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

S. Kurtz

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

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Introductory Note

This report attempts to identify problems that may be encountered as the concentrating photovoltaic (CPV) 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. This update contains two parts in response to this suggestion.

As the CPV industry grows, the coverage of this industry has increased in the mainstream press. If the mainstream press covers recent events, it will not be necessary to update this report. If you feel that further updates of this report may be useful, please email Sarah_Kurtz@nrel.gov.

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. One strategy for reducing module cost is to reduce the amount of semiconductor material needed (the cost of the silicon solar cells typically comprises more than one-half of the module cost). 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. The higher-efficiency cells can reduce the cost per watt if the cost of the small cells is a small fraction of the total cost. The high- and low-concentration approaches are described in Parts I and II of this report, respectively. Usually high-concentration systems operate at concentration ratios >100.

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

Recently, concentrator cells have been reaching increasingly impressive efficiencies, inspiring new interest in the high-efficiency, high-concentration approach. The current[1] record efficiency is 40.8% for a three-junction GaInP/GaInAs (1.3 eV)/GaInAs(0.9 eV) cell.[1] A historical

[1] As this report goes to press, we note that the Fraunhofer has announced a new record, 41.1%, see: http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise

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 direct-gap materials and can be grown with near-perfect quality. The multijunction approach has been described extensively in the literature.[2-11]

When compared with solar thermal approaches, CPV provides a qualitatively different approach, typically with lower water usage, greater flexibility in size of installation, and the ability to respond more quickly when the sun returns on a cloudy day. The tracking used for CPV also implies relatively higher electricity production per installed kilowatt, compared with fixed flat plate.

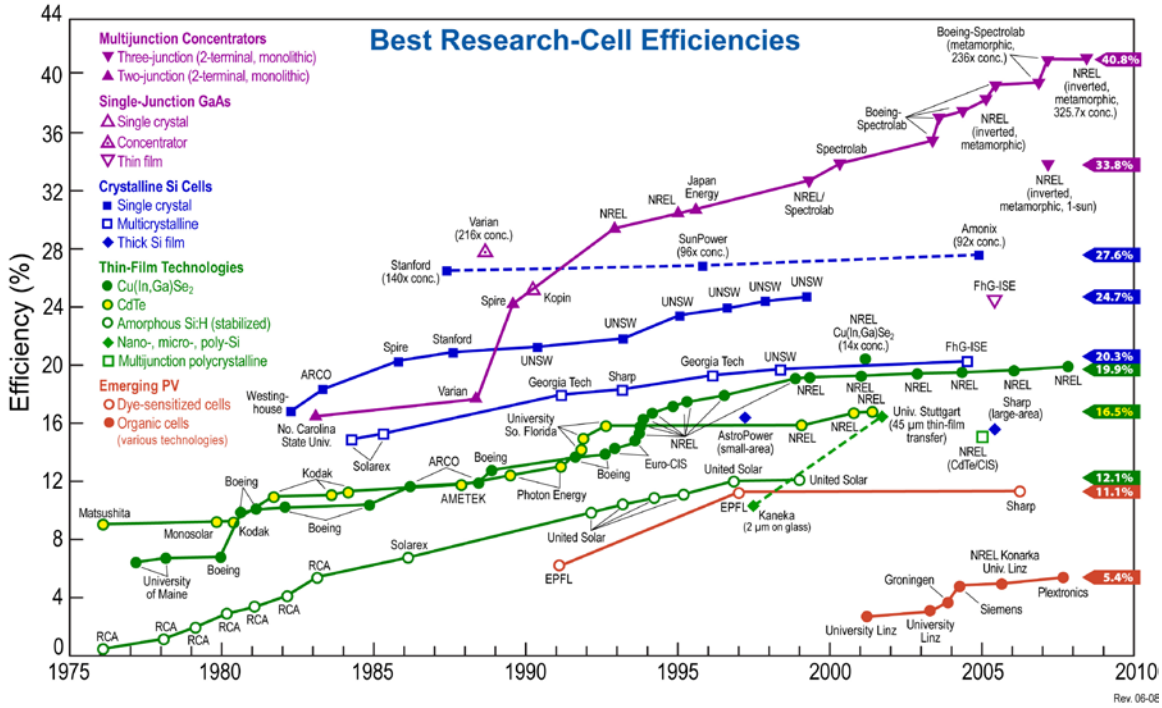

Fig. 1. Historic summary of champion cell efficiencies for various photovoltaic technologies. The highest efficiencies have been achieved for multijunction solar cells, increasing at a rate of almost 1% per year in recent years. Multijunction cell efficiencies have the potential to approach 50% in the coming years.

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 about 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 mushroomed, and the CPV industry is now growing rapidly. Cumulative investment in CPV is now 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.[4-6]

Some cost analyses have predicted that using high-efficiency concentrator cells can lead to very low costs for solar electricity.[5,6] These studies imply that there is a potential for cost-effective implementation of high-concentration systems even in locations such as Boston, Massachusetts, as shown in Fig. 2 (reprinted with permission).[6] The cost assumptions used to calculate the data in Fig. 2 are tabulated in Table 1. Other studies have also estimated the costs associated with CPV systems (see Table 2).[5] The energy payback of some CPV systems has also been studied.[12] Demonstration that these cost structures can be achieved will require development of a reliable CPV product followed by large-scale deployment. Installations

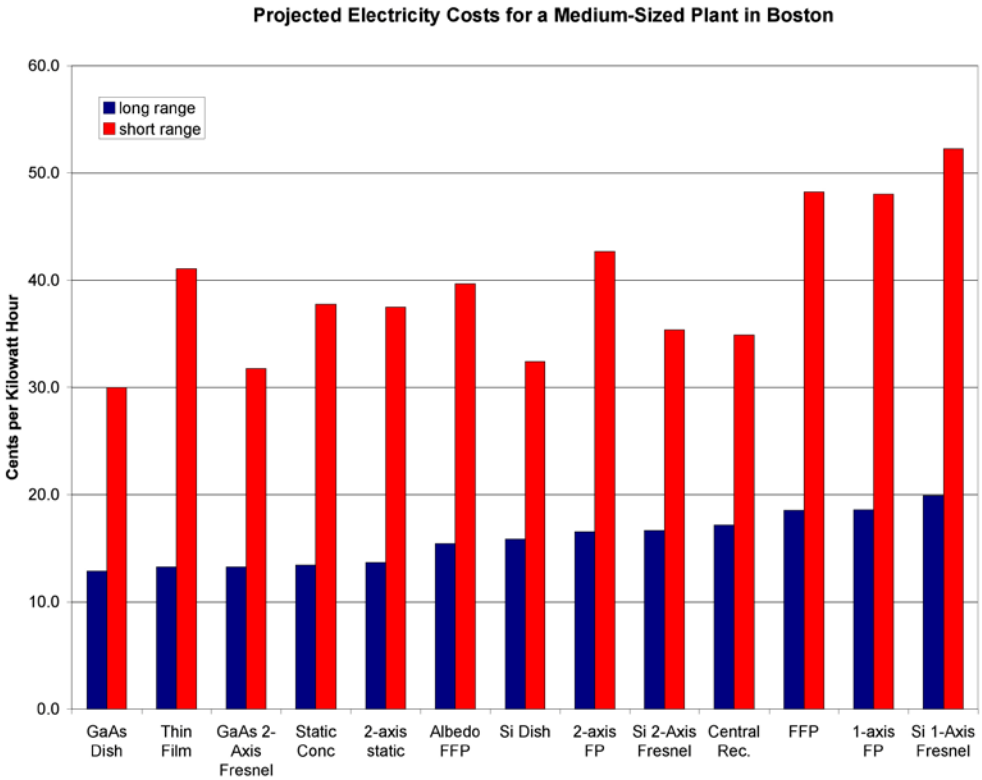

Figure A3 (from Ref.[6], color modified). For medium-sized plants in Boston, the GaAs dish surprisingly maintains its lead, despite the lower direct normal solar resources. (In other words, a dish based on 35% efficient cells is something of the ultimate technology.) The thin-film approach is a close second place. (R.M. Swanson, "The Promise of Concentrators," *Prog. Photovolt. Res. Appl.* 8, 93111, ©2000 John Wiley & Sons Limited. Reproduced with permission.)

Fig. 2. Cost of electricity calculated for a set of technologies as presented in Ref.[6]

Table 1. Cost Assumptions Used to Calculate the Cost of Electricity Presented in Figure 2

Table A1 (in Ref. [6]). 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

Table 2. Cost Assumptions and Cost of Electricity for CPV Estimated by Ref. [5]

Table II. Module, plant, and electricity costs in Madrid and in an extremely good location (EGL) (2000 kWh/m^2 Normal Direct Irradiation NDI per year) of a III-V module operating at 1000 ×,[27] equipped with 1 junction (1J) or 2 junction (2J) cells

	Short term	Long term		
	1 J	2 J	1 J no learning	2 J learning
Substrate wafer ($ per cm^2 wafer area)	8·50	8·50	8·50	2·37
Cells ($ per cm^2 cell area)	13·4	15·85	15·85	4·43
Cells ($ per m^2 aperture area)	134	159	159	44
Optics, heat sink, and assembling ($ per m^2 aperture area)	131	131	131	69
Module ($ per aperture area)	265	290	290	113
Cell efficiency (%)	23·1	37	45	45
Module efficiency (%)	19·0	30·5	37·1	37·1
Module ($ per Wp)	1·39	0·95	0·78	0·31
Area related BOS ($ per m^2 aperture area)	114	114	114	60
Power related BOS ($ per Wp)	0·22	0·22	0·22	0·12
Plant price ($ per m^2 aperture area)	526	589	607	271
Madrid NDI (W/m^2·year)	1826	1826	1826	1826
Performance ratio	0·606	0·606	0·606	0·606
Cost of electricity in Madrid ($ per kWh)	0·186	0·130	0·110	0·050
Cost of electricity in EGL ($ per kWh)	0·131	0·091	0·077	0·035

Table 2 source: A. Luque, G. Sala, and I. Luque-Heredia, "Photovoltaic Concentration at the Onset of its Commercial Deployment," *Prog. in Photovolt.* **14**, 413-428, ©2006 John Wiley & Sons Limited. Source: M. Yamaguchi and A. Luque, "High Efficiency and High Concentration in Photovoltaics*," IEEE Transactions Electron Devices,* 46: 2139, ©1999 IEEE. Reproduced with permission.

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. Several of these companies are projecting that they will install >10 MW in 2009, implying that the cost differences between the various approaches will become increasingly clear in the next couple of years.

An additional potential advantage of the CPV approach is 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 company has demonstrated it, the relative ease of scale-up of CPV is logical and could be a significant advantage in a rapidly growing market.

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 is very nicely summarized in PHOTON International's recent article.[13] PHOTON estimates 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. Table 3 provides a list of more than three dozen CPV companies. 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. If the world economic situation does not limit the companies' ability to negotiate contracts, CPV

installation rates could increase dramatically in 2009. PHOTON International estimates that 50 MW of high- and low-concentration PV may be installed in 2009. Even a much smaller number would imply very significant growth.

Table 3. Summary of CPV Companies

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)	
Arima Ecoenergy	Lens, pedestal	Taipei, Taiwan		50 kW	7 MW/y
Boeing	Mirror, Pedestal	Seal Beach, CA, USA			
Concentracion Solar La Mancha	Lens, pedestal	Ciudad Real, Spain			11 MW/y
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	>2 MW/y
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 certification	
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			
Green and Gold	Lens, pedestal	South Australia			
Greenfield Solar	Reflective, edge-illuminated Si cells	Cleveland, OH, USA			
GreenVolts	Small mirrors, carousel	San Francisco, CA, USA	>1 kW	2 MW in progress (2009 completion)	

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
Guascor Foton	Lens, pedestal	Ortuella, Spain	~10 MW (Si)	10 MW (Si based)	15 MW/y
IBM	Lens	Armonk, NY			
Isofoton	Lens, pedestal	Malaga, Spain		400 kW Puertollano	10 MW/yr
Menova	Modified trough	Ottawa, ON, Canada			
Morgan Solar	Non-tracking, building integrated	Toronto, ON, Canada			
OPEL International	Lens, pedestal	Shelton, CT, USA			
Pyron	Lens, carousel	San Diego, CA, USA	>1 kW		
Scaled Solar	Dish	San Francisco, CA, 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	50 MW/y
Soliant Energy	Lens, flat pivot	Pasadena, CA, USA			
SUNRGI	Lens	Hollywood, CA, USA			
Xtreme Energetics	Two designs: central station and rooftop	Livermore, CA, USA			
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, [13] 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 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. 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 goals 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.

Prototype Testing

Many of the companies currently have one or multiple prototypes on sun. Initial prototypes are usually on the order of 1 kW in size, with subsequent prototypes in the 2–30-kW range.

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. Usually, the initially measured performance is less than 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.[14]
- Misalignment of cell with optics or poorly designed optics so that some of the light misses the cell.

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. 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. This year, the Accelerated Aging Workshop, which was sponsored and organized by the U.S. Department of Energy and the national laboratories, included a breakout session for the CPV industry. 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.[15]

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).	Initial draft is being discussed.
IEC 61730 – PV module safety qualification	Draft under development
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.

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 need.

However, a technical basis for the performance rating is not well established. Some questions that need to be addressed include:

- How should the variable spectrum be treated?
- If spectral effects are to be addressed, what is the best approach (reference cells, spectral radiometer, etc.)?
- Should ambient temperature or cell temperature be used for the rating?
- 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?
- Should the historic value of 850 W/m^2 be replaced with 900 or 1000 W/sq^2?

Energy rating is most important for power purchase agreements and utility applications. The methods for these ratings are still being debated; methods that give precise and accurate ratings require technical studies. The methods used for predicting energy production for flat-plate systems are well enough documented to convince most investors, but investors have much less confidence in similar predictions for CPV systems. This puts CPV companies at a disadvantage for some applications.

A useful tool would be a model that could take readily available data and create a set of hourly data for 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., PV Watts) are available for flat-plate systems and might be extended to CPV systems.

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 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 can cause small-angle scattering.

Cell Supply

A key concern of all of the CPV companies has been the availability of concentrator cells. Spectrolab, Emcore, and Azur Space are currently 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. These 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	Report having achieved >37% cells.
Azur Space (RWE)	Heilbronn, Germany	Report 36% efficiency; custom designs available.
CESI	Milano, Italy	Have been selling space cells since early 1990s.
Cyrium	Ottawa, Canada	Solar cells are available for independent evaluations.
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	Have demonstrated state-of-the-art efficiencies with two separate partners.
Microlink Devices	Niles, IL, USA	Multijunction cells in development
Quantasol	Kingston upon Thames, Surrey, UK	Multijunction cells with quantum wells
Sharp	Japan	Have demonstrated high efficiencies, but have not indicated plans for full commercialization.
Spectrolab	Sylmar, CA, USA	Datasheet describes minimum average 36% cells and cell assemblies at 50 W/cm^2.
Spire (Bandwidth)	Boston, MA, USA	Datasheet describes typical 35% cells at 500 suns.
VPEC	Ping-jen city, Taiwan	Multijunction cells in development

** List does not include a number of other companies in R&D or stealth modes.

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

- Arima reported achieving a 37.5% efficiency at ~200 suns. (P.K. Chiang, "What cost and efficiency target [should] Arima plan for?").
- 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").

A quick review of the companies in Table 5 implies that the supply of cells could quickly mushroom. The efficiencies from the new companies are expected to be inferior to those from Emcore and Spectrolab, but may be acceptable to some CPV companies (see below). Some CPV manufacturers are now using Azur Space as their primary supplier. A number of companies are fabricating cells with efficiencies greater than 30%; some have demonstrated efficiencies in the range of 35%. 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. 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.

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 about a factor of 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.

Just as some silicon PV companies are moving toward vertical integration, many of the CPV companies are considering vertical integration with cell companies to ensure adequate cell supply. In contrast, the cell companies are trying to avoid vertical integration in order to retain their ability to supply many CPV companies. The situation may become very complex as companies attempt to define whether to merge or separate these efforts. Examples: Emcore (cell and system supplier) has announced a spin-off of its CPV systems company; Spectrolab (cell supplier) is owned by Boeing (system supplier); Arima Ecoenergy is developing CPV systems alongside of Arima's development of multijunction cells. Many discussions of mergers appear to be ongoing.

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 1% per year in recent years. Efficiencies are expected to continue to increase toward 45%–50%, although maybe at a slower rate. Spectrolab has reported a record efficiency of 40.7%.[2] Emcore claims an efficiency of 39%. NREL has described a new, inverted structure at 40.8%.[1] Although a 50% solar cell should be achievable, the addition of multiple junctions may add cost and may have marginal benefit in terms of additional energy production in the field.

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. 3. The cell cost in $/W is strongly dependent on concentration. Emcore reported a sale to Green and Gold at $24 million for 105 MW. This 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. 3 caption. This analysis assumes that cell cost is fixed. In practice, more efficient cells tend to cost more, implying that the curves in Fig. 3 would be flatter in a specific scenario.

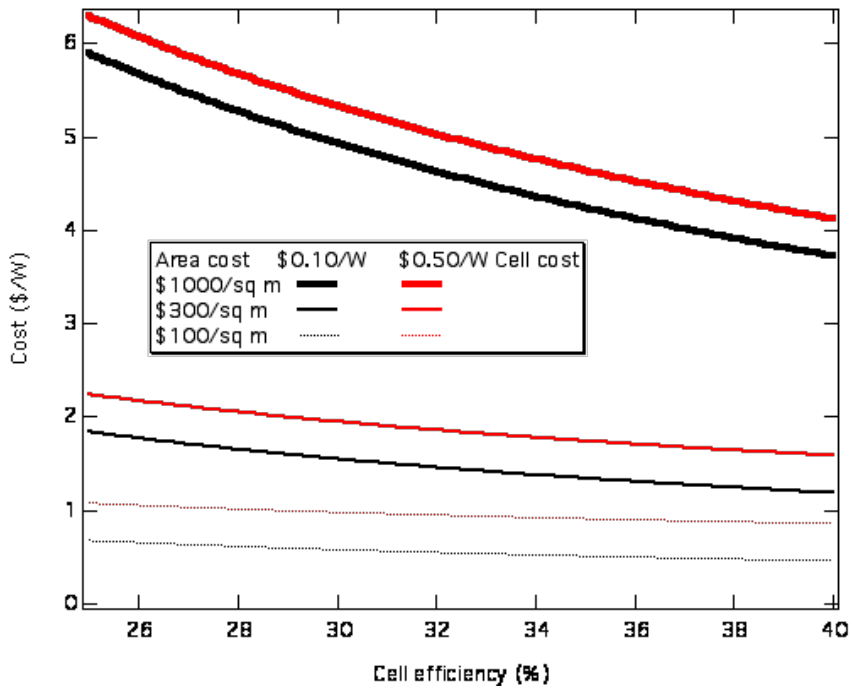

Fig. 3. Total system cost as a function of cell cost (either $0.10/W or $0.50/W) and non-cell costs (taken in the range of $100-1000/m^2). The system power was decreased from 850 (standard reporting conditions) to 690 W/m^2 to account for optical and thermal losses. The equation used to calculate these data was Cost ($/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 announced plans to

build a second plant in Quapaw, Oklahoma, to help service this growing market. In addition, if the inverted method[11] of fabricating the multijunction cells becomes popular, the substrates may be reused or the material recycled. 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).[16] 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%).[16]

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.[17] It is significant that the PET catalyst percentage of the Ge market has declined from 31% in 2005 to 15% in 2007.[18] 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.

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. Whereas 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.[19] 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 currently 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 they have now also developed a full module, so it is not yet clear how their business model will evolve.

The expertise needed to create these cell assemblies is fairly well established in the LED industry, so this 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.

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. 4).[20] 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. 4, labeled "EPI Lift-off," is potentially relevant to the inverted, metamorphic approach,[11] 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.

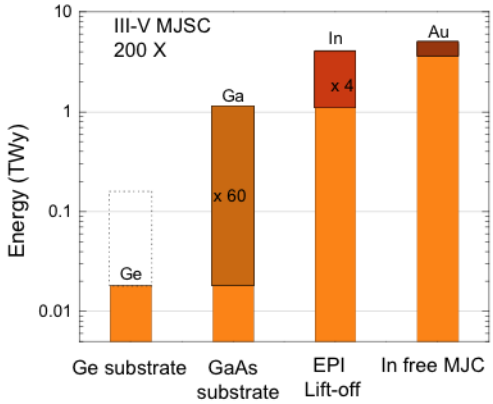

Fig. 4: Potential energy limits imposed to III-V multi-junction cells (200 sun concentrations). The third and fourth columns show the extrapolated potential of this technology if the substrates are ignored.

Fig. 4. Material availability study from Ref.[20] (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. Low-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 approach can also be applied to thin-film PV such as copper indium gallium diselenide (CIGS) or cadmium telluride (CdTe). The primary cost advantage is achieved with even a small concentration of light. A concentration ratio of 2–4 reduces the amount of semiconductor material to one-half or one-quarter of the original cost.

Low-concentration PV falls between flat-plate PV and high-concentration PV. The design of low-concentration systems can incorporate components from each of these. For instance, some high-performance, flat-plate PV modules or cells can be incorporated directly into low-concentration designs without significant performance losses. Similarly, the tracking systems from either the high-concentration PV or from flat-plate PV may be used in low-concentration systems.

This advantage 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.[21] 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%. 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 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.

Currently, in terms of the number of companies and total investment, the development of low-concentration systems is lagging 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, the company deployed hundreds of kilowatts of this low-concentration technology.[22] 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. Although, ENTECH's early efforts were not a commercial success, today's companies can learn much from ENTECH's early field experience.

BP Solar also developed a linear-focus, low-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.[23] 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 low-concentration designs has increased significantly in recent years, as shown in Table 6 and as was noted in PHOTON International's recent summary of CPV.[13] 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. 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. Solaria and Skyline Solar have both been selected for funding by the U.S. Department of Energy through its Incubator Program.

Table 6. Summary of Companies Developing Low-Concentration PV Products

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
Abengoa Solar	Reflective, linear, Si cells	Madrid, Spain		1.2 MW	
Archimedes	Reflective, linear, Si	Stuttgart, Germany			
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	Fort Worth, TX, USA	>100 kW in the 1990s		
JX Crystals	Reflective, linear, Si cells	Issaquah, WA, USA	>100 kW	>100 kW	
Maxxun	Luminescent	Eindhoven, Netherlands			
MegaWatt Solar	Reflective, linear, 20X, pedestal	Hillsborough, NC, USA		50 kW	
Netcrystal	Non-tracking, Si cells	San Francisco, CA, USA			
Opel International	Reflective, linear, Si cells	Shelton, CT, USA			

Company	Type of System	Location	On Sun in 2007*	On Sun in 2008**	Capacity**
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			
Silicon CPV	Fresnel (point focus) 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	Linear Fresnel lens, ~40X, Si cells	Reading, UK			
WS Energia	Reflective, linear, 2X Si modules	Oeiras, Portugal	24 kW	263 kW	>2 MW planned in 2009
Zytech Solar	Reflective, linear, Si modules	Zaragoza, Spain			

*Estimated to nearest factor of 10, unless company supplied specific number.
**Based on public presentations or Web site announcements/press releases. Note that these differ from those presented in PHOTON International, [13] giving separate validation. We do not dispute the validity of PHOTON's numbers.

Manufacturing

The low-concentration PV industry lags the high-concentration PV industry in terms of number of companies, but the installation volume is already comparable to that of the high-concentration PV companies. Low-concentration approaches usually build on the existing know-how of the flat-plate PV industry in providing high volumes of Si cells or 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 is projected to ease in coming years, smaller capital investment often translates to smaller risk, allowing the scale-up to happen more easily.

Cell Supply

Historically, a key challenge of the low-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. Typically, as with the high-concentration approach, there is benefit to purchasing higher-efficiency cells. The buried-groove-contact cells and back-point-contact cells have been of special interest for low-concentration applications in the past. With the current shortage of silicon feedstock, most companies can easily sell silicon cells as fast as they can make them, providing little motivation for companies to develop both one-sun and concentrator product lines. However, any of the silicon cell companies could diversify in preparation for the possibility that low-concentration approaches could become important. The most common low-concentration design is currently using one-sun silicon modules with mirrors on either side to boost the irradiance. Companies that may provide cells for higher concentration use include CSUN (China Sunergy), Q-cells AG, SunPower, NaRec, and BP Solar. 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 low- and high-concentration approaches share 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 detail in Part I and are not repeated here.

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. Although only a couple of companies have completed large low-concentration systems, about two dozen companies are publicly developing products. The reduced need for silicon could allow these companies to grow at a rate that significantly exceeds that of the rest of the industry. 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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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. This revision (February 2009) updates the report with CPV industry statistics from 2008.

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