COMPARED PERFORMANCE OF FRESNEL-BASED CONCENTRATORS AT ARRAY LEVEL

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ABSTRACT: At module level (one single solar cell), the Fresnel-Köhler (*FK*) concentrator comprises a perfect irradiance uniformity along with quite high concentration-acceptance angle product and loose manufacturing tolerances. At the same time, it maintains the efficiency/simplicity of other Fresnel-based concentrators. All these facts, along with the pill-box shape of its transmission curve, permit an enhanced performance of this device, compared to its competitors, at array level, because the system is less sensitive to manufacturing errors and cells dispersion, and current mismatch is less likely to occur. Or the same performance can be achieved at a lower cost, exhausting the tolerance budget by using inexpensive fabrication techniques. Depending on the concentrator, the actual power delivered by an array might drop significantly with respect to the sum of the power delivered by single modules. Under certain circumstances, the *FK* can reach a 1-10% electrical efficiency increase with regards to other concentrators sharing the same technology.
Keywords: Concentrators, Cost reduction, PV array, Performance

1 INTRODUCTION

Minimizing energy cost (€/kWh) is necessary for the success of concentrated photovoltaic energy (*CPV*). Key to minimizing this cost is an efficient and low cost optical design, goals best met with the fewest elements and the maximum tolerances, but always maintaining the high concentration (>500) that offsets the cost of expensive high-efficiency multi-junction solar cells. A useful merit function for a *CPV* optic is the concentration-acceptance product [1], defined as:

$$CAP = \sqrt{C_g}\,\sin(\alpha)$$

where C_g is the geometric concentration and α the acceptance angle, often defined as the incidence angle at which the concentrator collects 90% of the on-axis power [2]. A more practical definition tells it is the angle at which the generated photocurrent is a 90% of the maximum (often achieved at normal incidence). This definition gather all optical and electrical effects and therefore is more realistic. It is remarkable that for a given concentrator architecture, the *CAP* is rather constant with C_g.

For a given C_g, α measures the total tolerance available to apportion among the following: (1) shape errors and roughness of the optical surfaces, (2) concentrator module assembly, (3) array installation, (4) tracker structure finite stiffness, (5) sun-tracking accuracy and (6) solar angular diameter (7) lens warp (8) soiling. Each of these items can be expressed as a fraction of the tolerance angle, so that all together comprise the tolerance budget. Alternatively, for a given acceptance angle, a higher *CAP* allows a higher concentration, consequently reducing cell usage (and cost). The actual impact of *CAP* on receiver costs has been analyzed recently in a work that compares several Fresnel-based systems [3]. The comparison denies a somewhat widespread understanding that tells the usage of Secondary Optical Elements (*SOE*) is expensive. The work shows the costs of equivalent enlarged solar cells (to keep the acceptance at a minimum level) is far beyond the sum of costs *SOE* + cell of a high-performance concentrator.

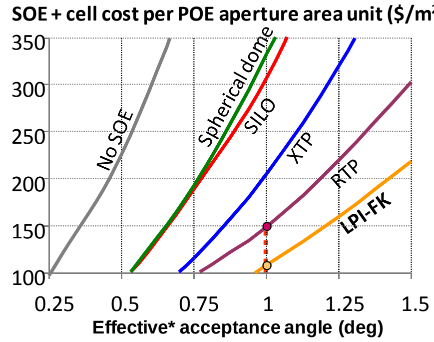


Figure 1 *SOE* and solar cell cost per Fresnel lens unit area as a function of the effective acceptance angle α*. The *SOE's* have no *AR* coating. Cell and *SOE* costs are taken from current market prices.

Figure 1 shows some estimated costs of receivers per system-aperture unit area for 6 different concentrators based on Fresnel lenses, as a function of the acceptance angle. Notice the so-called Fresnel-Köhler (*FK*) concentrator clearly outstands among them, enabling cost cuts of about 33% with respect to the best competitor (*RTP*) if a minimum acceptance angle of ±1deg is required.

LPI-patented Fresnel Kohler [4] system uses the principles of optical integration [5][6] and nonimaging optics [7] to attain unique performance features, such as compactness (reduced optical depth keeping performance), perfect irradiance uniformity over the solar cell (this is important because the cell efficiency depends on it, but also to assure the long term cell and concentrator reliability), a very good *CAP* (away from the thermodynamic upper bound but still beyond conventional Fresnel concentrators) and loose manufacturing tolerances (typically, the *FK* withstands alignment errors of 15% and 65% the size of the cell, laterally and longitudnally, respectively). Additionally, the *FK* is free of chromatic effects (in other Fresnel systems different wavelengths produce different irradiance distribution on the cell -chromatic aberration of the irradiance [8], and the cell efficiency can be significantly affected, due to local current mismatch between the top and middle junctions).

In one of its versions, it consists of a Fresnel lens comprising four identical folds, along with a free-form secondary lens, also divided in four sectors. The *POE* and *SOE* sectors work in couples. Each pair of *POE-SOE* folds form image onto each other and the integration effect produces a perfectly uniform square spot onto the solar cell (see Figure 2).

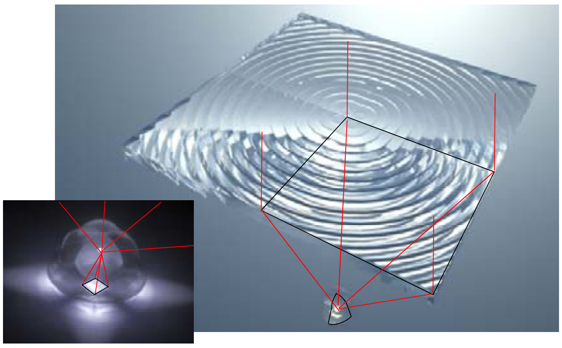


Figure 2 Rendered views of the *FK* two optical stages showing the working principle of the *FK* concentrator: Each pair of *POE-SOE* sectors form reciprocal images according to the Köhler principle- and attain a perfectly uniform square sun spot on the solar cell. The Fresnel facets are exaggerated, for clarity purposes.

Notice the *FK* attains all the advanced features mentioned above (and some others as we will show in this work), without giving up the simplicity of the other Fresnel approaches. This means that it can be manufactured with the same potentially-inexpensive techniques (continuous roll embossing, hot embossing, compression molding, *etc.* for the *POE*; glass molding for the *SOE*).

These are some performance enhancements we can attain by using high acceptance angle solutions:

- Array performance (low series connection mismatch)
- Efficient energy production under wind loads
- Collection of circumsolar
- Lower sensitiveness to soiling –dirt-.
- Insensitivity to lens warp.

And these, some of the different aspects we can act on aiming at a cost reduction.

- Optical components manufacturing (shape and roughness)
- Module assembling
- Tracker structure stiffness
- Tracking accuracy

The *FK* performance at array level (several modules in a series connected layout) will be compared with its main competitors (those named *XTP* and *RTP*, both two-stage optics systems comprising two-stage optics) in Section 2.

The comparison uses realistic simulations (spectral ray tracing, electrical modeling of a multi-junction solar cell) to find out the actual electrical power delivered. The performance of an array consisting of several units of any of these systems connected in series is in part restricted by the worst modules, and can be predicted assuming the modules have manufacturing inaccuracies whose effect can be treated statistically using the *photocurrent characteristic* of each device.

2 ARRAY PERFORMANCE

2.1 Current mismatch

There are several ways to connect the cells within a large *CPV* system, always combining series/parallel layouts. In general, these systems need to rise the voltage up to a certain level (some hundreds of volts) to make the DC-AC converters work efficiently. For *MJ* solar cells, whose operating voltage is about 3V, this implies *N*=100-200 cells in series in each row sometimes.

In an *N*-cells series-connected row, the power delivered by the array can be far from expectations, especially in *CPV* systems, owing to the so-called photocurrents mismatch. Indeed, in a naked series-connected row, the maximum photocurrent reachable is limited by the worst cell (either having poor electrical efficiency or having a poor illumination).

In order to prevent large power losses, the concentration cells have a diode in parallel so that each cell can be by-passed if the gain in current balances the drop in voltage.

Figure 3 shows the case of two *CPV* modules connected in series and the equivalent *IV* characteristic [9]. In this simple case, the array equivalent short circuit current is the maximum of I_{SC1}, I_{SC2}, and the open circuit voltage *Voc* equals the sum of the open circuit voltages of the two cells.

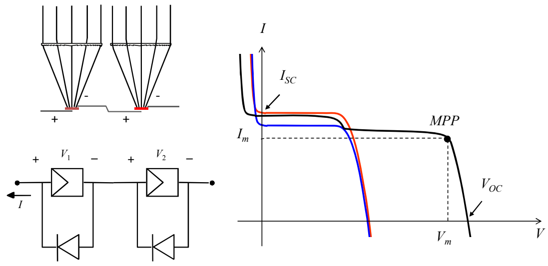


Figure 3 Series connection of two *CPV* modules.

The *Maximum Power Point* $MPP=(V_m, I_m)$ can be approximated considering:

$$I_m \approx MIN\{I_{SC1}, I_{SC2}\} \qquad V_m \approx V_{m1} + V_{m2}$$

With V_{m1} and V_{m2} being the *MPP* voltage for cells 1 and 2, respectively. Since, for a single isolated cell in a row,

$$V_m I_m = FF \cdot I_{SCi} \cdot V_{oci}$$

With *FF* being the fill factor of such cell, we can assume that, for few *N* modules, it holds:

$$P_{array} = N \cdot FF \cdot V_{oc} MIN\{I_{SCi}\} \quad i = 1 \ldots N$$

As long as all cells have the same fill factor and V_{oc}. This holds because for few cells, having some cell by-passed implies a huge relative voltage drop, that can be justified only if one of currents is really low (cell or optics damaged).

When N increases, it might be worth having some cells by-passed, because the relative voltage loss (a few volts in a large sum) is negligible compared to the photocurrent increase (the same for all the series) we may obtain dropping the worst cells.

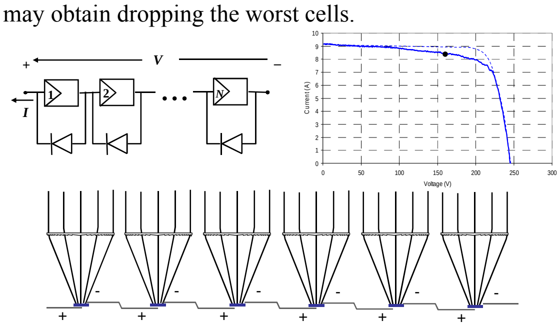


Figure 4 Series connection of *N CPV* modules.

In that case, the array *IV* characteristic changes as shown in Figure 4, where the ideal curve is also shown. The *MPP* can be approximated, in that case, by:

$$P_{array} = [(N-k)FFV_{oc} - kV_D]MIN\{I_{SCi}\} \quad i = 1...k$$

With k being the number of by-pass diodes acting, V_D the diode cut-in voltage (typically 0.3V) and $MIN\{I_{SCi}\}$ being the minimum of the short circuit currents delivered by the N-k cells that remain working.

In conventional flat plate systems, the current mismatch either deals with the use of poor-performance cells in combination with good cells, or with some shading –or dirt- of a given set of cells. Unfortunately, in a *CPV* system, the effect is more likely to show up and manufacturers notice important performance drops when going from module to the array level. In this case, a cell can deliver a lower photocurrent than expected, no matter how good it is, due to the addition of a few sources for problems, such us:

- Bad optics
- Bad alignment between parts
- Bad sun aiming of certain modules

2.2 Effects of current mismatch on power delivered. Comparison of Fresnel-based *CPV* systems

Here we will model such kind of effects statistically and will calculate the effect on the actual power delivered by the array in the three different systems shown in Figure 5.

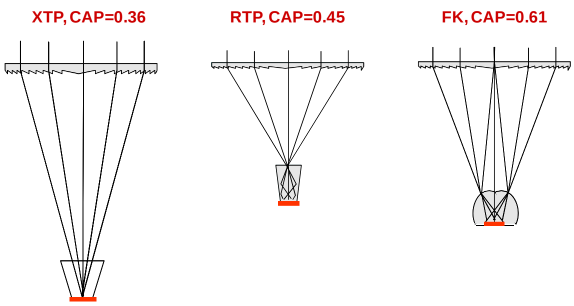


Figure 5 Cross-section of the three Fresnel-based systems that will be compared in this work. Notice their equivalent *f-number* (optical depth to lens diagonal) is different in each case, the *FK* and *RTP* being more compact.

The concentrators named *XTP* and *RTP* showed better skills than other Fresnel optics in the cost comparison mentioned above. They have Fresnel lenses as *POEs* and a truncated pyramid hollow mirror and a pyramid lens as *SOEs*, respectively. There are a few companies in the field whose systems are based on these concepts.

For a given concentration level, each architecture has a *photocurrent characteristic* $Isc_i(\varepsilon)$ that shows the maximum photocurrent achievable as a function of the sun beam angle at the aperture of the Fresnel lens. As we anticipated before, such curve can be utilized to determine the actual acceptance angle of a device.

Let us consider these case-study systems are part of a series connected row using cells and optics whose parts do not perform exactly the same. Let us consider there are assembly/alignment inaccuracies as well. For each module, we can gather all these effects in a *distorted* photocurrent characteristic that differs from the ideal one, and that tells the actual performance we can expect from each unit.

For simplicity reasons, let us assume all the cells have the same V_{oc} and FF, while the achievable short circuit currents at normal incidence can vary according to a Gaussian distribution of average $<Isc>$ and standard deviation σ_{Isc}. This accounts both for the different optical losses and the different cells electrical efficiencies among modules. Additionally, we can model the manufacturing and assembly errors by means of a shift ε in the angular transmission characteristic, which tells these errors are equivalent to having the modules not perfectly aimed at the sun (0deg). Let's assume these series of N "equivalent" angular misalignments is statistically distributed according to a normal distribution whose average is $<\varepsilon>= 0°$ and the standard deviation is σ_ε. The combination of these two statistics leads to an overall performance that is implicit to the charts shown in Figure 6.

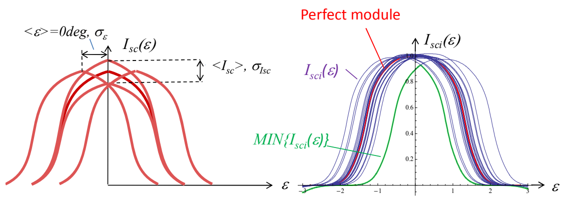


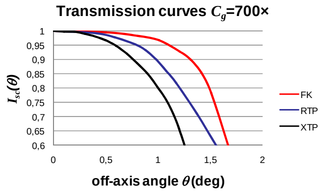
Figure 6 Statistical model applied for the comparison of this work. Each concentrator is modeled using its *photocurrent characteristic* $Isc_i(\varepsilon)$ modulated to simulate alignment errors (lateral shifts of curves) and cells/optics efficiency mismatch (amplitude variations).

When the tracker is perfectly aimed, the poorest modules (those whose $I_{SCi}(0)$ are smaller, meaning their equivalent shift, along with a reduced photocurrent are the worst among samples) compromise the performance and, depending on the photocurrent drops, some modules can be by-passed for the sake of electrical power. The number of by-pass diodes acting varies in each case, as we show below, and the maximum power reachable can be calculated through the following Equation, when $\varepsilon = 0$.

$$P_{array} = \left[(N-k)FFV_{oc} - kV_D\right]I_{SCk}(0^\circ)$$
$$with\ I_{SCk} = MIN\{I_{SCi}(\varepsilon)\}\ i = 1...k$$

We have applied this statistics to the three systems mentioned above, assuming they have the same entry aperture area and same optical efficiency, and therefore they have the same <*Isc*> at normal incidence. For each σ_{Isc} and σ_ε, we have repeated the same statistics for a series of 200 modules of all three concentrators, and we have repeated the experiment 5 times (notice each time the statistics generate a different collection of shifts and amplitudes, which is what most likely happens in real life, where each series-connected row shows different inaccuracies each time). For each experiment, we have found the *MPP* achievable by each concentrator, and have determined the number of by-pass diodes ON.

First, we carried out this experiment for a constant concentration C_g=700× and therefore different acceptance angles for the case-study devices. The normalized current characteristics and the actual acceptance angles in this case are shown in Figure 7.



Type of Concentrator	$\alpha_{90\%}$
FK	±1.31°
RTP	±0.98°
XTP	±0.78°

Figure 7 Scenario 1: the three systems have the same concentration (C_g=700×) and therefore different acceptance angles.

The results for this first scenario are shown below, where P_{array} is referred to the maximum power reachable P_{max} (both σ_{Isc} and σ_ε being null).

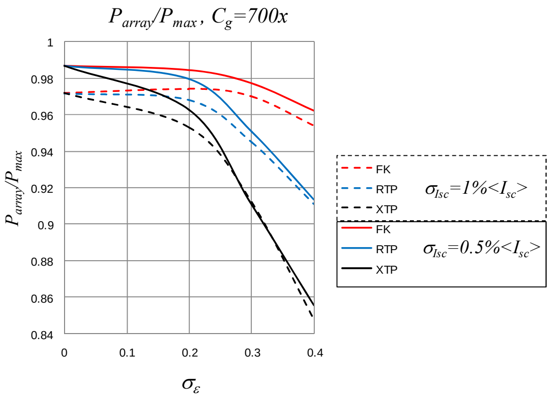
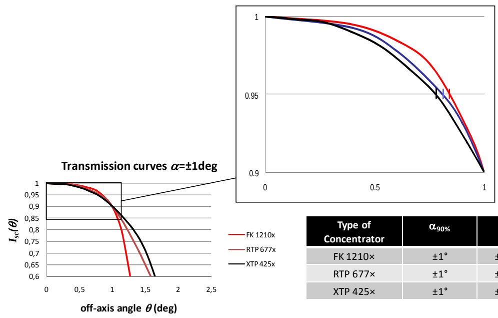


Figure 8 Expected power delivered by each array, relative to maximum, as a function of σ_ε, for two different photocurrent standard deviations (1% -dotted line- and 0.5%) about average with Scenario 1 assumptions. Notice the relative drops between systems are larger in the latter, when the effect of the lower acceptance prevails.

Notice P_{array} lowers with increasing σ_{Isc} and σ_ε, as expected. The *FK* outperforms the other two systems, reaching 7% increases (absolute) with respect to *XTP* in some cases (σ_{Isc} =0.5% and σ_ε=0.3deg). The benefits of the *FK* system at array level are more evident for low photocurrent variations, since in this case the effect of the acceptance angle dominates. If the set of cells shows huge variations in their electrical performance (large σ_{Isc}), the current mismatch is dominated by the cells themselves and the benefits of having better optics are negligible.

We can carry out the same experiment using the same systems, but this time having the same acceptance angle (±1deg) and therefore different concentrations. In this case, all three photocurrent characteristics cross the 0.9 I_{SCmax} level at the same acceptance angle, but each has a different shape, the *FK* curve being more planar at lower angles and showing a more steeped drop beyond the acceptance (pill-box shape). In other words, the *FK* attains a wider acceptance if defined at 95% transmission (see detail in Figure 9).



Type of Concentrator	$\alpha_{90\%}$	$\alpha_{95\%}$
FK 1210×	±1°	±0.85°
RTP 677×	±1°	±0.81°
XTP 425×	±1°	±0.78°

Figure 9 Scenario 2: same acceptance angle ±1deg for the three case-study systems, but different concentration (see Table and legend). Notice the *FK* still performs better than its competitors if we look at the acceptance defined at 95% transmission

The results for this second experiment are shown below.

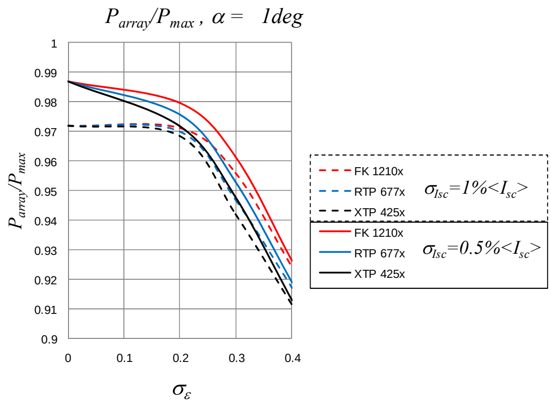


Figure 10 Expected power delivered by each array, relative to maximum, as a function of σ_ε, for two different photocurrent standard deviations (1% -dotted line- and 0.5%) about average with Scenario 2 assumptions. Notice there are still significant relative drops between systems despite they have the same acceptance angle. For instance, The *FK* can deliver 1% more power than the *XTP* for misalignments of σ_ε = 0.3deg, for small I_{SC} variations.

Even in this case we can notice differences in the array efficiency, especially when we compare the *FK* and *XTP*. For instance, for standard deviations in the misalignments of about σ_ε = 0.3deg the *XTP* delivers 1% less power, in average, with all the assumptions mentioned above.

3 CONCLUSIONS

The actual opportunities for the *CPV* to finally enter the energy generation market with success depend on its ability to demonstrate reliability and cost effectiveness, the conventional sources being the real benchmark in this case.

Current *CPV* systems need to improve their performance (considering energy, not power) and reduce their costs at the same time. The *FK* outperforms Fresnel-based *CPV* systems while still being simple. Its large tolerance budget can be partly exhausted applying inexpensive manufacturing techniques (loose manufacturing tolerances, insensitiveness to warp) and partly kept to assure high performance (preventing current mismatch, for instance).

In all the comparisons carried out so far, the *FK* concept clearly outstands among other solutions based on Fresnel lenses. Despite the important performance benefits, converting the latter into *FK*-systems do not imply dramatic technological changes: a slight re-design of the optics and the change of *POE* and *SOE* moulds suffices in most cases.

4 ACKNOWLEDGEMENTS

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