A high-performance photovoltaic concentrator

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Fresnel-Köhler concentrators offer a simple and cheap system to convert sunlight into electricity at competitive cost.

Concentrating photovoltaic (CPV) systems contain small, sophisticated solar cells that transform a large amount of light collected and directed onto the cells into electricity. CPV systems offer higher conversion efficiency than conventional, flat-plate solutions (>30% using current multi-junction solar cells) and reduce the number of cells needed. The result is a decrease in total energy cost, as long as the cost and complexity of the additional elements (optics, heat sinks, and tracking system) are reasonable. CPV is, therefore, one of the most promising options for development of the solar-energy market.

Efficient and low-cost concentrator optics are key to minimizing electricity costs, requirements best met by high manufacturing tolerances (implying a high acceptance angle) while maintaining a high concentration (>500 STX) to offset the cost of expensive, high-efficiency solar cells. In addition to concentration and tolerance angle, optical photovoltaic concentrators must meet specifications regarding, e.g., simplicity and irradiance uniformity on the cell. The former facilitates mass production while the latter preserves cell efficiency while also assuring long-term cell and concentrator reliability. Fresnel-Köhler (FK) concentrators are advanced optical concentrators based on low-cost Fresnel lenses that simultaneously produce high concentration, high tolerance, and excellent light homogenization on solar-cell surfaces.

A useful merit function for CPV optical design is the effective concentration-acceptance product (CAP*), defined as $\text{CAP}^* = \left(\frac{C_g}{\sin \alpha^*}\right)$, where $C_g$ is the geometric concentration ratio (which describes the actual reduction in cell usage achieved) and $\alpha^*$ is the effective acceptance angle (the incidence angle at which the concentrator collects 90% of the on-axis power as measured by actual photocurrent curves). CPV systems with high CAP* outperform low-CAP* designs and more likely achieve competitive energy-generation costs. For a given concentrator architecture, the CAP* is rather constant with $C_g$ and can be considered an attribute of the architecture: increasing $C_g$ implies a reduction of $\alpha^*$ and vice versa. The CAP* of the FK architecture is the highest reported among concentrators based on flat Fresnel lenses.\(^1\)

To attain good irradiance uniformity on the solar cell, we applied our own design methods\(^2\) to generate a four-fold Köhler integrator array comprising two free-form optical surfaces, combining the lower surface of the Fresnel lens as a primary optical

Figure 1. (right) 3D view of the Fresnel-Köhler (FK) concentrator. POE: Primary optical element. (top) Close-up of the center of the FK Fresnel lens showing the four sectors. (bottom) Molded-glass FK secondary optical element (SOE).
Figure 2. Irradiance distribution (top cell spectrum, in solar units) on the cell for an FK concentrator with geometric concentration ratio $C_g = 625$.

Figure 3. Fresnel-based concentrators. From left to right and top to bottom: Fresnel (no SOE), spherical-dome, single-optical-surface (SILO), reflective and dielectric-filled truncated-pyramid (XTP, RTP), and FK concentrators.

Figure 4. (top) Effective concentration-acceptance product (CAP*) for the different designs versus $f$ number (ratio between Fresnel-lens-to-cell distance and Fresnel-lens diagonal). (bottom) SOE and solar-cell cost per Fresnel-lens unit area. LPI: Light Prescriptions Innovators.

We analyzed FK concentrator performance through ray-tracing, assuming adoption of a polymethylmethacrylate Fresnel lens (index of refraction $n \approx 1.49$), a BK7 crown-glass SOE ($n \approx 1.51$), and a high-efficiency ($\approx 38\%$) commercial triple-junction photovoltaic cell. Figure 2 shows the excellent irradiance uniformity achieved for the top subcell. (We obtained similar results for the middle and bottom subcells.)

We compared the FK concentrator’s performance with those of five commercial Fresnel-based CPV designs (see Figure 3). From left to right, we show ray traces for Fresnel-lens systems with no, hemispherical glass-dome, single-optical-surface, and hollow reflective and dielectric-filled truncated-pyramid concentrators, as well as the FK concentrator. Figure 4 (top) shows that the FK setup outperforms all competitors in terms of CAP* achievable, especially in compact (low $f$ number, defined here as the ratio between Fresnel-lens-to-cell distance and...
Fresnel-lens diagonal) systems. FK optical efficiency at normal incidence ranges from 88 to 90% for a large range of $f$ numbers, provided that an antireflective coating is used on the SOE. The resulting CAP is approximately constant for most $f$-number values ($\text{CAP}^* \approx 0.57$ and 0.61 without and with perfect coating, respectively).

We also performed a partial system-cost comparison by looking at the ‘receiver’ (cell+SOE) cost for each of the six designs, based on real SOE costs from glass suppliers and assuming that cell price is proportional to area (at $7/\text{cm}^2$). Figure 4 (bottom) shows that the FK design produces the cheapest receivers, especially when we consider a moderate-tolerance-angle scenario ($\alpha^* > 1^\circ$), which is required to attain reasonable energy production throughout the year at competitive costs.

In summary, FK concentrators are simple but reliable and robust high-performance devices that are suitable for mass production. We expect them to demonstrate economic feasibility very soon. Our continuing efforts range from feasibility studies and design to prototyping and characterization. The first prototypes measured perform as expected (efficiencies > 30% and acceptance matching the models). Depending on market evolution and full-system performance, it is likely that at least one CPV system comprising FK devices will be ready for commercialization within a year.

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References