Technology Advances in Delivering Cost-Competitive Solar Energy

Abstract

The prevalent approach for generating solar electricity is through photovoltaic (PV) systems that use semiconductor PV material to convert sunlight directly into electricity. The market is currently dominated by silicon-based flat-plate PV, which produces electricity by having sunlight directly strike panels tiled with sheets or wafers of expensive PV cell material. Flat-plate PV has defined the solar electricity market since its emergence 30 years ago, and drove the market's recent rapid growth to $7 billion in 2005. However, recent silicon feedstock shortages and rising wafer prices have highlighted the need for technologies which can advance the market beyond current flat-plate PV and its underlying cost limitations.

Concentrator photovoltaic (CPV) approaches enable lower total system cost by reducing the amount of PV material used. They use mirrors or lenses to focus sunlight collected from a given receiver area onto a much smaller area of PV material, and in some cases use higher efficiency, non-silicon PV material. This paper describes a particular high-performance CPV solution which compared to average flat-plate PV, uses 1/500th as much PV material and produces nearly twice as much electricity for a given collection area. The proposed solution is also smaller, cheaper, and easier to manufacture. These improvements enable generating electricity at less than half the cost possible with existing flat-plate technologies, potentially opening large new markets for clean solar energy.

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The Market for Solar Electricity

Rising fossil-fuel prices, recent geopolitical developments, and environmental concerns have led to growing demand for renewable energy sources such as solar. Not only is solar energy secure, widely available, and carbon-free, but more energy from the sun strikes the earth every hour than is consumed on the planet in a year [1].

Though sunlight is considered a “compelling solution” to the “need for clean, abundant sources of energy,” solar energy currently provides only 0.01 percent of the total electricity supply [1]. However, recent market trends, regulatory pressures, consumer incentives, and technological advancements are together driving solar energy costs down relative to conventional fossil fuel-derived energy.

Increasing global investor interest has helped bring solar energy into the mainstream. In 2005, solar investments were thirty times higher than a decade ago and already twice the 2004 level. Solar sector investments represented more than one-third of the total money invested by venture capital firms in the entire U.S. energy industry [2]. Furthermore, the top three initial public offerings (IPOs) of 2005 were all solar companies. As one solar entrepreneur put it, solar is the “next big disruption” and “dwarfs any business opportunity in history” [3].

Bold subsidy programs and regulations—including feed-in tariff laws, renewable portfolio standards, tax credits, and rebates—in a few key markets such as Japan, Germany, and California have significantly contributed to lowering consumers’ solar costs over the past 30 years. In Japan, subsidies have gradually been reduced and solar electricity is considered to be competitive with conventional electricity [4]. The Japanese market is expected to maintain solar growth and low prices without subsidy, and the burden of maintaining low costs has now passed onto manufacturers [5].

While Japan has the most installed solar electricity, Germany is the fastest-growing market. But California’s expansion of its solar incentive program by $3 billion in January 2006 has made it one of the most aggressive in the world, and a number of U.S. states are also expanding or considering their solar and other renewable energy options. China also initiated a solar subsidy program in early 2006, with the goal of making solar energy a critical component for addressing the exploding energy needs of the significant Chinese market. Substantial new programs are also under way or being considered in Australia, India, Portugal, South Korea, Spain, and other large markets.

Compared to conventional and other renewable energy sources, solar power is especially attractive because it can be easily scaled down or up. Solar electricity can also be generated nearer to consumers and even on site, which greatly reduces or eliminates transmission costs. Furthermore, the increasing adoption of variable-pricing or net metering schemes also favors solar electricity. Under these schemes electricity rates are higher when peak demand is highest, and this generally correlates to when more solar energy is available and electric output highest.

Solar costs are also presently being lowered through higher volume production, improved manufacturing techniques, and alternative solar technologies that reduce the amount of semiconductor material. Total installed system costs can further be reduced through cheaper “balance-of-system” components such as inverters and labor (which can be reduced through improved design and installation techniques).

However, there is consensus in the industry that broad market success for solar will come only when costs are competitive with conventional fossil fuel-derived electricity—without subsidies. The bold incentive programs and rapid solar market growth described above have already lowered the effective cost of solar PV systems to consumers. This in turn has driven the higher volumes that have lowered actual manufacturing costs, making solar electricity even more cost-competitive. Rising fossil-fuel prices have further reduced the gap between conventional and solar electricity. But most of the technological advances thus far have only been incremental, and without a dramatic technological advance like the solution proposed in this paper it would take another decade or more for solar costs to get within striking distance of conventional electricity.

Flat-plate PV Dominates the Market

The prevalent approach to solar generation of electricity is through "photovoltaic" (PV) systems which convert sunlight ("photons") directly into electricity ("voltage")[1]. In fact, grid-connected PV is the fastest-growing energy technology in the world In just a four-year period (2000-2004), capacity grew at an average of 60 percent a year [6].

Solar PV cells—the basic semiconductor device for converting sunlight into electricity—are usually grouped together and electrically configured into modules, panels, and arrays. The dominant technology for these cells is based on single-crystal or polycrystalline silicon. "Flat-plate" PV panels produce electricity when sunlight directly strikes the surface area of a panel tiled with sheets or wafers of expensive silicon PV cell material. Flat-plate silicon PV has been the primary solar product on the market for the last three decades and during the market's recent rapid growth to $7 billion in 2005. Most installations today are on rooftops, but larger field-based installations of 10 megawatts (MW) or more are becoming common, and there are several plans for installations in the 100 MW range.

The silicon material cost accounts for a substantial portion of the total installed PV system costs, and is generally considered one of the best opportunities for lowering overall costs and increasing the competitiveness of solar electricity. Furthermore, given the size of the global energy market and the ultimate potential of solar as a conventional electricity source, even a moderate reduction in the cost of solar can enable further market expansion.

Despite widespread interest and support for solar PV systems, cost and performance advantages are therefore needed to advance the market beyond current flat-plate PV and to make PV competitive with electricity from conventional sources.

The Opportunity for Concentrator Photovoltaic (CPV)

Flat-plate silicon PV is dominant today, but silicon feedstock shortages and rising wafer prices have highlighted the need for technologies which can lower costs by reducing the amount of silicon or other semiconductor PV materials. To significantly change the economics of solar electricity requires alternatives such as thin-film solar technologies or concentrating technologies [7].

Thin-film solar technologies use semiconductor materials such as CIGS (copper indium gallium selenide), a-Si (amorphous silicon), or CdTe (cadmium telluride) and are fabricated

1 Besides PV where sunlight is used for direct electrical conversion, other solar power approaches include solar thermal energy where heat is used to drive turbines and generate electricity.

with cheap roll-to-roll processes. Though these non-silicon technologies have received a fair amount of media and research attention, they face a number of financial and technical limitations including more use of scarce and expensive source materials (e.g., gallium and indium), modest efficiencies, and reliability issues. Concentrator PV (CPV) approaches, on the other hand, offer an effective, practical way to keep solar cell conversion efficiencies high while keeping semiconductor material costs down.

CPV technologies use relatively inexpensive optics such as mirrors or lenses to "concentrate" or focus light from a relatively broad collection area onto a much smaller area of active semiconductor PV cell material[2]. Since the PV semiconductor material dominates the costs of the solar PV system, reducing the amount of PV material required to capture a given amount of sunlight leads to substantially lower system cost and resulting cost per watt of output [8].

Some CPV modules reduce the amount of PV material used by as little as 2-5 times and for these, silicon is typically used as the semiconductor material. For higher concentrations that reduce PV material use by 100-1000 times more, it can be cost-effective to use higher efficiency cells that increase the electricity generated from a given collection area—even though this PV material can cost up to ten times more than silicon. Currently, the most efficient approach is multi-junction cells that achieve up to 40 percent conversion of the sun's energy into electricity, by using stacked layers of III-V compound semiconductor materials to capture more of the solar spectrum. In addition to enabling more electricity from a given amount of sunlight, multi-junction cells obtain even higher efficiencies at higher concentration levels.

Since CPV systems work by focusing sunlight onto a targeted area, they must be pointed directly at the sun and require trackers that follow the sun's trajectory throughout the day. Though this has historically been an adoption barrier for CPV relative to flat-plate PV, there have been a number of cost and reliability improvements, and trackers are commonly used in large field-based installations of even flat-plate PV. CPV has generally been viewed as most suitable for utility-scale applications, where tracking systems would be mounted on land to generate 10-100 MW of electricity. However, improved system features including lightweight trackers and recent technological advancements are allowing CPV to be mounted on rooftops, where it can generate 10-100 kilowatts of electricity at many commercial sites or 1 MW or more on large industrial rooftops.

SolFocus: Breakthrough Concentrator Photovoltaic (CPV) Incubated at PARC

The Palo Alto Research Center (PARC) recently signed a broad agreement with California-based start-up SolFocus to jointly develop CPV systems that can deliver low-cost, reliable solar energy.

For over three decades PARC has been conducting interdisciplinary research in the physical, computational, and social sciences to deliver innovations with proven commercial value. PARC today is applying its unique combination of competencies to provide strategic research

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2 All concentrator systems—including CPV, Stirling dish engine systems, and solar-thermal-electric turbine systems—operate on the same concentrating principle, but the given receiver area over which sunlight is gathered ranges from a few centimeters for CPV, to meters or tens of meters for Stirling systems, to hundreds of meters for other solar-thermal-electric systems.

services, technology, and intellectual property to diverse industry and government partners. PARC is also pursuing broad initiatives in areas such as biomedical sciences and “clean technologies” or Clean Tech.

One particular thrust of PARC’s Clean Tech initiative is reducing the cost of solar energy, and PARC scientists have been applying expertise in optical system design, optoelectronics, and advanced materials and processes for electronic packaging to address this problem. The SolFocus venture allows PARC to directly contribute to the solar energy industry, participate in broader markets, and continue developing high-impact technologies.

Building on its relationship with PARC, and with strong early contributions in optical design [10, 11] from researchers at the University of California at Merced, SolFocus has already developed two related, low-cost CPV module designs: Gen 1 and Gen 2. Up to 2 MW of the Gen 1 design will be installed in 2006-2007 at pilot sites in California, Hawaii, and Shanghai, China. The Gen 2 design further improves performance and reduces costs at higher volume production, and will be available for test installations a couple of years later. Both module designs are targeted for rooftop- and field-installed solar systems, and the Gen 1 design may also be used for other applications such as augmenting conventional lighting in buildings.

CPV is increasingly seen as a compelling approach to solar electricity, and venture funding for CPV technologies is on the rise. Among available CPV solutions the SolFocus design is a strong contender for short- and long-term cost advantages, which is the critical metric for market success. Partly in recognition of this, SolFocus won the grand prize at the 18th NREL Industry Growth Forum which was sponsored in November 2005 by the Department of Energy’s National Renewable Energy Laboratory (NREL). SolFocus CEO Gary Conley was recognized at this event as the Clean Energy Entrepreneur of the Year (2005).

The Technology

SolFocus’ CPV modules are enabled by the highest-efficiency solar cells available—triple-junction cells with efficiencies approaching 40 percent at the operating point of 500-sun concentration. For a given receiver area over which sunlight is collected, the SolFocus CPV modules use only 1/1000th of the expensive multi-junction solar cell material to convert the same amount of sunlight as other PV systems. The modules track the sunlight with a two-axis system and then concentrate it using innovative imaging and non-imaging optics. They also optimize reliability and low-cost manufacturing with practices borrowed from the high-volume semiconductor industry. The SolFocus CPV modules therefore halve the costs and operate at double the efficiency of average flat-plate PV.

Specifically, both of SolFocus’ CPV module designs:

- use glass—which can easily meet 30-year life requirements;
- use dry, passive cooling—thus requiring no liquids or fans;
- have modules with no moving parts—which avoids mechanical failure in the module;
- are fully “enclosed”—so there are no exposed mirrors or open fire hazards;
- use mirrors or reflective elements—which allow purely reflective light entry and avoid the chromatic aberration of lens-based concentrators;

- use minimal components—because they have a number of “double-purposed” materials;
- have one-quarter the focal length of other systems—making them extremely compact; and
- integrate the manufacturing capabilities of existing vendors—thus enabling the rapid launch of products.

While the Gen 1 prototype employs discrete optical elements, tailored imaging, and 1 cm^2 cells, the Gen 2 design incorporates small reflective concentrator elements in a single, flat, molded glass tile with mirrors on both sides; employs a non-imaging optical design; and uses 1 mm^2 cells.

Specifically, the smaller, thinner, “one-piece” Gen 2 design:

- uses the flattest optics—similar to the geometry of Cassegrain optical telescopes;
- reduces processing steps—by fabricating the optical elements in a single glass pressing;
- can be assembled with high-throughput, automated technology;
- packs flat for low shipping costs and associated benefits of offshore manufacturing; and
- avoids seals, filters, coverglass, and hard-to-clean surfaces [12].

Together, these CPV module designs yield dramatic improvements in size, durability, and scalability. They enable significant cost reductions, a quicker return on investment, and operate at higher efficiencies than average flat-plate PV.

SolFocus’ CPV modules promise to lower the costs of solar electricity to less than half what is available today, and position PV to be competitive with electricity from conventional sources.

About PARC's Clean Tech Efforts

The Palo Alto Research Center (PARC)—the birthplace of ubiquitous computing, the graphical user interface (GUI), the Ethernet, the first commercial mouse, laser printing, and many other industry-transforming innovations—conducts interdisciplinary research in the physical, computational, and social sciences.

PARC is now applying a unique combination of its competencies to drive innovations in the "clean technologies" or Clean Tech sector. The Clean Tech focus areas listed below: 1) require broad competencies and multi-disciplinary teams; 2) allow PARC to participate in dynamic new markets; and 3) support PARC researchers' desire to apply technologies that have positive environmental and social impact.

PARC Clean Tech currently includes:

- Solar Energy Generation Solutions—including concentrator photovoltaic (CPV) systems and novel manufacturing approaches for silicon solar cells;
- Energy Distribution Solutions—including sensor networks for the intelligent power grid;
- Energy Conservation Solutions—including simplified, fine-grained sensing and climate control in office buildings;
- Clean Water Solutions—including post-filtration bio-agent concentration, fresh- and waste-water analysis, purity monitoring, and bio-agent detection (through electrostatic traveling wave-based particle manipulation, ultraviolet or UV emitters, and optical detector technologies);
- Air Quality Solutions—including contaminant monitoring (through electrostatic traveling wave-based particle manipulation, ultraviolet or UV emitters, and optical detector technologies); and
- Paper Reduction Solutions—including a new type of re-writeable paper that minimizes paper use for transient applications such as cover sheets, e-mail printouts, and other temporary documents.

Online Information

About PARC/ SolFocus' technology (including images): www.parc.com/cpv

About PARC's Clean Tech initiative: www.parc.com/cleantech

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