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Acceptance of a Solar Field Composed of Small-Size PTC Applying to Standard ISO 24194

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Abstract. The verification of solar field performance is possible through international standards EN ISO 24194 since 2022 and using results of standard ISO 9806 from the collector testing previously. However, for concentrating solar collectors this verification is not always done by the industry, and the large-size collector efficiency are guaranteed by the contractor from different components separately or a test done in an existing facility.

Keywords: Concentrating Collector, Testing; Solar Field, SHIP

1. Introduction

One of the European Union strategies defines the objective to achieve climate-neutral economy in 2050. Energy efficiency, energy security and decarbonization are part of the dimensions proposed to achieve its objectives. The parabolic trough collector (PTC) with single-axis solar tracking is a potential candidate for providing thermal energy to the industry, so contributing to the decarbonization of this sector. The verification of the output thermal production of a solar field in a Solar Heating Industrial Process (SHIP) reinforces the confidence of investors and insurers and, thus, ensures greater bankability of the projects.

Recently in 2022, an international standard EN ISO 24194 [1] was published by the European standardization committee CEN TC 312 “Thermal solar systems and components” to validate the solar field composed by solar thermal collectors. Normally, the solar thermal collector has been already tested according to standard ISO 9806 [2] and certified by a certification body. A lot of countries already accept SolarKeymark label as a certification scheme [3] and make it mandatory for those solar products on their market. Nowadays only 5 concentrating tracking collectors are certified SolarKeymark, and only 2 are single-axis tracking [4]. In Spain, SolarKeymark is not mandatory for now, however the testing of solar thermal collectors according to ISO 9806 is mandatory [5]. In the bibliography, many studies give the efficiency of concentrating tracking solar collectors and more particular PTCs, but without following any recognized standardized testing method or testing in accredited laboratories [6-8] which gives less confidence in the results obtained.

In the past the industry used the results of large-size PTC from the components separately to check the performance guarantee, for acceptance of solar field for CSP (Concentrating Solar Power) or SHIP plants. The optical efficiency was calculated from the mirror reflectance (from measured similar to standard draft IEC 62862-3-5 [9] and standard UNE 206016 [10]), the transmittance of the glass cover and the solar absorbance of the absorber (from measured similar to standard IEC TS 62862-3-3 [11]), the intercept factor of the concentrator (from simulations or measurements with no-standardized deflectometry or photogrammetry techniques) and possible tracking errors. And for the heat losses a_1 and a_2 or a_8 were obtained from measurements similar to standard IEC TS 62862-3-3 [11].

In continuation to previous studies [12-13], in this paper one small-sized PTCs for SHIP applications has been developed through optical design and thermal modelling. Those results were validated by outdoor experimentation using international standard ISO 9806 [2]. Then, a series of 6 collectors were mounted and monitored, and a procedure of performance checking based on standard EN ISO 24194 [1] was validated to verify the production of this small solar field.

2. Material

The collector used for this study is the third prototype developed within the R&D project COSMOS [14] with two other partners from Navarra region. This industrial research project has been designed to create a new low-cost PTC for SHIP applications in the medium temperature range (between 100ºC and 200ºC) and to contribute to the decarbonization of the industrial sector. CENER main role was to test the collector prototype and verify the performance of a small solar field in a real environment.

This PTC prototype consists of a parabolic aluminum reflector with a receiver tube without vacuum and a flat glass cover. The gross area was measured based on the definition ISO 9806 and it was obtained a gross length of 2.54 meters, a gross width of 1.23 meters and a gross area of 3.12 m^2. The small solar field consists in 6 collectors in series with a single electrical motor for the solar tracking. The solar field gross area is 18.72 m^2.

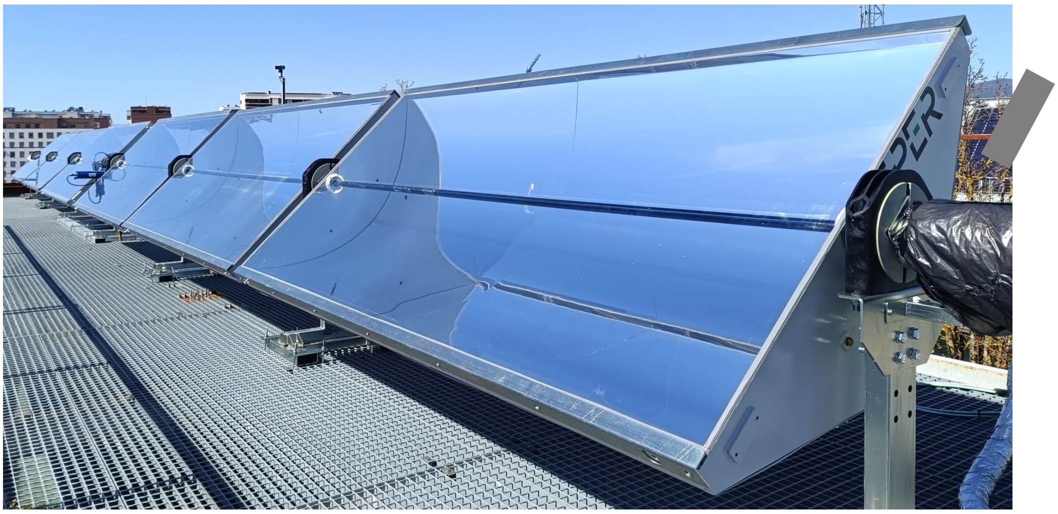

Figure 1. *Pictures of the 6 collectors' series*

3. Methodology

3.1 Verification procedure

The solar field verification according to standard EN ISO 24194 [1] consists in monitoring the inputs and outputs of the solar loop and compared the measured output thermal power to the estimated output thermal power for at least 20 consecutive valid data points.

The criteria for selecting valid data is according detailed in part 5.4 of standard EN ISO 24194 [1] (no shading, change in collector mean fluid temperature ϑ_m ≤ 5 K, ambient temperature ϑ_a ≥ 5 °C, wind velocity ≤10 m/s and solar direct irradiance on the collector plane $G_{bn}\cos(\theta)$ ≥ 600 W/m^2).

The criteria for considering valid a solar field is explained in 5.9.1 [1]. The checking of solar collector field performance procedure consists in comparing the average measured thermal power output $\dot{Q}_{meas}$ for all valid data point with the average estimated thermal power output $\dot{Q}_{estimate}$ using the measured weather data and temperatures in collector loop.

Previously, the solar collector module should have been tested preferably by an accredited external laboratory (Solarkeymark or similar). In this case, the solar collector prototype has been tested in CENER accredited testing laboratory according to standard ISO 9806 [2].

3.2 Collector testing

The testing method for the collector prototype was according to standard ISO 9806 [2] under quasi-dynamic (QDT) conditions, also similar to procedure in standard IEC 62862-3-2 [15] specific to large-size PTC. Measurements were conducted in an experimental testing rig in the facilities of the CENER testing laboratory which is accredited by ENAC (Spanish National Accreditation Entity). CENER is also recognized by most Solar Keymark certification bodies (AENOR, DINCERTCO, KIWA, CERTIF) in Europe, as well as by the Solar Rating & Certification Corporation (ICC-SRCC) in USA. The test facility allows testing concentrating solar thermal collectors up to 220°C and 25 bar with liquid water as heat transfer fluid and up to approximately 25 m^2 of aperture area. The prototype of the solar collector was mounted, and the testing campaign used 13 sunny testing days between October 6th 2023 and January 12th 2024, with temperatures between 15ºC and 160ºC. The sensors used are detailed in Table 1.

Table 1. *Sensors used for the testing and monitoring the miniserie*

Physical value measured	Equipment and brand name	Measurement Uncertainty estimation
Data acquisition	Multiplexer Brand AGILENT model 34970 A	2.3 µV for irradiance / 5.4 mV for ambient temperature
Direct normal solar irradiance	Brand Eppley model NIP	1.2 % (Level I)
Global solar irradiance	Brand Kipp&Zonen model CMP11 on horizontal	1.3% (Level I)
Ambient temperature	Brand NRG model 110S	0.05 ºC
Inlet and outlet temperatures	Pt100 sensor Brand Guemisa type 1/10 DIN A	0.03 ºC
Flow rate	Brand KROHNE model Optimas 6400 C15	0.83 %

The measured output power $\dot{Q}_{meas}$ of the collector is calculated with Eq. 1., with $\dot{m}$ the mass flow, c_f the specific heat, ϑ_o and ϑ_i the oulet and inlet fluid temperature respectively.

$$\dot{Q}_{meas} = \dot{m} \cdot c_f \cdot (\vartheta_o - \vartheta_i) \tag{1}$$

Then, the measured output power values were ajusted to a theoritical model with a multiple linear regression. This model for the optical and thermal collector's efficiency was according to Eq. 2 in the international standards ISO 9806 [2], simplified for concentrating solar collectors.

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} K_b(\theta_i) G_{bn} cos\theta_i - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_5 \frac{d\vartheta_m}{dt} \tag{2}$$

The input variables are the direct solar irradiance G_{bn}, the fluid and ambient temperatures ϑ_o and ϑ_i, and the flow rate $\dot{m}$. The different terms of Eq. 1 described different effects:

- The first term is the collector optical efficiency. The optical efficiency relative to beam solar radiation $\eta_{0,b}$ and the K_b factor is the IAM (Incidence Angle Modifier) relative to beam radiation. The IAM factor K_b was modelized by a second order polynomial equation as in Eq. 3.

$$K_b(\theta_i) = 1 - b_1 \cdot \theta_i - b_2 \cdot {\theta_i}^2 \tag{3}$$

- The second and third terms are the heat losses. The coefficient a_1 and a_2 are related to heat losses with respect to the difference between average fluid temperature ϑ_m and the ambient temperature ϑ_a. Another heat losses coefficient a_8 is also contemplated in standard ISO 9806 [2] similar to IEC 62862-3-2 [15], but which only makes sense when testing above 300ºC which is not the case here.
- The last term is the coefficient a_5 which is the effective thermal capacity which depends on the derivate in time of the mean fluid temperature $\frac{d\vartheta_m}{dt}$. This parameter describes the energy storage due to the thermal capacitance of the working fluid and the absorber tubes.
- Other terms are considered in the whole model in ISO 9806 [2] but can be neglected for concentrating tracking glazed solar collectors such as the diffuse radiation, wind speed and IR radiation effects.

The collector characteristics ($\eta_{0,b}$, K_b, a_1, a_2 and a_5) are parameters results of this test. The optical efficiency parameter $\eta_{0,b}$ is theoretically equivalent to the product of optical properties of the concentrator and the receiver but it is determined as a unique value in this test.

3.3 Solar field verification

After having testing one collector, six collectors were mounted in series in order to test a mini solar field of this new design. The small solar field was tested in same testing loop between January and May 2024. The verification of the solar field was achieved based on ISO 24194 [1] during 26 clear sky days. The procedure of verification of the performance of the solar thermal collector field was based on standard EN ISO 24194 [1] including concentrating collectors, as already explained in part 3.2.

The measured thermal power output $\dot{Q}_{meas}$ of the solar field is also calculated with Eq. 1 in part 3.1. The estimated thermal power output $\dot{Q}_{estimate}$ is calculated using the model given by Eq. 4 for concentrating collectors with geometric concentration ratio C_R ≥ 20 and temperatures ϑ_m below 300ºC, similar Eq. 1 from the ISO 9806 [1] adding some safety factors.

$$\dot{Q}_{estimate} = A_G \cdot \left(\eta_{0,b} K_b(\theta_i) G_{bn} \cos(\theta_i) - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_5 \frac{d\vartheta_m}{dt}\right) \cdot f_{safe} \tag{4}$$

The measured variables and the sensors used for the solar field verification are the same as the one for the collector testing in Table 1. The collector characteristics ($\eta_{0,b}$, K_b, a_1, a_2 and a_5) are the same parameters results from part 3.2. The safety factors are given by Eq. 5 and defined as bellow, and should be agreed previsouly between both parties, the solar field engineering and the testing laboratory.

- The safety factor f_P considering heat losses from pipes etc. in the collector loop. This factor was estimated based on an evaluation of the pipe losses. In this case, to estimate the thermal losses in the joints between collectors, it was considered a radiation and a natural convection with the environment applied on the area of a cylinder of diameter equal to the diameter of the joint and length equal to the distance between collectors.

- The safety factor considering measurement uncertainty f_U was estimated according to ISO/IEC Guide 98-3 [16]. In this case, the uncertainties of the sensors used are presented in Table 1.
- The safety factor for other uncertainties f_0 e.g. related to non-ideal conditions such as: non-ideal flow distribution or unforeseen heat losses. In this case, a value of degradation on the absorber coating of some receiver tubes were estimated. And the possible solar tracking errors were neglected by removing the data that the solar field clearly was defocused.

$$f_{safe} = f_P \cdot f_U \cdot f_0. \tag{5}$$

According to EN ISO 24194 [1] part 5.9.1 “Checking collector field performance“: if the average measured power (for at least 20 consecutive valid data points) is equal to or greater than the average power corresponding to the calculation of the estimated power, then the estimated power is verified. So the checking of solar collector field performance procedure consisted in comparing the average measured power output $\dot{Q}_{meas}$ for all valid data point with the corresponding average power calculated $\dot{Q}_{estimate}$ using the measured weather data and temperatures in collector loop, as shown in Eq. 6, for at least 20 valid data points.

$$\left(\overline{\dot{Q}_{meas}}\right) \geq \left(\overline{\dot{Q}_{estimate}}\right) \tag{6}$$

For this data treatment, an open-source software according to EN ISO 24194 [1] exists, SunPeek [17-18] developed by AEE. But, even if SunPeek allows to input concentrating collectors, tracking is not yet covered [19]. So, in this case some own developed R programs were used.

4. Results

4.1 Collector

For the solar collector 715 valid data points, average of 5 min measurements, have been obtained over a testing campaign of 13 days. The spread is within a wide range for each input is: direct normal irradiance on the plane of the collector $G_{bn}\cos(\theta)$ within [405; 919] W/m^2, mean fluid and ambient temperatures difference $\vartheta_m - \vartheta_a$ within [-4.7;141.7] ºC, incidence angle θ_i within [0;63]º, mass flow rate is quasi-constant within [0.06; 0.08] kg/s.

The results of the single prototype of the solar collector according to standard ISO 9806 [2] are summarized in Table 2 from previous study [20].

Table 2. *Results of the single collectpr prototype [15]*

Physical value measured	Symbol	Value	Expanded uncertainty	Unit
Experimental optical efficiency based on beam irradiance	$\eta_{0,b}$	0.744	± 0.002	-
Heat loss coefficient	a_1	0.643	±0.023	W/(m^2·K)
Temperature dependence of the heat loss coefficient	a_2	0.0019	± 0.0002	W/(m^2·K^2)
Effective thermal capacity	a_5	9625	± 763	J/(m^2·K)
IAM first order coefficient	b_1	9.32E^{-4}	--	1/º
IAM second order coefficient	b_2	1.60E^{-4}	--	1/º ^2

4.2 Solar field

For the small solar field more than 74 valid data points, average of 10 min measurements, have been obtained over a testing campaign of 4 days (2024 April 19th to 21st). The spread is within a wide range for each input is: direct normal irradiance on the plane of the collector $G_{bn}\cos(\theta)$ within [614; 1012] W/m^2, mean fluid and ambient temperatures difference $\vartheta_m - \vartheta_a$ within [1.5;52.5] ºC, incidence angle θ_i within [0;48]º, mass flow rate is quasi-constant within [0.3697; 0.3698] kg/s.

The values of the 3 safety factors used for the solar field verification are detailed in Table 3. The value of f_P was determined by a theorical calculation. The value of f_U was determined using standard ISO/IEC Guide 98-3 [16] and the uncertainties of the sensors for external calibration laboratories certificate. The value of f_0 was estimated, and it is the more critical parameter.

Table 3. *Safety factors values*

Physical value measured	Symbol	Value	Porcentaje error [%]	Standard recomended range
Safety factor taking into account heat losses from pipes, etc.	f_P	0.947	5.3	Normally only a few %.
Safety factor taking into account measurement uncertainty (average value over the data set)	f_U	0.969	3.1	0.9 - 0.95 could be recommended depending on accuracy level.
Safety factor for other uncertainties	f_0	0.980	2.0	Should be close to 1; unforeseen heat losses.

The comparative of the valid data for measured power output $\dot{Q}_{meas}$ and estimated power output $\dot{Q}_{estimate}$ is shown in Fig. 2. This figure is based on Fig. 3 from EN ISO 24194 [1].

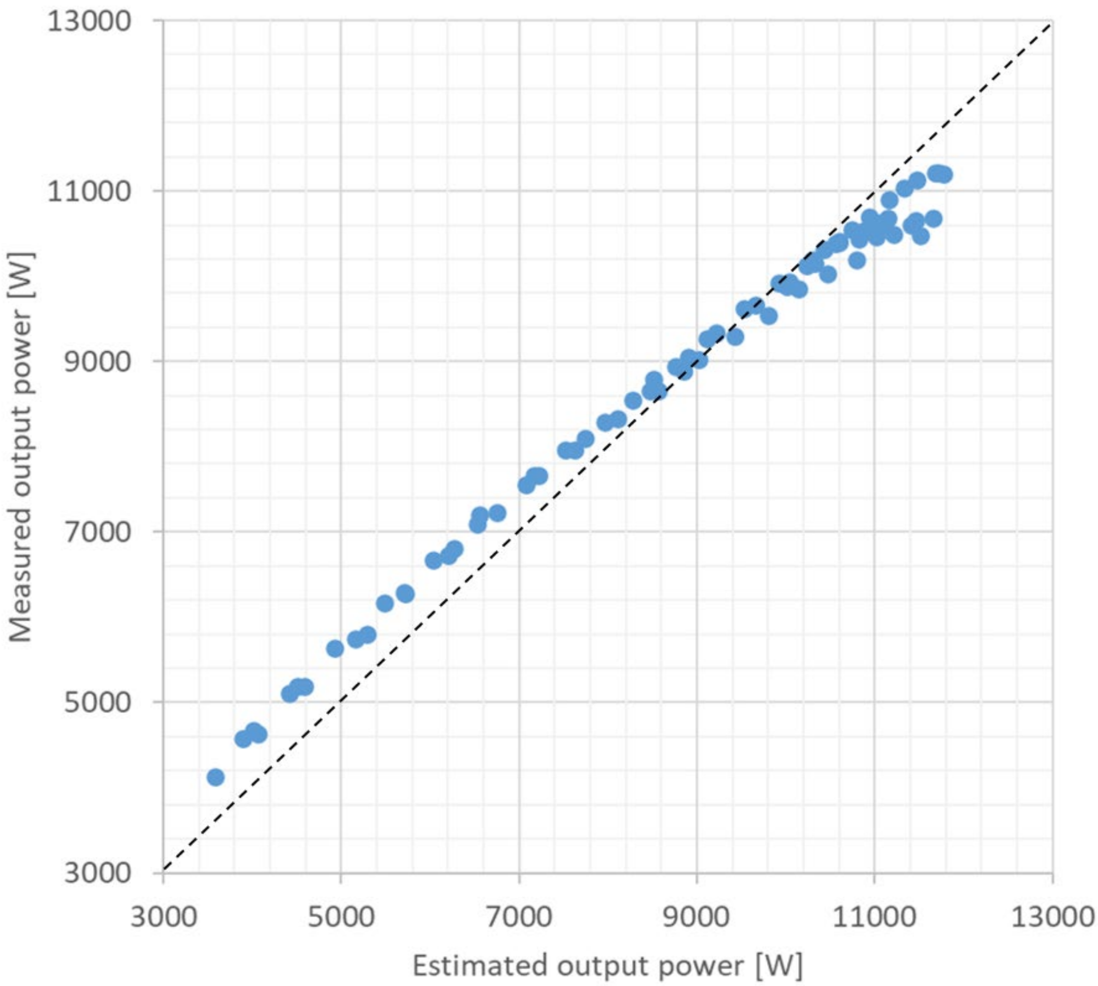

Figure 2. *Estimated output power calculated versus the measured power output*

From individual valid data points in Fig. 2, the measured thermal power output $\dot{Q}_{meas}$ are slightly higher than estimated thermal power output $\dot{Q}_{estimate}$ during the morning, and slightly smaller close to solar noon. This effect could be due to some solar tracking errors, and that the value of f_0 is not well estimated.

The average value for the measured thermal power outputs $\left(\overline{\dot{Q}_{meas}}\right)$ and for the estimated thermal power output $\left(\overline{\dot{Q}_{estimate}}\right)$ are shown in Table 4. And the verification criteria from Eq. 6 ($\left(\overline{\dot{Q}_{meas}}\right) \geq \left(\overline{\dot{Q}_{estimate}}\right)$) is fulfilled. So, the solar field production is considered as satisfactory.

Table 4. *Verification criterium*

Physical value measured	Symbol	Value	Unit
Average measured power output	$\left(\overline{\dot{Q}_{meas}}\right)$	8751	W
Average estimated power output	$\left(\overline{\dot{Q}_{estimate}}\right)$	8738	W

5. Conclusions

This study presents the procedure of a solar field performance verification according to EN ISO 24194 [1] with concentrating solar collectors. For this study, a small solar field composed of 6 PTC is used, and the results of one single PTC prototype is used [15] (previously tested according to standard ISO 9806 [2]). A good agreement was found between the average value for the measured thermal power outputs $\left(\overline{\dot{Q}_{meas}}\right)$ and the average estimated thermal power output $\left(\overline{\dot{Q}_{estimate}}\right)$, considering the necessary safety factors. So, the combination of standards ISO 24194 [1] and ISO 9806 [2] could be applied for accepting solar concentrating fields regarding Solar Heat Industrial Process applications.

In future study, more data will be acquired, and special care will be taken to the solar tracking errors.

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Data availability statement

The data are not publicly available for confidentiality.

Author contributions

Fabienne Sallaberry: Conceptualization, Methodology, Data curation, Investigation, Software, Formal Analysis, Writing – original draft. **Alberto García de Jalón**: Project administration, Methodology, Supervision. **Roberto Astiz**: Methodology, Visualization. **Egoitz San Miguel**: Supervision.

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Competing interests

The authors declare that they have no competing interests.

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