The Great Illumination

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The fascination with solar energy goes back further than Jimmy Carter and his view of a solar panel on every 1970's rooftop. It predates the solar cell kits popular in the 1950's during the space race. Long before Einstein's first Nobel Prize honored his explanation of the photon-electron duality, humans have been longing for more energy from the sun. Human desires aside, all energy does derive from our divine Sol. I challenge you to find any material object on planet earth that was not created by the sun's energy. Plants, *and* the creatures that feed on them, *and* the products derived from plants, *and* the fuel made from long-decomposed plants, are all inextricably connected to the sun. Less obvious is the sun's connection to the concrete, steel and glass used to construct the building you're sitting in right now. But the energy used to extract, melt, and form those materials came from the fossil fuel energy charged from the sun millions of years ago. Even radioactive uranium, produced in super novae from now-extinct stars gained its power in a solar reaction. Only geothermal heat and sulfur-loving critters at the bottom of the ocean are independent of the sun's reach. Only now, after thousands of years of aspiration, does Man have the capacity to use the sun to power his endeavors in a significant way – with solar power.

Why Solar? Why Now?

Readers of this magazine make, assemble, and use printed circuit boards. The electronics industry is a growth business, and the PCB sector benefits from the increasing value of the circuit board as part of the final device. But true growth enthusiasts, like those old enough to remember the wild west of the 1980s PCB market, are bored by the recent 5% compound annual growth rate signaling a mature sector. As a matter of course, corporate strategists, like those at my company, look to technology sectors adjacent to core competency for expansion opportunities. Electronics analysts will have a hard time missing the Energy and Storage sector, which Prismark Partners expects to deliver a 25% CAGR 2007-2012. Now that's a business! It sure looks a lot more like the growth years of the embryonic PCB and semiconductor segments.

But what about the huge, unpredictable swings of the PV industry? Yes, the industry suffered last year as the available capital needed to fund solar module installations, government subsidies, and capacity expansion was severely restricted. How much did this slow the runaway bandwagon of solar cell makers? In a recent analysis by authors from (among other contributing firms) the National Renewable Energy Laboratories (NREL), the credit crunch of 2009 had a significant impact on solar cells. The expected growth in PV was reduced down from as high as 40GWp in 2012 to a more realistic average estimate of 21 GWp. This set of data gathers market forecasts from over a dozen financial, research and consulting firms that closely follow the sector. But for perspective, the downgrades bring the expected annual compound growth to "just" 40% for 2008-2012. Not too bad for a slumping industry, where annual growth rates over the past five years regularly exceeded 50%. (See figure 1.)

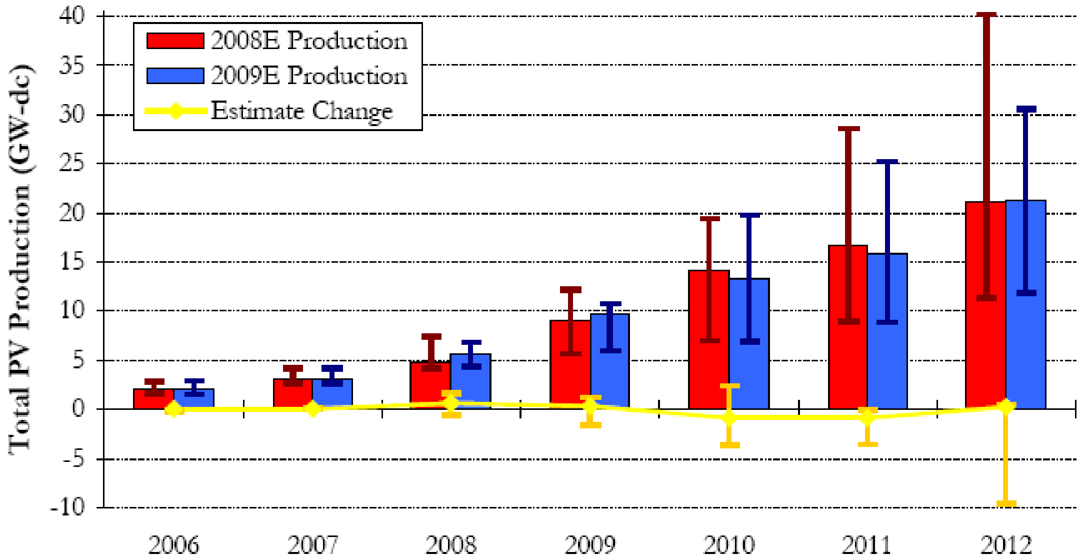

Figure 1: NREL's Summary of PV Analysts' Growth Forecasts

Who will consume all this solar power? In the residential market, I imagine solar modules soaking up the rays from atop my forward-thinking neighbor's roof. You can easily visualize banks of solar panels adorning the flat rooftops of supermarkets, malls, Wal-Marts, and Starbucks. But solar energy has many more applications. Huge solar farms are sprouting up in East Africa, Spain, and the American Southwest, feeding opportunistic utility companies. Thousands of villages in remote parts of India depend on PV trees to power telecom outposts and local water pumping stations. Don't forget where all these solar applications got their start – hundreds of miles above Earth where thousands of satellites soak up pure electromagnetic radiation unfiltered by our protective atmosphere.

How Does This Affect Me? Are Solar Cells Really Just Silicon Circuit Boards?

We're all aware of the recent popularity of green energy. And as part of the electronics supply chain, we receive frequent tantalizing reports from the world of solar cells. Why? Is there such a connection between the two technologies? Indeed, there is a very strong similarity between solar cell manufacturing and printed circuit board manufacturing. Both industries start with a substrate of specialty, electronic grade material. The substrate is treated and etched to specific functional targets using wet chemical and mechanical methods. Patterns of circuitry and electrical contacts are formed on both sides of the device, which might include multiple layers of functional material and images. Cleanliness and quality is of high importance, as is assuring a predictable, automated, high throughput production environment. This is where the PV and PCB sectors are differentiated from the semiconductor industry. In PV and PCB, cost and productivity concerns will dominate, so that primary focus will be placed on expanding capacity and economies of scale, rather than applying total focus on the highest possible functional performance.

I strongly believe that the PCB engineering mentality (in-line automated processing with strong focus on cost and "good-enough" technology) will be the right way to approach PV. This approach will produce the manufacturing winners. The semiconductor mentality of "quality at any cost" and batch processing will not win. That said, the equipment and cleanliness needed for PV does require specialized built-for-purpose facilities. So, I don't anticipate PCB companies co-manufacturing solar cells on process lines adjacent to circuit board production lines.

Today's PV

I'm obligated to give a bit of perspective to the solar electricity industry. Skip ahead if you've seen the many treatments of this information splashed all over the media in recent years. Solar power consists of solar thermal and solar electric technologies. Solar thermal units heat water in glass tubes to offset gas/electric hot water energy costs, while photovoltaic "PV" systems directly absorb sunlight and extract electrons from photosensitive materials. The PV material used defines the solar energy market segment. Since the 1950's, crystalline silicon has dominated PV technology. Silicon wafers exist as two classes, each with a nearly equal market share, monocrystalline silicon grown into cylindrical boules, and polycrystalline silicon cast into ingots from molten silicon. Overall, crystalline silicon represents 88% of the PV energy produced annually.

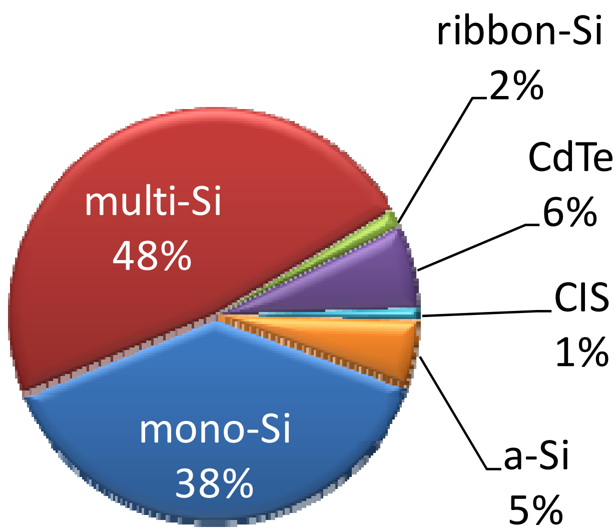

Figure 2: Technology Types in Photovoltaic Manufacturing 2008
(Sources: PV Consulting and Photon International)

Of the 12% or so of PV that is not based on crystalline silicon, virtually all is lumped into the category known as "Thin Film" PV. Thin film exists as a wide variety of technologies including amorphous silicon, cadmium telluride, copper indium selenide, and copper indium gallium diselenide. The 5% of the market producing amorphous silicon is composed of more than two dozen smallish manufactures. Most of the balance of thin film is manufactured by just one company, Ohio's First Solar with the industry's low-cost cadmium telluride offering, now at about 1 gigawatt of production per year and manufacturing power at a cost of less than $1/watt.

A Staggering Market

The 7.3 gigawatts produced in 2008 represent about 60 million square meters of PV modules. Looking more closely at the 6.3 GWp of crystalline silicon modules, we can estimate the number of cells produced using a module efficiency number of 130Wp/m^2. The calculation yields 48 million m^2 of silicon area, and if all cells were made using the new 156mm standard size, we find that nearly two billion individual cells were made. A standard 30 megawatt production line might produce 1500 cells per hour. So you can visualize some 200+ production lines around the world spitting out a finished wafer every two seconds. And that's before the continued capacity increase during 2009. Factor in the 30-50% annual growth in coming years, and one begins to view opportunities in the PCB industry in a less favorable light. It won't take long for PV, at US$37 billion, to overtake the annual US$50 billion PCB industry. Can an industry really survive this kind of growth? The semiconductor industry did. Prismark Partners shows a very close overlap of the revenue growth curves comparing the two industries in their early years.

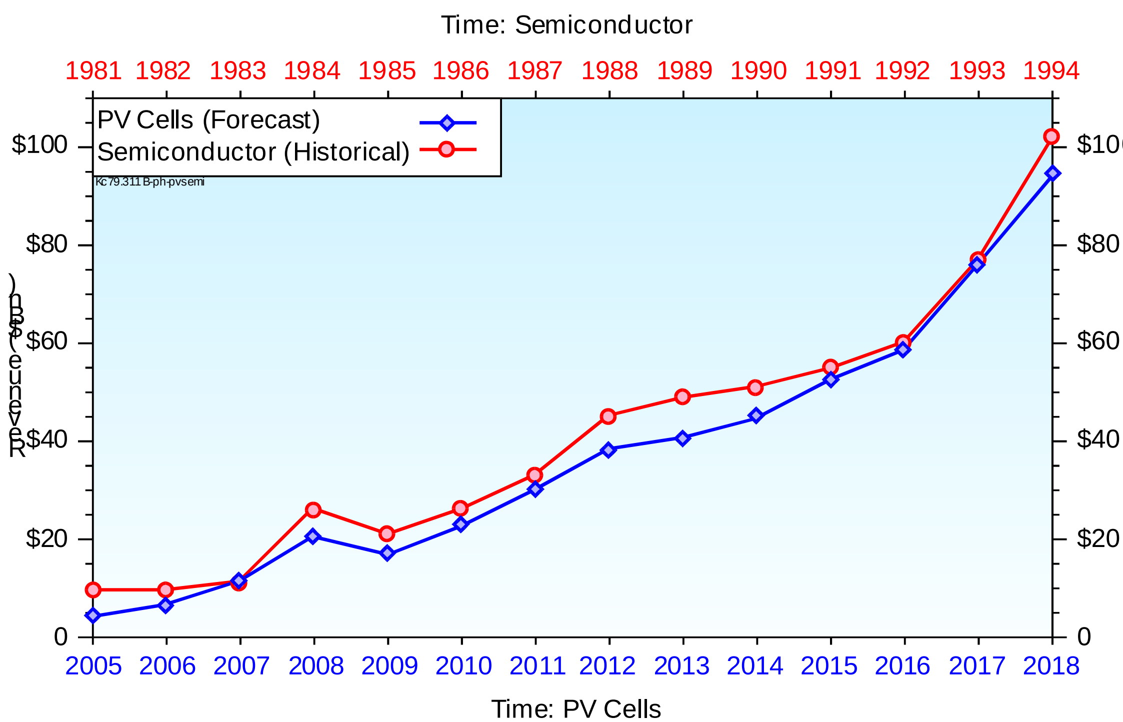

Figure 3: Historical Growth of Semiconductor Market Compared with Forecasted PV Market (Source: Prismark)

Measuring Value

1000 W/m^2. This simple rule of thumb will allow you to make estimates on everything from cell production, to efficiency increases, and even the number of modules you'll need to install on your house to power your big screen TV. When the sun's rays encounter the Earth, each square meter of area receives a continuous 1370 watts. But ozone and water vapor in the atmosphere scatter and absorb the radiation, reducing the effective solar energy reaching Earth's surface. The actual energy varies widely with latitude and cloud coverage, so testing laboratories adopt 1000 W/m^2 for a unit of energy traveling through Earth's atmosphere at an oblique angle with a representative "air mass" (AM1.) When conducting standardized measurements, the labs use a specific light spectrum at 1000 W/m^2, and report the findings of this best case condition as Watts peak (Wp.)

Overall, the global average for available solar energy is about 200-400 W/m^2, which factors in the hours of reduced sunlight at twilight, dusk, and nighttime. Even so, the sun's power is impressive. At one atmosphere, the sunlight energy falling on an area the size of an average automobile for four hours is equivalent to that stored in 1 gallon of gasoline.

Sun's Energy at Earth's Surface	1000 $Watts/m^2$
multiplied by	
Area of a 'Standard' 156mm Wafer	0.0243 m^2
multiplied by	
Efficiency of a Typical Solar Cell 16%	0.16
equals	
Power Output of a Typical 156mm cell	3.89 Watts peak

The usefulness of this mathematics is shown in this exercise demonstrating the extra power gained from eliminating a particular solar cell problem known as shadowing. Shadowing is the term used to describe the amount of sun which is blocked from reaching the silicon p-n junction because it reflects off the metal surface conductors.

Sun's Energy at Earth's Surface	1000 $Watts/m^2$
multiplied by	
Area of Screened Paste on a Typical Cell	(2) 0.2cm bussbars, (60-70) 120µm fingers = 18.2 cm^2 = 0.00182 m^2 0.00182 m^2
multiplied by	
Efficiency of a Typical Solar Cell 16%	0.16
equals	
Power from Eliminating Shadowing	0.29 Watts
multiplied by	
Selling Price of Solar Cells (Jan 2010)	$2.50/Wp
equals	
Extra Value from Shadowless Modules	$0.73 per cell
An increase of…	7.4% relative to typical cells

Shadowing is just one of the many ways that can reduce the potential full power of a silicon solar cell. With the exciting race toward optimizing solar cells, the industry is benefiting from research teams throughout the world looking for ways to eliminate these power drains. Some of the energy lost is unavoidable and relates to the physics of photons interacting with the photoactive materials.

Power Loss in the Theoretical Solar Cell

Reduces 1000 W/m^2 to 330 W/m^2
Photons with energy less than the bandgap
Photons with energy more than the bandgap
Loss in converting voltage to usable current

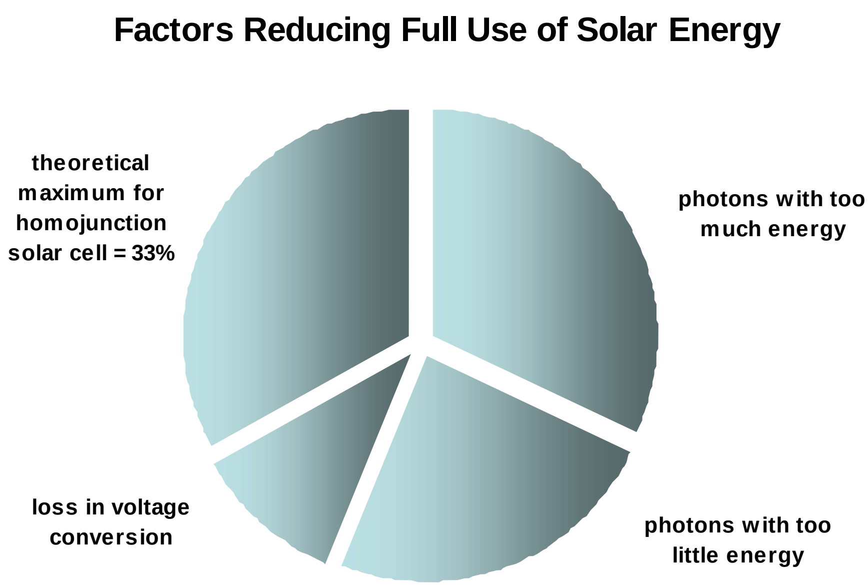

Figure 4: Factors Reducing the Full Use of Solar Energy (Source: Encyclopedia of Chemical Technology, 3rd Ed.)

Shockley and Queisser calculated the maximum amount of energy that could be extracted from a single-junction photovoltaic cell in 1961. The fundamental physics will limit our PV cells' performance to about 33%, so there's not much we can do, other than stacking up multiple junctions or concentrating the light using lenses. But 33% is not too bad, so we should focus on the more mundane aspects of PV manufacturing which have, so far, limited our best cells to about 25%. I've chosen to use silicon PV for illustrative purposes, but these concepts also apply to thin film PV, which delivers efficiencies in the range of 4-10%.

Power Loss in the Practical Solar Cell
Reduces 330 W/m^2 to 250 W/m^2
Shadowing from sunny-side conductors
Resistivity of the electrical conductors
Recombination of electron-hole pair in the bulk silicon
Contact resistance of conductors to the silicon
Bulk resistivity of the silicon
Photons lost in the n+ diffused "dead zone"
Sub-optimal passivation at surfaces

Fortunately, there are many ideas for improving the average power production of an industrial solar cell, thereby closing the gap between today's 16% cells and the theoretical maximum 33%. Let's take a closer look at that problematic factor – shadowing. Shadowing can be reduced by making thinner conductors or moving the conductors to the rear side of the cell. Rear side conductors add manufacturing complexity and have some cost disadvantages. Also, many photons are lost when traveling through more than 50 microns of silicon. Improving the front-side conductors is more straightforward.

Improving Solar Cells with PCB Technology

Front side conductors on PV cells are normally formed by printing silver paste to about 120 microns and firing the paste into the silicon, enabling small frits of glass to cut into the silicon. The sintered silver creates a pathway for electrons to reach the surface silver. A leading idea is for replacement of the screened-on silver paste with chemically plated front-side nickel, copper, and silver. This is where PCB engineers will recognize the evolution of circuit technology. Printed circuits owe their name to early printing technologies for forming conductors on dielectric materials, including the screening of pastes containing conductive metal particles in suspension. PCB engineers know that this technique, still used on about 75% of production solar cells, is not the most cost effective and highest functioning way to form a conductor. Many years ago, the electronics industry applied chemical deposition of copper as the method of choice for building circuit conductors. Chemical deposition allows for highest throughput and automation. Copper provides one of nature's best conductors at a very attractive cost.

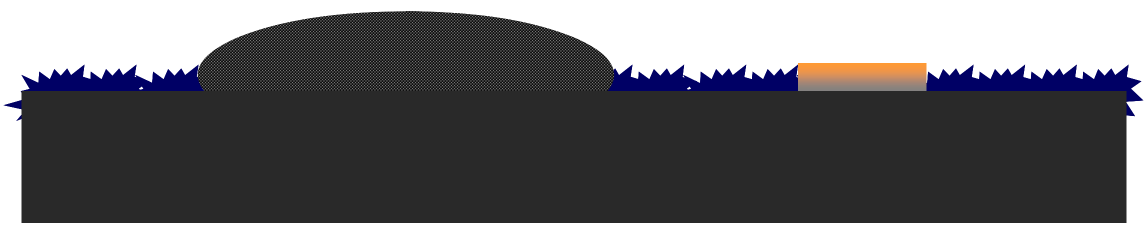

Figure 5a: Schematic Comparing Conductor Formation Techniques; Printed Silver Paste (left) and Plated Nickel, Copper, Silver

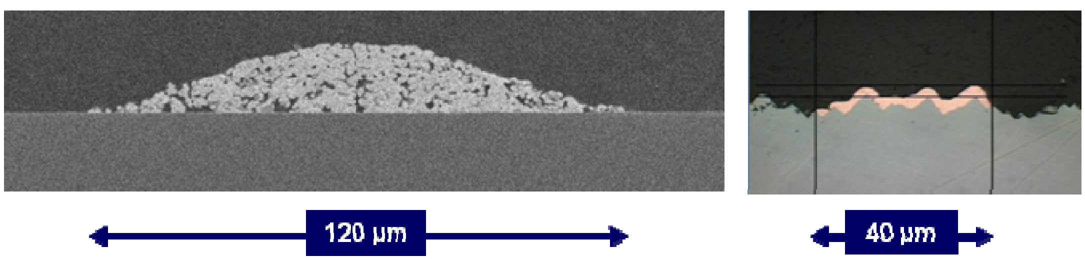

Figure 5b: Two Conductors of Equivalent Functionality; Printed Silver Paste (left) and Plated Nickel, Copper, Silver

Replacing screened silver paste is on the technology roadmap for every manufacturer of PV cells, silicon and thin-film, that now employs it. After all, silver paste can cost more than $600/kg, while copper metal costs about $1.50/kg.

Plating metal conductors certainly addresses the issue of shadowing, by narrowing the conductor by up to 70%. But plated conductors also address other functional aspects of PV efficiency. Existing silver paste technology forms an imperfect contact to the silicon, relying on glass frit to melt with the silicon in the hopes that a conductive path to silver will hitch along for the ride. Plated conductors use a thin nickel seed which, when sintered into silicon, provides a better contact for extracting those electrons effectively. Even the sintering of nickel is a cost benefit; nickel sintering at 400ºC uses half the energy compared to paste sintering at 900ºC, and nickel sintering does not emit gobs of VOC from the paste binder. By combining the benefits of a better contact and a narrower finger width, PV cell designers can capitalize on their ability to place more fingers throughout the cell, capturing more of the electrons before the recombine. Oh, and let's not forget that copper is up to 4 times more effective as a conductor than sintered silver paste, so the line resistivity challenge is reduced.

Plated Conductors compared with Screen Printed Silver Paste

Problem	**Benefit of Ni/Cu/Ag Conductor**
Shadowing	70% reduction
Resistivity of conductors	3x improvement
Recombination	allows closer finger spacing
Contact resistance to silicon	high nickel silicide conductivity
Bulk resistivity of the silicon	closer finger spacing
Photons lost in the n+ diffused "dead zone"	enables 'selective emitter' cell design

Plated metal conductor technology represents just one of the ways PCB processing techniques can be used to deliver the PV cells of the future. The overlap between the industries extends to image printing, laser patterning, through hole metallization (the metallization wrap-through "MWT" design) and film processing similar to processes used in flexible circuit manufacture. Several of the world's advanced PV institutions, such as Australia's University of New South Wales and Germany's Fraunhofer Institute for Solar Energy, foresee replacement of the screen printing process with an resist/etch technique or laser ablation methods which resemble the new laser defined imaging PCB techniques. As inkjet patterning becomes more attractive to the PCB industry with the advent of faster, more precise inkjet heads, the PV manufacturing sector is developing plans to scale-up inkjet use into larger production. Even traditional metal finishing processes will affect PV – new solar cell designs call for chemical treatments to etch, pattern and plate aluminum on the back-side of cells. It is just this sort of open innovation that defines the Wild West of the immature PV industry. New designs proliferate quickly.

Adding Value

Creating proposals for use of a new technology is different in today's PV industry than it was in the growth boom of the early PCB industry. One major change is the ease of measuring the value proposition. As detailed in the earlier summary table, solar cells are essentially a commodity item. They are purchased based solely on power output. A 16% efficient 156mm individual cell, selling at $1.50 per watt as a finished cell, will fetch $5.84. If your company can propose a process for adding an absolute efficiency increase of 0.3%, bringing the overall efficiency to 16.3%, that improved cell will now produce an extra 72 milliwatts and demand $5.95 on the open market. That extra $0.11/wafer doesn't sound like much, but the scale of solar cell production overcomes any lack of enthusiasm. A standard in-line production line is scaled for 50 megawatts, delivering 2500 cells per hour. By adding $0.11 of value to every cell, that line has now increased in value to the tune of $1.4 million per year. Some manufactures will have ten or more processing lines, so one technical improvement can increase a PV maker's gross earnings by $15 million.

That's not to say the improvements come without cost. There will be expenses in the form of new processing equipment, chemical consumables, installation & support, waste treatment, additional labor & engineering, water and electricity. The equipment vendors have very detailed tables itemizing all these costs; they can be vanishingly small (per watt) for a line making large numbers of cells – the costs quickly amortize. Chemical costs will be far less than existing paste costs, so this consideration is diminished. Less obvious is the calculation of risk. Even with the best planning, vetting, and pilot production experience, new processes experience glitches which can kill cells at the rate of one per second. Overall yields will eventually increase, but the engineers owning a new process need to have real-time contingency plans for worst case scenarios. It is just this risk-reward calculation that reminds us of the old days of PCB investment. Maybe the situation is more reminiscent of the semiconductor industry, where the costs are of a higher scale. Like semicon, however, technological improvement is highly regarded.

As you might suspect, technologists are flocking to this industry like moths to a porch light. They bring dozens of new ideas, all of which are promised to be the highest in function, the lowest in cost, and the best way to solve climate change. These include flexible organic PV, notably manufactured by Konarka in the old Polaroid factory in Massachusetts. Dye-sensitized cells are a longer-term favorite to bring low-cost and good performance to a small, flexible form factor. Other technologies promise to extract energy from all EMF radiation, including radio waves floating around on the darkest of nights. For more information on the universe of energy options, the US Department of Energy's Energy Information Administration, www.eia.doe.gov/fuelrenewable.html is a very accessible resource and can be additive to enthusiasts like me.

Anticipating Delays

Another dose of perspective here. Even with the recent explosive growth, solar energy represents less than one percent of the world's power production. The USA, for example, uses coal for just about half of its electricity production and solar contributed just 0.02% in 2007. This perspective brings, at once, frustration and awe, as we realize the enormous scope of the potential market.

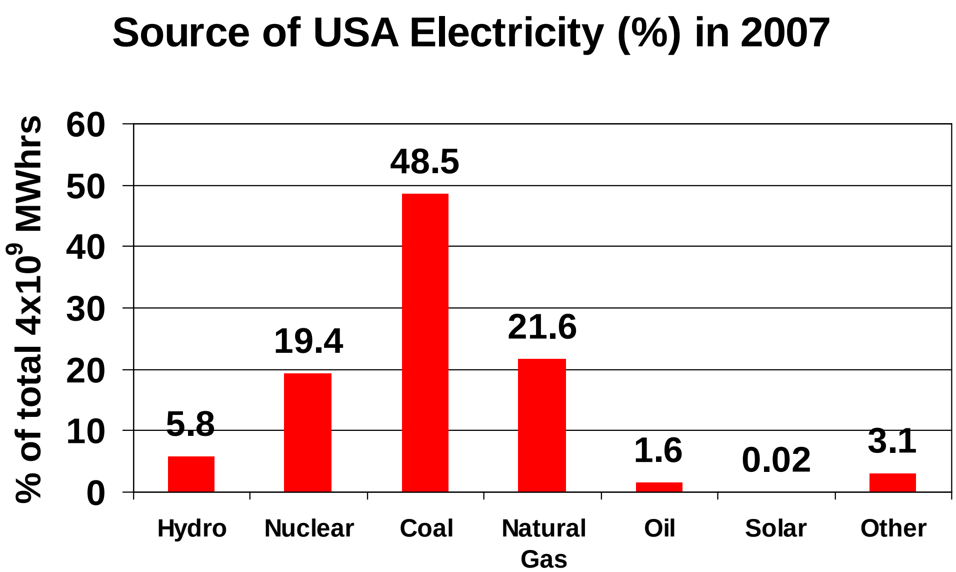

Figure 6: Source of Power for Electricity Generation in the USA (Source: US DOE Energy Information Administration)

With the rapidly evolving technology, the downward costs of raw materials, and other efficiencies of higher-scale manufacturing, economics dictates widespread use of PV in years to come. If anything, the rate of production should dramatically increase with attainment of grid-parity in California, Japan, and many other locations around the world. By no means a certainty, it's not lunacy to believe in the German Advisory Council on Climate Change and their 2050 prediction for solar to account for 20% of world energy production.

Do the Right Thing

Of the many reasons to enter the PV industry, you might be surprised to discover the number of people who state environmentalism as a main reason for participating. The solar energy community is full of enthusiastic technologists, managers, and engineers all proud that they're devoting their energies to a worthy cause. You don't need to believe in human caused global warming to join this club. Solar power is clean, producing no emissions. It eliminates costly and dangerous mining which claims many lives each year. It produces energy locally, preventing overhead power lines and the tremendous loss involved with long distance transmission. And it is completely renewable, without dependence on foreign, hostile governments. People really do believe in the elegance of farming power directly from the source – our Sun. Have you seen the light?

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