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Experimental Comparison between Direct and Indirect Methods Adopted for Evaluating CPV System Optical Performance

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ABSTRACT

In concentrating photovoltaic (CPV) systems, energy conversion efficiency depends on solar cell characteristics and optical parameters such as the optical efficiency (η_{opt}) that affects solar radiation concentrated on TJ cells. Hence, it is important to standardize η_{opt} definition, measuring methods and instruments to compare different CPV technologies. η_{opt} is linked to optical concentration factor (C_{opt}) representing how many times solar flux is increased by optics. The CPV systems optical characterization must be practical; so, two methodologies of concentrated solar flux are compared. Indirect method is based on generated photocurrent, while direct method on thermal sensors. The aim is to evaluate experimentally methodologies able to estimate C_{opt} and η_{opt} in CPV systems. An increase of C_{opt} from 16 to 310 until lens height of 24 cm with η_{opt} of 14%, is obtained by indirect methodology. As for direct methodology, an increase of cell-lens distance from 10.5 to 21 cm leads to variation of C_{opt} from 22 to 315 with η_{opt} of 16%. The methodologies results are comparable; indirect method underestimates the optical performances. The novelty of this paper is the comparison under same operation conditions (TJ cell size, C_{opt} range, η_{opt} and focal distance) of two methodologies able to determine optical parameters and standardisable for similar point-focus CPV configurations.

1. INTRODUCTION

The rise in energy requirements of residential and industrial users has increased the study of new technologies based on renewable sources. In particular, an evolution of traditional photovoltaic (PV) plants is represented by concentrating photovoltaic (CPV) systems [1] considered one of the most promising solar technologies determining high decrease of environmental pollution [2]. The sunlight is generally concentrated on Multi-Junction (MJ) solar cells, constituted by semiconductor materials of group III and V, with the aim to decrease the PV area proportionally with concentration level. Solar concentration is obtained by adopting optical devices generally cheap to balance the high cost of MJ solar cells [3]. The optical systems consist of lenses or mirrors, or a combination of both [4]. The main aim of these systems is to ensure high levels of efficiency and low unit costs of energy production. Hence, the global system efficiency is a key factor that in CPV systems is equal to ratio between electrical power and radiant power incident on system optics; this efficiency depends on the MJ cell and optics performances. The cell efficiency is dependent on its intrinsic characteristics, but its performances are limited by current technologies [5]. So, the only parameter which can be modified in CPV systems is the optical efficiency (η_{opt}). Therefore, it is basic to standardize optical efficiency definition, measuring methods and instruments to compare correctly different technologies, to find the optimum working conditions and to design the more convenient configuration.

The use of PV concentrators can increase the radiation incident on receiver and allows to adopt efficiently cells made from expensive materials. The solar concentration purpose is to increase the TJ cell performance raising the Direct Normal Irradiance (DNI) by the optical configuration [6]; the DNI amplification is called concentrated solar flux. However, this introduces a new loss factor represented by optical efficiency that limits the CPV system electrical performance. Hence, it is important to have an accurate evaluation of optical performances by means of proper instruments. The direct measurement of the concentrated solar flux on receiver is possible from an experimental point view. To evaluate it, indirect measurement methods are applied because there are no instruments suitable for this purpose with linear response in wide range of measures and adaptable to each typology of CPV system. So, the possibility to measure directly the concentrated solar flux is fundamental for the CPV systems development.

The choice of instruments able to measure the average irradiance respectively at optical system

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aperture (G_{in}) and receiving area (G_{out}) is very important, because these sensors need to have flat spectral response and cosine angular response for each solar spectrum wavelength. G_{in} and G_{out} can be directly measured only using thermal irradiance sensors with flat spectral response [7]. G_{in} can be evaluated by pyrheliometer. As for G_{out}, it is difficult to find an appropriate sensor able to support a wide range of flux, ensuring linearity in the measurement and with cross-calibration to pyrheliometer. The only thermal irradiance sensors that allow this measurement are the radiometers. The most common radiometers are Gardon radiometer [8] which if subjected to intense flows for long periods, could be subject to degradation [9], the Kendall [10] radiometers, which offer greater precision but are characterized by longer response times due to their cavity structure [11] and heat flux microsensors (HFMs). The microsensors are the most used from experimental point of view but there are not many examples in literature. An alternative direct method, widely used for optical systems such as Fresnel lenses, is based on the use of ccd cameras that capture the image of the focal point generated by the lens. The recorded light intensity is calibrated with a flux meter, allowing it to be converted into energy flux density, and thus obtain the concentrated solar flux distribution [12]. Another alternative to thermal irradiance sensors is represented by measurement of light power in narrow bands of wavelength or spectral irradiance [13], and the integration of this quantity on solar spectrum using a spectroradiometer. This method is used in [14] for the concentrated solar flux measurement in CPV systems to evaluate optical efficiency and performances evolution during the system lifetime.

In literature, rarely the optical parameters are directly measured because the irradiance is complex to evaluate in the receiving area. On the contrary, a more practical definition of optical efficiency considers the solar cell as part of optical system and the irradiance on TJ cell can be evaluated by means of the photocurrent I_{ph} that is linearly dependent on incident irradiance making it a direct indicator of the solar flux received. Moreover, considering that the TJ cell current does not change in low voltage part of I-V curve, the photocurrent is approximated to short-circuit current: $I_{ph} \approx I_{sc}$ [15].

G_{out} and G_{in} can be evaluated with the same approximation measuring the short-circuit current of couple of same solar cells illuminated by light at entrance aperture of concentrator. The solar cells use as irradiance sensor is practical and economic but sensible to working conditions change. The characterizations available in References [16]-[19] and based on this method are associated with CPV systems with limited values of concentration factor. Hence, the irradiance sensors are not used in high concentration field. Another indirect approach is based on energy balance to evaluate the concentrated power. The main limit of this method is the use of an active heat dissipation system, while the advantage is the absence of upper limits in measuring the concentrated solar irradiance. In literature, the energy method is above all used for point-focus CPV systems characterized by higher concentration factor values [20,21]. Another indirect method is the use of the photovoltaic collar, based on placing a series of solar cells around the receiver in order to measure the distribution of concentrated solar flux [22].

Considering experimental tests on CPV system equipped with Fresnel lens, the optical efficiency of a 12×12 cm^2 SoG Fresnel lens using the method based on irradiance sensors with a 2×2 cm^2 silicon solar cell, has been evaluated in [4]. In [17] the authors adopt the same method but with outdoor measurements, to analyze the optical efficiency of CPV system with geometric concentration factor (C_{geo}) equal to 1000, solar cell and SoG Fresnel lens with dome shaped secondary optics. Adopting the same approach, four different Fresnel lens measuring the short-circuit current of TJ cell are characterized in [4]. In [22] the photocurrent trend is studied and an optimal value for the optical efficiency is obtained for two different systems with SoG Fresnel lens and TJ solar cell (InGaP/GaAs/Ge), and C_{geo} equal to 300 and 1000. Another typology of CPV system is experimentally characterized in [15] by means of the indirect method based on the short-circuit currents.

In literature, related to CPV systems the most common method is based on solar cell use as receiver because are cheaper than other instruments. However, in [22] it is observed that the indirect evaluation of irradiance by short-circuit current leads to disadvantages and mistakes. On the other hand, the direct method based on thermal irradiance sensors allows a complete optical characterization but with high cost. Hence, the main aim of this paper is to present an accurate direct procedure for the concentrated solar flux and optical parameters measurement in CPV system, and to compare it with an indirect methodology. A point-focus CPV system, developed at Laboratory of Applied Thermodynamics of University of Salerno, is adopted for the experimental analysis. A measurement instrument able to estimate the concentrated solar flux in order to evaluate the optical performance of the experimental CPV system, is adopted. The results obtained by direct approach are then compared with those obtainable by an indirect method that adopts the electrical output of the system. The direct methodology proposed allows to develop a procedure suitable for different CPV systems working under same conditions in terms of TJ cell size, ranges of η_{opt}, optical concentration factor (C_{opt}) and focal distance.

2. EXPERIMENTAL COMPARISON BETWEEN DIRECT AND INDIRECT METHODS

The optical characterization of CPV systems involves the use of different approaches to define the best to be applied. In this paper, starting from an experimental CPV system, two methodologies are compared: an indirect approach [15] which evaluates the CPV system optical parameter through photocurrent analysis, and a direct approach based on the use of thermal sensors to evaluate C_{opt} and η_{opt}. Under uniform irradiation, the photocurrent varies linearly with it but this trend is not assured. In fact, some deviations can happen because the optics composition affects irradiance spatial and spectral distribution, and electrical mismatches are possible. Moreover, the comparison between photocurrent generated in concentration and not in concentration conditions is not correct, because this current is extremely sensitive to solar cell operation temperature [20]. Hence, the indirect approach determines more uncertain. On the other hand, the direct approach determines higher costs and some parameters are still difficult to evaluate. For this reason, in this paper a direct approach is proposed and compared with the indirect methodology, adopting the same experimental plant. The steps followed during the experimental analysis are reported in Figure 1.

2.1 *Optical Parameters*

The energy performances of CPV system depend on its optical characteristics. The relationships used to assess the optical performance of CPV systems are schematized in Table 1. In particular, the system global efficiency, equal to product between TJ cell electrical (η_{el}) and optical efficiencies (η_{opt}), is defined as shown in Equation 1 (Table 1).

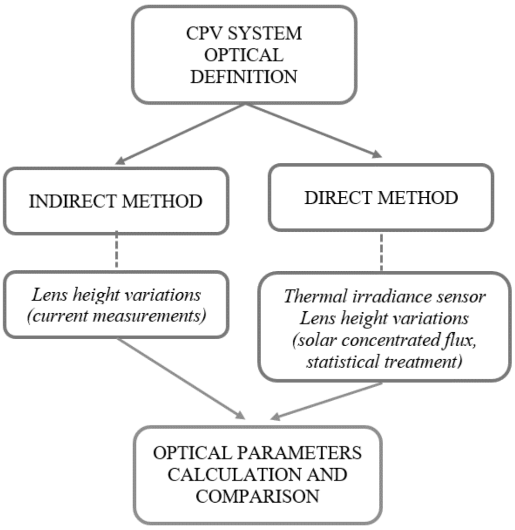

Fig. 1. Scheme of the experimental comparison.

Table 1. Key equations for optical performance of CPV systems.

Equation	Description	Expression	Refs.
1	Global system efficiency	$\eta_{system} = \eta_{el} \cdot \eta_{opt}$	[15]
2	Optical efficiency	$\eta_{opt} = \frac{P_{out}}{P_{in}}$	[17]
3	Concentrated solar flux	$G_{conc} = C_{opt} \cdot DNI$	[12]
4	Optical concentration factor	$C_{opt} = \eta_{opt} \cdot C_{geo}$	[15]
5	Direct method for optical efficiency	$\eta_{opt} = \frac{G_{out}}{G_{in} C_{geo}}$	[15]

The parameter that can be actually modified during the CPV system development is the optical efficiency equal to ratio between radiant power on the optics (P_{in}) and power that reaches the receiving area (P_{out}), as shown in Equation 2 (Table1).

Considering TJ cells with same area and Equation 1, solar radiation intensity incident on TJ cell and electric efficiency can be increased to produce more electricity; in fact, the current generated by TJ cell is proportional to solar radiation incident on receiver. The solar concentration purpose is to increase the cell output amplifying the Direct Normal Irradiance (*DNI*), once known the optical concentration factor (C_{opt}) defined as shown in Equation 3 (Table 1) where G_{conc} is the concentrated solar flux incident on TJ cell. C_{opt} is linked to C_{geo} defined as ratio between primary optics aperture and receiver areas once known the optical efficiency, as shown in Equation 4 (Table 1).

Hence, the fundamental parameters of CPV system that characterize optical performances are C_{opt} and η_{opt}. The parameter that links C_{opt} and η_{opt} is G_{conc}.

The optical performances evaluation of CPV systems can be accomplished by several methods that differ depending on how G_{conc} is obtained. In literature, direct and indirect methods are adopted for the measurement of G_{conc}. The direct methods allow to measure directly G_{conc}, while the indirect methods measure physical quantities with a functional relationship with it. In particular, the CPV systems are optically characterized using above all indirect methods, while direct approach with experimental tests is less used.

Considering Equation 2, in the direct method the optical efficiency can be calculated as ratio between the measures of power at optics aperture and on receiver [7], as shown in Equation 5 (Table 1) where G_{in} and G_{out} are the average irradiance respectively at optical system aperture and receiving zone.

2.2 *Experimental CPV System*

The experimental CPV system, realized in Laboratory of Applied Thermodynamics of University of Salerno, presents a point-focus configuration (Figure 2).

It integrates a Fresnel lens made of acrylic material (PMMA), with a circular shape and a diameter equal to 0.028 m, as the primary optics. A Triple-Junction solar cell with an area 5.5×5.5 mm^2, corresponding to a C_{geo} equal to 2036, is used as the receiver. A kaleidoscope made of polymethylmethacrylate (PMMA), that operates according to physical principle of total internal reflection, is used as the secondary optics. It allows to uniform the incident solar radiation improving the optical efficiency and avoiding chromatic aberration. The experimental CPV system presents a tracker that allows to maintain always the receiver perpendicular to the sunlight. The structure of the experimental system allows to vary the lens-cell vertical distance said focal height (*h*); it can modify C_{opt} varying the incident direct radiation on TJ cell. The experimental system is used with both the methods to evaluate the CPV system optical performances varying *h*.

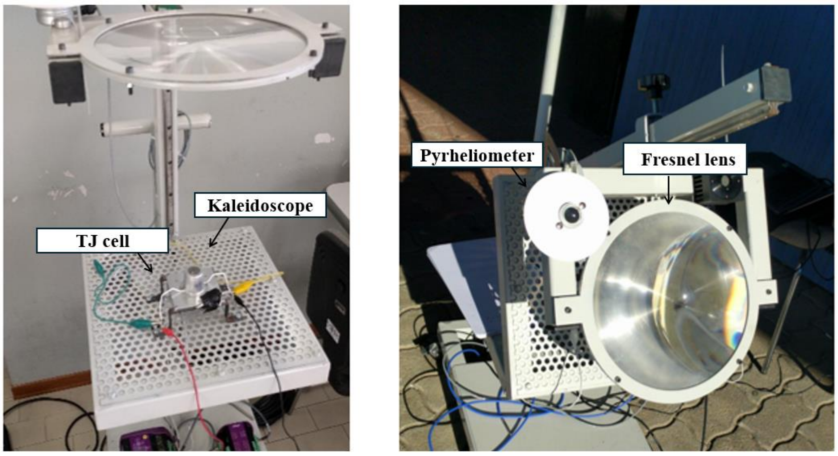

Fig. 2. CPV experimental system.

2.3 *Indirect Approach for Optical Analysis of CPV System*

The indirect approach based on generated photocurrent adopts the TJ cell as sensor. The photocurrent is assimilated to short-circuit current (I_{sc}) to define the C_{opt} of CPV system. As previously said, I_{sc} is used instead of irradiance measurement to reduce the costs.

Table 2. TJ cell characteristics.

Cell type	TJ (InGaP/GaAs/Ge)
Cell area	5.5 x 5.5 mm^2
$I_{sc,\ TJ}$ (A)	0.00435
Concentration (x)	1

The TJ solar cell, whose characteristics are reported in Table 2, can be located at variable distance from Fresnel lens; *h* is considered as variable in the characterization process. Hence, the experimental system allows to move the Fresnel lens on vertical axis respect to TJ cell and as consequence the incident direct radiation on solar cell can be modified together with the C_{opt} value. Scheme and measurement instruments are shown in Figure 3. In the operation phase, the output of CPV system is calculated, a variable load is connected to TJ cell and a data logger is used for the voltage and current measurements.

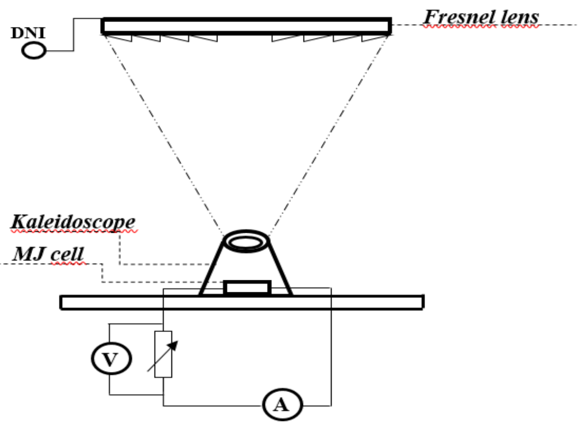

Fig. 2. Scheme of the CPV system for indirect approach.

The concentration factor is defined by dividing I_{sc} under concentrated light (I_{sc} *(x)*) with the $I_{sc,TJ}$ under light concentrated at one sun. I_{sc} at denominator corresponds to short circuit current. Hence, C_{opt} of CPV systems experimentally evaluated is equal to:

$$C_{opt} = \frac{I_{sc}(X)}{I_{sc,TJ}} \quad (6)$$

Concentration factor represents the amplification of direct irradiance incident on TJ cell and, from geometrical point of view, can be obtained as ratio between primary concentrator and cell areas. Starting from the experimental evaluation of concentration factor based on short-circuit currents under light illumination and considering the Equation 4, η_{opt} can be written:

$$\eta_{opt} = \frac{C_{opt}}{C_{geo}} = \frac{I_{sc}(X)}{I_{sc,TJ}} \frac{1}{C_{geo}} \quad (7)$$

Because the main aim of this paper is the experimental characterization of the TJ solar cell parameters under different C_{opt} values, an experimental procedure for the maximum C_{opt} value evaluation, is defined. The maximum C_{opt} value is experimentally evaluated varying the Fresnel lens height. The C_{opt} value experimentally determined is used for the definition of η_{opt} under different conditions. However, the photocurrent increases linearly with irradiance when concentration increases, but the constant of proportionality changes with concentration and temperature level. Moreover, an additional error is given by the photocurrent approximation with the short-circuit current.

2.4 Direct Approach for Optical Analysis of CPV System

The direct method proposed in this paper is based on thermal sensors able to measure the irradiance on optics aperture and TJ cell. The procedure of this methodology is subdivided in several steps. The first step requires the choice of thermal sensor necessary to measure the concentrated solar flux, and the adaptation of the experimental CPV system to selected sensor. The second step involves the methodology definition for using the chosen instrument. The last step considers all factors affecting the optical performances of a specific CPV system and the experimental campaign development. Once obtained the experimental results and the data processing, it is possible to evaluate the optical performances. Finally, regression equations which report the trend of C_{opt} and η_{opt} in terms of selected input, have been obtained. These equations are valid in specific ranges and allow to calculate, with distinctive coefficient of determination, the optical performances only giving the chosen input value.

Only the thermal irradiance sensors allow to directly measure concentrated solar flux or power. In particular, the market currently does not provide instruments for solar applications which can measure the flux in wide range from 1 to several hundred of suns depending on CPV system. An unconventional choice has been considered in this paper, selecting a device used above all in laser field. It is a power thermal sensor that measures in wide range of wavelengths of the solar spectrum. In [24] the same type of thermal irradiance sensor is used for a solar application, measuring the concentrated solar flux in a Dish/Stirling system. This device is cooled by air convention, absorbs in all solar spectrum and has a fast response measuring with accuracy equal to ±3%. The instrument has a sensible aperture area with diameter of 17.5 mm and measures the power in the range 10mW-30W. The ranges of sensible area and power have been carefully evaluated for the considered CPV system to have an instrument with area reproducing the TJ solar cell used in the characterization and able to measure the maximum solar flux obtainable.

To measure the concentrated solar flux using the Equation 5, the thermal irradiance sensor chosen has been integrated in CPV system. The sensor was positioned in receiving zone to exactly reproduce the solar cell. For this purpose, some changes to experimental prototype have been realized to integrate the thermal irradiance sensor. A CPV system identical and parallel has been built where the sensor has been located in same plane of primary system that includes the TJ cell (Figure 4).

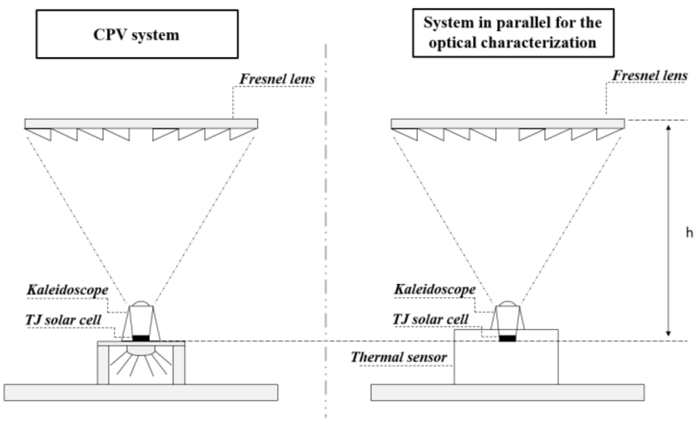

Fig. 4. Scheme of CPV system for direct approach.

The main aim of proposed procedure is the optical performance evaluation independently of receiver used. The presented methodology involves the direct measurement of all the variables included in the η_{opt} (Equation 2) and C_{opt} definitions:

$$C_{opt} = \frac{G_{out}}{G_{in}} \quad (8)$$

where P_{out} and G_{out} are respectively concentrated power and irradiance on the receiver, while P_{in} and G_{in} are power and irradiance at lens aperture area.

The direct solar radiation at lens aperture area, both in terms of power and irradiance, is obtained by means of pyrheliometer; this sensor is appropriate for measurements outdoors. Power and irradiance on receiver are measured with the thermopile sensor Ophir that ensures linearity in the measurements. A summary of the measured parameters and the instruments used to characterize the CPV system optical performances, is reported in Table 3. The experimental tests have covered a period of four months, with frequency of 2-3 days a week and daily duration of 5-7 hours. As for the data acquisition, the sampling interval has been 15s during experimental tests.

In order to acquire all data for complete optical description of CPV system and to compare the direct and indirect methods, the focal length has been varied to experimentally determine the optimal distance between lens and cell and to evaluate the optical performances in the off-focused positions. These parameters are all internal, the external variables, such as environmental temperature and direct normal irradiance, don't affect the optical performances. All the experimental outdoor measurements have been conducted considering values of DNI included above all in range 850-950 W/m^2.

3. RESULTS

The CPV system optical performances have been evaluated in this paper using both direct and indirect method. A comparison in terms of optical concentration factor and efficiency, has been proposed. The concentration factor increase due to Fresnel lens height variation reaches a maximum value varying continuously the TJ cell illumination, and then it decreases with both analysed methods. Referring to indirect approach, as shown in Figure 5, an increase of *h* value from 18 cm to 24 cm leads to variation of C_{opt} from 16 to 310. A further increase of *h* from 30 to 44 cm causes high decrease of C_{opt}. This means that the CPV system shows a symmetric trend respect to optimum value of *h* equal to 24 cm which corresponds to the highest C_{opt} for proposed CPV system.

Table 3. Physical quantities and instrumentation for measuring optical efficiency and concentration factor.

Magnitude	Description	Expression	Instrument
η_{opt}	optical efficiency	$\eta_{opt} = \frac{P_{out}}{P_{in}}$	
P_{out}	incoming power in the receiver		Thermopile sensor
P_{in}	incoming power in the lens		Pyrheliometer
C_{opt}	optical concentration factor	$C_{opt} = \frac{G_{out}}{G_{in}}$	
G_{out}	incoming irradiance in receiver		Thermopile sensor
G_{in}	incoming irradiance in the lens		Pyrheliometer

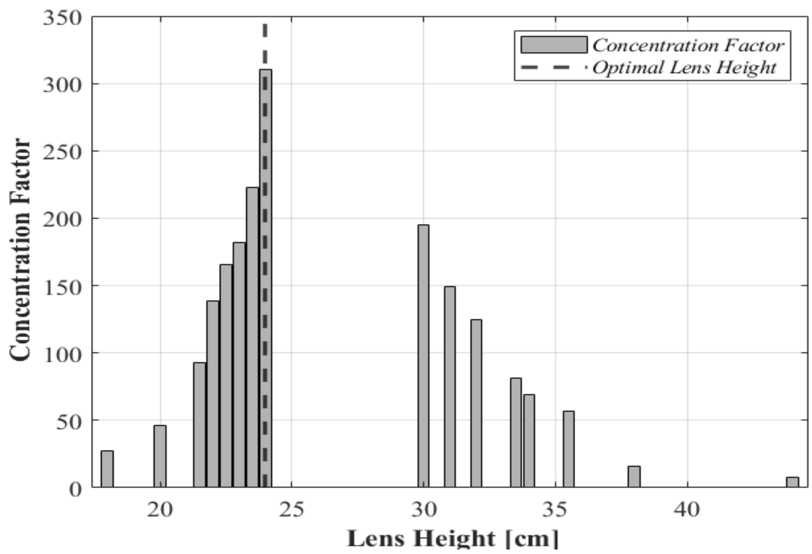

Fig. 5. Optical concentration factor as function of lens height with indirect method.

The results in terms of optical efficiency, with reference to indirect approach, have been reported in Figure 6. The maximum optical efficiency value obtained is about 14% with *h* equal to 24 cm. The optical efficiency values follow the C_{opt} trend that affects the system optical performances as function of lens height established. It is important to note that low values of efficiency are mainly due to status and impurity of lens. The values are not high because the authors wanted to use Fresnel lenses in the experimental system that were not very new and of limited cost in order to simulate a situation that was as realistic as possible. Hence, once the solar flux is correctly transferred from primary optics to receiver, by choosing the right lens height value, the kind of lens affects the optical performances.

Referring to direct method, a variable to consider is the receiver area and, considering Fresnel lens and kaleidoscope, C_{geo} is equal to 2036 in conditions of correct tracking. The measured values for concentrated power and irradiance on receiver are reported in Figure 7 for different lens heights. According to proposed procedure, these measurements have been related to the power and irradiance values evaluated at lens aperture area, so not in concentration conditions. Therefore, the experimental values of η_{opt} and C_{opt} have been obtained.

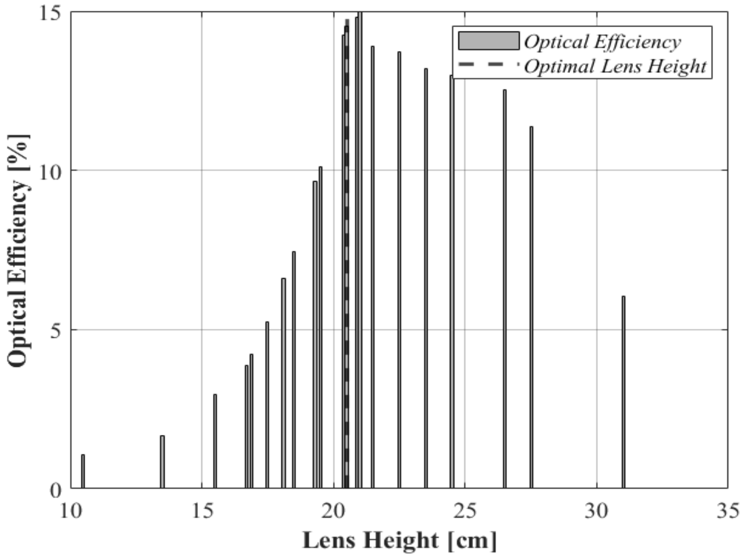

Fig. 6. Optical efficiency as function of lens height with indirect method.

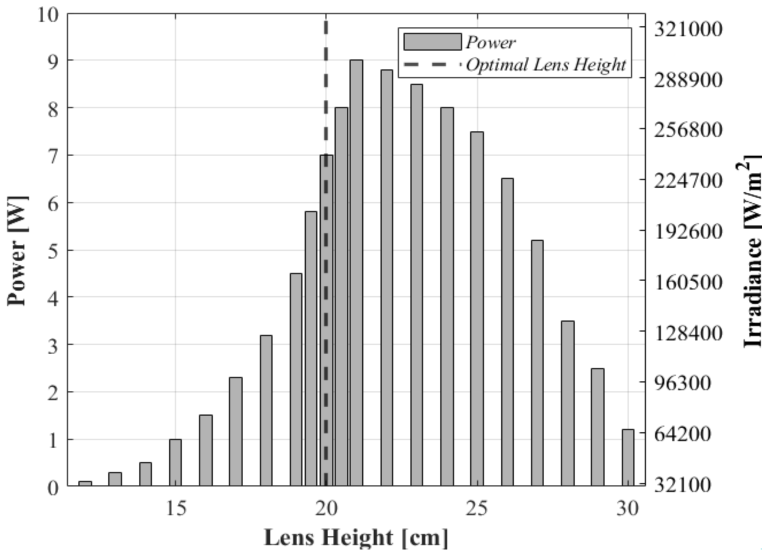

Fig. 7. Concentrated power and irradiance as function of lens height with direct method.

The values measured of C_{opt} are reported Figure 8. An increase of the cell-lens distance from 10.5 cm to 21 cm leads to variation of C_{opt} from 22 to 315. The lens height of 21 cm represents the optimal position experimentally measured where the CPV system presents the maximum C_{opt} equal to 315. Increasing the lens height over the optimal distance, a marked reduction of C_{opt} has been observed also with direct approach; by varying the distance from 21.5 cm to 31 cm, C_{opt} decreases to 123. By means of regression analysis, two equations respectively for C_{opt} growth below the maximum and for C_{opt} decline above the maximum, have been obtained (Table 4). In the range below the maximum, the C_{opt} growth trend is exponential with determination coefficient equal to 0.983. Conversely, above the optimal distance, C_{opt} decreases following a parabolic trend with coefficient of determination equal to 0.987. The regression equation for these trends (Equation 9 and 10), with their value of height ranges, are summarized in Table 4.

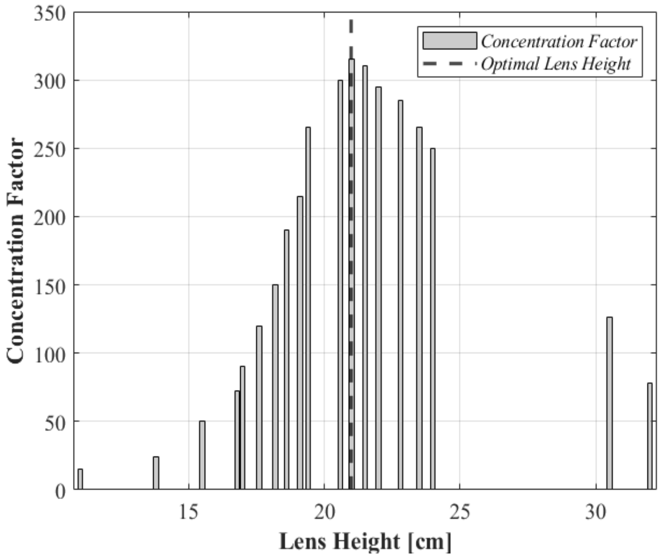

Fig. 8. Optical concentration factor as function of the lens height with direct method.

Table 4. Regression equation for C_{opt} and η_{opt} trends.

Equation	Description	Expression	Range
9	Exponential growth of C_{opt} below maximum	$C_{opt} = 0.972 \cdot e^{0.274 \cdot h}$	10.5cm≤h≤ 21cm
10	Parabolic decline of C_{opt} above maximum	$C_{opt} = -2.04h^2 + 91.1h - 732$	21.5cm≤h≤ 31cm
11	Exponential growth of η_{opt} below maximum	$\eta_{opt} = 0.0005 \cdot e^{0.276 \cdot h}$	10.5cm≤h≤ 21cm
12	Parabolic decline of η_{opt} above maximum	$\eta_{opt} = -0.00110h^2 + 0.0486h - 0.413$	21.5cm≤h≤ 31cm

As for η_{opt} it is possible to note the same trend by varying the lens height as reported in Figure 9. In the range of lens heights from 10.5 cm to 21 cm, the trend of growth is exponential with coefficient of determination equal to 0.981. Conversely, between 21.5 cm and 31 cm, the performances decrease with parabolic trend and with coefficient of determination equal to 0.986. The regression equation describing these trends (Equations 11 and 12) are reported in Table 4.

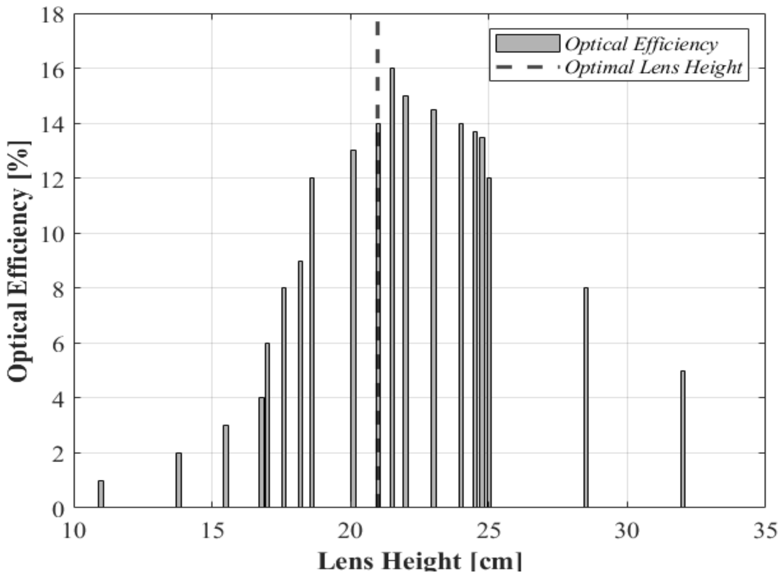

Fig. 9. Optical efficiency as function of lens height with direct method.

The best optical performances are obtained when all the concentrated solar radiation reaches the receiver. The maximum optical efficiency, reaching around 16%, is achieved when the spotlight is perfectly coincident with the kaleidoscope aperture. For heights below the optimal point, part of the concentrated solar irradiance is lost because the spotlight exceeds the kaleidoscope aperture area. For this reason, increasing the height in this range a consequent increase of concentrated solar irradiation is obtained, determining fast growth of optical performances. On the contrary, for heights higher than the optimal one, the spotlight is always included in aperture area of kaleidoscope, so the decline of optical performances is more gradual. The maximum point, where the best optical performance has been estimated, represents a discontinuity point in the trend of two intervals. This is due to different physical principle that governs the operating in the two ranges. By calculating the absolute deviation of normalized heights, for minimum deviation of 0.07 in the range of distances cell-lens under the optimal point, the calculated C_{opt} value is 65.4% respect to maximum C_{opt}. In the range above the maximum point, the C_{opt} value is 88.6% respect to the maximum C_{opt}. Considering a maximum deviation of 0.5, the C_{opt} value is 7% and 39.1% respect to maximum value respectively in ranges under and above the optimal point. The percentage decrease of optical performances below and above the optimal value are reported in Figure 10 for different absolute deviation.

The experimental results of direct methodology, reported in Figure 8 in terms of optical concentration factor, have been successively compared with the indirect method results for the same CPV system and under similar operation conditions. In indirect methodology, the C_{opt} values have been experimentally calculated evaluating the short-circuit current under light illumination. In particular, in Figure 11 it has been noted that for lens heights lower than the optimal value, the values calculated with two methods are close, although the indirect short-circuit method returns estimates which are always smaller than those calculated with the direct method. For lens heights higher than the optimal value, the estimates of short-circuit method are also smaller (Figure 12).

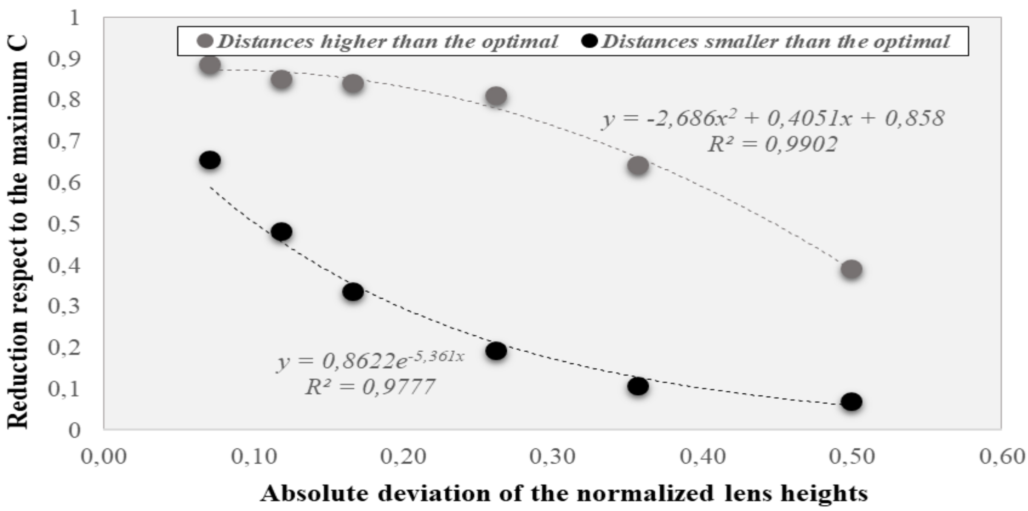

Fig. 10. Percentage reduction of optical concentration factors measured at different lens heights, below and above the maximum value.

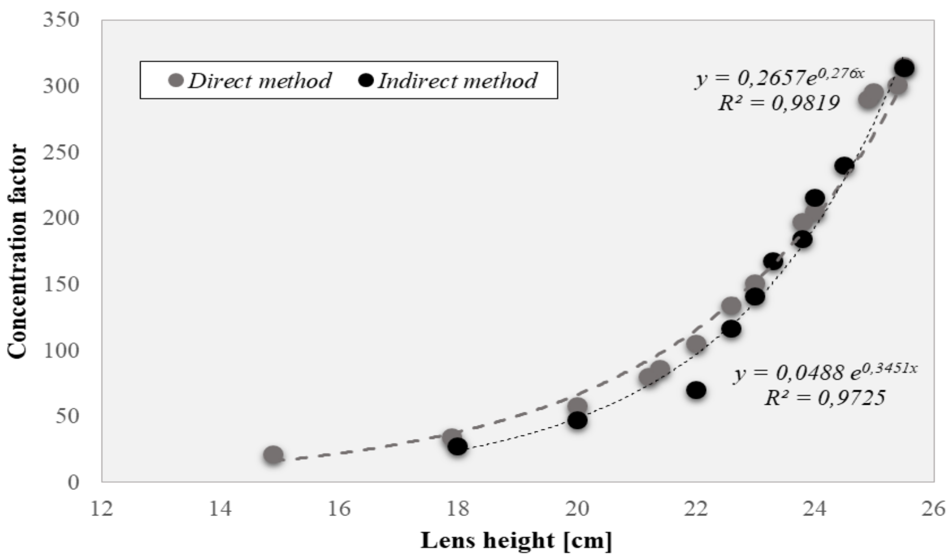

Fig. 11. Optical concentration factor measured with the direct and indirect method for lens heights below the maximum.

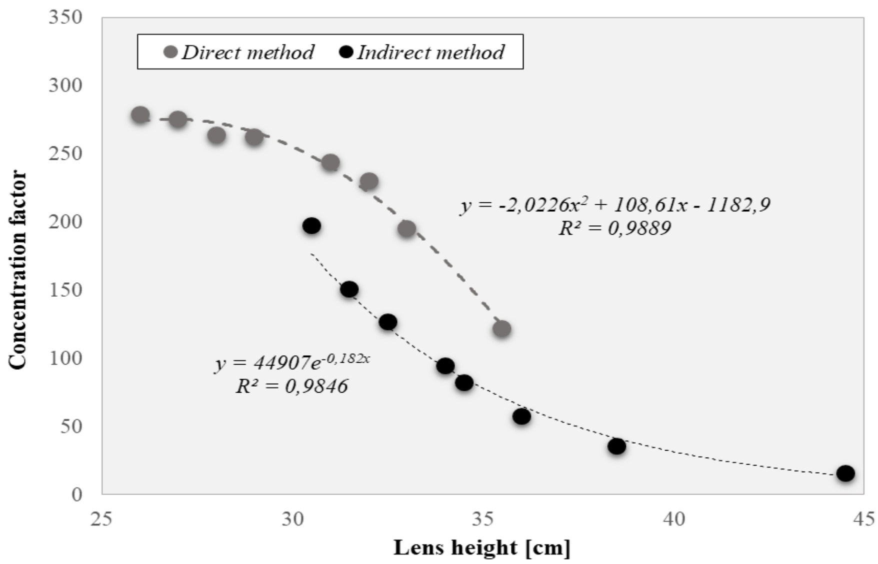

Fig. 12. Optical concentration factor measured with the direct and indirect methods for lens heights above the maximum.

Hence, the comparison between the two approaches reveals that their trends are similar but the short-circuit method provides a constant underestimation of optical performances when compared to the direct measurement results (Figure 13). In the range of heights below the optimal one, the values calculated with the two methods are close because of the operating conditions. In fact, in this case the kaleidoscope is totally illuminated and is able to transfer solar irradiance to receiver with homogenous spatial distribution and discrete spectral distribution. On the contrary, for heights above the optimal one the light spot has diameter smaller than aperture area of the kaleidoscope. In this situation the secondary optics is malfunctioning as the TJ cell [24] and there is consequent lower generation of short-circuit current. Generally, the photocurrent has linear trend when the solar irradiation is uniform, but this is not always possible. In particular, some deviations can be can due to optics composition that influences the irradiance spatial and spectral distribution, and determines electrical mismatches. Moreover, the comparison between photocurrent generated under concentration and not in concentration conditions is not correct, because the current is influenced by solar cell operation temperature [20]. Hence, the indirect approach causes more uncertain but the direct approach determines higher costs and difficulty in the evaluation of some parameters.

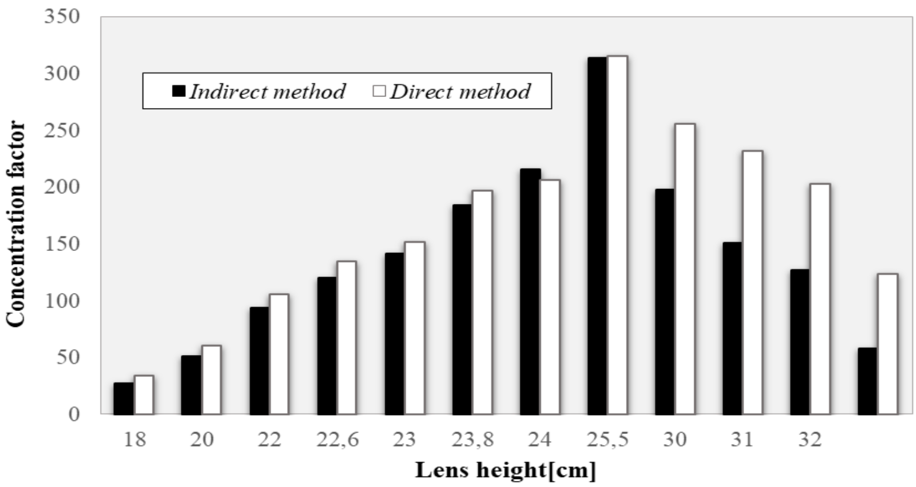

Fig. 13. Comparison between the concentration factors measured with the direct and indirect methods for different lens heights.

Finally, both methodologies show low values of η_{opt}. C_{opt} is the main parameter in the optical characterization of CPV systems and affects η_{opt} when the lens height varies. Low values of η_{opt} are mainly due to lens impurity [25]. Hence, once the solar flux is transferred from primary optics to receiver, by choosing the right lens height value [27], the typology of lens affects the optical performances. The selection of lens with lower degrees of impurity causes more expensive systems. However, as shown by CPV experimental system, the key parameter is C_{opt}; if higher values of C_{opt} are obtained, also with cheap lens, a high increase of system energy production is reached [28].

4. CONCLUSION

The optical characterization of CPV systems requires the comparison of different methodologies to define the most appropriate. In this paper an experimental comparison between indirect and direct methodologies to define the optical performances of CPV systems, has been presented. A prototype realized in Laboratory of Applied Thermodynamics of University of Salerno, has been adopted in the experimental analysis. This system is point-focus and presents a Fresnel lens as primary optics and a TJ solar cell as receiver. In particular, a direct methodology able to estimate directly the concentrated solar flux necessary to evaluate the optical parameters of CPV system, has been adopted. The direct methodology is based on thermal sensor, while the indirect methodology on generated photocurrent. The experimental system has been used for the optical characterization steps of both approaches by changing the lens height.

As for the indirect approach, an increase of C_{opt} from 16 to 310 until lens height of 24 cm, with maximum optical efficiency of about 14%, has been observed. Referring to direct approach, the measured values of concentrated power and irradiance on receiver have been calculated by thermal sensor. The experimental values of η_{opt} and C_{opt} have been evaluated, and C_{opt} has reached the maximum value of 315 with h equal to 21 cm, which represents the optimal position experimentally measured. By means of regression analysis, two equations respectively for C_{opt} growth below the maximum and for C_{opt} decline above the maximum, have been obtained. Similarly, the optical efficiency trends have been evaluated in terms of lens height; the best optical efficiency has been of about 16%.

The experimental results of direct approach have been compared with those of indirect method. Generally, two methods are comparable but the short-circuit method presents constant underestimation of the optical performances respect to direct method. Moreover, both methods present low values of η_{opt} mainly due to lens impurity. The choice of lens with lower degree of impurity determines more expensive systems but, as experimentally shown, the basic parameter is C_{opt}. If higher values of C_{opt} are reached, also with cheap lens, a high increase of system energy production can be obtained.

NOMENCLATURE

Symbols

C	concentration factor
CPV	concentrating photovoltaic
DNI	Direct Normal Irradiance, W/m^2
G	solar irradiance, W/m^2
h	lens height, m
I	current, A
MJ	Multi-Junction
P	power, W
PMMA	polymethylmethacrylate
PV	photovoltaic
TIR	total internal reflection
TJ	Triple-Junction gas constant, kJ/kgK
η	efficiency

Subscripts

conc	concentrated
el	electric
geo	geometrical
in	input
opt	optical
out	output
ph	photocurrent
sc	short-circuit

REFERENCES

[1] Fikri M. A., Samykano M., Pandey A.K., Kadirgama K., Kumar R.R., Selvaraj J., and Saidur R., 2022. Recent progresses and challenges in cooling techniques of concentrated photovoltaic thermal system: A review with special treatment on phase change materials (PCMs) based cooling. *Solar Energy Materials and Solar Cells* 241: 111739.

[2] Baiju A. and M. Yarema. 2022. Status and challenges of multi-junction solar cell technology. *Frontiers in Energy Research* 10: 971918.

[3] Renno C., 2019. Thermal and electrical modelling of a CPV/T system varying its configuration. *Journal of Thermal Science* 28: 123-132.

[4] Iqbal W., Ullah I., and Shin S., 2023. Optical developments in concentrator photovoltaic systems—a review. *Sustainability* 15(13): 10554.

[5] Ju X., Xu C., Liao Z., Du X., Wei G., Wang Z., and Yang Y., 2017. A review of concentrated photovoltaic-thermal (CPVT) hybrid solar systems with waste heat recovery (WHR). *Science Bulletin* 62: 1388–1426.

[6] Renno C., 2018. Experimental and theoretical analysis of a linear focus CPV/T system for cogeneration purposes. *Energies* 11: 2960.

[7] Brogren M., 2014. Optical efficiency of low-concentrating solar energy systems with parabolic reflectors. *Doctoral dissertation*, Acta Universitatis Upsaliensis.

[8] McLaughlin L., Laubscher H. F., Nguyen J., Banh L., and Konings J., 2023. Development of readily available and robust high heat flux Gardon gauges. In *SolarPACES Conference Proceedings*, 2.

[9] McLaughlin L., Laubsher H.F., Schroeder N., Armijo K., Konings J., Dolce R., and Van de Bos K., 2024. Flux sensor measurement and calibration requirements intensity heat flux applications: A trade study. *SolarPACES Conference Proceedings*.

[10] Verma R.N., Kumar R., Dixit A., and Chandra L., 2018. A low temperature water-cooled radiation calorimeter for estimation of concentrated solar irradiance. *Solar Energy* 167: 194–209.

[11] Thelen M., Raeder C., Willisch C., and Dibowski G. 2017. A high-resolution optical measurement system for rapid acquisition of radiation flux

density maps. *AIP Conference Proceedings* 180: 150005.

[12] Zhang K., Su Y., Wang H., Wang Q., Wang K., Niu Y., and Song J. 2022. Highly Concentrated Solar Flux of Large Fresnel Lens Using CCD Camera-Based Methos. *Sustainability* 14(7): 11062.

[13] González C., Vilaplana J.M., Bogeat J.A., and Serrano A., 2022. Comparison of global UV spectral irradiance measurements between a BTS CCD-array and a Brewer spectroradiometer. *Atmospheric Measurement Techniques* 15(13): 4125-4133.

[14] Bengoechea J., Ezquer M., Petrina I., and Lagunas A.R., 2011. Experimental set-up to evaluate the degradation of the optical components of a CPV module. *AIP Conference Proceedings* 1407(1): 84-87.

[15] Renno C., Petito F., Landi G., and Neitzert H.C., 2017. Experimental characterization of a concentrating photovoltaic system varying the light concentration. *Energy Conversion and Management* 138: 119-130.

[16] Benítez P., Miñano J.C., Zamora P., Mohedano R., Cvetkovic A., Buljan M., and Hernández M., 2010. High performance Fresnel-based photovoltaic concentrator. *Optics Express* 18(101): A25-A40.

[17] Wiesenfarth M., Steiner M., Wolf J., Schmid T. and Bett A.W., 2014. Investigation of different Fresnel lens designs and methods to determine the optical efficiency. *AIP Conference Proceedings*, 1616(1): 97-101.

[18] Wiesenfarth M., Dörsam T., Eltermann F., Hornung T., Siefer G., Steiner M., and Gombert A., 2015. CPV module with Fresnel lens primary optics and homogenizing secondary optics. *AIP Conference Proceedings* 1679(1): 10000.

[19] Peharz G., Jaus J., Nitz P., Schmidt T., Schult T., and Bett A.W., 2008. Development of refractive secondary optics for FLATCON modules. In *23rd European Photovoltaic Solar Energy Conference*, 3.

[20] Estrada C.A., Jaramillo O.A., Acosta R., and Arancibia-Bulnes C.A., 2007. Heat transfer analysis in a calorimeter for concentrated solar radiation measurements. *Solar Energy* 81(10): 1306-1313.

[21] Pérez-Rábago C.A., Marcos M.J., Romero M., and Estrada C.A., 2006. Heat transfer in a conical cavity calorimeter for measuring thermal power of a point focus concentrator. *Solar Energy* 80(11): 1434-1442.

[22] Mittiga A., 2005. Misura della distribuzione del flusso della radiazione solare concentrata mediante collare fotovoltaico: limiti, prototipi e prime misure. *Enea.*

[23] Verlinden P.J., Lewandowski A., Bingham C., Kinsey G.S., Sherif R.A., and Lasich J.B., 2006. Performance and reliability of multijunction III-V modules for concentrator dish and central receiver applications. In *IEEE 4th World Conference*, May 2006.

[24] Sabatelli V., Copeta C., Bruno A., and Marano D., 2015. Sviluppo e sperimentazione di un prototipo di radiometro per la caratterizzazione del flusso solare in ricevitori a geometria cilindrica. *ENEA*, September 2015.

[25] Renno C. and F. Petito. 2018. Triple-junction cell temperature evaluation in a CPV system by means of a Random-Forest model. *Energy Conversion and Management* 169: 124-136.

[26] Maka A.O. and J.M. Alabid. 2022. Solar energy technology and its role in sustainable development. *Clean Energy* 6(3): 476-483.

[27] Martínez J.F., Steiner M., Wiesenfarth M., Helmers H., Siefer G., Glunz S.W., and Dimroth F., 2022. Global energy harvesting potential of CPV/PV hybrid technology. *arXiv preprint*, 2205.12858.

[28] Iqbal W., Ullah I., and Shin S., 2023. Optical developments in concentrating photovoltaic systems: a review. *Sustainability* 15(13): 10554.