

Photovoltaics (Solar Cells)

April 7, 2006

Solar cells, or photovoltaic cells, transform light, usually sunlight, into electric current. Few power-generation technologies are as clean as photovoltaics (PV). As it silently generates electricity, PV produces no air pollution or hazardous waste. It doesn't require liquid or gaseous fuels to be transported or combusted. And because sunlight is free and abundant, PV systems, especially baseload Space Solar Power, may eliminate uncertainties surrounding oil, gas, or other energy fuel supplies from politically unstable regions.

Because PV systems burn no fuel and have no moving parts, they are clean and silent, producing no atmospheric emissions or greenhouse gases to cause detrimental effects on our water, air, and soil. Compared with electricity generated from fossil fuels, each PV-produced kilowatt eliminates up to 830 pounds of nitrogen oxides, 1,500 pounds of sulfur dioxide, and 217,000 pounds of carbon dioxide, *every year*, according to National Renewable Energy Laboratory (NREL) research¹.

Isle Royale National Park, on an island in Lake Superior, Michigan is 47 miles from the nearest electric utility. The park uses five small solar electric systems to generate its electric power, helping to eliminate some safety and human-comfort concerns associated with the diesel-powered generators used earlier. Figure 1.



The big problem with solar energy collected on earth is that the sun doesn't shine 24 hours every day. Anywhere. Even highly favorable locations, such as the Arizona desert, only provide acceptable sunshine for power production about six hours per day. Most locations have fewer hours of sun and often clouds, fog, precipitation or haze for long periods, not to mention dust, leaves, hail, and even abuse by animals.

High temperatures can also reduce PV power production. Storing massive quantities of electrical energy overnight or for cloudy days to provide utility-scale baseload power on earth is not cost effective (except for a few price-insensitive buyers, such as the military or hospitals). Very few situations can economically justify the massive storage of electrical energy.

By placing large PV arrays in space, however, they can be even more environmentally benign and storage is unnecessary, since in GeoSynchronous Orbit (GSO) the sun shines over 99% of the year. GSO provides much more intense sunlight nearly continuously with no clouds, eliminating the storage problem and utilizing those valuable photovoltaic cells

10 times more effectively. Some day commercial companies may even manufacture PV and other components in space - from lunar regolith or captured asteroid materials.

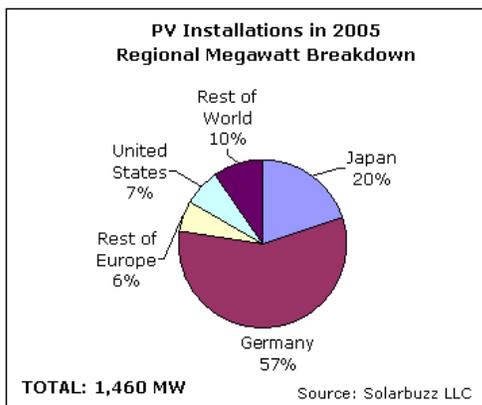
As we will outline, fabricating the PV we need to build SSP is chiefly a matter of increasing production levels for *space* PV from one hundred kilowatts annual production upwards to many Gigawatts, and tuning those production lines to space-qualified thin film. This transition capability has already been demonstrated for amorphous silicon, the most mature space qualified thin film.

Global PV Production

Global annual PV production levels exceeded 1 Gigawatts for the first time in 2004. In 2005, PV became a \$7.5 billion per year industry. Solarbuzz expects the industry to top \$18.5bn in 2010. While PV production has been growing at about 36% per year for the previous decade, in 2004 it notched a 62% growth.²

Preliminary estimates for 2005 by PV News show global PV cell production increased more than 40% from nearly 1200 MW in 2004 to 1727 MW in 2005. The real surprise is the more than doubling of cell production by small, global producers outside of the major markets to 289 MW, a dynamic likely to continue in 2006.

European cell production increased by 44%, approximately the same rate as worldwide production, resulting in 452 MW. German companies grew their producer share to 78% in Europe. Under Germany's revised 2004 "Feed-in Law" tariff structure, compensation for ground-mounted PV systems can be up to 45.7 euro cents/kWh; PV installations on buildings are up to 57.4 euro cents/kWh.³ Last year sunny Spain, approved a renewable energy law modeled on Germany's, so we anticipate faster growth there.



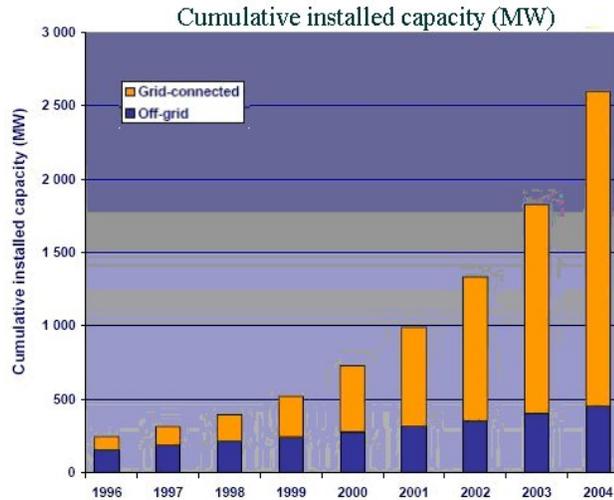
www.solarbuzz.com/Marketbuzz2006-intro.htm Figure 2.

Japan experienced a decrease in installations over the year, but an increase in production of 38%. The top four producers make up more than 95% of domestic Japanese production. Sanyo almost doubled production while the other three increased by one-third.

The U.S. market continued its slow growth, gaining just 10% over the prior year as both GE and Shell lost ground. Shell is rebuilding its solar cell research and production.

Of the top 14 cell companies in the world, the largest production increase was achieved by Suntech with almost three times the volume produced in 2005 over 2004. Suntech Power Ltd. is a Chinese-Australian joint venture. Europe's top producer, Q-Cells, more than doubled production.

BP Solar dropped from number 3 to number 7. Sharp produced 32% more cells and Kyocera 35%, while Sanyo jumped from 7th to 4th place with 105 MW of its efficient amorphous silicon.⁴ Solar electric energy production accounts for about 0.1% of the world's total energy demand.



Source: IEA-PVPS, www.iea-pvps.org Figure 3.

Worldwide annual PV installation is projected to reach 3.2 Gigawatts by 2010, continuing its strong growth in spite of current problems; notably a growing shortage of silicon feedstock. Light weight, efficient, low cost and durable photovoltaic cells are an essential key to building SSP. Can industry make such cells necessary for SSP to succeed? Unquestionably.

Since their first use to power small satellites in space in 1958¹, PV continues to decline in cost, increase in efficiency, broaden in usage and increase in production. Photovoltaic cells, or PV, is used for long distance calls, television via satellite communication systems, water pumping, desalination, lighting, refrigeration, and even flour milling in remote villages without access to nearby utility power lines. With subsidies, PV has increasingly been attached to feed into the central electric power grid. PV applications today are diverse and increasingly robust.

¹ William Cherry suggested to RCA Labs in 1956 that photovoltaic cells be developed for Earth-orbiting satellites. In 1958 a small PV array on the Vanguard I space satellite powered its radios, followed by PV-powered Explorer III, Vanguard II, and Sputnik-3 later that year. Silicon solar cells are still the most widely used energy source in space.



Alexander Bushell's PV - powered "hospital in a box", can fit in the back of a truck. It allows a team of "three trained staff to carry out life-saving surgical operations almost anywhere in the world to the standard you would expect in any European hospital".

All you need to run it is a truck battery, and that can be charged up by the solar panel. In most of Africa, the solar panel would capture enough electricity in one day to provide power for five days of surgery. . The basic kit will cost £14,000. (US\$25,000) Figure 4.

Bushell's "hospital in a box" includes an operating table, equipment holder, lighting, anesthesia and monitors, and a plastic tent to provide a clean surgical environment. The kit contains basic instruments for general surgery, from cataracts to a burst appendix to treatment for serious burn victims. Additional modules are available for specialized surgery.⁵

Interestingly, Honda will begin manufacturing thin film solar cells in 2007. Composed of non-silicon compound materials, they require 50% less energy, and thus generate 50% less CO₂, during production compared to conventional silicon solar cells. Module conversion efficiency is about 12%, close to the level of existing Silicon cells. Honda researchers say they can get as high as about 15% in laboratory cells.

Solatec LLC introduced flexible, rooftop-mounted solar panels for hybrid vehicles, starting with a kit for the 2004-2006 Toyota Prius. The \$2,195 kits are sold through dealer franchises.

A prototype operating in the Northeast under mixed driving conditions averages 55 MPG city and 62 MPG highway - a 10 percent improvement over the pre-installation mileage.⁶ Figure 5



By using thin film made from CIGS (copper, indium, gallium and selenium); Honda achieves a 50% reduction in energy consumed during manufacturing compared to conventional crystal silicon solar cells. Honda says its next-generation solar cell has achieved the highest level of photoelectric transfer efficiency for a thin film solar cell (almost equivalent to the conventional crystal silicon solar cell).⁷

PV cells produce a direct current, which can be used to operate motors and lights or to maintain the charge in batteries, which are also direct current. Inverters can convert the

direct current from PV cells to alternating current for other applications. Cells can be connected in parallel or series to create array fields, or wings, of any size or power rating.

With the help of various subsidies, Japan, Germany, the U.S., and many other urbanized countries mount PV on house rooftops to generate power, reducing power purchased from the utility and supplementing the grid (very slightly) through sales of excess electricity to the utility,⁸ such as the system pictured below in Hawaii.



PV on a Pearl Harbor aircraft hanger. Figure 6.

PowerLight Corp. of Berkeley, CA, and the US Navy on Oct. 13, 2005 dedicated a 309 kW PowerGuard system on a historic aircraft hanger at Pearl Harbor, Hawaii.

This “largest federal PV system in Hawaii”, was funded with a \$2.5 million federal appropriation. Connected to the Navy's Ford Island electric grid, it saves the Navy \$40,000 per year, based on Hawaiian Electric Company rates.⁹

PV varieties

PV is classified into two categories: crystalline silicon and thin film. Many products are assembled from these types. Crystalline is available in single-crystal, polycrystalline, and crystalline ribbon. Typical crystalline wafer thicknesses range from 150 μm (1 micrometer (μm) is 1 millionth of a meter) to 300 μm . These dominate today's PV marketplace.

Terrestrial single crystal commercial efficiencies range between 15 % and 18 %. The efficiency of a solar cell is the percentage of the incident energy, usually the sun's, that the device converts to electricity. Polycrystalline, or multicrystalline, cells are less expensive to produce and increasingly popular, but are marginally less efficient, with an average efficiency around 14 %.

Crystalline silicon has shown a record efficiency of over 24% AM 1.5 (air mass 1.5)¹⁰ and thin film solar cells a record efficiency of over 19% AM 1.5 with production module efficiencies reaching 12.2% AM 1.5.¹¹ "Thin film solar cells, despite their lower efficiency, promise lower material and production costs, resulting in a technology that may break the \$1 per watt cost barrier needed to compete with electrical power generated from fossil fuels."¹²

Key thin film technologies include amorphous silicon (a-Si), copper indium selenide (CIS) and its alloys such as copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and multijunction designs -- triple junction group III-V solar cells, such as gallium arsenide (GaAs), have reached conversion efficiencies of 30%.

By bonding layers of different light frequency response into "multijunction" products, efficiencies above 30 percent have been achieved. Besides higher efficiency, multijunction solar cells have improved radiation resistance as compared to silicon. Gallium arsenide (GaAs) triple junction polycrystalline solar cells are commercially available at 28% efficiency from Spectrolab (Sylmar, CA) and Emcore (Albuquerque, NM). These triple junction PV cells are used on the vast majority of satellites.

Solar cell efficiency can be increased by the use of junction materials with optimal bandgaps for the AMO (air mass zero) solar spectrum. Spectrolab's approach has been to design five and six junction solar cells. Modeling indicates that 35% efficiency is practicable from the six junction solar cell. Sze¹³ states that a three junction solar cell has an ideal maximum efficiency of 56%.

In contrast to silicon solar cells, which are 100-300 microns thick, typical thin film cells use only 1-2 microns of their semiconductor materials, so they are about a hundred times thinner than crystalline silicon. Because the PV materials are so thin, they need a structural substrate, typically made of low-cost glass, metal or advanced plastics and polyimides such as Kapton.

The goal is to minimize thermal expansion coefficient mismatch between the substrate and film – achieving excellent thermal and dimensional stability. Ultimately, this is expected to

reduce the costs of thin film faster than polycrystalline silicon, since it can be manufactured much less expensively than silicon cells.

The tiny chemical amounts in thin film technologies provide important environmental and marketing advantages. For example, the growing shortage of raw silicon feedstock, which is of increasing concern to the mainstream crystalline market, has almost no effect on thin film costs, since they use such small amounts.¹⁴

Module efficiencies reported for thin film PV range from 7 % (a-Si) to 14 % (CIS). Laboratory-scale solar cell record efficiencies for single layer CIGS, cadmium telluride and amorphous silicon technologies are 19.3 percent, 16.7 percent and 13.1 percent, respectively¹⁵. Commercially available product efficiencies are significantly lower. Lower conversion efficiencies, however, means larger photovoltaic array areas are required to produce the same amount of electricity.

Amorphous silicon has been commercially available for nearly 20 years and is space qualified. United Solar Systems', a joint venture between ECD and Canon, triple-junction cells have been measured by NASA Lewis Research Center under AM-O space illumination at beginning of life efficiency of 12% for a small area cell. The cells are radiation hard, and perform exceptionally well in the high temperatures encountered in the space environment.

“United Solar's triple-junction cells on SS have been subjected to proton and electron irradiations of various energies and fluences.¹⁶ It has been found that defects that are created by irradiation can be annealed out and cell efficiency restored at the prevailing temperature of ~70 °C in orbit.¹⁷

“A real life test was carried out on board the MIR Space Station. Cell data was sent by telemetry, and minimal (virtually no) change in performance was detected during the 19 months. United Solar is also developing solar cells using a 1-2 mil thick kapton substrate which could result in a specific power density exceeding 2000 W/kg.¹⁸

Sunlight has been shown to contribute to decline in efficiency of a-Si through the Staebler-Wronski Effect (SWE). However a “re-annealing” process has been observed in several venues on earth, with SWE dominant during winter and re-annealing (healing) taking place during summer heat. This re-annealing improves PV efficiency closer to the original “nameplate” efficiency.

Thin film solar cell technologies, originally developed as a high production volume, low-cost terrestrial power generation source, offer advantages in terms of cost, specific power (W/kg), stowability (Watts per cubic meter), cost (\$/W) and radiation resistance for space solar arrays.

The lowest cost thin film (per watt) is amorphous silicon, which also holds the record for specific power density at 1256 watts per kilogram (W/kg) – important to minimize space transportation costs. Of the three mature thin film technologies, CIGS-based PV offers

both the highest performance and reliability,¹⁹ so CIGS solar cells may yet be the most promising thin films for space application. Continuing development has targeted these goals for CIGS:

1. 1000 W/kg at the component level (vs. 250-350 W/kg for III-V & Si).
2. Moderate power densities of $>170 \text{ W/m}^2$ (vs. 170-300 W/m^2 for Si & III-V B.O.L, respectively);
3. Superior radiation tolerance (EOL/BOL = 0.85-0.90 vs. 0.70-0.80 for III-V & Si, respectively);
4. Equivalent connectivity for producing “supercell” or sub-array assemblies;
5. \$20-30/W projected production costs (vs. \$130-270/W for Si and III-V cells, respectively); and
6. Provide equivalent or superior reliability for various orbital configurations.

Terrestrial thin film solar cells have been significantly modified for space use, and goals for conversion efficiency in large-area cells have been set at 15%. The major issues addressed for adaptation of terrestrial solar cells to space use has involved the transition of thin film solar cells to flexible substrates, the development of inorganic transparent protective coatings, characterization of radiation-induced damage, and characterization of thermal and light-induced radiation damage recovery.²⁰

A few of the many companies claiming thin film PV development are Daystar (www.daystartech.com), Iowa Thin Film Technologies (www.iowathinfilm.com), Nanosolar (www.nanosolar.com), Konarka (www.konarka.com), Nanosys (www.nanosysinc.com), NREL (www.nrel.gov/ncpv/thin_film/pn_techinfo_latest_updates.html), and United Solar Ovonic (www.ovonic.com/res/2_2_thin_film/resource_reports.htm).

These are scarcely known beside 2005’s global PV leaders - Sharp, Kyocera, Shell, and Sanyo. However, Shell has just sold off its conventional PV business to SolarWorld and plans to focus on thin film as Honda Motor Co. has announced it will soon start full-scale production of CIS class thin-film PV products²¹. Note that both terrestrial and space PV are manufactured by many of the companies pursuing this “holy grail”. Terrestrial will continue as the most lucrative PV market – until SSP becomes dominant.

"In the last 20 years, thin film has been the hope. We think it is getting closer and closer, and we think in two to three years it will become mainstream. We’re getting more silicon than anyone else in the world, but we really could double sales if we had more silicon. Concentrators also make a lot of sense for large fields. We expect that will happen in three to five years." - Ron Kenedi, Vice President of the Solar Energy Group at Sharp Electronics²²

Paula Mints, Navigant Consulting, says thin films made up 7 percent of the solar market in 2005, or 90.2 megawatts. Michael Rogol, an analyst for CLSA Asia-Pacific Markets, expects thin films to jump to over 10 percent of the 2-gigawatt, \$16-billion solar market in 2006.

PV concentrators, using lenses to focus the sunlight to higher concentrations, can approach 40% efficiency. Boeing-Spectrolab, under contract to NREL and the Department of Energy, announced 39 percent efficiency at 236 suns at the European photovoltaic conference in Barcelona, Spain²³.

Ongoing work to adapt a-Si and polycrystalline CIGS (and alloys), the current thin film leaders, to space use involves thinning and transitioning the existing substrates to 1-mil-thick polymer substrates, modifying the active device layers to optimize the solar cells for the AMO solar spectrum, increasing in conversion efficiency through readjustment of cost/performance trade-offs, and improving electrical contacts to withstand space thermal cycling conditions. Large area a-Si solar cells optimized for space have demonstrated 9% efficiency on polyimide substrates.²⁴

Protective coatings for space are also being developed by AFRL. The coatings are required to have high transparency, high emissivity for passive thermal control, and good mechanical properties to resist cracking during flexure. The coatings incorporate a thin conductive outer layer to prevent high voltage arcing from solar flares, etc., and are inorganic to resist atomic oxygen attack. An antireflection coating increases cell performance.

Initial depositions of low temperature, vacuum-deposited coatings of alumina and silica have met the essential requirements for the protective coatings. Non-vacuum-deposited coatings are also being investigated for potentially favorable cost/performance trade-offs. Transition of thin film solar cells to space ultimately rests on the ability of the technology to withstand the space environment. This testing is, in part, in preparation for an AFRL space flight experiment called the Deployed Structures Experiment.

BIPV

Solar panels on the ground have historically been bulky, pricey, and difficult to install. New manufacturers are integrating PV into building materials, turning windows – or whole skyscrapers – into solar power generators. Building-Integrated PhotoVoltaics components, or BIPV²⁵, is replacing many traditional building elements, while also producing electricity.

Wafers of the crystalline material are made into cells and soldered together to achieve the desired voltage. Working with fabricators, an architect can tailor the module to suit the design. A connector can be installed at the edge of the panel in lieu of a junction box to allow for uninterrupted views.

Photovoltaic-generated electricity can be used as is, stored in a battery for later consumption, or, in the most common building scenario, converted to alternating current

(AC) by an inverter for immediate use in the building. Excess solar electricity can also be “sold” to the power company.

Architects can now specify photovoltaic shingles, metal standing-seam or exterior insulation systems for the roof; glazing that produces electricity while allowing various degrees of transparency; solar-collecting spandrels; insulated glass units, and sunshade elements for curtain-wall systems. A 20-story building has about 10 times more window area that can collect solar energy than it does roof area. BIPV has become a \$7 billion industry.

“It’s like a power-plant skin on a building,” says XsunX CEO and president Tom Djokovich. “We’re seeing a revolution where solar is disappearing into the building,” says Ron Pernick, co-founder of energy research firm Clean Edge. XsunX plans to begin selling its manufacturing technology to glass and optical-film makers and collecting licensing fees and royalties.²⁶

XsunX is building a new solar production facility to produce electricity from sunlight on their Power Glass(tm) windows.²⁷ Historically, most BIPV was retrofitted onto existing structures. Today, however, building materials (roofing, glazing, curtain walls) in new construction are overtaking the BIPV retrofit market.

In recent years, the fastest growing energy technology has been the grid-connected PV market segment in industrial countries, growing over 60% per year from 2000 - 2004. It covers more than 400,000 rooftops in Japan, Germany, and the United States. Of the 410 MW installed across Europe in 2004, 403 MW was grid connected and 8 MW was off-grid.²⁸

National PV priorities differ. Off-grid applications dominate in Sweden, Norway and Finland, where the most common applications are for vacation cottages. In Portugal, France and Mexico, however, achieving rural electrification is the leading objective. In the USA, Canada, Australia and Korea, commercial applications dominate, such as for telecommunication applications.

Virtually all satellites orbiting our earth today are powered by photovoltaic cells. In addition to the production of electricity, the sunlight produces a slight amount of heat in the cells that must be conducted or radiated away. With reasonable care, their lifetime is approximately 20 to 30 years, declining slowly, as techniques such as re-annealing appear to provide extended life for a-Si.

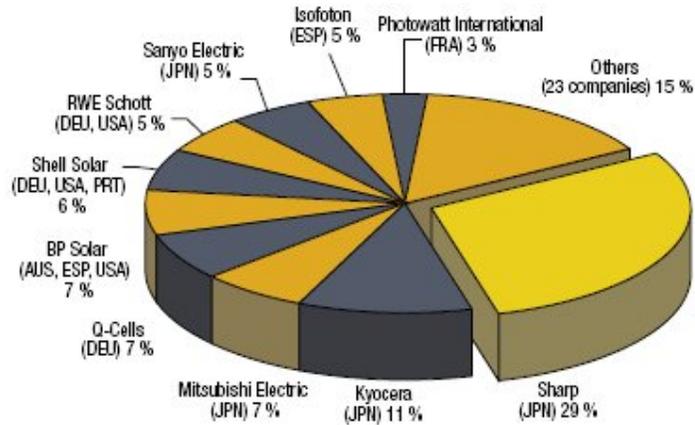


The International Space Station has many large PV panels that change sunlight into electric energy to power the space station's needs.

This picture shows the ISS in LEO, where they are illuminated about half of each day. Solar Power Satellites would orbit at GeoSynchronous Orbit (GSO), where they are illuminated 99% of the year. Source: NASA Figure 7.

Current research focuses on developing manufacturing technology to help reduce costs of the traditional single-crystal silicon cell and on producing solar cells from less expensive materials. Promising alternatives include thin films of amorphous silicon, copper sulfide/cadmium sulfide, and gallium arsenide.

Sharp continues to lead the world in PV cell production; predicting sales for fiscal 2005 to rise to 150 billion yen (\$1.26 billion) from 117 billion yen (\$980 million) for fiscal 2004.



Source: IEA-PVPS, www.iea-pvps.org Figure 8.

When a new house is built in Japan it has 4 kW of peak PV on its roof, and it literally has a zero energy bill. The buyer doesn't see this subsidized cost, it is rolled into the mortgage. What will happen when the subsidy ends? Paul Maycock predicts that with PV electricity cheaper than utility-generated energy in Japan, their market will easily continue to grow 25% per year, "more or less forever."

This is largely because Japan's retail electricity cost is about 22 cents per kWh, while typical U.S. retail electricity costs are 8.5 cents per kWh.²⁹ Christopher O'Brien, Sharp's

vice president of strategy and government relations for the solar division, says that when Japan ends its subsidies, there is no question Sharp will be able to sell in an unsubsidized market.

Sharp's President Katsuhiko Machida has said, "If solar power, which produces no greenhouse gases, can be competitive in price, consumers will choose solar, so there is potential for the business to grow rapidly," he said. Machida predicted by around 2010 the electricity fee for home using solar power could be halved from the current 47 yen (40 cents) per kilowatt hour to 23 yen (19 cents), the same as current rates for conventional electric power generated by oil and coal.

Sharp projects a record profit for the fiscal year through March 2006 of 87 billion yen (\$756 million), up 13 percent from the previous year. Fiscal 2005 sales were projected to grow 8 percent to 2.75 trillion yen (\$23.9 billion), also a record high for Sharp, from 2.5 trillion yen for fiscal 2004. Sharp's performance stands out among its Japanese rivals, many of which are struggling to post profits amid falling prices of consumer electronics products.³⁰

The SolarBee solar-powered water circulator aerates ponds by circulating the top 2 feet of water at a rate of up to 10,000 gallons per minute.

The SolarBee's mixing action greatly accelerates the biological and chemical processes that clean up wastewater, freshwater, and potable water.³¹

Source: SolarBee, Figure 9



Manufacturing Cost and Projections

Total PV module shipments are expected to reach 2783.1 MW by 2009, with a value of \$8.2bn, from 973.1 MW in 2004, according to Business Communications Company, Inc.³² Clean Edge research expects solar photovoltaics (including modules, system components, and installation) will grow from an \$11.2 billion industry in 2005 to \$51.1 billion by 2015.³³

Currently PV suppliers are building highly-automated "autolines" to produce 200 - to 500-megawatts of wafers per year. "The capital cost for these solar-cell plant is projected to be around 50 cents-per-watt, although the industry is attempting to spend "half of that" said Richard Swanson, president of SunPower Corp.³⁴ For these companies using traditional crystalline silicon wafers, the polysilicon feedstock represents 25 percent of the module BOM (bill of material) in 2005, rising to 40 percent by 2007.

Keshner and Arya designed a “Solar City” factory that would process 30 million sq. meters of glass panels per year and produce 2.1 – 3.6 GW (peak output, terrestrial) of solar panels per year — 100x the volume of a typical, thin-film, solar panel manufacturer in 2004. With a reasonable selection of materials, and conservative assumptions, this “Solar City” can produce solar panels and hit the price target of \$1.00 per peak watt (6.5x - 8.5x lower than prices in 2004) as the total price for a complete and installed rooftop (or ground mounted) solar energy system.

Their breakthrough in solar energy price comes without the need for any significant new invention. It comes entirely from the manufacturing scale of a large plant and the cost savings inherent in operating at such a large manufacturing scale. At \$1.00 per peak watt for a complete and installed system, the payback time in states like California (see CSI below) is under 5 years. Therefore, Keshner and Arya expect the demand for solar energy systems to explode.

At that price, there will be demand for small solar energy systems installed on residential rooftops (4 – 6 kWp each), much larger systems on commercial rooftops (0.5 MWp each) and even larger systems for the wholesale generation of electricity at competitive wholesale rates (10 – 100 MWp each). With a 30 year lifetime, assuming 6% interest, a solar farm costing \$1.00 per peak watt installed will generate electricity at \$0.02 per kWhr in the southwest desert and \$0.03 per kWhr across much of the U.S.³⁵

California Solar Initiative

The California Public Utilities Commission passed the California Solar Initiative (CSI) in January 2006. This historic plan provides \$2.8 billion in customer incentives for solar projects on existing residential buildings, as well as all public buildings, industrial facilities, businesses, and agricultural facilities.

Over the next 11 years, this will provide for the installation of approximately 3000 MW of solar energy. The California Energy Commission, meanwhile, will provide \$400 million in incentives for new homes, specifically targeting collaborations with the builder / developer community.

“I see the global PV market as a tripod between Japan, Germany and now the U.S.,” said Gordon Handelsman, Sr. Director of Marketing and Sales for Shell Solar, also a solar PV manufacturer. “The U.S. has been the lagging piece of the stool, this will address that.” The CSI is the largest solar energy policy ever enacted in the U.S. and second only to Germany in terms of global solar policy.

Through mid-November 2005, California led the US in PV installations with 130 MW_{AC} of grid-connected solar capacity, and a distant third on a worldwide basis behind Germany and Japan.³⁶ The new initiative will roughly triple the annual amount of state funding to subsidize solar power by tacking a new fee of about \$1.10 a month on utility bills.

The goal is to install solar energy on 1 million buildings statewide by 2017, generating 3,000 Megawatts of electricity (at daily peak production), the equivalent of six large power plants, or enough to serve 2.3 million people. California's current peak demand is about 60,000 megawatts, just 100 megawatts of which are solar. One megawatt can power about 1,000 homes.

Public support for the plan was repeatedly mentioned as a critical factor in bringing this plan to the CPUC. Over 50,000 people wrote to the CPUC asking them to pass a long-term solar rebate program - more public comment than the CPUC has ever received on any issue, including the 2001 energy crisis.³⁷

CSI rebates beginning this year will stay at the \$2.80 per watt mark and will gradually decline for the following ten years. By design, the rebates will decline by 10 percent per year through the duration of the program. The money will come from existing funds already earmarked for solar power and a very small additional surcharge on monthly electric bills over eleven years.³⁸ Details on the California Solar Incentive program can be found at <http://www.cpuc.ca.gov/static/energy/solar/index.htm>

In the USA, only New Jersey has solar incentives that rival California's CSI, although many other states have adopted solar and renewable energy incentives. In March, 2006, New Mexico established a 30 percent individual tax credit for the purchase and installation costs for solar electric and solar thermal systems, up to \$9,000 for each system.

New Mexico's residential tax credit, available for 10 years, is designed to augment the new federal credit, so both credits may be used. The bill provides \$3 million for solar electric tax credits and \$2 million for solar thermal tax credits each year.³⁹ More info is available at www.pnm.com/customers/pv/home.htm.

You can discover solar and other renewable energy incentives for your state at the Database of State Incentives for Renewable Energy, www.dsireusa.org a comprehensive information resource on state, local, utility, and selected U.S. government renewable energy incentives.

Terrestrial Solar Costs

Arizona ought to be a great place for power from the sun. It receives as much or more hours of sunshine, or solar energy per day² than any other state. The high desert of the American southwest is usually cloudless with none or few clouds to obscure the bright sun. If any area could support using photovoltaic power for the primary energy source it ought to be Arizona. Like most states with plenty of sunshine, Arizona subsidizes solar power installations. You would expect that if terrestrial solar power could be economical, Arizona would have the best chance.

Solar Buzz tracks the price of Residential, Commercial and Industrial size PV electrical installations in sunny or cloudy climates. In a sunny climate, such as Arizona, in March

² "insolation" is typically given in kilowatt-hours per square metre per day)

2006 they expected a commercial scale fifty kilowatt installation would cost \$344,368 or \$27.65 per kWh. The same fifty kilowatt installation in a cloudy climate (most sites in the US) would cost 60.83 cents kWh⁴⁰.

The city of Tucson's Southeast Service Center has been equipped with solar panels for about two years, and uses an average of 3,000 kilowatt-hours of electricity per month. On average about a third of that total is supplied by the building's photovoltaic system.

The city's energy manager, Vinnie Hunt says, "It costs me 23 cents per kilowatt-hour to generate the electricity³, but I can buy it for 9.3 cents. That kind of says it all. Tucson Electric Power's Hansen said that although using the power of the sun to make electricity is still an expensive option, "Solar is not plug and play yet... it's a lot of plug and pray."

Terrestrial PV is usually quoted as peak power, or the output at full sun. That means the other 18 hours of the average Arizona day, Vinnie must have power from other baseload generation, such as coal or nuclear to operate.

Rapid growth causing polysilicon shortage

Historically, the PV industry purchased off-spec silicon material that was rejected by the electronics industry, as semiconductors, or integrated circuits, require much higher purity silicon. As the solar industry has grown, its demand has surpassed the available off-spec silicon supply. The availability of reasonably priced polysilicon feedstock may be a barrier to continued strong PV market growth during 2006 and 2007.

The polysilicon shortage has slashed some analysts' projected growth for the global PV industry to numbers from 5%⁴¹ to approximately 20%⁴² in 2006 and 2007 – down from more than 40% in 2004 and 2005. Globally, polysilicon manufacturers are increasing capacity; Munich-based chemical manufacturer Wacker, for example, is expanding its polysilicon manufacturing capacity from the present 5,500 tons to as much as 9,000 tons beginning in 2008.⁴³

Yano Research, however, expects the Japanese photovoltaic (PV) market to continue growing 30 to 40% during 2006 and 2007 reaching 2,350 MW, or 665 billion yen in value, in fiscal 2008.⁴⁴ The European Photovoltaic Industry Association envisions reducing crystalline wafer thickness to 150 μm , compared to 300 μm in 2004, to optimize the use of raw material and reduce cost. Sharp is working to reduce their cell film thickness from 200 μm to 180 μm ,⁴⁵ as other manufacturers are also pushing wafer thickness down.

Supply chain checks confirm that polysilicon contracts are sold out through 2007. The contract price of polysilicon at \$60/kg in 2005 doubled from \$30/kg in 2003.⁴⁶ For companies using traditional mono- or polycrystalline silicon – 91 percent of industry – the

³ "The Solar Switch", a six part series) By Mari Jensen, Tucson Citizen/Associated Press, 2001-06-29 http://cnniw.yellowbrix.com/pages/cnniw/Story.nsp?story_id=21932680&ID

polysilicon feedstock represents 25 percent of the module BOM (bill of material) in 2005. Contract prices are anticipated to reach \$80 per kg in 2007, with the spot price remaining over \$100 per kg.

The current polysilicon shortage is projected to remain extremely tight in 2006 and 2007, increasing the incentive toward thin film. They estimate that in 2010 thin film technology could provide 1 GWp of PV modules: almost 20% of the market, driven by record polysilicon industry prices and profits and the fact that thin-film is nearly immune to the polysilicon shortage.

Analysys International says there is an enormous polysilicon shortage in the Chinese market, and this will become the bottleneck hindering the rapid development of the solar PV energy industry in China in the coming years. "The gap between demand and supply is huge in China. The total demand in 2005 was 2,825 tons while the supply was only 130 tons," says Zhao Yuewang, analyst from Analysys International.⁴⁷

A recent solar energy report from Piper Jaffray said that because of the tight silicon supply market, "Sharp does not expect to grow its polysilicon wafer production in 2006 and is focusing its efforts on thin film and concentrator technologies." The report said the silicon situation is similarly affecting other manufacturers around the globe as well. It is an open question whether producers can maintain their growth (e.g. by shaving wafer thicknesses for 2006) given that stockpiles are very low.

Mark Cortez, Director of Marketing for Sharp's solar energy division, said the company has some thin film solar under development that competes with traditional silicon-based PV, particularly when factoring in the higher efficiency degradation that affects solar PV when under high temperatures.

Cortez clarified that while the silicon situation is often described as a silicon shortage, it is more accurate to say that the markets are growing faster than the supply. Therefore it makes sense to find and develop technology that avoids that problem.

Sharp Corporation, the largest producer of solar photovoltaic modules in the world, in November 2005 signed its first major research partnership with Sandia National Laboratory, the US's premier solar energy research facility.⁴⁸ The partnership between Sandia and Sharp will focus on photovoltaics and fuel cells.⁴⁹

The bottom line cost - PV at GSO

Space solar cells will eventually be manufactured for 1/10 the cost, per kilowatt/hr, as terrestrial cells. The reverse is true now, with space PV greatly more expensive than terrestrial PV. First we must pay the costs to transition to space PV. The cost of space power generation depends on

1. PV manufacturing cost (\$ per Watt);

2. cost of space transport to GSO (\$ per kilogram); this is largely dependent on specific power density (Watts per kilogram) and stowage, or the packing volume factor (Watts per meter³). Thin film fabric will be rolled up like great rolls of carpet or paper for launch – with PV as thin as paper. United Solar Ovonic's amorphous silicon triple-junction space cells, originally developed for terrestrial applications, currently have the highest specific power density of any space PV fabric.
3. cost of array assembly at GSO;
4. solar cell efficiency -- both initially and after environmentally- induced degradation during the array's service life. Efficiency is the primary factor dictating the size and operational mass of the solar array for a given power production level.
5. Damage repair, and/or annually averaged service. This is termed Operations & Maintenance (O&M). Its goal is to maximize service life.

Reannealing, for example, is one feature that has been shown to be a promising O&M benefit for a-Si. This process reverses much of the damage inflicted by solar and other radiation. Maintaining high efficiency is crucial in this variable radiation environment.

Newer plastic backing materials, specifically tailored for space application should be optimized. Like space transportation, PV must be developed in concert with the SSP marketplace which will require truly massive quantities of very low cost PV thin film fabric, in addition to high volume cargo transport to GSO.

Ten times more sun (and revenue) in high orbit

How much total energy or power per year would a terrestrial PV collector of a given efficiency and size collect here on terra firma versus GSO? We are not comparing peak PV power, when the sun is high on a clear day, but the annual or daily (integrated) average power. The best research we can document (below) says that number is very close to 10 to 1 for the average US site (and also for Japan, the PV leader, where most of the world's PV is installed, since we are at similar latitudes).

Using NREL's standard tables as listed at
<http://solstice.crest.org/renewables/solrad/data/index.html>

Another source is
http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/serve.cgi

Solar Radiation by City for Flat-Plate
 Collector Facing South at Fixed Tilt = Latitude

Major US Cities Average

	kWh/m ² /day
Los Angeles, CA	5.6
New York, NY	4.6
Chicago, IL	4.4
Washington, DC	4.6
San Francisco, CA	5.4
Detroit, MI	4.2
Philadelphia, PA	4.6
Boston, MA	4.6
Dallas, TX	5.4
Atlanta, GA	5.1
Houston, TX	4.8
Seattle, WA	3.7
<u>Miami, FL</u>	<u>5.2</u>
US Average	4.78

Therefore, multiplying by 365 days, the total power per year for an average US site is

1745. kWatts/m² per year for Flat-Plate Collector

Now up at GSO Solar Radiation is more intense at 1.367 kWatts/m²,
so multiplying by the hours in a year, we compute 11930. kWatts/m² per year

(GSO orbit means the sun is in shadow approximately 33 hours total per year - at midnight during the equinoxes, so we actually used 8760 minus 33 = 8727. During these times of eclipse, GSO satellite operators, like NOAA, usually provide power to the satellite with batteries.) Therefore solar radiation is

6.84 times brighter at GSO.

(What about sun tracking? If sun tracking is added to any solar array location, the collected power increases by only 20%, moving the US average power to 2095 kWh per year, which would reduce the expected advantage of GSO to 5.7. However, this substantially increases the operational costs by using power and increasing maintenance, so that extremely little installed PV capacity actually tracks the sun; it is not cost effective, they are usually roof mounted like shingles. By comparison, in space, such as GSO, sun tracking is nearly always done.)

Based on the best studies available, by Texas Utilities's Electric Park, the expected (nameplate) rating for their PV system was predicted to be 140,000 kWh however their actual production was close to 100,000 kWh. The cause was attributed to summer heat, smog and haze. Based on their studies, the typical US average advantage of GSO over terrestrial PV solar energy collection would be

$$6.84 * (140/100) = 9.6$$

and **probably a bit higher** since Texas (and TU's Electric Park) is a better PV site than average US sites. (See EPRI Tech Report -106409 or RS-106409 for further details of TU's PV study.) More important, from TU's actual system studies was the fact that peak PV performance coincided with early spring or late fall when electric system power use and demand was at annual lows.

It would be much preferable for peak power output to occur in the summer, or at least winter, since these are the peak energy demand periods. A Kilowatt-hr in summer is more expensive, or valuable, than a Kilowatt-hr in spring or fall. GSO production is again better than terrestrial because production is steady or flat throughout the year.

Fully evaluating this impact is a topic for further study of a particular regional market, but you can check your own summer electric power bill rates against spring rates. This is definitely a negative impact on terrestrial bottom line power availability, value and the corresponding revenue. This negative attribute of terrestrial solar is also shared with wind power.

Many other minor details could be mentioned. For example, PV on earth sees a slightly different power spectrum than at GSO. This means that even more energy is actually available at GSO – if the PV at GSO were tuned to capture it. Terrestrial PV cannot hope to capture energy which does not penetrate the atmosphere.

(To compare the relative performance of different PV designs, standard spectra have been defined which approximate the real solar standard spectra. PV is tested and rated at Air Mass numbers – AM0 is what PV would receive in high orbit, like GSO, with no atmospheric cover, whereas AM1 means a normal – sun directly overhead at sea level – air mass cover. AM1.5 is officially defined as the “solar spectral irradiance distribution (diffuse and direct) incident at sea level on a sun-facing 37-degree tilted surface, with atmospheric conditions of: precipitable water vapor, 14.2 mm; total ozone, 3.4 mm”⁵⁰)

We should also consider the effect now known as "global dimming". Many scientists have measured the loss of sunlight at about 2-3% per decade in different regions during much of the last half of the twentieth century. This has been concentrated at the northern and mid latitudes. The effect varies greatly over the globe, but some published estimates of the global average value are:

- 5.3% (9 W/m²) over 1958-85 (Stanhill and Moreshet, 1992)
- 2%/decade over 1964–93 (Gilgen *et al*, 1998)
- 2.7%/decade (total 20 W/m²) up to 2000 (Stanhill and Cohen, 2001)
- 4% over 1961-1990 (Liepert 2002)⁵¹

Further studies are seeking to measure and predict this "global dimming" more accurately. We will not include this effect in this comparison, although it would likely increase GSO's advantage – highlighting the vagaries of being below the earth's increasingly burdened

atmosphere.⁵² Variations due to “global dimming” have not yet been understood well enough to be placed into the Air Mass specifications.

We should also note that forty to fifty percent of Space Power satellite output is expected to be lost during the end-to-end wireless power transmission (WPT) process through the atmosphere; that is moving the power from the space PV output to your electric power grid input. See that chapter for further details.

So if we had a PV array on earth that collected 1000. kWatt hours per year, we would expect that array to collect about 10,000. kWatt hours per year if it was orbiting at GSO.

Regardless of these asides, we are quite close to a 10 to 1 PV power advantage for GSO over terrestrial PV, specifically the US, European, Japanese or similar mid-latitudes, for a PV collector of given efficiency averaged over its daily or annual operation.

Space PV cost

Space photovoltaics have suffered from a deplorably low manufacturing volume to date, but by analogy to terrestrial levels, established learning curves and experience, what could we project about space PV costs if we manufacturing were increased to provide for a demand of many Gigawatts per year?

The transportation cost of putting PV into GSO can overshadow the purchase price for lower specific power density even if the PV is high efficiency, since space transportation is very expensive at current low launch volumes. Since launch costs have been so high, other factors such as efficiency and reliability overshadowed space PV costs.

As surely as launch costs will decline as launch volume increases and commercial launch businesses assume prominence, space PV costs will then be pushed below terrestrial solar module costs as space PV volume (total wattage deployed or installed) increases and exceeds terrestrial PV volume.

Essentially all the current cost differential, between terrestrial and space PV, is due to manufacturing volume. In 2005, the world produced 1.74 Gigawatts (at peak output) of terrestrial PV materials. Less than 100 kilowatts per year of space PV, by comparison, is now manufactured. We have a very long way to go to approach global electricity production levels.

To achieve just a 1% share of the World Electricity Supply in 2025, assuming that world electricity demand will be 175% of 2005 world Electricity demand, would require a 31% per year annual growth rate for the intervening twenty years. Global electric generation in 2003 was 15,852. billion Kilowatthours, or 15.9 quads. Approximately 48 quads of energy were used to generate this electricity, the difference **wound up as waste heat**.

In a 2004 NREL study, Keshner and Arya⁵³ claim the PV industry is ready to undergo an inflection in lower cost, higher volume manufacturing. The technology is now very close to good enough; the key issue is cost, they point out. California's Solar Initiative (CSI), passed in January, 2006, may provide enough additional impetus to accomplish that inflection for terrestrial.

Keshner and Arya's "Solar City" factory would produce 2.1 – 3.6 GW of solar panels per year— about 4x the volume of the entire solar panel industry in 2004. At these new economies of scale, "Solar City" can hit a price target of \$1.00 per watt as the total price for a complete and installed solar energy system. (That implies module prices would be 55 cents per watt.⁴) They claim this is the trigger point in price for PV manufacturing to undergo this inflection.

This breakthrough in PV price comes entirely from the design of a large factory and the cost savings inherent in operating at such a large manufacturing scale. No significant new invention is needed. Large companies outside the U.S. are being motivated to invest strongly, supported by *their* respective government rebates for solar electricity installations, making solar electricity generation even more competitive.

“Similarly, in the mid 1990's, the DRAM industry (which supplies memory chips for computers, etc.) went through a similar inflection point. Before the inflection, the industry was initially based in the U.S. and dominated by many small manufacturers. Factories were modest in capital cost and were used flexibly to manufacture a large variety of semiconductor chips in addition to DRAM's.

“In the mid 1990's, several companies in Japan invested heavily to create highly automated DRAM factories. Each factory was completely dedicated to producing only one product and to produce that product in very high volumes: DRAM's. The equipment was specialized for DRAM's, the manufacturing processes were tuned and tuned again—just for DRAM's— and the operations were tuned for DRAM's.

“As a result, manufacturing costs came down dramatically and product yields went from under 50% — typical in the U.S. — to over 90% in Japan. By the end of the decade, all U.S. manufacturers had left the business with the exception of Micron Technologies.

“Micron followed the Japanese companies in building dedicated and highly automated factories. They also petitioned the U.S. government for price protection. Recently, the PV industry has seen the Sharp company in Japan enter the solar panel industry, grow rapidly and take roughly a 50% share of the worldwide market in just a few years. This is clear evidence that the inflection point is near.” - (Keshner)

⁴ A PV module today represents 50 - 60% of the total installed cost of a Solar Energy System. “Price Index Context” <http://www.solarbuzz.com/ModulePrices.htm>

A typical terrestrial polycrystalline module (Kyocera) produces 160 Watts (peak) and weigh 16 kg., or 10 W per kg⁵⁴. Such modules can be purchased for \$3.92 Watt for crystalline silicon and \$3.76 per Watt for terrestrial thin film. (These happen to be the same specific power as the International Space Station's photovoltaic array assemblies, which cost far more money. The ISS's high-performance multiple band gap space cells (not the complete arrays) sell for about \$300 per Watt).

A factor of over ten thousand times higher volume is the real reason terrestrial PV is cheaper. Also terrestrial PV modules are about one hundred times heavier per watt than space PV. Space thin film is being manufactured at specific power densities exceeding 1000 W per kg. Eventually terrestrial PV will be far more expensive, per annual power output (Watts per dollar) – when space PV volume is mass produced in great enough volume:

Shifting Mass production from terrestrial PV to space PV

Except for the well documented historical fact that space qualified cells have required complete, exhaustive and very expensive Military specifications (MIL spec), intensively documented testing, and traceability from the raw material to finished product – thin film space PV could eventually be less expensive than terrestrial polysilicon PV – *if manufacturing volume were equal.*

And will be less expensive as volume goes up and material used plunges. Commercial specifications will replace Mil Spec, just as SunPower on March 22, 2006, become the first solar panel manufacturer worldwide to pass the tough, new TUV Certificate to IEC61215 Edition 2 for its Solar Panels.⁵⁵ We look to the day when there will be many manufacturers earning a commercial space PV IEC Certificate.

Certain manufacturing designs are different for space or terrestrial PV, for example, space PV should have the negative layer on top of the positive layer, making it more resistant to radiation; which is critically important for cells used in space. Terrestrial PV must be humidity or water resistant, which may be ignored for space PV.

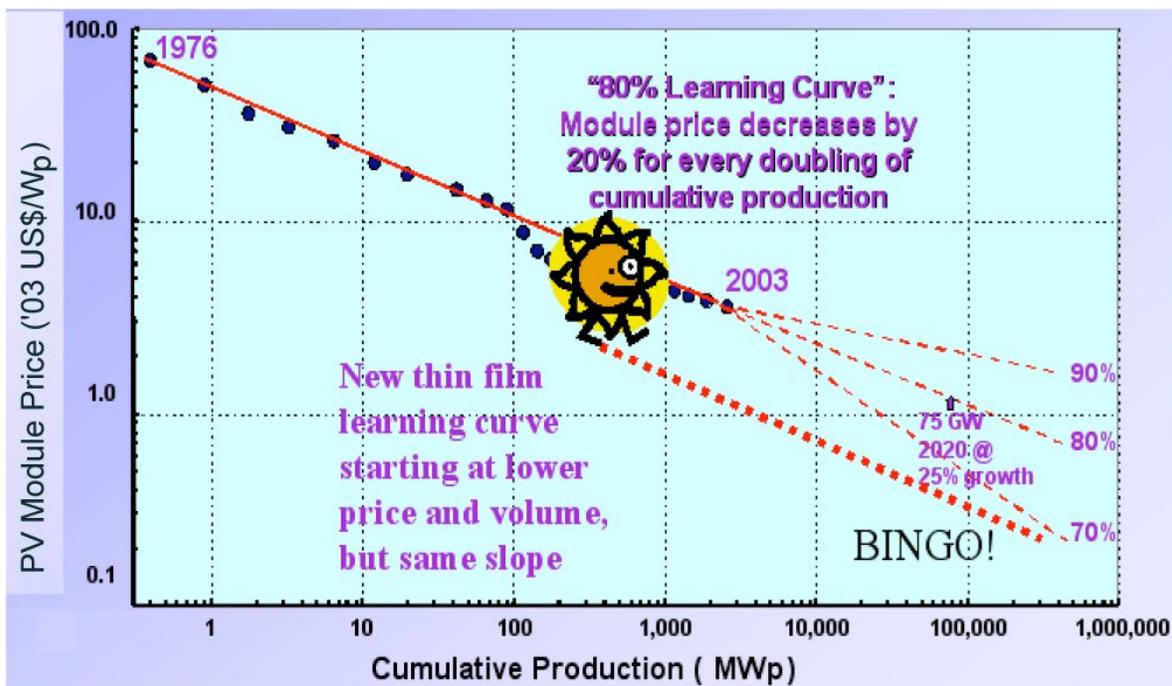
Some tests, such as Temperature Cycling are of value to both PV types, but in general, most terrestrial cells have different requirements no longer requiring exhaustive and expensive MIL spec testing and documentation requirements. Terrestrial cell costs today are hugely reduced since this unnecessary historical MIL spec paperwork is unnecessary now for terrestrial PV. Eventually this will be dispensed with for space PV, since it will also eventually be unnecessary.

Thin film PV is typically cheaper to manufacture than crystalline silicon PV cells because it uses so little material. This price difference between thin film and crystalline silicon is now (2006) reflected in the price of terrestrial modules and is expected to increase. As we

mentioned earlier, the growing shortage of raw silicon feedstock, of great concern to the mainstream crystalline market, has almost no effect on thin film costs, because they use such small amounts of materials.⁵⁶

These economies of scale were applied to the terrestrial PV market by Keshner, and they would apply equally to the space market, in fact more so because there is much less material (steel, glass, aluminum, asphalt, etc.,) required weights per watt.

This declining cost with greater cumulative production is called a learning curve. Between 1968 and 1998, the worldwide cumulative installed capacity of PV modules doubled more than thirteen times, from 95 kW to 950 MW, while costs (\$/W_p) were reduced by an average of 20.2% for each doubling.⁵⁷ This process is shown in the chart below. Notice the inflection which is predicted for lower thin film costs.



Source: Zweibel, NREL Figure 10.

In Conclusion

This Cumulative Production curve predicts \$.30 per Watt PV at 100 Gigawatts cumulative production. Cumulative global PV production will easily pass 10 GW during 2008. If that 10 GW were in space it would produce 100 Gigawatts. Yes, that can't be done for various reasons, but we could educate our government representatives that we need subsidies for commercial space PV production, not just for terrestrial PV production.

This is why we suggest separate legislation to provide an 85% subsidy to new private or public/ private businesses, such as SunSat Corp, which are contracting for space photovoltaic arrays and 30 % subsidy to established businesses contracting for space

photovoltaic arrays. These funds would go to those businesses buying space photovoltaic arrays as tax credits, for example. (Another 85% subsidy would be provided to new private or public/ private businesses, such as SunSat Corp, to discount the price of space transportation.) Virtually all energy forms now being manufactured are being subsidized by the government, with the notable and glaring exception of SSP - the only clean baseload solution.

If we fail to strongly invest soon in increasing space PV production – moving terrestrial manufacturing production to space now, while oil prices are “modest” – we will find it greatly more difficult as rising oil prices all too swiftly increase prices for feedstock, labor, processing, transportation and an endless list of other cost increases. The US Army Corps of Engineers has joined a growing chorus of experts in predicting “World oil production is at or near its peak”.^{58 59} Saudi Arabia, the bellweather for global oil production has not increased oil production in three years (since April 2003).

Testifying before Congress, Exxon Mobil reported record quarterly profits of \$10 billion in the July-September quarter, 2005. Together with Chevron, ConocoPhillips, BP America, and Shell Oil they earned more than \$25 billion in *quarterly* profits.⁶⁰ Congress felt our oil, gas and nuclear energy companies needed financial assistance, so Congress awarded \$12 billion in additional subsidies to them in the 2005 Energy Bill. Perhaps this may provide a few months delay? If Congress isn't going to get serious about clean baseload energy, maybe it's time to buy a horse and move to Texas ...

The thing about my jokes is, they don't hurt anybody. You can take 'em or leave 'em. But with Congress, every time they make a joke, it's a law! And every time they make a law, it's a joke! - Will Rogers

There is tide in the affairs of men, which, taken at the flood, leads on to fortune; omitted, all the voyage of their life is bound in shallows and in miseries;

On such a full sea we are now afloat; and we must take the current the clouds folding and unfolding beyond the horizon when it serves, or lose our ventures.

- William Shakespeare

Links for Further Reference

Center for Renewable Energy & Sustainable Technology Solar - www.crest.org/solar
DOE Energy Efficiency and Renewable Energy newsletter, the *EERE Network News*,
www.eere.energy.gov/news/subscribe.cfm and
Conservation Update bimonthly, summarizing state renewable energy projects
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Wood burning stoves or Biomass, Hydroelectric, Geothermal and Solar Thermal
Electric, Fuel Cells, Municipal Solid Waste, CHP/Cogeneration, Tidal Energy, and
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First Solar, 602-414-9300, www.firstsolar.com

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Shell Solar, +31-20-630-2423, www.shell.com/home/Framework?siteId=shellsolar

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