Technical specification IEC TS 62989:2018 – Primary optics for concentrator photovoltaic systems

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Thomas Arndt, Steve Askins, Jaione Bengoechea, Sam Carter, Cesar Dominguez, Rebeca Herrero, Thorsten Hornung, Hideto Kasai, Rene Kogler, Ralf Leutz, David Miller, Peter Nitz, Steve Scott, Marta Victoria, and Philippe Voarino

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Thomas Arndt1, Steve Askins2, Jaione Bengoechea3, Sam Carter4, Cesar Dominguez2, Rebeca Herrero2, Thorsten Hornung5, Hideto Kasai6, Rene Kogler1, Ralf Leutz7, a), David Miller8, b), Peter Nitz5, Steve Scott9, Marta Victoria2 and Philippe Voarino10

1Evonik Industries AG, Kirschenallee, 64293 Darmstadt, Germany
2Universidad Politécnica de Madrid, Instituto de Energía Solar (UPM-IES), ETSI Telecomunicación, Ciudad Universitaria, 28040 – Madrid, Spain
3Centro National de Energías Renovables (CENER), Ciudad de la Innovación 7, 31621 Sarriguren (Navarra), Spain
4RayGen Resources Pty Ltd, 15 King Street, Blackburn, VIC 3130 Australia
5Fraunhofer Institut für Solare Energiesysteme (ISE), Heidenhofstraße 2, 79110 Freiburg, Germany
6Kuraray Co. Ltd., Ote Center Building 1-1-3, Otemachi, Chyoda-ku, Tokyo 100-8115, Japan
7leopil – Leutz Optics and Illumination UG (haftungsbeschränkt), Schellingstraße 87, 80799 München, Germany
8National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway., Golden, CO 80401-3211, USA
9Orafol Americas, Inc., 120 Darling Drive, Avon, CT 06001-4217, USA
10Commissariat à l’énergie atomique et aux énergies alternatives (CEA), Département des Technologies Solaires, Laboratoire PhotoVoltaique à Concentration, 50 avenue du Lac Léman, 73375 Le Bourget-du-Lac, France

a)Corresponding author: ralf.leutz@leopil.com
b)david.miller@nrel.gov

Abstract. The first edition of the Technical Specification (TS) on Primary Optics for Concentrator Photovoltaic (CPV) Systems, IEC TS 62989:2018, has been published by the International Electrotechnical Commission (IEC), on March 8th, 2018. TS 62989 covers aspects related to the primary optics including: product identification, optical characteristics, mechanical characteristics, materials, (design) geometry, and visual appearance. This paper focuses on the key aspects of the norm, including optical performance, in order to promote the awareness and use of the standard. We describe the three methods intended to measure the key optical characteristics of the primary elements, i.e. focal spot size and optical efficiency, by using the encircled energy. The three methods are using different light sources, optical components and receiver sensors, but yielded very similar results in a round robin test. This justifies the continued use of all three methods. The use of a website (opticstests.pbworks.com) for documentation of discussions and references was novel to the standard development. The website proved to be useful for the introduction of new members of the group. The website helped to keep track of changes to the document as well as the required actions of the project team.

INTRODUCTION

Initiated five years ago, the Technical Specification (TS) on Primary Optics for Concentrator Photovoltaic (CPV) Systems, IEC TS 62989:20181, has been published by the International Electrotechnical Commission (IEC, FIGURE 1). The vote in favor of the norm was unanimous.

The scope of the Technical Specification IEC TS 62989 reads1: “This Technical document encompasses key characteristics of primary optical elements (lenses and mirrors) and lens or mirror parquets for Concentrator Photovoltaics including: optical performance, mechanical geometry, mechanical strength, materials, and surface...
morphology. The document identifies the essential characteristics, the corresponding quantities of interest, and provides a method for measurement of each quantity.

This document allows lens and mirror manufacturers, concentrator module manufacturers, test laboratories and other interested parties to define lens/mirror qualities and inspect lenses and mirrors. There are no pass/fail criteria associated with the document.

The use of a website (opticstests.pbworks.com) for documentation of discussions and references was novel to the standard development. The website was used to introduce new members of the group. At the same time, it helped to keep track of changes to the standard document as well as action items for the project team. Besides, the website provided dates for upcoming meetings, next steps, as well as all associated files and background references.

![IEC Webstore](https://webstore.iec.ch/)

**FIGURE 1.** IEC TS 62989:2018 published on March 8th, 2018, now available for purchase at [webstore.iec.ch](http://webstore.iec.ch)

**NORMATIVE APPROACH**

TS 62989 was designed so that it has no pass/fail criteria. TS 62989 is descriptive, and allows its users to understand the characteristics of Primary Optics for Concentrator Photovoltaic Systems.

The authors of the norm started by establishing a hierarchical list of characteristics of Primary Optics. These characteristics could be measured using scientific methods of testing and evaluation. While many of the characteristics are determined using existing standards developed for other industries, relevant details of measurement as well as the characteristics’ use is specified in TS 62989 for CPV. The methods yield parameters, which are quantitative values, or in some cases qualitative decisions, which have to be reported along with the key details of the experimental set-up used for the method. The list of characteristics is classified according to scientific fields into six Tables, which are, 1 Product identification, 2 Optics (optical characteristics), 3 Mechanics (mechanical characteristics), 4 Materials, 5 Geometry (from the primary optical element design), 6 Visual appearance.

The Tables contain up to fifteen characteristics in up to three levels of hierarchy. A number next to the characteristics refers to the appropriate section in the text, where the characteristics are defined, the methods is then presented, and the reporting of the yielded parameters is prescribed. Typically, the order is, Heading, Definitions, Setup of experiment, Procedure, and Presentation of results.

There are sections of scope, normative references (related standards), and global definitions preceding the Tables. There is a bibliography closing the text. The total length of the norm is 35 pages.

**FOCAL SPOT SIZE AND OPTICAL EFFICIENCY**

One of the most important characteristics of the CPV Primary Optics is the optical efficiency, which motivated the creation of the standard. TS 62989 describes the three methods intended to measure the key characteristics of the
primary optics, i.e. focal spot size and optical efficiency, by way of encircled energy. The three methods are using different light sources, optical components and receiver sensors, but yielded very similar results in a round robin study. This justifies the documentation of all three methods.

**Encircled Energy**

The encircled energy is defined as accumulated radiometric power in a circle on the target as a function of the radius of the target area.

![Encircled Energy Graph](image)

**FIGURE 2.** Example of efficiency versus focal spot size. Encircled energy level of 95% for the intercept radius \( r_{\text{intercept}} \).

The encircled energy concept is explained in graph of **FIGURE 2.** The graph identifies the accumulated power as a function of the radius of the target area. The intercept radius and the optical efficiency can directly be read from the graph. For this Technical Specification, we define the intercept radius \( r_{\text{intercept}} \) of a target area in which 95% of all irradiance enters. We assume that in an area with two times the radius \( r_{\text{intercept}} \), all irradiance is contained.

**Methods**

This section describes the methods central to the norm, i.e. the determination of focal spot size and optical efficiency. Methods shall be reported in detail, with the intention that the reader is able to assess the validity of results. The Methods and round robin refer to refractive (lens) measurements, but the procedures described are applicable to reflective (mirror) measurements.

**Method A (CENER)**

Method A can be used to characterize the light distribution spatially and spectrally at the focal area. The method requires a collimated Xenon lamp and a spectroradiometer (wavelength range from 300 nm to 1600 nm) with several apertures attached to its head. Method A provides the intercept radius and the optical efficiency along with the spatial distribution of the spectral irradiance at the focal spot. In order to achieve this, the focal distance is measured by placing sample and detector in line with the source. A diaphragm is closed to be smaller than the size of the focal spot area. Moving the detector in the three directions in space until the measured radiant flux is maximized, allows the identification of the focal point. Opening the diaphragm at its position on the focal point allows to construct the encircled energy graph. It is necessary to subtract dark measurements, i.e. measurements taken in dark condition. The intercept radius can thus be determined.
Method B (UPM-IES)

Method B uses a solar simulator, classified as class A for the category spatial non-uniformity described in IEC-60904-9-1 (forthcoming). The collimation angle of the beam shall be $(4.65 \pm 0.05)$ mrad, defined as the angular radius, with respect to a vector normal to the test plane, containing 90% of all incoming light flux. The detectors used in Method B are a translucent Lambertian diffusing surface, a CCD (charge-coupled device) camera, and a calibrated solar cell. The method allows to determine the focal distance and the intercept radius by focusing with the primary optics onto the diffusing surface, and photographing that surface from the opposite side until the tightest spot marks the focal distance. The intercept radius can then be calculated. By adding adequate filters to the CCD camera the spot of light for wavelength separation (e.g., corresponding to every subcell within a multijunction solar cell) can be measured.

The optical efficiency is measured by means of a calibrated solar cell. The direct beam fraction of the irradiance entering the primary optical element is measured. Then, the cell is placed into the focal spot; the irradiance there can be measured. The optical efficiency is the ratio of the radiant flux (in W) in the focal plane (target plane) to the radiant flux on the entrance aperture. The encircled energy and the intercept radius can be calculated.

Method C (ISE)

Method C uses a collimated narrow bandwidth LED typically red, $622 \pm 7$ nm, and a scientific CCD camera chip without the camera lens to characterize the spatial light distribution at the focal spot. The focal distance is determined from an image of the camera chip; the shape of the focal spot at the approximate focal length is of simple geometry, such as round, rectangular, or square, rather than having the shape of a star, for example. The signal of the chip is integrated to yield the signal on the target area. With the help of a reference measurement without primary optics, and a neutral density filter to stay within the response of the chip, irradiance maps are provided. The tightest spot with the lowest intercept radius gives the focal distance. The optical efficiency can be calculated from the data available from the irradiance maps with and without the primary optics in the path of the light.

Round Robin Test

A Round Robin test is a measurement series performed by several laboratories using different equipment and Methods (as described above as Methods A-C) in order to compare and assess this equipment and these methods.

Setup

A Round Robin study was conducted to allow for the assessment of the accuracy and suitability of available Methods. Five laboratories initially agreed to participate in the study; one laboratory could not provide any measurements for unknown reasons, one laboratory experienced a technical failure with their CCD camera, which could not be fixed in time for data assessment and conclusion of the study. For each laboratory, one set of six Fresnel lenses was industrially produced using a tool designed for neither SOG (silicone-on-glass) nor PMMA (Polymethylmethacrylate), i.e. with a refractive index around 1.45. Three lenses were made in PMMA, three lenses were made in SOG, all lens sets were sent in parallel to the laboratories in Refs. [2,3,4], and measured according to the Method available there.

As the refractive index used for the lens design is unknown, no true focal length, or reference focal spot size can be given. Just like in real life, the laboratories had to use their respective methods in the way intended, i.e. in approximating the characteristics of the lens. In that sense, our Round Robin is a blind test.

The data to be reported by the laboratories had been decided upon by the standards working group, and fixed into a spreadsheet file.

Measurements

Some results by the groups are presented in the order of appearance in the Methods section. The group at CENER (Method A) presented the irradiance maps in the target plane, in arbitrary units and in percentage, for three wavelength bands, for a PMMA lens (FIGURE 3).
The group at IES-UPM measured data which yields a good example of the focal spot distance and focal spot size, see FIGURE 4. We arithmetically averaged the data for the measurement series, for the two materials PMMA and SOG.

FIGURE 3. Irradiance maps of a PMMA lens presented by the CENER group in Method A.
FIGURE 4. Intercept radius values for the PMMA and SOG lenses measured at UPM-IES. The values measured for the three specimens for each material are arithmetically averaged. Intercept radius is measured for the light converted by the top and middle subcells in a classic MJ solar cell. The spot is photographed using a CCD camera and adequate low-pass and high-pass filters.

An example for the encircled energy calculated from data measured is given in FIGURE 5, as given by Fraunhofer ISE. This data set, like the ones above have been arithmetically averaged for the materials PMMA and SOG. In this case, lenses have been measured in two temperature regimes, i.e. at 25°C and 50°C. As shown, the encircled energy for the specimens in PMMA does not show any variation for the two temperatures. PMMA expands thermally in an isotropical fashion, and the change of the refractive index for the delta in temperature remains too small to be affecting the encircled energy. The SOG lenses show a clear influence of their more complex way of expanding under heat; the silicone expands significantly stronger than its superstrate glass. Consequently, silicone prisms change shapes, and the size of the focal spot changes for temperature variations, and with it the encircled energy. The temperature-induced change of refractive index might also be responsible for the change in focal spot size. Understanding the two effects completely is still an open research topic.

FIGURE 5. Encircled energy as measured by Fraunhofer ISE for the PMMA and SOG lenses. Data for specimens are arithmetically averaged. Results are given for lens temperatures of 25°C and 50°C.
Results

The results reported by the participating laboratories were compared and found to be within acceptable tolerance brackets. TABLE 1 summarizes the Methods and results.

TABLE 1. Summary of the results attained during the round robin measurements. For methods A-C, average intercept radii, focal distances and optical lens efficiencies are calculated using the measurements of three samples for each method. Measurements were carried out at temperature within the range 25-27.5°C. The descriptions of the method include the bandwidth and collimating angle of the light source.

<table>
<thead>
<tr>
<th>Method</th>
<th>Intercept radius (mm)</th>
<th>Focal distance (mm)</th>
<th>Optical efficiency (%)</th>
<th>Description of the method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOG</td>
<td>PMMA</td>
<td>SOG</td>
<td>PMMA</td>
</tr>
<tr>
<td>A</td>
<td>1.53±0.04</td>
<td>1.07±0.04</td>
<td>104.5±0.01</td>
<td>83.0±0.01</td>
</tr>
<tr>
<td>B</td>
<td>1.18±0.03</td>
<td>0.96±0.03</td>
<td>105.9±0.3</td>
<td>86.1±0.3</td>
</tr>
<tr>
<td></td>
<td>1.27±0.03</td>
<td>0.98±0.03</td>
<td>106.5±0.3</td>
<td>86.4±0.3</td>
</tr>
<tr>
<td>C</td>
<td>0.93±0.01</td>
<td>0.53±0.01</td>
<td>103.3±0.1</td>
<td>84.1±0.1</td>
</tr>
</tbody>
</table>

The measurement uncertainty taking into account errors of the light source intensity, geometry, and other inaccuracies is given by Fraunhofer ISE as ±2.0 percentage points, by UPM-IES as ±2.6 percent, almost identical. Reproducibility is better than 1.0 percentage points for different measurement series (Fraunhofer ISE). These limits are thought to be quite representative of all measurements. There are not enough data points to allow for a statistical analysis.

Interlaboratory results vary more widely than measurement uncertainty for one experimental setup. The use of very different wavelengths, in particular, is thought to be responsible for the observed differences in intercept radius and focal distance. The central value of the optical efficiency is close for all three laboratories and both materials. The variations between measurements of the three laboratories and for the two materials PMMA and silicone-on-glass (SOG) are small enough to justify the use of all three methods. For the intercept radius, the three laboratories give different results (possibly due to their using of different collimation angles of the sources), but focal distances and optical efficiencies are very similar. The agreement in TABLE 1 is surprising as the details of the Methods and their equipment vary widely. It was agreed that all three Methods be included in TS 62989.

ADDITIONAL CHARACTERISTICS

Additional methods and characteristics described in the Technical Specification include: hail impact, optical haze, refractive index and Abbe-number, spectral transmittance, and yellowness index, among others. The geometry of the primary optical element can be given in suitable electronic data format.

CONCLUSIONS

Five years and over sixty meetings were required to arrive at the present Technical Specification IEC TS 62989. We believe that this effort is justified in that it stimulates the standardization of the markets around concentrating photovoltaics (CPV). TS 62989 enables stakeholders in the CPV market to assess key characteristics of primary optical elements, including the optical efficiency.

Standards can provide ways to document technical developments in a way agnostic of material choices, corporate and laboratory interests, and political agendas. This being said, we know that standards are no guarantee of balanced views; our case, however, can be seen as scientifically strong, incorporating input from all major industrial stakeholders and continents. Using a website to organize the standard development proved valuable. The website served as central address for actions, meeting dates and document version control.
In three years’ time, IEC TS 62989 is up for a second edition. In the meantime, working on a technical specification on secondary optical elements could support the goal of covering the full optical system in concentrating photovoltaic systems.

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REFERENCES