The Path to 1 GW of Concentrator Photovoltaics Using Multijunction Solar Cells

Raed A. Sherif, Richard R. King, Nasser H. Karam, and David R. Lillington
Spectrolab, Inc., 12500 Gladstone Ave, Sylmar, CA 91342, USA

ABSTRACT

This paper presents an overview of the status of the High-Concentration Photovoltaic (HCPV) module technology and discusses the steps required to take it from to the production of gigawatts in the near future. The paper discusses the impact of the recent advances in multijunction cell technology on the economics of concentrator system.

Introduction

Multijunction (MJ) solar cells are the most efficient photovoltaic devices with 32% conversion efficiencies at 1-sun and above 37% under concentrated sunlight [1]. They have traditionally been used to power satellites and other spacecraft, *e.g.*, the Mars Rover mission, as their higher efficiency enables higher specific power generation for the spacecraft. Multijunction cell technology was recently inducted into the Space Technology Hall of Fame in recognition of its contribution to the advancement of satellite technology, thus enhancing the quality of life on earth. The use of MJ cells to generate clean energy for terrestrial applications has been sought because, when combined with high concentration, MJ cell modules have the potential of producing the lowest $/watt amongst solar technologies [2]. In a High Concentration Photovoltaic (HCPV) module, *e.g.*, at 500 suns, one cm^2 of cell area produces the same amount of electricity as 500 cm^2 of cell area would produce without concentration. Cost reduction in this case is achieved by replacing the more expensive semiconductor area by the less expensive materials, *e.g.*, mirrors and lenses. Of course, the cost equation is never that simple. With high concentration, there is a need to provide dual-axis tracking, and heat dissipation becomes much harder to achieve. Nonetheless, when everything is factored in, HCPV modules with MJ cells seem to fare well among other solar technologies in terms of cost.

With that in mind, we take note that to date there is less than 1 MW of installed power using concentrator photovoltaics, and only 1 kW of that is using MJ solar cells. We need to investigate why HCPV modules with MJ cells, which have the potential for achieving better cost than other solar technologies, are not already dominant in the field, producing electricity for utility companies as well as for commercial and residential consumers.

In this paper, we will start with reviewing the HCPV module technology as of the end of 2004. This will be followed by discussion of the path towards achieving 1 GW of electricity using concentrator MJ cells.

HCPV Module Overview

In order to design HCPV modules, there are several questions that need to be answered. First, the designer needs to define whether the concentration will be achieved via reflective or refractive optics. A reflective optics system is likely to be one that uses central receiver, where an array of cells densely packed close to each other receives the concentrated sunlight. This is the case of the Solar Systems module currently operating in central Australia [3]. The module is shown in Fig. 1. There are currently 10 systems in operation, producing over 200kW of electricity using Sunpower's co-planar silicon cells, with about 25% efficiency at standard test conditions. With dense arrays, active cooling is required to maintain the cells at reasonable operating temperature. In the Solar Systems module, this means the cells will operate at a maximum temperature of only 45° C. Such low operating temperature has the advantage of producing low levels of thermal stresses on the solar cells and the solder joints connecting them to the cooling plates.

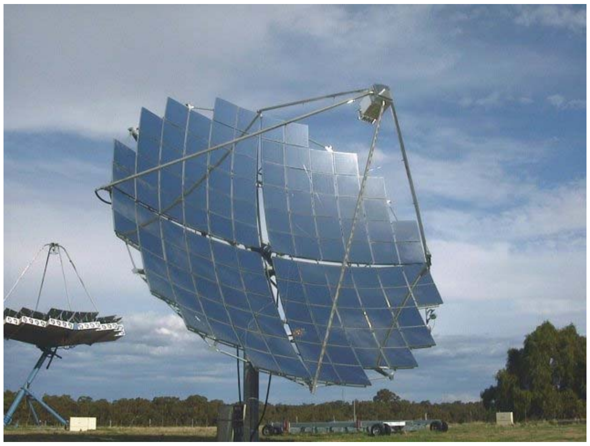

Fig. 1. The Solar Systems Module in Australia

The Amonix module takes a different approach [4]. In this module, a parquet of Fresnel lenses concentrates the light on individual cells mounted on a heat sink, as shown in Fig. 2. Because the cells are spaced far apart from each other, this approach allows passive cooling of the cells without raising the temperature much above the ambient. Expected temperature rise above the ambient is dependent on the wind speed, as with any passive cooling system. Typical operating cell temperature is only 20-25° C above the ambient air. The Amonix module also uses the same co-planar Si cell technology. There are currently over 700kW of installed modules in the US, located mostly in Arizona (operated by the Arizona Public Service utility company) and in Nevada.

Fig. 2. The Amonix Mega Module

A new addition to the family of HCPV modules is the Concentrating Technologies (CT) micro dish module currently installed at the APS Solar Test & Research (STAR) facility in Tempe, AZ. Although its output is very small, under 1kW, its significance comes from the fact that it is the first demonstration of the multijunction cell technology in a grid-connected, high concentration module [5]. The approach taken by CT in this module is a combination of reflective optics and the distributed location of small cells typical of refractive concentrators, thus avoiding the use of active cooling in a central receiver. This is accomplished by having a micro array of mirrors focusing the light on individual Power Conversion Units (PCUs), as shown in Fig. 3. Each PCU has a secondary optical element to homogenize the light before it falls on the cells, and a heat sink attached to the back of the PCU to radiate heat to the ambient air.

Fig. 3a. The Concentrating Technologies Module

Fig. 3b. Individual Power Conversion Units receiving Concentrated Sunlight in the CT Module

Another concentrating photovoltaic module that uses triple-junction solar cells is the Pyron module. The photovoltaic cells are arranged in “light troughs” which are covered by lenses with short focal length, as shown in Fig. 4. The troughs are arranged on a platform mounted on a circular ring floating on a thin layer of water. The platform follows the azimuthal movement of the sun by turning around its vertical axis. The troughs follow the sun’s elevation by tilting around their horizontal axes. This type of tracking allows the module to have a low profile, thus enhancing its resistance to wind loads. This module is currently located in El Cajon, CA.

Fig. 4. The Pyron Module

In addition to the above modules, there are currently several other HCPV modules that are in the development and early prototyping stages. We expect that in the next 2 years, many more HCPV modules will be installed in the field.

Concentrator MJ Cell Technology Roadmap

Concentrator solar cells for terrestrial applications have shown a rapid surge in demonstrated efficiency in recent years. Multijunction cells have reached the point at which the next set of technology improvements are likely to push efficiencies over 40% [6].

The path to achieve higher cell efficiency is based on bandgap engineering, where the subcells of the MJ cell stack are engineered to achieve best utilization of the solar spectrum. Lattice-matched (LM) triple-junction cell structures have achieved world-record of 37.3% under 175 suns, as measured by the National Renewable Energy Laboratory (NREL) using the concentrator terrestrial AM1.5D, low-AOD spectrum [1].

Recent advances in lattice-mismatched or metamorphic (MM) triple-junction structures look very promising. The GaInP/GaInAs/Ge with 8%-In in the middle cell base at a 0.5% lattice mismatch with respect to the Ge substrate has reached 36.9% under the same concentrator terrestrial spectrum [1]. By adjusting the Indium content in the GaInAs subcell, we can achieve lower middle subcell bandgap which leads to better utilization of the spectrum and, hence, higher cell efficiency, as shown in Fig. 5.

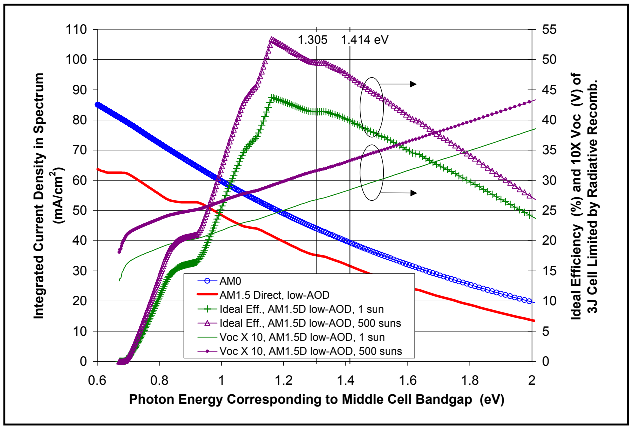

Fig. 5. Impact of Middle Subcell Bandgap on 3J Cell Efficiency

The lower middle subcell bandgap, however, comes at the expense of increasing the lattice-mismatch between the GaInAs and Ge substrate. The challenges associated with growing a mismatched structure on top of the Ge substrate include the use of buffer layers to minimize the spread of threading dislocations that can result from the lattice mismatch into the active cell regions. The light I-V parameters of the world-record LM and MM cells are shown in Fig. 6. Note that the MM cell has lower voltage due to the lower bandgaps of its top and middle subcells, but this is counteracted by the higher current of the MM cell, due to the ability of the upper two subcells to utilize longer wavelengths in the solar spectrum.

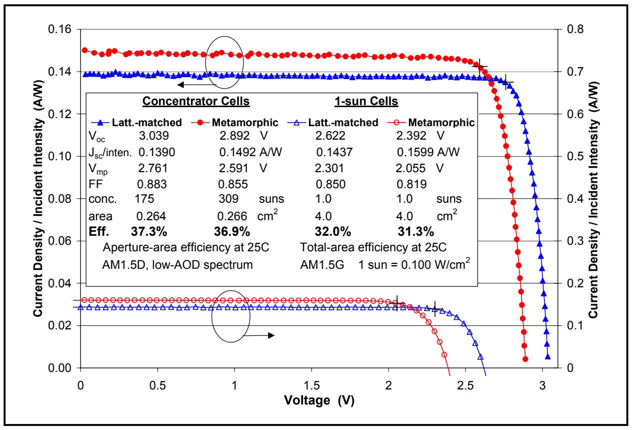

Fig. 6. Light I-V of World-Record LM & MM 3J Cells

Research into the development of 4-, 5- and 6-junction solar cells is also progressing. The use of 1-eV GaInNAs material is a key part of the development of these devices and has been investigated by NREL. Spectrolab has demonstrated some 5- and 6-junction cell structures that look promising, with the cells achieving higher voltage and lower current than traditional triple-junction cells [1]. Lower current helps reduce the series resistance associated with concentrator cells.

The on-going effort to optimize the MJ device structure is funded by several government agencies as well as by the PV industry. We believe that near term goals of 40% cell efficiency, and long-term goals of 45% and above are quite feasible. Figure 7 shows Spectrolab's concentrator MJ cell technology roadmap.

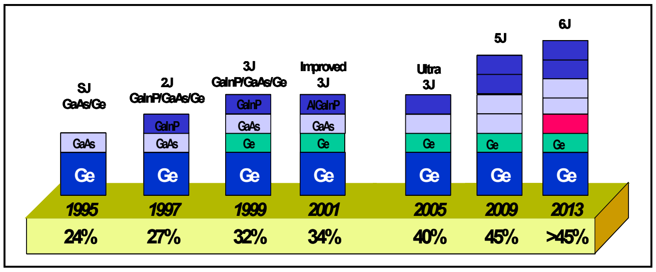

Fig. 7. Concentrator MJ Cell Technology Roadmap at Spectrolab

HCPV Module & MJ Cell Economics

The growing interest in HCPV module technology is a reflection of the favorable economics of this type of module. This was largely enabled by the fact that the cell efficiency has increased, and is likely to continue to increase as we have discussed in the last section. The cell efficiency, in fact, is very leveraging to the overall system cost. Figure 8 shows how the cost of energy production in a HCPV system is dependent on the cell conversion efficiency (assuming concentration of 500 suns), while Fig. 9 shows how the HCPV system energy cost compares with that of fixed flat plate PV systems.

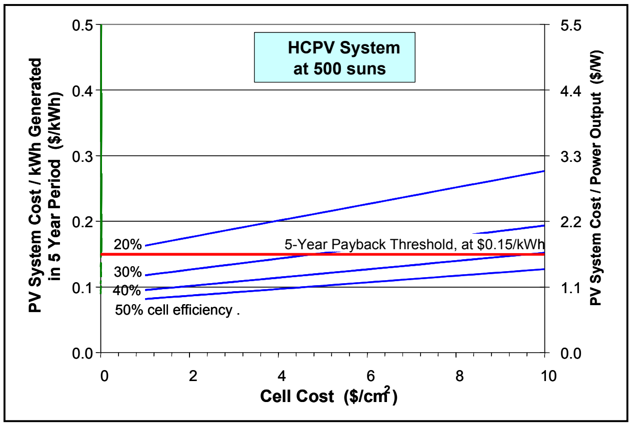

Fig. 8. Impact of Cell Efficiency on HCPV System Cost

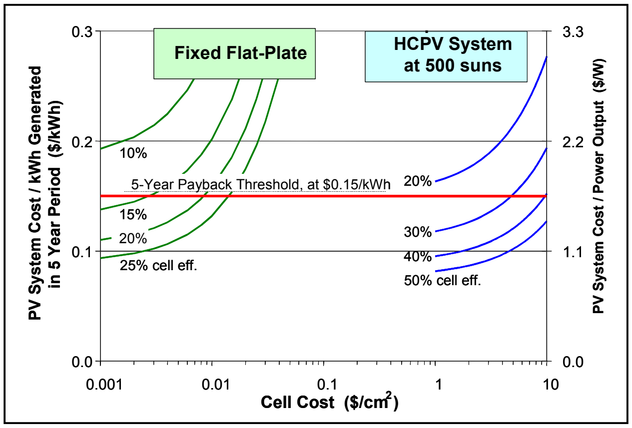

Fig. 9. Comparison of HCPV and Flat Plate PV System Energy Costs

The data presented in the above charts are based on the cost parameters proposed by Swanson in [2]. The data is assumed at production volumes of 5-10 MW per year. The data suggests that a 30% cell needs to be under \$5 per cm^2, while a 40% cell can be almost twice as expensive, for the HCPV system at (500 suns) to have a 5-year payback period. It is important to note, however, that the cell efficiencies in these charts are actual operating efficiencies not efficiencies measured at standard test conditions.

We now take a close look at the cost of fabrication of MJ cells to determine where we are at present, and how we can meet the cost targets shown in the previous charts.

The cost of fabrication of MJ cells involves 3 elements: (i) The Ge wafer cost, (ii) The cost of growing the device structure in the Metal Organic Vapor Phase Epitaxy (MOVPE) reactors, and (iii) The cost of cell fabrication, including deposition of the anti-reflection coating and the metal pattern on the wafer, saw dicing process to separate the cells from the wafer, and cell testing. The breakdown of the costs of the above elements is dependent on several factors, including the quality of the Ge wafers to be used, the size of the cells to be fabricated (which determines the number of cells to test and the number of cuts required to separate the cells from the wafer), and the cell efficiency specs (which impact the electrical yield). The volume of production and the manufacturing efficiency (*e.g.*, level of automated processes vs. manual labor) are clearly some of the key factors that determine the final cell price. Figure 10 provides the projected cell price for a 1cm x 1cm cell aperture area (physical cell size is 1.1cm x 1.0cm) at different volumes of production and under different scenarios.

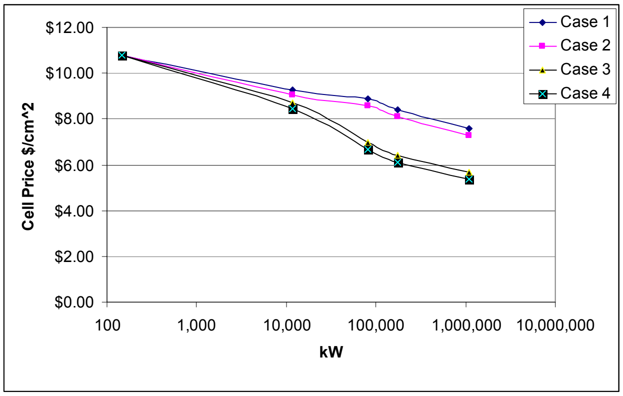

Fig. 10. Projected Cell Price at Different Volumes

In the above figure, Case 1 refers to the situation where no specific material or process cost reduction activities are included. Price reduction with volume is driven primarily by the economies-of-scale. In Case 2, price reduction is driven by a combination of the economies-of-scale and Ge wafer cost reduction. The Ge wafer cost reduction in this model is driven by the growth of the MJ cell structure on “terrestrial-grade Ge wafers” allowing for higher defect counts in the wafer. The idea behind the use of lower quality Ge wafers is motivated by the fact that some minor shunts that are visible at 1-sun will be insignificant at the high current densities under concentrated sunlight. In Case 3, no material cost reduction is implemented; rather the cell price reduction is driven by economies-of-scale and cell fabrication process improvements. The main driver here is the use of an alternative process to the saw-dicing process to separate the cells from the wafer and implementing a more cost-effective approach, *e.g.*, scribe-and-break or laser cutting. Case 4 combines everything, *i.e.*, it includes cost reduction driven by economies-of-scale, the use of terrestrial-grade Ge wafers, and the implementation of cell fabrication process improvements.

Another way of looking at the projected cell prices is to express the price as $/watt. Of course in this case, the concentration level and the cell efficiency need to be specified. Figure 11 shows the projected cell price in terms of $/watt assuming 50 W/cm^2 incident energy on the cells. The data is presented for different cell efficiencies and it takes full account of all cost reduction activities discussed previously.

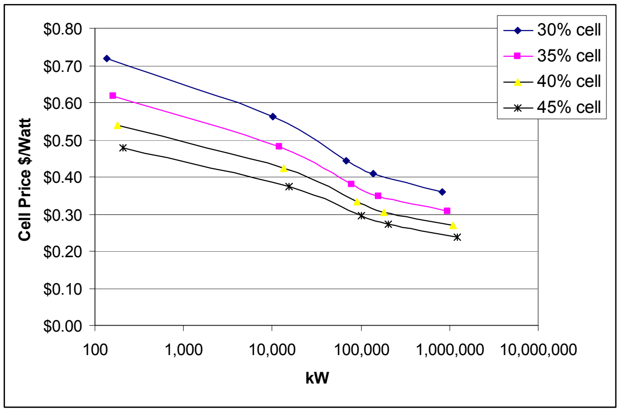

Fig. 11. Projected Cell Price expressed as $/watt

Performance, Reliability, and Cost Tradeoffs

In HCPV modules, the issues of cost, performance, and reliability are closely tied to each other. The price charts of the previous section were all presented at concentration ratios of 500 suns because this is a moderate concentration that can readily be achieved with a variety of primary optics systems, and because much of the available data is at this concentration [7]. For a given collector area, the same module output can be obtained from smaller cells subjected to higher concentration ratios, or larger cells subjected to smaller concentration ratios. For example, a 1000 cm^2 collector with optical efficiency of 90% can provide concentration of 1000 suns on 0.9cm^2 cell, or 500 suns on 1.8cm^2 cell. Assuming both cells operate at the same efficiency at the range of 500-1000 suns, it can be argued that the module with the smaller semiconductor area will be cheaper. Following that logic, the concentration ratio should be pushed higher to several thousand suns, driving the semiconductor area to be even smaller. There are, however, some tradeoffs that must be understood before we can decide on the optimal concentration ratio.

At higher concentration ratios, maintaining the tracking accuracy becomes more difficult (and hence more expensive). Further, heat removal from the cells becomes more challenging. The heating problem can be made simpler if the power density (W/cm^2) is reduced (*i.e.*, use lower concentration ratio) and/or the absolute power (W) is reduced (*i.e.*, use smaller cells). The use of smaller cells, though it enables higher concentration ratios to be achieved and makes heat removal simpler, means that there are more cells to be fabricated out of a wafer and more parts to be assembled in a module. Further, the reliability of MJ cells in ultra-high concentration regimes (above 1000 suns) are yet to be fully understood. Issues of tunnel junction stability at the higher current densities generated in ultra-high concentration regimes must be addressed. The performance, reliability, and cost tradeoffs of MJ cells in HCPV modules at concentration ratios of a few hundred suns to a few thousand suns will be discussed in greater detail in [8].

Opportunities and Barriers to Market Entry

It is clear that recent advances in MJ cell technology are making concentrator PV module look very attractive. However, the technology requires some large-scale production in order for its cost advantages to start to materialize. The question then becomes how do we get from the present status, with less than 1 MW of concentrator PV systems worldwide, to the situation in which gigawatts of electricity are being supplied by HCPV systems.

Reliability

One key issue facing the HCPV technology is to overcome its perceived lack of reliability. The key to reliability in the field has always been the existence of test standards [9]. This conclusion is supported by the early experience of flat plate PV modules, where the creation of test standards provided “uniform and repeatable tests that enabled identification of design and/or fabrication deficiencies” before deployment [9]. The high reliability of flat plate PV modules, coupled with the strides made to reduce their cost over the years, has been responsible for the excellent market growth that flat plate modules have enjoyed over the last decade.

The definition of HCPV module qualification standards started in 1997 and resulted in the publication of the IEEE 1513-standards in 2001 [9]. The Amonix module, for example, has been going through the qualification tests that are defined in this document, with the tests being performed at the Arizona State University Photovoltaic Testing Lab. Solar Systems, on the other hand, are performing their own qualification tests taking into account their specific module operating conditions. It is important that the qualification tests take into account the peculiarities of each type of HCPV system. For example, the temperature swings of HCPV modules are quite different from those generated in flat plate PV modules. In a HCPV module, the cells are likely to operate at higher temperatures. More importantly, in the case of partial shadow, the cell temperature will drop very rapidly in a HCPV module, while the temperature change will be much slower in flat plate modules. As the shadowing condition disappears, the cell temperature in HCPV modules comes up again almost instantaneously. In other words, the cells could be subjected to tens of temperature cycles in one day of the HCPV module operation, whereas flat plate modules will experience fewer and less severe cycles per day. Another important distinction is the fact that cells are usually soldered to the heat sinks in HCPV modules, while they are usually connected to the heat sink by thermal adhesive in flat plate modules. Solder joints are more rigid and, therefore, can break more easily in temperature cycles. Even more critical is the fact that the loss of thermal interface in HCPV modules will lead to instant failure of the cells, whereas the impact in flat plate modules is not as severe. In short, we believe that extreme care must be taken in defining and performing the qualification tests for HCPV systems to make sure that all failure mechanisms are properly addressed.

Markets

Aside from reliability, one issue that has been a barrier against the entry of HCPV modules into the marketplace has been the perception that these modules can only serve the utility energy markets. This has meant that concentrator modules have needed to compete (in price) with the conventional (and cheaper) fossil fuel plants. The success of flat plate PV modules is due in part to its ability to offer solutions for remote, off-grid (distributed energy) markets. The rapid growth of flat plate PV modules that is being fueled today, 30-40% growth over the last 5 years, has been mainly driven by roof top applications.

In order for HCPV modules to penetrate the distributed energy market, they must demonstrate high reliability to the point of being almost maintenance-free. They need to be modular in construction, where as small as 1-2kW of power can be provided for customers. And, in order to penetrate the rooftop applications, they need to present different designs (low-profile designs with minimal impact to performance from wind loads).

One particular market that needs to be explored by the HCPV community is in the developing world. This is driven in part by the fact that developing countries happen to be among the sites with the most plentiful direct solar energy resource. More importantly, however, it is driven by the fact that in a HCPV system, most of the system components can be manufactured and assembled locally. The part that requires specialized manufacturing capability is the MJ solar cell itself. But since the cost of the MJ cell is only a small fraction of the overall system cost, the use of HCPV modules can be regarded as a means of not just creating energy but also as a source of job creation in local communities. The cheaper labor cost in these countries will help lower the cost of the entire system. Some of the early work can be funded by international agencies to promote the use of renewable sources of energy.

Manufacturing Capabilities

Any discussion of photovoltaic cell production at the gigawatt level and above cannot be complete without addressing the capabilities of the manufacturers to meet the demands. Among the distinct advantages of HCPV systems are the similarities they have with wind energy, specifically when it comes to large-scale production [9]. Wind energy systems have grown from negligible power output in the mid 1970s to over 20 GW of power worldwide as of today. The similarities between the two technologies are: (1) They both use relatively common materials (with the exception of the MJ cell itself), and (2) They both can follow an assembly line type of production [10]. This leaves the fabrication of the MJ cells as the greatest potential obstacle to achieving gigawatts of production. After all, the number of MJ cell suppliers is very limited worldwide. Spectrolab, being the world leader in this field, has the infrastructure to produce up to 7000 wafers per week. At a concentration of 500 suns, this is equivalent to 7 MW per week. Thus the existing capacity of a plant of Spectrolab's size can generate 350 MW of concentrating photovoltaics per year, more than 1/3 of the way to 1GW/year production. This observation reveals another powerful advantage of the HCPV technology: operation at 500 suns has the effect of increasing the manufacturing capacity of a one-sun PV plant by approximately the same ratio of 500X.

Conclusions

The concentrating PV module technology can produce electricity at competitive prices, thanks in great part to the recent advances in multijunction cell technology. Large-scale deployment of HCPV systems will depend on demonstrating reliable field operation. Module reliability must be coupled to the definition and execution of a qualifications test procedure that takes into account the peculiarities of the HCPV systems. Novel designs that can target rooftop applications will greatly help the technology penetrate this fast-growing market segment. Potential opportunities for the HCPV modules in developing markets need to be investigated once reliability is proven. The similarities between the concentrating PV systems and wind energy systems suggest that a fast transition is possible to take HCPV module production from the 1MW of today to over 1 GW in the near future.

REFERENCES

[1] R. King et al., “Metamorphic III-V Materials, Sublattice Disorder, and Multi-Junction Solar Cell Approaches With Over 37% cell Efficiency,” *Proc. 19th European Solar Cell Conf. & Exhibition,* Paris, France 2004.

[2] R.M. Swanson, “The Promise of Concentrators,” *Prog. Photovolt. Res Appl.* **8**, 93-111 (2000).

[3] D. Holland, “Overview of Solar Systems,” Presentation at the International Solar Concentrator Conference, Alice Springs, AU, November 2003.

[4] V. Garboushian et al., “A Novel High-Concentration PV Technology for Cost Competitive Utility Bulk Power Generation,” Amonix website.

[5] R. Sherif et al, “First Demonstration of Multjinction Receivers in a Grid-Connected Concentrator Module,“ Proc. 31st IEEE PVSC, Florida, January 3-7, 2005.

[6] R. King et al., “Pathways To 40%-Efficient Concentrator Photovoltaics,” submitted to the 20th European Solar Energy Conference, Barcelona, Spain June 6-10, 2005.

[7] R. Sherif et al., “The Performance & Robustness of GaInP/GaInAs/Ge Concentrator Solar Cells in High-Concentration Terrestrial Modules,” *Proc. 19th European Solar Cell Conf. & Exhibition*, Paris, France 2004.

[8] R. Sherif et al., “Multijunction Cells in High- and Ultra-High Concentration Modules,” submitted to the 20th European Photovoltaic Solar Energy Conference and Exhibition, Barcelona, Spain June 6-10, 2005.

[9] R. McConnell, “Large-Scale Deployment of Concentrating PV,” Proc. 29th IEEE PVSC, New Orleans, LA 2002.

[10] V. Garboushian, “Continuous Installations of PV in the Southwest,” IEEE PVSC, New Orleans, 2002.