# NEW SOLAR CELLS FOR AN UNDIFFERENTIATED, OVERCAPACITY, ROCKET SHIP

Impattern Solutions

<u>**New solar cells for an undifferentiated, overcapacity, rocket ship**</u>

**Michael P.C. Watts**

**Impattern Solutions**

**4-8-2013**

## Summary

The solar cell business is growing rapidly at 30% CAGR, is overcapacity by 2x, with the vast majority being made the same way – a rocket ship of a business with overcapacity and no differentiation – is there an opportunity for new solution ?

The best poly-crystalline single junction cells have achieved 20% efficiency, it seems to me that the best opportunities are;

1) Add up and down photon converters to get to 25-30% module efficiency
2) Add IR absorbers and water heat exchange to get to 50% efficiency
3) Get direct band-gap thin film materials to similar efficiency as silicon, and then maximize manufacturing productivity to halve module cost.

The dominant material, Silicon, is an almost perfect material to convert our suns radiation in a single junction photodiode. Polycrystalline silicon cells are being made with efficiencies up to 20% out of a possible maximum of 30%. The only competitive opportunity is for a direct bandgap material with similar internal efficiency that can be manufactured in thin film cells at much higher speeds and lower costs. I estimate that costs could be halved in an optimal thin film system.

However today's direct bandgap materials, CdTe and CIGS, are significantly less efficient than Silicon, and are being fabricated at similar process speeds. The result is that they have a minimal cost advantage, and require a larger area to generate the same amount of energy. The area requirement has proven an insurmountable barrier for house roof applications. Thin film silicon cells require even larger areas and not appear to have a role at all.

Strategies for using more of the suns spectrum; such as patterning, up and down photon conversion, or heat trapping do not distinguish between the different PV materials. The up and down photon conversion and heat trapping do offer a realistic path to capturing significantly more of the suns energy.

The race between the PV materials looks to me as pure a manufacturing play as you can find. The largest possible area production capability using the technology for producing the highest quality cells, is the only way I can see to displace poly-crystalline silicon cells. I think it should be financially viable. The latest factories are requiring a capital investment of $2 /W to generate panels at $1 /W. A thin film factory supporting the highest throughputs could support a capital investment of $4-5/W. To make an impact a capacity of several 100 MWatts is needed, plus a high tolerance for a long term commitment.

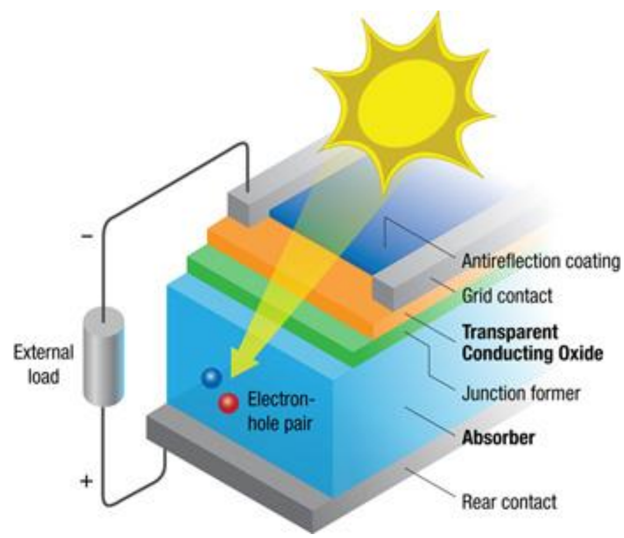
## Introduction

The solar cell business is exponentially growing but has become rather gruesome over the last year or so, …is there any real opportunity to insert new technologies ?

I have talked about the solar opportunity in a series of blogs at www.semimd.com. This is a compilation of my most recent thoughts. Let's start by looking at the challenges of the solar market, then I will identify the weaknesses of the existing polycrystalline silicon technology, consider alternative materials, and alternative strategies to capture more of the suns radiation.

## Background

Photovoltaic solar cells (PV) are going to be a key to reducing our use of fossil fuel. The suns radiation is converted to electricity by a semiconductor diode. For each photon that is absorbed with a minimum energy, an electron hole pair is created, as shown in Figure 1.




*Schematic of a PV solar cell, from NREL*

The semiconductor material is the absorber in Figure 1 and consists of 2 doped regions, n type with excess electrons, and p type with excess holes. The diode junction is formed at the interface and separates the electron and hole, generating electricity.

Most of the cells are made on 150 mm square polycrystalline silicon wafers and tiled together to form a module shown in Figure 2a. A lower cost manufacturing process for thin film solar cells makes the cell directly on meter sized glass as shown in Figure 2b.

*Figure 2a Module made from tiled silicon wafers*   *Figure 2b Module made from single thin film cell*

*From www.made-in-china.com*

**<u>If the goal is to be a leader in the solar business, what is needed ?</u>**

Understanding the opportunty starts from the underlying drivers of the industry. The "Moore's law" for solar in Figure 3 shows how pricing has scaled with experience – roughly halving for each order of magnitude in cumulative production, without any revolutionary technology drivers.

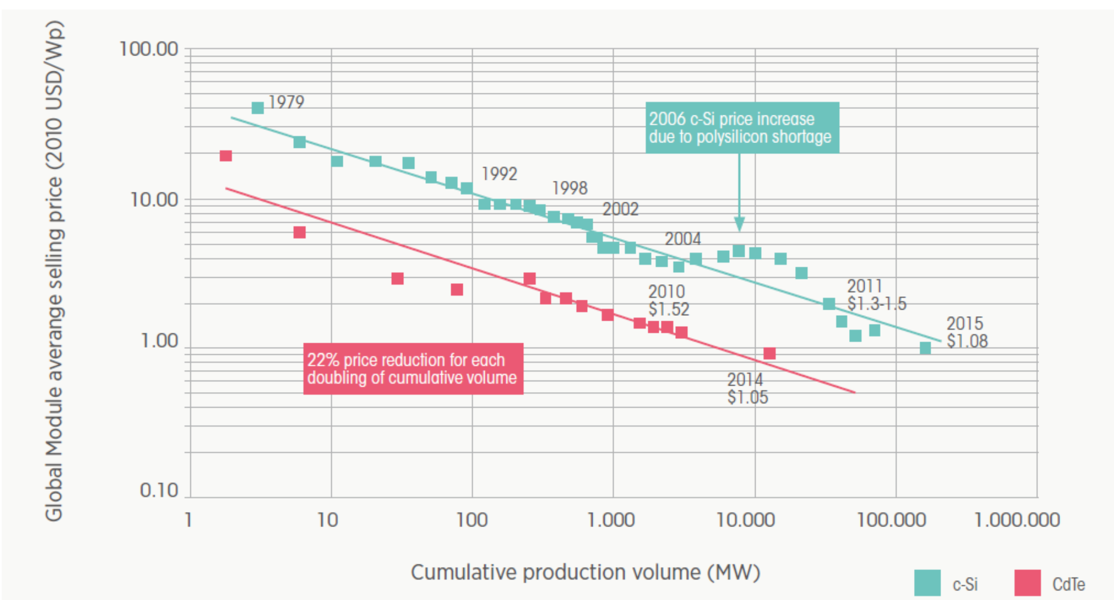



*Figure 3 Historical solar module pricing trends showing the price dropping with manufacturing experience, from Irena*[1]

---

[1] "Renewable Energy Technologies Cost Analysis Series; Solar Photovoltaics", IRENA 2012 p16

The pricing trend is almost exclusively an experience and volume manufacturing story. It shows the hickup in 2009 when polysilicon supplies were limited and prices rose, letting thin film in. At the same time as prices have been dropping, the market has been growing at 30% CAGR, and will probably do so through 2020. The cell suppliers may be whining about recent price trends, the reality is that there is nothing unexpected about these trends.

The vast majority (>80%) of this capacity is conventional polycrystalline silicon (polySi), with very little technology differentiation. Everyone sees the same trend and are expanding, so total available capacity is roughly 2x demand. The bottom line this is an undifferentiated, overcapacity, rocket ship to a huge long term opportunity --- very difficult to survive unless you have huge resources and unlimited stamina. The recent high profile failures at Suntech CI, Solyndra US, Bosch GE, are all examples of the challenges. The fact that Samsung are committing to solar should be a warning to all… they have an impressive record in Flash, LCD, and LED's.

The market is roughly 50 GWatt in 2013, and the market leaders have 5% market share or 2.5 GWatt of product per year. I would submit that a company needs to be 1/10 of the leaders to be a significant player, and to build 0.25 GWatt requires 3-4 production lines. If the learning is kept in house, the graph above suggests a 2x cost disadvantage over the leader. Therefore, I would submit that to break in to the leaders you need 3-4 lines and significant technology or cost advantage just to level the playing field.

**<u>What opportunities are there to replace polySi ?</u>**

There are 3 ways to displace polySi, improve internal efficiency, increase wavelength range of solar absorbtion, decrease cost by manufacturing with the highest possible productivity.

The polySi photocell has an efficiency of around 20% and a theoretical maximum of 30%, giving an internal efficiency of around 66% and has been improving very slowly for 20 years. An improvement of 0.3x is a theoretical possibility.

Silicon absorbs 30% and misses about 70% of the suns energy, so there is up to a 2x opportunity in absorbtion.

The silicon photo cell is manufactured on 150 mm wafers. Thin film cells use much less semiconductor material, and can be manufactured as meter sized cells resulting in significant cost savings.

**<u>What limits the conversion efficiency of different materials ?</u>**

The sun is a hot black body radiation source that is being converted to electricity by a room temperature band gap semiconductor. Any photon with energy greater than the band gap creates a single electron hole pair, so low energy photons below the bandgap do not create current, and high energy photons do not generate any more current than band gap photons.  This limits the maximum conversion to around 30%, as shown below in Figure 4.

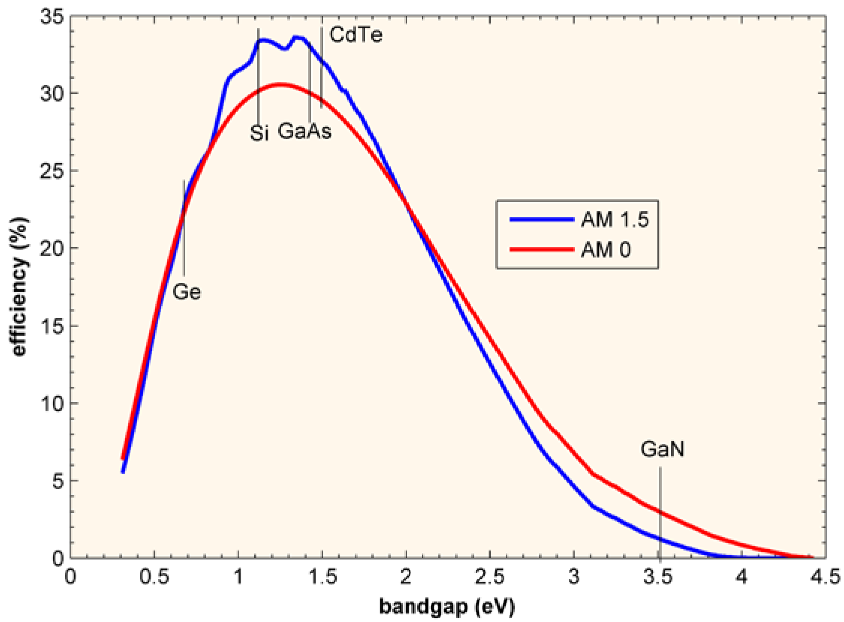



*Figure 4 Convolution of solar spectrum and a single junction band gap semiconductor from* [www.pveducation.org](http://www.pveducation.org)[23]

The optimal band gap for our sun is around 1 eV, and silicon is an optimal material for a single junction cell. The alternatives to silicon such as GaAs, CdTe, and CIGS also all have band gaps around 1 eV, all offering the same maximum possible efficiency.

The alternate materials, CdTe and CIGS,  are direct bandgap semiconductors, and as a result have much high absorbtion for a given thickness than indirect bandgap silicon. Higher absorbtion means that the cells can be 20x thinner, enabling  "Thin-film solar cells". Thin cells use less raw materials and can be fabricated on large area substrates. The challenge in thin film PV solar the  creation  of  thin sheets of low defect crystals on either glass, plastic or metal films; the most difficult challenge in hetero-epitaxy. CdTe cells are made by sublimation. CIGS are more exotic in that they are a binary  solid solution of CuInSe and CuGaSe, with a number of different deposition strategies; the most effective are sputtering or co-evapaoration. There is a particular wide range in efficiencies reported for CIGS, with lower cost production techniques producing much lower efficiencies.[4]

---

[2] Shockley W, Queisser HJ. Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. Journal of Applied Physics [Internet]. 1961;32:510-519. Available from: http://link.aip.org/link/?JAP/32/510/1

[3] Tiedje T, Yablonovitch E, Cody GD, Brooks BG. Limiting Efficiency of Silicon Solar Cells. IEEE TRANSACTIONS ON ELECTRON DEVICES. 1984;ED-31

[4] "Renewable Energy Technologies Cost Analysis Series; Solar Photovoltaics", IRENA

The NREL best cell efficiency data gives a clear sense of the progress in that has been made over the last 20 years (Figure 5). For single junction cells, single crystal GaAs has the best performnce,  close to the theoretical maximum, the best  polycrystalline silicon has 20% efficiency.

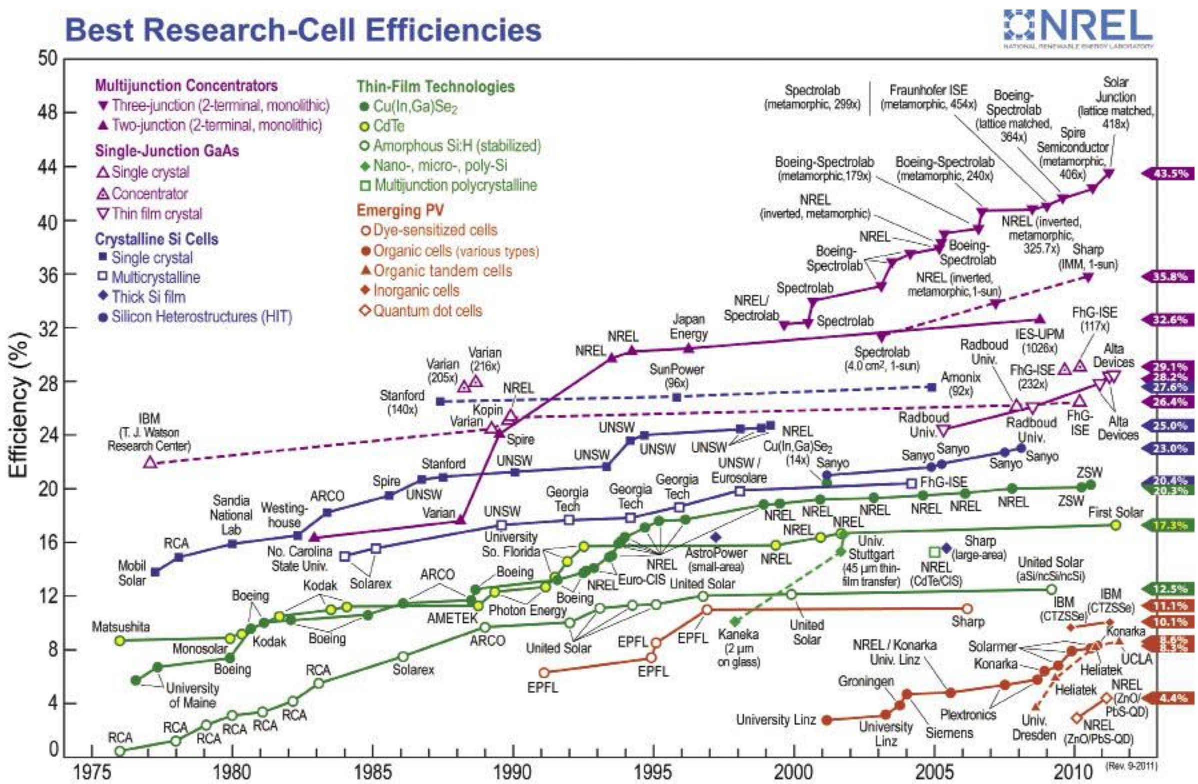



*Figure 5 Best of cell efficiency data from NREL*

There are additional losses when the cells are assembled in to modules. Average production module performance summarized by IRENA[5] are; thick polycrystalline silicon (14%), CdTe (9.5%) and CIGS  (9%).  Seeing as all these material have the same theoretical maximum the differences are in the internal efficiency is a typically dependent on the quality of the epitaxy and the semiconductor growth process.   Silicon growth has been researched for as long as transistor have been made, so there is a huge learning advantage to silicon.

The lower efficiency of the non silicon material means that there must be a proportionally larger area of cells to generate the same energy. This has proved to be a major barrier to home installations, but not to large generation plants. The same applies to  thin film silicon cells which much less efficient because they absorb less of the light, as a result about twice the area is needed to generate the same power. The market place has shown that even with significantly lower prices, thin film silicon has not been able to compete.

To date, none of the single junction alternatives have created cells with better internal efficiency than thick polySi cells, and certainly do not suggest any immediate prospect of exceeding mature poly-silicon technology.

[5] "Renewable Energy Technologies Cost Analysis Series; Solar Photovoltaics", IRENA 2012 p10

**What levels of cell manufacturing productivity are being achieved ?**

Thin film manufacturing technologies do offer an opportunity to radically improve manufacturing productivity. The dominant manufacturing technology today is devices created on polycrystalline silicon wafers 180 um thick and 0.15 m on a side, that leverage the huge technology base in silicon semiconductors. However to build meters of cells at low cost, meter sided substrates are needed. For many years, roll to roll processing has been used to fabricate very large areas of printed sheets, from newspapers to imprinted optics at meters a minute. More recently, the market for very large LCD TV's has driven the development of equipment to deposit semiconductor grade silicon on glass 2.2 m on a side, at 1 every 2 minutes.

Looking at published data for facility capacities and substrate size I estimate that ;

> Poly-crystalline Si process line moving 0.15x0.15 m substrates at an impressive 1200[6] substrates an hour = 27 $m^2$ per hour.
>
> First Solar process CdTe on 1.2x0.6m substrates in 60 MW facility[7] which works out as at 100 substrates an hour = 30 $m^2$ per hour
>
> A German CIGS plant operates at 30 MW[8] facility = 15 $m^2$ per hour.
>
> Amorphous Si thin film plant operating at 75MW[9], processing 2.2x2.2m glass at 30 an hour = 154 $m^2$ per hour.

The analysis above suggests that existing CdTe and CIGS plants have the same or poorer productivity as polySi lines. However, a thin film cell made in a high volume line, with the same efficiency as polySi, would have a 6x productivity opportunity.

My take is that with an efficiency disadvantage and similar manufacturing scale, non-Si thin film solutions today are behind polySi which explains their competitive challengies.

**What is the module cost per watt opportunity ?**

To understand the opportunity in module cost, let's consider a test case of a new factory that Panasonic[10] is building in Malaysia for $540 M, with a capacity of 300 MWatts per year, and will require 1,500 staff. It is easy to calculate the contribution of 5 year deprecation per watt ($0.40) and labor ($0.10). The silicon cost in 2012 has been estimated[11] as $0.36 /W, the total material cost for a polycrystalline silicon module were $0.69/W, and with a total module cost of $1.2/W. These numbers are generally consistent with industry reports[12 13], and with silicon costs at $20Kg.

---

6 http://www.nrel.gov/news/features/feature_detail.cfm/feature_id=1629
7 First Solar annual report 2012
8 http://en.wikipedia.org/wiki/Copper_indium_gallium_selenide_solar_cells
9 http://www.pvtech.org/chip_shots_blog/sunfab_reanimated_amat_thin_film_pv_customers_t_solar_masdar_pv_show_signs
10 www.smartplanet.com/intelleigent-energy/panasonic-to-buil-580-milion-solar-cell-factory/10795

11 http://www.akbars.net/
12 "Renewable Energy Technologies Cost Analysis Series; Solar Photovoltaics", IRENA 2012
13 "$1/W Photvoltaic systems" US Dept Energy 2010.

A thin film module factory with the same productivity, capital costs, labor and cell efficiency would have a negligible silicon cost, and higher substrate cost netting out at $0.95 /W (- 20% of polySi) for the module.

A thin film factory running at maximum productivity would have 6x higher throughput, making the depreciation and labor components negligible, netting a module cost of $0.55 /W (-54% of polySi)

The manufacturing opportunity for thin film with the same cell efficiency and raw material cost is to halve the total module cost. The latest polySi factories are requiring a capital investment of $2 /W to generate panels at $1 /W. It looks like a thin film factory supporting the highest throughputs could support a capital investment of $4-5/W.

**How can solar cells use more of the suns output ?**

There are a number approaches to utilize more of the suns radiation; increased absorption, multi junction cells, photon conversion , heat absorbing cells, and angular coupling.

Increasing absorption has been looked at by an number of groups as a way to make very thin (50-400nm) cells and patterning layers to increase the absorption of the film using plasmonic resonance effects (Figure 6). Results published at Photonics West this year suggest a 10-20% improvement in efficiency for very thin cells using very little semiconductor [14] [15]

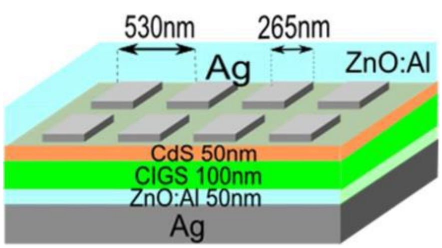



*Figure 6 Example of a patterned cell from Clement at CNRS France*

In the comparison with polySi cells, these are ways to reduce the amount of semiconductor in the cell, rather than to increase the efficiency of the cell.

The established approach to increasing the utilization of solar radiation is to increase the number of junctions. The 4 junction cell shown in Figure 7 uses a cascade of progressively lower energy band gaps to collect a wider wavelength range. These are only used in concentrators because the device are so expensive, however there is a performance gain up to 43%, or a gain of 2x relative to polySi cells.

[14] Ragip A. Pala, Justin White, Edward Barnard, John Liu, and Mark L. Brongersma Adv. Mater. 2009, 21, 1–6
[15] http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1672482

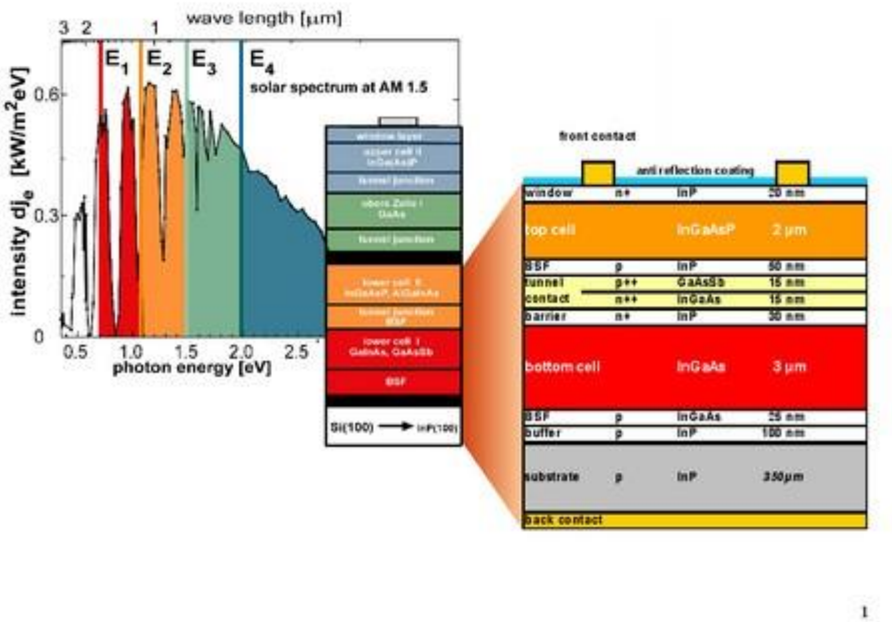



*Figure 7 Schematic of multi-junction cell* [16]

Rather than collect a wider range of photon energies, an alternative is to down convert one higher energy photon to 2 band gap photons, and up convert 2 low energy photons to 1 band gap photon, illustrated below in Figure 8 .

[16] *http://www.tu-ilmenau.de/pv/forschung/*

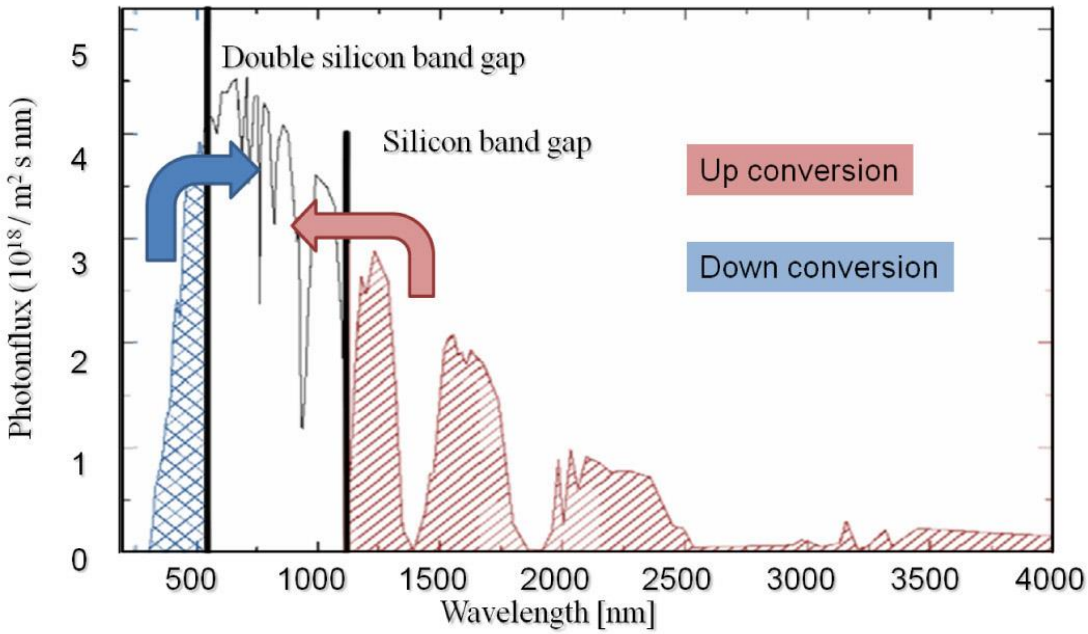



*Figure 8 Illustration of up and down conversion*[17]

Efficient phosphors for down conversion have been developed for LED's where a blue LED is used to pump a phosphors that emmitts white light. Researchers clam suggests another 10% absolute efficiency or 0.3x improvement available for down shift. There is a EU project "NanoPhoSolar" that includes 3G Solar to develop down shift materials. A team from Sydney University have demonstrated efficient visible light upconversion, and have modeled the solar cell application and suggest 0.3x gain in a polySi cell is possible. They are working on IR upconverting materials. It looks like there is a 0.6x opportunity in a cell with both up and down conversion that could result in a 30% cell.

Even a 30% cell would still dissipate the rest of the suns energy as heat, so why not utilize the heat directly ? Its less elegant, or high tecky, but can be very effective. SolarWall have developed an integrated PV heat collection system, with the heat going to the house hot water system shown in Figure 9 .

[17] *http://spie.org/x48772.xml*

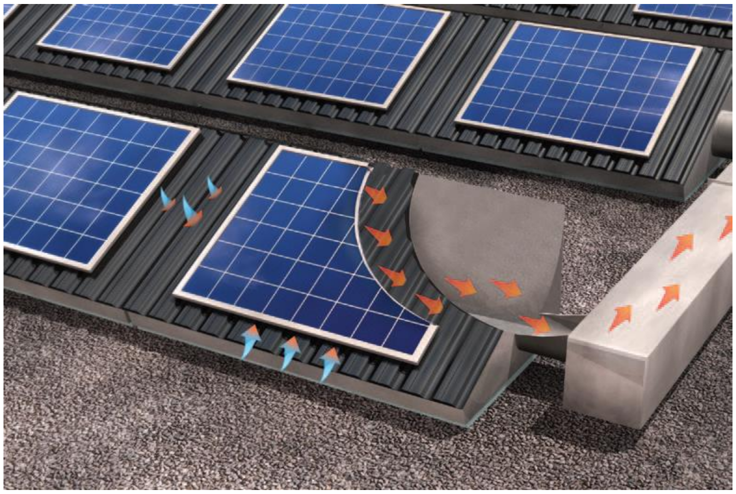


*Figure 9 Schematic of the Solar Wall PV/T solution, from Solar Wall*

The performance of the SolarWall PV/T hybrid technology improves the total solar efficiency to over 50%, but there needs to be heat exchange modifications to use the heat to warm water. In the green – house business this looks like a really interesting alternative.

The fact that the IR is absorbed effectively is simply because a black body will absorb black body radiation very effectively. Using the heat generation directly has been a popular solution for solar power stations. These are large installations where lenses are used to focus energy and generate steam, or drive a Stirling engine. A team at Stanford[18] had proposed an interesting alternative where a hot surface acts as a thermionic emitter of electrons to directly create electricity, and the residual heat is used to drive a Stirling engine. Melosh from Stanford calculates that " their process can get to 50 percent efficiency or more under solar concentration, but if combined with a thermal conversion cycle, could reach 55 or even 60 percent -- almost triple the efficiency of existing systems."

My take is that these strategies to capture more of the suns radiation offer a real opportunity and will work with any single junction material. They do not change the competitive balance between polySi and the thin film cells.

**<u>A strategy for new solar cells that can enable a well differentiated rocket ship</u>**

The best poly-crystalline single junction cells have achieved 20% efficiency, it seems to me that the best opportunities are;

4) Add up and down photon converters to get to 25-30% module efficiency
5) Add IR absorbers and water heat exchange to get to 50% efficiency
6) Get direct band-gap thin film materials to similar efficiency as silicon, and then maximize manufacturing productivity to halve module cost.

The reasons that poly crystalline silicon have resisted the competitive challenge from thin film cells are pretty clear. Silicon is an almost perfect material to convert our suns radiation, and polycrystalline cells are being made with impressive internal efficiencies greater than 66%. The only competitive opportunity is for a direct bandgap material with similar internal efficiency that can be manufactured in thin film cells at much higher speeds and

[18] http://news.stanford.edu/news/2010/august/new-solar-method-080210.html

lower costs. The latest results for CdTe are getting closer to parity in performance, however the manufacturing productivity today is also very similar so they do not have a core competitive advantage. The efficiency is still poorer that polySi which means larger area of cells are needed to generate the same power.

There are attractive ways to use more of the suns radiation; the combined PV, water heating scheme is simple and easy to implement. The up and down conversion materials also look very attractive. Combining these with PV would result in well over 50% energy capture.

The PV future looks to me as pure a manufacturing play as you can find. Large area production capability has a 2x cost advantage. Once parity in efficiency has been demonstrated, a major investment in large area manufacturing capability would pay off with a competitive advantage proportional to the manufacturing productivity advantage. A baseline factory would have a capacity to build over 0.3GWatts of product a year. This leads to a related problem which is until the product becomes a market leader, the factory will be under-utilized and the cost will be proportionally higher.

Obviously this is not a traditional start up opportunity. The scale of the investment, the need to grow into high utilization and to deal with the price pressures from overcapacity, is probably best suited to large corporations with a commitment to a very large long term goal.

I suggest that the strategy should be to find a module solution with much greater than 2x advantage over polySi, commit to a 200 MW factory, and have the backing to build a minimum of a new factory every 2 years, with low margins and negative cash flow. If you wait 3 years, the financial barriers to entry will double….. sounds like fun !