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When it comes to photovoltaic (PV) cells, Wall Street is concerned primarily with established companies employing traditional silicon-based technologies. However, record high oil prices based on genuine long-term supply worries has Wall Street increasing its interest in companies developing other PV technologies and materials, because at least for the immediate future, all types of PV technologies will thrive. This is despite the fact that the price of polysilicon, a key material used in traditional silicon-based solar cells and semiconductors, is expected to come down within the next six months. Lower polysilicon prices would seem to dampen interest in alternative non-silicon PV technologies because of their lower efficiencies in harnessing solar energy.

In fact, it is easy to foresee a segmented industry with a dual focus. One segment would focus on silicon-based photovoltaics using rigid, bulky solar panels primarily in large-scale applications such as producing power for utilities. A second segment would focus on low-cost technologies based on nanomaterials and conductive polymers to provide flexible PV products for buildings with better efficiencies and aesthetics.

Silicon-based Photovoltaics
The generally higher efficiencies (12-22 percent) of rigid solar cells based on silicon technology have made silicon the photovoltaic of choice despite its relatively high manufacturing costs. One way to bring down cost is through a modified manufacturing process called silicon ribbon growth that reduces the number of processing steps to six from the nine used in conventional bulk silicon growth based on ingot technology. Evergreen Solar (www.evergreensolar.com), a recognized leader in the field, has been developing interesting manufacturing processes using ribbon silicon technology.

Regardless of whether silicon solar cells are based on ingot or ribbon growth manufacturing technologies, however, increasing energy conversion efficiency will always be an issue. One way to attain greater efficiency is to increase solar cells' spectral sensitivity by using broader or different regions of solar radiation, by better matching the solar emission and producing higher



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absorption coefficients, and by using a higher fraction of sunlight that eliminates losses through excessive heating of the silicon cell. For example, a 2004 patent, "High Efficient PN Junction Solar Cell" (US6696739B2) describes a solar cell showing improved energy conversion efficiency by minimizing the shading loss while reducing the manufacturing costs.
Still another way of lowering cost is through the technique of concentrated photovoltaics. Passive optical elements are used to concentrate sunlight onto photovoltaic cells resulting in more energy output while using fewer PV cells.

Thin Films and Plastic or Polymer-based Photovoltaics
The first generation PV cells, developed in the 1970s, used monocrystalline or polycrystalline silicon. These are the rigid panels most people think of whenever solar cells are mentioned. These PV cells are made of semiconductor wafers in glass and require complex manufacturing processes.

The second generation, developed in the '80s, is known as thin films. It still requires low-pressure, high-temperature film deposition and complex manufacturing processes. Cadmium telluride (CdTe) cells are the most successful technology of this generation because of their very high conversion efficiency combined with a bandgap that is very close to the theoretically calculated optimum value for solar cells under un-concentrated sunlight. This is also an ideal PV cell for use in concentrated photovoltaics.

The majority of these second-generation cells are placed on glass, so they remain rigid. However, Global Solar (www.globalsolar.com) announced in March 2008 that it has developed a proprietary process for manufacturing flexible thin-film copper indium gallium diselenide (CIGS) photovoltaic modules. While other companies produce CIGS on glass, Global Solar is thought to be the only company with CIGS on flexible materials. CIGS cells are deposited on a stainless steel backing which also makes them lightweight and durable.

Organic Solar Cells
Plastic or polymer-based photovoltaics, developed in the '90s, are considered third- generation solar cells. Also called organic solar cells, these cells use photoactive or photosensitive dyes and conducting polymers that can be manufactured at high speeds and low temperatures. Manufacturing costs can be reduced as a result of using a low temperature process similar to printing instead of the high temperature vacuum deposition process typically used to produce



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the first and second generation cells. Reduced installation costs are achieved by producing flexible rolls instead of rigid crystalline panels.

Currently, third generation solar cells are not as efficient as the first- or second-generation cells, but their lower cost offsets this deficiency. In the long term, these materials should cost even less and, using quantum dots to decrease the bandgap of the base material, they should reach higher efficiency levels than conventional cells.

Efficiency Improvements Being Explored
University of Notre Dame researchers have shown that adding carbon nanotubes to a titanium dioxide film doubles the efficiency of converting ultraviolet light into electrons when compared with the performance of nanoparticles alone. (Titanium dioxide is a main ingredient in white paint.) Without the carbon nanotubes, electrons generated when light is absorbed by titanium dioxide particles have to jump from particle to particle to reach an electrode. Many never make it out to generate an electrical current. The carbon nanotubes provide a conduit for electrons for a more direct route to the electrode, improving solar cell efficiency.

Titanium dioxide, however, absorbs only ultraviolet light, leaving most of the visible spectrum of sunlight to be reflected rather than absorbed. In dye-sensitized solar cells, a one-molecule thick layer of light-absorbing dye is applied to the titanium dioxide nanoparticles to catch more of the spectrum. Another approach coats nanoparticles with quantum dots or nanocrystals, which act as tiny semiconductors. Unlike conventional materials in which one photon generates just one electron, quantum dots are able to convert high-energy photons into multiple electrons. Other ways of improving collection of electrons within a solar cell include forming titanium dioxide nanotubes or complex branching structures made of various semiconductors.
Emerging Leaders in Printed Photovoltaics

Konarka Technologies (www.konarka.com) recently announced the first demonstration of manufacturing solar cells by highly efficient inkjet printing. "Demonstrating the use of inkjet-printing technology as a fabrication tool for highly efficient solar cells and sensors with small area requirements is a major milestone," says Rick Hess, President and CEO at Konarka. "This essential breakthrough in the field of printed solar cells positions Konarka as an emerging leader in printed photovoltaics." Inkjet printing is commonly used for controlled applications of functional materials solutions in specific locations on a substrate (RFID tags, for example), and it can provide easy and fast deposition of polymer films over a large area. Another leader in

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organic or plastic solar cells (third generation PV) is Plextronics (http://www.plextronics.com), a company concentrating on printed electronics technology.

Konarka's Power Plastic technology is focused on delivering lightweight, flexible, scalable, and manufacturable products. The inkjet demonstration confirms that organic solar cells can be processed using printing technologies with little or no loss compared with clean-room semiconductor technologies, such as spin coating. Inkjet printing could become a smart tool to manufacture solar cells with multiple colors and patterns for lower-power requirement products, such as indoor or sensor applications.

According to Solar Cells Info (solarcellsinfo.com), by 2009 at the latest, Konarka plans to bring multiple forms of its product to market-everything from tiny cells for sensors to fabric-based (solar cells embedded in awnings, for example) and larger building panels. The process involves printing or coating nanoparticles such as quantum dots or nanocrystals onto other material. Hess says Konarka is currently working with U.S. Green Building Council LEED designers on custom installations.

Final Thoughts
On the environmental side, it is estimated that compared to fossil fuel electricity generation, each kW of installed solar PV power annually saves up to 25 kg (55 lbs) of nitrogen & sulfur oxides, and offsets 600 to 2300 kg (1300 to 5100 lbs) of carbon dioxide, depending on the fuel mix and solar insolation (Incident solar radiation). It is worth noting that only a few years ago, while oil prices were relatively low, the growth of interest in PV technologies was based mostly on the environmental concerns rather than the concern on exhaustion of fossil fuel reserves and the recent higher oil prices. It is now clear that the dual focus of PV technologies along with improving the efficiency and reducing costs of the various PV systems will ensure sustained growth in this industry.

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