Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry

Sarah Kurtz

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5200-43208
Revised November 2012

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry

Sarah Kurtz

Prepared under Task No. PVA7.4401

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5200-43208
Revised November 2012

Contract No. DE-AC36-08GO28308

NOTICE

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry

Introductory Note

This report attempts to summarize the status of the concentrating photovoltaic (CPV) industry and to identify problems that may be encountered as the industry matures, with the ultimate goal of increasing the growth rate of the CPV industry. This report strives to guide industry investments as well as to help set research agendas for the National Renewable Energy Laboratory (NREL) and other R&D organizations.

Recent progress in the CPV industry is impressive, and has recently drawn more attention from the mainstream PV community. Specific examples are summarized in the report. If you have suggestions about this report, especially to update the tables to show your company's latest installations or add your company's name, please e-mail Sarah.Kurtz@nrel.gov.

Executive Summary of Recent Changes to the CPV Industry

The high-concentration PV industry has made great strides in the last year, including:

- After installing MW-size fields in 2010, led by an Amonix 30-MW (AC) field in Colorado, the CPV industry installed more than 40 MW in 2011 and may exceed 100 MW in 2012, despite the oversupply of the PV market.
- A 43.5% cell (GaInP/GaAs/GaInNAs(Sb)) from Solar Junction is the current world record with inverted metamorphic cells close behind with 42.6% and 42.4% from NREL and Emcore, respectively. Semprius has announced a 33.9% efficiency for a module made with Solar Junction's cells.
- A new trend in the industry toward standardization could reduce costs: while the main CPV companies have carefully engineered proprietary products, companies servicing the supply chain are beginning to offer off-the-shelf optics and testing equipment. This sort of standardization is known to reduce the time and cost of bringing a new product to market, potentially helping the industry to be more competitive if prices are reduced for all companies. However, a key feature of the CPV industry is the wide variety of designs being pursued by the various companies. The companies must continue to innovate even while some parts of the supply chain become standardized.
- Dozens of companies are still working on developing products or participating in the supply chain despite the ongoing industry-wide shakeout. There is a small increase in the fraction of the community exploring reflective approaches.
- Version 40 of the Solar cell efficiency tables published by Progress in Photovoltaics includes a 33.5% efficiency for a 1 m^2 Amonix module, measured at 850 W/m^2 direct irradiance and 20°C ambient.

Si-based CPV approaches are also making significant strides:

- Solaria, SunPower, Skyline, and others could show dramatic growth in coming years.
- Dozens of companies are working on developing products or participating in the supply chain.

The Promise of CPV

Today's photovoltaic (PV) industry is growing into significance, now providing ~2% of the electricity in Spain and Germany. The character of the industry is changing with dramatic reduction in silicon module costs in 2011 and signs of saturation of growth of some markets. Reduced enthusiasm for large incentives is slowly shifting the primary market away from countries like Germany and Spain. In some cases, the low module costs are enabling markets that are cost effective (because of lots of sunshine and relatively high conventional electricity prices) without incentives. While the module oversupply is causing a painful shakeout among manufacturers, the associated shift of the market to non-incentivized markets may be helpful in the long run for CPV companies because of a tendency to shift the market toward sunny locations where CPV systems perform their best. Additionally, as module costs drop to the point where balance of system costs have become more important, some segments of the market are beginning to place a higher value on efficiency. This is challenging the thin-film companies to at least match the efficiency of similarly priced silicon modules or further reduce their prices. The allure of demonstrated CPV module efficiency > 30% with the possibility of reaching 40% module efficiency is successfully enticing investment into CPV companies and interest from potentially long-term customers, though at a far reduced rate than previously. Also, the relatively low capital investment needed for a CPV factory makes investment in CPV manufacturing a lower risk than for some other types of PV; the capital investment risk for CPV tends to be distributed between the cell, lens, tracker, and other suppliers and is reduced overall because these investments may be diverted to other products.

CPV approaches vary widely according to the type of cells used, the concentration ratio, type of optics (refractive or reflective), and the geometry. For this report, we have chosen to treat the types of systems in two parts as described in Table 1. Part I discusses CPV using multijunction (GaAs-based) concentrator cells, which, because of their high cost, require concentration ratios higher than ~400X. Part II discusses medium-concentration systems (typically 10X–20X, but with some as low as 2X) that require silicon or other types of concentrator cells; a wide range of approaches is included. Table 1 includes a description of Part III, but this discussion has been discontinued because interest in this approach has decreased. Appendix A summarizes a cost evaluation of all technologies.

Table 1. Description of Classes of CPV Treated in Parts I–III of This Report

Part	Class of CPV	Typical Concentration Ratio	Type of Converter
I	High-concentration, MJ cells	>400X	Multijunction
II	Medium-concentration, cells	~3X–100X	Silicon or other cells
III	Enhanced concentration, modules	<3X	Silicon modules

The **value of CPV within the PV R&D and investment portfolio** can be summarized as:

- Lower capital investment because of the reduced use of semiconductor material compared with flat-plate silicon; this reduces risk for the investor and allows more rapid adjustment of plans based on changing markets.
- High energy yield (kWh/installed kW) associated with the use of tracking and small temperature coefficients; in areas with high direct-normal irradiance, this can be a significant effect, providing lower cost of electricity even for products with higher $/W cost. If shading is minimized, the output may also provide a better match to the load profile than fixed PV.

- Higher efficiency, allowing smaller module area; in some cases, CPV requires less than half the module area to deliver the same power (note that this may not translate to higher energy for a given field if the systems are widely spaced to reduce shading).
- Lower product costs are being demonstrated because of a reduced use of semiconductor material and because of a potentially steeper learning curve.
- Potential for reduced installation costs because of the high efficiency of modules.
- Qualitatively different approach that complements low-efficiency approaches and contributes to a strong technology portfolio for solar; just as there is a battery for every application, CPV may provide a different solution that is especially useful for (for example) applications that are hot and sunny.
- Low environmental impact for pedestal-mounted systems.

CPV joins flat-plate PV in providing these benefits:

- Renewable electricity source with a cost that already competes with conventional electricity sources in some locations
- Modular: can be installed in sizes ranging from kilowatts to multiple megawatts
- Production profile that is fairly predictable and is a relatively good match to the load profile
- Low maintenance
- Low water use
- Can be installed with minimal environmental impact, sometimes in configurations that allow dual use of the land
- Low carbon intensity and energy payback that can be less than a year.[1]

These will be discussed in greater detail throughout this report.

Part I. High-Concentration CPV Using High-Efficiency, Multijunction Solar Cells

Concentrator cells have achieved increasingly impressive efficiencies, inspiring interest in the high-efficiency, high-concentration CPV (HCPV) approach. There are currently seven multijunction cell architectures with reported efficiencies in the 40% range (Table 2). The exact structures could be further differentiated within each of these architectures. The current record efficiency is 43.5% by Solar Junction[2]. This cell uses a dilute nitride alloy for the lowest junction and is grown by molecular beam epitaxy. NREL[3] and Emcore[4] have demonstrated inverted metamorphic, 3-junction cells with efficiencies of 42.6% and 42.4%, respectively. Spire achieved 42.3% [5] efficiency with a bi-facial approach (GaInP/GaAs on the front and GaInAs on the back of a GaAs wafer). Other structures and measured efficiencies[6-10] are tabulated in Table 2. A historical summary of champion cell efficiencies is shown in Fig. 1. Multijunction concentrator cells have achieved much higher efficiencies than any other approach. This is not surprising for two reasons: (1) the highest theoretical efficiencies may be achieved if multiple semiconductor materials (with a range of bandgaps) are chosen to match the spectral distribution of the sun, and (2) the compound semiconductors used in these cells are mostly direct-gap materials and can be grown with near-perfect quality in mass production. The multijunction approach has been described extensively in the literature.[6-8,11-20]

Table 2. Summary of Champion Efficiencies for Multijunction Cells

Cell Architecture	Champion Efficiency*	Company	Comments
Dilute nitride	43.5% (NREL) (>43% @ 400–1000 suns)	Solar Junction	The exact structure has not been published, probably GaInP-GaAs dilute nitride, all lattice matched
GaInP/Ga(In)As/GaInAs[3,4]	42.6% @ 327 suns (NREL) (40.9% @ 1093 suns)	NREL	Inverted metamorphic
	42.4% @ 325 suns (NREL) (41% @ 1000 suns)	Emcore	
GaInP-GaAs-wafer-GaInAs[5]	42.3% @ 406 suns (NREL)	Spire	Requires epi growth lattice matched on front and mismatched on back of GaAs wafer
GaInP-Ga(In)As-Ge[6]	41.6% @ 364 suns (NREL)	Spectrolab	Commercially available; lattice matched
GaInP-GaInAs-Ge[7]	41.1% @ 454 suns (Fraunhofer ISE)	Fraunhofer ISE	Mismatched; similar to design sold by Spectrolab
GaInP-GaInAsQD-Ge[10]	~40%	Cyrium	Uses quantum dots in middle junction
GaInP-GaInAsQW-Ge	~40%	Quantasol/JDSU	Uses quantum wells in middle junction

*Efficiencies were measured at the indicated accredited test laboratory.

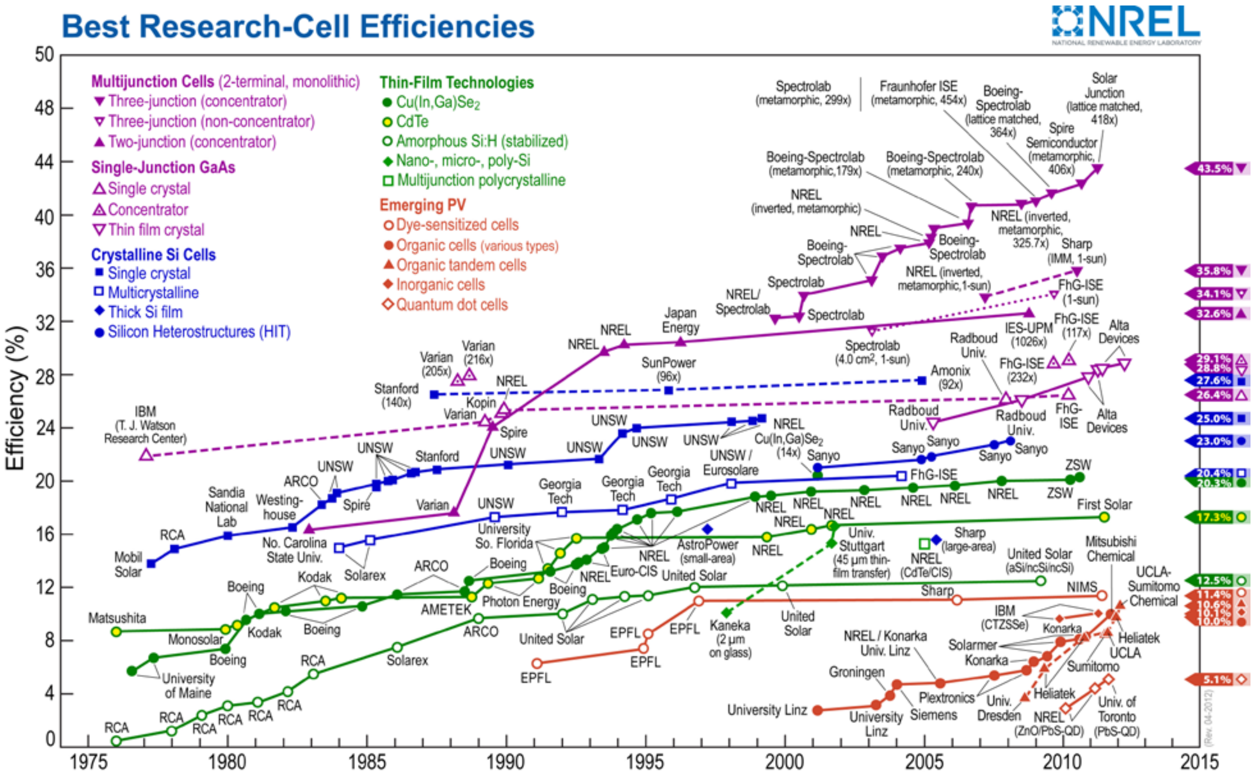

Figure 1. Historical summary of champion cell efficiencies for various PV technologies. The highest efficiencies have been achieved for multijunction solar cells; these efficiencies are still increasing each year. Multijunction cell efficiencies have the potential to approach 50% in the coming years.

When compared with solar thermal approaches, CPV provides a qualitatively different approach, typically with lower water usage and greater flexibility in size of installation, but with greater sensitivity to cloud transients and without storage. The tracking used for CPV also implies relatively higher electricity production per installed kilowatt, compared with fixed flat plate (see below).

Ten years ago, there was little commercial interest in CPV for the following reasons:

- The PV market was dominated by rooftop applications, whereas most CPV products are better suited to solar fields.
- The champion concentrator cell was only ~35% efficient, compared with ~43% today.
- The total size of the industry was less than one-tenth of what it is today, making near-term, high-volume CPV deployment unlikely (i.e., CPV achieves ultralow cost only when the volume of manufacturing is large).

In the last 10 years, the solar industry has grown exponentially, doubling about every two years, and the CPV industry has grown rapidly, with dozens of companies developing new products. Cumulative investment in CPV is >$1 billion. Solar fields, which often use tracked systems, are becoming more common, providing a potentially huge market for CPV products. With the overall PV market growing in the gigawatt range, CPV has an opportunity to enter the market with production of tens or hundreds of megawatts per year. This is significant because CPV is unlikely to achieve low costs when manufacturing at less than tens of megawatts per year. Ten years ago, it would have been difficult for companies to have confidence that they could find markets for the needed volume. The growth of the market, and especially growth of the market segment that uses trackers, is an important contributor to the increased interest in CPV. The potential for CPV industry growth has been widely discussed in recent years.[13-15,21]

The most important current advantage of the CPV approach may be the reduced need for capital investment (scalability). The growth of the silicon PV industry has been challenged by the need for capital investment, especially in silicon purification facilities. By reducing the amount of semiconductor material, the capital investment need is also reduced. Although no CPV companies have demonstrated it, the relative ease of scale-up of CPV is logical and could be a significant advantage in a rapidly growing market. Suncore, Soitec, Amonix, and SolFocus are now positioned to begin a ramp up in production, enabling the needed reduction in cost.

Some cost analyses have predicted that using lenses or mirrors to concentrate the light on small cells can lead to low costs for solar electricity.[14,15] These studies imply that there is a potential for cost-effective implementation of CPV systems even in locations such as Boston, Massachusetts.[15] The cost assumptions published in references [14,15] are out of date, but the fundamental conclusion that CPV has the potential for lower costs still stands.[1] The uncertainty in the cost estimates is greater than the difference between the estimated costs, implying that it is too early to predict which technologies will achieve the lowest costs for each application. In a reexamination of his earlier cost analysis (presented as the opening talk at CPV6), Richard Swanson projected that the HCPV, thin-film PV, and low-concentration PV (LCPV) approaches all have similar costs (within the uncertainty of the analysis). Maintaining a portfolio of technologies increases society's chance of identifying the best options; CPV represents a qualitatively different approach from both silicon and thin-film PV and has a credible path to playing an important role in PV markets, especially in sunny locations. Demonstration that a low-cost structure can be achieved will require development of a reliable CPV product, followed by large-scale deployment. The CPV industry has made dramatic progress toward this in the last five years.

Installations of the first megawatts of products are often subsidized by venture capital. However, when production passes 10 MW (or 100 MW for the best-funded companies), the selling price and actual cost must quickly converge. In 2008, a number of CPV companies installed ~1 MW. Because of the global economic recession, 2009 was a slow year for the CPV industry, but 2010 showed a dramatic surge in growth with a number of 1-MW systems installed. Amonix completed a 30-MW field near Alamosa, Colorado, around the end of 2011 and has already observed > 32 MW generated from the plant. Concentrix was purchased by Soitec and is planning to install 150 MW for San Diego Gas & Electric by 2015, constructing a 200-MW/y manufacturing facility in the San Diego, California area. Suncore has announced plans to build a 1-GW/y factory over the coming years and is already operating the first 200-MW/y line. SolFocus is starting 450 MW of projects in Baja. As the installation volume increases, the cost of CPV products will become increasingly clear. Once these baseline costs are established, some have predicted that the learning curve for CPV costs will be steeper than for flat-plate costs.

CPV, like all PV technologies, is most cost effective for sunny regions with clear skies. The benefit of clear skies is most obvious for CPV systems, because they use the direct beam and do not effectively capture diffuse light. This solar resource is often referred to as direct-normal irradiance (DNI). Although the diffuse light is not effectively captured by CPV, DNI resources are greater than resources available to fixed flat-plate panels in some environments because of the

---

[1] The energy payback of some CPV systems has also been studied.[1] Peharz G and Dimroth F, "Energy Payback Time of the High-concentration PV System FLATCON," *Prog. Photovolt.* 13, 627-734 (2005).

value of tracking; the resource available to flat-plate PV increases if the flat-plate modules are tracked to follow the sun. Large flat-plate PV systems today are often mounted on one-axis trackers. Figure 2 shows the ratio of DNI to global irradiance on a one-axis tracked surface.

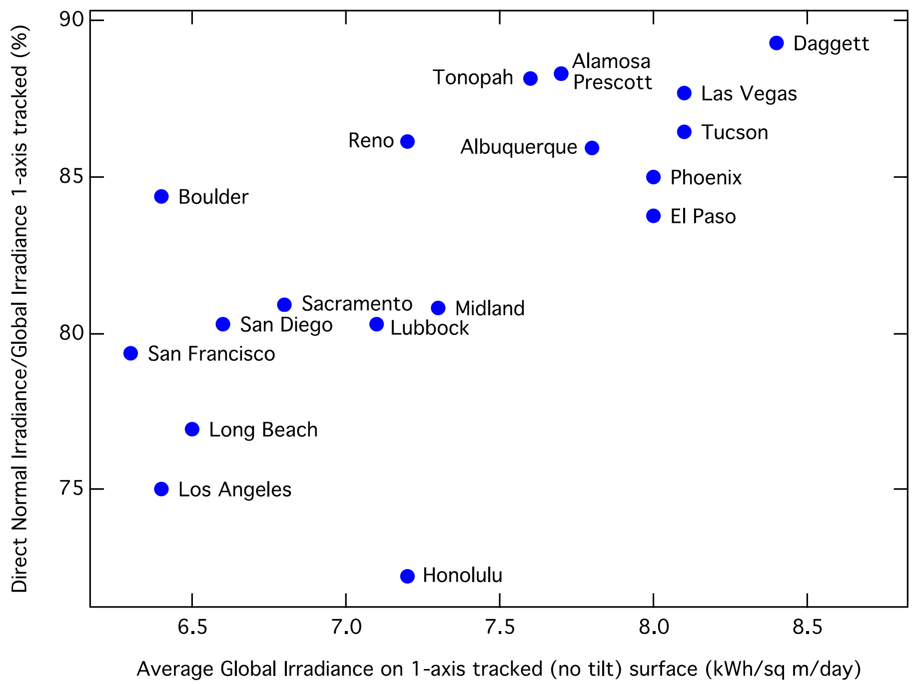

Figure 2. Ratio of DNI to global irradiance on a one-axis-tracked surface (no tilt) as a function of the average daily irradiance. Source of data: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

Current Status of the CPV Industry

The year 2011 may have been a turning point for the CPV industry as Amonix completed the first >10-MW field, and the manufacturing capacity of the CPV industry began to grow in the hundreds of MW/y range for the first time.

Although attention often focuses on cell efficiencies, in recent years, the module and system efficiencies have advanced significantly. Progress in Photovoltaics (DOI: 10.1002/pip.2267) recently reported a measurement of 33.5% efficiency for a ~ 1 m^2 module made by Amonix. The module was measured at 850 W/m^2 direct irradiance relative to an ambient temperature of 20°C, a disadvantage compared with the standard test conditions (of cell temperature of 25°C) typically used for flat-plate PV and being discussed as a standard for CPV as well.

Table 3 provides a list of more than four dozen CPV companies pursuing designs with multijunction cells. Although many of these companies are just getting started, others have had prototypes on sun for multiple years and are ramping up production. Two key trends are seen in 2011: a number of acquisitions, and increased involvement in China. Consistent with the rest of the PV industry in 2012, we can expect a reduction in the number of solvent companies. Past history of the growth of the CPV industry has been documented in previous versions of this report and by PHOTON International articles.[22,23]

Table 3. Summary of Multijunction HCPV Companies

(This information changes rapidly. Companies described in gray appear to have moved away from this approach, but should not be discounted completely.)

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated in 2012*	Manufact. Capacity*
Abengoa Solar	Lens, pedestal	Madrid, Spain			400 kW		
Alitec	Lens, pedestal	Navacchio, Italy					
American CPV		Orange, CA, USA					
Amonix	Lens, pedestal	Torrance, CA, USA	+240 kW (MJ) ~14 MW (Si)	3 MW	40 MW	30 MW	~100 MW/y
Angelantoni Industrie	Lens	Italy					
Arima Ecoenergy	Lens, pedestal	Taipei, Taiwan	330 kW			100 kW	7 MW/y
Becar-Beghelli	Reflective	Italy			prototypes		
Beijing Enterprises Holding Company	Lens, pedestal	China			1 MW		
Boeing (recently sold to SES)	Mirror, Pedestal	Seal Beach, CA, USA					
BSQ Solar		Spain					
CBF Engineering	Refractive. Pivot and roll	Vicentino, Italy					
Chengdu Zsun	Lens, pedestal	Chengdu, Sichuan, China					
Circadian Solar		Coventry, UK					
CompSolar (Compound Solar Technology Co.)	Refractive & reflective designs	Hsinchu Science Park, Taiwan		32 kW			30 MW/y
Concentracion Solar La Mancha	Lens, pedestal	Ciudad Real, Spain					11 MW/y
Concentrating Solar Systems		Bangalow, Australia					
Concentrating Technologies	Small mirror, pedestal	Alabama					
Concentrix Solar (see Soitec)							
Cool Earth Solar	Inflated mirrors	Livermore, CA, USA					
Daido Steel	Lens, pedestal	Nagoya, Japan	30 kW	100 kW			
Delta Electronics	Lens, pedestal	Taiwan					>2 MW/y
Edtek	Mirror, pedestal, hybrid	Kent, WA, USA					

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated in 2012*	Manufact. Capacity*
EMCORE	Lens, tilt & roll	Albuquerque, NM, USA	1 MW, original design		See Suncore		10 MW/y
ENEA	Lens, Si cells, pedestal	Portici, Italy					
Energy Innovations	Lens, each module tracked	Pasadena, CA, USA	13 kW		300 kW		~ 20 MW/y
Enfocus Engineering	Lens, flat pivot	Sunnyvale, CA, USA					
Entech	Lens, pedestal	Keller, TX, USA					
ESSYSTEM	Lens, pedestal (Green & Gold)	Gwangju-city, Korea					
ETH Zurich	Reflective trough; refractive secondary	Zurich, Switzerland					
EverPhoton	Lens, pedestal	Taipei, Taiwan					
Green and Gold Energy	Lens, pedestal	South Australia					150 MW/y**
GreenVolts	Lens, tilt & roll	San Francisco, CA, USA			3.5 MW	5 MW	
Guascor Foton (now Foton HC)	Lens, pedestal	Ortuella, Spain	12 MW (Si-based, Amonix)	100 kW MJ			15 MW/y
Heliocentric	Reflective dish						
Helios Solar CPV	Lens (Green & Gold)	Denver, CO, USA					
Heliotrop	Lens, pedestal	France	small module prototype in 2009	30 kW planned			1 MW/y
Huanyin Electronic		Jiangsu, China					
IBM	Lens	Armonk, NY					
IDHelio	Lens, hybrid PV-thermal	Albi, France					
Isofoton	Lens, pedestal	Malaga, Spain	400 kW Puertollano	30 kW		7 MW	10 MW/y
Jiangsu White Rabbit	Lens	Jiangsu, China					
Menova Energy	Fresnel reflector	Markham, ON, Canada					
Morgan Solar	Lateral photon collection	Toronto, ON, Canada					8 MW/y
MST	Lens, pedestal	Rehovot, Israel		50 kW			Setting up manufacturing
On-sun systems	Lens, novel tracking	Herefordshire, UK					

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated in 2012*	Manufact. Capacity*
OPEL International	Lens, pedestal	Shelton, CT, USA	~400 kW	0.3 MW			3 MW/y
Pirelli Labs	Lens, pedestal	Milan, Italy		7 kW			
Pyron Solar	Lens, carousel	San Diego, CA, USA			20 kW	100 kW	
Rehnu	Dish	Tucson, AZ		0.5 kW		20 kW	
Renovalia		Madrid, Spain				300 kW	
SahajSolar	Lens	Gujarat, India					
Scaled Solar	Dish	San Francisco, CA, USA					
Semprius	Microlens	Durham, NC, USA		small systems	5 kW	20 kW	
Shanghai Solaryouth	Lens	Shanghai, China				2.6 MW	
Shap	Reflective	Rome, Italy					
Sharp	Lens, pedestal	Japan					
Soitec (previously Concentrix)	Lens, pedestal	Freiburg, Germany	0.93 MW	1.57 MW	2.18 MW (2009–2011 numbers from Soitec)	20 MW	70 MW in Freiburg; 140 MW in San Diego
Sol3g	Lens, pedestal	Cerdanyola, Spain					12 MW/y
Solar Systems	Dish, pedestal; developing central receiver (heliostat)	Victoria, Australia	1.3 MW				5 MW/y
SolarTech	Lens, pedestal	Phoenix, AZ, USA					
Solar*Tec AG	Lens, pedestal	Munich, Germany					
SolarTron Energy Systems	Small dish	Nova Scotia, Canada					
Solergy	Glass lens	Piedmont, CA			100 kW		
SolFocus	Small mirror, pedestal	Mountain View, CA, USA	500 kW	2.5 MW	4 MW	10 MW	50 MW/y
Soliant Energy (purchased by EMCORE)	Lens, flat pivot	Pasadena, CA, USA		100 kW			
Soltec Energias Renovables	Reflective	Spain					
Spirox	Lens, pedestal	Hsinchu, Taiwan	6.5 kW				
Square Engineering	Lens, side support	Pune, India					
Sun Synchrony	Miniaturized reflectors	Alameda, CA, USA					

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated in 2012*	Manufact. Capacity*
Suncore Photovoltaic Technology (Sanan Optoelectronics & EMCORE)	Lens, pedestal	Fujian, China		3 MW	2 MW	50 MW	200 MW/y
SunCycle	Rotating lens/mirror	Eindhoven, Netherlands		0.5 kW			Plan product launch in 2011
Sunfish	Central receiver	Denbighshire, UK					
SUNRGI	Lens	Hollywood, CA, USA					
Suntrix	Lens	Shanghai, China		60 kW	250 kW		
Xtreme Energetics	Two designs: central station and rooftop	Livermore, CA, USA					
Zenith Solar	Dish, hybrid	Nes Tziona, Israel	70 kW		250 kW hybrid		
ZettaSun	Lens, internal tracking	Boulder, CO					
Zytech Solar	Reflective	Zaragoza, Spain					
Totals			14 MW (Si) 5.5 MW (MJ)	10 MW	~50 MW	~100 MW	

*Based mostly on public presentations or website announcements/press releases. Note that some companies refrain from posting information about their deployments, so the lack of a number may not mean that they have made no installations.
**Includes capacity of Green and Gold Energy technology through ES System, Energies AC Gava, Square Engineering, Solar Ace, and Zolar Distributors.

Most PV technologies have required years of development before showing success on a large scale. First Solar's rapid expansion was based on years of development work. As the CPV companies transition from the prototyping phase of development to scaling up manufacturing, they will encounter familiar problems. The following discussion reflects the concerns that have been raised by industry participants during discussions related to this study.

Prototype Development

CPV companies are exploring a wide range of CPV approaches. Each has done its own assessment of which designs will give the best performance, lowest cost, and longest reliability. The range of types of designs continues to expand. Primary considerations include:

- Performance: Optical efficiency, cell cooling, and performance losses associated with manufacturing imperfections, soiling, tracking errors, flexing in the wind, thermal expansion/contraction, or wind stow.
- Cost: Use of inexpensive components, ease/automation of assembly.
- Reliability: Degradation of optics, poor performance of tracker or other loss of alignment, loss of adhesion or breakdown of bonds between cell and the optics and heat sink, etc.

Prototype Testing

After designing and assembling the prototypes, the most immediate need of many of the companies is testing. Testing needs may be broken into two parts: the first quantifies the performance and identifies opportunities for improving performance; the second assures that the performance is stable, preferably over decades of use. The initially measured performance is usually lower than is hoped for. Identification of the cause of the performance loss can be complicated.

Some of the types of diagnostics include:

- Low short-circuit current
  - Optical losses (may be caused by soiling of optics, condensation within the module, imperfect optical interfaces, manufacturing imperfections, misalignment)
  - Mismatch of multijunction cell design with observed spectrum. This can be complicated to diagnose because it may vary with time of day and cell alignment. It is best diagnosed with a single lens-cell assembly by monitoring the fill factor throughout a sunny day.[24]
  - Misalignment of cell with optics or poorly designed optics so that some of the light misses the cell, or misalignment of tracker.
- Low open-circuit voltage
  - Poor heat-sink design can be detected quickly by measuring the heat-sink temperature
  - Poor thermal contact between cell and heat sink.
- Low fill factor for string of cells
  - This can result from inconsistencies in the alignment or from inconsistent component quality. The acceptance angle (measured at the maximum power point) of a single-lens cell assembly should be similar to that of a string of cells. If the acceptance angle for the string is larger, or if the operating temperature of the cells is not the same for all cells, there may be some variation in the alignment. A quick way to identify variations is to look for bypass diodes that are activated, and especially to see if different bypass diodes are activated as the alignment is changed or the spectrum varied.
  - Variability of the optical transmission or the solar cell performance may also cause lower fill factors. Again, looking for the activated bypass diodes will help to identify the problematic lenses or cells.
  - If the fill factor is low because of a series-resistance problem, this can quickly be distinguished from the above problems. Poor electrical connections, inappropriate cell design, or non-uniform illumination of the cells are common causes.

The above list is not meant to be an exhaustive guide to identifying causes of poor performance, but gives a sense of the many ways that the performance can be compromised.

There is concern that failures in the field for even a single company could discredit the entire CPV industry. Sharing observations of failures can facilitate early detection of failures, reducing the probability of premature deployment, but companies are often reluctant to do so. In 2008, the Accelerated Aging Workshop, which was sponsored and organized by the U.S. Department of Energy (DOE) and the national laboratories, included a breakout session for the CPV industry (see p. 46). It was suggested that the national laboratories should place the highest priority on the cells, bonding, and packaging, although a myriad of other concerns were also expressed.[25] The Photovoltaic Module Reliability Workshops in Feb. 2010, Feb. 2011, and Feb. 2012 also included break-out sessions on CPV that discussed spectral issues, quantitative predictions using the weather to predict lifetime of the cell attachment, revisions of the thermal cycling qualification test, etc.

Standards

Some testing standards are available, but the standards for CPV are behind those for flat-plate PV. Table 4 summarizes a few of the key IEC standards for PV and tabulates those that have CPV versions. Clearly, the CPV industry and customers must work together to establish CPV versions of the standards to form the foundation for the emerging CPV industry.

Table 4. Summary of Standards

Silicon PV Standard	Corresponding CPV Standard
IEC 60904 – Photovoltaic devices. Part 1: Measurement of photovoltaic current-voltage characteristics. Part 2: Requirements for reference solar devices. Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method. Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device. Part 8: Measurement of spectral response of a photovoltaic (PV) device. Part 9: Solar simulator performance requirements. Part 10: Methods of linearity measurement.	Each of these building blocks is being addressed as the more complex standards are developed (see below).
IEC 61215 – Crystalline silicon terrestrial PV modules. Design qualification and type approval.	IEC 62108 – CPV modules and assemblies. Design qualification and type approval.
IEC 61853 – Photovoltaic (PV) module performance testing and energy rating. Part 1: Irradiance and temperature performance measurements and power rating (Committee draft is approved).	Draft under development: IEC 62670. Power rating for CPV. In addition, technical specifications for an acceptance test and for use of an average performance ratio to define an energy rating.
IEC 61730 – PV module safety qualification	Draft under development: IEC 62688
UL 1703 – Flat-plate photovoltaic modules and panels	Draft under development: UL 8703 – Concentrator photovoltaic modules and assemblies; STP formed in late 2009.

Manufacturing Scale-Up and Retesting

After reliable prototypes have been demonstrated, companies must automate the manufacturing and then retest the reliability to ensure that subtle changes in the design do not negatively impact reliability. Some of the companies have planned for high-volume manufacturing from the start, but all companies must include this step in their development plans at some stage.

The details of high-volume manufacturing will be key toward cost reduction. Automated manufacturing of complete systems under a single roof will take substantial effort to set up, but may show significant advantages in the long run. Most companies have found that preassembly can greatly reduce installation costs.

Some recent advances include:

- In early 2012, Amonix completed a 30-MW (AC) field in Alamosa, Colorado.
- Suncore is now operating a 200-MW/y manufacturing plant in Huainan, China.
- Soitec broke ground on a 200-MW/y manufacturing plant in San Diego, California.

Performance (Power) Rating

A power rating is traditionally used as a nameplate rating and is useful for sizing of inverters and other system parts as well as for verification of system delivery under some contracts. The IEC Technical Committee 82 Working Group 7 has defined:

Standard Concentrator Test Conditions:
• 1000 W/m^2 irradiance
• 25°C cell temperature

Standard Concentrator Operating Conditions
• 900 W/m^2 direct-normal irradiance
• 20°C ambient temperature.

Efforts are underway to define the procedure for measuring the power rating and also for an energy rating standard.

The National Solar Radiation Data Base and other solar resource data that include the direct resource usually include the circumsolar resource, which most HCPV systems cannot use. The importance of this effect has not been quantified, although anecdotal information implies that it can be significant in locations with pollution or other sources of haze that cause small-angle scattering.

Cell Supply

A significant number of companies have demonstrated the capability for epitaxial (single-crystal) growth of multijunction cells. They are summarized in Table 5.

Table 5. Summary of Companies with Capability for Epitaxial Growth of Multijunction Cells

Company Name/Web Link	Location	Comment
Arima	Taipei, Taiwan	Reported achieving >40% cells.
Azur Space (RWE)	Heilbronn, Germany	Commercial product ~40%; champion 41.2%.[26]
CESI	Milano, Italy	Datasheet reports 38% efficiency.
Compound Solar Technology	Hsinchu Science Park, Taiwan	Website shows I-V curve with 33.4% efficiency.
Cyrium	Ottawa, Canada	Datasheet describes typical >39% cells.
EMCORE	Albuquerque, NM, USA	Datasheet describes typical 39% cells and receivers at ~500 suns.
Epistar	Hsinchu, Taiwan	Multijunction cells are in development.
IQE	Cardiff, Wales, UK	Has purchased stake in Solar Junction (see below).
JDSU	Milpitas, CA, USA	Has purchased Quantasol (see below)
Microlink Devices	Niles, IL, USA	Multijunction cells removed from substrate in development
Quantasol	Kingston upon Thames, Surrey, UK	Multijunction cells with quantum wells, claim ~40%; Purchased by JDSU.
RFMD	Greensboro, NC, USA	Multijunction cells in development
Sharp	Japan	Has demonstrated high efficiencies, but has not indicated plans for commercialization outside of supplying cells for its own CPV systems.
Solar Junction	San Jose, CA, USA	Announced 43.5%, confirmed by NREL and Fraunhofer ISE. Setting up manufacturing under IQE
Spectrolab	Sylmar, CA, USA	Is selling 40% product. Shipped ~35 MW in 2009, and ~100 MW in 2010 (@500X).
Spire (Bandwidth)	Boston, MA, USA	Announced 42.3% efficiency, NREL confirmed; Sold to Masimo Semiconductor
VPEC	Pingjen City, Taiwan	Multijunction cells in development

Recent developments in the cell industry:

- Solar Junction set a record efficiency of 43.5% in 2011 and reports shipping 42%-efficient cells in 2012.
- A primary trend in 2011 and 2012 is toward acquisitions, reducing the total number of cell companies.
- At CPV8 (April 2012), NREL and Emcore announced 42.6% and 42.4% efficiencies, respectively, for the inverted metamorphic cell.

A quick review of the companies in Table 5 implies that the supply of cells could be expanded quickly. The entry of large companies such as JDSU could bring the experience of the larger industry for making cheaper cells. Essentially all of the companies in Table 5 can fabricate cells with efficiencies greater than 30%; some have demonstrated efficiencies approaching or exceeding 40%. Although all of the companies on this list have some capability for growing multijunction cells, not all of them have demonstrated a capability for high-yield manufacturing. The most immediate concern about the concentrator cells expressed by CPV representatives is whether the reliability testing is adequate.

The injection of forward-bias current during thermal cycling is observed to damage some *cells*. Two studies presented at CPV-7 concluded that the cause of the damage could not be linked to defects in the cells, and that the cell failures appear to be caused by voids under the busbars leading to thermal runaway in the cells.[27]

The current cell production capacity exceeds the CPV installation rate but that gap narrowed with the increased manufacturing volume in 2011 and 2012. Expansion of the manufacturing volumes should allow reduction in cost because of economies of scale.

Cell Efficiencies

Cell efficiencies have been increasing at a rate of about 0.5% to 1% per year in recent years. See Table 2 and Fig. 1 for summaries of champion efficiencies. Efficiencies are expected to continue to increase toward 45%–50%. The high cell efficiencies allow the optics to be more productive, so most companies desire cells with the highest efficiencies.

Substrate Supply

The manufacture of multijunction space cells in the last decade has been based primarily on germanium wafers supplied by a single company: Umicore (Brussels, Belgium). Now, multiple companies are developing a germanium wafer capability, including AXT (Fremont, California); Sylarus (St. George, Utah); and PBT (Zurich, Switzerland). Umicore has completed a plant in Quapaw, Oklahoma, to help service this growing market. In addition, some approaches (such as Semprius' use of Solar Junction cells or the inverted method[20] of fabricating the multijunction cells) make possible reuse of the wafers avoiding the need for large quantities of substrates and the flexibility to use either Ge or GaAs substrates. Although it is possible that the industry could be so successful as to create a shortage of wafers, this is not currently on the horizon.

Germanium (Ge) metal is obtained principally as a by-product of zinc refining or coal-burning (recovered from the fly ash). In 2007, Ge suppliers produced about 100 metric tons, most of it in the form of germanium tetrachloride ($GeCl_4$) and germanium dioxide (GeO_2).[28] Canada and China are the world's largest Ge sources, each supplying more than one-third of world production. Mining companies indicate there is a 50-year known reserve at today's consumption rate, and that this reserve does not include vast new reserves available in Africa (especially the Democratic Republic of Congo). The major Ge consumers in 2007 were fiber optics (35%), infrared optics (30%), PET catalysts (15%), and electronics and solar applications (15%).[28]

Wafer-industry experts tell us there is sufficient Ge to support a CPV installation rate of ~4 GW/yr. Industry experts also point out that a significant Ge consumer, PET plastics, is moving aggressively to replace Ge with lower-cost catalysts, and at least two Chinese PET manufacturers have reported using a titanium-based solution.[29] It is significant that the PET catalyst percentage of the Ge market has declined from 31% in 2005 to 15% in 2007.[30] As worldwide Ge production increases and PET demand diminishes, the experts contend that there will be ample Ge available to support even the most optimistic terrestrial III-V CPV market scenarios through 2030 and beyond. Although these numbers are several years old, recent studies reach similar conclusions[31].

Optics

The primary concerns expressed about the optics are related to the reliability. Yellowing or pitting of plastic lenses, the need for washing, etc., are all concerns. Some companies are using glass lenses to avoid the abrasion expected for plastic lenses. The availability of optics has not been a concern. The recent development of off-the-shelf, high-quality optical components could change the way companies approach CPV product development.

Most optical designs include both primary and secondary optics to increase tracking and alignment tolerance, although some companies have chosen to avoid the cost of an optical secondary by carefully maintaining alignment quality and sacrificing a few percent in performance under some circumstances.

For the primary optic, the majority of companies have chosen to use lenses rather than mirrors. In general, the direct-transmission approach simplifies the optical design and facilitates passive cooling, reducing design and maintenance complexity. Historically, companies have favored the use of acrylic in the lenses, with injection molding providing a cost benefit at the highest volumes (embossing provides a cost benefit at lower volumes). There is also strong interest in using glass to reduce abrasion and increase lifetime. Currently, there is increased discussion of the use of silicone-on-glass lenses, which provide the benefit of excellent durability with ease of manufacture, but require some special design to avoid loss of alignment at lower temperatures.[32,33] All-glass lenses are more difficult to manufacture. Additional (beyond abrasion and ease of manufacture) considerations include: quality of manufacture, retention of alignment at all temperatures and humidities, chromatic aberrations (which may be avoided to some extent by using total internal reflection), absorption losses, adhesion (for silicone-on-glass lenses), and sensitivity to UV-induced degradation.

The fraction of companies using reflective designs is relatively small, but reflective designs can have the potential to be lower in cost if they use low-cost reflectors, and the relative number of companies exploring reflective designs has increased in the last couple of years. If the control of the shape of the mirror is near perfect, reflective designs reach higher concentrations than some refractive designs because of the avoidance of chromatic aberrations. Thermal management designs associated with reflective optics are more likely to use active cooling. (Active cooling has the disadvantage of added maintenance and parasitic power consumption, but may have the advantage of being able to keep the cells cooler than passive designs on hot days.) Creativity can help to reduce shading losses associated with placement of the cooling systems.

The secondary optics are sometimes exposed to ~100 W/cm^2 intensities, implying that any absorption can cause large increases in temperature (in some cases vaporizing polymeric materials). Even if the secondary optic is 100% transparent, it may run hot because of being attached to the cell, which may operate 40°C or more above ambient temperature. The secondary optics must be able to withstand both high temperatures and the potential stress from differential expansion if the temperature is non-uniform. If the secondary optic becomes soiled, the associated heating can lead to catastrophic failure. The secondary should also be designed to maintain the highest possible optical efficiency, even when the system is misaligned for some reason. Reflective secondaries that redirect off-target light may have no impact on the optical efficiency as long as the system alignment is maintained. Refractive secondaries typically cause a reduction in optical efficiency by a few percent, but usually increase the energy production enough to justify their use if their cost is acceptable. The expected UV stress on secondaries is especially problematic for designs using reflective primary optics. Most lenses are engineered to absorb UV strongly, preventing these harmful rays from reaching the optical secondaries and cells.

Trackers

Trackers require periodic maintenance, and glitches in performance or outright mechanical failure can decrease performance and increase maintenance costs substantially. The Institute of Concentration Photovoltaics (ISFOC) reports that trackers account for >50% of observed problems in the field.[34]

Some companies expressed the desire for standardization and the associated reduced cost. As flat-plate companies have increased their use of trackers, the number of companies supplying trackers has also increased. The IEC technical committee 82, working group 7 is working to specify the attributes of a tracker, how to measure these, and how to detect design problems.

Trackers are also in demand for flat-plate and solar-thermal applications. In recent years, there is evidence that the community's investment in trackers is improving performance and reducing costs. An interesting trend is a small movement toward smaller trackers, which leverage designs for concentrating solar thermal heliostats. An example is Energy Innovations' 29% module that is designed for mounting on small trackers, leveraging heliostat experience from eSolar, a sister company.

Power Electronics

As DC-DC converters have become cheaper, more efficient, and with excellent reliability (e.g., DC-DC converters are used in laptops to convert the varying battery voltage to the voltage needed to run the computer), interest has grown in using them for PV modules. For CPV, there is special benefit to using them for two reasons. (1) It can be a challenge to create a dish with uniform irradiation on a central receiver; use of DC-DC converters could allow the image on the central receiver to be non-uniform without substantial loss of performance. (2) Whereas tracked flat-plate systems can use back tracking to avoid shading early and late in the day, HCPV systems must be 2-axis tracked and, thus, must experience shading when the sun is low in the sky. Use of DC-DC converters could avoid dramatic losses associated with this shading, so could enable a field with more closely spaced CPV pedestals.

Cell Bonding and Encapsulation

The bonds between the cell and heat sink and between the cell and the optics (or air) can be problematic. Many of the companies report degradation of these bonds during stress testing and have had to study multiple designs. One study reported subjecting five encapsulant materials to the equivalent of 20 years of UV exposure, and found only one that did not degrade.[35] Optical coatings may, for example, darken over time or trap moisture and accelerate degradation. A wormlike bubble has been found at the interface between the cell and the secondary optics. The cell suppliers and system integrators need to work together to understand potential issues here, but concerns over competition and protecting proprietary processes inhibit the necessary disclosure and cooperation.

Weathering from sunlight is well known; when the sunlight is concentrated 1000 times, or even higher locally, the associated weathering problems can be severe, although much of the UV light may be absorbed by the optics before reaching a sensitive component.[36] Accelerated testing of the effect of concentrated light is especially challenging, though some companies have been developing the tools to do this testing[37].

Cell Assembly/Receiver Fabrication

The solar cells must be attached to a heat sink and electrical connections completed. In most cases, the resulting piece is called a receiver or cell assembly. Most of the cell companies have developed a couple of standard concentrator cell assembly/receiver designs. Ideally, cell assemblies can be tailored to match each CPV optical design. For each design, the assembly equipment must be automated and the final product carefully tested.

The expertise needed to create these cell assemblies is fairly well established in the LED industry, which represents a business opportunity for such companies. It is not yet clear whether it is better for the cell mounting to be done by the cell companies or another company in the supply chain.

Enclosure Design

The system enclosure must be designed to avoid dirt burning onto the optics and moisture condensation that can either obscure the optics or "fry" the cells. Although this appears to be a mundane problem, it is quite challenging. If the enclosure is sealed, atmospheric pressure variations can cause the optics to deform like a balloon. If the enclosure does not breathe well, the optics may act as insulation, causing the cells to run hotter.

The companies are experimenting with many approaches to this, including desiccant and active ventilation. One interesting approach is to use material that blocks transmission of liquid water, but allows water vapor to be transported, such as the membranes made by Gore.

All parts of the enclosure, including the attachments for the optics and the cells, must be robust enough to survive transportation, installation, and wind.

Material Availability Limits

Projections of material availability are always complicated by the potential development of new mining techniques driven by increased demand. Nevertheless, raw material costs have been rising lately. Here, we reference a study by Feltrin and Freundlich (Fig. 4).[38] Their use of 200X as the concentrating factor is conservative compared with what most companies are currently pursuing (500X–1200X). The first bar implies a fairly severe limitation regarding the availability of Ge, based on U.S. supplies. Compared with the first bar, the second bar implies 60 times higher availability, this time limited by Ga availability. The third bar in Fig. 4, labeled "EPI Lift-off," is relevant to Semprius' printing approach coupled with Solar Junction cells or with the inverted metamorphic approach[20] with availability of indium as the limiting factor, allowing four times higher production than indicated by the second bar. More studies of this sort are needed to gain confidence in the conclusions, but these data imply that material availability will not prevent the success of CPV.

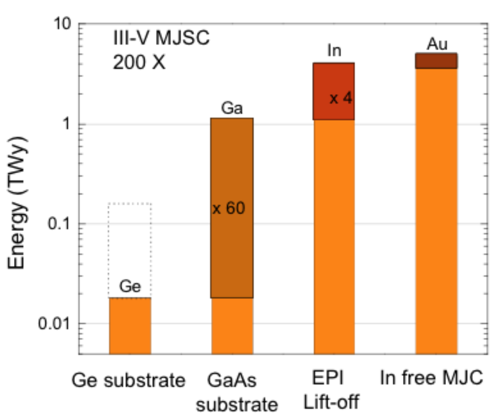

Fig. 4: Potential energy limits imposed to III-V multi-junction cells (200 sun concentrations). The third and fourth columns show the extrapolated potential of this technology if the substrates are ignored.

Figure 4. Material availability study from Ref.[38] (A. Feltrin and A. Freundlich, "Material Challenges for Terawatt Level Deployment of Photovoltaics," *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion*, ©2006 IEEE, Reproduced with permission.) The dotted box includes the supplies they estimated would be available worldwide.

Summary

The use of concentrated sunlight on very small, but highly efficient (~40%) solar cells has the potential to provide cost-effective, large-scale, solar-electricity generation, especially in sunny locations. More than a dozen companies have learned to fabricate multijunction concentrator cells, positioning themselves to respond to the growing demand for these cells. Dozens of companies are developing concentrator photovoltaic systems, and several have already deployed >1 MW in the field. This industry is showing signs of being poised for substantial growth in the next years as the world embraces solar energy.

Part II. Medium-Concentration Approaches Using Silicon or Other Cells

The silicon PV industry has grown dramatically in recent years. The industry is working hard to cut costs for every step of the manufacturing and installation processes. Significant effort has focused on thinning the silicon wafers in order to reduce the usage of silicon material. A complementary approach is to reduce the area of silicon needed by using optics to redirect the light toward smaller cells. This provides the possibility of much more dramatic reduction in the use of silicon and also allows the possibility of decreased cost for the non-silicon costs associated with the cells. (The non-silicon costs can be half of the total cell cost and may actually increase rather than decrease as the silicon cell is thinned). High-efficiency, single-junction GaAs cells made in an inexpensive way could also be attractive. Alta Devices' recent achievement of 29% one-sun efficiency makes these cells quite attractive.

The use of silicon, instead of III-V multijunction, cells leverages the huge investment already made in the silicon supply chain. Although the silicon cells must be able to handle the higher currents, most of the elements of the supply chain are unchanged. This reduces both the development time and cost for new products.

Perhaps the more significant advantage of using the medium-concentration approach is the divorce it brings from the silicon supply chain. In an uncertain, and risk-averse, investment climate, investors are likely to choose approaches that reduce the required capital expenditure and, especially, a capital expenditure that must be made for growth predicted far into the future. The scalability of products depending primarily on glass, metal, and plastic (instead of cells) may enable growth of a silicon-based CPV industry.

Some investors see a medium-concentration, silicon-based product as less risky than HCPV. Using familiar cells and low-accuracy trackers may be perceived as more "bankable" than the high-efficiency, disruptive approach described in Part I. Higher risk translates directly to a need to demonstrate a lower cost in order to interest the investors.

Although the primary semiconductor cost reduction is achieved with even a small concentration of light, a medium concentration allows use of slightly more expensive, but more efficient, cells. Just as efficiency can be leveraging for HCPV, the higher efficiency can be important for silicon-based CPV.

The possibility of increased performance must be balanced with the loss of solar resource that comes from a reduced use of diffuse light. The maximum acceptance angle is a function of the concentration and the index of refraction of the medium.[39] Specifically, for a linear concentration ratio, C, and index of refraction, n, the theoretical maximum acceptance angle, θ, can be found from

$$C = n/(\sin \theta).$$

For point-focus systems, this concentration may be achieved in both dimensions, implying the square of the above concentration may be reached. For fixed systems, a small acceptance angle can dramatically reduce the available resource. For 2-axis tracked systems, and low concentration ratios, the reduction in the available resource may be less than 10%. The maximum acceptance angle that can be achieved theoretically is plotted as a function of the concentration ratio in Fig. 5. Most Si-based CPV systems are able to use the circumsolar solar resource (light that is outside of the direct beam, but within a couple of degrees of the direct beam). The circumsolar resource varies strongly with location, and can be significant in some locations.

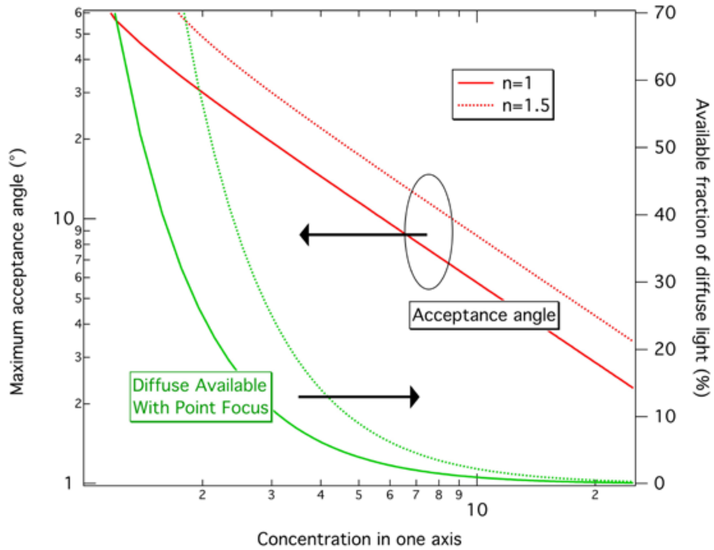

Figure 5. The theoretical maximum for the acceptance angle (red curves; left axis) that can be achieved as a function of linear concentration and the fraction of diffuse light that can be collected theoretically (green curves, right axis) assuming that the diffuse light is isotropic.

Tracking

If a tracker is cost effective for flat-plate modules, chances are that it can also be cost effective for concentrator modules. Thus, the increased use of trackers for flat-plate applications may pave the way for concentrator systems.

A contradictory viewpoint is that trackers will not be used in the future because PV costs are or will be low enough that it may no longer be cost effective to use a tracker. Thus, we conclude that low-cost trackers are likely to be key to the success of low-concentration systems. There is strong evidence that tracker cost is decreasing.

The tracker accuracy requirement for low-concentration systems may be relaxed (compared with those for high-concentration systems), potentially reducing cost, increasing reliability, and increasing energy production.

Current Status – Companies Involved

In terms of the number of companies and total investment, the development of medium-concentration systems currently lags that of high-concentration systems. But the approach has attracted significant interest in recent years as silicon PV companies look for creative ways to continue to reduce cost.

More than a decade ago, BP Solar developed a linear-focus, medium-concentration system using Si cells. Working with the Instituto de Energia Solar within the EUCLIDES project, BP Solar used a reflective trough, first demonstrating a single unit and then scaling up to 480 kW with multiple troughs.[40] Today's companies may learn from the EUCLIDES experience, which suffered from inadequate design testing before scale-up.

The number of companies working on medium-concentration designs has increased significantly in recent years, as shown in Table 6 and elsewhere.[22] The range of approaches extends from the types of systems just described to designs that can function much like flat plate, including holographic and luminescent concentrators. Although in the early developmental stages, many of these companies are making good progress and are receiving substantial public recognition. A number of other companies are not listed in Table 6 at their request. Solaria has certified its low-concentration design to UL1703 and IEC61215. The company estimates that it can achieve a cost that is 40% lower than conventional silicon.

Table 6. Summary of Companies Developing Low- or Medium-Concentration PV Products Using Silicon or Other Cells

(This information changes rapidly. Companies described in gray appear to have moved away from this approach, but should not be discounted completely.)

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated for 2012	Capacity *
Aavid Thermalloy	Refractive, 10X	Concord, NH					
All Optronics	15X	Tucson, AZ					
Anhui Yingtian Renewable Energy	Reflective	Anhui, China	>50 kW				
Absolicon Solar Concentrator	Reflective trough, Si cells, thermal hybrid	Harnosand, Sweden			9 small systems are documen-ted on website (since 2006)		
Banyan Energy	Flat-plate 10X, total internal reflection, Si cells	Berkeley, CA					
Cogenra Solar	Reflective, hybrid PV-thermal	Mountain View, CA		50–100 kW			
Covalent Solar	Luminescent, multiple types of cells	Boston, MA, USA					
CPower	Reflective, 25X–30X (point focus), Si cells	Ferrara, Italy	9 kW				
Entech	Linear Fresnel lens, Si cells; hybrid PV-thermal	Fort Worth, TX, USA					

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated for 2012	Capacity *
Greenfield Solar	Reflective, edge-illuminated Si cells (not systems)	Cleveland, OH, USA					
HyperSolar	Optical coating	Hackensack, NJ, USA					
IDHelio	Lens, 20X, hybrid PV-thermal	Albi, France				1 kW	
KD Solar Co.	Holographic 3X	Kyunggi-Do, Korea					
Maxxun	Luminescent	Eindhoven, Netherlands					
MegaWatt Solar	Reflective, linear, 20X, pedestal	Hillsborough, NC, USA	35 kW				
Netcrystal	Non-tracking, Si cells	San Francisco, CA, USA					
Optoi	Reflective, Si cells	Trento, Italy					
Optony	Thin-film cells	Silicon Valley, CA, USA					
Pacific Solar Tech	Dome-shaped lens, Si cells	Fremont, CA, USA					
Pirelli Labs (CIFE)	Static	Milan, Italy					
Prism Solar Technologies	Holographic, Si cells	Lake Katrine, NY, USA					
Pythagoras Solar	Building integrated	Hakfar Hayarok, Israel					
QD Soleil	Luminescent	Palo Alto, CA					
Silicon CPV	Fresnel (point focus, 120X) Si cells	Essex, UK					
Skyline Solar	Reflective, 14X, Si cells	Mountain View, CA, USA	24 kW	83 kW	?	700 kW	100 MW/y by end of 2011
Solaria	2X–3X, small strips of Si cells	Fremont, CA, USA	20 kW	1.2 MW	>10 MW		40 MW/y
Solaris Synergy	15X linear reflective, Si cells floating on water	Jerusalem, Israel	1 kW				

Company	Type of System	Location	On Sun in 2009*	Installed in 2010*	Installed in 2011*	Estimated for 2012	Capacity *
Solbeam	Tracking optics in flat configuration	Laguna Niguel, CA, USA					
Stellaris	Static, 3X "see-through," Si cells	North Billerica, MA, USA					
SV (Silicon Valley) Solar	Flat-plate dimensions	Sunnyvale, CA, USA					2 MW/y
Sunengy	Fresnel (point focus), Si cells in water	Sydney, Australia					
SunPower	Reflective, 7X, Si cells	San Jose, CA		~24 kW			
Sunseeker Energy	Lens	Schindellegi, Switzerland					
Thales Research	Static, reflective	Severna Park, MD, USA					
Transform Solar	Low X, Sliver cells	Boise, Idaho, USA					
Whitfield Solar	Fresnel lens, ~40X, Si cells	Reading, UK		9 kW			
Zytech Solar	Reflective, Si modules; 4X–150X	Zaragoza, Spain					
Totals			~150 kW	~150 kW	~1 MW		

*Based on public presentations or website announcements/press releases. Note that some companies refrain from posting information about their deployments, so the lack of a number may not mean they have made zero installations.

Cell Supply

Historically, a key challenge of the medium-concentration approach has been obtaining a consistent supply of solar cells that function well under the desired concentration. The primary difference between standard, one-sun solar cells and concentrator cells is the need for a reduced series resistance. In addition, the cells may need to be fabricated in different geometries and may benefit from improved thermal contact with a heat sink. As with the high-concentration approach, there is typically a benefit to purchasing higher-efficiency cells. Buried-groove-contact cells and back-point-contact cells have been of special interest for medium-concentration applications in the past.

Current market conditions provide a surplus of one-sun cells and associated opportunities for finding concentrator cells. The following paragraph is retained for its utility despite the current lack of difficulty in identifying silicon concentrator cells.

SunPower offered off-the-shelf silicon concentrator cells at one time, and now has the capability to make high-efficiency silicon cells appropriate for use anywhere between one and 250 suns. However, SunPower has chosen a vertically integrated business model and is no longer interested in selling silicon cells (either one-sun or concentrator). NaREC (Alex.Cole@NaREC.co.uk) has expressed an interest and willingness in making custom silicon concentrator cells. Alta Devices has set a record efficiency with a GaAs cell at one sun, providing a new opportunity.

The medium-concentration approaches face many of the same challenges as prototype and tracker development and testing, as well as the need for development of appropriate standards. These are discussed in Part I and are not repeated here.

Novel Approaches

Luminescent concentrators have attracted substantial attention in recent years, proposing that light be absorbed and then reemitted within a sheet of glass or other material that acts as a waveguide. The glass (wave guide) directs the reemitted light to the edges, where it is converted to electricity by a concentrator cell. Two fundamental processes can lead to an enhancement of brightness. The first is dependent on the index of the material; a higher index of refraction can lead to a small enhancement. A more dramatic enhancement is achieved if a luminescent material absorbs high-energy light and reemits it at a lower energy. To understand how this works, consider a material in glass that absorbs light and luminesces at the same wavelength. If the luminescent-material is put into the glass at a concentration allowing light to be absorbed during one pass through the glass, then light reemitted for lateral transmission will be reabsorbed within a distance that is similar to the thickness of the glass. The light may be absorbed and reemitted many times before reaching the edge of the glass. Each time the light is reemitted, there is a chance that it will escape from the glass, and, because the direction is randomized with each reemission, the probability of this light reaching the edge of the glass is small, resulting in no increase in concentration.

Next, in contrast, consider a material that absorbs a high-energy photon and luminesces a low-energy photon. If the absorption coefficients of the two photons differ dramatically, then it is possible to choose a concentration of luminescent material that absorbs the high-energy light in one pass, but allows the low-energy light to travel long distances within the glass before being reabsorbed. In this case, very high concentrations can be achieved, theoretically. This limits the ability of a luminescent concentrator to concentrate light with energy close to the reemission energy. Although a luminescent concentrator provides an elegant way to concentrate light, it relies on identification of stable materials with the appropriate luminescent properties. So far, this approach has not been successful at achieving the needed performance, but new nanomaterials could lead to breakthroughs in this area.

Summary

The use of optical concentration to reduce the amount of silicon needed per watt in solar systems has the potential to provide cost-effective, large-scale, solar-electricity generation that is less sensitive to market volatility. Almost two dozen companies are publicly developing products. The reduced need for silicon and associated capital expenditures could allow these companies to grow at a rate that significantly exceeds that of the rest of the industry.

Part III. Silicon Modules with Enhanced Concentration

In 2007 and 2008, when silicon modules were in short supply, many companies devised creative methods for making their silicon modules generate more electricity. Specifically, adding mirrors to enhance the irradiance on the modules was commonly used. Interest in this approach has decreased since then, so this report no longer tracks these companies, but we note that interest could easily resume if a new shortage develops.

Acknowledgments

We extend our sincere gratitude to the *many* individuals who have contributed to this report over the years. Special thanks go to Richard Swanson, Bob Conner, Doug Rose, Matt Evans, Geoff Kinsey, Greg Peisert, Jerry Olson, Bob Cart, Brad Hines, Jeff Gordon, Craig Cornelius, Lori Greene, Gianfranco Sorasio, Susan Moon, Carl Bingham, Dan Friedman, and Ed Cahill. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

References

[1] Peharz G and Dimroth F, "Energy Payback Time of the High-concentration PV System FLATCON," Prog. Photovolt. 13, 627-734 (2005).

[2] Sabnis V, Yuen H, and Wiemer M, "High-Efficiency Multijunction Solar Cells Employing Dilute Nitrides," CPV8, Toledo, Spain, 2012 (AIP).

[3] Geisz JF, Duda A, France RM, Friedman DJ, Garcia I, Olavarria W, Olson J, Steiner MA, Ward JS, and Young M, "Optimization of 3-junction inverted metamorphic solar cells for high-temperature and high-concentration operation," CPV8, Toledo, Spain, 2012 (AIP).

[4] Aiken D, Dons E, Miller N, Newman F, Patel P, and Sharps P, "Commercial concentrator cell results and record IMM solar cell efficiency," CPV8, Toledo, Spain, 2012 (AIP).

[5] Wojtczuk S, Chiu P, Zhang X, Pulver D, Harris C, and Siskavich B, "42% 500X Bi-Facial Growth Concentrator Cells," CPV-7, Las Vegas, NV, USA, 2011, (AIP).

[6] King RR, Boca A, Hong W, Liu X-Q, Bhusari D, Larrabee D, Edmondson KM, Law DC, Fetzer CM, Mesropian S, and Karam NH, "Band-gap-engineered architectures for high-efficiency multijunction concentrator solar cells," 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 2009.

[7] Guter W, Schöne J, Philipps SP, Steiner M, Siefer G, Wekkeli A, Welser E, Oliva E, Bett AW, and Dimroth F, "Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight " Appl. Phys. Lett. 94, 223504 (2009).

[8] King RR, Law DC, Edmondson KM, Fetzer CM, Kinsey GS, Yoon H, Sherif RA, and Karam NH, "40% efficient metamorphic GaInP/GaInAs/Ge multijunction solar cells," Appl. Phys. Lett. 90, 183516 (2007).

[9] Geisz JF, Friedman DJ, Ward JS, Duda A, Olavarria WJ, Moriarty TE, Kiehl JT, Romero MJ, Norman AG, and Jones KM, "40.8% Efficient Inverted Triple-junction Solar Cell with Two Independently Metamorphic Junctions," Appl. Phys. Lett. 93, 123505 (2008).

[10] Wheeldon J, Walker A, Valdivia C, Chow S, Theriault O, Beal R, Yandt M, Masson D, Riel B, McMeekin D, Puetz N, Wallace S, Aimex V, Ares R, Hall T, Fafard S, and Hinzer K, "Efficiency Measurement and SImulations of GaInP/InGaAs/Ge Quantum Dot Enhanced Solar Cells at up to 1000-Suns Under Flash and Continuous Concentration," CPV-7, Las Vegas, NV, USA, 2011, (AIP).

[11] Geisz JF, Kurtz SR, Wanlass MW, Ward JS, Duda A, Friedman DJ, Olson JM, McMahon WE, Moriarty TE, Kiehl JT, Romero MJ, Norman AG, and Jones KM, "Inverted GaInP/(In)GaAs/InGaAs triple-junction solar cells with low-stress metamorphic bottom

junctions," Proceedings of the 33rd IEEE Photovoltaic Specialists Conference, San Diego, CA, 2008 (IEEE).
[12] Olson JM, Friedman DJ, and Kurtz S, in Handbook of Photovoltaic Science and Engineering, edited by A. Luque and S. Hegedus (John Wiley and Sons, West Sussex, England, 2003), p. 359-412.
[13] Bosi M and Pelosi C, "The Potential of III-V Semiconductors as Terrestrial Photovoltaic Devices," Progress in Photovoltaics 15, 51-68 (2007).
[14] Luque A, Sala G, and Luque-Heredia I, "Photovoltaic Concentration at the Onset of its Commercial Deployment," Progress in Photovoltaics 14, 413-428 (2006).
[15] Swanson RM, "The Promise of Concentrators," Prog. Photovolt. Res. Appl. 8, 93-111 (2000).
[16] Hering G, "X marks the spot," PHOTON International April, 123 (2007).
[17] Baur C, AW B, and F D, "Triple-junction III-V based concentrator solar cells: Perspectives and challenges," Journal of Solar Energy Engineering 129, 258-265 (2007).
[18] Hering G, "Vertically integrated at 520 suns," PHOTON International March, 86-87 (2008).
[19] in Concentrator Photovoltaics, edited by A. Luque and V. Andreev (Springer Series, 2007).
[20] Geisz JF, Kurtz SR, Wanlass MW, Ward JS, Duda A, Friedman DJ, Olson JM, McMahon WE, Moriarty T, and Kiehl J, "High-efficiency GaInP/GaAs/InGaAs triple-junction solar cells grown inverted with a metamorphic bottom junction," Appl. Phys. Lett. 91, 023502 (2007).
[21] Vol. 2011 (2011).
[22] Hering G, "Dawn of 500 suns," PHOTON International 2008, 146 (2008).
[23] Hering G, "Staying focused," PHOTON International 2009, 130 (2009).
[24] McMahon WE, Emery K, Friedman DJ, Ottoson L, Young M, Ward JS, Kramer C, Duda A, and Kurtz S, "Fill Factor as a Probe of Current-Matching for $GaInP_2$/GaAs Tandem Cells in a Concentrator System during Outdoor Operation," Progress in Photovoltaics: Research and Applications 16, 213-224 (2008).
[25] "http://www1.eere.energy.gov/solar/pdfs/accelerated_aging_report_2008.pdf"
[26] Guter W, Kern R, Kostler W, Kubera T, Lockenhoff R, Meusel M, Shirnow M, and Strobl G, "III-V Multijunction Solar Cells - New Lattice-Matched Products and Development of Upright Metamorphic 3J Cells," CPV-7, Las Vegas, NV, USA, 2011, AIP, p.
[27] Araki K, Al Taher O, Nagai H, Hebert P, and Valles J, "Are Electro-Luminescence Defects in Concentrator III-V Cells Responsible to Thermal Runaway and Sudden Death?," CPV-7, Las Vegas, NV, USA, 2011, AIP.
[28] http://minerals.usgs.gov/minerals/pubs/commodity/germanium/mcs-2008-germa.pdf, USGS Mineral Commodities Summary, January (2008).
[29] http://www.foodproductiondaily.com/news/ng.asp?id=72474-wellman-pet-carbonated, "Titanium PET bottles take the pressure," (2006).
[30] http://minerals.usgs.gov/minerals/pubs/commodity/germanium/germamcs06.pdf, (2006).
[31] Depuydt B, Bergman E, Khorenko V, Leutz R, Melia J, and Hoflich A, "Scalability of CPV towards multi-gigawatt deployment," CPV8, Toledo, Spain, 2012 (AIP).
[32] Askins S, Victoria M, Herraro R, Dominguez C, Anton I, and Sala G, "Effects of Temperature on Hybrid Lens Performance," CPV-7, Las Vegas, NV, USA, 2011, AIP.
[33] Hornung T, Neubauer M, Gombert A, and Nitz P, "Fresnel Lens Concentrator with Improved Thermal Behavior," CPV-7, Las Vegas, NV, USA, 2011, AIP.
[34] Rubio F, Martinez M, Sanchez D, Aranda R, and Banda P, "Two years operating CPV plants: Analysis and results at ISFOC," CPV-7, Las Vegas, NV, USA, 2011, AIP.
[35] Araki K, Uozumi H, Kondo M, Takamoto T, Agui T, Kaneiwa M, Egami T, Hiramatsu M, Miyazaki Y, Kemmoku Y, Akisawa A, Lee HS, EkinsDaukes NJ, and Yamaguchi M, "Development of a new 550X concentrator module with 3J cells - performance and reliability," Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Orlando, Florida, 2005 (IEEE), p. 631-634.

[36] Miller D, Kempe M, Kennedy C, and Kurtz S, "Analysis of transmitted optical spectrum enabling accelerated testing of multijunction concentrating photovoltaic designs," Optical Engineering 50, 13003-13001-13017 (2011).
[37] Lamarche P, "The custom HALT environmental chamber," CPV8, Toledo, Spain, 2012 (AIP).
[38] Feltrin A and Freundlich A, "Material Challenges for Terawatt Level Deployment of Photovoltaics," (2006).
[39] Welford WT and Winston R, "The Optics of Nonimaging Concentrators: Light and Solar Energy," Academic Press (1978).
[40] Arboiro JC, Sala G, Molina JI, Hernando L, and Camblor E, "The EUCLIDES concentrator: a lightweight 84 m long structure for sub-degree tracking," 2nd World Conf. on Photovoltaic Energy Conversion, Vienna, 1998 (IEEE), p. 2229-2232.

Appendix A. Cost Evaluations

When pursuing any new technology, it is essential to evaluate whether it will be cost competitive. However, it is also essential to recognize that cost estimates can have substantial uncertainty, and that placing emphasis on small cost differences could lead to unwise decisions in the long run. The cost of electricity from PV systems depends on the location and mounting details; the strongest cost driver is the cost of the money used to create the initial installation.

In 2000, Swanson published a comprehensive study comparing the expected costs of electricity for multiple PV technologies (Fig. 6 and Table 8).[15] In April 2010, Swanson revisited this study in his plenary presentation at the CPV-6 conference. He noted that many of the projections made in 2000 were accurate within 10% or 20% of what is found today. However, the area-related balance-of-system costs dropped more than projected for fixed mounting [projected to be $88/m^2$ (2010 $); in 2010 estimated to be $57/m^2$] and 1-axis mounting [projected to be $113/m^2$ (2010 $); in 2010 estimated to be $80/m^2$]. The costs of 2-axis trackers did not come down as much as projected, perhaps because this segment of the market has not grown as robustly as the others.

Inverter costs also dropped more than projected (projected to be 38 cents/W; in 2010 estimated to be 30 cents/W). Swanson's conclusion (presented in April 2010) is that HCPV (multijunction III-V), LCPV (silicon), and thin-film (CdTe) approaches are in a dead heat. Adjusting to current dollars, he reported that the relative costs of HCPV, LCPV, thin films, and crystalline silicon were projected to be 0.86, 1.35, 1.18, and 1.33, but are now found to be 1.0, 1.0, 1.0, and 1.13, respectively. He noted that the crystalline silicon costs dropped more than projected because of unexpectedly rapid market growth. SunPower's high-efficiency, low-cost silicon cells have reduced the cost of the low-concentration approach, explaining much of the increased interest in this approach documented in Part II of this report. The HCPV approach has not yet increased in volume adequately to define its cost, so the uncertainty in this analysis is emphasized. Learning from Swanson's comparison of 10-year-old predictions to today's reality, we may expect that the uncertainty in the relative projections can be as much as 50%. It will be interesting to see how these costs evolve in the next ten years!

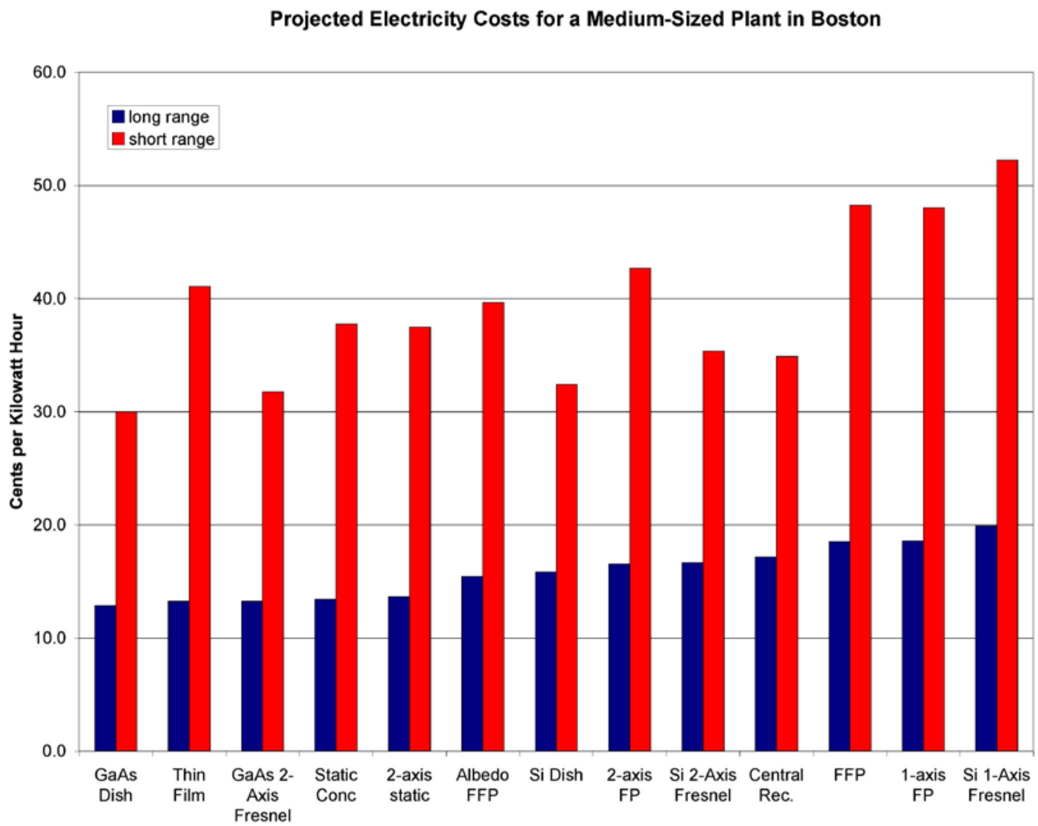

Figure A3 (from Ref.[15], color modified). For medium-sized plants in Boston, the GaAs dish surprisingly maintains its lead, despite the lower direct normal solar resources. (In other words, a dish based on 35%-efficient cells is something of the ultimate technology.) The thin-film approach is a close second place. (R.M. Swanson, "The Promise of Concentrators," *Prog. Photovolt. Res. Appl.* 8, 93111, ©2000 John Wiley & Sons Limited. Reproduced with permission.)

Figure 6. Cost of electricity calculated for a set of technologies as presented in Ref.[15]

Table 8. Cost Assumptions Used to Calculate the Cost of Electricity Presented in Figure 6

Table A1 (in Ref. [15]). Detailed assumptions for medium-sized PV plants. (R.M. Swanson, "The Promise of Concentrators," *Prog. Photovolt. Res. Appl.* 8, 93111, ©2000 John Wiley & Sons Limited. Reproduced with permission.)

MEDIUM PLANT-ALBUQUERQUE		GaAs Dish	GaAs 2-Axis Fresnel	Si Dish	2-axis static	Si 2-Axis Fresnel	Thin Film	Static Conc	Central Rec.	Albedo FFP	2-axis FP	Si 1-Axis Fresnel	1-axis FP	FFP
Desert (Albuquerque)	KWhr/m2/day	6.566	6.566	6.566	8.624	6.566	6.336	6.336	5.025	6.336	8.624	6.08	7.41	6.336
Diffuse (Boston)	KWhr/m2/day	3.626	3.626	3.626	5.782	3.626	4.554	4.554	2.775	4.554	5.782	3.42	4.94	4.554
Albedo factor		1	1	1	1	1	1	1	1	1.3	1	1	1	1
BOS Area (low)	$/m2	70	70	70	70	70	70	70	70	70	70	70	70	70
BOS Area (high)	$/m2	140	140	140	140	140	140	140	140	140	140	140	140	140
BOS Power (low)	$/W	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
BOS Power (high)	$/W	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Tracking (low)	$/m2	35	35	35	35	35	0	0	35	0	35	20	20	0
Tracking (high)	$/m2	67	67	67	67	67	0	0	67	0	67	40	40	0
Module (low)	$/m2	90	115	90	115	115	75	85	30	85	75	90	75	75
Module (high)	$/m2	160	230	160	230	230	150	160	60	165	150	160	150	150
Cell (low)	$/m2	30000	30000	15000	300	15000	0	300	20000	200	200	5000	200	200
Cell (high)	$/m2	100000	100000	20000	1000	20000	30	1000	25000	400	400	15000	400	400
Cell Efficiency (high)		0.3325	0.35	0.26	0.21	0.27	0.12	0.21	0.26	0.2	0.2	0.24	0.2	0.2
Cell Efficiency (low)		0.285	0.3	0.23	0.17	0.24	0.08	0.17	0.23	0.15	0.15	0.2	0.15	0.15
Operating Temp.		65	65	65	60	65	55	60	65	60	55	65	55	55
deta/dteta		2.20E-03	1.90E-03	2.20E-03	3.30E-03	2.20E-03	2.00E-03	3.30E-03	2.20E-03	3.30E-03	3.30E-03	2.40E-03	3.30E-03	3.30E-03
Concentration		1000	1000	400	4	400	1	4	400	1	1	50	1	1
Module Transmission		0.85	0.85	0.85	0.9	0.85	0.95	0.9	0.85	0.95	0.95	0.9	0.95	0.95
BOS eff		0.85	0.85	0.85	0.9	0.85	0.9	0.9	0.85	0.9	0.9	0.85	0.9	0.9
Conc premium		0	0	0	0	0	0	0	0	0	0	0	0	0
O&M cost (low)	¢/KWhr	0.8	0.8	0.8	0.8	0.8	0.2	0.2	0.8	0.2	0.8	0.8	0.8	0.2
O&M cost (high)	¢/KWhr	2.0	2.0	2.0	2.0	2.0	0.8	0.8	2.0	0.8	2.0	2.0	2.0	0.8
Cost-diff low	¢/KWhr	12.8	13.2	15.8	13.7	16.6	13.2	13.4	17.1	15.4	16.5	19.9	18.6	18.5
Cost-diff high	¢/KWhr	30.0	31.8	32.4	37.5	35.4	41.1	37.7	34.9	39.6	42.7	52.2	48.0	48.2
Cost-Desert low	¢/KWhr	7.4	7.7	9.1	9.4	9.5	9.6	9.7	9.8	11.1	11.3	11.5	12.6	13.4
Cost-Desert high	¢/KWhr	17.5	18.4	18.8	25.8	20.4	29.7	27.3	20.2	28.7	29.3	30.3	32.7	34.9
Cost-low	$/W	1.59	1.64	1.99	2.71	2.10	2.16	2.19	1.66	3.18	3.32	2.38	3.20	3.05
Cost-high	$/W	3.70	3.94	4.02	7.49	4.42	6.69	6.14	3.33	8.18	8.58	6.27	8.30	7.89