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STATUS OF PHOTOVOLTAIC CONCENTRATOR MODULES AND SYSTEMS*

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ABSTRACT

Several leading line- and point-focus photovoltaic concentrator system development programs are reviewed, including those by ENTECH, SEA Corporation, AMONIX, and Alpha Solarco. Concentrating collectors and trackers are gaining maturity and reaching product status as designs are made more manufacturable and reliable. Utilities are starting to take notice of this emerging technology, and several privately-funded utility installations are underway. Several advantages are offered by concentrators, including low system and capital cost and rapid production ramp-up. These are discussed along with issues generally raised concerning concentrator technology.

1. THE INCENTIVE TO USE CONCENTRATORS

Concentrating PV collector technology offers several advantages compared to one-sun PV collectors:

- Low system cost potential in low production quantities.
- Low manufacturing plant capital cost.
- Rapid production ramp-up with minimal material supply limitations.
- Good power match to utility needs due to tracking.

The most important incentive to pursue concentrator technology is its potential to reduce system cost. This is achieved two ways; reducing cell area and increasing cell efficiency. The cell is the most costly single item in most PV collectors, representing 30 to 50% of the module cost. Reducing cell area a factor of 10 to 500 can theoretically reduce module cost by up to 30 to 50%. In practice, except for low concentration (2-15X) collectors, concentrator cell cost per unit of cell area is higher than for one-sun cells and there are additional costs (lenses, housing, etc.) in a concentrating collector, so the full benefit of cell area cost reduction is not realized. However, because more can be spent on the cell, its efficiency is higher. In addition, concentration inherently increases cell efficiency because cell voltage increases. These factors more than compensate for decreased efficiency due to the concentrating optics and any higher cell operating temperature. High efficiency is important because the collector cost is only a fraction of the entire system cost. Increasing collector efficiency reduces required collector area and thus the area-related balance-of-system (BOS) costs which include the support structure, wiring, installation, land, etc. An example helps illustrate the importance of this concept. A 1/3 cost reduction of a \$3/W collector combined with \$3/W in BOS costs results in a \$5/W system. A 1/3 increase in efficiency of the same collector results in a \$4.50/W system. Concentrators have the potential to provide both benefits; lower collector cost and higher efficiency. Peak cell efficiencies for three commercial-ready technologies range from 16% for Solar Energy Application (SEA) Corporation's cells to 19% for ENTECH's cells to 26% for AMONIX's cells. All three designs are expected to have cell costs in the range of 50-60¢/W (at normal operating cell temperature and 850 W/m^2) at production levels of 3 MW/yr. This compares with about \$2/W for commercial one-sun crystalline silicon cells at operating conditions. Populated tracking array costs are expected to be between \$1 and \$2/W at operating conditions at production levels of a few megawatts using already-demonstrated technology.

Another important incentive to use concentrators is reduced manufacturing plant capital cost. This is especially important in the low-volume startup phase when the company is struggling to break even, and even more important for very high volume production when large investments are involved. The majority of collector cost is in cell production

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equipment. Concentrators that use cells produced on a one-sun line reduce the magnitude of production capital by the concentration ratio, 10-20X. Point-focus concentrator manufacturers can use existing semiconductor plants, incurring little capital expense for the cell production. And at 200 to 500X, these designs need to process much less silicon per megawatt than one-sun collectors. The availability of low-cost silicon to support gigawatt markets does not become an issue with concentrators. In EPRI's plant comparison of a 100MW 500X concentrator plant and a copper-indium-diselenide (CIS) flat-plate plant, the concentrator requires $7.2M of manufacturing equipment and 294 employees while the CIS plant requires $127M of equipment and 484 employees. [1]

Concentrator technology is well suited to rapid expansion of production capability because concentrator manufacturers are mainly integrators of components produced using off-the-shelf volume production equipment or existing manufacturing facilities. 3M can manufacture line-focus lenses measured in acres per day. One-sun cells are available in volume from numerous manufacturers, and point-focus cells can be manufactured in existing semiconductor plants. Trackers can be manufactured using high-volume roll-form equipment. SEA Corporation has developed an automated receiver assembly station designed to produce 25 MW/yr at a capital cost of less than $100K. Point-focus receivers can be manufactured using high-volume printed-circuit board production processes.

Concentrator-generated electricity provides a good match to utility needs because collectors track the sun. Utilities value power availability which they measure using capacity factor. Tracking enables a collector to reach its peak output rapidly and maintain it throughout the day, achieving a high capacity factor. Even though the energy available to a tracking concentrator is roughly the same as that available to a fixed flat plate collector in high direct-normal insolation regions, the power produced by the tracking concentrator is more uniform throughout the day. ENTECH's array in the PVUSA project at Davis, CA achieved the highest capacity factor of any PV collector tested at the site (30-35%) during the important summer months. [2] One-sun systems are increasingly being tracked for this reason.

The concentrator approach provides a proven solution offering high quality electricity with low technical risk. In contrast to several thin film approaches being pursued, there are no fundamental breakthroughs required. Commercial success just requires product iteration to achieve a mature design and production volume to reduce costs. There are, however, several issues that must be addressed when considering concentrators.

2. CONCENTRATOR ISSUES

When discussing concentrator system, several issues are invariably raised.

- Tracker reliability and accuracy.
- Cell operating temperature.
- Potential market.
- Breaking through the production volume barrier.

Precision tracking is viewed as a concern for concentrators by some. There are applications where tracking is not suitable, namely some developing countries without a suitable infrastructure, or isolated, critical applications. However, for most applications, and especially large utility PV systems, tracking reliability is not an issue. Electric motors can operate very reliably with minimal maintenance as evidenced by refrigerators, well pumps, and tracking satellite dishes. Microelectronic controls and commercial satellite-dish motor/actuator units offer inexpensive, reliable tracking systems that can be used on a wide range of system sizes. The SolarTrak controller developed by Sandia requires less than $50 in parts, and satellite dish motor/actuators start below $100. [3] A modular system eliminates the chance that a single field level failure can shut down the system since each tracker operates independently. Tracker reliability becomes a manageable, small, operation and maintenance (O&M) cost. Self-contained, PV-powered tracking units are being developed to operate in large systems or in remote sites without the need to run supply power lines. Tracker accuracy need only be in the 0.5 to 1° range to maintain over 95% of on-track performance. This is well within the 0.1° range achievable by controllers. Even high concentration designs achieve this tolerance, by using secondary optical elements.

Low temperature improves PV cell efficiency. Concentrators operate at temperatures that vary from the same as one-sun collectors up to roughly 15°C above one-sun collectors. Although the focusing lens conjures up images of burning objects with a magnifying glass, in fact good heat sinking keeps cell operating temperature quite cool. Concentrator cell temperature is more related to lens area (incident power) and heat sink size (a cost issue) than to concentration ratio. Measurements made at Sandia show that concentrators ranging from 10 to 500X operate with cell temperatures varying between 25°C and 45°C above ambient, whereas one-sun collectors operate between 20°C and 30°C above ambient. For the previously mentioned reasons, even at these hotter temperatures concentrator cells are generally more efficient than one-sun cells.

Concentrators have traditionally been viewed as primarily appropriate for bulk utility power generation due to the requirement for tracking, but recent developments in low-cost, reliable drives and controls have opened the door to using concentrators in applications as small as 1 kW. The remote (non-grid connected) power market offers a potential opportunity for concentrators due to the higher allowable power cost compared with the grid-connected market. More importantly, it is a current and growing market with the capability for steady sales to sustain a startup concentrator company. Both SEA and ENTECH are developing 1-kW units to compete in these smaller power applications. We also see concentrators as the best option in the 10 to 500-kW range for the expanding hybrid PV/fossil power system market for high-insolation regions of the world. Ultimately, the high volume demand from the grid-connected market, including distributed systems located in sites such as parking lots, is expected to drive the PV industry, and in that market concentrators can excel.

The dilemma for concentrators is that a technology with no current production volume is trying to compete with manufacturers producing 10MW/yr. Detailed proprietary cost estimates provided by concentrator manufacturers support the assertion that concentrators will cost less than current one-sun modules at production levels above a few MW/yr. The challenge is to achieve this volume in order to bring costs down. SEA Corporation takes advantage of existing one-sun production volume by using one-sun cells. All concentrator manufacturers act as integrators for many components, leveraging off the manufacture of other products. Still, concentrators will be at a disadvantage until they gain market acceptance and generate sufficient sales volume to put them on cost parity with one-sun collectors.

3. CONCENTRATOR SYSTEM STATUS

Photovoltaic concentrator designs have undergone many years of development and maturing to reach the current product development stage. Several programs have supported this evolution including the U.S. Department of Energy's (DOE) Concentrator Initiative (CI) and PV Manufacturing Technology (PVMaT) Programs, development and testing support at Sandia National Laboratories, and the Electric Power Research Institute's (EPRI) integrated high-concentration PV program (IHCPV). The CI Program has ended except for funding of SEA's development program. Progress achieved by the CI Program is reviewed in [4]. Several designs are reaching the stage of product readiness. This requires a safe, reliable, collector design that can be produced in volume quantities. It also requires offering a full system including tracking.

Collectors are evaluated at Sandia using a test sequence developed to identify design weaknesses that may cause premature failure. [5] Once a design has passed this test sequence, it must be produced using processes that ensure the original design quality is maintained for every article. Sandia has worked with several manufactures to institute quality control procedures during production. The final hurdles are product validation and user acceptance. This requires installing units in end-use applications and simultaneously identifying any final reliability issues while building user confidence in the system. Small scale tests of one to several units are needed to provide the confidence to install large scale hundred kilowatt or multi-megawatt systems. Concentrators are well on the way in this process. Table 1 summarizes the key parameters of several systems.

3.1 ENTECH's 21X Line-Focus System

ENTECH has the most experience of any of the concentrator system suppliers, having developed four generations of line-focus modules and having installed several large systems. Its modules have performed well, achieving high efficiency and capacity factors. [2] Under the CI program and with subsequent funding under the PVMaT program, ENTECH made numerous design and component changes that drastically reduce the labor content of its fourth generation module. [6] The lens, formerly individually solvent-laminated to thick (3-mm) acrylic superstrate sheets by ENTECH, is now laminated during the production process by 3M to thin (1.5-mm) impact-resistant Dupont Implex® superstrates which are delivered on 180-m rolls. Instead of individually molding cell prismatic covers by hand, ENTECH can now

Fig. 1 - ENTECH's 1-kW Sunline Array with Fourth-Generation Modules

purchase the covers prebonded to an adhesive film in rolls of 10,000. ENTECH replaced stamped copper cell interconnects, solder paste, and water-soluble flux with solder-plated copper ribbon (currently used in the one-sun industry) and no-clean flux, saving 80% of its interconnect costs. It replaced the alumina-loaded silicone dielectric under the cells with Dupont

Tefzel® film, saving significant labor involved in mixing, applying, testing and patching, and it also developed a low-labor, front-surface encapsulation process that survives a wet hipot test. The module endplates were modified to accommodate variable pivot mount locations. Thus one module design can be balanced for the different receivers used. Module length was increased from 3 to 3.6 m, increasing the aperture achieved for a given module's assembly labor. Two of these fourth-generation modules are currently undergoing evaluation at Sandia. Last year Sandia measured cells from three suppliers for ENTECH's module that achieved a peak efficiency of 18.9% at 20X. ENTECH has signed agreements with two Texas utilities (Central and South West, and T.U. Electric) to install two 100-kW systems this year. It is also developing a 1-kW Sunline unit for remote applications that uses the Sandia SolarTrak controller. (Fig. 1)

3.2 SEA Corporation One-Axis 10X System

Solar Energy Application (SEA) Corporation, funded by the CI Program and now also by the California Energy Commission (CEC), approached its design with a view to manufacturing. [7,8] Its narrow lens enables it to use a thin, low-cost, sheet-aluminum heat sink which contrasts with the heavy (55 kg) extruded heat sink used by ENTECH. To handle the larger number of parts per aperture area resulting from its design, SEA has completed an automated receiver assembly station that is designed to handle one cell every two seconds, or 25MW per year in three shifts. At production volumes of a few MW per year using $4/wafer cells, SEA will be able to manufacture populated tracking arrays for $1-2/W, well below the current $3-4/W cost of mounted one-sun

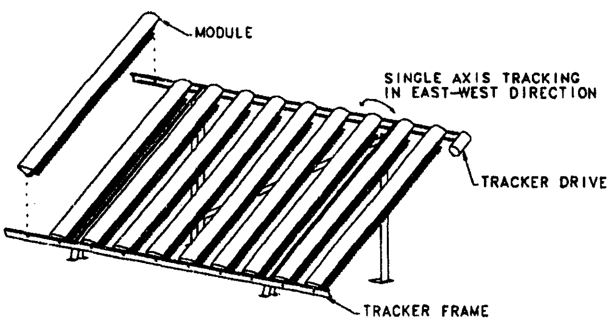

Fig. 2 - SEA's One-Axis Tracking Array

collectors. SEA's tracking structure is minimal, aided by the fact it tracks only in one-axis. (Fig. 2) The line-focus lens is designed to accept sunlight in the annual declination range of ±25°. SEA is pursuing an extruded lens design, which if successful will be very low cost with acceptable efficiency (up to 84%), and Sandia has funded and tested a prototype 3M Lensfilm® design which is more expensive but higher efficiency (over 90%). Perhaps the most important feature is that the 10X module is designed to use one-sun cells. Thus it can leverage the one-sun industry production volume and take advantage of the cell cost reductions being achieved by the one-sun industry. SEA currently has a contract with the Sacramento Municipal Utility District (SMUD) to deliver a 48-kW system this year. Siemens Solar is providing the cells which are cut three per wafer.

3.3 AMONIX 260X Point-Focus System

EPRI sponsored an integrated receiver backplane module design that is now undergoing testing at Georgia Power's Shenandoah Environment & Education Center test site in Newnan, GA. The cell supplier, AMONIX, has done an excellent job fabricating a high efficiency cell that it can produce at a number of available semiconductor plants. AMONIX reports it has good control of its cell production processes and is able to consistently produce cells in the 23 to 26.5% peak efficiency range, with lot averages of 25% at 250 suns. By using available semiconductor fabrication capacity, AMONIX can purchase just the facility time it needs and avoid the capital and overhead of its own cell facility. The company estimates there is currently 250MW/yr of idle semiconductor plant capacity in the United States.

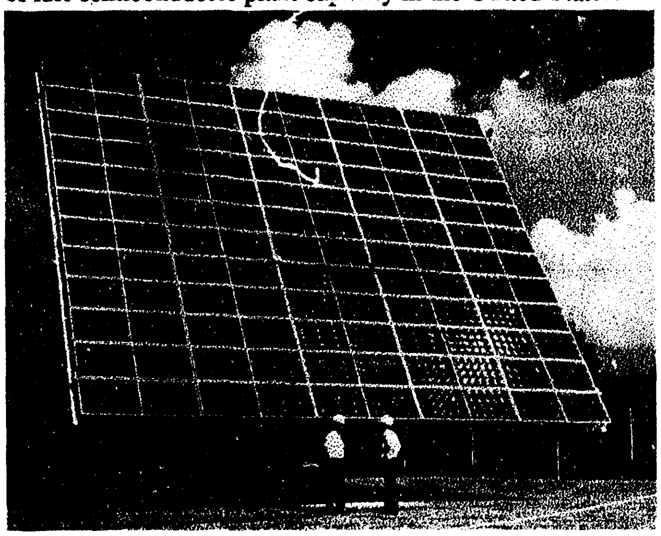

Fig. 3 - EPRI/AMONIX 260X Tracking Array

AMONIX recently took over responsibility for the full system integration and is teaming with Fresnel Optics on the lens and with Scientific Analysis, Inc. on the tracker development. In the last few months AMONIX has made significant improvement in the integrated receiver backplane design and says it has solved the soldering process issues. Its tests show the backplane can pass thermal and humidity/

freeze cycling. By using high-volume printed circuit board production technology, the design drastically reduces assembly cost associated with the interconnect and heat sink components. The module operates at 260X using a high-efficiency (88%) 18-cm lens in a parquet made by Fresnel Optics. In outdoor tests AMONIX is measuring performances that correspond to a 22% peak module efficiency. EPRI's 20-kW tracking structure being tested at the Shenandoah test site (Fig. 3) eliminates the module housing. Instead the lens and backplanes are field-assembled to the structure. AMONIX is targeting the utility market and plans to begin system level testing with selected utilities soon.

3.4 Alpha Solarco System

Alpha Solarco (AS), a participant in the CI Program, recently retrofitted its 15-kW, 125 sq. m array in Pahrump, NV (Fig. 4) with 100 second-generation 500X point-focus collectors. [11,12] It identified a new glass for its refractive secondary optical elements (SOEs) which would not solarize, or turn color, under ultraviolet light. It also learned how to manufacture SOEs to eliminate cords, or striations of variable refractive index that could affect optical performance. Considerable effort was spent to identify an adhesive processes to bond the SOE to the cell and to bond the heat spreader to the housing that would survive Sandia's environmental cycle tests. Four-cell backplane sections were successfully thermal and humidity/freeze cycled by Sandia.

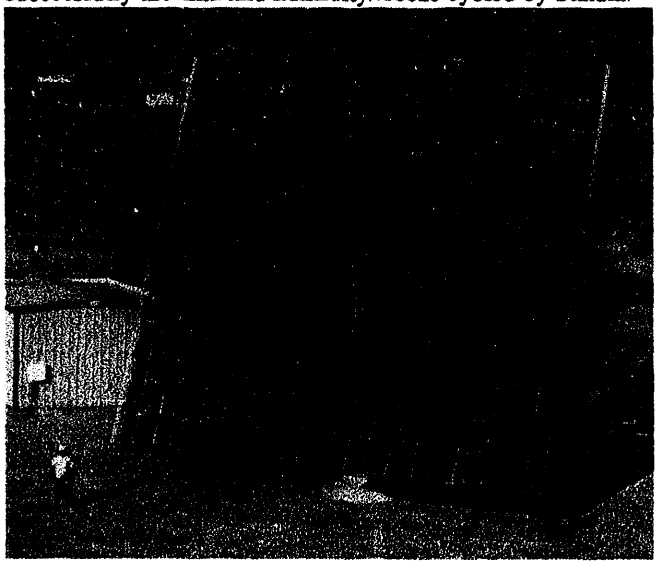

Fig. 4 - Alpha Solarco's 15-kW Array in Pahrump, NV

Alpha Solarco improved its lens/housing sealing approach to eliminate water entry. Currently AS is completing a 2MW/yr production facility in the town of Qinhuangdao, China as part of a joint venture in a program with a Chinese firm. It plans to begin development of a next-generation module based on Sandia's Concept-90 technology. [13]

3.5 Other Concentrator Manufacturers

Solar Kinetics, Inc. (SKI) developed a 280X point-focus concentrator module under the CI Program, several versions of which were tested at Sandia. The status of SKI's PV program is uncertain following cancellation of the CI Program. Midway Laboratories is selling Powersource™ point-focus collectors mounted on a tracker sold by Array Technologies (formerly Wattsun). Midway uses the same 3M lens used by Alpha Solarco, a glass SOE, and cells made by Astropower at a concentration ratio of 150X. Sun Energy Development, Inc. (SEDI, formerly AESI) is developing a 12.5kW turntable array design of 300X point-focus collectors. Each collector contains eighteen ASEC cells having a 1-cm diameter active area, glass SOE's and a 3x6 element Fresnel lens parquet.

4. CONCLUSIONS

Photovoltaic concentrators are in the transition phase between being a developing technology and a commercial product. Recent design advances have been directed at improving collector manufacturability, and several medium-sized (50-100kW) installations have been funded by utilities. Designs spanning the range from low to high concentration are represented. With their potential for lower cost than current photovoltaic systems and rapid production scale-up with a minimal capital investment, concentrators offer the potential to expand existing markets and to open new markets to renewable energy systems.

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TABLE 1
CONCENTRATOR COLLECTOR ARRAY DESCRIPTIONS

Manufacturer Contact/Phone	Focus/ Concentration	Potential Cell Source	Aperture (mxm, m2) (% active)	Cells/Mod. Arrange.	Lens Element (cmxcm)	Lens to Cell (cm)	Tracker	Module Weight kg, kg/m²	Heat Exchanger	Operating Cell Temp. (3 m/s wind 20°C amb. 880 W/m²)	Efficiency: Lens, SOE	Efficiency: Collector (25C cell)	Efficiency: Collector (@ op. temp)	Avg. Operating Values (20°C amb, 880 W/m²) I_{max}	V_{max}	P_{max}
ENTECH DFW Airport, TX Mark O'Neill 214-456-0900	Line Focus 21X geom. 16-19 suns	Solarex, BP Solar, Siemens, Deutsche Aero.	0.85x3.66 3.1 m² 100%	37 1x37	NA	72.6 peak 50.6 rim	Tilt/Roll 223 m² Sunline 6.2 m²	100 kg 32 kg/m²	aluminum extrusion, finned	45-55°C	89.5%, NA	16% (18% cell) 18%* (20% cell)	13% (18% cell) 14.5%* (20% cell)	21A 23A*	17V 17V	360W 395W*
SEA Corp. Santa Clara, CA Neil Kaminar 408-986-9231	Line Focus 10X geom. 6-8 suns	Siemens	0.254x 3.05 0.77 m² 100%	36 1x36	NA	30.4 peak 24.9 rim	1-axis polar 9.24 m²	5.5 kg 7 kg/m²	aluminum stamped, anodized 0.8mm	45-50°C	85%, NA	14.0%* (16.5% cell) 15.3%* (18% cell)	12.8%* (16.5% cell) 14.0%* (18% cell)	4.8A* 5.3A*	18V* 18V*	87W* 95W*
AMONIX Torrance, CA Vahan Garboushian 310-325-8091	Point Focus 261X geom. 190-220 suns	AMONIX	0.178x0.178 0.759 m² 100%	24 4x6	17.8x17.8 (7"x7")	53.0	Az/El 127.5 m²	~11 kg ~15 kg/m² (sidewalls are part of array)	aluminum backplane sheet, 2 mm	65°C	88%† 99%	22%† (25% cell)	20.0%† (25% cell)	17.3A†	7.7V†	133W†
Alpha Solarco Cincinnati, OH Don Carroll 513-771-1690	Point Focus 492X geom. 330-400 suns	ASEC, Spectrolab	0.46x2.83 1.295 m² 96.8%	24 2x12	22.9x22.9 (9"x9")	30.4	Az/El 125 m²	26 kg 21 kg/m²	aluminum backplane sheet, 1.5mm	60-70°C	85%, 92-96%*	12.5%‡ (18% cell) 17%* (22% cell)	10.4%‡ (18% cell) 15%* (22% cell)	9.5A‡ 13A*	12.7V‡ 12.7V	120W‡ 165W*
Solar Kinetics Dallas, TX Gus Hutchison 214-556-2376	Point Focus 282X geom. 200-240 suns	ASEC, Spectrolab, SunPower	0.346x2.23 0.77 m² 93.0%	24 2x12	17.3x17.3 (6.81"x6.81")	25.4	Az/El 15.4 m² or 77 m²	14.7 kg 19 kg/m²	aluminum backplane sheet, 1mm	60°C	85%, 98%*	14% (18% cell) 17%* (22% cell)	12.3% (18% cell) 15.3%* (22% cell)	5.7A 7.1A*	13.6V 13.6V	77W 96W*

*= estimated † = measured by AMONIX ‡ = measured by SW Technology Development Institute

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