

Renewable, sustainable, ecologically rational and profitable.



Sun light can be converted into electricity at affordable prices: it's always been clean, and it is now about to be profitable as well.

Thanks to the rapid increase in the conversion efficiency of multijunction solar cells, and the possibility of offsetting their high cost by using fewer cells to produce the same amount of electrical energy, the cost of electricity converted via CPV (Concentrated Photovoltaics) can now virtually compete on a purely economic basis with conventional sources.

To make this feasible, the concentrator parts that replace the numerous solar cells normally used in traditional photovoltaic conversion, and specially the optical elements, need to be inexpensive. LPI transfers all sophistication to the design stage, providing optical parts that perform near the theoretical limits, without substantially increasing the mass production cost of the optics. In other words, for a given system architecture, the optics achieve the **maximum acceptance** angle for a given **concentration factor** (or vice versa) and thereby the system efficiency is optimized. The tolerance budget (system acceptance) can be partly invested in an operational safety margin

that will prevent energy drops under not only tracking errors but will also minimize real up-front costs, such as: cheaper materials, relaxed manufacturing and assembly tolerances, and easier/faster installation/alignment costs.

Very sensitive to environmental issues, and strongly committed to a sustainable energy future, LPI has assembled a team of innovators that has developed solar solutions for the real world. With more than 20 years' experience in the field, LPI is presently designing CPV systems for major companies. Thanks to the skills of the team and to proprietary tools like the SMS (Simultaneous Multiple Surfaces) method of design, LPI has recently achieved record-breaking conversion efficiencies in this field.

LPI's versatility and flexibility is probably more evident in this application of its optical technologies than elsewhere. Indeed, services range from consultancy and design to manufacturing of optical parts, all the way to research and technology development. Once LPI understands a customer's market-strategy, it works in close concert to develop a thorough statement of requirements and then presents candidate architectures and an exclusivity plan.

Examples of Solar CPV Applications.

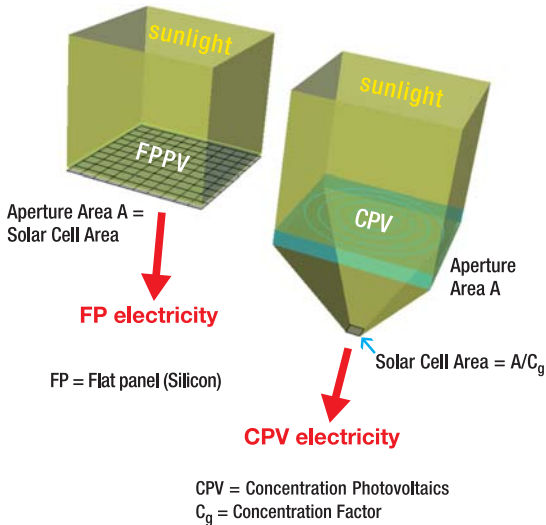
A highly tolerant design for low costs and efficient CPV system.

LPI's expertise in nonimaging optics makes it a force in modern Concentrated Photovoltaics (CPV) design.

The objective of CPV is to reduce the cost of energy generation by concentrating the equivalent of many suns on high efficiency "multi-junction" solar cells. Although the cost of these cells is much higher than that of silicon cells, the optical concentration offsets these costs by reducing the cell area needed to produce the same amount of electrical energy.

On the other side of the cost equation, CPV systems utilize only the direct solar energy (no diffuse sunlight is collected) and must be installed on a tracker that follows the sun. Aiming accuracy of the tracker and manufacturing tolerances are two factors that influence the cost of electrical production.

As achieving low cost optics is mandatory in order to decrease CPV generated electricity costs, CPV concentrators must not only be massproduced but must withstand environmental stresses for several decades. Therefore, a successful CPV strategy is to have a highly tolerant design that relaxes the manufacturing requirements of the optics, the alignment tolerances, and the tracking accuracy of the CPV system.



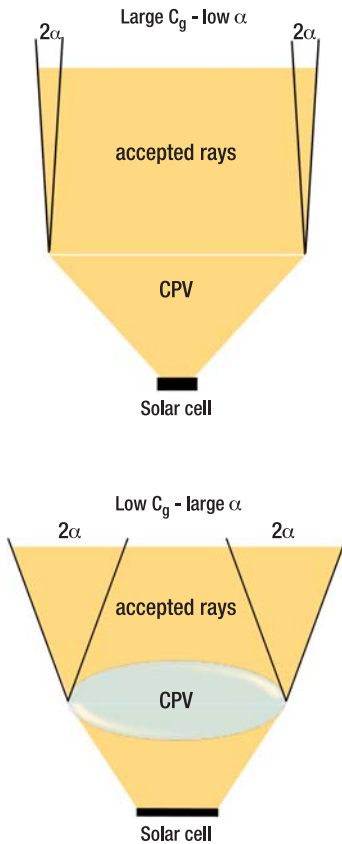
Practical and simple solutions achieved by LPI's SMS method (Simultaneous Multiple Surface Method).

The tolerance of a design is summarized (in a first approximation) by the so called tolerance (or acceptance) angle. This angle is not only the maximum allowable tilting angle of the perfect concentrator design, with respect to the direct solar rays but is also a measure of the tolerance available for the remaining parts of the system. This tolerance angle gives room for imperfections in:

- 1 shape and roughness errors of the optical surfaces,
- 2 concentrator mounting tolerances,
- 3 array assembling tolerances,
- 4 tracker structure finite stiffness,
- 5 sun tracking accuracy,
- 6 slack in the tracker gears, and
- 7 sun's angular extension.

All of these factors can be expressed in terms of the tolerance angle and together form a tolerance budget. For any concentration range (number of suns), a design providing the maximum tolerance is always a benefit because, in general, there is no penalty in the production cost of better optical designs vs. standard ones. The maximum available tolerance angle is bounded on the upper side by a theoretical physical limit. This limit is tighter as the concentration factor increases.

LPI's SMS (Simultaneous Multiple Surface Method) is a unique and proprietary design method that allows for optical designs very close to the theoretical limit with practical and simple solutions. This is most important for high concentration prescriptions (wherein the theoretical tolerance limit is tightest), but it is also important for medium concentration prescriptions because the cost of the optics in this case tends to be a greater part of the total cost of the system and, therefore, tolerant, low cost optics become more important.





Free form optical devices achieved by the LPI's SMS 3D method.

The SMS-3D method allows LPI to design free form optical devices (i.e.: devices whose surfaces are not constrained to a particular symmetry, neither linear nor rotational) and to use the extra degrees of freedom given by the lack of symmetry constraints to improve the concentrator's performance and simplicity. For instance, the SMS-3D method has been successfully used to achieve irradiance uniformity on the cell independent of the concentrator's aiming direction and also, in certain concentrator mirror configurations, to avoid self shadowing.

The secondary optical element (SOE) shown in the figure on the left is a good example of free form devices. This is used in an XR configuration where both the SOE and the primary optical element (POE) are free form.

The SMS method is not constrained by any particular architecture. LPI has a complete suite of proprietary architectures for CPV designs using mirrors, Fresnel lenses, TIR lenses, refractive SOEs, reflective SOEs, etc. SMS-3D free form solutions can gain benefits from any of these architectures without adding to the manufacturing cost of the molded parts.

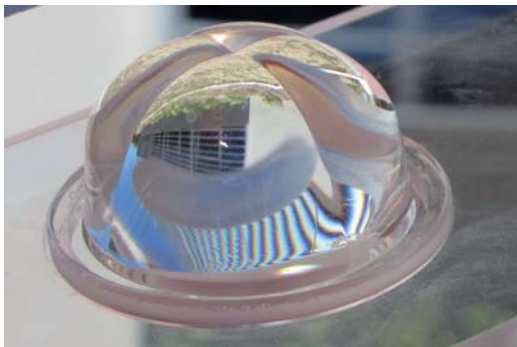


An example: the XR, combining high concentration and high tolerance angle capabilities.

The concentrator shown in the figure on the left uses a mirror-refractive lens combination called an XR, combining high concentration and high tolerance angle capabilities. Because the primary element is a mirror, in rotationally symmetric solutions, the position of the cell and the heat sink would cause partial shading of the POE, thereby lowering its efficiency. This is solved using the SMS-3D for free form solutions, in which the cell/heatsink position (as the figure shows) does not shadow the primary mirror. In this example, developed with the Boeing Company, the SMS-3D XR-700 concentrator has proven electrical efficiency of >31% for a 6 unit module (as shown in the figure below).



Fresnel-Köhler concentrator (FK).



This patented Fresnel-based concentrator contains a Köhler integrator scheme that homogenizes the irradiance on the cell independently of the position of the sun. Conventional (rotationally-symmetric) Fresnel lens concentrators produce very high irradiance peaks on the cell (for instance, a 500X concentrator can produce local irradiance peaks above 10,000 suns). This not only has deleterious effects on the cell efficiency but also compromises cell reliability and longevity. This problem can be solved with a Köhler integrator design. Köhler integrating optics consisting of two arrays of lenticular elements which improve the performance (full array efficiency, acceptance angle, irradiance uniformity, manufacturing tolerances) of the conventional Fresnel solution while maintaining its simplicity.

The solution in this case is comprised of 4 distinct quadrants in the POE working in unison with four nodes in the SOE (see the close-ups of both parts in the figures on the left).

The LPI FK concentrator offers a balanced solution between the easily manufactured but low-performing conventional Fresnel lens system and the high-performance but more difficult to manufacture and more sophisticated XR concentrator.



Maximizing the Efficiency/Cost Ratio via Boosting of the Tolerance Budget of Fresnel System.

The picture on the left shows a 625X FK concentrator using a 1cm² Spectrolab triple junction solar cell. This system utilizes two stages of optics: 1) a 4-quadrant primary Fresnel lens and 2) a four-node refractive secondary optic. Together this system produces perfect irradiance uniformity on the cell (never surpassing 600 suns for a DNI of 1000W/m²) and maintaining high concentration and acceptance angle (± 1.4 degrees). The latter attribute, allows for a very loose level of manufacturing-alignment tolerances, which will reflect in the costs of manufacturing and can also preclude cell mismatch at the array level, maximizing the production of energy throughout the year. These two factors are essential for decreasing the LCOE (Levelized Cost of Energy).

Models of this system predict an optical efficiency of 87% and 83% with or without AR coating, respectively, which can lead to electrical efficiencies higher than 30%, if cells with 38.5% efficiency are used. The FK maintains these outstanding performance features even in highly-compact systems (equivalent f-number = 1).

For instance, if we specify an f-number of 1, we can estimate how the acceptance angle will vary for different concentrations. The table on the left summarizes how the acceptance angle changes for different concentrations in the FK concentrator.

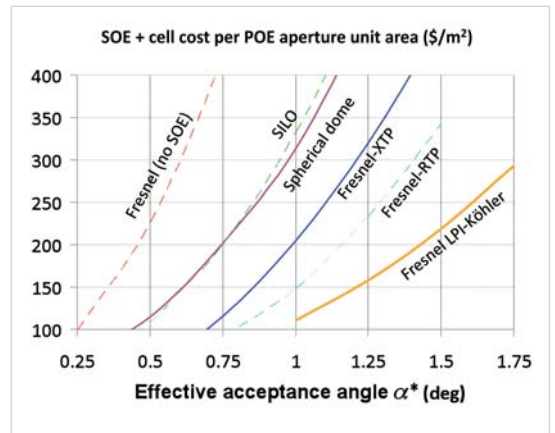
C_g	No AR coating on SOE	Perfect AR coating on SOE
	α	α
625	$\pm 1.43^\circ$	$\pm 1.52^\circ$
1,000	$\pm 1.13^\circ$	$\pm 1.20^\circ$
1,500	$\pm 0.92^\circ$	$\pm 0.98^\circ$



SOE Effect on the cost of CPV system.

The figure on the right shows the cost/m² of (the SOE + solar cell) in various optical architectures for Fresnel-based systems as a function of the effective acceptance angle α^* (aim-error angle at which the cell photocurrent achieves 90% of perfect on-axis). All these concentrators have equal POE Fresnel lens entry aperture area (625 cm²), while different SOEs have been analyzed: 1) No SOE; 2) SILO (a single-surface rotational symmetric lens as a secondary that images the primary on the cell); 3) spherical dome; 4) XTP (a hollow reflective truncated pyramid); 5) RTP (a dielectric-filled truncated pyramid); and, finally, 6) The LPI FK architecture.

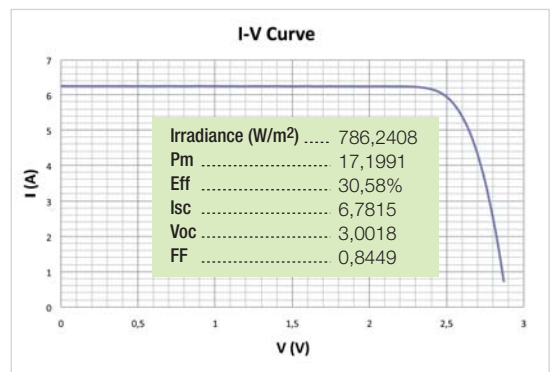
To compare among different concentrators, pick an effective acceptance angle α^* (i.e., so they are all tolerance-equivalent). This assumes module assembly, array installation, structure and tracker design tolerances are the same for all the cases, and therefore the cost is common and need not be compared. For instance, if we specify $\alpha^* = \pm 1^\circ$, the FK concentrator has an (SOE+cell) cost of about \$110/m², while for the RTP, the XTP and the SILO the cost is \$150/m², \$200/m², \$340/m², respectively. It is remarkable that if no SOE is used the cell cost is \$670/m² (outside the graph!) for $\alpha^* = \pm 1^\circ$, because to achieve this α^* the C_g must be only 104x. (Systems with no SOE usually are designed for smaller α^* values, which increase the assembly, installation and other costs.)



FK demonstrator characterization.

The graph on the right shows the I-V curve for an LPI FK design with $C_g = 650X$ concentrating on a 1cm² C3MJ Spectrolab solar cell (38.5% cell efficiency), that reaches electrical efficiency of 30.6%.

The efficiency figure shows what can be achieved at the module level without the use of AR coatings either on the primary or the secondary optics.



A complete suite of proprietary architectures for CPV designs.

These free form Köhler solutions are not limited to the present FK concentrator. Even for the conventional Fresnel lens as a primary, multiple options for improved secondary lenses are envisaged for future improvements. The true innovation in these new designs is that they consist of free-form Köhler integrating arrays. This degree of freedom enables the design of optical surfaces that can perform different attributes at the same time (such as improvement of the device performance without affecting its cost). This also allows for good irradiance uniformity and high tolerance angles at high concentration values.

Each CPV optical architecture offers different possibilities, which facilitate varied requirements. LPI offers many proprietary architectures from which to choose and also the capability of prototyping and manufacturing free form optical components.



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