SPIE Newsroom

10.1117/2.1201306.004925

Wide-angle, high-concentration photovoltaics to compete with flat plate systems

Rubén Mohedano, Aleksandra Cvetkovic, Pablo Benítez, Juan Carlos Miñano, Maikel Hernández, Pablo Zamora, and Juan Vilaplana

A novel photovoltaic concentrator enables highly uniform irradiance on a small number of efficient solar cells.

The maximum electrical power of a photovoltaic (PV) energy installation depends on three factors: the available irradiance, the size of the systems collecting sunlight, and the rate at which the device transforms light into electricity (the conversion efficiency). Developers can maximize the irradiance by carefully selecting the site and orientation of the solar facility. But they can only expand their sunlight collection systems for standard flat plate PV devices by increasing the number of solar cells, at greater cost. Here, we consider the advantages of an alternative PV system that produces more energy without increasing the number of cells used (actually, reducing it), by improving the conversion rates. We also present a new device that may enhance the commercial viability of such technologies.

Standard flat plate PVs[1] (FPPVs) seek to maximize sunlight collection using a panel whose surface is typically covered more than 80% by solar cells. These both gather and convert light into electricity, often at rates of <20%.[2] In contrast, less commonly used concentrated PV systems (CPVs) separate the processes of sunlight gathering and conversion (see Figure 1). CPVs employ triple-junction solar cells, in which each p-n junction is tuned to a different light wavelength, to achieve efficiency rates of >40%. Compared with FPPVs, the cells used in CPVs are small: the cells' area is $1/C_g$ times smaller than that of the optics entry aperture, C_g being the geometrical concentration factor. Consequently, the solar cell component of the system cost is also small. However, despite these advantages, the technology is not yet cost-competitive with FPPVs because it requires other parts that are seldom needed in flat plate systems, and which can increase the overall cost. For example, most concentrators only accept

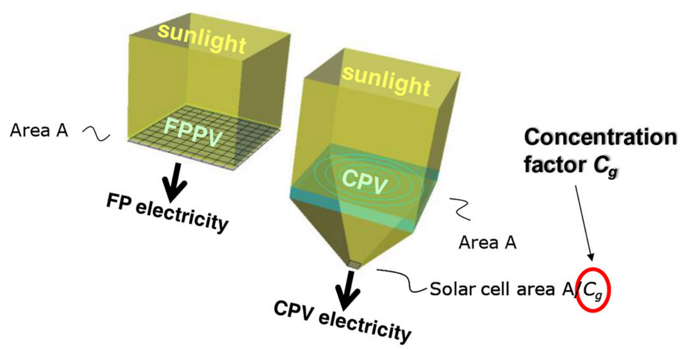

__Figure 1.__ Concentrated photovoltaic systems (CPVs) replace solar cell plates with a panel of optics that concentrate sunlight onto a set of small, high-performance solar cells, where light is converted into electricity. FP: Flat plate.

direct normal irradiance and therefore need unobstructed light, or must use trackers to follow the sun's movement across the sky. They also require optics and heat sinks (which enable efficient cell performance at reasonable temperatures under concentrated sunlight). Furthermore, CPVs need to combine high tolerance angles—the maximum angle at which incoming sunlight can be captured—and high concentration, which requires cost-effective parts that can be mass-produced. Resolving these issues may enable CPVs to be cost-competitive with FPPVs. Here, we present a new concentrator for use in a CPV system that has acceptance angles wide enough to compensate for some of these technical issues, and could potentially reduce the overall module cost.

Our device, the Fresnel-Köhler concentrator (FK),[3,4] is simple but achieves high concentration and wide tolerance/acceptance angles. It comprises a concentrator with two lenses, one of which is Fresnel in design and has a large aperture and short focal length. The wide angles overcome the problems of lens

Continued on next page

10.1117/2.1201306.004925 Page 2/3

roughness, form factor errors, soil on the optical parts, small tracking failures, and assembly imperfections, any of which can divert the sunbeam and prevent it from hitting the cells. The very uniform irradiance on the solar cell, which avoids chromatic aberration,[5] and its protection from humidity prevent cell failure and reductions in power output.

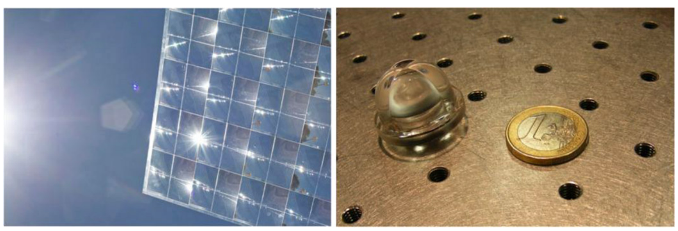

Figure 2. *Left: The VENTANA primary optics panel. Right: Glass secondary optics developed by the authors. Both optics units are divided into four sections to perform the Köhler function, which enables uniform irradiance and color over the solar cell, while maintaining high concentration and tolerance angles.*

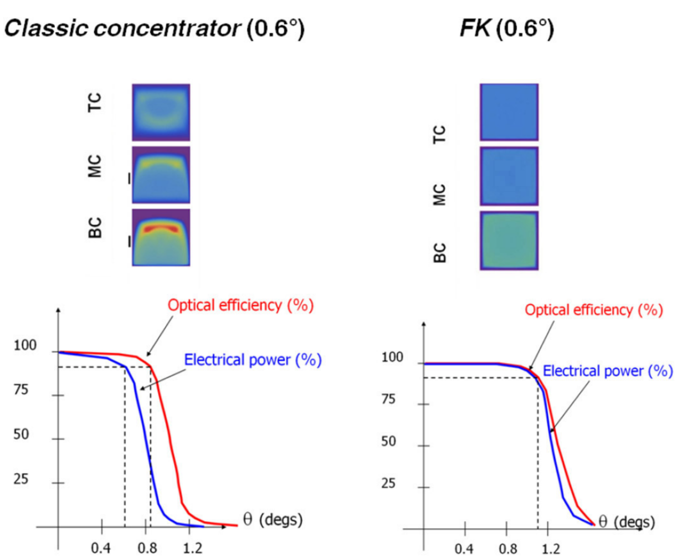

Figure 3. *Left: The influence of chromatic dispersion of irradiance on the different sub-cells is evident in a classic Fresnel concentrator, since the electrical power is much more sensitive to the sun's incidence angle than the optical efficiency itself. Right: In the Fresnel-Köhler (FK) concentrator the effect is hardly noticeable because of the well-balanced irradiance uniformity, no matter the wavelength or incidence angle of sunlight. During simulations the sun's rays hit the concentrator's entry aperture at 0.6° incident angles. BC, MC, TC: Bottom cell, middle cell, top cell.*

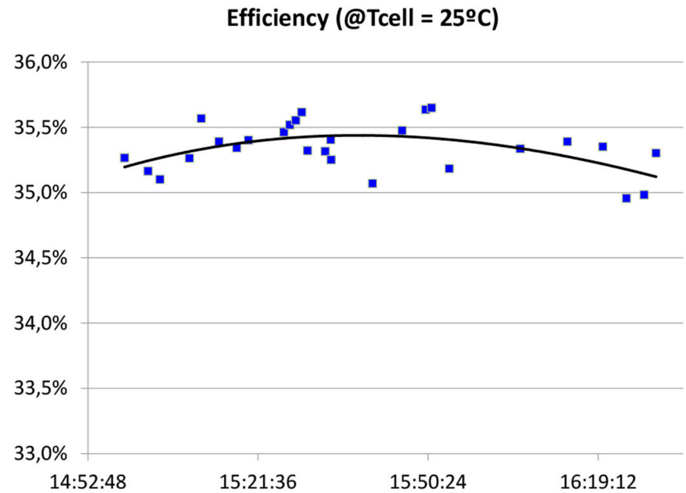

Figure 4. *First results of the attempt by Light Prescriptions Innovators and Solar Junction to break the world record conversion efficiency at the module level: measured module efficiencies corrected for $T_{cell} = 25^{\circ}C$ (direct normal irradiance = 961± 1.5% W/m^2 during the tests).*

The first customized FK-based system was installed in 2010,[6] and the first commercial model, the VENTANA, became available in 2012. The device's primary lenses come in the form of a 1×1m^2 poly(methyl methacrylate) panel comprising 36 units, which are aligned with 36 secondary lenses and the corresponding cells (see Figure 2).

This system, where $C_g = 1024\times$, attains a maximum electrical efficiency of >32% (varying by ±0.5% in a wide ±10mm range of secondary lens shifts with regard to primary lenses along the optical axis), using a 39% multi-junction cell.[7] We were able to increase the module efficiency by a relative 3–4% using antireflective (AR)-coated glass or high-transparency Savosil for the secondary lenses. The measured acceptance angles are in excess of $\pm 1^{\circ}$. The irradiance pattern on the cell is almost perfectly uniform, which prevents the drop in power output often seen in Fresnel-based concentrators[8] when they track the sun less than perfectly (due to the deterioration of fill factor—a measure of efficiency—and short circuit current, I_{sc}) (see Figure 3).

Light Prescriptions Innovators and Solar Junction, whose cells achieve the maximum conversion efficiency reported so far, are currently jointly developing a world record conversion efficiency CPV module combining their respective state-of-the-art concentrator optics and cells. During tests, we calculated a nonlinear regression with a set of efficiency measures throughout a day, where the peak of that regression reached around 35.5%

Continued on next page

efficiency (corrected @$T_{cell} = 25^{\circ}$C, see Figure 4). We used a 1024× FK concentrator, whose primary lens is manufactured using silicon on glass, while the secondary lens is of Savosil (both the primary and secondary lenses are AR-coated on their top surfaces).

During a two-year test, the FK has shown very high efficiency, feasibility, and other practical advantages that enhance system reliability. The technology may enable CPVs to be competitive with flat plate solar cells once the device is in widespread use, and mass production of its components reduces the final module price. The development of an industrial cost-effective recipe for manufacturing receivers (the assembly of cell circuit and secondary lens) yielding reliable long-lasting devices, and the achievement of a world record efficiency at the module level, are the two main immediate goals for the next stages of this project.

The authors wish to thank the support of the European Regional Development Fund in the early stages of FK technology.

Author Information

Rubén Mohedano, Aleksandra Cvetkovic, Maikel Hernández, and Juan Vilaplana
Light Prescriptions Innovators (LPI)-Europe
Madrid, Spain

Rubén Mohedano obtained his PhD in January 2002, focusing on non-imaging optics design and manufacturing. He is currently managing director of the LPI office in Europe, and has participated in several major illumination, automotive, and concentration PV projects for various companies.

Aleksandra Cvetkovic joined LPI-Europe in 2009, and has participated in more than 20 projects involving concentrated PVs and solid-state lighting. She received her PhD from the Polytechnic University of Madrid in 2009, where her research focused on non-imaging optics design, manufacturing, and applications.

Maikel Hernández obtained his PhD from the Polytechnic University of Madrid in 2003. His research is on non-imaging optics design, manufacturing, and applications. He joined LPI-Europe in 2003, and has been involved in several projects in concentrated PVs, automotive, and illumination applications.

Juan Vilaplana obtained his degrees in engineering of materials and mechanical engineering in 2003 and 2006, respectively, from the Polytechnic University of Valencia. Since he joined LPI-Europe in 2008, he has been a mechanical engineer for prototyping and manufacturing concentrated PV systems. He is co-author of several communications for international congresses.

Pablo Benítez, Juan Carlos Miñano, and Pablo Zamora
Technical University of Madrid (UPM)
Madrid, Spain

Pablo Benítez is professor of electronics, optical communications, and optics. He has published many papers on non-imaging optics and is co-inventor of the 2D and 3D simultaneous multiple-surface non-imaging optical-design methods.

Juan C. Miñano has been involved in non-imaging optics since 1982 and has developed several optical design techniques with immediate application to optoelectronics, such as the SMS method. Since 1997, he has been a professor at UPM, and since 2000 he has collaborated with LPI as a senior scientist.

Pablo Zamora received his degree in telecommunications engineering from UPM in 2005. He is currently a researcher in the Department of Physical Electronics. His research is focused on optics design, manufacturing, and testing of non-imaging devices, with application to PV solar energy.

References

1. A. Luque and S. Hegedus (eds.), **Handbook of Photovoltaic Science and Engineering**, 2nd ed., John Wiley, 2011.
2. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, *Solar cell efficiency tables (v41)*, **Prog. Photovolt.: Res. Appl. 21**, pp. 1–11, 2013.
3. P. Benítez *et al.*, *High performance Fresnel-based photovoltaic concentrator*, **Energy Express, Opt. Soc. Am. 18** (S1), pp. A25–A40, 2010.
4. P. Benítez, A. Cvetkovic, M. Hernández, J. C. Miñano, and P. Zamora, *Fresnel-Köhler (FK)*, **US Patent 8,000,018**, 2011.
5. P. Espinet-González *et al.*, *Triple-junction solar cell performance under Fresnel-based concentrators taking into account chromatic aberration and off-axis operation*, **Proc. Am. Inst. Phys. 8th Int'l Conf. Concentrat. Photovolt. Syst. 1477**, pp. 81–84, 2012.
6. R. Mohedano *et al.*, *Progress in Fresnel-Köhler concentrators*, **Proc. Am. Inst. Phys. 7th Int'l Conf. Concentrat. Photovolt. Syst. 1407**, pp. 270–273, 2011.
7. P. Zamora *et al.*, *Experimental characterization of Fresnel-Köhler concentrators*, **J. Photon. Energy 2** (1), p. 021806, 2012.
8. L. W. James, **Use of Imaging Refractive Secondaries in Photovoltaic Concentrators**, Contractor Report SAND89–7029, Sandia Labs, Albuquerque, NM, 1989.