A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

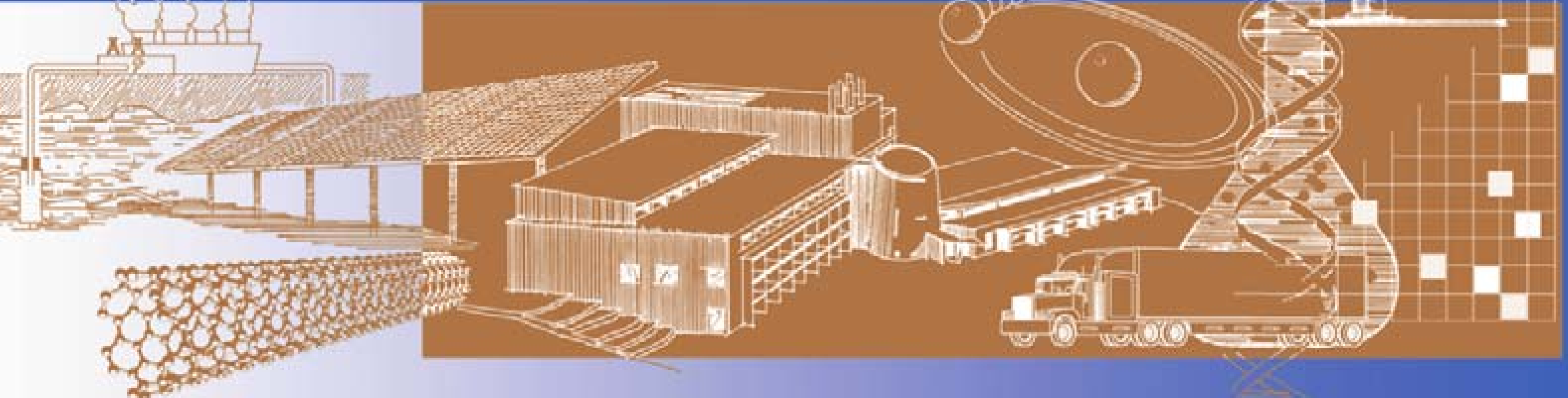
National Renewable Energy Laboratory
Innovation for Our Energy Future

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

S. Kurtz

Technical Report
NREL/TP-520-43208
Revised September 2008

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



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

Technical Report
NREL/TP-520-43208
Revised September 2008

S. Kurtz

Prepared under Task No. PVA7.4401

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

NOTICE

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

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

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

Introductory Note

The status of the solar industry is changing rapidly. If you would like this report to reflect the latest developments at your company, please send these to Sarah_Kurtz@nrel.gov. We will attempt to update this report periodically.

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.

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 minimal. The high- and low-concentration approaches are described in Parts I and II of this report, respectively.

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 record efficiency is 40.8% for a three-junction GaInP/GaInAs (1.3 eV)/GaInAs(0.9 eV) cell. [1] 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 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.

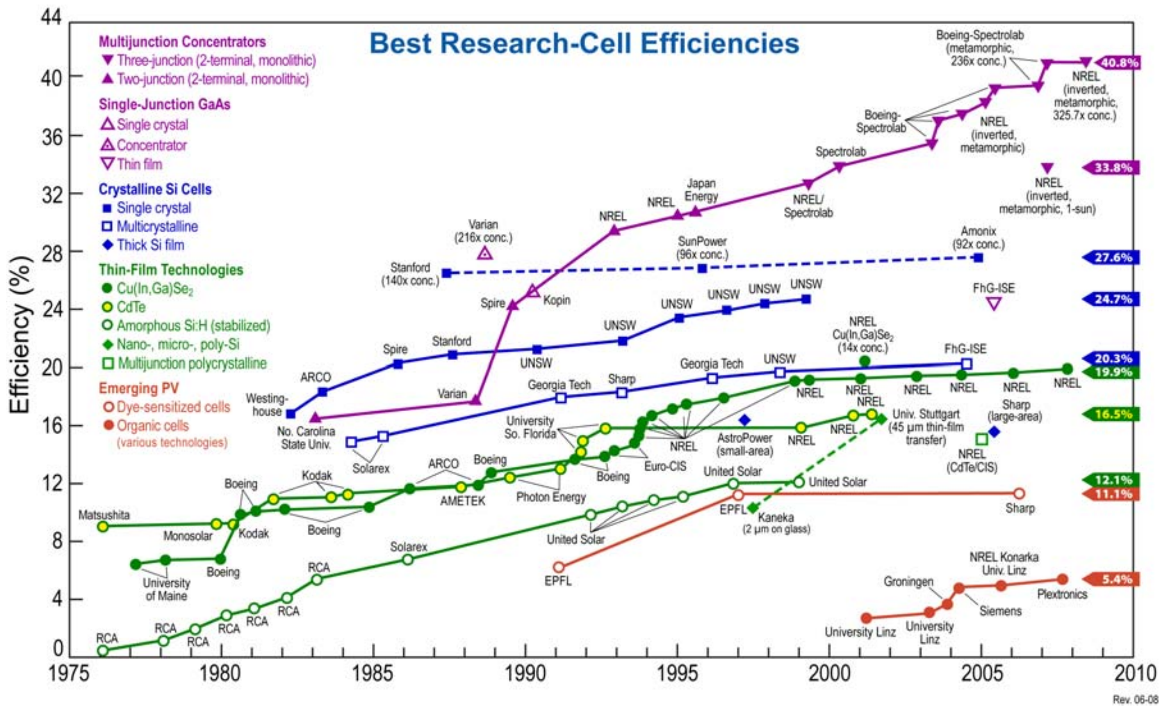


Fig. 1. Historic summary of champion cell efficiencies for various photovoltaic technologies. The highest efficiencies have been achieved for multijunction solar cells, increasing at a rate of almost 1% per year in recent years. Multijunction cell efficiencies have the potential to approach 50% in the 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] The Bosi review includes almost 100 references.

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.[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. Many are watching for the success of this demonstration.

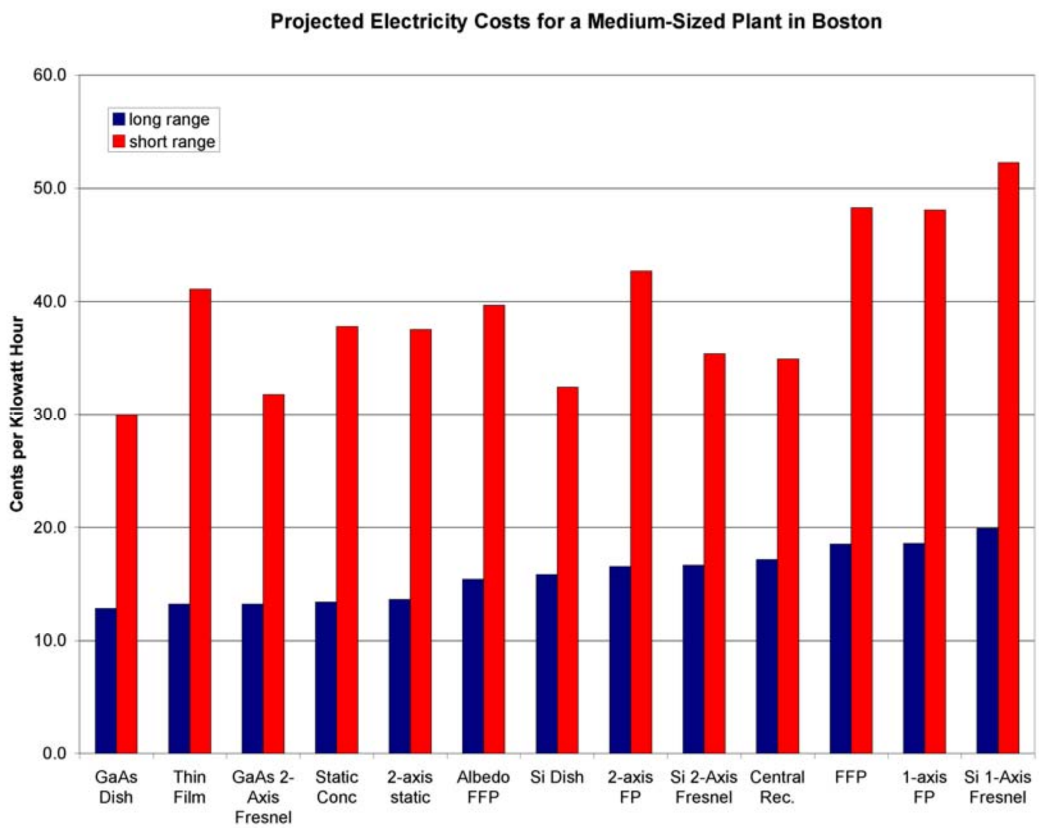


Figure A3 (from Ref.[6], color modified). For medium-sized plants in Boston, the GaAs dish surprisingly maintains its lead, despite the lower direct normal solar resources. (In other words, a dish based on 35% efficient cells is something of the ultimate technology.) The thin-film approach is a close 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.

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 company has ever 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 CPV Industry

Table 3 provides a partial list of today's CPV companies. This list has grown substantially in the last 5 years. Perhaps more important than the length of the list is the level of investment in the industry and the movement toward large-scale production. The industry has been projecting installations in the megawatt range for 10 years. In 2007, for the first time a CPV company delivered on such a projection: Guascor Foton installed 6 MW of high-concentration, silicon-based systems, using Amonix's CPV technology.[13] A company that might have attracted a $1-million investment 10 years ago may hope to attract $100 million today. Not surprisingly, the larger investment rates are enabling faster progress in the development, with multiple companies now reporting stable on-sun operation for months or years. At the Concentrated Photovoltaic Summit '08, Solar Systems reported on-sun operation for 2 years with no measurable degradation. Similarly, Emcore showed stable operation of a 2.5-kW system for 8 months, and ISFOC (Instituto de Sistemas Fotovoltaicos de Concentración) noted only "trivial" issues for systems at its CPV test site. ENTECH has been testing a 1+ kW triple-junction-cell concentrator array outdoors since July 2003 under a NASA-funded program, with no detectable performance degradation.[14] Reliable operation on-sun is the primary milestone that must be reached before CPV companies can begin the sort of rapid expansion that First Solar has demonstrated to be possible for a new technology. These reports of stable on-sun operation are an indication that rapid expansion could occur within the coming years.

Table 3. Summary of CPV Companies

Company	Type of System	Location	On Sun in 2007
Abengoa Solar	Multiple designs	Spain, USA	
American CPV		Orange, CA, USA	
Amonix	Lens, pedestal	Torrance, CA, USA	>100 kW (Si-based)
Arima Ecoenergy	Lens, pedestal	Taiwan	
Boeing	Mirror, Pedestal	Seal Beach, CA, USA	
Concentracion Solar La Mancha	Lens, pedestal	Ciudad Real, Spain	
Concentrating Technologies	Small mirror, pedestal	Alabama	>1 kW
Concentrix Solar	Lens, pedestal	Freiburg, Germany	~100 kW
Cool Earth Solar	Inflated mirrors	Livermore, CA, USA	>1 kW
Daido Steel	Lens, pedestal	Nagoya, Japan	
Emcore	Lens, pedestal	Albuquerque, NM, USA	>10 kW
Energy Innovations	Lens, carousel	Pasadena, CA, USA	
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	
GreenVolts	Small mirrors, carousel	San Francisco, CA, USA	>1 kW
Guascor Foton	Lens, pedestal	Ortuella, Spain	~10 MW (Si-based)
IBM	Lens	Armonk, NY	
Isofoton	Lens, pedestal	Malaga, Spain	
Menova	Modified trough	Ottawa, Ontario, Canada	
OPEL International	Lens, pedestal	Shelton, CT, USA	
Pyron	Lens, carousel	San Diego, CA, USA	>1 kW
Sharp	Lens, pedestal	Japan	
Sol3g	Lens, pedestal	Cerdanyola, Spain	>10 kW
Solar Systems	Dish, pedestal	Victoria, Australia	>100 kW
SolarTech	Lens, pedestal	Phoenix, AZ, USA	
Solar*Tec AG	Lens, pedestal	Munich, Germany	
SolFocus	Small mirror, pedestal	Mountain View, CA, USA	>10 kW
Soliant Energy	Lens, flat pivot	Pasadena, CA, USA	
Xtreme Energetics	Two designs for central station and rooftop	Livermore, CA, USA	

As documented in Table 3, multiple CPV companies have installed more than10 kW of prototypes in 2007. Many have plans to install hundreds of kilowatts or multiple megawatts in 2008.*

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. 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.

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. Most companies are testing prototypes and would like to accelerate the 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.

---

* Solar Systems and Amonix spent about 20 years developing Si-based concentrator systems. The advent of higher efficiencies for multijunction cells has motivated these two companies to reengineer their Si-based products. In the meantime, Amonix has worked with Guascor Foton to begin deployment of their Si-based CPV product at the multimegawatt scale. Table 3 shows these three companies with the largest installed systems in 2007, reflecting the many years of engineering invested in these systems.

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 60904-1 – Photovoltaic devices. Part 1: Measurement of photovoltaic current-voltage characteristics.	
IEC 60904-2 – Photovoltaic devices. Part 2: Requirements for reference solar devices.	
IEC 60904-3 – Photovoltaic devices. Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data.	
IEC 60904-5 – Photovoltaic devices. Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method.	
IEC 60904-7 – Photovoltaic devices. Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device.	
IEC 60904-8 – Photovoltaic devices. Part 8: Measurement of spectral response of a photovoltaic (PV) device.	
IEC 60904-9 – Photovoltaic devices. Part 9: Solar simulator performance requirements.	
IEC 60904-10 – Photovoltaic devices. Part 10: Methods of linearity measurement.	
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 (out for vote).	Initial draft being discussed.

Manufacturing Scale-Up and Retesting

After reliable prototypes have been demonstrated, companies must automate the manufacturing of these 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.

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?

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 for 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 and Emcore are currently shipping concentrator cells to multiple CPV companies, and all CPV companies reported adequate cell availability as of this writing. In the last few months, a significant number of new companies have demonstrated the capability for epitaxial (single-crystal) growth of multijunction cells. These are summarized in Table 5. Multiple start-up companies are developing recipes and are supplying samples in small volumes.

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

Company Name/Web Link	Comment
Spectrolab	Datasheet describes minimum average 36% cells and cell assemblies at 50 W/cm^2
Emcore	Datasheet describes typical 36% cells and receivers at 470 suns
Spire (Bandwidth)	Datasheet describes typical 35% cells at 500 suns
Cyrium	North America
Microlink Devices	North America
Azur Space (RWE)	Europe
CESI	Europe
Energies Nouvelles et Environnement (ENE)	Europe
IQE	Europe
Arima	Asia
Epistar	Asia
Sharp	Asia
VPEC	Asia

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

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). A number of companies are fabricating cells with efficiencies greater than 30%; some have demonstrated efficiencies in the range of 35%. As part of this study, cells were measured for both Arima and VPEC, confirming that these companies have cells approaching or exceeding 35%. We expect that these companies will be marketing multijunction solar cells in the near future. 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 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.

Emcore's current production capacity is ~300 MW/yr at 1000 suns, with expansion in progress to boost that capacity to 350 MW/yr by mid-2008. Spectrolab has plans for capacity in a similar range. Both Emcore and Spectrolab report that their primary barrier to expansion is confidence in future sales. As is standard in the business world, they are hesitant to invest in new capital equipment before expanded orders are in hand. Incremental additions to capacity can be implemented in less than 6 months once firm orders have been received. Additions requiring expansion into new facilities may require about a year depending on how long it takes to build a new building or acquire access to appropriate facilities. 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. This consideration would tend to associate lower cell costs with a small number of cell companies. In 2007, cell supply was a primary concern among CPV representatives. With the growing number of companies with cell capability, this concern is substantially reduced.

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%. 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.

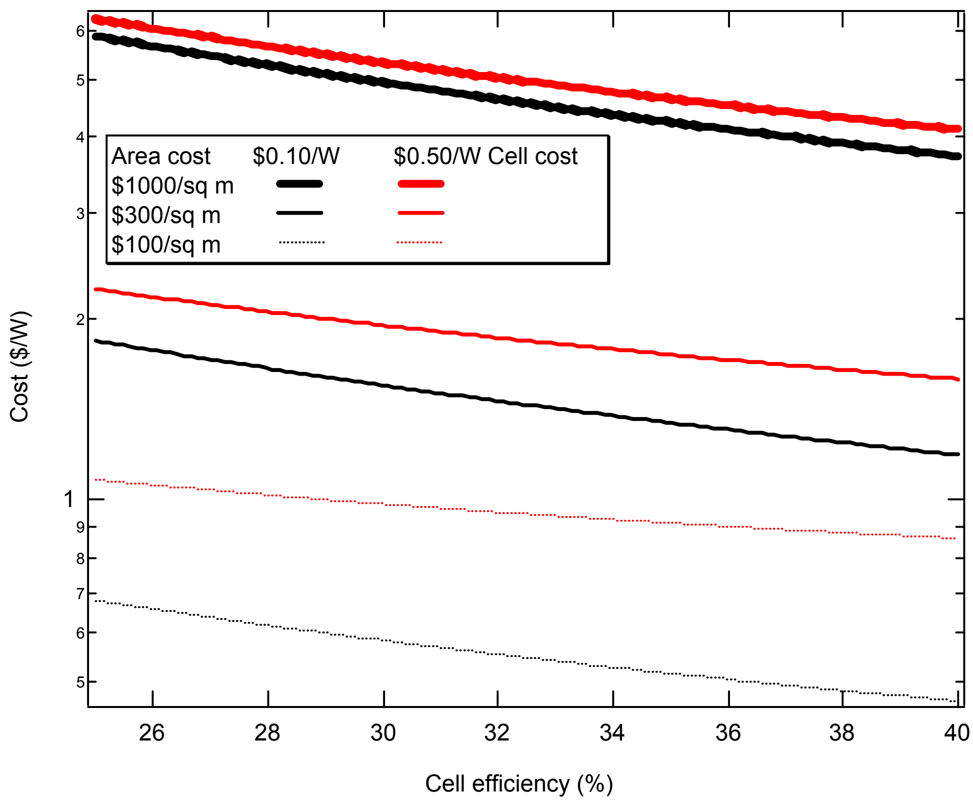


Fig. 3. System cost as a function of cell cost and non-cell costs. The power was decreased from 850 to 690 W/m^2 to account for optical and thermal losses. The equation used to calculate these data was Cost (\$/W) = Area cost (\$/m^2)/Efficiency X 690 (W/m^2)) + Cell cost (\$/W). The definition of cell 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.

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 the 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, we identified only one company (in addition to the cell companies) that is marketing multijunction CPV cell assemblies: Delta Electronics of Taiwan. 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.

Underwriters Laboratories (UL) certification is required for building-integrated applications. UL is developing the capability to complete a UL certification on CPV systems.

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. The dotted box includes the supplies they estimated would be available worldwide. 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.

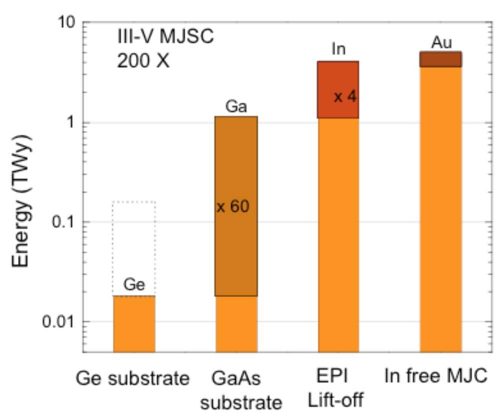


Fig. 4: Potential energy limits imposed to III-V multi-junction cells (200 sun concentrations). The third and fourth columns show the extrapolated potential of this technology if the substrates are ignored.

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.)

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 30 companies are developing concentrator photovoltaic systems, and many have already deployed 1–100 kW 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.

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 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 could be viewed as paving the way for concentrator systems when PV system costs are reduced.

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 may conclude that low-cost trackers may be key to the success of low-concentration systems.

Currently, 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, 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. 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.
JX Crystals has deployed more than 100 kW. WS Energia was selected from 3500 candidates for recognition in the LIVE EDGE competition. Solaria was 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
Covalent Solar	Luminescent, multiple types of cells	Boston, MA, USA	
CPower	Reflective, 25X–30X (point focus), Si cells	Ferrara, Italy	
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
Maxxun	Luminescent	Eindhoven, Netherlands	
Morgan Solar	Non-tracking, building integrated	Toronto, ON, Canada	
Netcrystal	Non-tracking; Si cells	San Francisco, 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		CA, USA	
Solaria	2X–3X; Si cells	Fremont, CA, USA	
Solbeam	Tracking optics in flat configuration	Laguna Niguel, CA, USA	
Stellaris	Static	North Billerica, MA, USA	
Silicon Valley Solar	Flat-plate dimensions	Sunnyvale, CA, USA	

Company	Type of System	Location	On Sun in 2007
Sunengy	Liquid; Si cells	Australia	
Thales Research	Static, reflective	Severna Park, MD, USA	
Whitfield Solar	Linear Fresnel lens, ~40X; Si cells	Reading, UK	
WS Energia	Reflective, linear, Si modules	Oeriias, Portugal	>10 kW
Zytech Solar	Reflective, linear, Si modules	Zaragoza, Spain	

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. Companies that may be involved include 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 originally planned 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, almost 20 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.

Acknowledgments

We extend our sincere gratitude to the *many* individuals who contributed to this report. Special thanks go to David Danzilio, Geoff Kinsey, Greg Peisert, Jerry Olson, Bob Cart, Brad Hines, Jeff Gordon, Craig Cornelius, Lori Greene, and Susan Moon. This work was funded by the U.S. Department of Energy under Contract No. DE-AC36-99-GO10337.

References

[1] 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).

[2] 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).

[3] 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.

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

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

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

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

[8] 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).

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

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

[11] 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).

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

[13] Presented at the Concentrated Photovoltaic Summit '08, http://www.cpvtoday.com/eu08/.

[14] Mehdi IS, George PJ, O'Neill MJ, Matson R, and Brockschmidt A, "High voltage solar concentrator experiment with implications for future space missions," Solar Power from Space and 5th Wireless Power Transmission Conference, Granada, Spain, 2004.

[15] *Accelerated Aging Testing and Reliability in Photovoltaics Workshop II Summary Report,* April 1 and 2, 2008, http://www.eere.energy.gov/solar/solar_america/pdfs/accelerated_aging_report_2008.pdf

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

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

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

[19] 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.

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

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

[22] 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.

[23] 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.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
Revised September 2008	Technical Report	

4. TITLE AND SUBTITLE
Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry (Revision)

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Sarah Kurtz

5d. PROJECT NUMBER
NREL/TP-520-43208

5e. TASK NUMBER
PVA7.4401

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-520-43208

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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; this revision adds low-concentration approaches using silicon or other inexpensive solar cells.

15. SUBJECT TERMS
concentrating photovoltaics; CPV; concentrator cells; industry; vertical integration; prototype development; qualification standards; material availability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPONE NUMBER *(Include area code)*