Photovoltaics

Lighting the Way to a Brighter Future

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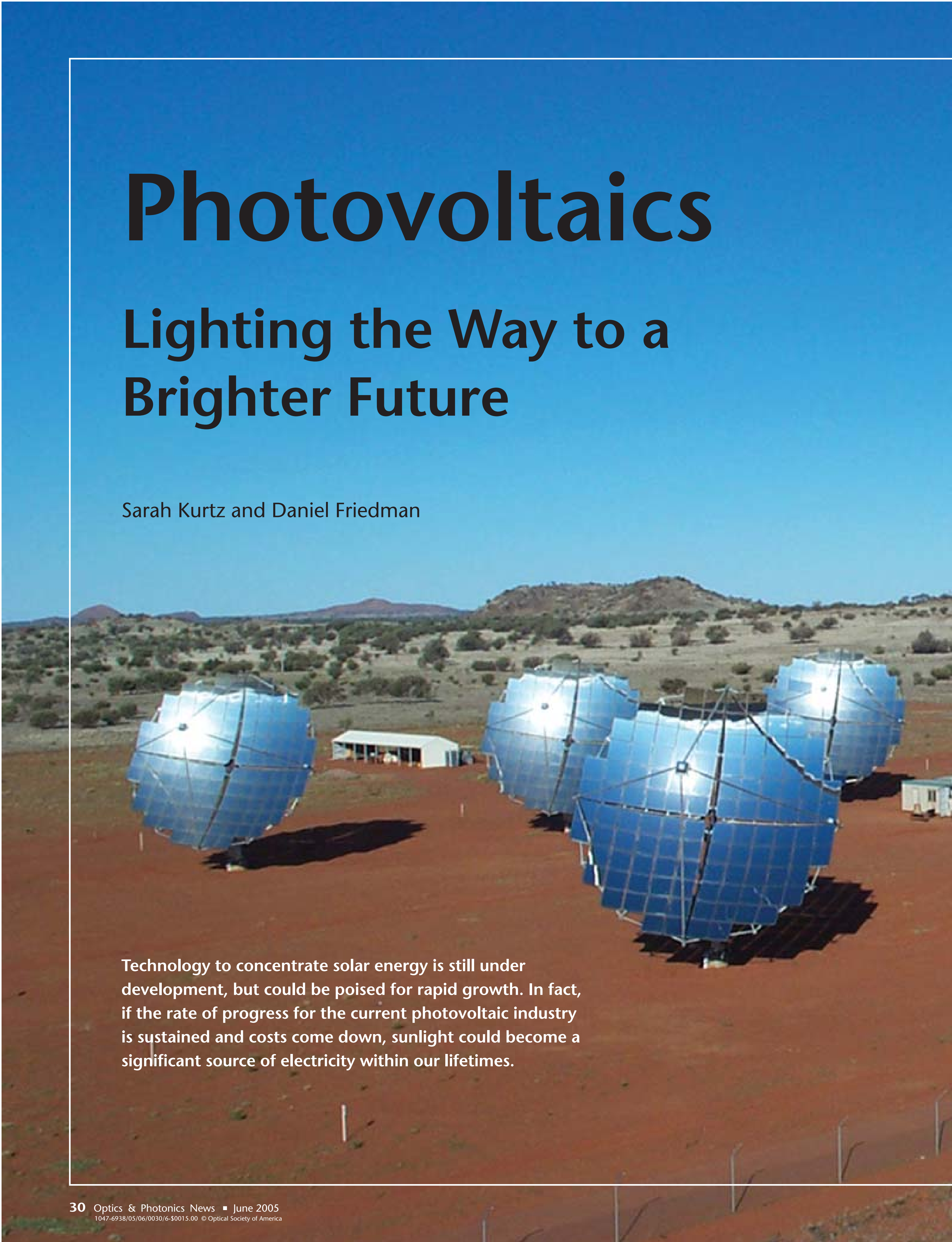

Technology to concentrate solar energy is still under development, but could be poised for rapid growth. In fact, if the rate of progress for the current photovoltaic industry is sustained and costs come down, sunlight could become a significant source of electricity within our lifetimes.

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Solar Systems installation in Pitjantjara, Australia. Solar Systems uses a reflective dish to focus sunlight on a single large-area receiver using densely packed silicon cells made by SunPower Corp. (Sunnyvale, Calif.).

The photovoltaic resource

Sunlight is a powerful, renewable—and often overlooked—source of energy. In 2003, the United States generated about four trillion kWh of electricity. Present-day photovoltaic technology could generate this amount of electricity in 10^4 km^2—which is only 3 percent of the area of Arizona! The challenge, however, lies in finding cost-effective ways to harness sunlight and convert it into convenient forms of energy such as electricity or fuel.

The need to tap new sources of energy has become increasingly pressing, as the specters of global warming and the rising price of fossil fuels continue to loom large in this country and the world. Global carbon dioxide levels are rising at a rate of 1.5 to 3 ppm per year. In 2004, they reached 379 ppm, substantially above historic values of 200 to 300 ppm. Moreover, some computer models predict that they could reach up to 970 ppm by the end of the century. Increases in the price of oil and natural gas, as well as greater energy demand and pollution, further underscore the need to find energy alternatives.

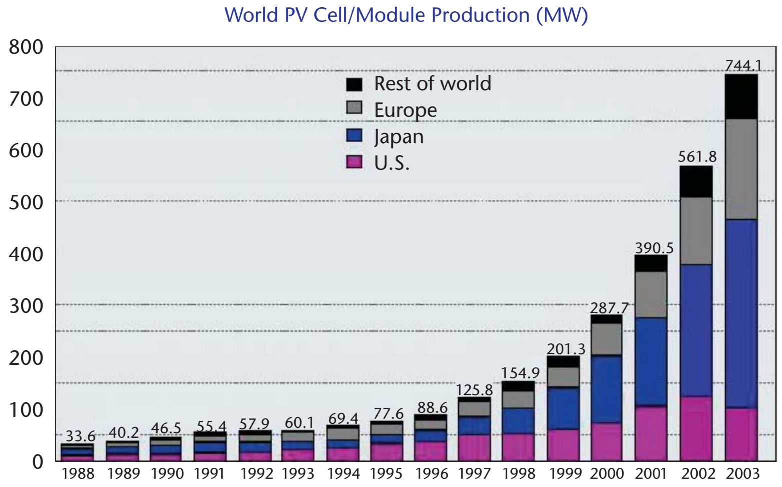
Solar cells are often viewed as an ideal technology for generating solar electricity because their operation is clean and quiet.* Government programs in Japan, Germany, California and other places offer financial incentives to encourage solar installations. (For more information on the financial incentives being implemented in various states, visit www.dsireusa.org.)

Largely as a result of such programs, sales of solar modules have increased dramatically in recent years (see Fig. 1). Although the total electricity generation from solar cells is merely a fraction of total electricity consumption, the current installation rate (about 1 GW/yr) is now comparable to the creation of one large conventional power plant each year.

This increased production rate has helped reduce industry costs so that solar cells are more affordable than ever before. Nevertheless, the question remains about whether the cost is low enough for solar electricity to become a substantial part of our energy supply in the near future. If the current photovoltaic (PV) industry growth rate of about 40 percent per year could be sustained, the annual world installations of PV would reach 0.1 to 1 TW in 2024. By way of comparison, the world's electricity generating capacity in 2002 was 3.46 TW.

Concentrator photovoltaics

Inexpensive solar cells are required for flat-plate solar panels because the irradiance of sunlight provides only about 1 kW/m^2. More than 90 percent of today's solar cells are made from silicon, mostly in a form that creates modules with an efficiency of 10 to 15 percent. One approach to further reducing the cost of solar electricity is to use inexpensive lenses or mirrors to focus, or "concentrate," the light on a smaller area of



Source: Paul Maycock, *PV News*, March and April 2004

Figure 1. History of shipments of solar modules. The 2004 shipments are estimated to be 1200 MW. The growth is fastest for large-size applications, including installations greater than 1 MW.

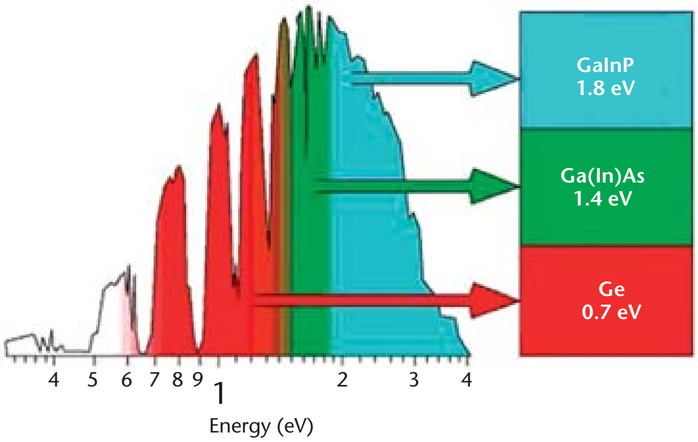


Figure 2. Solar spectrum and schematic of how the different portions of the spectrum are used by three different materials in the solar cell. The Ga(In)As and $Ga_{0.5}In_{0.5}P$ alloys are grown epitaxially on a germanium wafer. A three-junction cell with this structure made by Spectrolab, Inc., was measured to have an efficiency of 37.3 percent using light concentrated 175 times.

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* This article focuses on photovoltaic technologies, which convert light energy into electricity, because they are the authors' area of expertise. However, solar thermal technologies are also a very important renewable energy source. They use the sun's heat to harness energy, with applications ranging from solar water heating to solar thermal systems for producing electricity.

solar cells. Typical concentration ratios range from 2 (in some spacecraft or static terrestrial photovoltaic configurations) to 500 or greater.

Higher concentrations lower the cost of the solar cells as a fraction of the system cost, so that it becomes worthwhile to use more expensive but very high-efficiency solar cells. High-efficiency solar-cell technology includes certain types of silicon cells, as well as multijunction cells based on III-V semiconductor materials.

Multijunction cells use different materials that are optimized to absorb different parts of the solar spectrum, and have demonstrated efficiencies greater than 37 percent under concentrated light. (This record efficiency was achieved by Spectrolab, Inc., Sylmar, Calif., based on, and licensed from, technologies developed at the National Renewable Energy Laboratory dating back to 1984.)

The schematic in Fig. 2 illustrates how, in a 37.3 percent efficient cell made by Spectrolab Inc., the visible part of the spectrum is absorbed by $Ga_{0.5}In_{0.5}P$, the near infrared light by Ga(In)As, and the mid-infrared light by Ge. The solar spectrum changes because of absorption and scattering of the atmosphere.

Numerous reference spectra have been defined to facilitate comparison and design of solar cells. The American Society for Testing and Materials has recently revised its standard (G173) for the direct spectrum (i.e., light that penetrates the atmosphere without being scattered) so that it is more representative of the spectrum observed in the deserts in the southwest part of the United States. Most concentrator systems can focus only direct beams.

The efficiency measurement of the solar cell described in this article used the low aerosol optical depth spectrum, which can be obtained from Keith Emery at the National Renewable Energy Laboratory (NREL). The actual spectrum reaching the solar cell in a concentrator system is modified by absorption or imperfect reflection of the optics.

These cells typically cost several dollars per square centimeter. Although they are too expensive for use in flat-plate panels, they can be cost-effective in systems that concentrate the light by a factor of roughly 400 times or more. The Department of Energy, through the NREL, is currently funding the High Performance PV Project to increase the efficiency of these cells to greater than 41 percent, with a module efficiency of greater than 33 percent. Achievement of the latter goal will require improvements in the optics, providing research opportunities for optical engineers.

Figure 3. Amonix system installed at Arizona Public Service's site in Phoenix, Ariz. The Amonix systems use an array of Fresnel lenses to focus light on silicon cells that are distributed across the backplane.

Optics challenges

The challenge for the optical engineer is to design optics that focus sunlight from a large collection area onto a much smaller solar-cell "receiver" while minimizing problems such as optical losses, irradiance non-uniformity, chromatic aberration and the effects of tracking error. There are two main categories of optics to accomplish this: refractive optics, or lenses, and reflective optics, or mirrors. Each approach has advantages and drawbacks.

Refractive optics can be made very compact using Fresnel lenses (either imaging or non-imaging), and consequently do not suffer from excessive chromatic aberration, to which multijunction cells are especially sensitive. Optical efficiency is decreased by absorption in, or reflection by, a lens.

Reflective optics, on the other hand, must be very carefully aligned, whereas Fresnel lenses are less sensitive to misalignment. Ultimately, efficient operation and low cost are the keys to success; achieving these requires careful integration of the optics with the solar cells, each affecting the design of the other.

Ultimately, the performance of a system is more dependent on the quality of the components and care of the system design than by the choice between refractive and reflective optics.

Currently, two companies, Amonix, Inc. (Torrance, Calif.), and Solar Systems

Figure 4. Concentrating Technologies 1-kW system installed at Arizona Public Service site in Phoenix, Ariz. This is the first grid-connected system using multijunction solar cells. The narrow cylinder seen in front of each mirror is a heat radiator, at the bottom of which the receiver cell is mounted.

Pty Ltd. (Melbourne, Australia) are installing concentrator systems at a rate of greater than 100 kW/year. (See sidebar on p. 35.) The two companies have chosen different optics: Amonix uses refractive optics while Solar Systems uses reflective optics.

Selecting the size of the photovoltaic receiver (i.e., of the illuminated area) is a key design decision that will affect the optics. Imagine that a system is sized to capture 500 square feet of incident solar flux and then focus it down to one square foot. Is it better to use one receiver of one square foot, or several hundred receivers of correspondingly smaller size?

Although it is easier to maintain or upgrade the receiver package with a larger receiver, the small receivers have the advantage of not requiring active cooling. Once again, Amonix and Solar Systems have made different design choices.

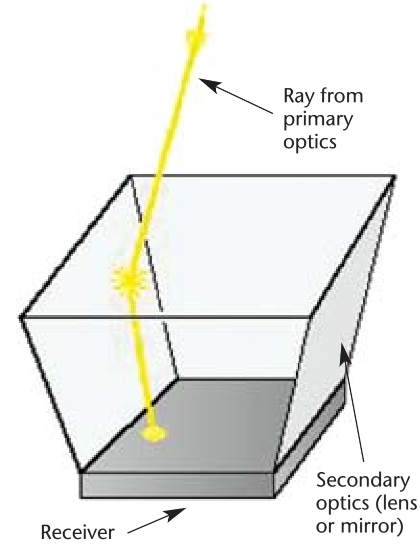

Figure 5. Secondary optics for reducing sensitivity to tracking error of concentrator systems. The optimal shape for the lens or mirror surface will generally be more complex than are these simple planes.

Amonix favors an array of small receivers (see Fig. 3, p. 33). By contrast, Solar Systems uses a single large receiver that captures all the light for their 20 kW dish (see image on p. 30). Concentrating Tech. (Huntsville, Ala.) has chosen a compromise design that uses mirrors to reflect light onto small, distributed, passively cooled solar cells (Fig. 4).

The need for constant irradiance across the receiver poses an additional challenge for the large-area receiver design. Silicon solar cells generate about 0.7 V. Therefore, a 20 kW system can be created by connecting all of the cells in parallel, resulting in a rather impractical 0.7 V, 30 kA system, or in series, resulting in a high-voltage, low-current system.

In practice, the interconnection of the silicon cells is a combination of series and parallel connections configured to provide the desired system voltage.

The current generated by a series-connected string of cells is determined by the solar cell that generates the smallest current. If the illumination on one cell is less than the others by 10 percent, then the output of the entire string of cells will be decreased by 10 percent. Producing uniform irradiance without decreasing the optical efficiency is a challenge, especially when possible misalignment is considered.

Another optics design issue that must be considered for concentrator systems is how much angular error can be tolerated in the accuracy with which the optics point at (track) the sun. At 500 suns (500 times concentration), a tracking accuracy of much better than one degree is required for a simple system with just one primary lens or mirror. (One sun = 1mW/mm^2.) Achieving such tracking accuracy is costly and increases reliability concerns.

Even if the overall system is pointed in the correct direction, misalignments can be caused by thermal expansion or by flexing of the system under high wind load. For this reason, considerable ingenuity has gone into the creation of systems that include secondary optical elements to reduce the tracking accuracy requirements. This can be accomplished with either a secondary mirror or lens mounted close to the receiver, as pictured schematically in Fig. 5.

Over the years, many different designs have been proposed for concentrator systems. The success of any of these will require careful integration of the solar cells with the optics into a high-performance, reliable system.

A bright future

Flat-plate solar cells have grown into a more than $1 billion per year industry, and are showing substantial progress toward a mature market. By contrast, the concentrator photovoltaic industry is still in its infancy. It's not yet clear whether reflective or refractive systems show greater promise, and it may well turn out that each type of system has its preferred niche.

Substantial research is needed to improve the efficiency of the cells, the efficiency of the optics and the reliability of the entire system. The design of the cells and the optics are interconnected, and a change in one may require a change in the other. Further advancements are needed to improve performance and reduce cost.

Once a low-cost, high-performance concentrator system has been developed, the concentrator industry may grow very quickly. If the systems operate at 1,000 times concentration, the current multijunction solar-cell production capacity in the United States could supply manufacturing of almost 1 GW/yr.

The capital cost required to build a factory that can produce concentrator systems is expected to be about a factor of five less than that required to make a factory with an equivalent amount of flat-plate manufacturing capability.

Photovoltaic technology is still evolving but holds promise as a renewable energy alternative. If costs can be reduced enough to penetrate the broader electricity-generation market, we can envision using optics to create a future brightened by solar electricity.

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Concentrators in the Marketplace

As the sizes of solar installations have increased, so too have the number of market opportunities for concentrator systems. Indeed, concentrator companies are now finding an opportunity to grow. Amonix, Inc., in Torrance, Calif., has partnered with Arizona Public Service in Phoenix to install more than 600 kW of their concentrator systems in Arizona and elsewhere (see Fig. 3, p. 33).

Solar Systems in Melbourne, Australia, has installed about 250 kW of systems in the Australian outback (see p. 30) and is in the midst of installing about 500 kW of systems, with negotiations in progress for an additional 5 MW. These systems help drive the small electrical power grids that are located in remote locations. The high cost of transporting fuel to run the diesel-powered mini grids makes the economics attractive.

High-efficiency, multijunction concentrator cells are now generating electricity into the grid in a 1-kW, reflective system built by Concentrating Technologies and installed with Arizona Public Service (see Fig. 4, p. 34). Many other companies are developing concentrator products. Pyron in La Jolla, Calif., has integrated multijunction cells mounted under an optical homogenizer into their concentrator prototype (see photo). Their system is unique because it is positioned over a pond of water, which is used to cool the cells. The system's low profile avoids high wind loading as well as being more aesthetically pleasing.

Prototype of concentrator system made by Pyron. The system stays aligned with the sunlight by pivoting along each row of lenses and rotating around the circular ring.

ENTECH, Inc., in Keller, Texas, has incorporated multijunction cells into Fresnel-lens concentrator systems used for space exploration. ENTECH has successfully flown its point-focus mini-dome Fresnel lenses on the PASP-Plus mission (1994-95) and its line-focus arched Fresnel lenses on the Deep Space 1 mission (1998-2001).

ENTECH is currently developing its next-generation space concentrator, called the Stretched Lens Array (see photo) for NASA, and is adapting this technology (color mixing lenses over multijunction cells) for ground applications. A 1-kW ENTECH ground demonstration system has been successfully tested by NASA and Boeing near the summit of Mount Haleakala in Hawaii.

Stretched-Lens Array developed by ENTECH, Inc., for deployment on NASA missions.

Energy Innovations is developing low-cost concentrator systems for installation on rooftops. Their first model, which is currently being testing and is planned for release at the end of 2005, is a low-concentration (25 times) system using a low-profile heliostat of mirrors reflecting onto a receiver composed of one-sun cells. The panels can be linked together, much like traditional PV panels, into a grid-tied, rooftop system. High-concentration models using high-efficiency, multijunction cells are planned for future versions.

Sharp (Japan) is a well known producer for the terrestrial (flat-plate) solar market. The company has developed a concentrator module with multijunction cells and a domed Fresnel lens, and are also looking at other concepts. Sharp plans to begin marketing concentrator systems in a couple of years. The size of Sharp and its current market position as the largest producer of concentrators imply that this is a product to watch.