Photovoltaics: From Waste to Energy-maker

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One recurring theme in nature is that anything which creates a waste product tends to also create an ecological niche for something which uses that product. This has also occurred in technology. It is relatively common for waste products which contain energy to find uses, but we may be about to see something a little different and more radical. For the past century, millions of tons of a particular waste product have been piling up all over the earth. This waste product contains no useful energy or rare elements, so its potential has taken longer to be widely recognized. It might just become something far more important to the future: a cheap and abundant energy-maker.

Languishing in labs and landfills

One of the most consistent elements of technological advancement is the gap between discovery and widespread commercialization. The first oil well in the USA was Drake's, in 1859; it took 54 years before the Model T reached mass production, and even longer before the internal combustion engine reached half of US households. The mechanism of nuclear fission was pieced together between 1934 and 1939, the first human-engineered fission chain reaction was in 1942, and Oyster Creek, the first nuclear plant to be ordered commercially, went on-line in 1960 (26 years); today, nuclear still accounts for only about 20% of US electric generation. Nuclear fusion was first initiated by humans in 1952 (the Ivy Mike test), but has yet to be demonstrated as a self-sustaining reaction under laboratory conditions (55 years and counting).

Some important energy sources were originally waste products. Naptha (gasoline) was originally an almost unmarketable byproduct of the production of kerosene lamp oil from petroleum. It found some uses such as cleaning fluid, but no application could use all that was being produced until the invention of the carburetor for the internal combustion engine. Now demand for gasoline and diesel fuel is the main driver for oil production. What was once discarded has become the industry's raison d'etre.

Previous responses to oil price spikes depended on technology already on the market. The US generated a substantial amount of its electricity from oil through the 1960's. When the oil price shocks of the 1970's hit, the response was to accelerate the on-going construction of nuclear electric plants; no new "Manhattan Project" was required, because the old one did just fine. Today, only about 3% of US electric generation comes from oil and oil byproducts (including petroleum coke).

We are ten to twenty years late in beginning our response to peak oil. Given the delay between invention and widespread commercialization, our productive responses from now until about 2025-2030 will come from inventions and resources already known but not yet widely used, languishing as they wait for us to take notice. Photovoltaics are one of these small but growing sources of energy.

Today's state of the art in PV

There are 4 major flavors of photovoltaic cell on the consumer market today:

1. Single-crystal silicon.
2. Polycrystalline silicon.
3. Amorphous silicon.
4. Thin film (silicon, CdTe, and CIGS are most widely used).

Some elements, like gallium, are in limited supply and cannot supply a great deal of power via photovoltaics. Others have few constraints; silicon is the 2nd most abundant element in Earth's crust (27.7% by weight). By all rights we should be able to make as many silicon PV cells as we want; we should be able to cover the planet with them.

The reality is different and more strange. Silicon PV production began as an offshoot of the semiconductor industry. The chip industry started with circular wafers made into single crystals by dipping a slowly turning crystal into a molten bath of silicon and drawing it out incrementally; the continuous turning created a rough cylinder consisting of a single crystal, which was sliced into wafers. Single crystals create the most efficient cells, but this is a slow and expensive process. Far from covering a planet, it remains far outside the typical household budget to completely cover even the house's roof.

New processes are changing this. Polycrystalline and amorphous silicon films are much cheaper than large single crystals, in both money and energy. But until recently the PV industry has been too small to be worth its own supply of silicon, so it has survived on the surplus from the semiconductor industry. This surplus had a way of disappearing when electronics were hot, squeezing out the PV industry. But this may be about to change in a very big way, and the consequences may be earth-shaking.

The chemistry of a revolution

This story starts about as far away from PV as you could think of, back in mines producing phosphate rock. Phosphates have long been in high demand as fertilizer (phosphorus is an essential element of life) and phosphate rock (fluoroapatite, $Ca_3(PO_4)_3CaF_2$) is today's major mineral source of the P in the KNP of fertilizers. This rock is dissolved in sulfuric acid (H_2SO_4) to release phosphoric acid, gypsum ($CaSO_4$) and hydrogen fluoride (HF).

Hydrogen fluoride is nasty stuff. Today's method of disposal is to combine it with silicon dioxide (quartz sand) to make fluorosilicic acid, and then neutralize it with sodium hydroxide (lye) to make sodium fluorosilicate, Na_2SiF_6. This has some minor uses as a source of fluoride for drinking water, but far more is produced than can be used. It's been piling up for a long time. If Fluoride Alert's figures can be trusted, roughly a million tons of this stuff (containing about 600,000 tons of fluorine) is made every year.

That million tons of silicate also contains about 147,000 tons of silicon. It's been sitting there ever since.

That resource got noticed some time ago, during the alt-energy boom which followed the 1970's energy crisis. SRI International engineered a process which mixes sodium fluorosilicate with metallic sodium (Na). The fluorine has a greater affinity for sodium than silicon, so the result is sodium fluoride and elemental silicon. SRI claims that this process is simple and cheap (under $15/kg in volume), and easily scaled up to 1000 tons/year. The process got shelved after energy got cheap during the mid-80's, but the world has changed again and SRI has dusted it off. Per their presentation at last May's Clean Tech conference, the silicon can be turned into solid pellets, or cast directly into round crystals *or ribbons*.

Enter Evergreen Solar. Evergreen's "string ribbon" process produces 100-micron (0.1 mm) thick polycrystalline silicon ribbons directly from a molten silicon bath. Here's the new prospect for PV silicon: semi-toxic fertilizer waste and metallic sodium in, production-ready rectangular polysilicon wafers out.

Quantity matters

Making silicon is one thing. Making enough cheap enough to seriously change our energy situation is another thing entirely; you can burn Chanel No. 5 perfume, but you're not going to run even one heavy truck on it all year and the pricetag will make anyone less well-heeled than Bill Gates have second thoughts. So the important questions are,

1. How much silicon is really available,
2. How much (area) of wafers can it make,
3. How much power (peak) could they produce, and
4. How much will it all cost?

How much silicon: The million tons may not all be available. Some of it may be contaminated, or unsuitable for whatever reason. But since SRI claims to have tested this process, let's assume that enough raw material is produced to make 112,000 metric tons of silicon per year. That allows a bit over 20% of wastage. The specific gravity of silicon is about 2.8, so 112,000 metric tons would be about 40,000 cubic meters of solid elemental silicon.

How much area can it make: cast into ribbons 0.1 mm (10^{-4} meters) thick, it would make a staggering 400 million square meters of wafers. This is enough to cover a square 20 kilometers (roughly 12.5 miles) on a side.

How much peak power could they produce: Evergreen Solar is reputed to produce cells which are about 12% efficient. At the standard 1000 W/m² irradiance, the 400 million square meters of panels would produce a peak 48 billion watts of power. That's ***48 gigawatts***, more than 10% of US average electric consumption. We could probably add that much power *every year*, just from the waste produced in Florida from current mining. There are other phosphate mines, and probably a lot of raw material piled up over the years.

How much will it all cost: This is where things get into serious guesswork. SRI claims a cost (after sale of byproducts) of $14-something per kilogram of raw silicon. Let's round up to $15/kg and then multiply by ten to account for the cost of casting into ribbons, doping, printing electrodes, laminating onto glass and attaching connections (production of 400 square km per year will have some serious automation applied to it, so it shouldn't be all that expensive). A square meter of 100-micron cells has only a tenth of a liter of silicon, or 280 grams. Multiply by $150/kg and we get a price of $42/m² or about 35 cents per peak watt. The annual pricetag for all of this (112 million kg/year at $15/kg, times ten) would be just $16.8 billion. That's downright cheap; at less than $4.00 per square foot, it would be highly competitive with conventional roofing. We might see a situation where non-PV surfaces become the exception.

The consequences

It took a lot of money and smarts to create this development, but it may be very cheap to crank it out like popcorn. For the rough price of 1 year of the war in Iraq, we could make peak PV generation equal to about half of the nameplate capacity of every generator on the US grid. Further improvements in either the thickness (100 microns may not be the limit) or the efficiency (12% is just where things are today) of the cells would make watts even cheaper and more attractive.

Would we be able to absorb that much solar power? I'd like to say "probably". Today's just-in-time generation would make it difficult, but two developments would make it almost trivial: ice-storage cooling and battery-powered vehicles. Ice-storage is already starting to take off, driven by the difference between peak and overnight electric rates. The PHEV revolution is nascent, but leads inexorably to the pure EV at the limit. These developments are a grid manager's wet dream, allowing generation to be averaged over hours instead of seconds. They'll help a lot with wind, but cheap daytime PV power will drive both of these trends.

One question on everyone's mind is how this would fare in a monetary crisis. I think it depends whether it gets started soon enough. If it takes too long, there won't be either capital or barter to get it established in such an uncertain environment. But if it is already in motion, the picture looks very different to me. A cheap energy producer made in a country with a fickle currency (and a base of technology and labor which will be looking very hard for options) becomes a very attractive item for international trade. Everybody wants to make a profit, so part of the return trade would be the raw materials (sodium) and machine parts to make more. It would make little sense to outsource the labor to countries with strong currencies, so the work would stay where the raw material now sits piled in dunes. Some of the product would stay at home, too. What would a rapidly-growing source of cheap energy do to an economy and currency sunk by expensive energy? It's hard to see how the declining trend would fail to reverse itself.

Conclusion

To summarize the points above,

- We've been ignoring a major supply of silicon-containing material.
- This material can be made into elemental silicon very cheaply.
- The silicon product is ready for direct fabrication into raw wafers for PV cells.
- These PV cells may be extremely cheap: about 3 peak watts per dollar.
- If we used all the annual supply of this silicon source, we could create peak capacity of about 10% of US average electric consumption every year.
- If we used the stockpiles accumulated over the last several decades, we could go a lot faster than that.
- Cheap renewable energy producers would be an economic engine and could even help rescue a moribund economy and currency.

I know this is a rhetorical question, but what are we waiting for?