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

Technical Report
NREL/TP-520-43208
Revised November 2009

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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.

The first version of this report described the value of CPV based on multijunction concentrator cells. Representatives from a number of companies suggested including information about low-concentration approaches using silicon or other inexpensive cells as well. More recently, it has been suggested that the Si CPV market may be split into multiple segments. This update contains three parts in response to these suggestions.

Recent progress in the CPV industry is impressive, although much of the progress has been largely ignored by the mainstream PV community. Specific examples are summarized in the report. If you have suggestions about this report, 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:

- Demonstration of full-scale products with high efficiency: 29% for small module and 25% AC for a full-scale system.
- Multiple companies have set up manufacturing, taking the big step from prototype development into manufacturing with an aggregate production capacity >100 MW/y.
- The approach is attracting some big names, including such companies as RFMD and JDSU, both of which have expressed interest in the multijunction concentrator cell business.
- Dozens of companies are working on developing products or participating in the supply chain.

Si-based CPV approaches are also making significant strides:

- The number of companies pursuing Si-based CPV has increased as Si PV companies face the difficult decision of how much to invest in their future supplies of silicon; some companies are looking at Si-based CPV as a way to reduce expenditures associated with ramping silicon material/cell supply and as a way to reduce risk in the case of a silicon shortage.
- Skyline Solar is testing ~30 kW.
- WS Energia is projecting installation rates in >MW/y range.

The Promise of CPV

Today's photovoltaic (PV) industry is growing at a rapid rate, but the industry would grow even faster if costs could be reduced for both the final products and the capital investment required for scale-up. For today's risk-adverse investors, reduced capital expenditure translates to reduced risk. One strategy for reducing module cost is to reduce the amount of semiconductor material needed. Many companies are thinning the silicon wafers to reduce costs incrementally; others use thin-film coatings on low-cost substrates (such as amorphous/microcrystalline silicon, cadmium telluride, or copper indium gallium diselenide on glass or other substrates). CPV follows a complementary approach and uses concentrating optics to focus the light onto small cells. The optics may be designed for low or high concentration. Low-concentration concepts use silicon or other low-cost cells; high-concentration optics may use more expensive, higher-efficiency cells. Higher-efficiency cells can reduce the cost per watt if the cost of the small cells is a small fraction of the total cost.

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 three 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) that require silicon or other types of concentrator cells; a wide range of approaches is included. Part III discusses the use of conventional silicon modules with enhanced performance from mirrors on either side of the modules.

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 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 coefficient; 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.
- Higher efficiency, allowing smaller module area; in some cases, CPV requires less than half the module area to deliver the same power.
- Lower product costs expected because of a reduced use of semiconductor material compared with flat-plate silicon and because of a steeper learning curve.
- Better match to load profile because of excellent performance in late afternoon (as a result of tracking and lower temperature coefficients).
- Qualitatively different approach that complements low-efficiency approaches and contributes to a strong technology portfolio for solar, especially for the sunniest locations.

CPV joins the rest of 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
- Can be installed with minimal environmental impact
- Low carbon intensity and energy payback that can be less than a year.[1]

These will be discussed in more detail throughout this report.

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

Concentrator cells have recently been achieving increasingly impressive efficiencies, inspiring interest in the high-efficiency, high-concentration approach. The current record efficiency is 41.6% for a three-junction, lattice-matched GaInP/GaInAs (1.4 eV)/Ge cell.[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. The multijunction approach has been described extensively in the literature.[2-14]

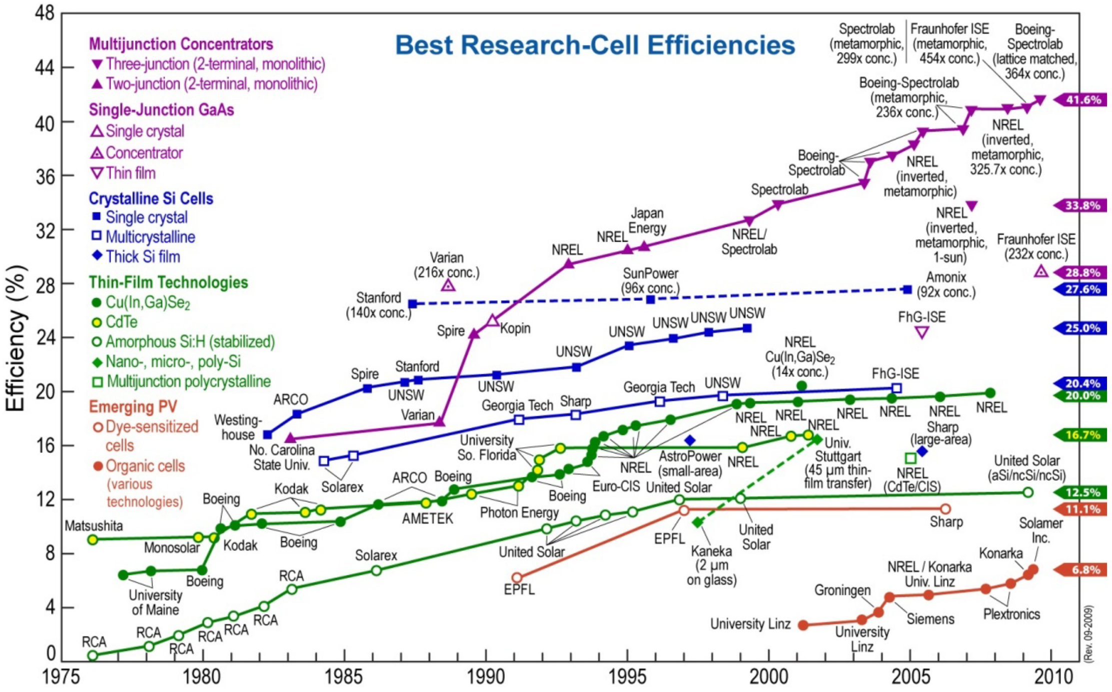

Fig. 1. Historic summary of champion cell efficiencies for various PV technologies. The highest efficiencies have been achieved for multijunction solar cells; these efficiencies are still increasing each year. Multijunction cell efficiencies have the potential to approach 50% in the coming years.

When compared with solar thermal approaches, CPV provides a qualitatively different approach, typically with lower water usage and greater flexibility in size of installation. 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 building-integrated or rooftop applications, whereas most CPV products are better suited to solar farms.
- The champion concentrator cell was only ~30% efficient, compared with >40% 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 low cost only when the volume of manufacturing is large).

In the last 10 years, the solar industry has grown exponentially, and the CPV industry has grown rapidly, with dozens of companies developing new products. Cumulative investment in CPV is on the order of $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.[6-8]

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.

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.[7,8] These studies imply that there is a potential for cost-effective implementation of CPV systems even in locations such as Boston, Massachusetts.[8] The cost assumptions published in references [7,8] 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. 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 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.

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

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[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).

installed ~1 MW. Several of these companies are planning >10 MW projects, implying that the cost differences between the various approaches will become increasingly clear in the next 2–5 years. 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 is most cost effective for sunny regions with clear skies. Most CPV systems 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 lost, the DNI resource is often greater than the resource available to fixed flat-plate panels because of the value of tracking. Figure 2 shows the ratio of DNI to global irradiance for a latitude-tilted surface.

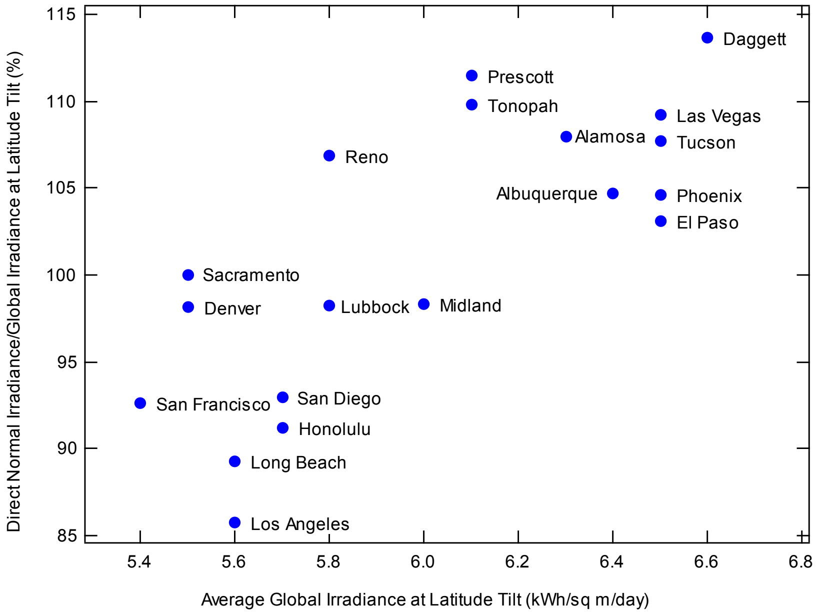

Fig. 2. Ratio of DNI to global irradiance on a latitude-tilted surface as a function of the average daily irradiance. Source of data: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

Current Status of the CPV Industry

The year 2008 was very important for the CPV industry because it marked the first time that multiple companies surpassed 1 MW of installations. The status of the industry was very nicely summarized in a 2008 *PHOTON International* article.[15] PHOTON estimated that 6.5 MW of high-concentration, multijunction PV systems were installed in 2008. We can confirm 3 MW, with an additional >3 MW in progress. We expect that these numbers are consistent with PHOTON's numbers, reflecting the time interval between shipment of modules and commissioning of the plants and at what point during that interval the installation is counted.

The 2007 Technology Roadmap for Concentrator PV, created under the U.S. Department of Energy's (DOE's) Solar Energy Technology Program, defined a number of metrics for the high-concentration CPV industry, as summarized in Table 2. Of note, between 2007 and 2009, the efficiency of commercial systems increased dramatically with multiple companies citing efficiencies around 25%. Energy Innovations reported measurement of a 29%-efficient module. Although not included in the 2007 Technology Roadmap (probably because the industry had not yet begun manufacturing), the industry has also shown dramatic progress in the last 2 years related to field installations and manufacturing capacity.

Table 2. CPV Industry Status as per Metrics Specified in the 2007 DOE Technology Roadmap. Systems in the Field and Manufacturing Capacity Have Been Added as Key Metrics for 2009.

Parameter	Status 2007	Status 2009	Future Goal (2015)
$/W installed cost	$7–$10/W	*	<$2/W
¢/kWh	>30¢/kWh	*	<7¢/kWh
System reliability	5 years	*	20 years
Commercial system efficiency	17%	25% (champion module 29%)	29%–36%
Champion device efficiency	40.7%	41.6%	48%
Commercial device efficiency	35%–37%	Typically 39%	42%
Optical efficiency	75%–85%	*	80%–90%
III-V cell cost, $/cm^2	$10–$15/cm^2	*	$3–$5/cm^2
Systems in the field	<1 MW**	~4 MW**	
Manufacturing capacity	<1 MW/y	~100 MW/y	

*These numbers are not well defined.
**Systems counted here incorporated multijunction cells.

Table 3 provides a list of more than three 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. Several claim to have more than 10 MW/y manufacturing capacity. The world economic situation has limited the companies' ability to negotiate contracts in 2009, but CPV installation rates are expected to increase modestly in 2009. In late 2008, *PHOTON International* estimated that 50 MW of high- and low-concentration PV might be installed in 2009.[15] However, a more recent PHOTON article described the CPV industry growth with less confidence.[16]

Table 3. Summary of CPV 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 2007*	On Sun in 2008**	Capacity**
Abengoa Solar	Lens, pedestal	Madrid, Spain			
American CPV		Orange, CA, USA			
Amonix	Lens, pedestal	Torrance, CA, USA	>100 kW (Si)	600 kW (Si-based)	30 MW/y
Arima Ecoenergy	Lens, pedestal	Taipei, Taiwan		50 kW (installing 300 kW in 2009)	7 MW/y
Boeing	Mirror, Pedestal	Seal Beach, CA, USA			
CompSolar	Lens, Pedestal	Hsinchu Science Park, Taiwan			
Concentracion Solar La Mancha	Lens, pedestal	Ciudad Real, Spain			11 MW/y
Concentrating Solar Systems		Bangalow, Australia			
Concentrating Technologies	Small mirror, pedestal	Alabama	>1 kW		
Concentrix Solar	Lens, pedestal	Freiburg, Germany	~100 kW	300 kW	25 MW/y
Cool Earth Solar	Inflated mirrors	Livermore, CA, USA	>1 kW		
Daido Steel	Lens, pedestal	Nagoya, Japan		30 kW, planned Dec. 2008	
Delta Electronics	Lens, pedestal	Taiwan		400 kW in progress; closing in 2009	>2 MW/y
Edtek	Mirror, pedestal, hybrid	Kent, WA, USA			
Emcore	Lens, pedestal	Albuquerque, NM, USA	>10 kW	400 kW	10 MW/y
ENEA	Lens, Si cells, pedestal	Portici, Italy			
Energy Innovations	Lens, each module tracked	Pasadena, CA, USA		UL certified	
Enfocus Engineering	Lens, flat pivot	Sunnyvale, CA, USA			
ENTECH	Lens, pedestal	Keller, TX, USA	>1 kW in 2003		
ESSYSTEM	Lens, pedestal	Gwangju-city, Korea			
EverPhoton	Lens, pedestal	Taipei, Taiwan		Installing 200 kW in 2009	
Green and Gold	Lens, pedestal	South Australia			50 MW/y
GreenVolts	Small mirrors, carousel	San Francisco, CA, USA	>1 kW	2 MW partially installed	
Guascor Foton	Lens, pedestal	Ortuella, Spain	~10 MW (Si)	10 MW (Si based - Amonix)	15 MW/y
IBM	Lens	Armonk, NY			

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
Isofoton	Lens, pedestal	Malaga, Spain		400 kW Puertollano	10 MW/yr
Menova Energy	Fresnel reflector	Markham, ON, Canada			
Morgan Solar	Lateral photon collection	Toronto, ON, Canada			
MST	Lens, pedestal	Rehovot, Israel			
OPEL International	Lens, pedestal	Shelton, CT, USA		>300 kW in progress	3 MW/y
Pyron Solar	Lens, carousel	San Diego, CA, USA	>1 kW	Installing 60 kW in Korea	
Scaled Solar	Dish	San Francisco, CA, USA			
Semprius	Microlens	Durham, NC, USA			
Sharp	Lens, pedestal	Japan			
Sol3g	Lens, pedestal	Cerdanyola, Spain	>10 kW	1.4 MW	12 MW/y
Solar Systems	Dish, pedestal; developing central receiver (heliostat)	Victoria, Australia	>100 kW	1.3 MW (0.7 MW multijunction; 140 kW test bed for central receiver)	5 MW/y
SolarTech	Lens, pedestal	Phoenix, AZ, USA			
Solar*Tec AG	Lens, pedestal	Munich, Germany			
SolFocus	Small mirror, pedestal	Mountain View, CA, USA	>10 kW	500 kW ISFOC 27 kW US	50 MW/y
Soliant Energy	Lens, flat pivot	Pasadena, CA, USA			1 MW/y
Soltec Energias Renovables	Reflective	Spain			
SUNRGI	Lens	Hollywood, CA, USA			
Xtreme Energetics	Two designs: central station and rooftop	Livermore, CA, USA			
ZettaSun		Boulder, CO			
Zytech Solar	Reflective	Zaragoza, Spain			

*Estimated to nearest factor of 10.

**Based on public presentations or Web site announcements/press releases. Note that these differ from those presented in *PHOTON International*,[15] giving separate validation. We do not dispute the validity of PHOTON's numbers.

Most PV technologies have required years of development before showing success on a large scale. First Solar's current expansion is based on years of development work. As noted above, the multijunction CPV industry may be preparing to emerge from the development phase. As the CPV companies transition from the prototyping phase of development to scaling up manufacturing, they will encounter the standard 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. 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.

These considerations are often interlinked, with improvements in performance and reliability also causing an increase in cost. Companies have demonstrated that each of these goals can be achieved separately; next we await the demonstration that all three can be achieved simultaneously. The companies reported that they have been successful in identifying solutions for the many technical problems, but that it can take some time to identify the suppliers needed to assemble all of the components. Several companies have completed prototype development, have created a datasheet describing their product(s), and are moving into manufacturing.

A key difference between 2007 and 2009 is that the collective experience of the workforce has advanced so that the prototype development phase can begin to decrease. Although much of the CPV prototype development is straightforward engineering, there was an acute shortage of engineers in 2007 with hands-on experience with CPV design. In 2009, as some companies are moving from design into manufacturing, there are dozens of engineers who now have significant experience with CPV design and testing. An experienced team can assemble a prototype in a shorter time, though perhaps not yet as quickly as investors would like.

Prototype Testing

Many of the companies have one or multiple prototypes in the field. Initial prototypes are usually on the order of 1 kW in size, with subsequent prototypes in the 2–30-kW range. Several of the companies are now testing fielded systems that are >100 kW in size.

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, 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.[17]
  - 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.

Most companies are testing prototypes and would like to accelerate the reliability testing. Many of the stress tests are designed to run over several weeks. If these could be replaced by highly accelerated stress tests (HAST), testing cycles might be reduced to less than a week. For example, higher temperature and humidity could be applied in a slightly pressurized system. Unfortunately, the technical basis for this sort of acceleration has not been established. Some efforts to do this have concluded that the use of harsher conditions for a shorter time can expose failure modes that are not observed in the field, defeating the purpose of the tests.

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 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.[18]

Some testing standards are available, but the standards for CPV are behind those for flat-plate PV. Dozens of standards exist for silicon PV. Many of these were developed by the IEEE or ASTM for use in the United States, and then were placed in the international arena through the IEC. 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).	New Work Item Proposal submitted for Part I in 2009. 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; New Work Item Proposal to be submitted in 2010
UL 1703 – Flat-plate photovoltaic modules and panels	UL 6703 – Concentrator photovoltaic modules and assemblies

Manufacturing Scale-Up and Retesting

After reliable prototypes have been demonstrated, companies must automate the manufacturing of them 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 summer 2009, SolFocus began construction (permitting) of a 10-MW field in Samaras, Greece.
- In October 2009, Opel announced completion of 330 kW in Tarragona, Spain.
- EVERPHOTON is planning a 1-MW installation in China.

- Amonix introduced a 53-kW system with a 25% AC conversion efficiency; in October 2009, Amonix announced the expansion of its Seal Beach, California, production facility, capable of manufacturing 30 MW/y.
- In October 2009, Energy Innovations reported a 29% module efficiency.

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 prioritized the power rating as the highest standards need, but a technical basis for the performance rating is not well established. Some questions that need to be addressed are:

- Should ambient temperature or cell temperature be used for the rating?
- Should the historic value of 850 W/m^2 be replaced with 900 or 1000 W/m^2?
- How should the variable spectrum be treated?
- If spectral effects are to be addressed, what is the best approach (reference cells, spectral radiometer, etc.)?
- What methodology should be established for indoor performance rating? Specifically, if flash lamps are used, how is the normal operating condition temperature determined and adjusted?
- Should issues related to acceptance angle, tracker alignment, etc., be considered?

The effect of the choice of using module temperature versus ambient temperature is shown in Fig. 3. The use of ambient temperature has the advantage of reflecting the quality of the thermal management design as well as being better at predicting performance in the field. Historically, there has been dissatisfaction with field performance of silicon modules because they seldom provide the rated power.

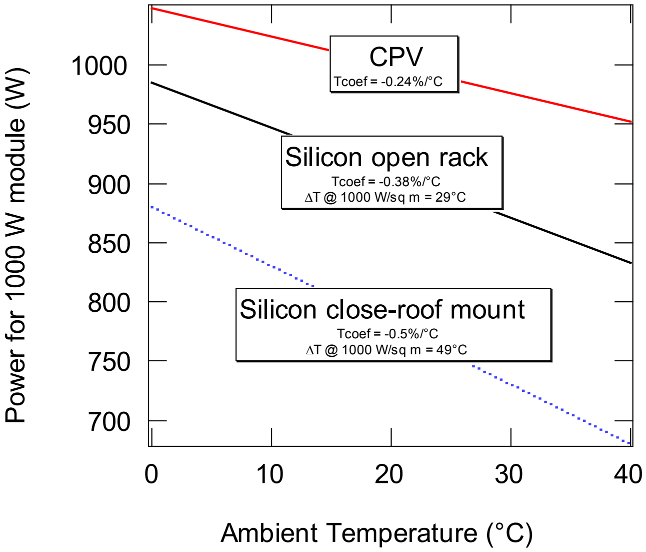

Fig. 3. Comparison of expected performance as a function of ambient temperature for a CPV module at 20°C ambient and a silicon module rated at 25°C module temperature and operated at 1000W/m^2 in two mounting configurations (using an empirical temperature model published by King[19]). The top curve for silicon assumes SunPower's better temperature coefficient (-0.38%/°C) and open-rack mounting; the more pessimistic curve assumes the more common temperature coefficient of –0.5%/°C and roof mounting. The empirical module-temperature models should be taken as rough estimates. The temperature coefficient for the CPV module was taken to be –0.24%/°C.

The TC82 WG7 is currently leaning toward using ambient temperature to define three ratings (Table 5).

Table 5: Summary of Reference Power Conditions
(intended at AM1.5; 2 m/s wind)

Condition	Direct Normal Irradiance ($W{\cdot}m^{-2}$)	Ambient Temperature (°C)
CSNC Concentrator Standard Nominal Conditions	850	20
HIC High Irradiance Condition	1000	20
HTC High Temperature Condition	850	40

Energy rating is most important for power-purchase agreements and utility applications. The methods for determining these ratings are still being debated. The methods used for predicting energy production for flat-plate systems are sufficiently documented to satisfy most investors, but investors have much less confidence in similar predictions for CPV systems. This puts CPV companies at a disadvantage for some applications. Pierre Verlinden, Solar Systems, has proposed that the electricity generated over a year's time be measured and compared with the same year's irradiance. This approach is related to the "performance ratio" measurement described in IEC 61724.

It is useful if the metrics used for CPV are relatively consistent with those used for flat-plate PV and that they are logical. For example, the peak-watt rating is generally assumed to imply the highest performance observed for a module or system. If the performance routinely exceeds the peak-power rating, the inverters and other aspects of the system must be appropriately sized. Some locations routinely experience DNI values of ~1000 W/m^2. If ambient temperature is used for the rating with 850W/m^2, modules in such locations will frequently generate more than rated power, and, in such circumstances, the capacity factors may become higher than would normally be expected for PV. Table 6 shows a simple, relative estimate of capacity factor based on only irradiance and temperature for Los Angeles, California, and Las Vegas, Nevada. When defining the power and energy-rating methodologies, it may be wise to make choices that facilitate comparison with flat-plate PV. Comparing these two locations, both of which might be considered possible markets for CPV, it is clear that the capacity factors expected for different locations are highly variable. We emphasize that the crude estimates shown in Table 6 neglect numerous derating factors. Nevertheless, they show that the 20°C ambient with 850W/m^2 rating yields a value similar to the flat-plate, one-axis tracked value for Los Angeles and a value slightly above the flat-plate, two-axis tracked value for Las Vegas. Thus, it is impossible to define a power rating that leads to a consistent correlation with flat-plate capacity factors.

Table 6. Simple Relative Capacity Factor Estimate Based on Average Irradiance Values for Los Angeles, CA (first four rows) and Las Vegas, NV (last four rows)

Configuration	Average resource (kWh/day/m^2)	Capacity factor at rated T	Estimated average temperature	Cap. factor w temperature correction
Latitude tilt (Si)	5.6	23%	Module @ 55°C	20%*(21%**)
Single-axis (no tilt) tracked Si	6.4	27%	Module @ 55°C	23%*(24%**)
Two-axis tracked Si	7.2	30%	Module @ 55°C	26%*(27%**)
CPV 2-axis tracked	4.8	24%(20%***)	Ambient @ 25°C	23%(20%***)
Latitude tilt (Si)	6.5	27%	Module @ 60°C	22%*(23%**)
Single-axis (no tilt) tracked Si	8.1	34%	Module @ 60°C	28%*(29%**)
Two-axis tracked Si	9.1	38%	Module @ 60°C	31%*(33%**)
CPV 2-axis tracked	7.1	35%(30%***)	Ambient @ 30°C	34%(29%***)

* Silicon temperature coefficient of –0.5%/°C
** Silicon temperature coefficient of –038%/°C
*** CPV temperature coefficient of –0.24%/°C. The second number uses 1000 W/m^2 instead of 850 W/m^2 for the CPV rating.

For modeling of expected performance at a new location, a useful tool would be a model that could take readily available data and create a set of hourly data for the direct spectrum, temperature, and wind speed. If the model were created, such data could be generated to represent an average day for each month of the year for any site in the United States. Tools for estimating energy production (e.g., PVWatts) are available for flat-plate systems and might be extended to CPV systems. Efforts are under way to improve the modeling for CPV in NREL's Solar Advisor Model.

Some companies are interested in solar resource data for Spain and other locations outside the United States. Such data exist, but this information is not widely available. The direct solar resource is strong in southern Spain, but is significantly reduced toward the northern part of the country.

The National Solar Radiation Data Base and other solar resource data that include the direct resource usually include the circumsolar resource, which most high-concentration CPV systems are unable to utilize. 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

The availability of concentrator cells has been a concern, but is not a problem in 2009. Spectrolab, Emcore, and Azur Space are shipping concentrator cells to multiple CPV companies, and all CPV companies reported adequate cell availability as of this writing. A significant number of new companies have demonstrated the capability for epitaxial (single-crystal) growth of multijunction cells. They are summarized in Table 7.

Table 7. 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	Reported 36% efficiency; custom designs available.
CESI	Milano, Italy	Datasheet reports efficiency >30%.
Cyrium	Ottawa, Canada	Solar cells are available for independent evaluations; claim an efficiency record >40%.
Emcore	Albuquerque, NM, USA	Datasheet describes typical 39% cells and receivers at ~500 suns.
Epistar	Hsinchu, Taiwan	Multijunction cells in development
IQE	Cardiff, Wales, UK	Has demonstrated state-of-the-art efficiencies
JDSU	Milpitas, CA, USA	Has marketed laser-powered electricity generators
Microlink Devices	Niles, IL, USA	Multijunction cells in development
Quantasol	Kingston upon Thames, Surrey, UK	Multijunction cells with quantum wells
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	Will be ready to share cells in 2010.
Spectrolab	Sylmar, CA, USA	Datasheet describes minimum average 36% cells and cell assemblies at 50 W/cm^2. Will ship 35 MW in 2009, and plan to ship 100 MW in 2010 (@500X).
Spire (Bandwidth)	Boston, MA, USA	Previously posted a datasheet; continue to offer epi services.
VPEC	Ping-jen city, Taiwan	Multijunction cells in development

In November 2008, at the 5th International Conference on Solar Concentrators in Palm Springs, California, several of these companies gave updates, including:

- Azur Space reported a 39.7% champion efficiency at ~300 suns; 36% for production. Capacity in 2008, 100 MW/yr (Gerhard Strobl, “AZUR SPACE Solar Power”).
- Emcore reported 39% at ~300 suns and capacity of 150–250 MW/yr (Dan Aiken “III-V Multijunction solar cells: A status report and roadmap”).
- Spectrolab projected 300 MW/yr capacity at its current facility in 2010 (Russ Jones, “Solar Cell Suppliers – Industry Perspective”).

More recent reports include:

- Cyrium reported a >40%-efficient champion cell in May 2009.
- Arima reported a >40%-efficient champion and 38%-efficient production cells.

A quick review of the companies in Table 7 implies that the supply of cells could be expanded quickly. The entry of large companies such as RFMD and JDSU could bring the experience of the larger industry for making cheaper cells. Some CPV manufacturers are now using Azur Space as their primary supplier. Essentially all of these companies 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 companies' capabilities are changing rapidly; the data presented here will quickly be out of date.

The most immediate concern about the concentrator cells expressed by CPV representatives is whether the reliability testing is adequate. Both Spectrolab and Emcore report that they have tested the cells and are confident of their stability and performance, but most CPV representatives were not satisfied with the detail of the test data. Emcore bases its 20-year cell (and receiver) warranty on (1) years of experience with space cells manufactured for operation at up to 250°C; (2) a firm understanding of both the physical-degradation mechanisms and the design/manufacturing methodologies needed to ensure long-term reliability of its CPV products; and (3) a year (and counting) of stable on-sun terrestrial operation at 500 suns. Spectrolab has a similar space heritage and has tested its CPV cells using the thermal-cycling, humidity, and humidity-freeze tests described in IEEE 1513-2001.

The injection of forward-bias current during thermal cycling is observed to damage some *cells*. The thermal cycling test is intended to stress the *attachment* between the cell and the heat sink rather than the *cells*. It is not yet well established whether application of forward-bias current is stressing a relevant failure mechanism, but it appears to be very effective in detecting a failed joint.

The existing qualification standards may or may not identify all of the degradation modes. High solar fluxes may be more harmful to encapsulant materials than to the semiconductor material. Si modules are known to exhibit corrosion associated with moisture ingress near the Ag gridlines. Thus, CPV cells with Ag grid lines could experience similar corrosion. Nevertheless, if CPV cells are operated in hot, dry climates, moisture ingress may be less of a problem. A technical basis has not yet linked the standard damp heat (85°C/85% relative humidity) with field performance for CPV systems. Until the correlation between accelerated testing and field-testing is established, most CPV companies are applying the standard damp heat test to identify potential failures.

The current cell production capacity exceeds the CPV installation rate by a factor of about 100, so cell availability is not an immediate concern. In the event of a rapid growth in demand for multijunction cells, the situation could quickly evolve into that which is currently observed for the silicon PV industry: Companies must plan on negotiating firm multiyear contracts so that the semiconductor suppliers can appropriately plan and finance their expansion.

Expansion of the manufacturing volumes should allow reduction in cost because of economies of scale. At the ICSC5 in November 2008, the cell companies predicted falling costs for cells in the coming years, up to 50% cost reduction in the next 2–5 years.

Cell Efficiencies

Cell efficiencies have been increasing at a rate of about 0.5% to 1% per year in recent years. Efficiencies are expected to continue to increase toward 45%–50%. Spectrolab has reported a record efficiency of 41.6%.[2] NREL has described a new, inverted structure at 40.8%.[3] Araki calculated[20] that idealized 3-, 4-, and 5-junction cells could have annualized efficiencies of 47.3%, 49.3% and 50.5%, respectively. Today's 3-junction cells are not ideal, implying that the addition of a 4th junction will have a greater effect on energy yield.

The trade-off between cell cost and cell efficiency is highly dependent on the relative costs of the cells and the systems. A simplistic analysis is shown in Fig. 4. The cell cost in $/W is strongly dependent on concentration. Emcore reported a sale to Green and Gold at $24 million for 105 MW, which translates to $0.23/W for a concentration ratio of 1100. The cell costs of $0.50/W and $0.10/W represent the high end of what Emcore is currently delivering and lower costs that might be achieved, respectively. The $1,000/m^2 area cost potentially includes not only the module costs, but also installation and land-use costs, and may approximate an entry-level system today. Lower costs will need to be achieved to be competitive in the marketplace; the $100/m^2 target is aggressive, but demonstrates how the role of cell efficiency changes when the system cost becomes dominated by the cell cost. Clearly, for $1,000/m^2 systems, efficiency is a strong cost driver. But, if the balance-of-system cost can be reduced to $100/m^2 without change in cell cost, then efficiency becomes less important. The evaluation of the importance of cell efficiency and cost is fairly straightforward once the system design (especially the concentration) is fixed and the relative costs are known. An example equation is included in the Fig. 4 caption. This analysis assumes that cell cost is fixed. In practice, more efficient cells tend to cost more, implying that the curves in Fig. 4 would be flatter in a specific scenario.

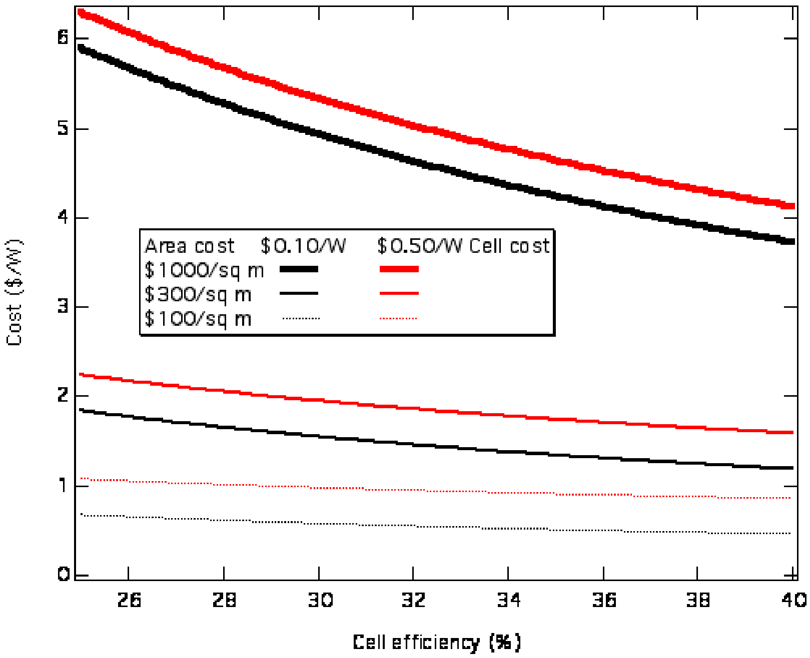

Fig. 4. Total system cost as a function of cell cost (either $0.10/W or $0.50/W) and non-cell costs (taken in the range of $100–$1,000/m^2). The system power was decreased from 850 (standard reporting conditions) to 690 W/m^2 to account for optical and thermal losses. The equation used to calculate these data was Cost ($/W) = Area cost ($/m^2)/Efficiency X 690 (W/m^2)) + Cell cost ($/W). The definition of cell cost in $/W has 20%–35% uncertainty, because it may or may not account for optical and/or thermal losses.

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 broken ground on a plant in Quapaw, Oklahoma, to help service this growing market. In addition, if the inverted method[13] of fabricating the multijunction cells or other approaches that reuse the wafers (e.g., Microlink, Semprius) become popular, the substrates may be reused or the material recycled. Some of these approaches use GaAs instead of Ge. 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).[21] Canada and China are the world's largest Ge sources, each supplying more than one-third of the world's Ge 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), where political stability (and therefore access) appears to be improving. The major Ge consumers in 2007 were fiber optics (35%), infrared optics (30%), PET catalysts (15%), and electronics and solar applications (15%).[21]

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.[22] It is significant that the PET catalyst percentage of the Ge market has declined from 31% in 2005 to 15% in 2007.[23] 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.

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 was not raised as a concern.

Trackers

Although industry representatives did not describe trackers as a serious problem, trackers are known to require periodic maintenance, and glitches in performance or outright mechanical failure can decrease performance and increase maintenance costs substantially.

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. A standard to specify the attributes of a tracker and how to measure them is being drafted by IEC TC82 WG7.

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.

Lead-Free Solders for Tracker Controllers

As the world has moved away from using lead in solder, the long-term (~30-year) reliability of the newer solders is not widely understood. The controllers for CPV trackers include soldered components that need to be reliable for many years. Although it is clear that lead-containing paints are a hazard to public health, the hazard of using leaded solder for cell interconnections or printed circuit boards for controllers is less clear. It would be useful for the national laboratories to quantify the risks associated with these uses of lead. Some possibilities for responding to the need for reliable printed-circuit boards include: identifying a lead-free solder or method for applying that solder to provide the needed reliability, and/or identifying companies that supply low-cost leaded solders and the associated electronics boards.

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.[24] 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. Accelerated testing of the effect of concentrated light is especially challenging and has not been well defined.

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. Spectrolab and Emcore 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. Although more than a dozen companies are developing a cell capability and more than 30 companies are developing CPV systems, far fewer companies (in addition to the cell companies) are marketing multijunction CPV cell assemblies. Delta Electronics of Taiwan has developed a receiver, but recently announced a withdrawal from selling cell assemblies at the end of 2009, because of the economic downturn.

The expertise needed to create these cell assemblies is fairly well established in the LED industry, which represents a business opportunity for such companies. In the long run, it is probable that entities with cell assembly capabilities will be targeted for acquisition, as the industry later moves toward vertical integration. It is not yet clear whether Delta Electronics' withdrawal will be a small or major problem for the community.

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.

Skilled Labor

The availability of appropriately skilled labor is a challenge for all of the CPV companies. Nevertheless, individuals with experience working with LEDs, optical design, reliability testing, etc., are making important contributions to developing CPV prototypes. This difficulty is shared across the board among renewable energy firms today.

Utility Interactions

Electricity bills use a variety of algorithms for defining charges. An understanding of these is necessary to calculate payback times for installations in different billing areas. Some of the companies expressed a desire to have this information compiled for easy access.

Material Availability Limits

Projections of materials 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. 5).[25] Their use of 200X as the concentrating factor is conservative compared with what most companies are currently pursuing (500X–1000X). 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. 5, labeled “EPI Lift-off,” is potentially relevant to the inverted, metamorphic approach,[13] 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.

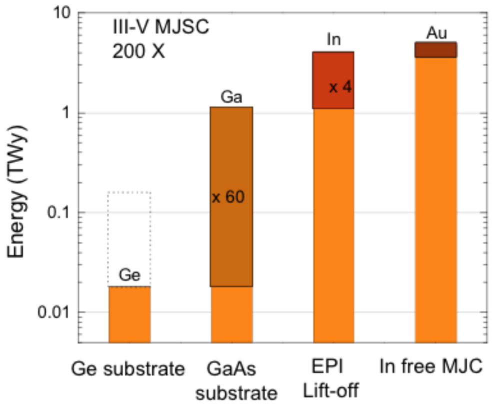

Fig. 4: Potential energy limits imposed to III-V multi-junction cells (200 sun concentrations). The third and fourth columns show the extrapolated potential of this technology if the substrates are ignored.

Fig. 5. Material availability study from Ref.[25] (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. About three dozen 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 enthusiastically 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). Thin-film PV such as copper indium gallium diselenide (CIGS) or cadmium telluride (CdTe) may also be used in CPV, but will not be discussed in this report.

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 2007 and early 2008, PV industry growth was limited by the community’s ability to predict the need for purified silicon and to create the investment needed for the appropriate scale-up. In an uncertain, and risk-adverse, investment climate, the investors are likely to be attracted to approaches that reduce the required capital expenditure and, especially, a capital expenditure that must be made for growth predicted far into the future. The capital expenditure may be reduced all along the supply chain for the Si poly, ingot, wafer, and cell manufacturing. The scalability of products depending primarily on glass, metal, and plastic (instead of cells) may enable growth of a silicon-based CPV industry in the coming years, especially as there is evidence that this approach is getting attention by some mainstream companies in recent years.

Some investors see a medium-concentration, silicon-based product as less risky than high-concentration CPV. 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 high-concentration CPV (see Fig. 4), 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.[26] 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 two-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. 6. 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.

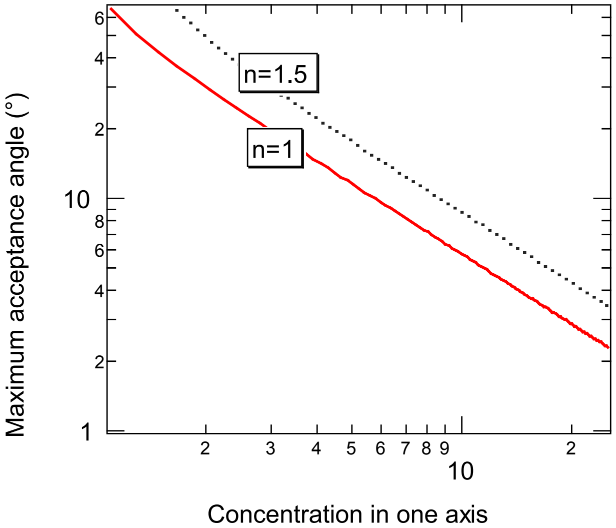

Fig. 6. The theoretical maximum for the acceptance angle that can be achieved as a function of linear concentration

Tracking

A few years ago, most systems were deployed on rooftops in a fixed configuration, but recently the number of systems deployed on trackers has increased. 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 be paving the way for concentrator systems.

A contradictory viewpoint is that trackers will not be used in the future because PV cost must be significantly reduced in order to compete with fossil fuels. As the PV module cost is reduced, if the tracker cost is not reduced by a similar amount, 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, 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 low-concentration systems currently lags that of high-concentration systems. However, the approach is not new: ENTECH developed a linear ~20X concentrator system using silicon cells in the 1980s. In the 1990s, ENTECH deployed hundreds of kilowatts of this low-concentration technology.[27] The performance of these was well documented through the PVUSA project, demonstrating the highest efficiency of the systems studied. However, it appears that this was a technology before its time: The market for tracked systems was very small in the 1990s, and ENTECH needed high volume to achieve competitive costs. After several years of developing concentrators for space applications, ENTECH, in partnership with WorldWater, is now marketing these systems afresh (and also adding a hybrid thermal feature). Although ENTECH's early efforts did not lead to a commercial success, today's companies can learn much from ENTECH's early field experience.

BP Solar also 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.[28] Today's companies may also 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 8 and as was noted in the *PHOTON International* November 2008 summary of CPV.[15] 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 8 at their request.

Table 8. 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 2007*	On Sun in 2008**	Capacity**
Arontis Solar Concentrator	Reflective trough, Si cells	Harnosand, Sweden			
Banyan Energy	Flat plate 10X, total internal reflection, Si cells	Berkeley, CA			
Covalent Solar	Luminescent, multiple types of cells	Boston, MA, USA			
CPower	Reflective, 25X–30X (point focus), Si cells	Ferrara, Italy		>10 kW	
ENTECH	Linear Fresnel lens, Si cells; hybrid PV-thermal	Fort Worth, TX, USA	>100 kW in the 1990s		

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
Greenfield Solar	Reflective, edge-illuminated Si cells	Cleveland, OH, USA			
KD Solar Co.	Holographic 3X	Kyunggi-Do, Korea			
Maxxun	Luminescent	Eindhoven, Netherlands			
MegaWatt Solar	Reflective, linear, 20X, pedestal	Hillsborough, NC, USA		50 kW	
Netcrystal	Non-tracking, Si cells	San Francisco, CA, USA			
Optony	Thin-film cells	Silicon valley, CA, USA			
Pacific Solar Tech	Dome-shaped lens, Si cells	Fremont, CA, USA			
Prism Solar Technologies	Holographic, Si cells	Lake Katrine, NY, USA			
Pythagoras Solar	Static	Hakfar Hayarok, Israel			
QD Soleil	Luminescent	Palo Alto, CA			
Silicon CPV	Fresnel (point focus, 120X) Si cells	Essex, UK			
Skyline Solar	Reflective, 10X, Si cells	Mountain View, CA, USA			
Solaria	2X–3X, small strips of Si cells	Fremont, CA, USA			
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			
Thales Research	Static, reflective	Severna Park, MD, USA			
Whitfield Solar	Fresnel lens, ~40X, Si cells	Reading, UK			
Zytech Solar	Reflective, Si modules; 4X–150X	Zaragoza, Spain			

*Estimated to nearest factor of 10, unless company supplied a specific number.

**Based on public presentations or Web site announcements/press releases. Note that these differ from those presented in *PHOTON International*,[15] giving separate validation. We do not dispute the validity of PHOTON’s numbers.

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 the 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.

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). Making custom-designed concentrator cells for every company is a distraction for most cell companies. However, China Sunergy (will.xing@chinasunergy.com) and NaREC (Gordon.Whyte@narec.co.uk) have both expressed an interest and willingness in making custom silicon concentrator cells. Q-cells AG and BP Solar have also made silicon concentrator cells on occasion. There is also interest in the use of CIGS or CdTe. The concentrator version of the CIGS cell must be moved from a glass substrate to a metal or other thermally conducting substrate. Daystar planned in the 1990s to develop a low-concentration system using CIGS cells, but has now dropped the concentrator approach.

The medium-concentration approaches face many of the same challenges of 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 enhancement in 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 luminescence at the same wavelength. If the luminescent-material concentration is chosen so that the light is 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, 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. Thus, although a luminescent concentrator provides an elegant way to concentrate light, it is fundamentally limited in the efficiencies and concentration ratios it can achieve.

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, the addition of mirrors to enhance the irradiance on the modules has been commonly used. The silicon modules can be incorporated directly into low-concentration designs without significant performance losses. Similarly, tracking systems from either the high-concentration PV or from flat-plate PV may be used in low-concentration systems. By leveraging the infrastructure used for these other products, the product development time for these enhanced-concentration products can be quite short. Table 9 summarizes some companies that have pursued this approach. We note that the oversupply of silicon modules in 2009 has decreased, though not eliminated, interest in this approach.

Table 9. Summary of Companies Developing Low-Concentration PV Products Using Conventional Silicon Modules

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
Abengoa Solar	Reflective, linear	Madrid, Spain		1.2 MW	
Archimedes	Reflective, linear	Stuttgart, Germany			
Ehw	Reflective, linear	La Seyne sur Mer, France			
EVERPHOTON	2X	Taipei, Taiwan			
JX Crystals	Reflective, linear	Issaquah, WA, USA	>100 kW	>100 kW	
Opel International	Reflective, linear	Shelton, CT, USA			
WS Energia	Reflective, linear, 2X	Oeiras, Portugal	24 kW	263 kW	>2 MW planned in 2009

*Estimated to nearest factor of 10, unless company supplied a specific number.

**Based on public presentations or Web site announcements/press releases. Note that these differ from those presented in *PHOTON International*, [15] giving separate validation. We do not dispute the validity of PHOTON's numbers.

Manufacturing

This low-concentration approach builds on the existing know-how of the flat-plate PV industry in providing high volumes of Si panels and relatively low-cost trackers. Because the low-concentration approach is only incrementally different from flat-plate silicon, low-concentration product development may be completed more quickly than the high-concentration development. Once low-concentration products are fully developed, the companies may scale up production rapidly, being less encumbered by the need for silicon feedstock. Although the silicon feedstock shortage disappeared in 2008, the possibility that it could recur forces companies to make long-term plans. Smaller capital investment translates to smaller risk, allowing the scale-up to happen more easily. For this reason, Si-based CPV may be attractive to risk-adverse investors.

Abengoa has already installed more than 1 MW. WS Energia installed 218 kW in 61 installations in 2008: 8 systems in Italy, 6 in Spain, and 47 in Portugal. The company plans installation of 2083 kW in 2009: 240 systems in Portugal (3.7 kW each), one 400-kW plant in Italy, and one 800-kW plant in Spain). JX Crystals has deployed more than 100 kW. WS Energia was selected from 3500 candidates for recognition in the LIVE EDGE competition in 2007.

Summary

Large deployment of low-concentration PV will occur when companies are successful in combining the PV industry's capacity to provide high volumes of reliable flat-plate PV panels with the advanced capabilities of the sheet-metal and other conventional industries in providing precise, weatherable, moving structures at low costs. Installations in 2008 surpassed one megawatt and could easily climb to tens of megawatts per year in the near future.

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References

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

[2] 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.

[3] 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).

[4] 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).

[5] 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.

[6] Bosi M and Pelosi C, "The Potential of III-V Semiconductors as Terrestrial Photovoltaic Devices," Progress in Photovoltaics 15, 51-68 (2007).

[7] Luque A, Sala G, and Luque-Heredia I, "Photovoltaic Concentration at the Onset of its Commercial Deployment," Progress in Photovoltaics 14, 413-428 (2006).

[8] Swanson RM, "The Promise of Concentrators," Prog. Photovolt. Res. Appl. 8, 93-111 (2000).

[9] Hering G, "X marks the spot," PHOTON International April, 123 (2007).

[10] 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).

[11] Hering G, "Vertically integrated at 520 suns," PHOTON International March, 86-87 (2008).

[12] in Concentrator Photovoltaics, edited by A. Luque and V. Andreev (Springer Series, 2007).

[13] 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).

[14] Guter W, Scho□ne 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).

[15] Hering G, "Dawn of 500 suns," PHOTON International 2008, 146 (2008).

[16] Hering G, "Staying focused," PHOTON International 2009, 130 (2009).

[17] 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).

[18]http://www1.eere.energy.gov/solar/pdfs/accelerated_aging_report_2008.pdf.

[19] King DL, Quintana MA, Kratochvil JA, Ellibee DE, and Hansen BR, "Photovoltaic module performance and durability following long-term field exposure," Progress in Photovoltaics: Research Applications 8, 241-256 (2000).

[20] Araki K, Yamaguchi M, Kondo M, and Uozumi H, "Which is the best number of junctions for solar cells under ever-changing terrestrial spectrum?," 3rd World Conference on PV Energy Conversion, 2003, p. 307.

[21] http://minerals.usgs.gov/minerals/pubs/commodity/germanium/mcs-2008-germa.pdf, USGS Mineral Commodities Summary, January (2008).

[22] http://www.foodproductiondaily.com/news/ng.asp?id=72474-wellman-pet-carbonated, "Titanium PET bottles take the pressure," (2006).

[23] http://minerals.usgs.gov/minerals/pubs/commodity/germanium/germamcs06.pdf, (2006).

[24] 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.

[25] Feltrin A and Freundlich A, "Material Challenges for Terawatt Level Deployment of Photovoltaics," (2006).

[26] Welford WT and Winston R, "The Optics of Nonimaging Concentrators: Light and Solar Energy," Academic Press (1978).

[27] O'Neill M and McDanal AJ, "The 25 kilowatt SolarRow: a building bock for utility-scale concentrator systems," 25th IEEE Photovoltaic Specialists Conference, Washington D.C., 1996 (IEEE, New York), p. 1529-1532.

[28] 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.

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This report assesses the current status of the rapidly growing concentrating photovoltaic (CPV) industry, with an eye toward identifying key roadblocks to establishing a mature CPV industry. The original report published in July 2008 focused on the value of using multijunction solar cells and high-concentration approaches. A September 2008 revision added low-concentration approaches using silicon or other inexpensive solar cells. A February 2009 revision updated the report with CPV industry statistics from 2008. This November 2009 revision describes industry progress in 2009 and expands the discussion of Si-based CPV.

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