Trends in Photovoltaics

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Outline

- Growth of PV industry
- Drivers remain cost and efficiency: $/W = cost / efficiency
- Mainstream wafer-based silicon trends
  - Cell structures
  - New process technologies
- Mainstream thin film trends
  - Improved materials
  - Scaling to drive cost reduction
- Balance of system trends

Rapid growth of market

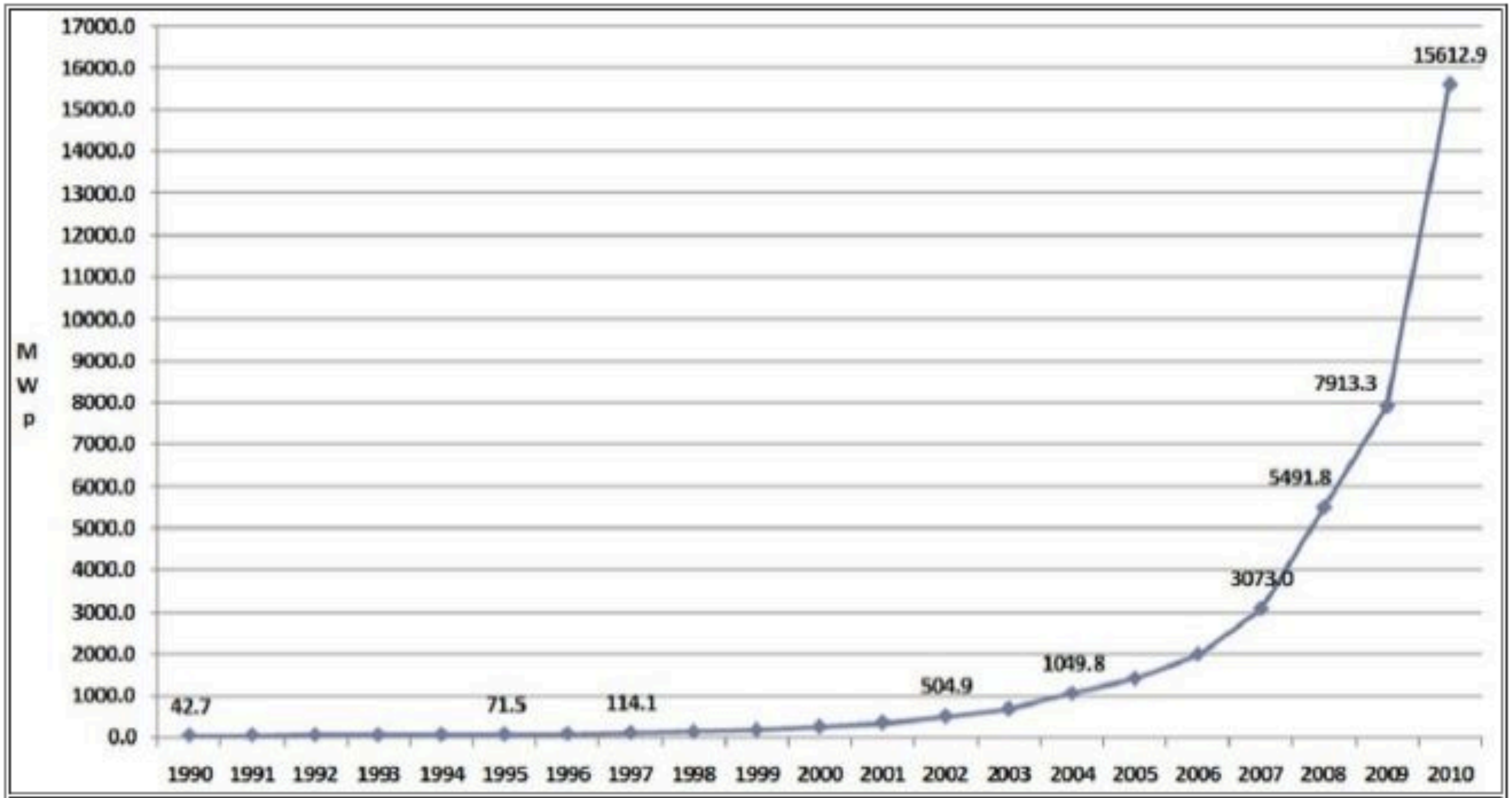
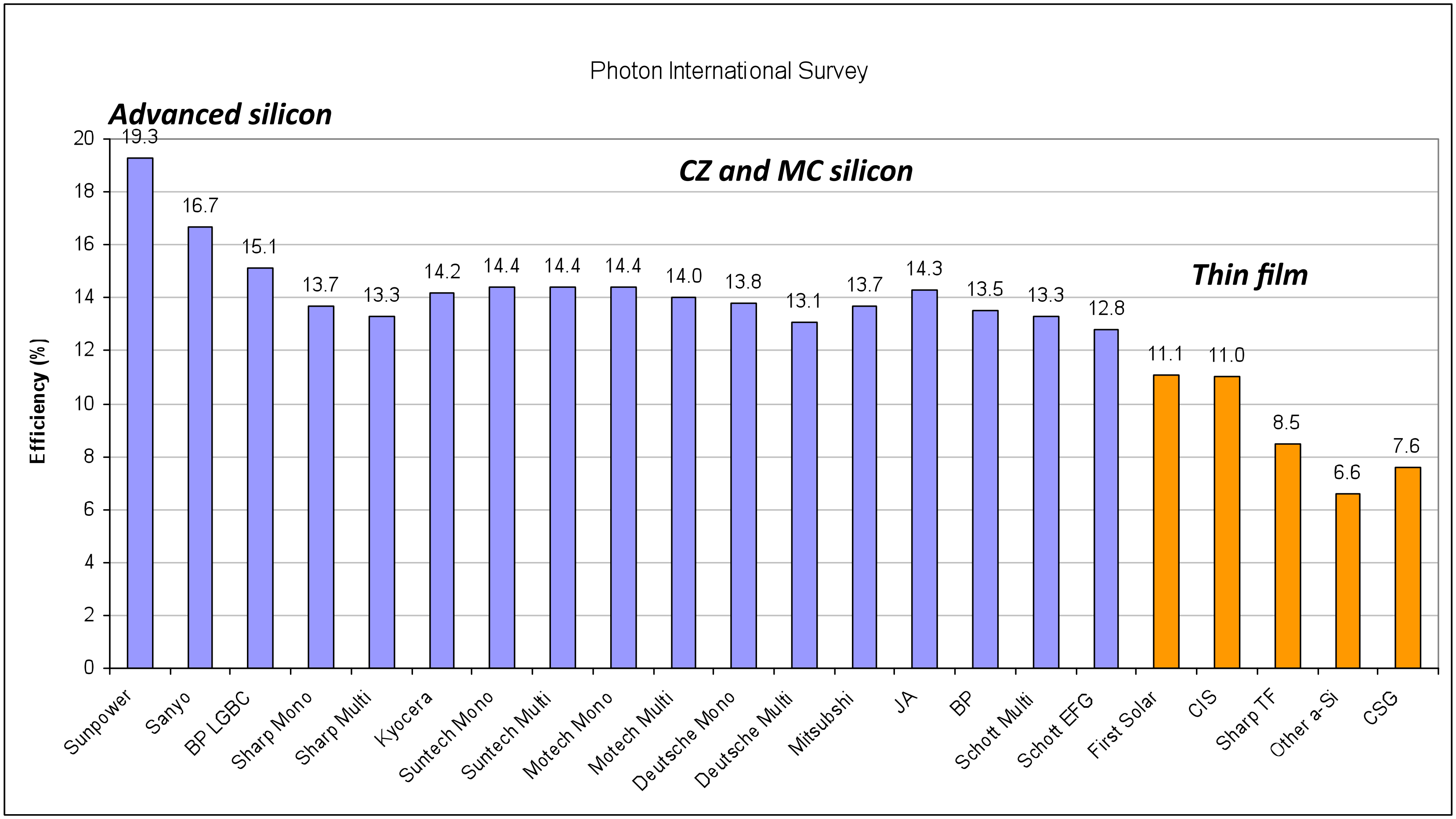


Figure 3: PV industry growth, 1990-2010 (estimate).

The PV market has shown explosive growth; 2011 could be over 20 GW!

P Mints, Navigant Consulting

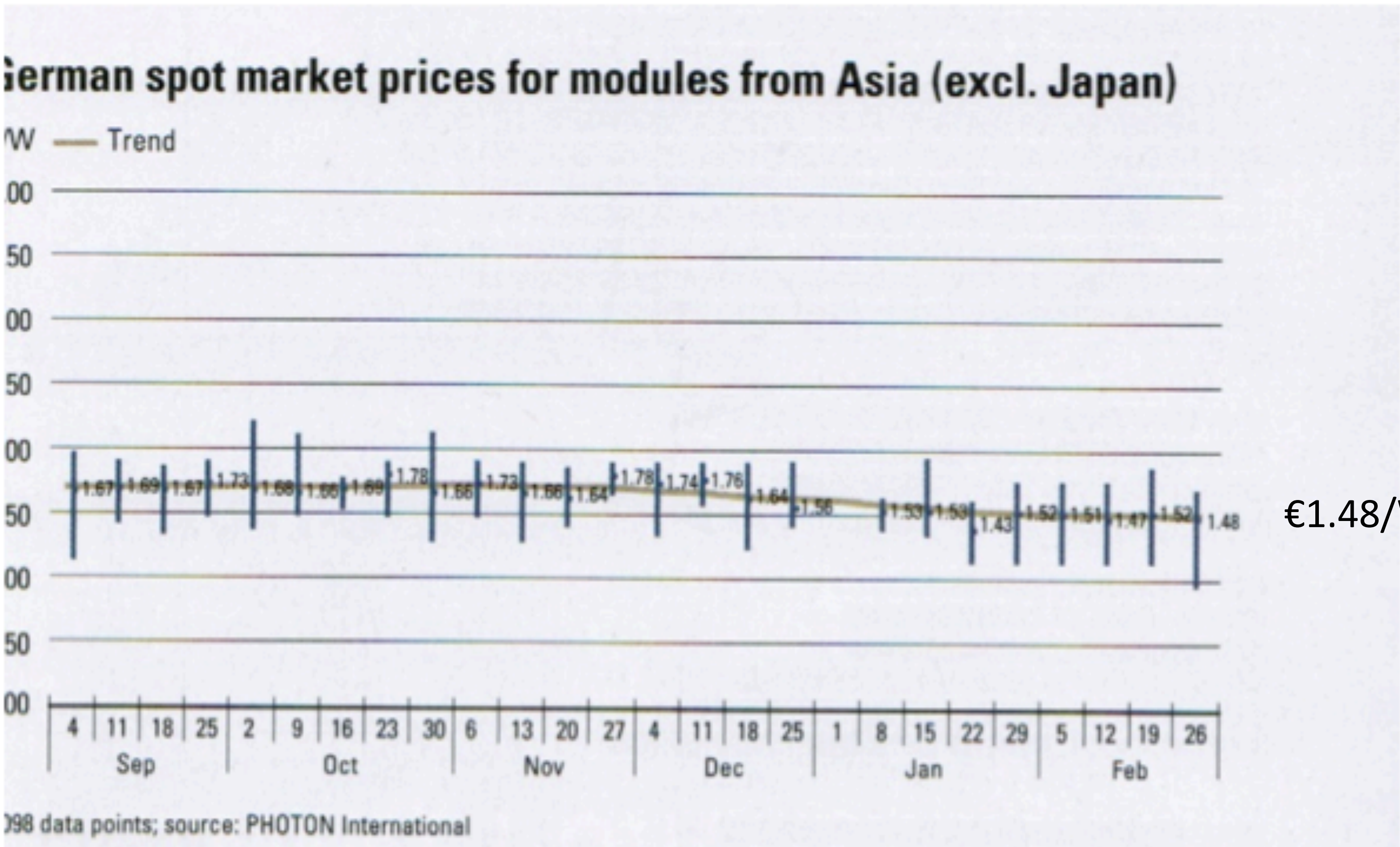
Module Efficiency – c-Si and Thin Film



- Thin Film suppliers need higher module efficiency with low manufacturing costs
- Silicon suppliers need incremental efficiency and cost gains to stay ahead of TF

Prices of silicon modules from China

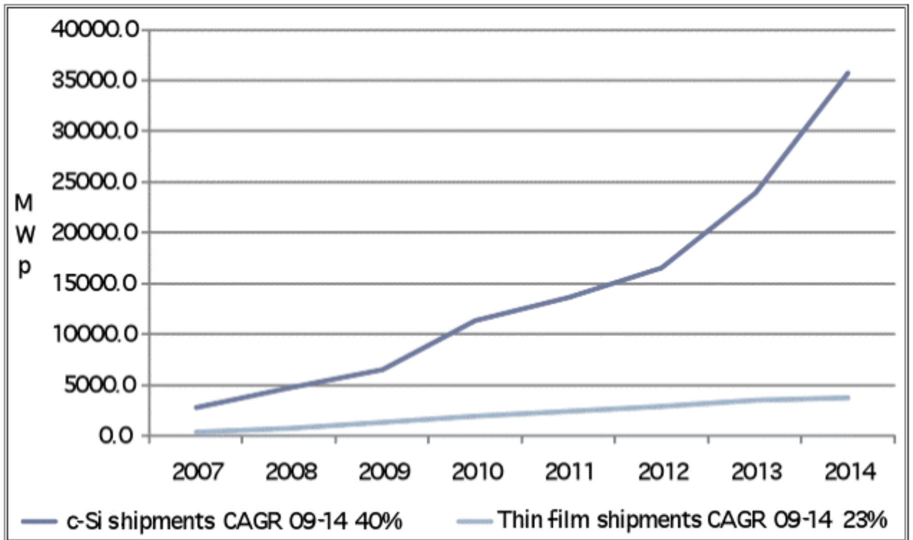
Wafer-based silicon modules from China are putting pressure on thin film technologies that trade efficiency for low production cost



€1.48/W

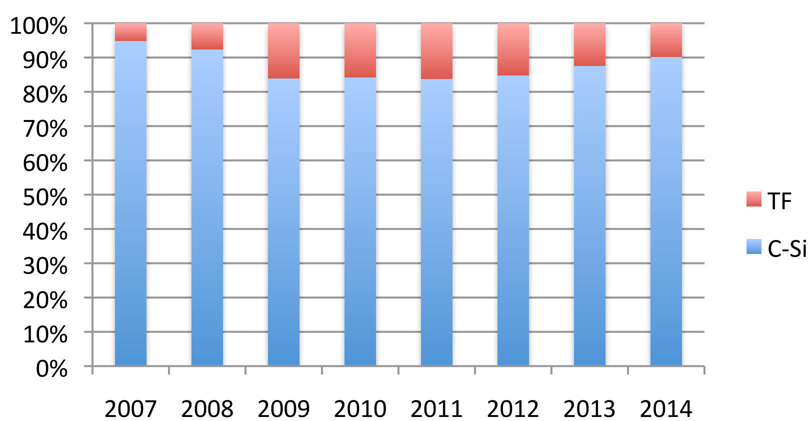
Photon International, May 2010

Thin film and wafer-based silicon shipments



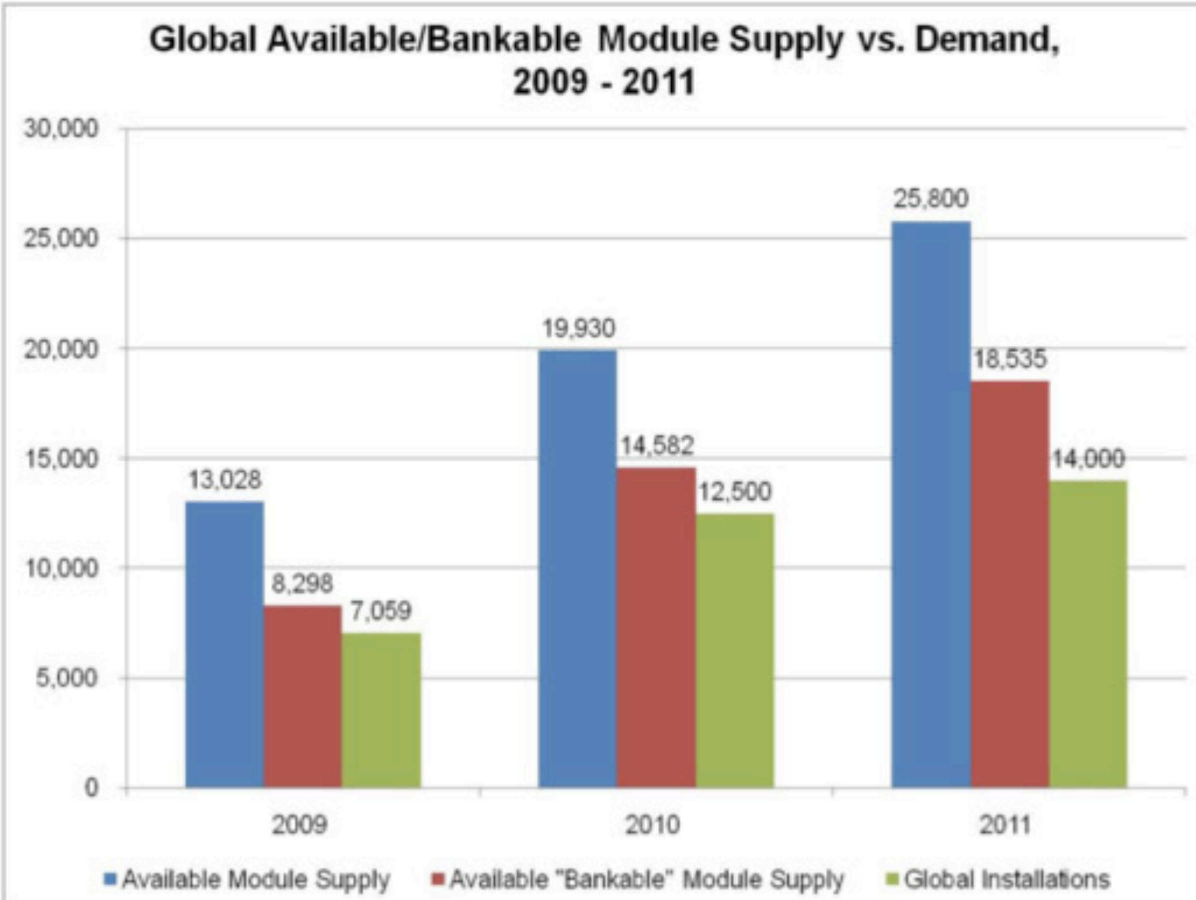
Technology shipments through 2014.

The wafer-based silicon market continues to be larger, because of higher efficiency and rapidly declining cost



P. Mints, Navigant Consulting

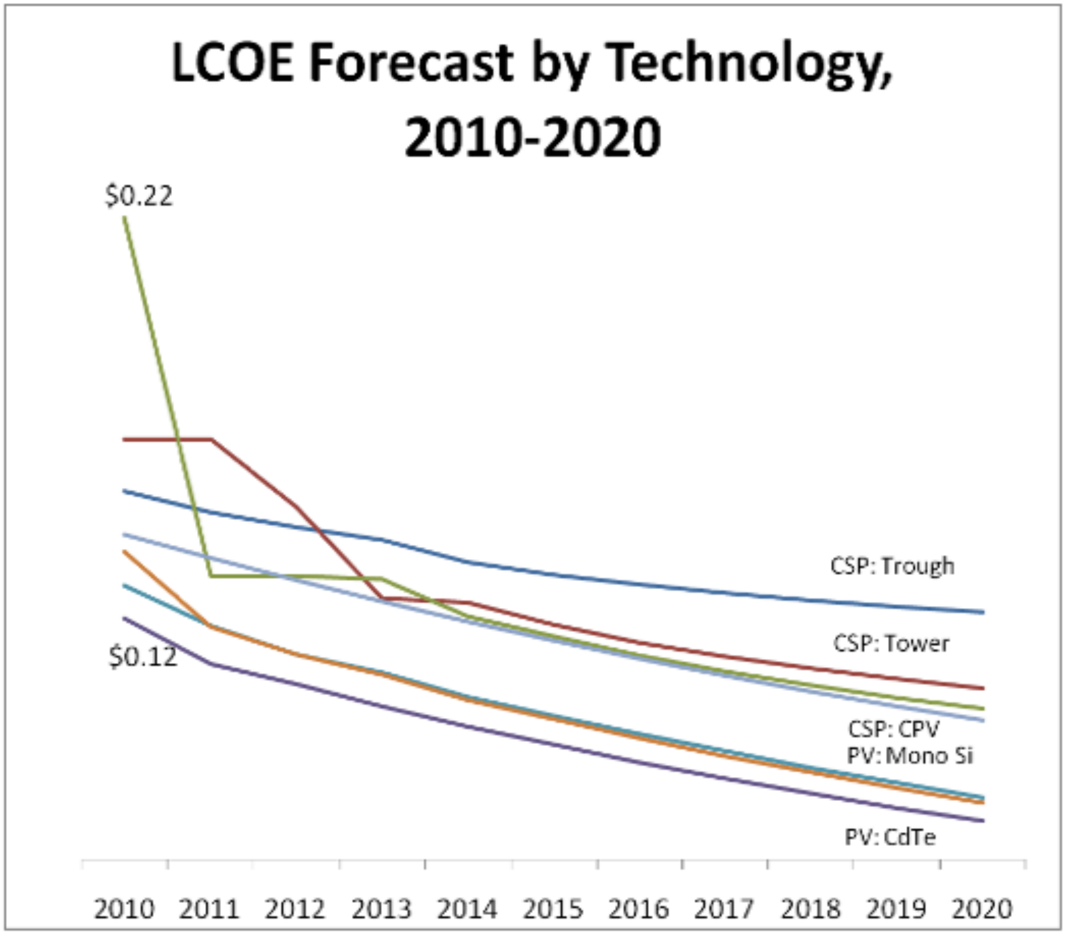
"Bankable" supply



Greentech media

Supply greatly exceeds demand, but only a portion comes from stable companies. Banks will only loan money to buy from these companies, especially for large projects.

LCOE: Concentrating Solar Power (CSP) and PV



LCOE includes all costs. Flat panel silicon comes out ahead, dropping to 6-7¢/W by 2020.

Greentech Media

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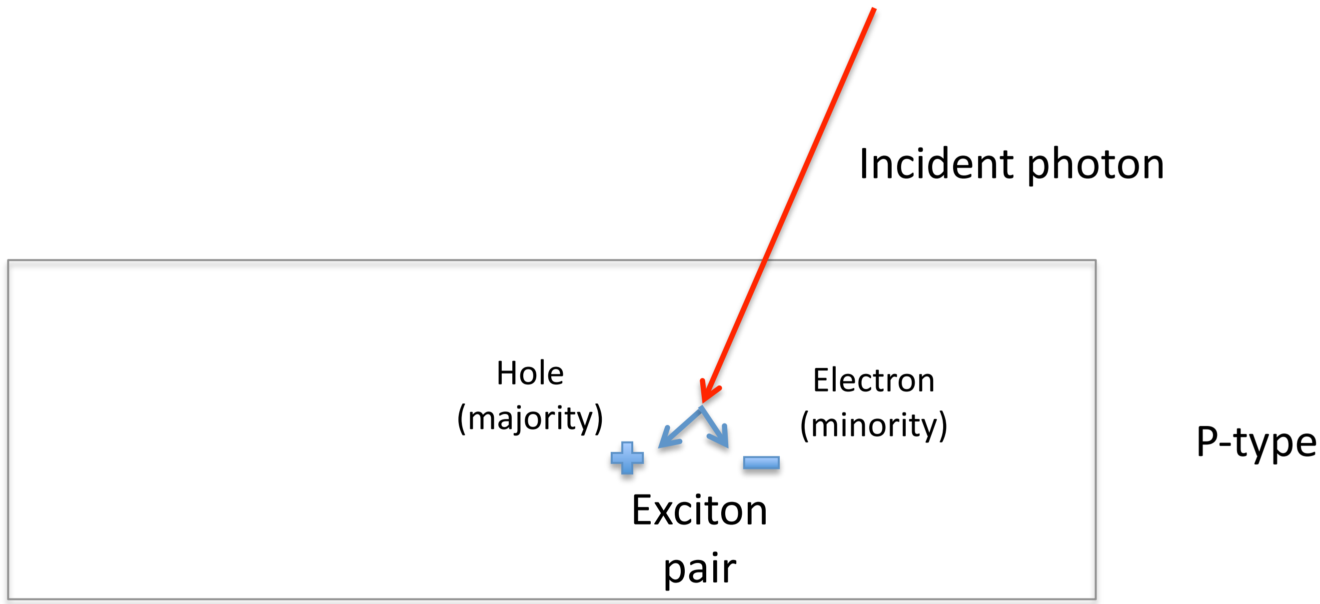
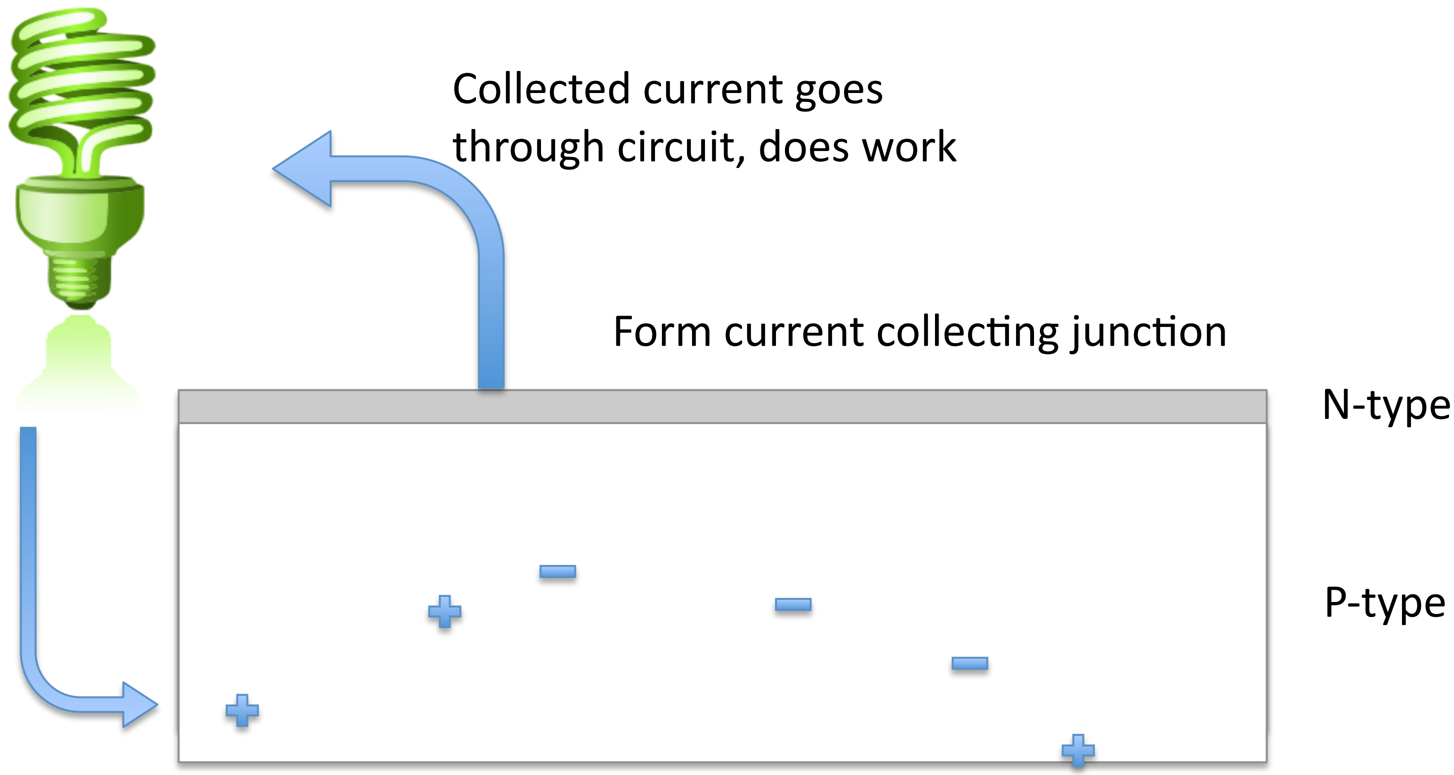
Solar cell background



Incident photon creates exciton pair of hole and electron

Solar cell background

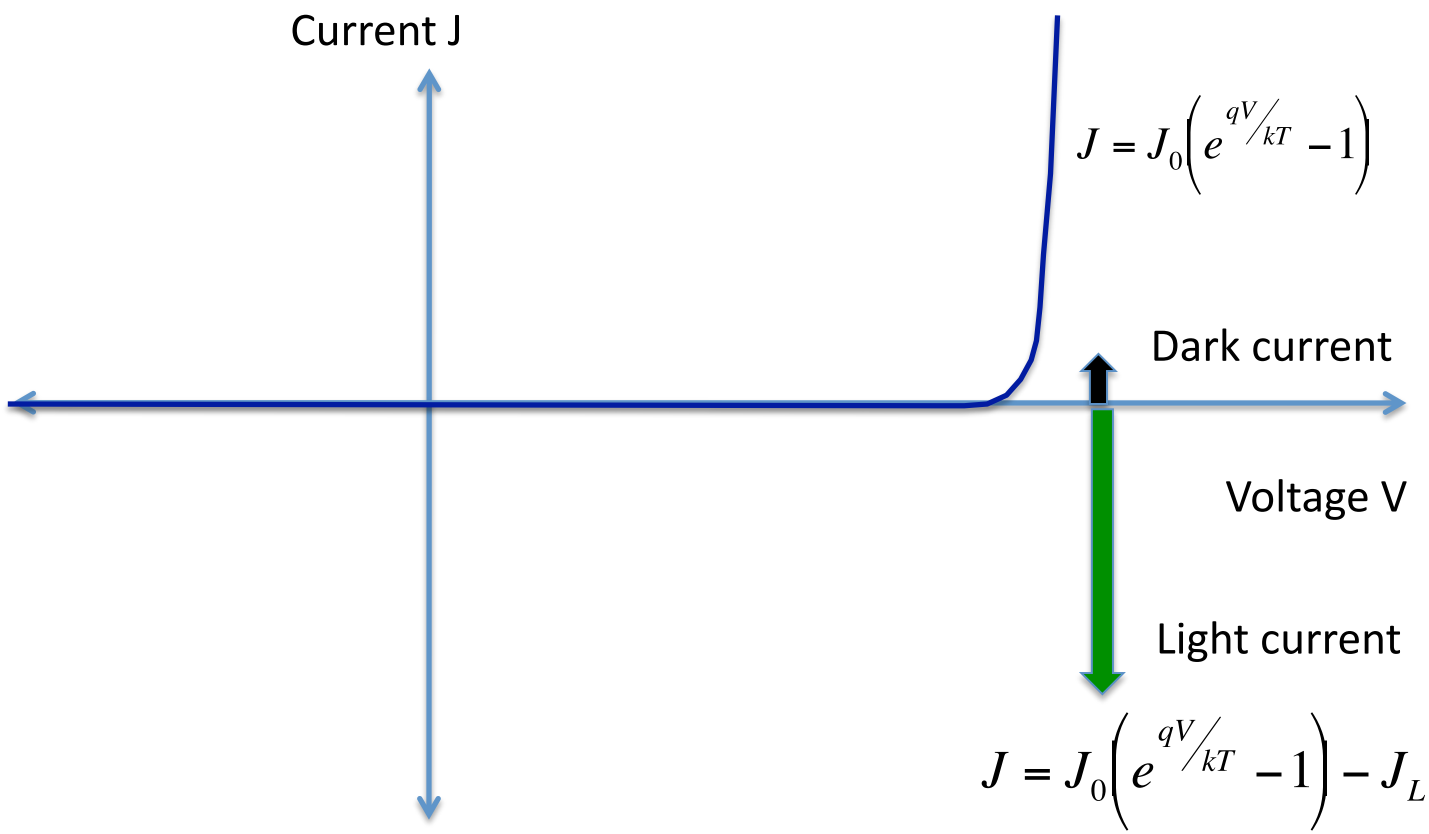


Good: minority carrier collected across junction, does work

Bad: minority carrier recombines at surface, is lost

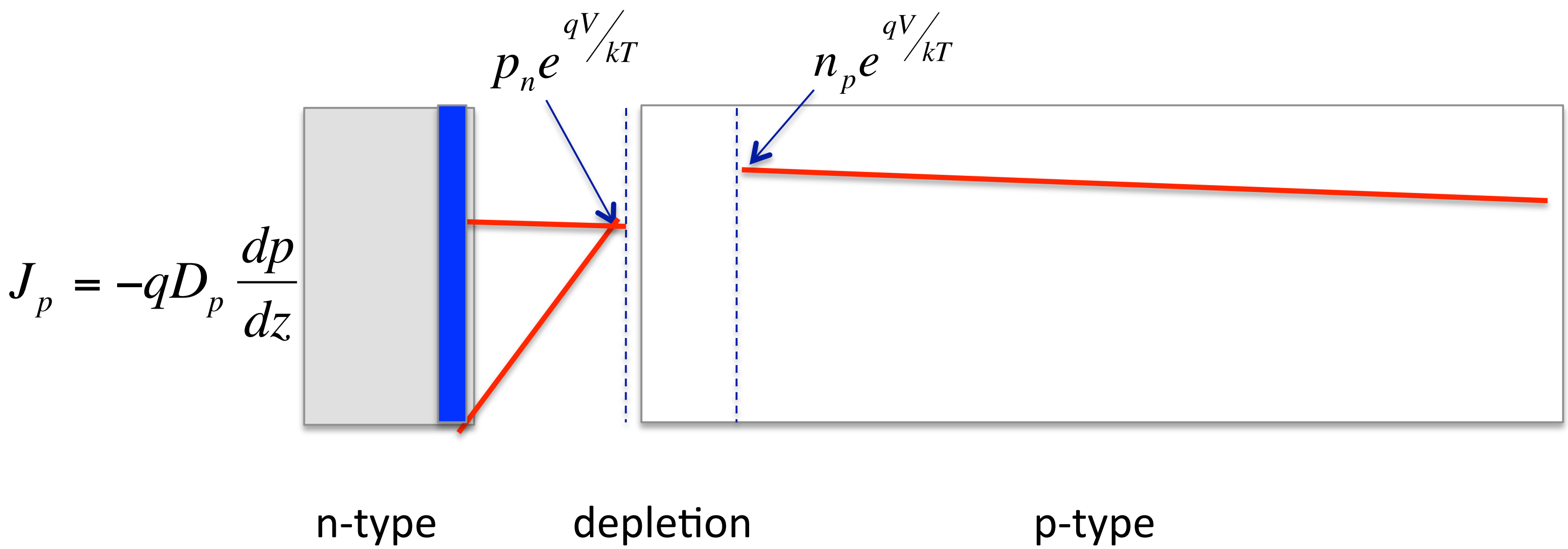
Bad: minority carrier recombines in bulk, is lost

Dark and Light currents work against each other



- Dark current works against generation current J_L
- High efficiency requires minimizing the dark current by making J_0 as small as possible

Minimizing J_0 with passivation or deep junctions



If the surface has no passivation and the n-type layer is thin compared to the diffusion length, the minority carrier concentration drops steeply and there is a high diffusion current away from the junction. This causes a high J_0.

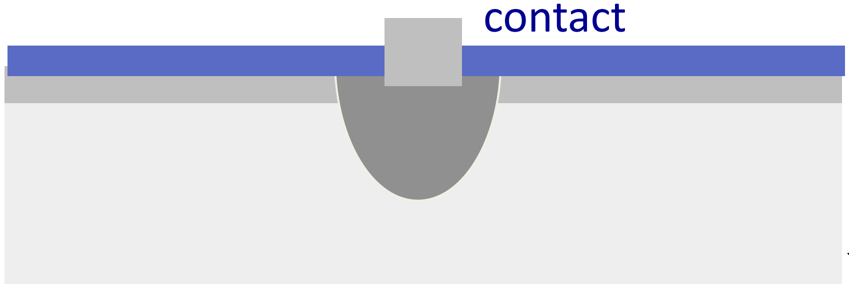
⇨ With high recombination, layers thick compared to diffusion length have low J_0.

With surface passivation, the minority carrier concentration is constant and there is no diffusion current away from the junction. This causes a low J_0.

⇨ With low recombination, layers thin compared to the diffusion length have low J_0.

Patterned structures needed

- Selective emitter
  - Deep diffusion under contact reduces effect of contact recombination
  - Shallow diffusion in field under passivated surface



- Point contacts with back reflector
  - Limited back contact area, deep diffusion reduces contact recombination
  - Back surface passivation reduces surface recombination
  - Back reflector (dielectric and reflective metal) increases collection

Patterned Si cell designs set efficiency records

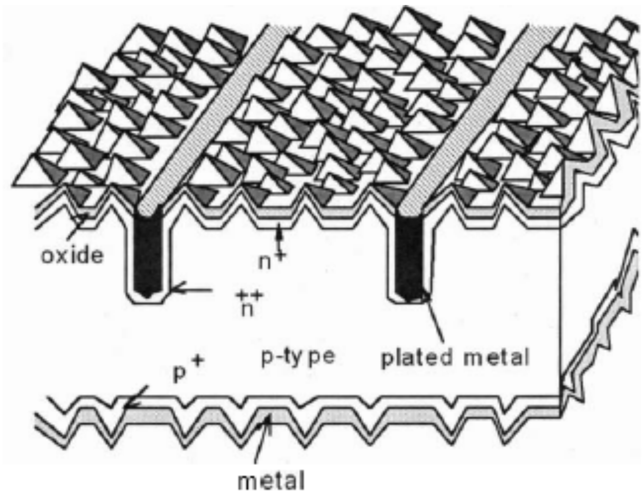


Figure 4.16. Cross-section of Laser Grooved Buried Contact Solar Cell.

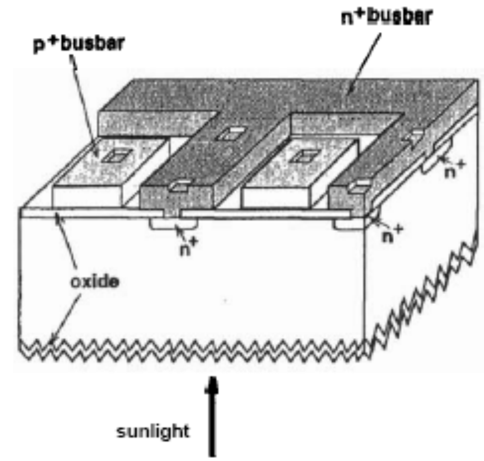


Figure 10.9: Rear point contact solar cell which demonstrated 22% efficiency in 1988 (cell rear shown uppermost].

- Advances such as laser grooving, surface field regions, and improved passivation yielded 17-18% in high volume.
- Sunpower manufactures the back point contact cell, currently >24%.
- The PERL cell (UNSW) holds the record of 25.0% (vs. ideal limit of ~28%) but is not commercially viable.

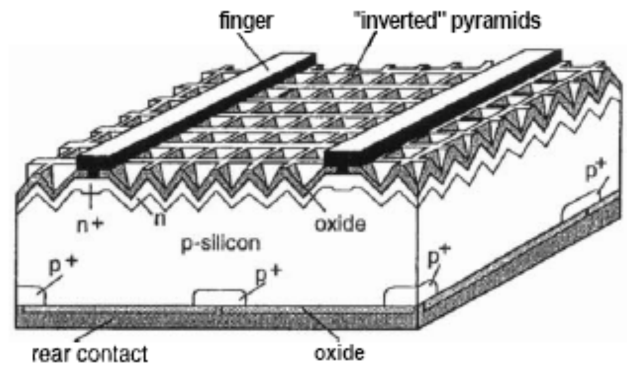


Figure 10.10: The PERL cell which took efficiency above 24% in the early 1990's.

Silicon ink selective emitter

Innovalight has reported a selective emitter using silicon ink printed to form high doped regions

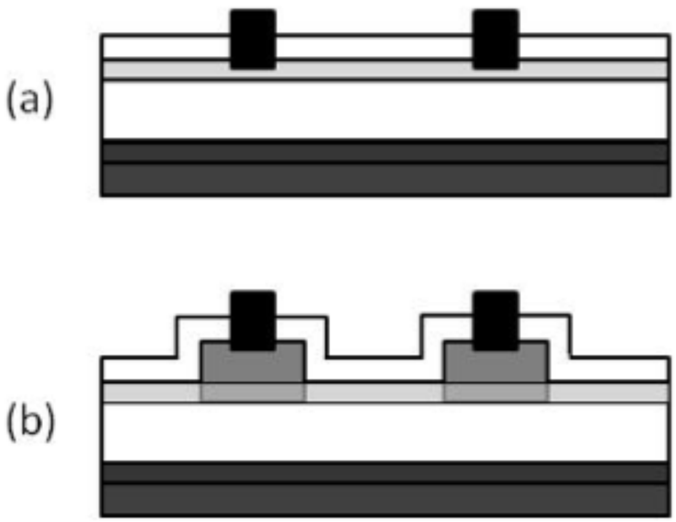


Fig. 2: (a) cross section of reference cell architecture, (b) cross section of Cougar cell architecture using Innovalight Silicon Ink.

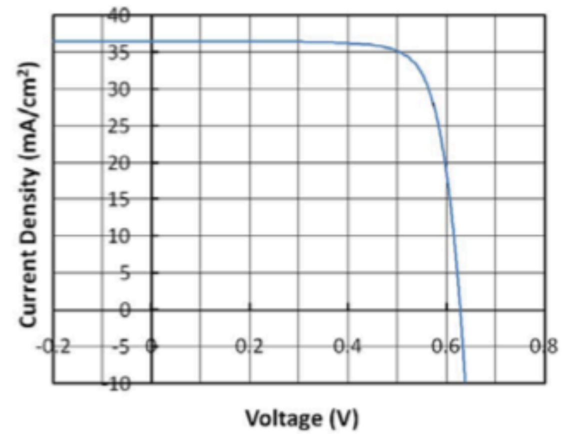


Fig. 4: One-Sun J-V characteristics of the best Innovalight selective emitter solar cell.

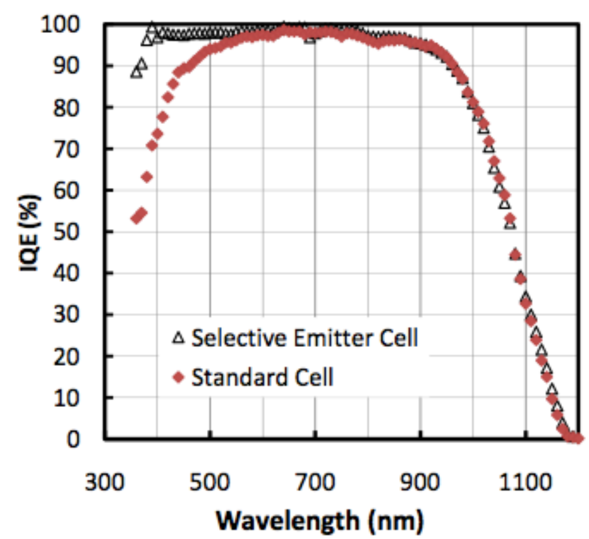
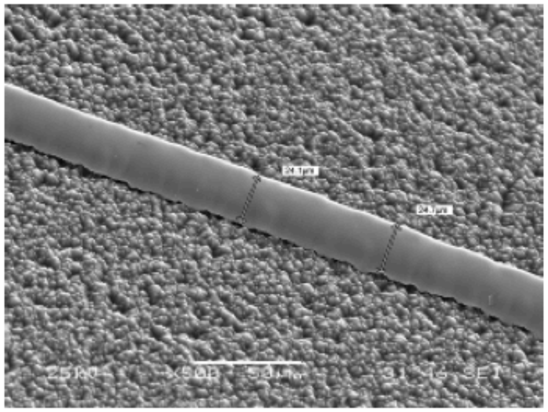


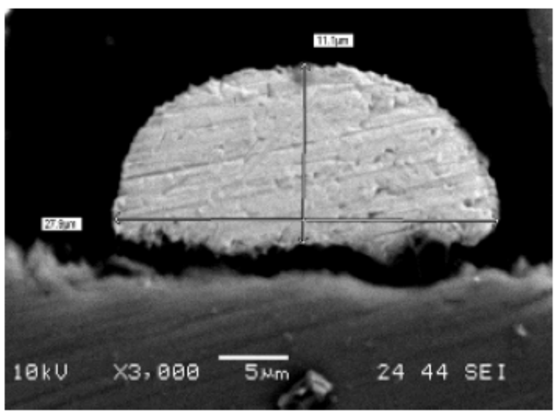
Fig. 5: Internal Quantum Efficiency (IQE) for standard and the selective emitter cells.

H. Antonaides, 2009 IEEE PVSEC, Philadelphia

Suntech's Pluto Cell



(a)



(b)

Figure 3: (a) Typical metal finger for the PLUTO cell demonstrating line width, height and aspect ratio the same as routinely achieved by the PERL cell using photolithographic and masking techniques. (b) Shows the cross-section of a typical PLUTO metal line.

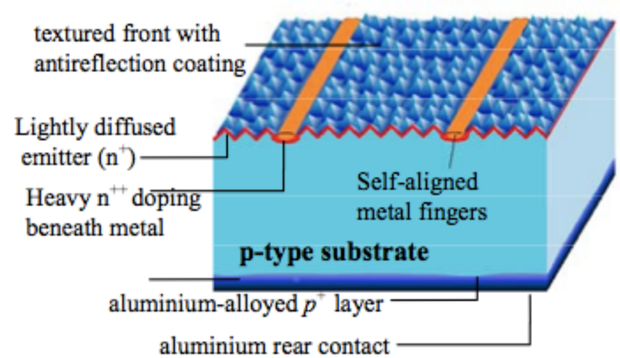


Figure 5: Schematic of the simplified PLUTO solar cell with screen-printed and fired rear aluminium contact and front metal lines only 20-25 microns wide.

Figure 6: Typical efficiency distribution for a single-day's production of the 34MW PLUTO production line following 6 months of operation. The bi-modal distribution has been shown to be caused by wafers fitting into two distinct categories based on quality.

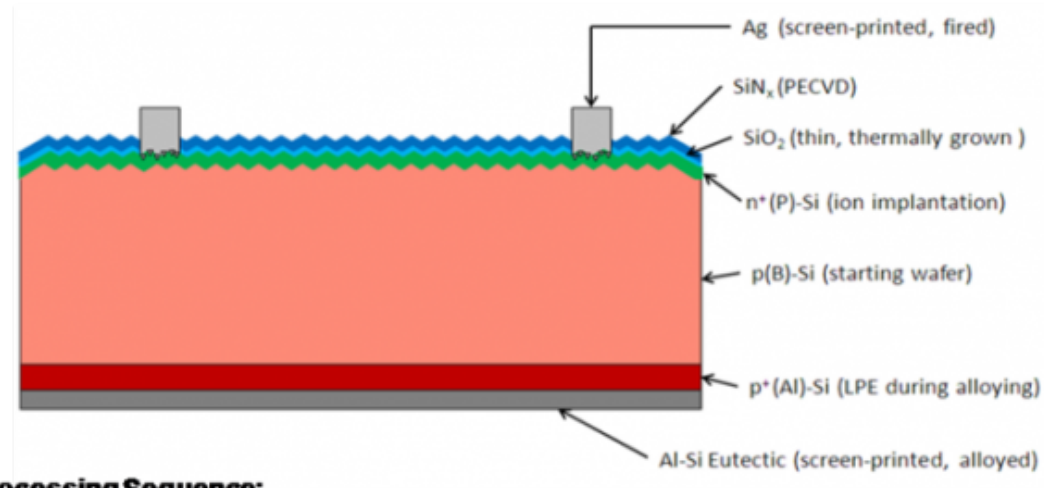
Process features

- Selective emitter
- Fine grid lines with high aspect ratio (enabling close spacing to minimize ohmic losses with selective emitter)
- Relatively little added cost over conventional process
- 1-2% absolute efficiency gain

From Shi, Wenham and Ji, 2009 IEEE PVSEC, Philadelphia

Suniva and Varian implant process

- Suniva in partnership with Varian has used implant to form emitters
- The process eliminates steps such as p-glass etch
- It provides a passivating oxide during implant anneal
- Efficiency of 19% is reported on 156 mm wafers
- Process opens the door to use of n-type silicon, with even higher efficiency

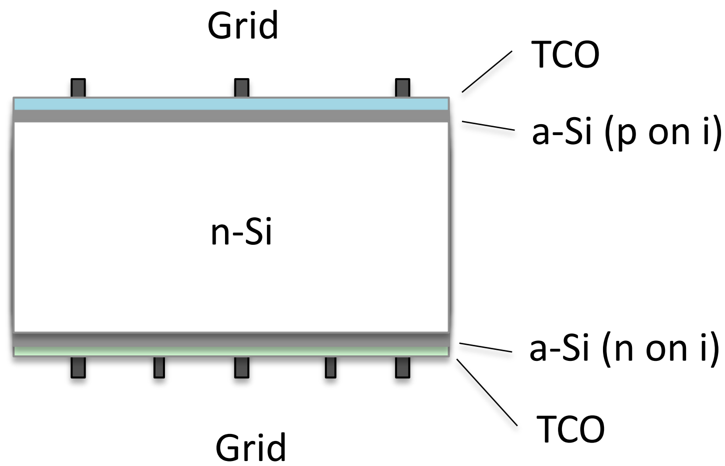


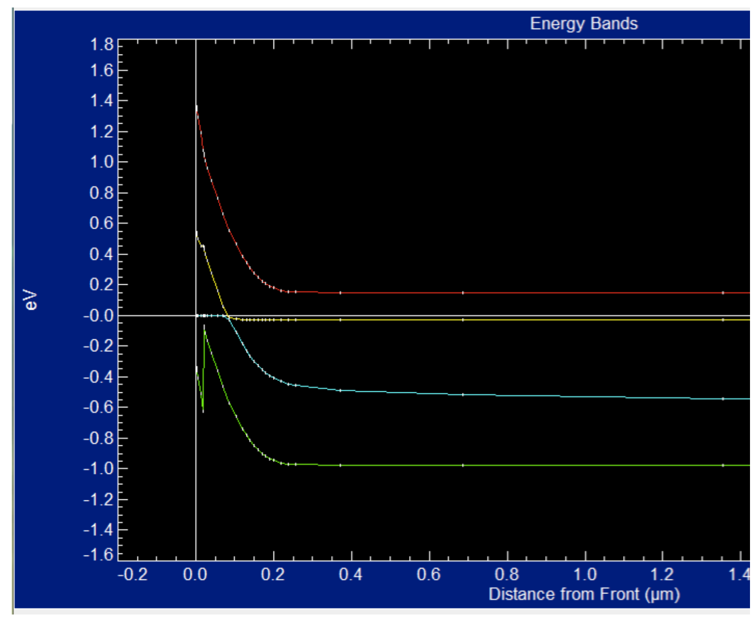
Processing Sequence:

1. Saw damage etch/texture
2. Implant phosphorus on front
3. Anneal implant damage and grow thermal oxide
4. Deposit SiN_x on front
5. Print/dry back Ag soldering pads
6. Print/dry back Al contact
7. Print/dry front Ag gridlines
8. Co-fire

Heterojunction cells (HIT)

- Sanyo reported lab efficiencies >22% using ultra-thin substrates; in production at 18.9% (per web site)
- Advantage is high efficiency and process that does not need high temperature steps
- Issues include intolerance to high temperature steps, surface preparation, need for extremely thin a-Si layers, and absorption in a-Si and TCO
- Basic patent recently expired (although many others are in force); some looking at this as way to make very thin cells.





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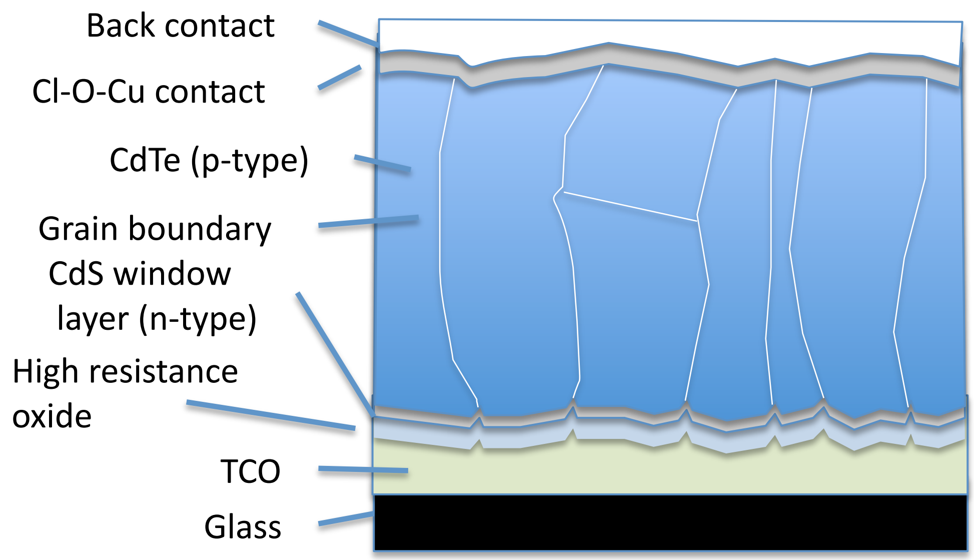
CdTe cell structure

The CdTe cell uses a hetero-junction between p-type CdTe and n-type CdS. The best lab efficiency is 16.1% (NREL), and commercial modules have efficiency in the mid-10% range. The high efficiency for a thin film cell comes from the columnar grain structure, high mobility, and short absorption length. Special features include a CdCl treatment to create p-type doping and increase grain size, and special anneals to get a good junction and back contact, and the high resistance TCO to reduce shunting through the thin CdS layer.



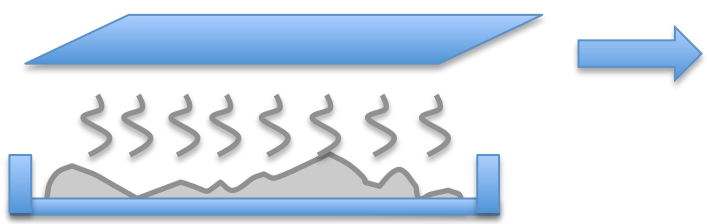
Some material properties:

Band gap	1.5 eV
Electron affinity	4.28 eV
Absorption coef	6×10^4/cm@600 nm
Index of refraction	3
Mobility (electron)	500-1000 cm^2/V-sec
Mobility (hole)	50-80 cm^2/V-sec

CdTe deposition is low cost

CdTe can be deposited by a number of processes, including sputtering, evaporation, screen printing, and spraying. The most successful commercial process is Close Space Sublimation. The glass substrate is heated to 600°C and brought close to a bed of CdTe heated to 650-750°C at a pressure of about 10 Torr. Layer thickness is about 4 µm, deposited at a rate of 1-5 µm/min.

Substrate at 600°C



CdTe at 650-750°C

This process is simple and yields the stochiometry and grain structure for best efficiency, which is why CdTe today offers the lowest $/W of any commercial product.

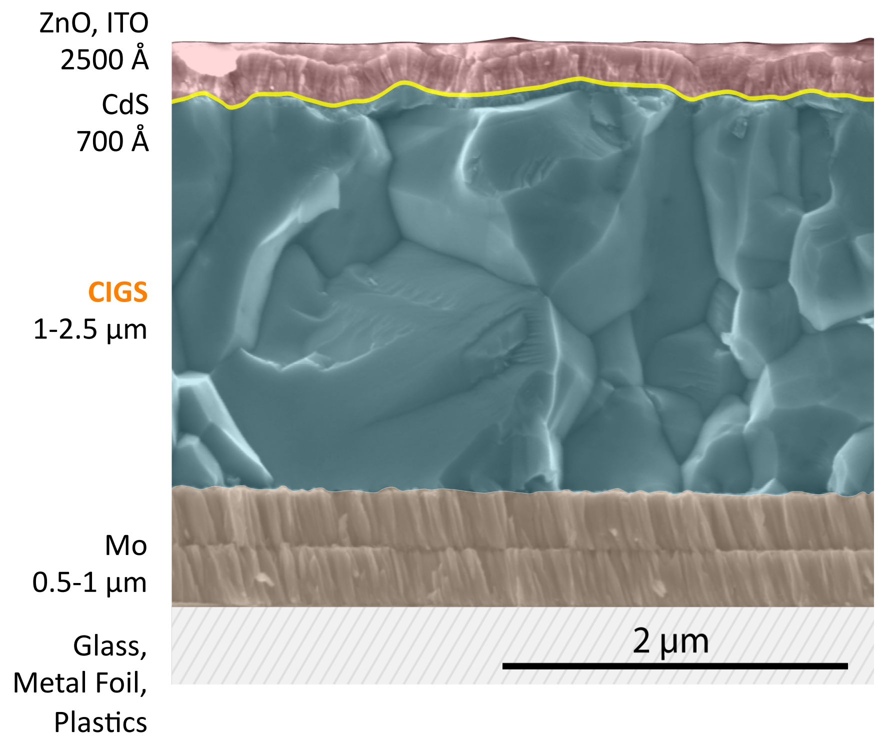
Issues include small module size, because glass softens at 600°C, and cleaning of excess CdTe in the chamber.

CIGS structure

CIGS has the highest efficiency of any thin film cell – 20.1% by ZSW. It uses a hetero-junction between p-type CIGS and n-type CdS. The CdS is often plated in a wet bath following deposition.

A back contact is formed with a two-layer Mo deposition. The paired layers reduce stress.

Unlike other thin film cells, the light is incident from the top (as opposed to through the substrate).



R. Noufi, 4th WCPEC, 2006

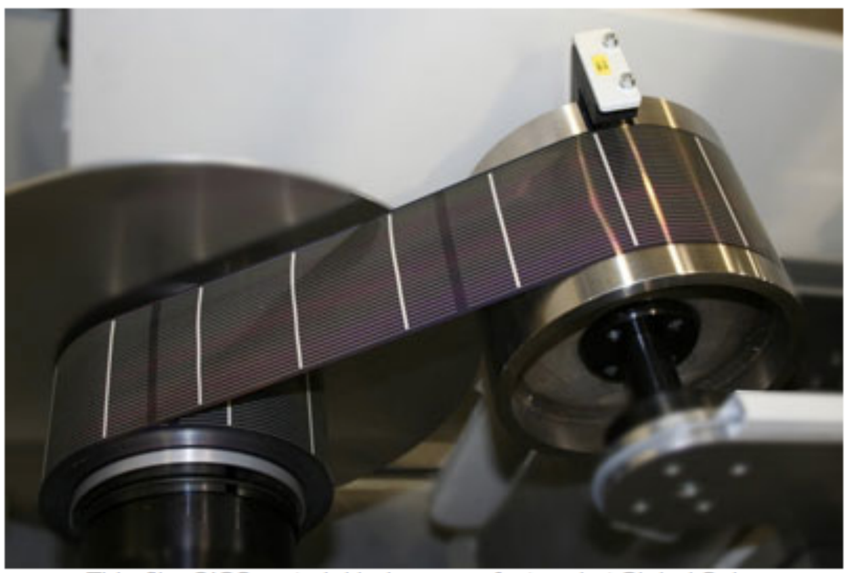
$$\frac{Cu}{(In+Ga)} = 0.82 - 0.95$$

$$\frac{Ga}{(In+Ga)} = 0.26 - 0.31$$

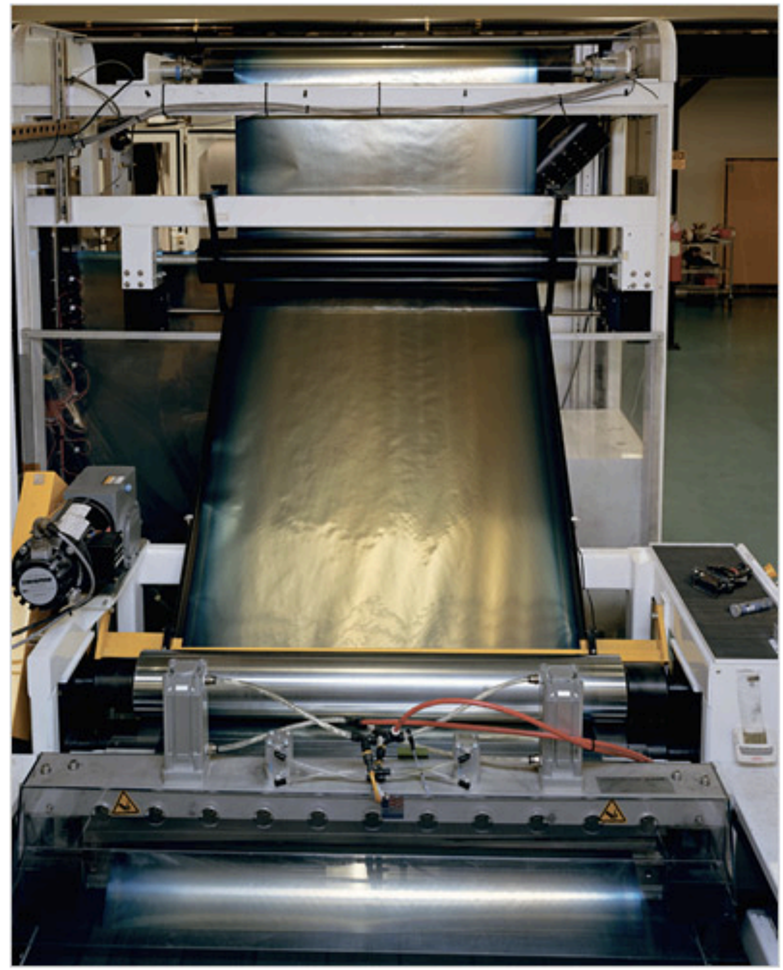
Reel-to-reel manufacturing

Offers low cost, high throughput cell manufacturing. Limitations include:

- Hard to integrate cells – usually cut up
- Still needs environmental encapsulation such as glass sheet for module
- Imposes limitations on substrate choice, which may affect efficiency.



Thin-film CIGS material being manufactured at Global Solar



Mitch Epstein for The New York Times

Plated CIGS

An interesting approach to forming CIGS is plating. This provides good stochiometry control, an issue with vacuum deposited films. SoloPower plates CIGS on a metal foil, making cells intended as silicon replacements with lower substrate cost.

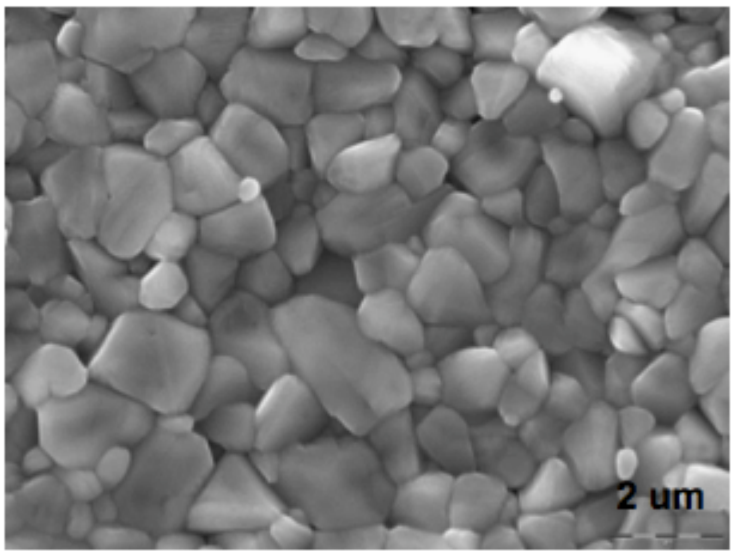


Figure 4: Top view SEM of a CIGS layer grown on a metal foil substrate

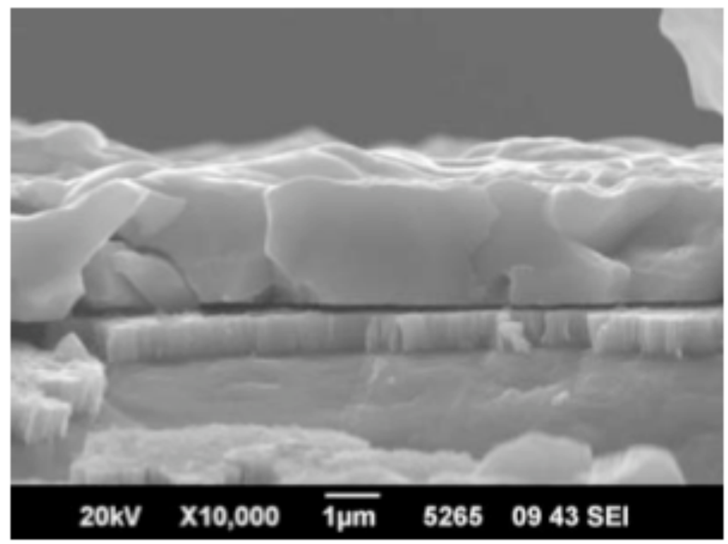


Figure 5: Cross sectional SEM of a CIGS layer grown on a metal foil substrate at elevated temperatures

Basol et. Al., 23rd European PVSEC, Valencia, 2008

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Micro-inverters and AC modules

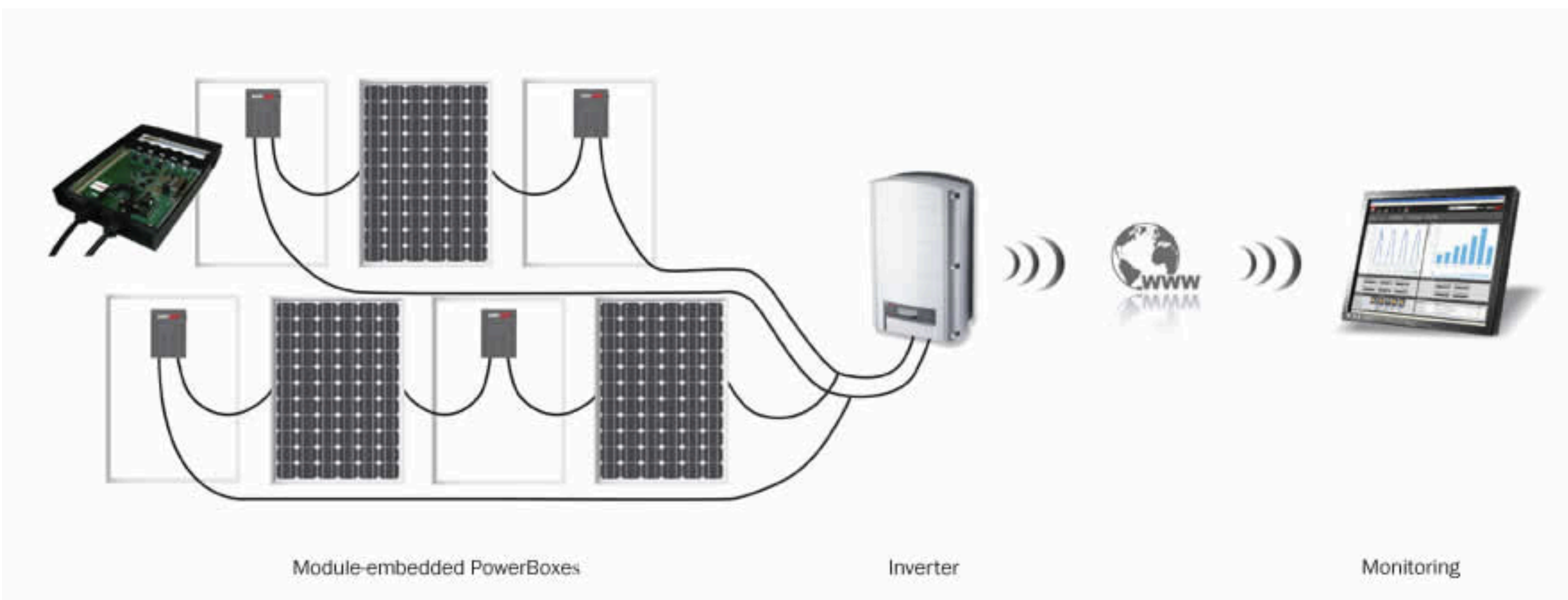
Micro-inverters mount on the back of the module, so each module has an AC output and can be connected directly to the grid.   Each module runs at its optimum output, so there are no matching issues. The system may be more expensive, and the inverters must have very high reliability.

Enphase micro-inverter

Power optimizers

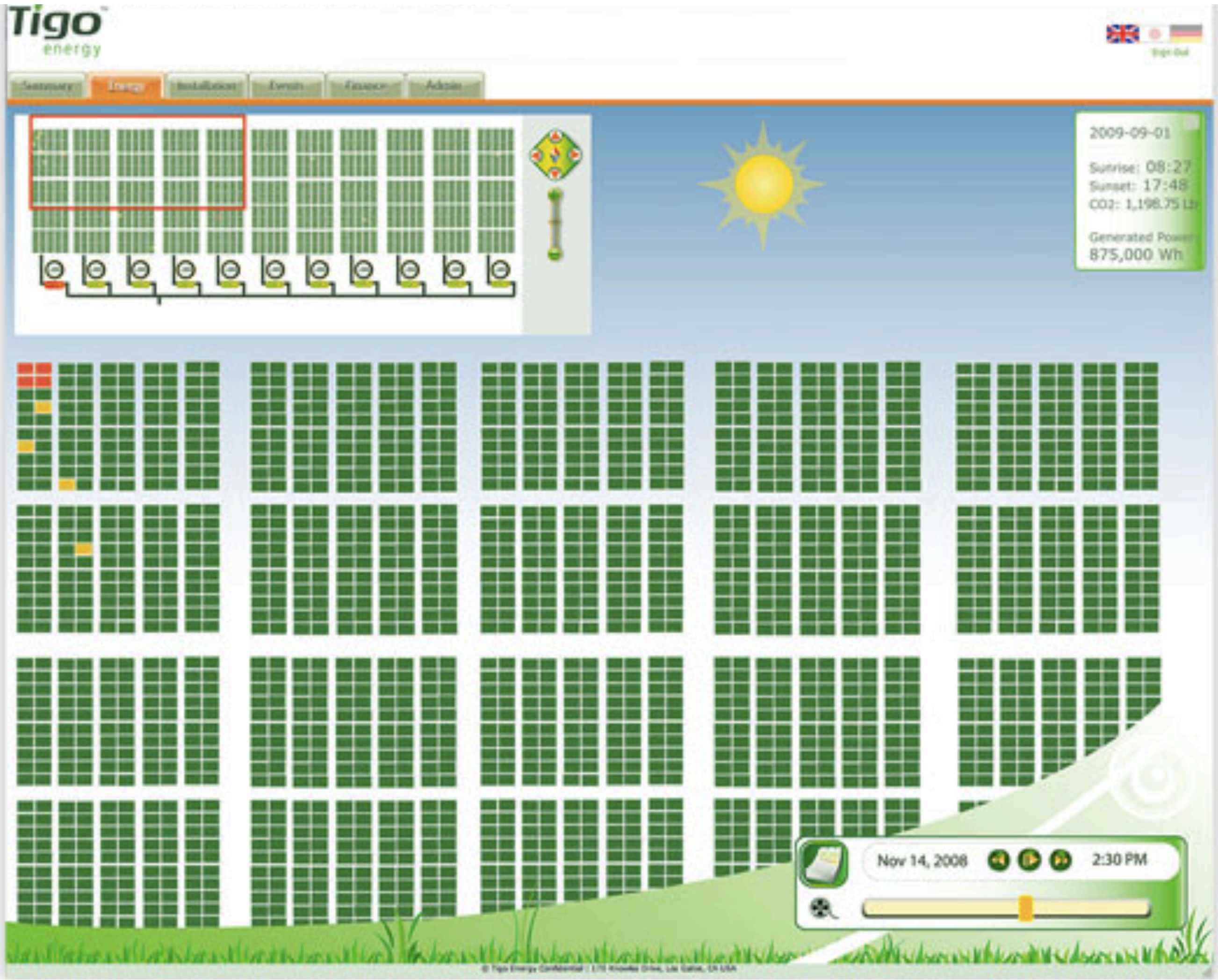
Power optimizers are small circuits, about the size of the junction box, that correct for mis-matches between series connected modules. Suppliers include Tigo, National Semiconductor (Solar Magic), and Solar Edge.

While improving performance with certain array configurations such as long series strings, cost remains an issue.

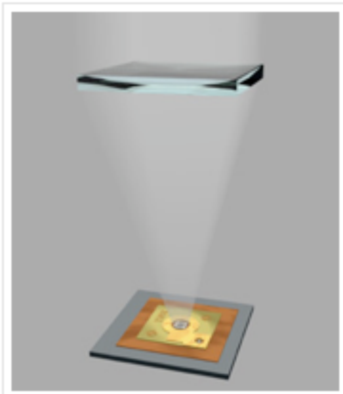


Other advantages of power optimizers

More sophisticated power optimizers communicate the status of each module over a web connection. This can be useful in maintaining large systems.

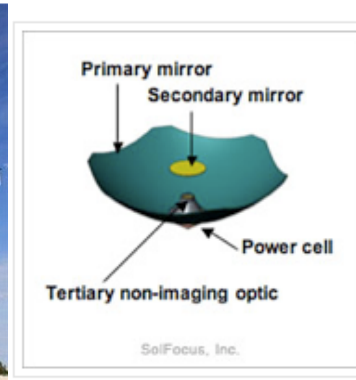


Concentrator approaches



Concentrix

Amonix



SolFocus

SolFocus Gen1 solar module prototype

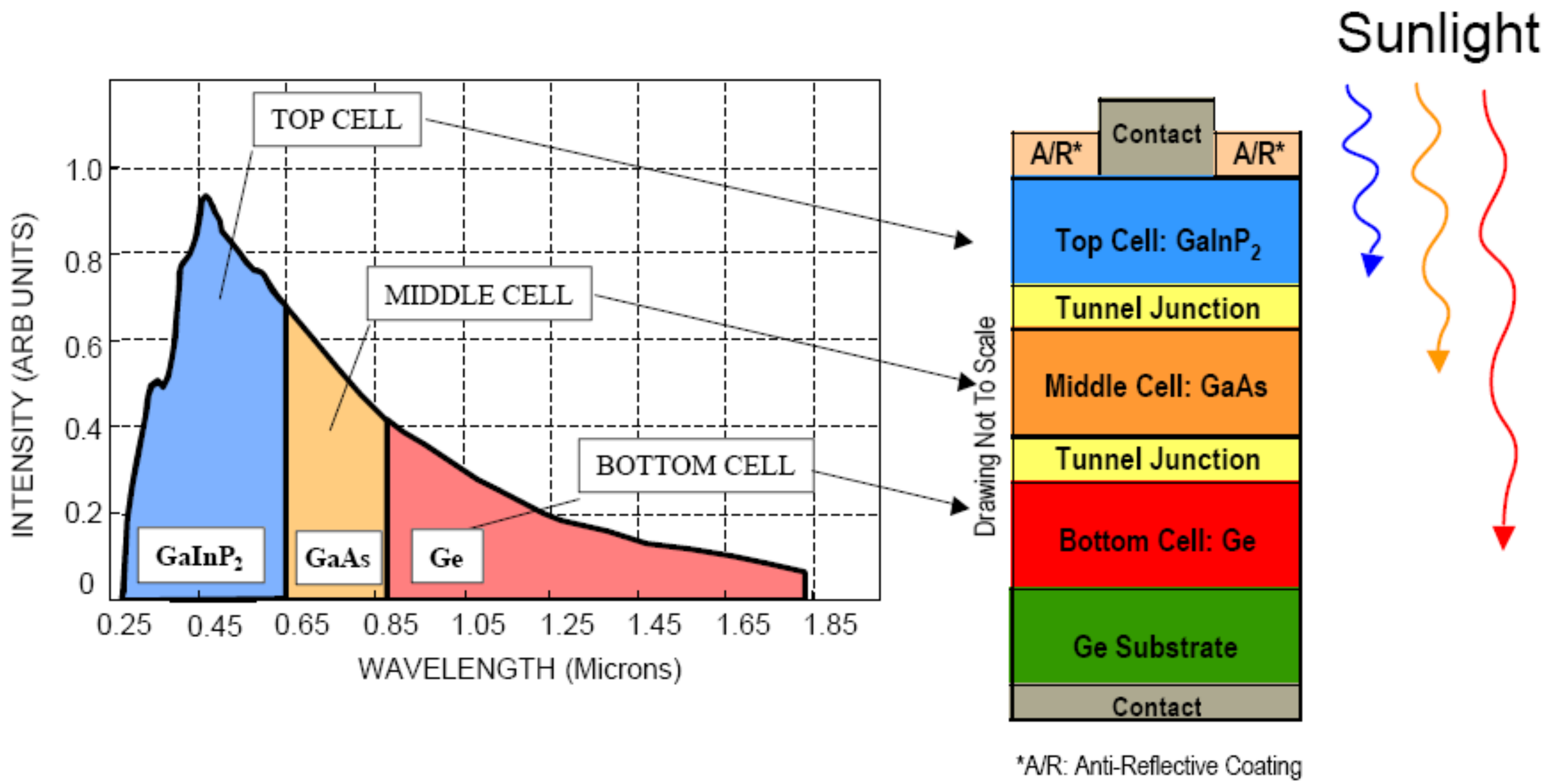
A fresnel lens focuses light onto a small high efficiency solar cell. The module consists of an array of lenses and cells

A mirror concentrates light onto a small high efficiency solar cell. Secondary optics can fold the optical path to reduce the size.

An important trade-off is tracking accuracy vs. concentration

- Low concentration (few tens of sun) have high margin, and low tracker cost, but less gain from using high efficiency, high cost cells.
- High concentration (>100 suns) requires better tracker, but can use better cells

41.6% concentrator cell designed for W/gm, not $/W



- Typical cell contains >20 layers;
- Designed for space, adapted for concentrators

Source: Spectrolab

Tracking flat panel – a hybrid solution with 24% gain

Nellis Air Force Base - 14 MW - Nevada, USA

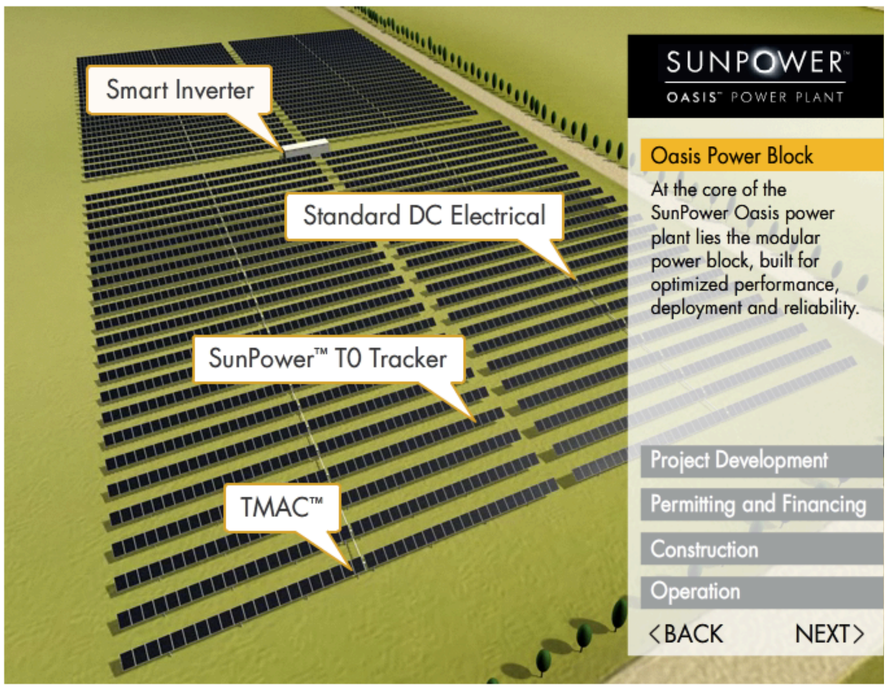
Bavaria Solar Park - 10 MW - Bavaria, Germany

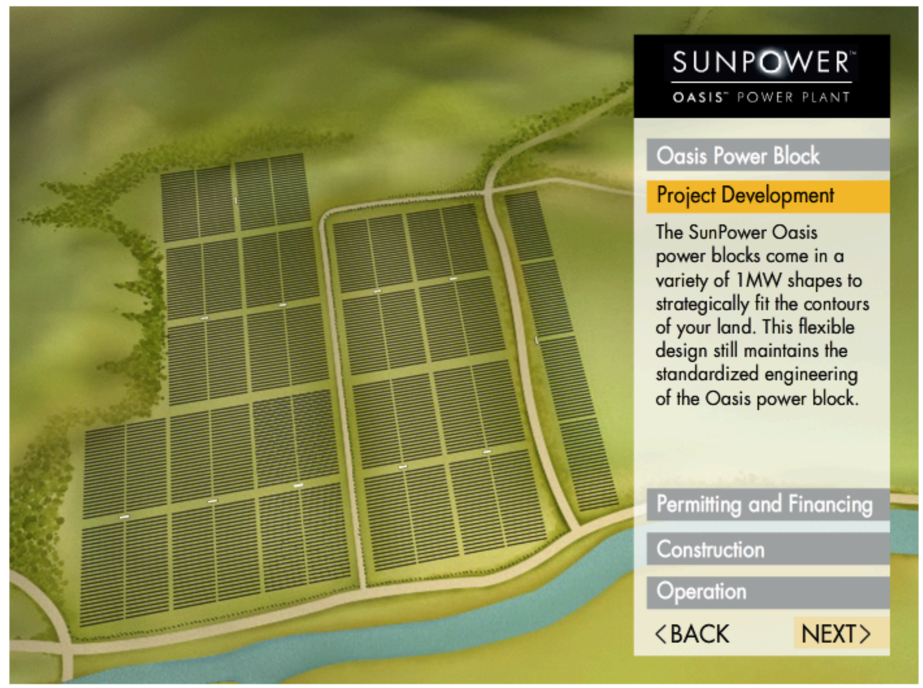
Applied Materials Sunnyvale – 1 MW

SunPower trackers and field applications

Megawatt modules

SunPower's Oasis system provides standard megawatt modules to standardize utility installations and thereby reduce cost and installation time.

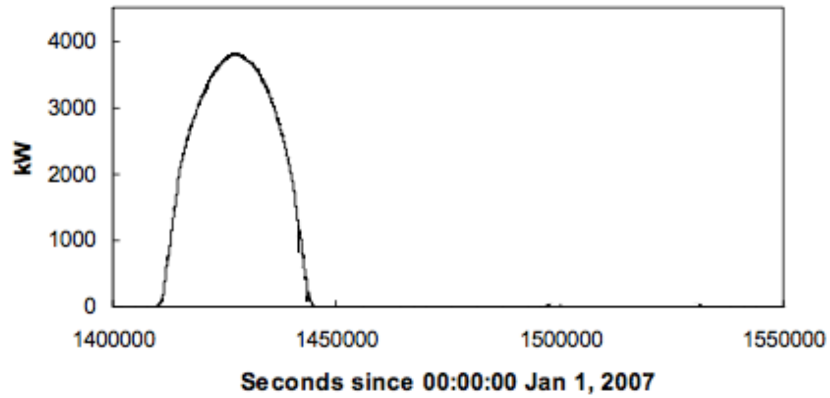


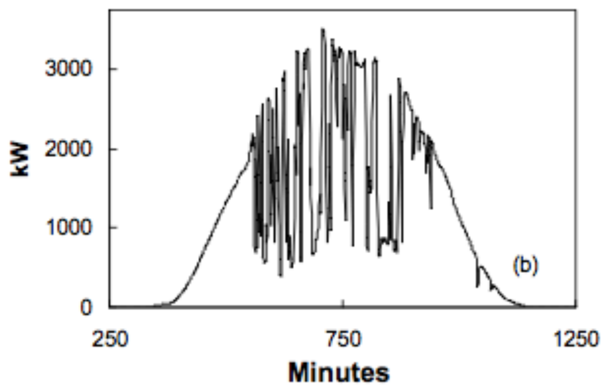


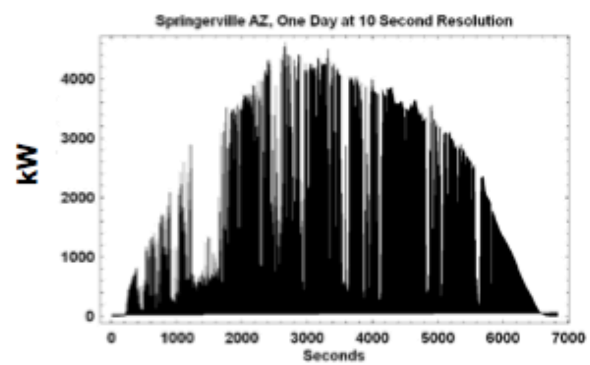
Why only off-grid systems include storage today

- Only lead-acid batteries are inexpensive enough to be considered today.
- These batteries need to run at low currents to recover the stored energy. For example, a battery may run at 5 amps and 12 volts, or 60 watts.
- A long string of batteries is needed to get useful power. In the above example, 20 batteries provide 1200 watts.
- They must also run at shallow discharge
- Such a battery bank is large and expensive.

Cloud Effects on Large Scale Solar Plant







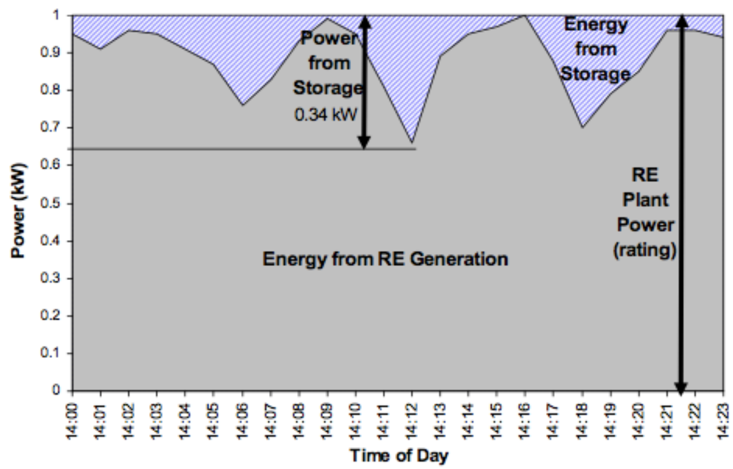
Source: Jay Apt & XX, CMU 4.6 MW TEP Solar Array (Arizona)

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

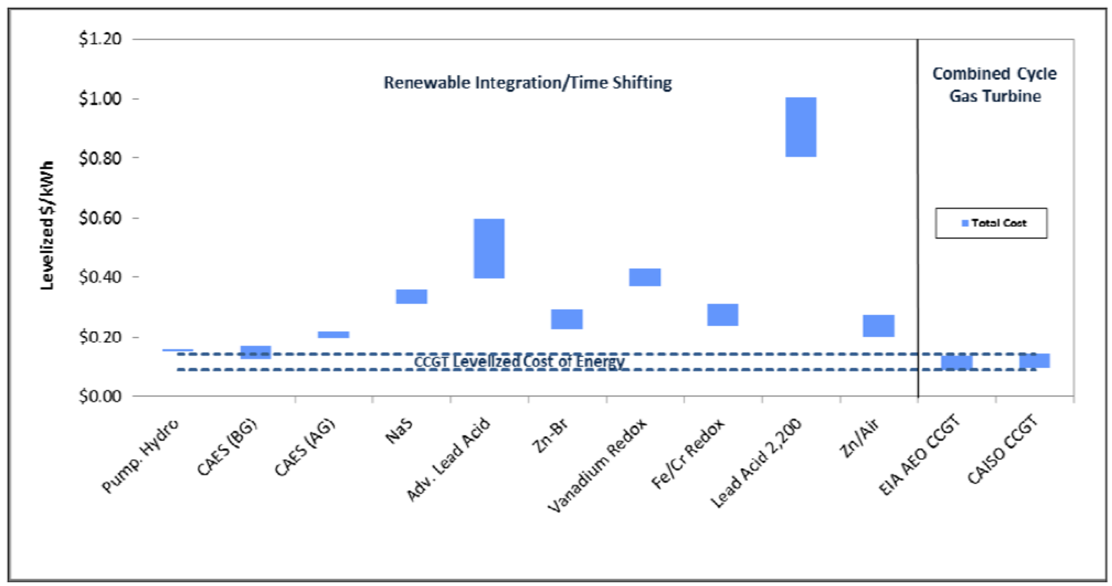
D. Rastler, EPRI

Renewable applications for batteries

- Renewables capacity firming
  Compensating for short-term drops in renewable output to provide constant generation to the utility.
- Renewables energy time-shift
  Storing off-peak renewable generation for use at high-value peak times to increase the value of the renewable energy.



Sandia report SAND2010-0815, 2/2010



Conclusion

- PV has transitioned to a large scale industry
  - Low module costs, <78¢/W (CdTe) and ~$1.10/W (Si) are fueling growth
  - Efficiencies are climbing for both Si and thin film
- Wafer-based silicon shows explosive cost reduction + improved efficiencies
  - New patterning trends are emerging with very little added cost
  - Silicon and manufacturing costs have dropped dramatically
- Thin Film continues to challenge wafer-based silicon
  - First Solar is the largest PV producer, and has the best cost and margins
  - Others have yet to prove whether they can compete at an equivalent level
- Balance of systems is the area of greatest cost leverage and continues to show significant innovation