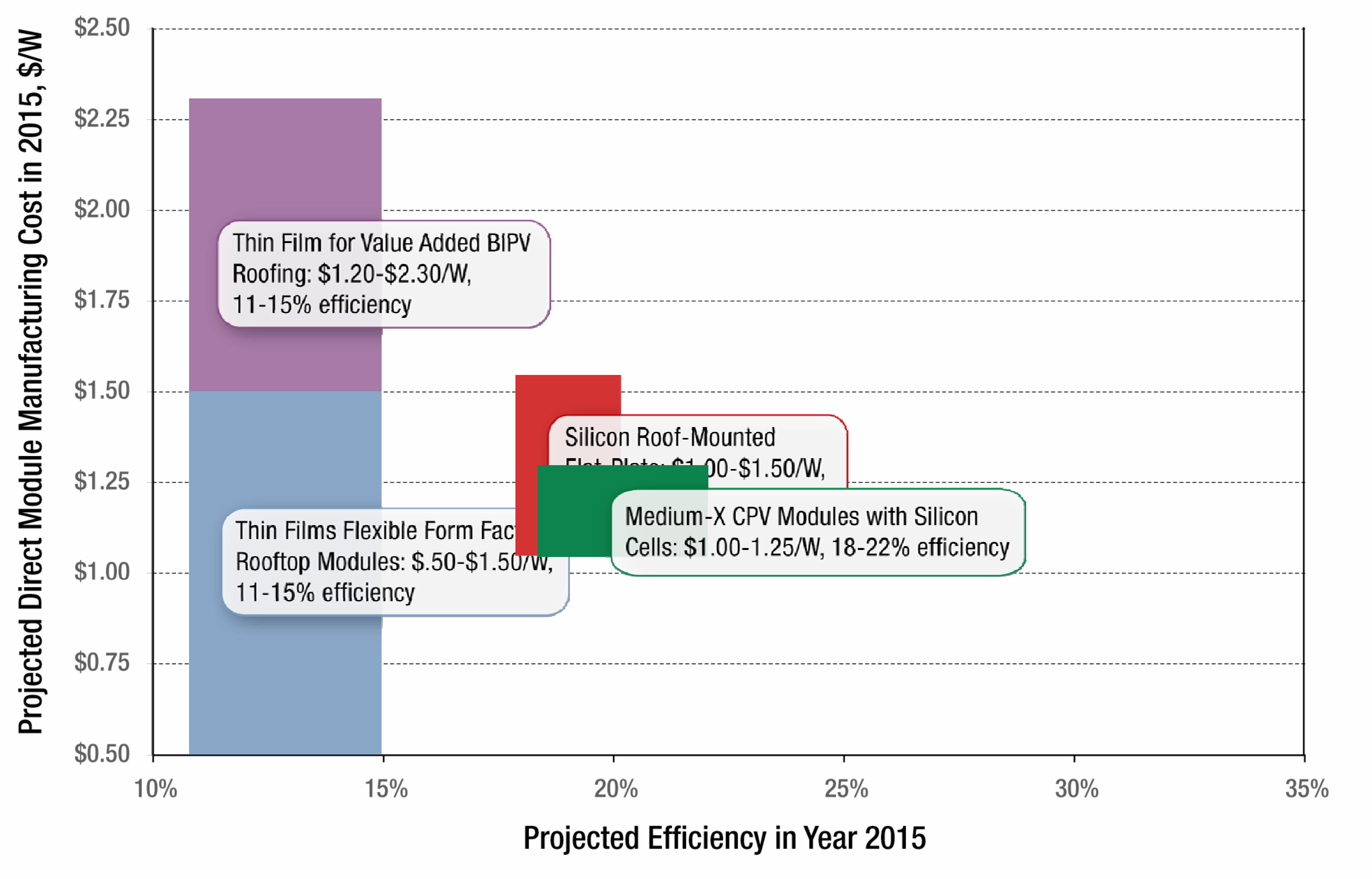
Carbon – High performance

Ultimately, PV industry will exhibit multiple commodity categories with suppliers exploiting diversified product designs for different applications.

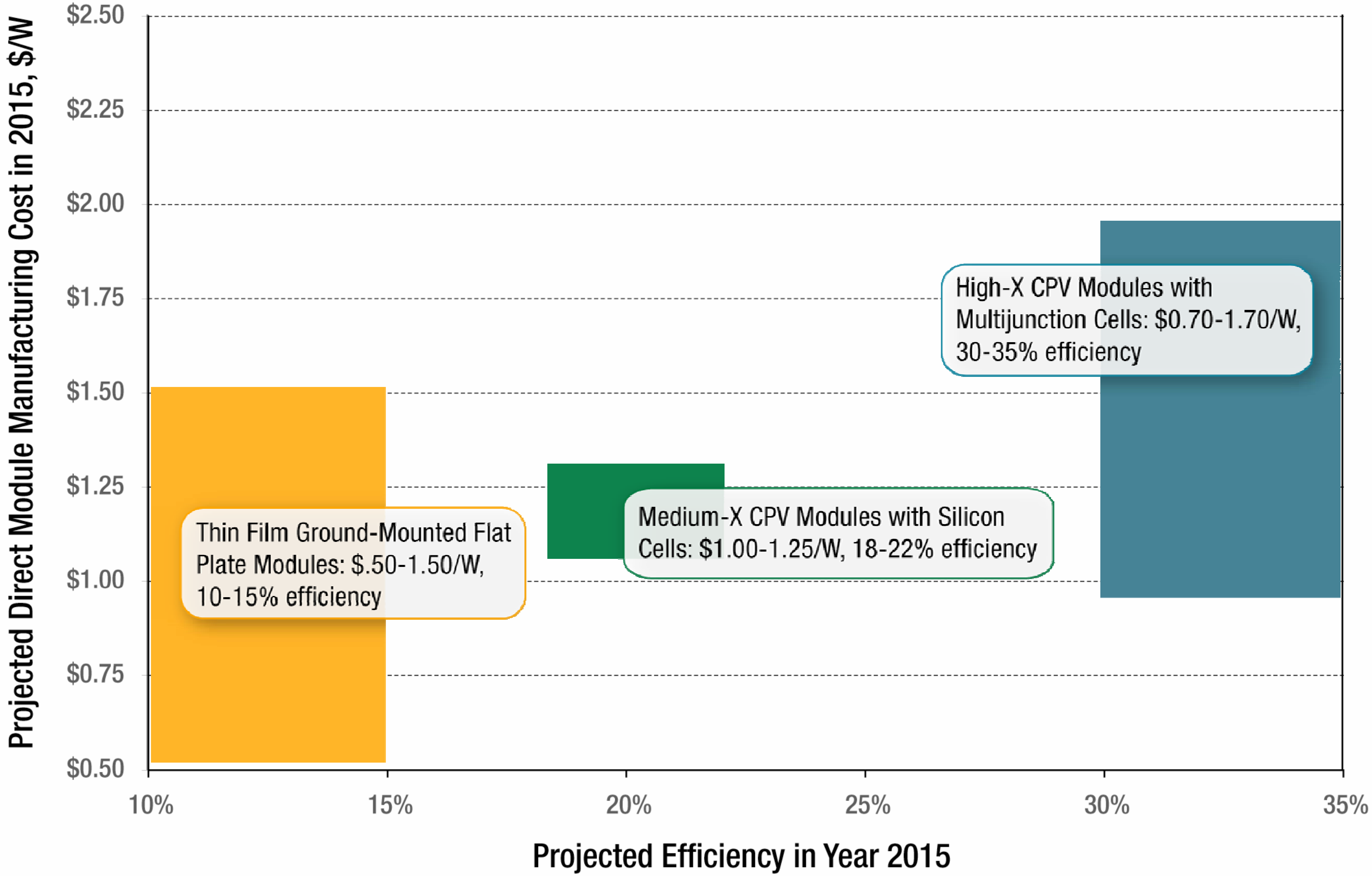
Area-constrained residential applications will require high efficiencies, but value-add can accommodate higher $/W



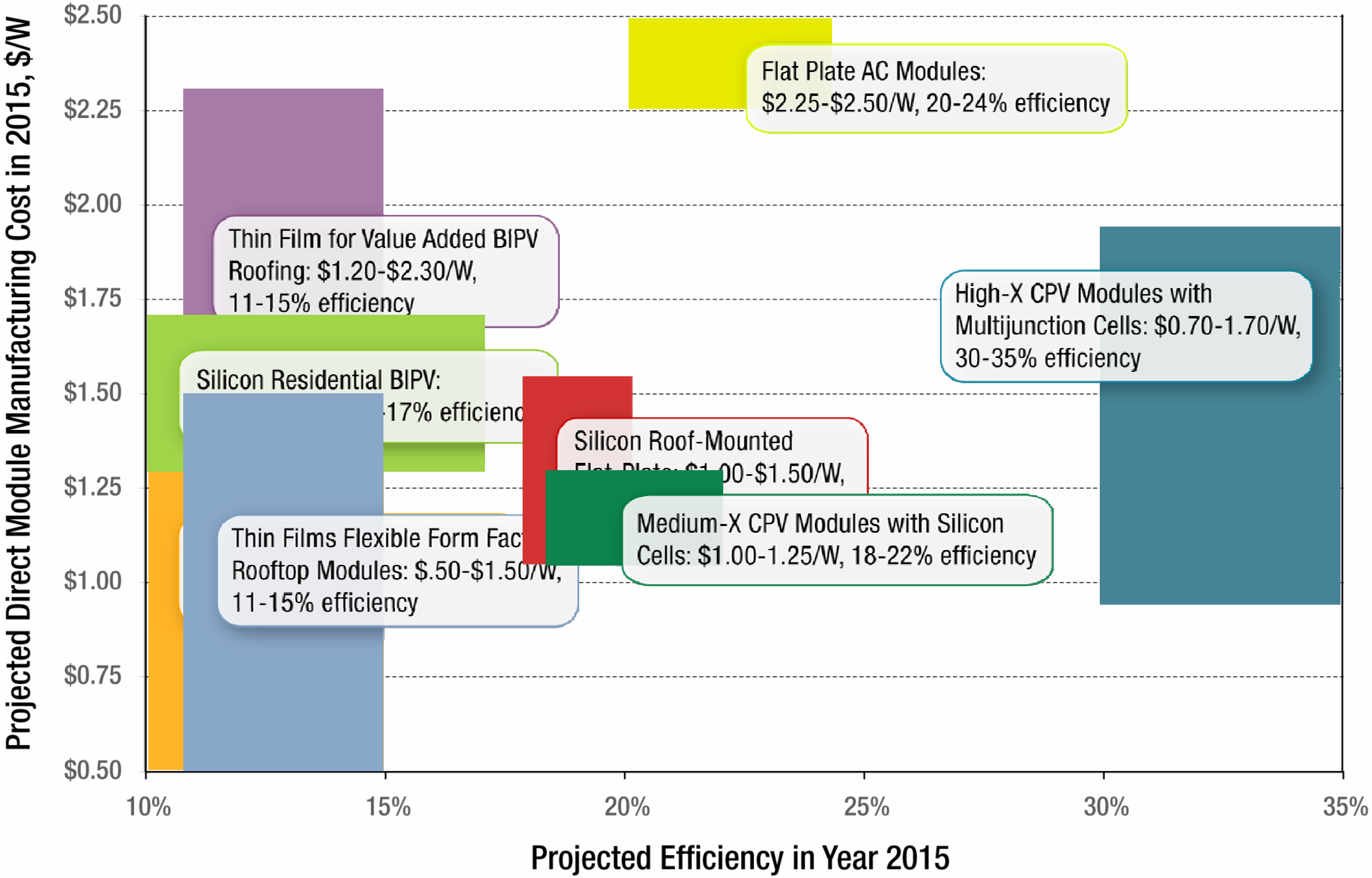
Commercial app's may accept lower efficiencies if $/W is lower and if form factor/BIPV reduce installation cost; c-Si and med-X CPV will play to customers seeking max kWh's



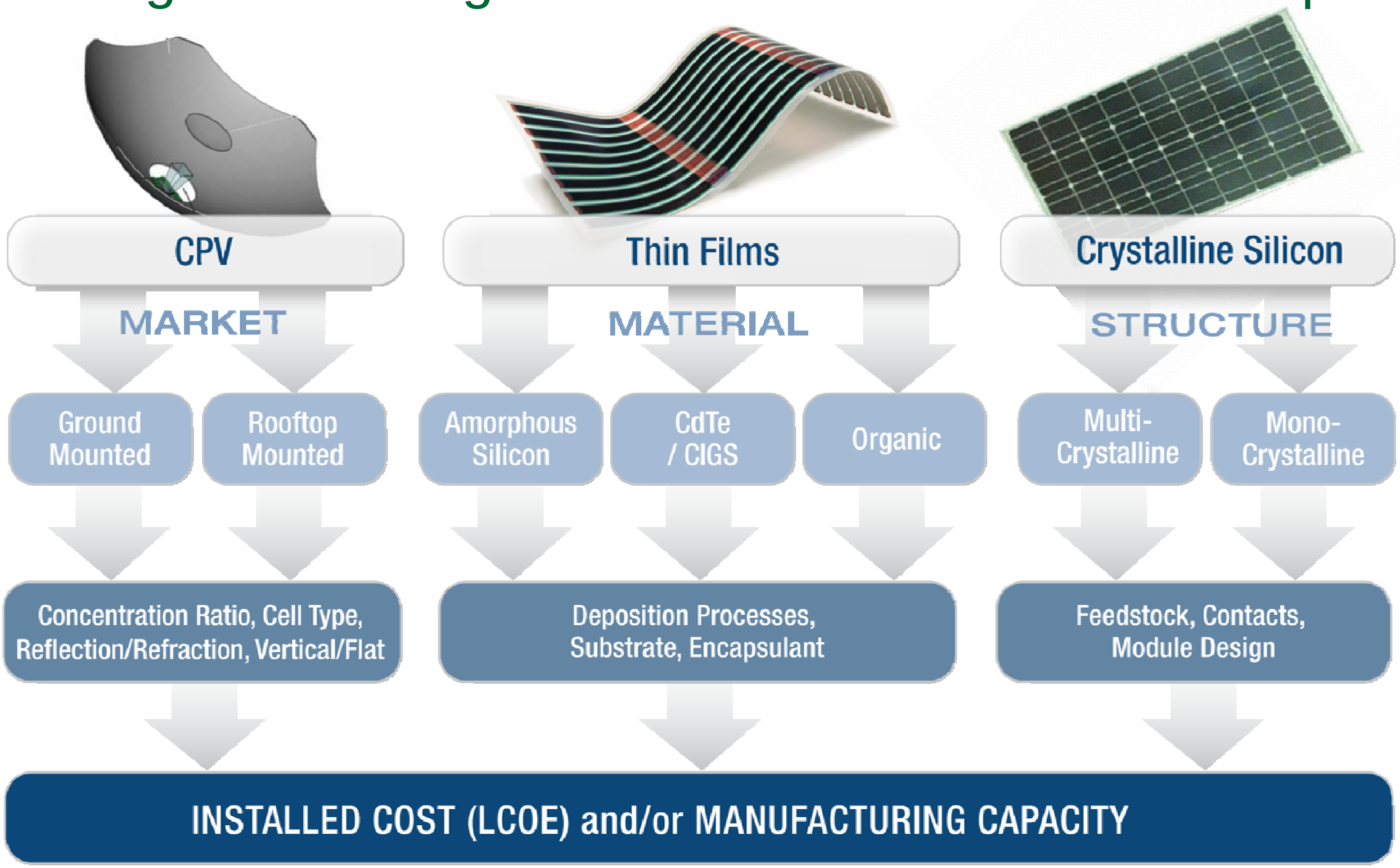
No consensus requirements for U.S. utilities yet – CPV seeing strongest interest but European-like flat plate TF module approach may play in certain circumstances



DOE will drive its R&D agenda towards optimal solutions for major markets – while consensus remains unclear, investors should focus on application fit/advantages

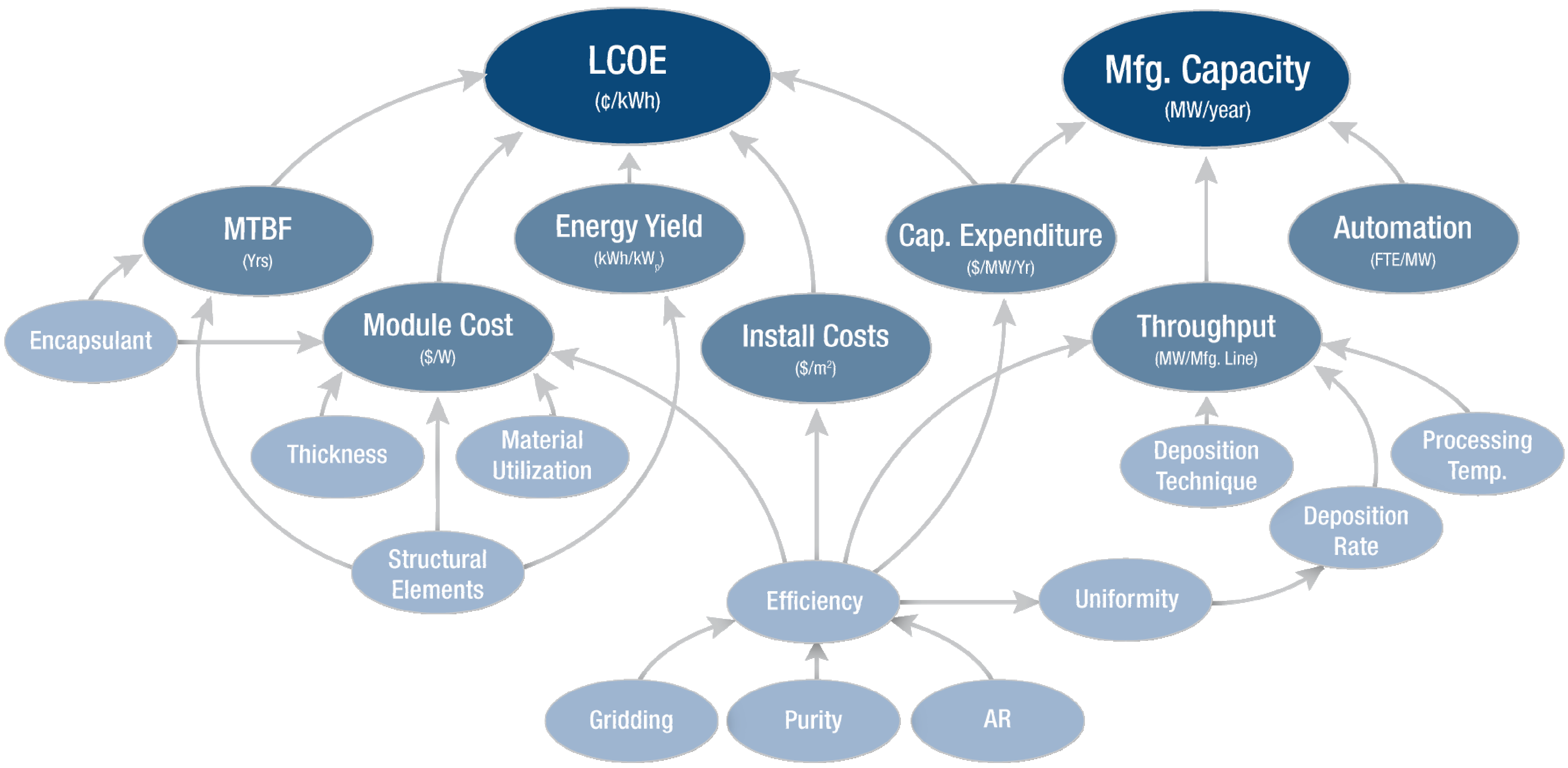


DOE approaches technology-based investments by assessing differentiation of process/performance and correlating to advantages for installed cost and scale-up



- Binning technologies allows an “apples to apples” comparison.
- Approach ensures best-in-breed funding across all promising technologies.

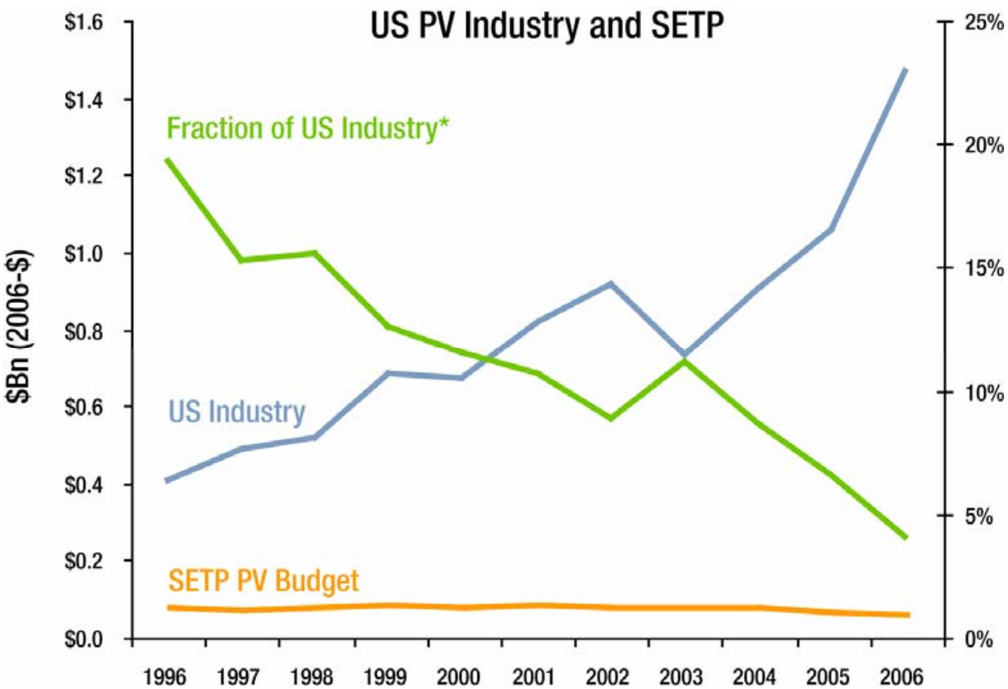
Assessment of potential in a commoditized market can be achieved through analysis of a constrained hierarchy of technology characteristics and manufacturing metrics

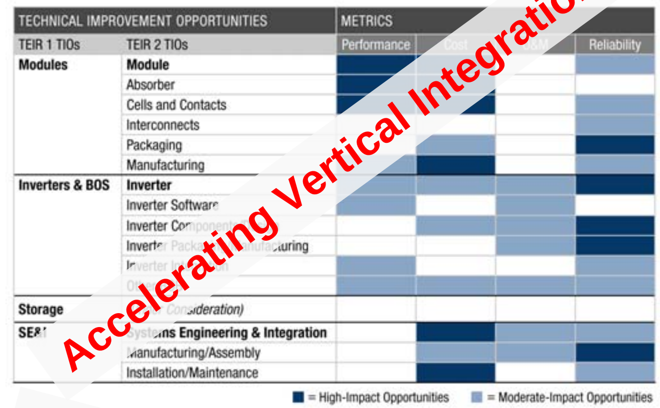


Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment “Gap” Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

To maintain relevance in an expanding industry, DOE is focused on “validating” new technology and accelerating change in supply chains and business models





Accelerating Vertical Integration

“Validating” Tech for Investors

SOLOPOWER

SOLARIA

Implications For DOE:

- Market viability eclipsing “science” results
- Private funding now available for R&D
- Cost trajectories are increasingly secure

Response by DOE:

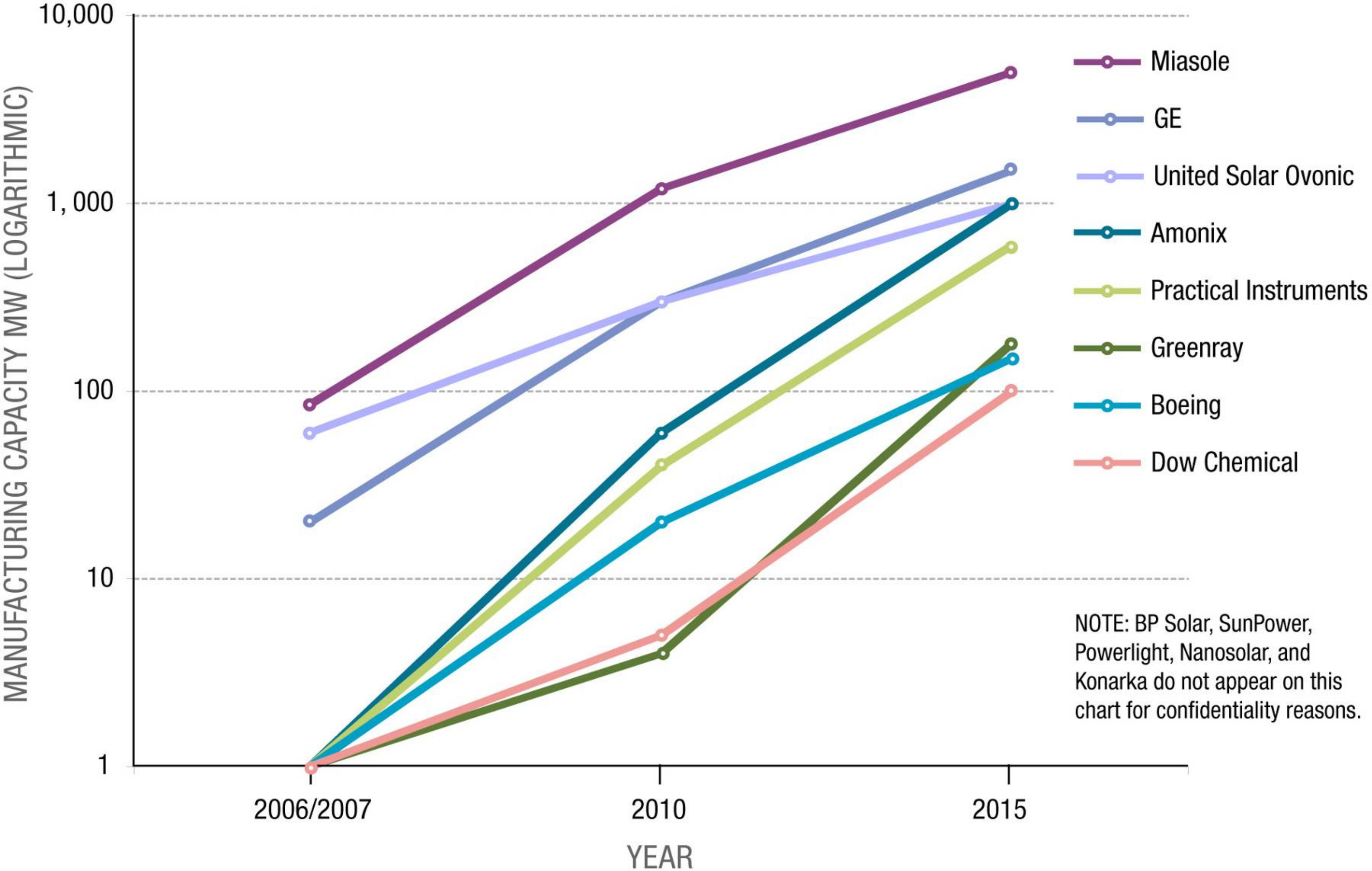
- Focus R&D on cost and production scale-up
- Validate technologies, align Lab R&D with industry
- Create/prepare markets for new product:
  - Regulatory environment & grid integration
  - Application “showcases”, gov’t purchasing

PV R&D pipeline will support technologies/companies, with funding opportunities calibrated to maturity

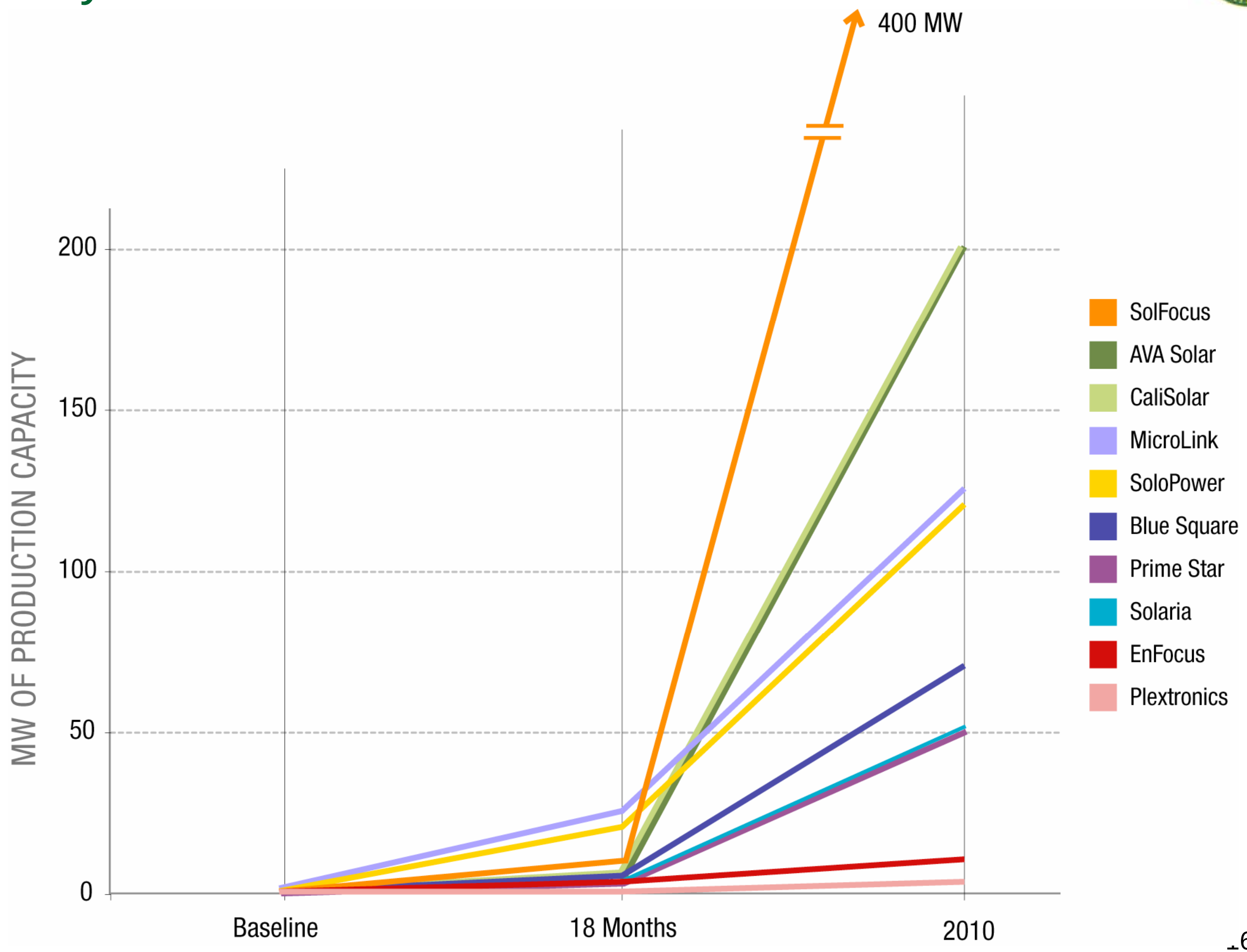
PHASES	Material & Device Concepts	Device & Process Proof of Concept	Component Prototype & Pilot Scale Production		System Development & Manufacturing	
SOLICITATION	Solar Energy Utilization	Future Generation PV Devices & Processes	PV Component / System Incubator	Advanced Inverters & Energy Management Systems	University Product & Process Development Support	Technology Pathway Partnerships
FUNDING SOURCE	DOE/O/S, BES	DOE / SETP	DOE / SETP	DOE / SETP	DOE / SETP	DOE / SETP
DESCRIPTION	New materials and pathways for solar to electric conversion	Novel devices or processes with potentially significant performance or cost advantages	Prototype PV components or systems produced at pilot-scale with demon-strated cost, reliability, or performance advantages	Design, test, and produce advanced inverters and energy management systems with improved reliability, enhanced value, and reduced costs	Universities perform targeted materials science and process engineering research in support of industry-led teams developing new PV systems for commercialization in 2010-2015	PV systems and components ready for mass production delivering energy at target costs
PROJECT LIFECYCLE	3 years	3 years	1.5 years w/ 9 mo. On/Off Ramp	3 years	3 Years	3 years
ANNUAL FUNDING LEVEL	$0.3 - 1.5 Million	≤ $300K	$1 - 2 Million	$1 - 2 Million	Up to $300,000/year	$2 - 7 Million
TEAM LEADS	Universities or Laboratories*	Businesses or Universities*	U.S. Commercial Entity	U.S. Commercial Entity	Universities	U.S. Commercial Entity
ELIGIBLE PARTICIPANTS	All	All	Universities / Laboratories*	All	Universities	Universities / Laboratories*
ENTRANCE CRITERION	Basic science properties conceived/simulated	Materials synthesized; properties observed	Coupon-scale PV cell; process demonstrated in lab; proof of concept demo	Power electronics and control system manufacturing capability	Identification of manufacturing process or component improvements possible through targeted research investigations.	Prototype components; pilot production demo; business case established
EXIT CRITERION	Materials synthesized; properties observed	Coupon-scale PV cell; process demonstrated in lab; proof of concept demo	Prototype components; pilot production demo; business case established	Pre-commercial inverters / energy management systems submitted for product certification	Incorporation of research results into commercial manufacturing operations or product designs.	Commercial PV systems and subsystems; scaled production demonstrated >25MW
TOPICS	• Single-crystal, poly-crystalline, amorphous, and nanostructured inorganic and organic materials • Electronic structure • Single or multiple junction solar cells	• New devices and structures using materials such as thin-film silicon, microcrystal-line/amorphous silicon, poly-crystalline metal chalcogenides and oxides, nanocrystal-line materials, biomimetic concepts, organic materials, photoelectrochemical cells, dye-sensitized materials, materials with low-dimensional quantum structures • Very-high efficiency epitaxial solar cells or other concepts	• Modules: multiple technologies (including CPV) seeking efficient material use, better performance, or improved manufacturing • BOS Components: higher reliability inverters, CPV trackers, rapid installation features, storage systems • Systems: controls and smart monitoring, integration of components, factory diagnostics	Lower cost, higher value systems resulting from: • integrated circuitries, • advanced thermal management, • advanced transient overvoltage protection, • micro-grid-ready controls, • replacement of unreliable components, • integration with storage or UPS, • compatibility with buildings applications, • communications options, • customer-friendly energy monitoring, • reduction in parts and installation steps, • standards compliance, • innovative packaging, • self diagnostics, and • incorporation of other new enabling technologies	Identifying and developing: • Fabrication processes to improve material properties during manufacture • Improved solar cell materials • Innovative device designs to improve solar cell efficiency • Simpler, lower cost manufacturing processes • New electrical contacting techniques for improved efficiency and reliability • Diagnostic techniques to identify properties and quality of solar cells materials during manufacturing • Improved materials utilization processes • Understanding of chemistry between encapsulants and solar cell materials • Providing careful long-term field testing of modules and systems in support of product improvement	• Partnerships with U.S. industry for projects that focus on development, testing, demonstration, validation, and interconnection of new PV components, systems, and manufacturing equipment • Technology improvements in PV system and component design, integration, and installation will be a focus • Cost reductions, performance enhancements, and reliability improvements are sought for all aspects of PV systems

NOTE: The NREL and SNL teams that are part of the SETP program will continue to provide technical support for these activities through the SETP but will not be direct participants

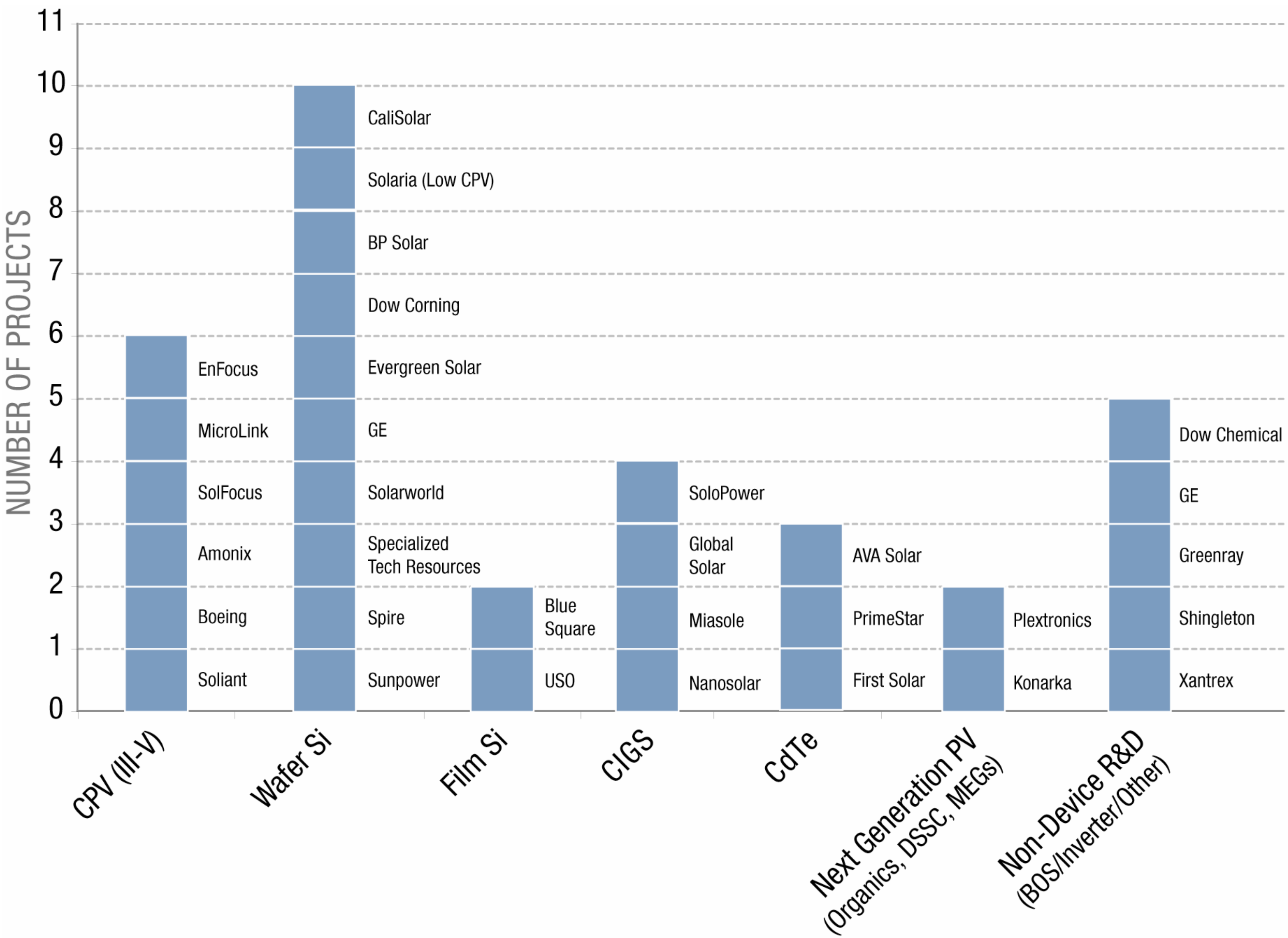
TPP Projects Will Develop Scale-able Manufacturing Processes, for Commercial Ramp in 2010-2015



Incubator Projects Aim to Quickly Ramp Production Capacity to Pilot and Commercial Levels



DOE's Portfolio Balances Technology, Maturity & Risk, with new early-stage companies adding diversity



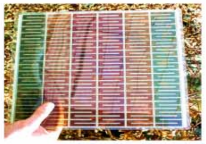
DOE National Lab module research balances various materials thru joint industry R&D and long-term research

4% | Organic PV

Customizing organic molecules for optimal cell efficiency in materials that can be processed without expensive vacuum chambers

1% | Dye Sensitized Cells

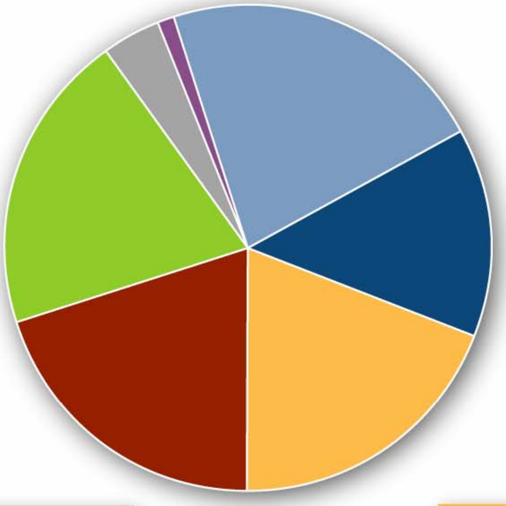
Advancing the efficiency and stability of inexpensive dye-based solar cells with novel nanostructures



22% | Wafer Silicon

Combining thin amorphous and wafer silicon to make high efficiency cells with smaller total amounts of silicon

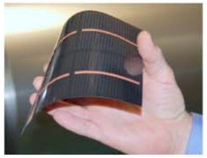
Developing new ink-jet printing methods for silicon electrical contacts



20% | Thin Films (CIGS)

Supporting the novel manufacture of CIGS cells from ink-based precursors

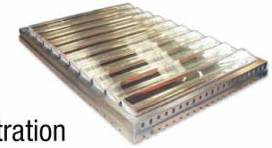
Transferring discovery that highest performance material has nanostructured patterns into a fast and uniform manufacturing process



14% | Concentrator PV

Devising strategies for making quicker, easier, less precise cells but maintaining record performance

Achieving record efficiencies (33.8%) even without concentration



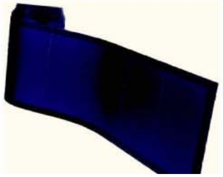
20% | Thin Films (CdTe)

Produced thinner films with same cell performance

Discovered a more durable way to make electrical contacts

19% | Thin Films (Silicon)

Developing methods of making thin silicon film solar cells on inexpensive glass and at low processing temperatures

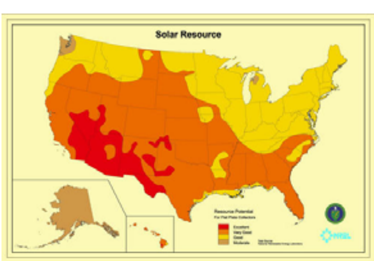


DOE National Lab program also provides testing & evaluation and manufacturing process development

Systems Analysis

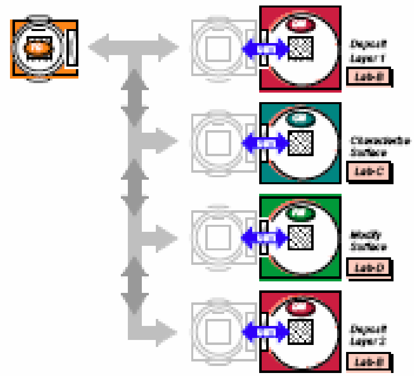
- •Advancing whole-system testing and analysis protocols
- •Developing improved inverter performance models, including long-term degradation
- •Investigating wireless irradiance and temperature sensing monitors and "smart" diagnostics
- •Working with Xcel (a Colorado utility) to conduct grid integration studies
- •Enhanced Solar Advisor Model, which is used to calculate performance and financial parameters of solar systems, by adding federal and state incentive tools among other improvements

Solar Resource Assessment



- •Completed development of National Solar Radiation Database Update with hourly irradiance and surface meteorological data for 1,454 stations in the U.S

Process Development Integration Lab

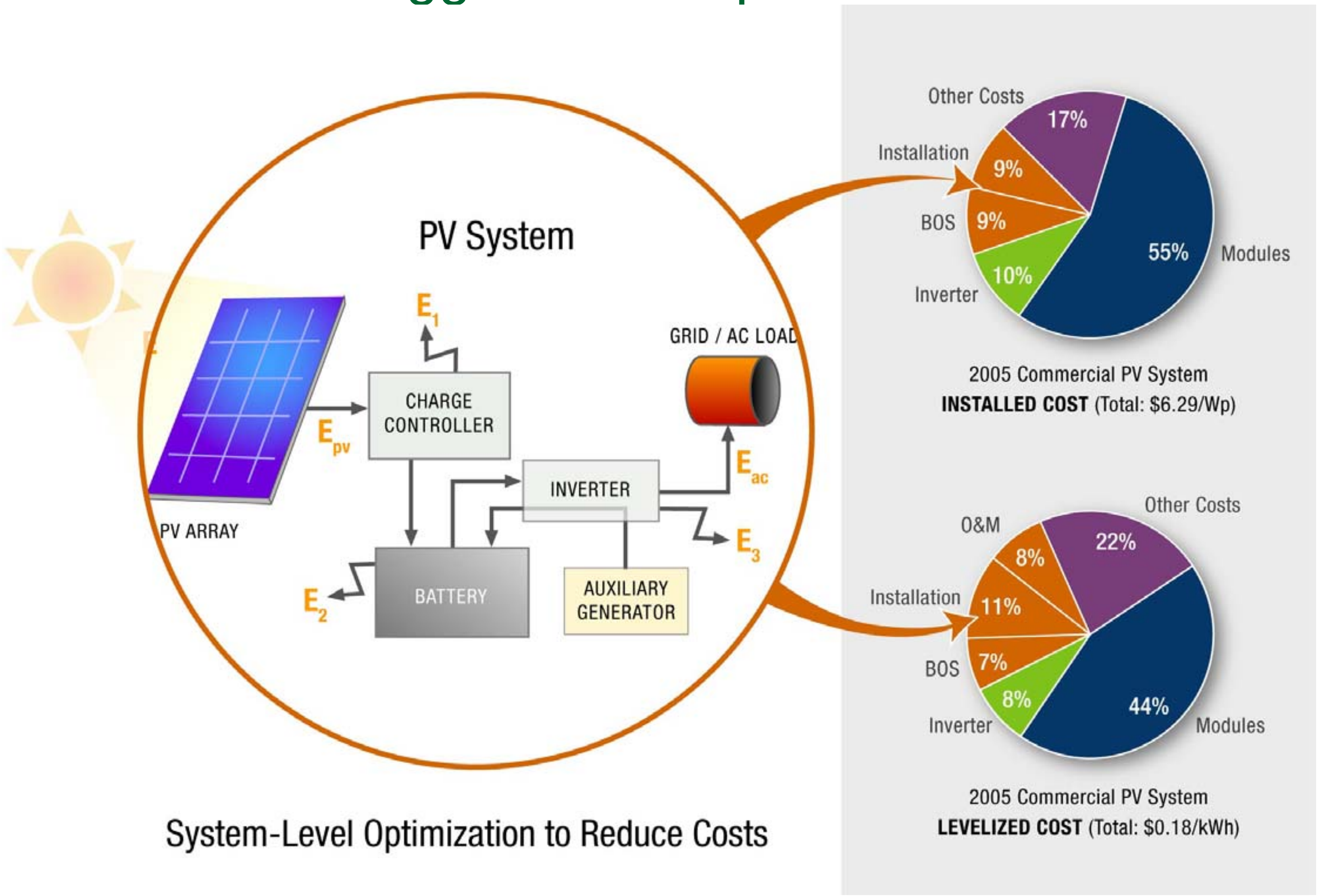


- •Acquired the first PDILPlatform (Silicon), which will allow industry and lab personnel to integrate and test deposition, processing, and characterization tools
- •Designed and ordered Platforms for CIGS, Atmospheric Processing, Electro-optic Characterization
- •Also invested in a silicon crystal growth furnace for testing solar cell feedstock

Reliability Testing

- •Aging modules through accelerated exposure, first Si and a-Si, then Cd Te and CIGS
- •Developed an improved strength and durability testing technique applicable to many PV module types
- •Added new equipment to simulate a variety of environmental conditions
- •Reaccredited for both cell and module measurement services (one of two labs in world with both accreditations)

Achieving US grid parity will require 2-3X improvement in cost/kWh for modules/inverters – O&M, installation require even more aggressive improvements



Significant opportunity remains in under-invested areas of power electronics, bundling with controls/storage, and sales/delivery channels.

Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment “Gap” Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

Will concentrators successfully enter and compete?

Many difficulties remain despite recent >40% efficiency record

1. Significant segregation between cells and optics manufacturers.
   - Lack of vertical integration increases margins and complicates growth of CPV

2. Falling cell costs (Si *and* III-V) reduce advantages of CPV modules
   - 2x-5x concentrators compete on a thin price differential between optics and cells
   - 200x-1000x CPV scene changes dynamically with record eff. and falling costs

3. Large (>10kW) HCPV is targeting same market/geography as CSP
   - Higher modularity of HCPV is less important than potential lower ¢/kWh of CSP
   - 3rd round offerings will be increasingly risky – must pick right tech *and* paradigm
   - Planned CSP installations should clarify comparison by 2010/2011

"Should I be nervous about my thin film investment?"

Requirements for successful entry into the TF PV Market Include:

1. Quick ramp-up (>100 MW/yr) to leverage scale-based cost reductions
   - Ramp up dependent on many things such as capex, financial backing, etc, but will be ***limited*** by how complicated the deposition process is – this will drive challenge in process "tuning" and cost/schedule for cloning lines
   - Barometer: Shake-down time required for a second production line (at >8% and ~25MW/yr)
   - Gradual **efficiency** improvements will likely be a minor component (<20%) of overall cost reductions. Others include **tax-breaks**, **capital depreciation**, **through-put**, and **scaling**.

2. Anticipate lower margins (<<45%) – It's good to be "First" (FSLR)
   - Even one additional high volume, low $/W, manufacturer may significantly reduce margins across all non-differentiated technologies as volume is perused over near-term profits
   - FSLR targeting 70¢/W by 2012, only reducing ASP by 6% annually on "take or pay" contracts. It's unlikely demand will support these prices if *your* low $/W company succeeds

3. Demonstration of reliability
   - Module reliability is as essential as cost or efficiency - Reliability must be proven/demonstrated *and* accepted by customers to assure product acceptance and mitigate warranty risk/liability.
   - Difficult to scale-up production while incorporating accelerated aging tests – testing at cell and module level should be done ASAP. Adopt proven module manufacturing techniques (at least initially - i.e. flat plate before flexible).

4. Robust success strategy if pursuing niche markets or leveraging unique form factors
   - Potential to transition technology from niche to generic high market penetration (i.e. GSE flexible to rigid) will be more difficult as gap widens with c-Si product performance and shipment volumes.

Entry, Survival, and Success in Silicon PV

Greater maturity, scale, and discrete-ness of value chain elements must influence entrance strategies for silicon PV companies.

1. Vertical Integration
   - Isolated cell, module, or system companies should look towards licensing or incorporation as a likely exit strategy.

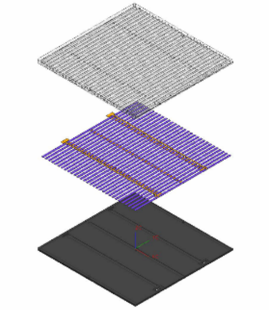
2. Competitive Scale
   - Segregated value chain segments (i.e. ingots, cells, modules) deliver economies of scale at higher production volumes than thin film technologies, meaning ramp must be especially steep.

3. Industry hiccups
   - Potential for an industry shakeout by 2010, driven by scaled-up players - Successful companies will either be vertically integrated or will have a significant best practice advantage for a segment of the value chain.

Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment "Gap" Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

"Gap 1": Mid-Concentration Regime



2x-8x

20x-100x

250x-1000x

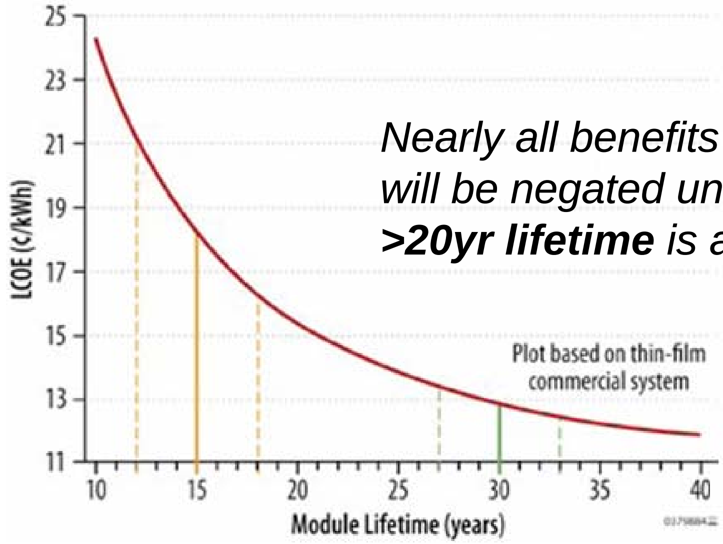
- Concentration ratios from 1.2x-1000x currently exist because of the infancy of CPV industry
- Moving forward, many approaches will be proven uncompetitive

- **Investment opportunities may exist in the 20-100x range**
  - Dependent upon the tolerances and costs of components
  - Dependent upon current III-V R&D progress

- **With lower concentrations:**
  - Higher tracker tolerances (single axis perhaps up past 50x)
  - Passive heat sinks (500x = 50W/cm2 ~ hot desktop CPU)
  - Lower cost optics (higher f-ratios, fewer elements, higher eff., etc)
  - Reduced Mfg. Costs (easier automation, fewer steps)
  - Reduced installation precision (perhaps allowing higher modularity)

"Gap 2": Encapsulates for Flexible Thin Film Modules

Moisture barrier levels of **10^{-6}g/m^2/day** or better need to be achieved

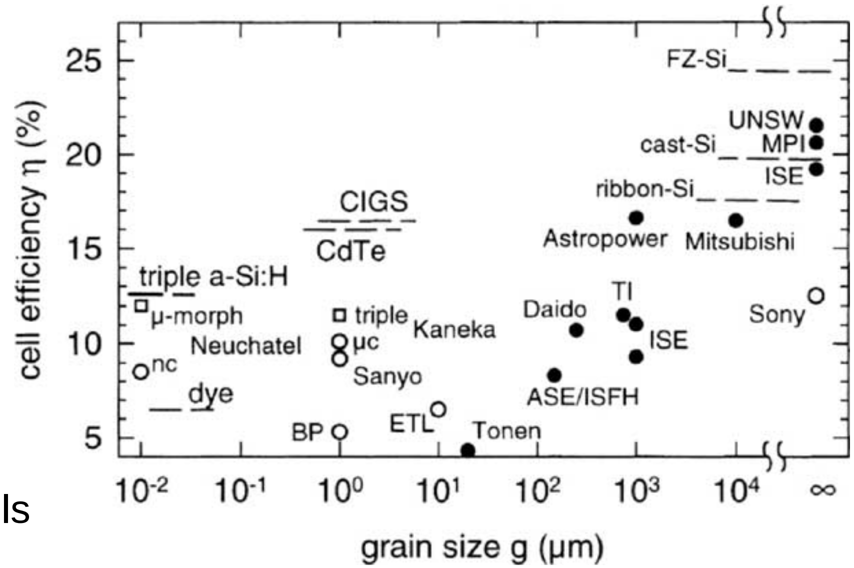


*Nearly all benefits of flexibility will be negated unless a **>20yr lifetime** is achieved*

Substrate	Benefits	Difficulties
Glass	Excellent barrier, Smooth, Thermal Expansion, Vacuum compatible	Rigid, Heavy
Flexible	Low kg/W, Durability, Removable, Potential low cost with high throughput	Curling, Stress, Poor adhesion
Polyimid	Monolithic integration	Worst efficiency, Low-temp deposition
Flexible metal	High deposition temp	Pin holes (roughness), Impurity diffusion

- Lower kg/W can significantly reduce manufacturing, shipping (weight, breakage) and installation cost.
- Flexible thin films allow for a *true* roll-to-roll process
- Flexible form factors may open up new markets for PV installations.

“Gap 3”: Crystalline Silicon Thin Films



R.B. Bergmann, Appl. Phys. A 69 (1999) 187–194.

c-Si efficiency at thin film costs

- Near-term potential - undercut traditional cells
- Long term potential - redefine c-Si module form factor – large area / flexibility

No fundamental problems with c-Si TF - Many interesting ideas from upstarts:

Approach±	Benefits	Difficulties
High Temperature	Large Grains, High Throughput	Impurity Diffusion
Low Temperature	Glass Substrate	Smaller Grains (Lower Efficiency)
Transfer/Liftoff Techniques	Superior Material, Glass Substrate	New Approach, Throughput

±Tradeoff exist across all three approaches: substrate material (silicon, glass, transfer), deposition technique (liquid, CVD, atmospheric), Optical and Electrical confinement

Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment “Gap” Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

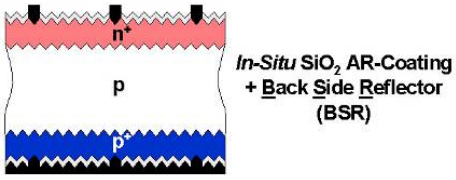
Wafer Silicon and X-Cutting Process Technologies

Novel Contacts, Diffusion and Surface Passivation for 20%-efficient Screen Printed Si Solar Cells

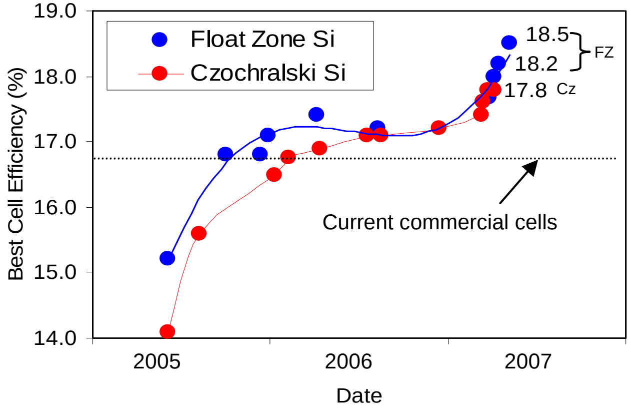
- PROBLEM: Most commercial c-Si solar cells lack the high quality contacts, enhanced short wavelength response, and excellent surface passivation required to achieve high efficiencies on thin wafers.
    - **Size of Problem:** 18-20%-efficient c-Si solar cells on 100-200 μm thick wafers are needed to reduce the installed PV system cost <$3.50/W$_p$. Today's cells are 14-17%-efficient on >200 μ m wafers.
- DESCRIPTION: Novel and low-cost cell processing technologies suitable for 20%-efficient thin Si cells have been developed to form diffused layers and surface passivation films simultaneously (STAR process), and high-quality, rapidly fired screen-printed contacts to lightly-doped emitters that also result in enhanced defect passivation and Al-BSF.
- IMPACT: These technologies have the potential to increase cell efficiencies by 3%, reduce cell processing time, ease wafer handling, and improve the utilization of polysilicon feedstock.
- IP POSITION: Georgia Tech has six patents, two disclosures, and two filed patent applications in these areas.
- TECHNOLOGY STATUS:
    - **Reduction to practice:** Commercial-scale cells with efficiencies of 18-19% have been demonstrated using screen printed contacts to high sheet resistance emitters and rapid thermal firing.
    - **Time constant to availability:** Currently available.
    - Special needs to implement: None.
    - **Capital Needs:** Semi-automated production line to scale-up for commercialization and selected R&D tools.

Technology Concept

Simultaneously diffused, Textured, in-situ oxide AR-coated solar cell (STAR Cell)



Results

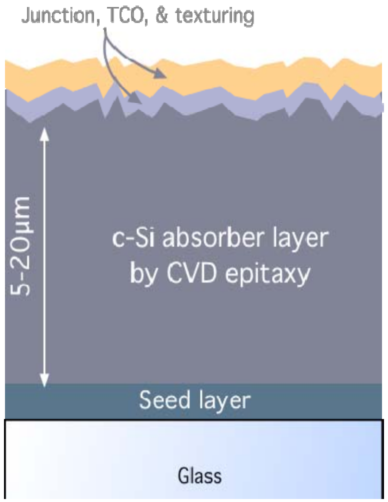


Ajeet Rohatgi | Georgia Tech | Phone: 404-894-7692 | ajeet.rohatgi.ece.gatech.edu

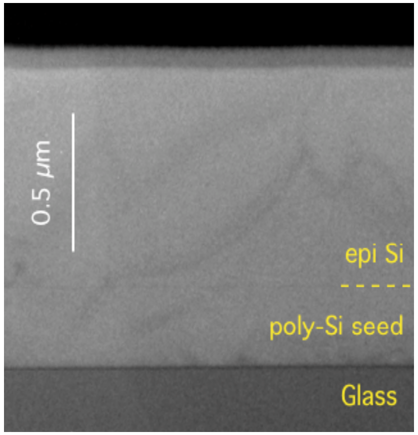
Wafer-replacement Silicon for Efficient, Low-cost PV

- PROBLEM: Costly energy & materials waste. Wafer fabrication currently at 0.6$/W - need to achieve 1$/W modules Current feedstock shortage raises wafer cost further
- DESCRIPTION: Reduced costs by replacing 200µm wafers with ~10µm films. Devices can be grown over large areas with versatile CVD. Fabrication of an inexpensive seed layer is followed by subsequent epitaxial device growth
- IMPACT: Dramatic cost reductions associated with reduced material usage and large area depositions. Transition to industry may leverage existing expertise from both thin-film and c-Si industry
- IP POSITION: NREL has demonstrated Seed growth and scalable epitaxy at >200 nm/min.
- TECHNOLOGY STATUS:
  - High-quality seeds exist,
  - Fast epitaxy demonstrated,
  - Devices expected in 18 months
  - Products ~5 years from market

Concept



Demonstration

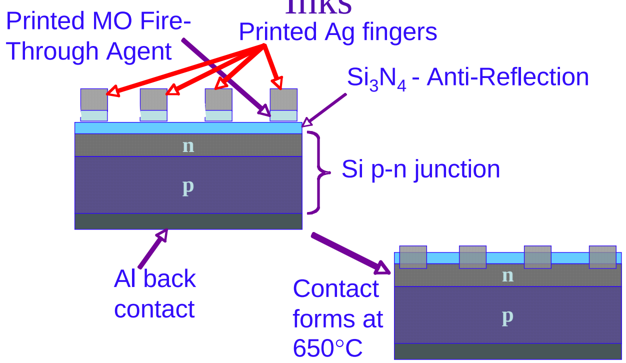


Howard Branz | NREL | Phone: 303-384-6694 | howard_branz@nrel.gov

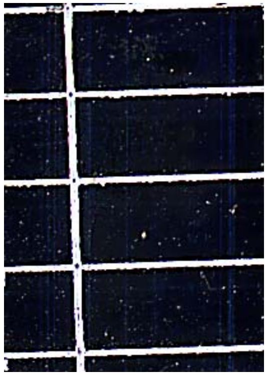
Ink-Based Direct Write Contacts for Solar Cells

- PROBLEM: Current contact methods for Si and other solar cells suffer from a lack of resolution, need to pattern with screens or photolithography, and direct contact with the cells.
  - Many next generation cells will require new approaches to doping and metallization of contacts.
- DESCRIPTION: A series of inks have been developed for metallizations (Ag, Cu, Ni, Al etc.) & burn through agents, that can be printed with high resolution (<50 µm) using inkjet cassettes.
- IMPACT: Direct write contacts offer improved resolution, better materials utilization, low cost, ready process integration, low capitalization cost, and broad applicability to PV and other electronic technologies.
- IP: NREL has a series of 5 patents and 2 recent disclosures in the area available for licensing.
- STATUS: The technology has been demonstrated for a number of solar cell systems.
  - There are 7 related inventions available for license.
  - The technology has been reduced to practice for Si with initial demonstrations as well for CIGS and OPV.
  - Currently Available
  - No special needs
  - Ink synthesis, direct write printer, thermal processing.

Development of Fire-Through Inks



12% Direct Write Si Cell



David Ginley | NREL | Phone: 303-384-6573 | david_ginley@nrel.gov

Plasmonic Photovoltaics

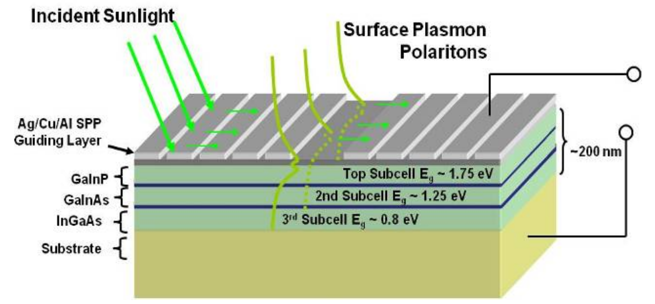
- PROBLEM: A basic requirement of a solar cell is that it be 'optically thick', i.e., thick enough to absorb the light incident upon it. However many other factors (cost, process simplicity, high efficiency) motivate cell designs that are as thin as possible. Plasmon-enhanced light absorption enables a solar cell to be much thinner (~50-100 nm) than its conventional optical thickness (3-4 micron for direct gap materials; > 100 microns for Si). Thus solar cells can potentially be made 50-2000X thinner than for conventional designs, reducing cost and enabling new cell designs.

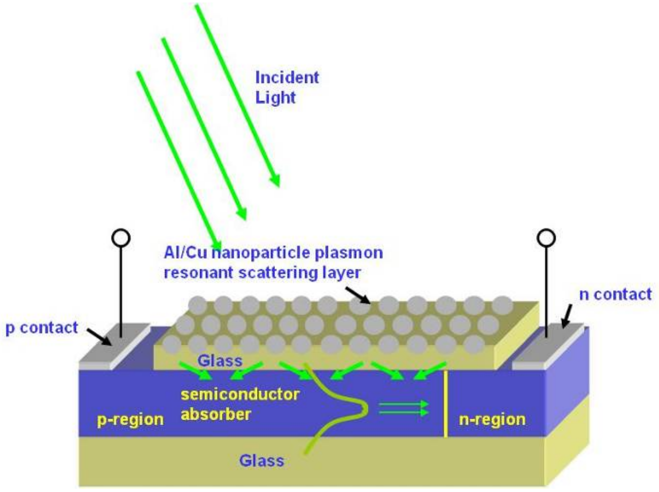
- DESCRIPTION OF INVENTION/TECHNOLOGY: The top or bottom of the cell is coated with a thin metallic (Ag, Cu, Al, Au) layer. Incident sunlight is coupled into surface plasmon polaritons(guided modes at a metal-semiconductor interface). These guided modes are highly localized (< 100 nm) to the interface, even for infrared wavelength near the semiconductor bandgap; this localization results in strong light absorption within 100 nm of the cell surface, enabling much thinner cell designs.

- IMPACT: Potentially very large since this is a very general technology for enhanced light absorption that is potentially applicable to many solar cell technologies.

- IP POSITION: 3 invention records (one filed patent application, two provisional applications).

- TECHNOLOGY STATUS: Currently available. Caltech is currently developing plasmonic cell designs for Si cells, III-V multijunction cells, dye-sensitized solar cells, II-VI quantum dot cells and polymer cells.
  - **Reduction to practice**: A 100X enhanced light absorption has been observed for CdSe quantum dot solar cells.
  - **Special needs to implement**: No special needs; varies by technology, but involves straightforward metal film deposition like that already employed in solar cell fabrication.





Thin Film & Organic PV Module Technologies

Continuous, In-Line Manufacturing of CdS/CdTe Solar Cells

- PROBLEM: Low cost manufacturing of CdS/CdTe photovoltaic modules with low cost of manufacturing (less than $1/Wp), low capital expenditures (less than $0.5 for 1 Wp/Yr.) and high materials utilization (~98%).
- SIZE OF PROBLEM: The terrestrial PV markets need GWs of low cost PV Modules
- DESCRIPTION OF INVENTION/TECHNOLOGY: Continuous in-line processing of CdS/CdTe solar cells in a single vacuum chamber operating at modest vacuum. The cycle time is two minutes. All processing steps are performed by thermal sublimation. NREL verified efficiencies of 12.44% demonstrated on low cost soda lime glass.
- IMPACT: Potentially very large (GWs/year) for the terrestrial flat plate PV market.
- IP POSITION: 2 US patents awarded. 3 patents pending
- TECHNOLOGY STATUS: The technology is being commercialized by AVA Solar in Fort Collins Colorado, with tens of millions in funding.
- REDUCTION TO PRACTICE: Technology demonstrated on 3”x3” substrates at CSU. AVA Solar will be demonstrating the 16”x16” system in the next two months.
- SPECIAL NEEDS TO IMPLEMENT: None

Technology Concept

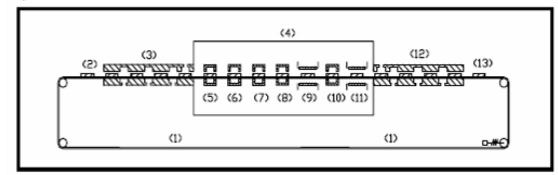
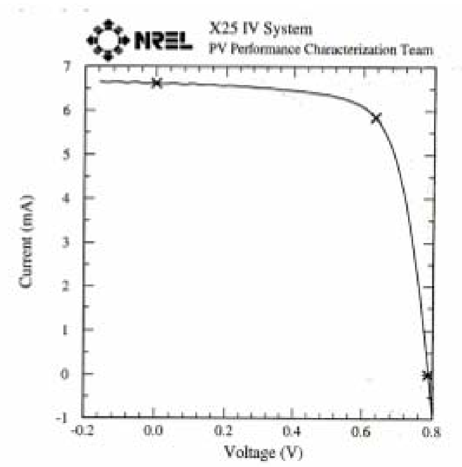


Figure 1.1 Schematic of the pilot scale CdTe PV processing system, (1) belt conveyor, (2) glass substrate, (3), (12) Air to Vacuum to Air seals, (4) vacuum chamber, (5) heating module, (6) CdS dep., (7) CdTe dep. (8) $CdCl_2$ dep./heat treatment, (9) $CdCl_2$ annealing and stripping, (10) back contact, (11) contact annealing, (13) completed device. For conciseness the schematic shows only one station each for 9, 10 and 11. Actual processing light

Results



V_{oc} = 0.7869 V
I_{sc} = 6.6183 mA
J_{sc} = 22.206 mA/cm^2
Fill Factor = 71.03 %

I_{max} = 5.8446 mA
V_{max} = 0.6341 V
P_{max} = 3.7062 mW
Efficiency = 12.44 %

W.S. Sampath | CSU | Phone: 970-491-8411 | sampath@engr.colostate.edu

Continuous, In-Line Manufacturing of CdS/CdTe Solar Cells

PROBLEM:
Further cost reduction of already inexpensive CdTe manufacturing

SOLUTION:
Continuous, In-line, low vacuum, high throughput, with high material utilization process

IMPACT:
Potentially near term, very high volume production

Technology Concept

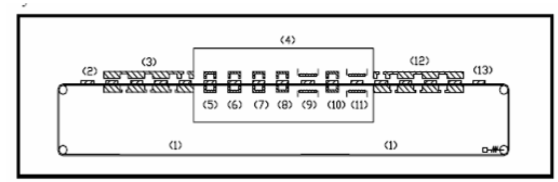
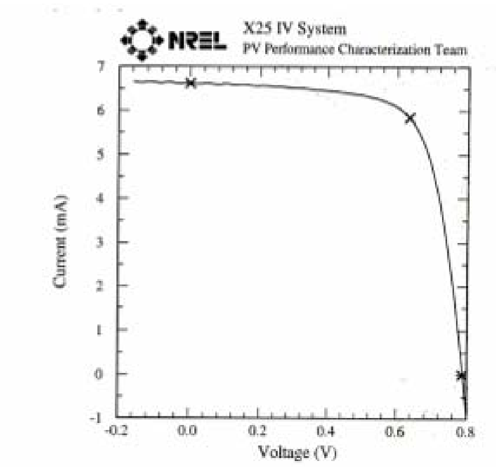


Figure 1.1 Schematic of the pilot scale CdTe PV processing system, (1) belt conveyor, (2) glass substrate, (3), (12) Air to Vacuum to Air seals, (4) vacuum chamber, (5) heating module, (6) CdS dep., (7) CdTe dep. (8) $CdCl_2$ dep./heat treatment, (9) $CdCl_2$ annealing and stripping, (10) back contact, (11) contact annealing, (13) completed device. For conciseness the schematic shows only one station each for 9, 10 and 11. Actual processing light

Results



V_{oc} = 0.7869 V
I_{sc} = 6.6183 mA
J_{sc} = 22.206 mA/cm²
Fill Factor = 71.03 %

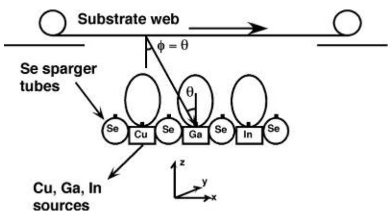
I_{max} = 5.8446 mA
V_{max} = 0.6341 V
P_{max} = 3.7062 mW
Efficiency = 12.44 %

W.S. Sampath | CSU | Phone: 970-491-8411 | sampath@engr.colostate.edu

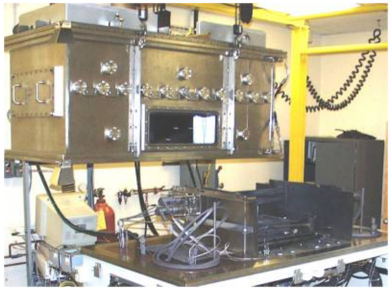
Multi-source In-line Deposition of $Cu(InGa)Se_2$ Alloys on a Flexible Web or Glass Substrate

- PROBLEM: High rate, continuous in-line deposition to reduce the manufacturing cost of $Cu(InGa)Se_2$ PV modules.
  - Multisource evaporation of $Cu(InGa)Se_2$ produces the highest efficiency thin film PV. Design and development of commercial-scale system is needed for low-cost manufacturing.
- DESCRIPTION:
  - Multi-source in-line deposition of $Cu(InGa)Se_2$.
  - Deposition of Mo on a flexible substrate.
  - Continuous high utilization growth of CdS.
- IMPACT: High throughput manufacturing of $Cu(InGa)Se_2$ PV modules.
- IP POSITION: University of Delaware, Institute of Energy Conversion has a package of 6 patents - Four patents on continuous in-line deposition technology for $Cu(InGa)Se_2$, one patent on surface deposition of CdS and one on growth of Mo, particularly, for deposition on a plastic substrate.
- TECHNOLOGY STATUS:
  - The technology has been reduced to practice in a pilot scale system and has been licensed by several companies.
  - Patents are available for non-exclusive license.

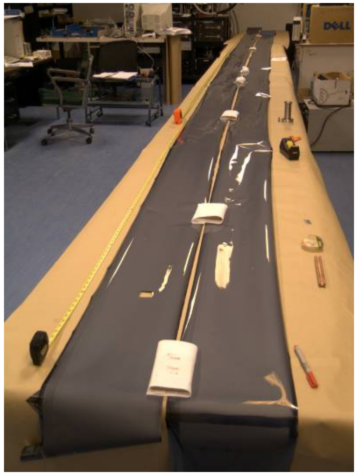
Concept



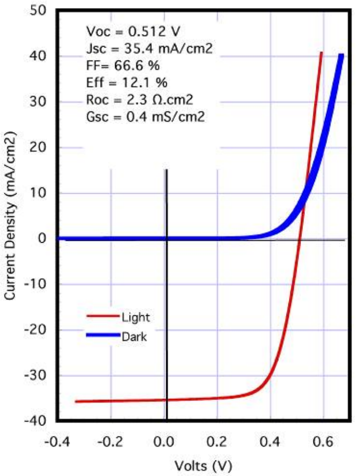
Prototype Operation



Product



Performance

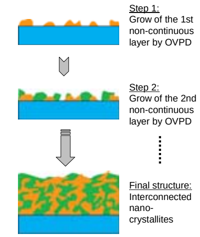


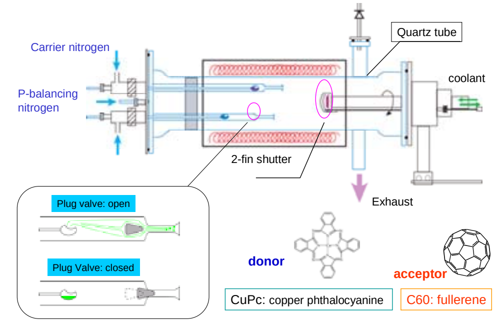
Robert Birkmire | Univ. of Delaware - Institute of Energy Conversion | Phone: 302-831-6220 | rwb@udel.edu

Ultra low-cost Organic Photovoltaic (OPV™) technology With Enhanced Application Capabilities.

- **PROBLEM TECHNOLOGY ADDRESSES:** Global Photonic Energy Corp. (GPEC)'s OPV™ technology will achieve cost/kw-hr performance that is competitive with fossil fuel generation in addition to numerous new product/market opportunities based on low-temp fabrication approaches.
  - Solar power remains 4+ times more expensive than what the typical residential consumer pays for electricity. Achieving <10 /kw-hr PV power will transform the PV and electricity generation markets.
- **DESCRIPTION OF INVENTION/TECHNOLOGY:** GPEC has developed a small-molecular organic photovoltaic technology through sponsored research of Dr. Stephen R. Forrest (VP of Research, Univ. of Michigan) and Dr. Mark E. Thompson (Dept. Chair, Univ. of S. California). GPEC is currently working on extending device performance and scaling/prototyping issues.
- **IMPACT:**
  - GPEC's research and development efforts in ultra low-cost organic vapor-phase deposition OPV™technology will create the new cost-experience curve necessary to accelerate PV market. Insights and manufacturing learning gained in scaling of OPV™ technology will have benefits to other government and DOE programs including OLED white-lighting initiatives and organic electronic efforts in general at the DOE, NSF, and DoD.
  - Low-temperature deposition, and organic semiconductors enable flexible and semitransparent PV applications (windows) as well as the direct coating of PVs on device enclosures for unobtrusive battery lifetime enhancement in mobile devices
- **IP POSITION:** GPEC has the exclusive world-wide license with rights to sublicense over 240 patents/patents pending covering foundational inventions in materials, device architectures and fabrication processes.
- **TECHNOLOGY STATUS:**
  - Over 240 patents issued/pending available for license
  - High performance research devices have been fabricated and tested and development sub-modules have been fabricated. Performance enhancement, prototyping and environmental stability testing priorities being advanced.
  - IP is available at present
  - Organic deposition systems currently being scaled for OLED production by Aixtron AG, Samsung and others. Organic Vapor-phase deposition (OVPD) approach enables nanomorphologies over large areas

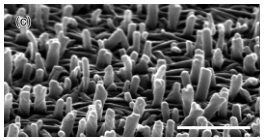
Technology Concept

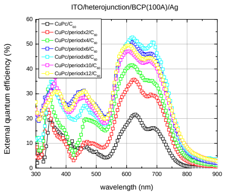


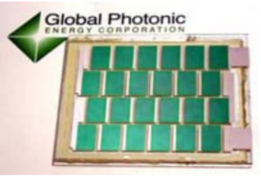


Results

Nano-morphologies via OVPD







Transparent PVs

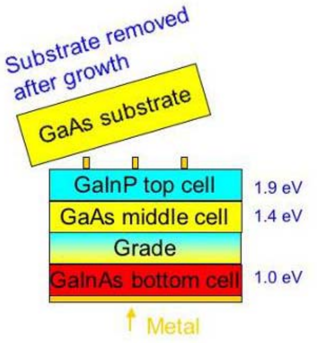
Aaron Wadell | Global Photonic Energy Corp. | Phone: 609-434-0002 X264 | awadell@globalphotonic.com

CPV Cell/Module Technologies

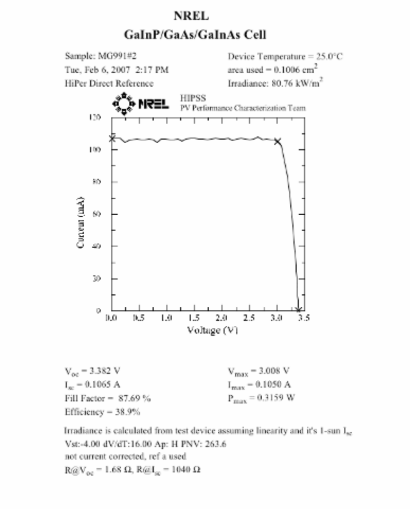
Monolithic Tandem Solar Cells for CPV based on Inverted, Lattice-Mismatched Epitaxial Growth

- PROBLEM TECHNOLOGY ADDRESSES: The viability of terrestrial concentrator photovoltaic power systems is enhanced by developing PV cells which are highly efficient, robust, and cost effective.
  - **Size of Problem:** Concentrator PV is an important, burgeoning component of the overall terrestrial PV industry. This technology is also highly attractive for space power since extremely high specific power (W/kg) is possible.
- DESCRIPTION OF INVENTION/TECHNOLOGY: Inverted epitaxial growth and lattice mismatched materials are used to achieve tandem solar cells with optimal subcell band gaps and a host of engineering advantages. The inverted cell structure is mounted to a secondary carrier (handle) and the parent substrate is removed, opening the possibility for its reclamation or reuse (reduced cost). Many specific variants of the basic design concept are possible (e.g., 3, 4, or 5 band gaps). A practical efficiency of 50% is possible with 4 band gaps.
- IMPACT: Potentially very large in terms of performance, operation, reliability, and cost reduction.
- IP POSITION: 3 invention records (two filed patent applications) and a number of related disclosures, patent applications, and patents.
- TECHNOLOGY STATUS: NREL is currently developing 3-band-gap cells; designs with 4 band gaps have been proposed for the DOE Program.
  - **Reduction to practice:** A 3-band-gap GaInP/GaAs/GaInAs cell has been demonstrated at NREL (see Results) with 38.9% efficiency. Emcore has also reduced a similar design to practice for space applications.
  - **Special needs to implement:** Production method for handle mounting and parent substrate removal.

3-Band-Gap Tech. Concept



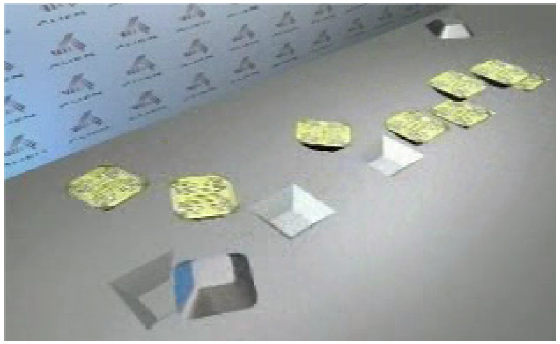
Results



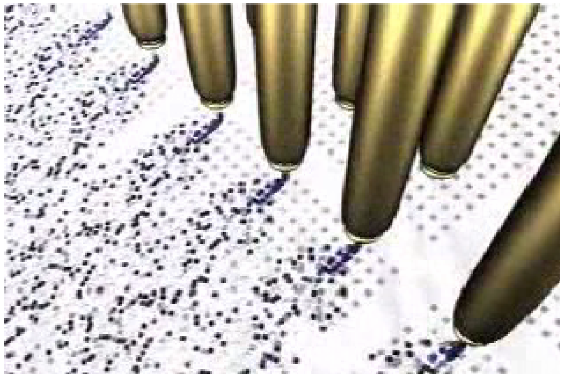
Mark Wanlass | NREL | Phone: 303-384-6532 | mark_wanlass@nrel.gov

Fluidic Self-Assembly for Low-Cost Manufacturing of Concentrated PV modules

- PROBLEM: The cost of assembling concentrated PV (CPV) modules contributes significantly to the cost of CPV generated electricity.
- DESCRIPTION: Parallel fluidic self-assembly is used to assemble module components in a single, low-cost manufacturing step.
- IMPACT: Allows high-efficiency CPV modules to be created at low-cost that are suitable for both point of use and utility applications.
  - Module assembly is achieved through fluidic self-assembly; providing the cost benefits of high-throughput, parallel manufacturing.
  - Allows the use of a module integrated, small-displacement tracking scheme that is significantly less complex (and costly) relative to current CPV tracking systems.
  - Allows for high concentration levels (100-1000 sun) where optimum efficiency of multi-junction cells is achieved.
  - Allows the scale of CPV units to be significantly reduced which facilitates simpler thermal management.
- IP POSITION: 5 disclosures filed related to inventions.
- TECHNOLOGY STATUS: Fluidic self-assembly has been demonstrated at a variety of research labs using a number of different assembly mechanisms with both Si and III-V chips.
  - Inventions related to using fluidic self-assembly to create modules are available along with complementary inventions.
  - We are at the initial stage of reducing these ideas to practice.
  - By building on proven fluidic self-assembly techniques, time to product could be ~2 years.
  - Requires fluidic self-assembly tools, lithography tools/metal printing tools, ovens for achieving ohmic contact with metallization.



Small PV cells self-assemble to predetermined sites on carrier substrate.



Large numbers of cells can be assembled in parallel. (www.alientechnology.com)

Gregory Nielson | Sandia Labs | Phone: 505-284-6378 | gnniels@sandia.gov

Multijunction Solar Cells Fabricated by Wafer Bonding and Layer Transfer

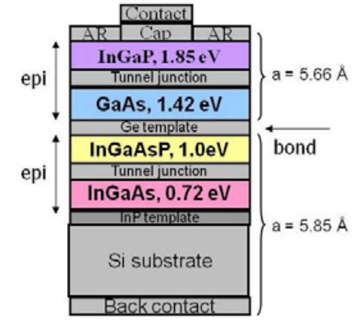
- PROBLEM TECHNOLOGY ADDRESSES: Optimizing the efficiency of III-V compound tandem multijunction solar cells requires an optimal bandgap for each subcell, which cannot be achieved using lattice-matched heterostructures. Also, multijunction cells require the use of expensive III-V substrate materials. Wafer bonding and layer transfer circumvents the lattice-matching constraint, and allows optimization of subcell designs. It also enables use of a lightweight, inexpensive (e.g., Si or other thermal expansion-matched) substrate.
  - **Size of Problem:** This approach can be used to reduce cost/W in terrestrial concentrator PV technology and is also applicable to space power where very high specific power (W/kg) is possible.

- DESCRIPTION OF INVENTION/TECHNOLOGY: Thin single crystal films of InP and GaAs are peeled from reusable InP and GaAs substrates and transferred to Si or other CTE-matched conducting substrates. Top subcells are lattice-matched to GaAs and bottom subcells to InP. The subcells are interconnected by direct wafer bonding. The early work on this solar cell technology was funded in part by DOE through NREL to Harry Atwater at Caltech while the company Aonex is funding further technology development under Dr. Atwater's guidance".

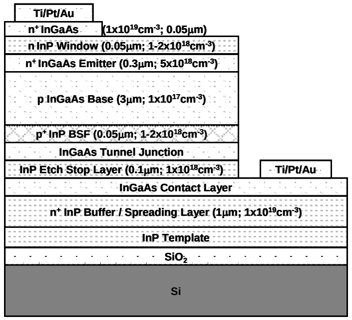
- IMPACT: Potentially very large in terms of performance, operation, reliability, and cost reduction.

- IP POSITION: 2 issued patents and related disclosures and patent applications.

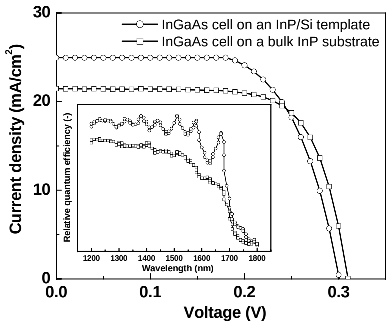
- TECHNOLOGY STATUS: Caltech has fabricated subcells and is developing integration methods for 4 junction cell fabrication.
  - **Reduction to practice:** GaInP/GaAs/Si and InGaAs/InP/Si subcells have been fabricated.
  - **Special needs to implement:** Conventional III-V MOVPE growth and wafer bonding facilities are required.



4J Cell



InP/Si Cell w/ Enhanced Photoresponse

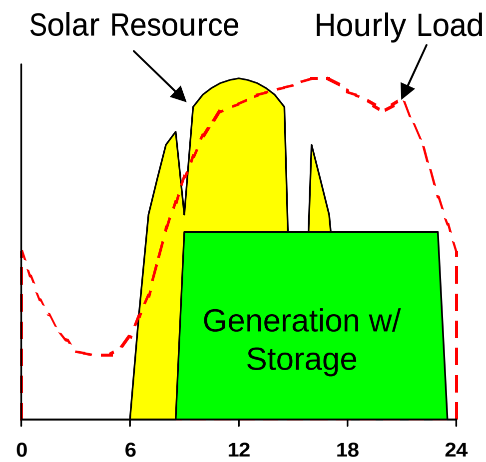


Harry Atwater | Caltech | Phone: 626-395-2197 | haa@caltech.edu

CSP Technologies

CSP industry is still taking shape for VC/PE investment – challenge is finding sustainable IP in key areas

- Thermal Storage R&D – enabling solar generated power to be delivered to grid any time it is needed by utilities
  - System concepts that reduce cost and improve cycle efficiency
  - Storage materials that operate at elevated temperatures and easily handled at ambient temperatures
  - Heat transfer fluids that can operate at elevated temperatures



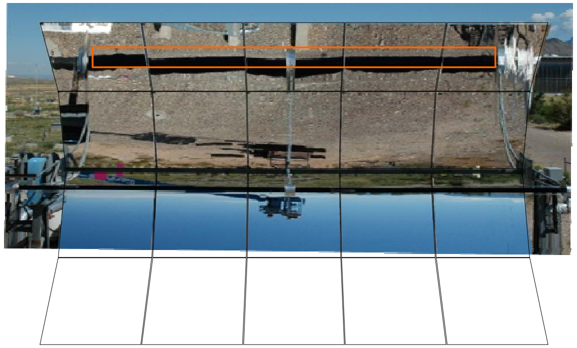
- Transition to High Volume Manufacturing – reduce costs and increase supply base for critical components
  - Glass or plastic mirrors for solar collectors
  - Thermal receivers
  - Collector or field electronics or controls

- Advanced Concepts – explore new technologies that could significantly reduce system and/or component cost
  - New industry concepts such as linear Fresnel and Distributed Power Tower
  - Novel, low cost heliostats, dish or trough structures
  - Alternative materials for reflectors, absorbers, or structures

Theoretical Overlay Photographic Alignment of Parabolic Trough Solar Collectors

- PROBLEM: Mirrors on parabolic trough collectors are currently inaccurately “aligned” by the use of fixtures.
- DESCRIPTION: Photographic image analysis techniques are used to quickly and accurately characterize alignment and specify adjustments.
- IMPACT:
  - Eliminate alignment errors on existing and future parabolic trough collectors
  - Potential large increase in performance (3 to 10%) of existing plants with minimal cost
  - Potential to increase capacity of California SEGS plants 10 to 35 MW
  - Enable improved performance in new collectors designs
- IP POSITION: Patent pending
- TECHNOLOGY STATUS:
  - Approach demonstrated and reduced to practice
  - Trailer mounted camera fixture/data acquisition developed and tested
  - Image analysis software still being developed
  - Licensing discussions with Florida Power and Light Energy (owner/operator of SEGS 3-9) initiated
  - Plan to characterize and align large number of mirrors at Kramer Junction trough plants this fall/winter

Theoretical image overlayed carefully surveyed photographic image to guide alignment



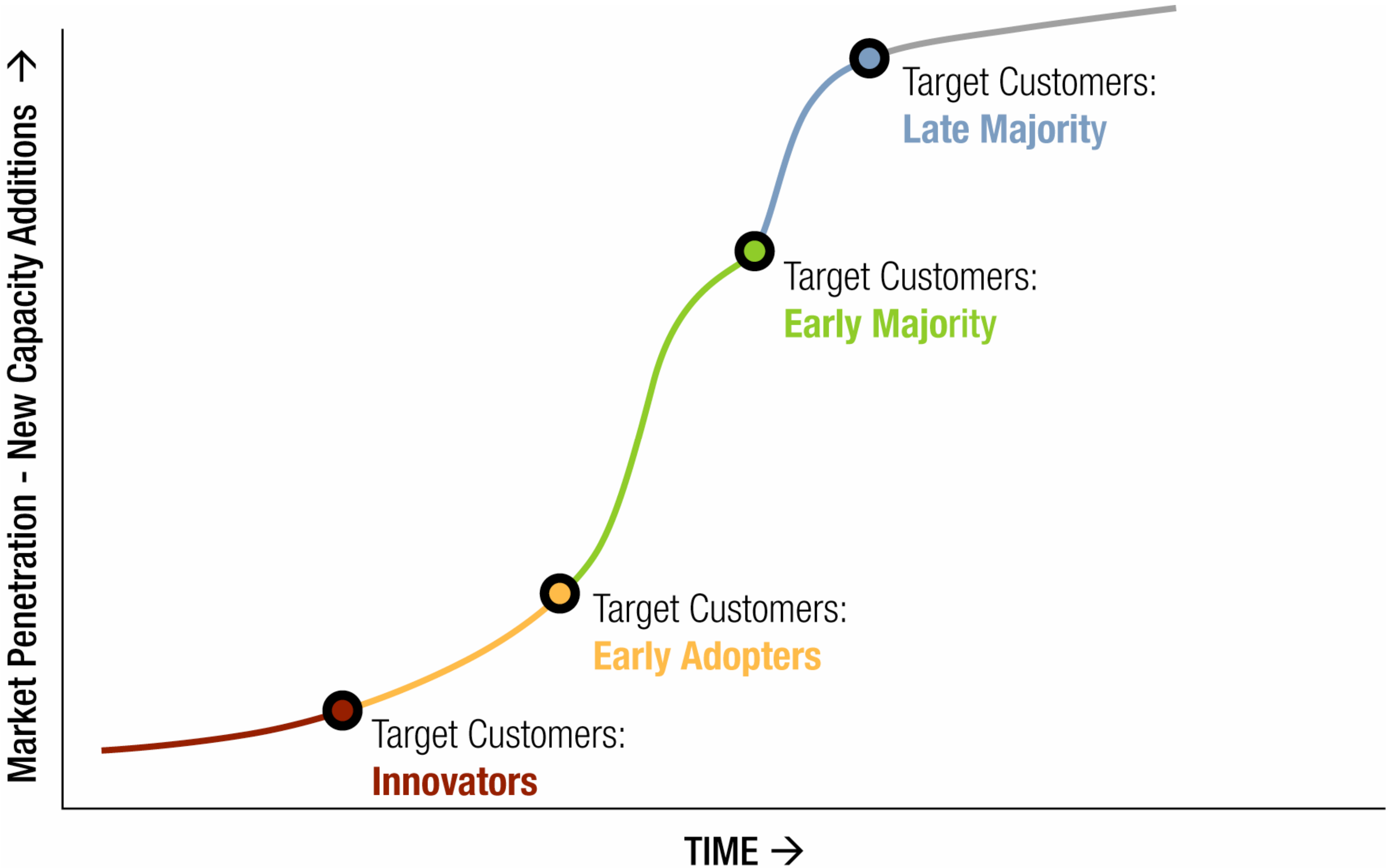
TOP Alignment Fixture

Richard Diver | Sandia Labs | Phone: 505-844-0195 | rbdiver@sandia.gov

Agenda

- Introduction to DOE Activities in Solar
- A Framework & Taxonomy for Solar (PV) Investing
- Current DOE Solar PV Investment Portfolio
- Key Investment Theses for VC/PE Investors
- Unexploited Investment "Gap" Areas
- Technology Showcase Opportunities
- A Vision for Solar PV Industry Evolution

A Path to Broad Market Capture for Solar PV



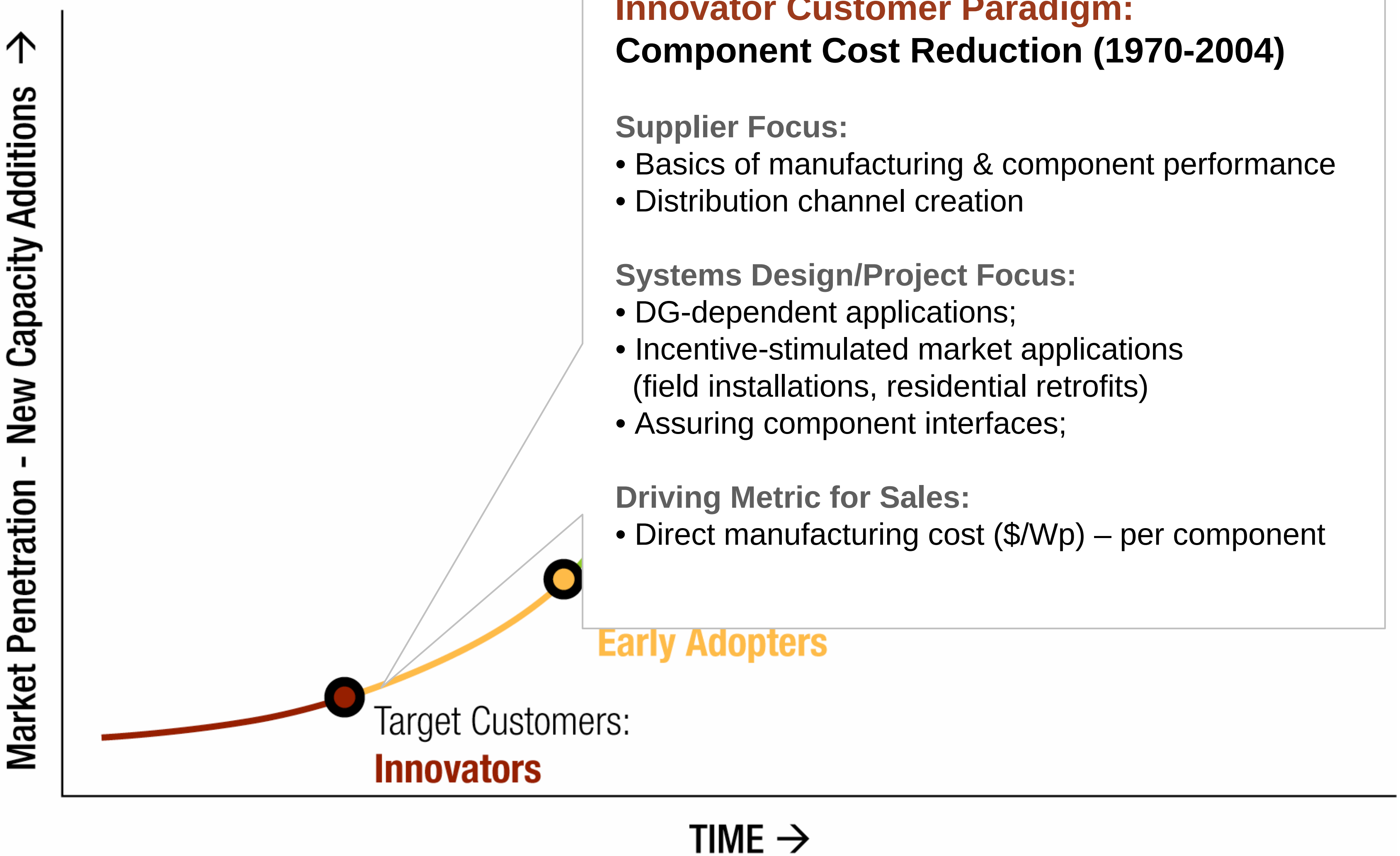
A Path to Broad Market Capture for Solar PV

Innovator Customer Paradigm:
Component Cost Reduction (1970-2004)

Supplier Focus:
- Basics of manufacturing & component performance
- Distribution channel creation

Systems Design/Project Focus:
- DG-dependent applications;
- Incentive-stimulated market applications (field installations, residential retrofits)
- Assuring component interfaces;

Driving Metric for Sales:
- Direct manufacturing cost ($/Wp) – per component



A Path to Broad Market Capture for Solar PV

Early Adopter Customer Paradigm:
System First Cost (2005-2008)

Supplier Focus:
- Vertical integration of value chain and/or upstream supply assurance;
- Cost structure reduction for margin protection (material utilization, scaling economies);
- Distribution channel assurance

Systems Design/Project Focus:
- New financing mechanisms;
- Methods for rapid design for optimization of cost/performance/installation

Driving Metric for Sales:
- Total system installed cost ($/Wp)

A Path to Broad Market Capture for Solar PV

Early Majority Customer Paradigm:
Lifecycle Ownership Cost (2009-11)

Supplier Focus:
- Production capacity expansion and application-driven product development;
- Differentiation of value chain strategies – vertical integration, turnkey plants/ equipment, "fabless" licensing;
- Yields, quality control, and reliability

Systems Design/Project Focus:
- Diversified ownership models for distributed PV (e.g. utility ownership);
- Standardized turnkey design configurations for replicable applications;
- PV-integrated building materials;
- Feedback to product development and improved component sourcing leverage

Driving Metric for Sales:
- Levelized Cost of Energy ($/kWh) – Lifetime Ave

A Path to Broad Market Capture for Solar PV

Late Majority Customer Paradigm:
User Value (2012+)

Component Supplier Focus:
- Development of differentiated application-specific product lines (horizontal integration thru acquisitions);
- Region-specific supply and distribution channels

Systems Design/Project Focus:
- PV integration with controls, efficiency and storage to match system output w/ dynamic use patterns;
- "Mix-and-match" designs use-driven and diverse, enabled by automated design practices;
- Enable dispatch-ability and grid compatibility for high market penetration
- Competition with solar thermoelectrics (CSP) for central station utility market

Driving Metric for Sales:
- Avoided Cost of Energy ($) – Annualized/Cumulative

For More Information:

DOE Solar Program/Analysis: http://www.eere.energy.gov/solar/solar_america/
PV Value Clearinghouse: www.nrel.gov/analysis/pvclearinghouse/
SNL PV Systems R&D: www.sandia.gov/pv
NREL Solar Research: www.nrel.gov/solar

Sign up for our Newsletter and Market Analysis: Send email to solar@ee.doe.gov

---

Questions on this Presentation:

Market Analysis
Email: robert_margolis@nrel.gov
Tel: (202) 646-5053

Technology Analysis
Email: scott.stephens@ee.doe.gov
Tel: 202-586-0565