Progress In FK Concentrators

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Abstract. The *FK* concentrator was first presented in 2008. Since then, various *CPV* companies have adopted this technology as base for their future commercial product. The key for this rapid penetration is a mixture of simplicity (the *FK* is essentially a Fresnel lens concentrator, a technology that dominates the market) and excellent performance: high concentration without giving up large manufacturing/aiming tolerances, enabling high efficiency even at the array level. All these features together have a great potential to lower energy costs. This work shows recent results and progress regarding this device, covering new design features, measurements and tests along with first performance achievements at the array level (pilot 6.5Kwp plant). The work also discusses the potential impact of the *FK* enhanced performance on the Levelized Cost Of Electricity (*LCOE*).

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INTRODUCTION

Minimizing concentrated photovoltaic (*CPV*) energy cost (€/kWh) can be achieved by both lowering costs (at all levels) and increasing the energy yield. An optical design can help meeting these two goals by:

- Being more efficient: using the fewest elements lead to low optical losses, easier assembly and alignment. Apart from that, the *FK* [1][2] produces a “white” spot on the solar cell, preventing the unwanted effect of chromatic aberration of the irradiance, that leads to cell efficiency drops [3].
- Utilizing optics feasible at large scale/low cost
- Showing loose manufacturing and aiming tolerances, but always maintaining the high concentration (>500) to
  - permit the high-efficiency multi-junction solar cells work at their best and use less of them
  - assure high energy yield (system performing closer to the sum of the power expected from the best modules, low series connection mismatch)
  - enable additional cost cuts (lighter structures, easier installation…) if there is still an excess of tolerances

Apart from low cost, *CPV* needs to demonstrate long term reliability. Also in this case the *FK* has advantages:

- it’s based on well known durable materials (*PMMA* or Silicone on Glass –*SOG*- for the primary lenses –*POE*-and glass for the secondary lenses –*SOE*-)
- Cell reliability and efficiency is not compromised by hot spots: the *FK* achieves a very uniform irradiance on the solar cell
- The input beam is split into four that are focused near the *SOE* top surface. When the concentrator is off-axis, these spots reach the housing back plate (where many elements lie, such as *CCA* and wires) divided and un-concentrated, and therefore burning of these elements is more unlikely. This might also help to avoid the usage (and costs) of additional protection parts.

The *CCA* is embedded into the *SOE* and therefore is protected from humidity

DESIGN SOFTWARE LOOKING AT ELECTRICITY GENERATION

The optical design of nonimaging *CPV* systems often start with the description of the wavefronts (defining the light entering the optic and the light reaching the solar cell) we'd like the optic to connect [4]. The same applies to the *FK* design at its origin, where the design recipe combines general nonimaging and *Köhler* integration principles [5]. Aiming at a better description of the best achievable performance (plant peak power) and to help taking good business decisions, the original software has been enhanced by the addition of analysis tools and optimization algorithms that take into account all the spectral characteristics at play, i.e. those of the source -the sun- and receiver (cell external quantum efficiencies *EQEs*) and those of the optical materials involved.

For a given technology (set of materials used in the primary optical element *POE* –typically *PMMA* or Silicone on Glass *SOG*- and secondary optical element *SOE*, typically glass), concentration ratio C_g, size of cell and *f-number* (here defined as the ratio of the optical depth to the *POE* diagonal), the design algorithm produces a family of preliminary designs whose features (such as photocurrent characteristic – expected short circuit current I_{sc} as a function of sun beam tilt angle-, actual acceptance angle –measured on the latter-, shape and size of SOEs) can be compared.

This approach has demonstrated the optimal assignation of rays varies depending on all the input parameters mentioned above, but also on the criterion to select the final design: with this tool the designer has the choice to look at a set of f-numbers, concentration ratios, maximum photocurrents, angular characteristics, size of optics so that he can pick up the more balanced choice, with more potential to reduce energy costs.

These design tools might even emulate the performance of the plant (array level) using a stochastic model that takes into account the cell binning and making some assumptions on the effect of assembly and manufacturing errors on performance, and for a particular electrical layout [6].

Summarizing, the design enables a complete optimization looking at the final cost of electricity produced, minimizing the risks and facilitating each *CPV* manufacturer select the best scenario

RECENT RESULTS

Two different *FK* systems have been prototyped so far, one of them reaching the array level: this complete *HCPV* system prototype has been developed by *Pirelli* in collaboration with *LPI*, other companies and Research Institutes. Here we will focus on this system, explaining the results achieved both at the module and at the pilot plant levels.

3.5 W module

The system has a 120×120mm^2 entry aperture area and geometrical concentration of 576×, the *f-number* being 1.2, and is meant to work with 5×5mm^2 3J solar cells. The pictures at FIGURE 1 show images of the *POE* and *SOE* elements of this system, where the 4 Köhler sectors are evident. This prototype comprises a *PMMA* Fresnel lens (picture-top, made by *Evonik* and *10x Technology*) and a *B270* glass secondary (bottom-left) in a configuration producing an almost perfect uniform square spot onto the 5x5mm^2 *MJ* cell, as the picture on the bottom-left shows.

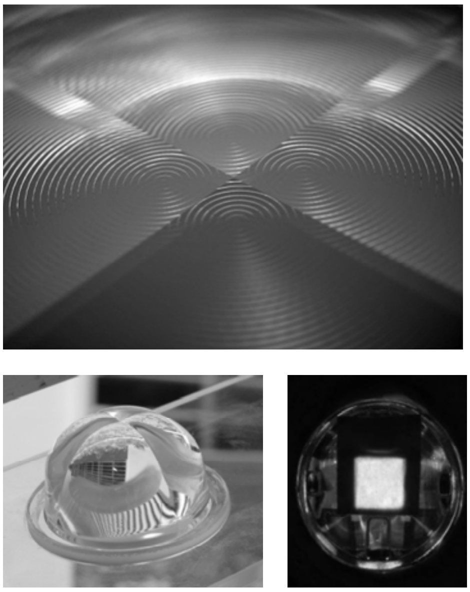

FIGURE 1 On the top, picture of the *FK* primary optical element. Bottom-left, Secondary optics. In both pictures, the 4- Köhler sectors are recognizable. Bottom-right, irradiance on the plane of the cell, showing a uniform white square spot.

A full characterization of this module was carried out in parallel by LPI and Pirelli, and the results achieved are shown in FIGURE 2.

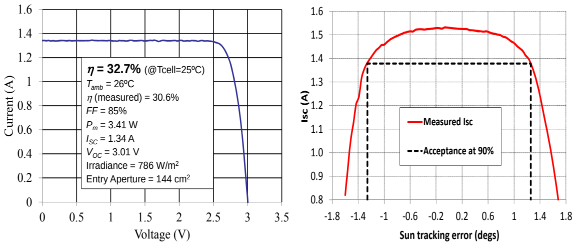

FIGURE 2 Measured IV curve, without temperature corrections and photocurrent characteristic $I_{sc}(\theta)$.

The single cell module achieves a peak efficiency of 30.6% (without temperature corrections!), using a commercial 3J cell with 38.0% efficiency. Its measured acceptance angle matches that of the simulations, and is ±1.26deg. The achievement of the theoretical value at the first try confirms the accuracy in the design software predictions.

6.5kWp pilot plant

Upon confirming the good performance of the 3.5W modules, the parquet prototyping phase was launched. The parquet panels are manufactured using roll-to-roll techniques in PMMA. In this case, each parquet module comprises 48 units of the 120x120mm^2 *PMMA* Fresnel lens shown above. The tracker holds 4 rows with 10 parquet modules.

FIGURE 3 shows a picture of the first *FK* prototype array, of 6.5kWp, manufactured by *Pirelli* and installed initially in Manresa (Spain). Such system was moved to *ENEA* facilities in Naples, where it is currently being monitored. This 6.5KWp system has attained electrical efficiencies up to 27% (DC at the entry of the inverter, without any temperature correction), which is outstanding since this was achieved at the first try, when the assembly process was not optimized yet.

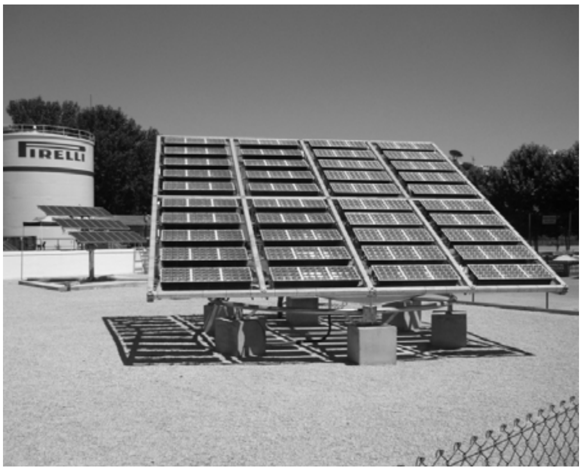

FIGURE 3 6.5kWp Pirelli Pilot Plant in Manresa (Spain). The tracker holds 40 panels comprising 48 Köhler lenses and cells each. Picture courtesy of Pirelli.

LCOE EXAMPLE

The goal of a solar power plant is to produce electricity at low cost, and in the end what really matters is the *LCOE*, defined as:

$$LCOE = \frac{Total\ Lifetime\cos t}{Total\ Energy\ produced} \quad (1)$$

In this section we mean to establish a comparison between two systems based on Fresnel lenses (the FK and the *F-XTP*, whose SOE is a truncated inverted pyramidal mirror) looking at the *LCOE* they can achieve and the profits they can potentially generate. We can utilize a simple approach for the calculation of the *Total Lifetime cost*:

$$Total\ Lifetime\ cost=CAPEX\times crf + OPEX \quad (2)$$

Where *CAPEX* is the investment and capital expenditures and the annuity factor *crf* is linked to *WACC*, the weighted average cost of capital along the 20 years lifetime.

Let us consider the *OPEX* and *crf* are identical for both systems, (although the FK should enable lower *OPEX* if we consider the wider acceptance values) and ranging a 3% of the CAPEX and 9% (*WACC* = 6.4%), respectively.

We will assume the two systems compared have same C_g, *f-number* and cells, and hence same kind of module housing and components. According to this assumption, when it comes to *CAPEX*, the only difference would deal with the secondary optics (slightly more expensive in the case of the *FK*) and the royalties fee, that applies to the *FK* optics only, resulting in rough *CAPEX* figures about 900\$/m^2 for the conventional system and 918\$/m^2 for the *FK*.

Finally, owing to the better acceptance characteristics the *FK* with respect to the *F-XTP*, and its impact on lowering cells series connection mismatch, we will assume the plant AC efficiencies are 29% for the former, and 25% for the latter.

With all these assumptions, and considering a 20 years Lifetime, the *LCOE* for these two systems would range 7 $cents/kWh and 8 $cents/kWh for the *FK* and benchmark system, respectively. Additional to this difference and the impact on profits produced when looking at the electricity fees that apply, there is the fact that the *FK* produces 893.6 MWh a year ahead of the *F-XTP*. The combination of higher selling margins and higher energy production implies the *FK* system yields benefits of 124K$ per year over the 25% conventional system. This means the original *CAPEX* over cost is paid off in one and a half years only, and the remaining 18.5 years the *FK* plant would be yielding important benefits over the conventional system.

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