Current status of the concentrating photovoltaic power industry

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ABSTRACT

Today's 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 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 (di)selenide on glass or other substrates). Concentrating photovoltaics (CPV) follows a complementary approach and uses concentrating optics, which may be designed for low or high concentration, to focus the light onto small cells. 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.

Introduction

Concentrator cells have recently 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 (1.3eV)/GaInAs (0.9eV) cell [1]. A historical summary of champion cell efficiencies is shown in Figure 1. Multijunction concentrator cells have achieved much higher efficiencies than any other approach. This is not surprising for two reasons: (i) the highest efficiencies may be achieved if multiple semiconductor materials (with a range of bandgaps) are chosen to match the spectral distribution of the sun, and (ii) 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.

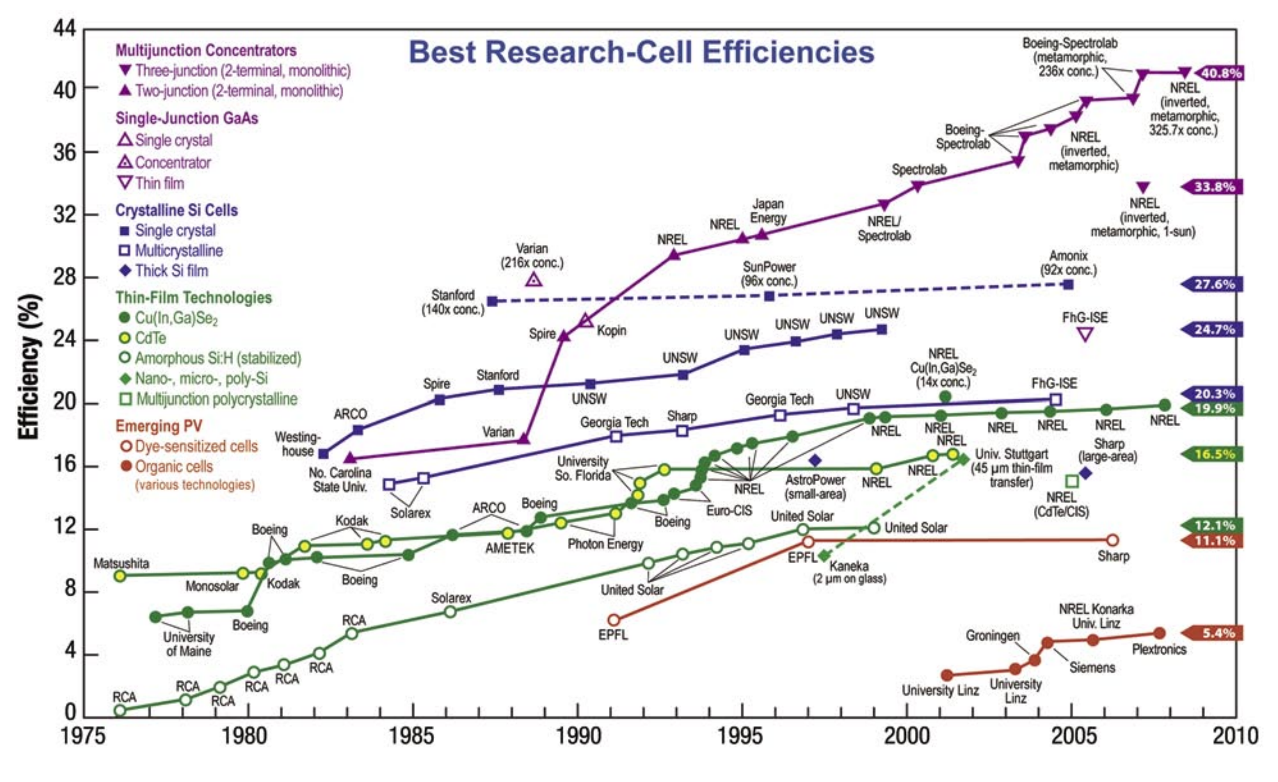

Figure 1. Historic summary of champion cell efficiencies for various photovoltaic technologies. The highest efficiencies have been achieved for multijunction solar cells, increasing at a rate of almost 1% per year in recent years. Multijunction cell efficiencies have the potential to approach 50% in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

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	>100kW (Si-based)
Arima Ecoenergy	Lens, pedestal	Taiwan	
Boeing		USA	
Concentracion Solar La Mancha	Lens, pedestal	Ciudad Real, Spain	
Concentrating Technologies	Small mirror, pedestal	Alabama	>1kW
Concentrix Solar	Lens, pedestal	Freiburg, Germany	~100kW
Cool Earth Solar	Inflated mirrors	Livermore, CA, USA	>1kW
Daido Steel	Lens, pedestal	Nagoya, Japan	
Emcore	Lens, pedestal	Albuquerque, NM, USA	>10kW
Energy Innovations	Lens, carousel	Pasadena, CA, USA	
Enfocus Engineering	Lens, flat pivot	Sunnyvale, CA, USA	
ENTECH	Lens, pedestal	Keller, TX, USA	>1kW since 2003; >100kW (Si based)
EVERPHOTON Energy	Lens, pedestal	Taipei, Taiwan	
Green and Gold	Lens, pedestal	South Australia	
GreenVolts	Small mirrors, carousel	San Francisco, CA, USA	>1kW
Guascor Foton	Lens, pedestal	Ortuella, Spain	~10MW (Si-based)
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	>1kW
Sharp	Lens, pedestal	Japan	
Sol3g	Lens, pedestal	Cerdanyola, Spain	>10kW
Solar Systems	Dish, pedestal	Victoria, Australia	>100kW
Solar*Tec AG	Lens, pedestal	Munich, Germany	
SolarTech	Lens, pedestal	Phoenix, AZ, USA	
SolFocus	Small mirror, pedestal	Mountain View, CA, USA	>10kW
Soliant Energy	Lens, flat pivot	Pasadena, CA, USA	

Table 1. Summary of CPV companies.

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 US$1 billion. Solar fields, which often use tracked systems, are becoming more common, providing a potentially huge

Company Name	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.

Table 2. Summary of companies with capability for epitaxial growth of multijunction cells.*

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 (reference 4) includes almost 100 references.

Some cost analyses have predicted that using high-efficiency concentrator cells can lead to very low costs for solar electricity [5,6,12]. These studies imply that there is a potential for cost-effective implementation of high-concentration systems even in locations such as Boston, Massachusetts [6]. The energy payback of some CPV systems has also been studied [13]. 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.

Current status of the CPV industry

Table 1 provides a partial list of today's CPV companies. This list has grown substantially in the last five 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. A company that might have attracted a US$1 million investment 10 years ago may hope to attract US$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 [12]. 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. Recent reports of stable on-sun operation are an indication that rapid expansion could occur within the coming years.

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. A significant number of new companies have recently demonstrated the capability for epitaxial (single-crystal) growth of multijunction cells. These are summarized in Table 2. Multiple start-up companies are developing recipes and are supplying samples in small volumes.

A quick review of the companies in Table 2 implies that the supply of cells is increasing. 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. 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 (i) years of experience with space cells manufactured for operation at up to 250°C; (ii) 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 (iii) a year (and counting) of stable on-sun terrestrial operation at 500 suns. Spectrolab has a similar space heritage and has tested its CPV

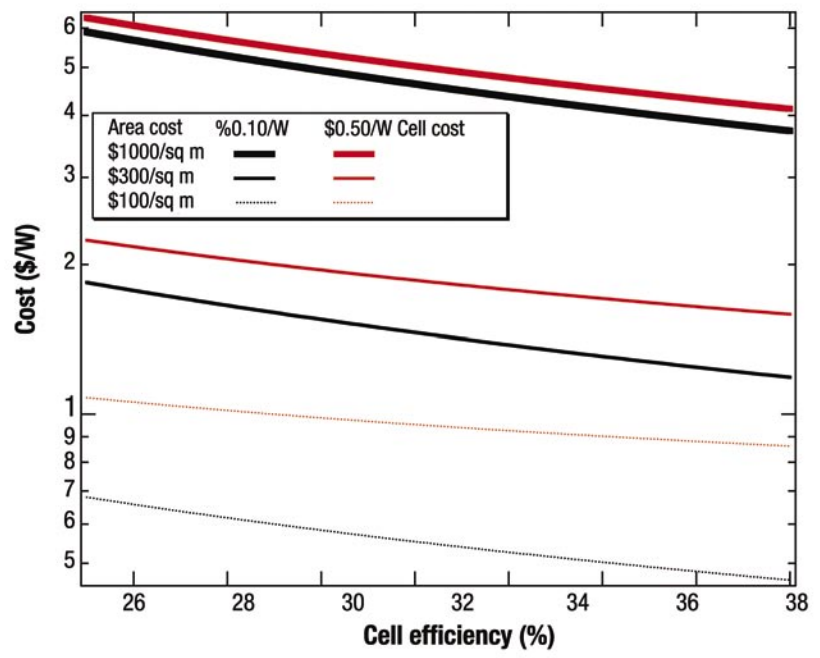

Figure 2. System cost as a function of cell cost and non-cell costs. The power was decreased from 850 to 690W/m^2 to account for optical and thermal losses. The equation used to calculate these data was Cost ($/W) = Area cost ($/m^2)/Efficiency x 690 (W/m^2) + Cell cost ($/W). The definition of cell cost in US$/W has 20%–35% uncertainty because it may or may not account for optical and/or thermal losses.

cells using the thermal-cycling, humidity, and humidity-freeze tests described in IEEE 1513-2001.

Emcore's current production capacity is ~350MW/yr at 1000 suns. 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. 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 particularly complex as companies attempt to define whether to merge or separate these efforts.

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, and are expected to continue to increase toward 45%–50%. Spectrolab has reported an efficiency of 40.7% [2]; Emcore claims an efficiency of 39%; and NREL has described a new inverted structure at a record 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 Figure 2. The cell cost in US$/W is strongly dependent on concentration. The cell costs of US$0.50/W and US$0.10/W represent, respectively, what is achievable today and what may be achieved in the future [12]. The US$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 US$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. For US$1,000/m^2 systems, efficiency is clearly a strong cost driver. But if the system cost can be reduced to US$100/m^2 without further increase in cell cost, then efficiency becomes unimportant. 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 Figure 2 caption.

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). Multiple companies are now developing a germanium wafer capability, including AXT (Fremont, California); Sylarus (St. George, Utah); and PBT (Zurich, Switzerland). 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. The current availability of germanium should support industry growth up to ~4GW/yr [12].

Conclusion

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 high-concentration photovoltaic systems, and many have already deployed 1-100kW 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.

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