Low-Cost 20X Silicon-Cell-Based Linear Fresnel Lens Concentrator Panel

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Abstract. The Entech Solar team has been developing, field testing, and refining line-focus Fresnel lens silicon-cell concentrators for three decades. In response to the new economics of one-sun photovoltaic modules which represent the competition for all concentrating photovoltaic (CPV) modules, we have recently completely redesigned our latest concentrator panel to be extremely material-efficient to achieve far lower manufacturing cost than for our previous generations of concentrators. Our new 20X concentrator panel draws heavily on our space concentrator technology developed under NASA and DOD programs. This paper describes the new 20X module and its key attributes.

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INTRODUCTION

Our new 20X concentrator panel draws heavily on two of the technologies from our company's heritage. The first is the use of high-performance, error-tolerant, arch-shaped acrylic lenses to focus sunlight onto fully encapsulated, prism-covered silicon cells made by conventional one-sun manufacturing processes [1]. We have successfully developed and field-proven several generations of such terrestrial concentrator modules and systems. The second is the use of small, thin stretched lenses over photovoltaic receivers mounted to thin radiator sheets in our space concentrators, developed for NASA and DOD [2]. These space concentrators use very little material to conserve solar array mass for space missions. By marrying these two "heritage" technologies, we have developed a new terrestrial concentrator panel that is very material-efficient, which minimizes manufacturing cost for ground applications using the same principles that minimize launch weight for space applications. The space module uses thin stretched silicone lensfilm over multi-junction cells mounted to a thin carbon-fiber composite radiator, while the terrestrial module uses thin stretched acrylic lensfilm over silicon cells mounted to a thin aluminum sheet for heat rejection. While the materials are different, the fundamental design is very similar for the space and ground photovoltaic concentrators. The only major difference is the addition of a glass sheet over the terrestrial module to protect the lensfilm and photovoltaic receivers from wind, rain, hail, and other elements of the ground environment.

EVOLUTION OF THE NEW DESIGN

For our previous generations of terrestrial 20X photovoltaic concentrators, we used very large acrylic lenses to focus onto relatively large silicon cells. Fig. 1 shows a 1990's vintage array of 288 of our large concentrators, which measured about 85 cm wide by about 3.7 m long. While this approach minimized parts count and assembly labor cost, it required a substantial aluminum heat sink to reject the large quantity of waste heat (about 2 kW of waste heat per module). This large module also had the acrylic lens exposed to the elements, requiring over 3.5 mm of acrylic material thickness to survive wind loads and hail impact. The large module was also bulky, heavy, and expensive to transport. While these modules performed very well in the field for long periods of time, they did not offer a path to module costs below $1 per Watt because of their high material content.

FIGURE 1. Previous Entech 100 kW CPV Array.

For our space concentrator arrays, including the award-winning SCARLET array on NASA's Deep Space 1 mission from 1998-2001, we developed much smaller lenses to minimize the mass of the radiator to reject waste heat to deep space [3]. The required thickness of the radiator for a desired cell temperature increases as the square of the lens aperture width. Our space lenses were sized at 8.5 cm wide to allow us to use a 125-micron-thick carbon fiber radiator while keeping the cell temperature only slightly warmer than for one-sun solar arrays in space. We also developed and patented a method of supporting very thin (150 microns) flexible lenses by stretching them from two end arches [4]. Fig. 2 shows an early prototype of our 9X Stretched Lens Array (SLA), which offers unprecedented specific power metrics (about 600 Watts per kg for lenses, receivers, and radiator).

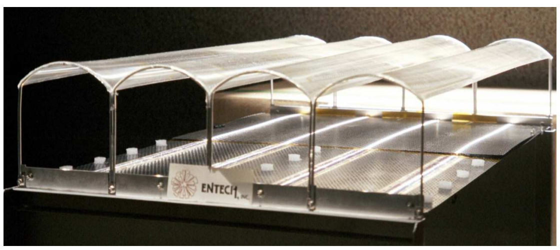

FIGURE 2. Entech Space Stretched Lens Array.

For our space concentrator array, we also developed a very robust fully encapsulated photovoltaic receiver capable of reliable high-voltage (400-600 V) operation in the plasma environment of space. This new receiver technology uses redundant dielectric layers between the cell circuit and the radiator, as well as transparent encapsulating layers above the cell circuit, including prism covers to eliminate gridline obscuration losses for the cells. In addition to adopting the material-efficient small stretched lens approach, we have also adapted the new photovoltaic receiver approach from our space work for NASA and DOD to our new terrestrial 20X CPV panel, known as SolarVolt™, shown in Fig. 3 [5].

FIGURE 3. Photo of New SolarVolt™ CPV Panel.

DESCRIPTION OF SOLARVOLT™

Figs. 4 and 5 show more details of the new CPV panel and receiver configurations, respectively. Six side-by-side thin (<< 1 mm) arched acrylic lenses are supported using the patented stretched lens array approach described above. Each lens (~ 15.5 cm aperture width) focuses sunlight onto a narrow strip of silicon cells (~ 8 mm active width) which are connected in series in a fully encapsulated robust photovoltaic receiver package, which includes a bypass diode and a prismatic cell cover for each cell. The cells and bypass diodes are made by conventional one-sun screen-printed solar cell manufacturing methods, resulting in very low cost. The lenses are made in ready-to-use form (no lamination required) by continuous roll-to-roll manufacturing methods, resulting in very low cost. The photovoltaic receivers are mounted to a thin aluminum pan ($\leq$ 1 mm thick), which is made from a single piece of coil-anodized aluminum sheet, resulting in very low cost. The pan is the only waste heat rejection surface needed to maintain the cell temperature at very reasonable levels. The lenses and photovoltaic receivers are protected against wind, rain, hail, etc., by an AR-coated 3.2 mm thick tempered solar glass window of exactly the same type as used by one-sun photovoltaic module makers, resulting in very low cost. The use of high-efficiency symmetrical-refraction arched lenses and prismatic covers to eliminate gridline shadowing losses results in excellent panel performance, with panel power output per square meter approximately equivalent to that for single-crystal silicon one-sun modules, while saving over 90% of the silicon cell area and cost.

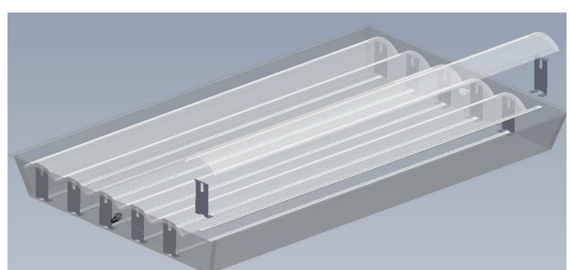

FIGURE 4. Schematic of New SolarVolt™ Panel.

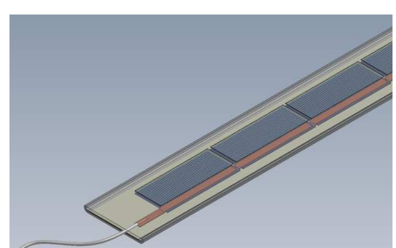

FIGURE 5. Schematic of New SolarVolt™ Receiver.

Each lens is supported by a pair of end arches which are tensioned by end arch spring clips, as shown in Fig. 4. Each pair of end arches and spring clips are indexed in location to the photovoltaic receiver in the focal line of the lens supported by that pair of end arches. The photovoltaic receivers are manufactured as complete assemblies before being bonded to the aluminum pan. The lenses are literally snapped into place over the end arch spring clips, and the front glass window is bonded to the front of the aluminum pan.

Each of the six receivers includes 60 series-connected silicon cells, each about 2.5 cm long, using the configuration shown in Fig. 5. The six receivers are wired in parallel with one another, with a combined panel output current of just over 6 Amps at just over 34 Volts at the peak power point at 25C cell temperature and 1,000 W/m^2 direct normal irradiance (DNI), i.e., standard test conditions (STC).

The overall dimensions of the SolarVolt™ panel are approximately 100 x 165 x 15 cm, and the weight is approximately 25 kg, of which the glass comprises 53%, the aluminum pan comprises 25%, and steel stiffeners comprise 11%. While the glass is admittedly heavy, it is very economical. Not counting this heavy but inexpensive glass element of SolarVolt™, the specific power (Watts/kg) of the new 20X module is more than 4X higher than for the old 20X modules shown in Fig. 1, resulting in a substantial reduction in material cost for the new SolarVolt™. Including the glass, SolarVolt™ still has more than twice the specific power of the old modules.

The new CPV panel continues to rely on Entech's symmetrical-refraction arched lens, but with much smaller dimensions in the new SolarVolt™ version, as shown in Fig. 6. This lens offers many unique features, including minimum reflection loss, maximum transmittance, sharper focusing, shorter F/#, and exceptional tolerances for errors and aberrations, including more than 100 times the shape error tolerance of flat lenses and more than 200 times the shape error tolerance of reflective concentrators [1]. These features are especially important for the simple stretched lens support approach, since the shape of the stretched lens is not perfect, but doesn't need to be for this error-tolerant optical concentrator. In the lower portion of Fig. 6, the outer region of the symmetrical refraction lens is shown, with solar rays being refracted through half of the required turning angle by the outer smooth convex surface, and through the remaining half of the required turning angle by the prismatic inner surface of the lens. As in our past generations of CPV modules, over 90% net optical efficiency has been measured for mass-produced ultra-thin acrylic lenses of the new SolarVolt™ design. The new lens provides about ± 0.75 degree sun-pointing tolerance without the need for secondary optics.

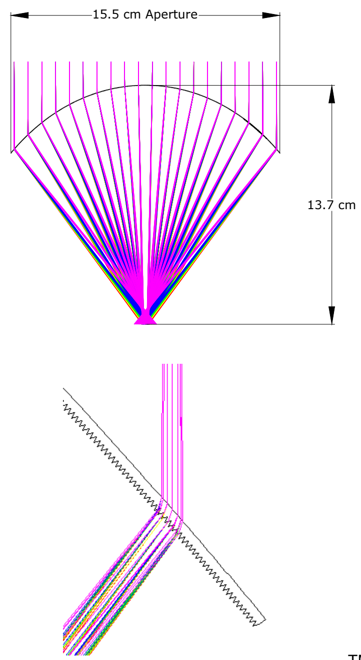

FIGURE 6. Ray Trace of New SolarVolt™ Lens.

The small aperture size of the new SolarVolt™ lens was selected based on thermal considerations, summarized in Fig. 7. For the selected lens aperture width, a 1 mm backplane radiator will keep the cell temperature in the same range as for one-sun modules.

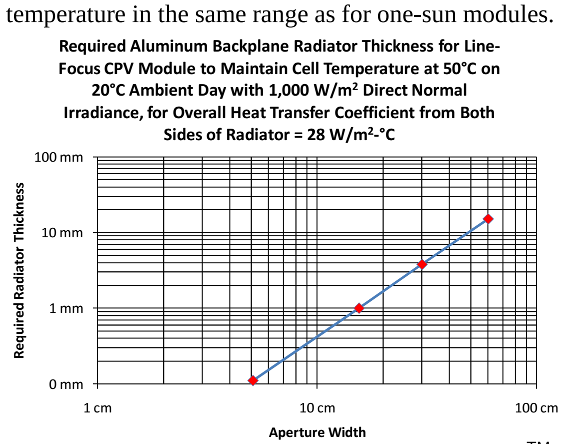

FIGURE 7. Thermal Considerations for SolarVolt™.

Both the SolarVolt™ cells and bypass diodes are produced using the same one-sun silicon cell manufacturing process. 51 pairs of cells and diodes can be made on one 125 mm pseudo-square wafer, and proportionally more can be made from larger wafers. So just over 7 conventional 125 mm wafers can provide all the silicon for a typical 200-230 Watt SolarVolt™ panel, compared to the 72 such wafers typically used in a one-sun module of similar power.

Since they use screen-printed silver paste metallization and the grid spacing is optimized for 20X concentration, the SolarVolt™ cells are relatively heavily metallized, with parallel gridlines typically covering 30-40% of the active area of the cell. The use of the refractive optical device called the prismatic cell cover, previously patented by Entech, is critical to obtain high performance from such cells [1]. When equipped with such prism covers, cells made by conventional one-sun cell manufacturing processes typically average 18-20% cell efficiency at 20X and 25C in our cell flash testing and grouping.

CURRENT STATUS OF SOLARVOLT™

We are planning to commercialize SolarVolt™ in 2012, after we complete several ongoing activities, including:

- the development and field testing of a new smaller version of our proven roll-tilt tracker platform for the new smaller SolarVolt™ panel
- IEC 62108 certification testing, which has been ongoing since last Fall
- manufacturing scale-up, both in-house and at our key suppliers

One unique piece of equipment developed at Entech is a 33-meter-long sun tunnel flash simulator, which illuminates the full-size SolarVolt™ panel with relatively collimated light (within ± 0.9 degree) at one-direct-sun irradiance (1,000 W/m^2). While not as collimated as sunlight (± 0.26 degree), the agreement of results between indoor and outdoor measurements has been very good, as shown in Fig. 8.

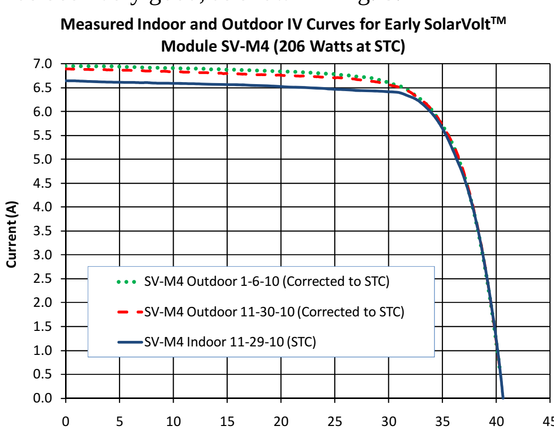

FIGURE 8. Indoor vs. Outdoor Data for SolarVolt™.

Our manufacturing cost model shows that SolarVolt™ can be manufactured and profitably sold at prices that we expect to be below crystalline silicon one-sun module prices when we introduce the new CPV panel to the market next year. And there is much room for cost reduction as we move down the learning curve that our one-sun competitors have already successfully traveled down.

Our SolarVolt™ technology is protected by a number of both issued and pending patents [e.g., 4 and 6].

FIGURE 9. The New (SolarVolt™) vs. the Old.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of our entire CPV team not only within Entech Solar, but also at our key supplier/partners for lenses, cells, and other key elements of SolarVolt™. We also gratefully acknowledge the support of our technology development programs over many years by NASA, DOD, and DOE.

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