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On-Site Testing and Certification of Large-Size Concentrating Tracking Solar Thermal Collector for Medium-Temperature CSP or SHIP Plants

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Abstract. The certification of large-size Linear Fresnel Reflector (LFR) or variable geometry collectors is possible through international standards ISO 9806 and IEC 62862-5-2. However, those concentrating solar collectors have a large-size design that makes it more complicated to test in an accredited permanent laboratory. So, the most common way to accredit those solar products is through on-site testing. In this study, one large-size LFR and one boosted Evacuated Tube Collector (ETC) with lateral reflectors were tested in-site according to the standard ISO 9806.

Keywords: Large-Size Collector; Solar Collector Testing; On-Site Testing; Optical Simulation; SHIP.

1. Introduction

The certification of solar collectors used for solar thermal energy, water heating or industrial processing, has been allowed through different international standards for decades through the international standardization ASTM, EN, IEC or ISO. But the LFR collectors or other large-size concentrating solar collectors have a design that makes it more complicated to test according the international standards testing method requirements and limits further its certification and launching in the market. The international committee ISO TC 180 for “Solar Energy” is dealing with standardization in the field of solar energy for space and water heating, cooling, air conditioning and also industrial process heating. Within this committee, the standard ISO 9806 is redacted within the WG4 “Solar collectors”. This international standard ISO 9806 [1] last revision in 2017 added some peculiarity for concentrating collectors, and this standard is now in revision with a planned date for publication for 2024. In parallel, in the international committee IEC TC 117 for “Solar thermal electric plants”, some standards were published specifically for large-size concentrating tracking solar collectors for CSP plants. In particular, standard IEC 62862-5-2 [2] published in 2022 describes the testing methodology for LFR collectors. However it refers to standard ISO 9806 specifically for the efficiency test and use the some efficiency model.

In the International Energy Agency (IEA-SHC), the task 64 [3] is also dealing with solar systems for Solar Heating Industrial Processes (SHIP). Unfortunately, the subtask specially dealing with the standardization and certification of those systems was canceled at the beginning of 2023 for lack of founding.

In the bibliography, many studies give the efficiency of LFR concentrating tracking collectors, but without certification purpose and without following a recognized standardized testing methodology [4], [5], [6]. But for those kind of collectors, Incidence Angle Modifier (IAM) values can only be determined for the accessible angles during the testing days, due to the Sun’s diurnal paths. Previous works give a detailed testing methodology for peculiar concentrating thermal collectors performed by CENER (large and small-size parabolic troughs, fixed reflector and mobile receiver, and others) [7], [8], [9], [10], [11] using experimental data and optical simulation.

In one particular previous work CENER with Fraunhofer-ISE compared and validated their results from experimental data and optical simulation for LFR collectors [12]. In this study, one large-size LFR and one ETC with lateral reflectors were tested in-site during the last years. The specificities of concentrating tracking solar collectors were detailed and in particular the way to characterize the optical efficiency at incidence angle and the IAM for the whole range of incidence angles even if the angles obtained during the testing campaign are limited.

2. Materials

The first collector for this study is one large-size LFR collector from the Spanish company Rioglass [13] tested by CENER for SRCC American label certification. This LFR prototype, model Sun2Heat V2, was tested in Aznalcóllar (Sevilla, Spain) on-site at customer-owned facilities during a testing campaign in 2020 and 2021 (37,504 ºN 6,245 ºO). The LFR prototype type concentrating collector consists of a receiver composed of 8 vacuum absorber tubes with tempered glass cover and selective coating. Reflectors oriented by a motor to optimize the tracking of solar radiation on the receiver, composed of 2 “V-shape” lines of 6 facets with 0.528 m width. The prototype had a gross length of 28.3 meters, a gross width of 6.29 meters (from one facet extremity to the other extremity), and an aperture area of 178 m^2. The orientation to the North-South axis is -2 mrad. The Figure 1 shows Rioglass LFR model Sun2Heat V2.

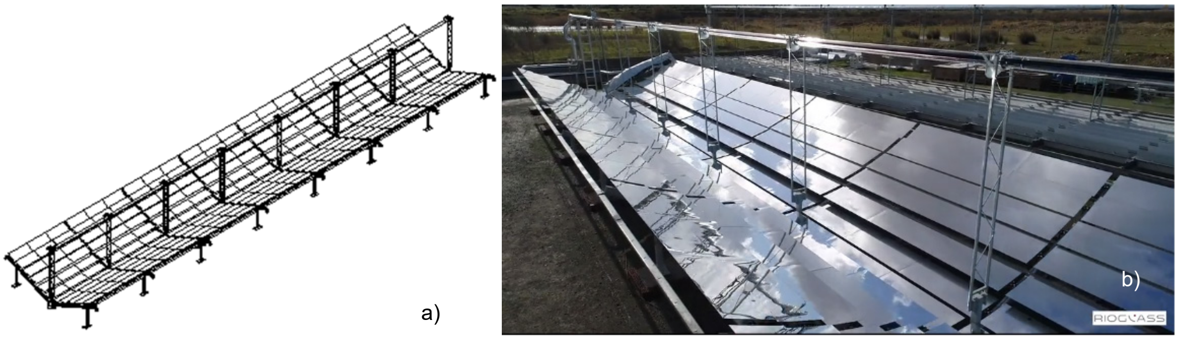
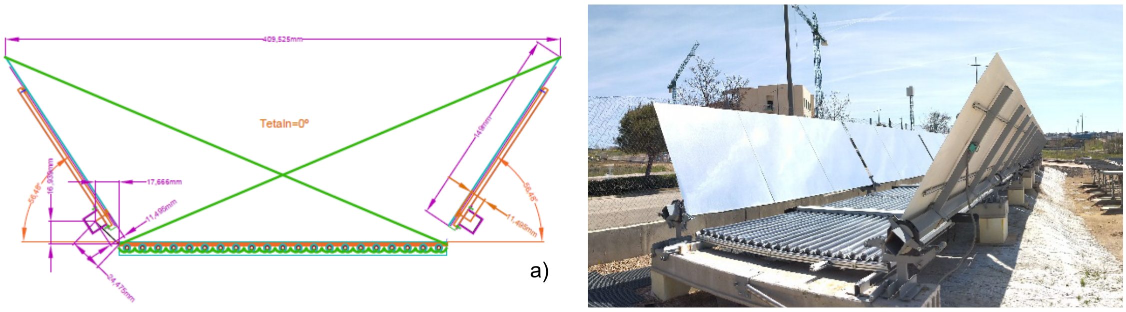


***Figure 1**. Rioglass LFR model Sun2Heat V2 (a) scheme (b) picture.*

The second collector for this study is in turn composed of 16 vacuum tube type collectors. Each tube is made of borosilicate cover and absorber with selective coating with aluminum CPC back reflector, model CPC XL 1921 from the Chinese-German company Linuo Ritter. It was built by the Spanish company Seenso [14] and tested at IMDEA facilities in Móstoles (Madrid, Spain) by CENER during a testing campaign in 2022 (37,549126 ºN, 6,316607 ºO). The collector is completed with lateral reflectors made of tempered glass with a silver substrate and with solar tracking on 1 axis to optimize the solar radiation on the collector. The whole collector is composed by 16 collectors Linuo Ritter CPC XL 1921 and 42 mirrors distributed in two groups of 21 units. The Figure 2 shows Seenso collector concept.



a) b)

Figure 2. *Seenso collector (a) scheme (b) picture.*

3. Methodology

3.1 Testing

Because of the large size of this kind of collectors it was necessary to test on-site. So a previous analysis was carried out for checking the compliance with the requirements of testing standard ISO 9806:2017 and with the requirements of the standard ISO 17025 [15] for the competence of testing laboratories.

In both cases, for Rioglass and Seenso collectors, some checking of the customer installations were performed. The location and the hydraulic testing loop stability for inner fluid temperature and flow rate within the testing range were checked, in particular the possibility of obstructions of the horizon, possible shadowing and the position of the collector respect to the ground. Some of the sensors used in the test should be the customer's, so it was checked that those sensors were correctly calibrated in an external laboratory. The measurement uncertainty of those sensors were used in the uncertainty evaluation which could increase the final expanded uncertainties values [16]. In both installations, the pyranometer, the pyrheliometer and the ambient temperature were provided and mounted by CENER and the inner and outlet fluid temperatures sensors and the flowmeter are owned by customer in its loop facilities (Rioglass for LFR and IMDEA for Seenso collector). For monitoring the inputs and outputs of the tested collector, various sensors were connected to a data logger mounted by CENER at customer facilities. The sensors owned by CENER which were installed at customer installations were carefully shipped to the testing site and some checking were done before starting the testing campaign, as well as at the end of the testing in CENER's lab..

The positions of the fluid temperature sensors and flowmeter was not always the one required by the standard ISO 9806. For the Rioglass facilities, the distance of the inner and outlet fluid temperatures sensors to the collector was 300 mm and 250 mm respectively; and the distance of the flowmeter to the collector was 40 meters. For the IMDEA facilities, the inlet temperature sensor was mounted at 30 m far away from the collector fluid entrance. All differences from ISO 9806 requirement were specified in the testing reports as a deviation to the accredited methodology by ENAC, the Spanish accreditation body.

The main difficulty in on-site testing activities may be the use of the customer loop installation which limits the temperature range and stability. The criteria ± 1 K stability for inlet temperature, ± 2 % stability for flow rate along the day and ± 5 % stability for flowrate along the testing campaign are not always possible depending on the installation, but this requirement could be avoided [17] (In previous tests, limits of up to 15 % for the flowrate stability and limits of up to 3.5 K for the inner temperature stabilty have shown to be acceptable if averaging intervals of 5 minutes are chosen). It was also important to test in a wide range of incidence angles at the two locations, in order to determine the biaxial IAM and some difficulties were experienced to obtain results at normal incidence when the installation is not close enough to the equator. Finally in-site checkings were performed in order to validate the testing loop of the customer.

For on-site testing the testing laboratory has to realize a visit on customer testing site to check that the installation fulfills the standard ISO 9806 [1] and ISO 17025 requirements, for instance the collector position (if there is any shadow obstruction analysis along the day, the horizon line), checking the customer Sensors location and accuracy from its calibration certificates, the customer hydraulic testing loop stability for inner fluid temperature and flow rate within the range, and verifying the laboratory sensors after its shipping to the customer site.

The main inputs and outputs of the solar thermal collector were: the inner and outer temperatures and of the fluid inside the collector, the mass flow rate, the direct normal solar irradiance. The pyrheliometer used for the direct normal solar irradiance was mounted on a solar tracker. The incidence angles were calculated based on the sun position using the algorithm given by Blanco-Muriel [18]. According to ISO 9806:2017 and the IEC CD 62862-5-2 standards, for a concentrating collector with a concentration ratio C > 20, the coefficients a3, a4, a6, a7 for thermal efficiency characterization (regarding the dependence on wind speed u and infrared radiation) and diffuse radiation IAM Kd can be set to zero. In both cases the wind speed was measured by an anemometer at a distance of 50 mm above and parallel to the collector front side and the solar diffuse irradiance was obtained from the pyranometers and pyrheliometers measurements. Wind speeds values greater than 4 m/s and diffuse radiation greater than 30% were discarded in the data processing, because the diffuse radiation IAM Kd and the coefficients a3, a6, a7 were removed from the physical model of the collector. In both cases as the fluid temperature tested was lower than 300ºC, the coefficient of thermal losses used has been a2 instead of coefficient a8 which was set to zero. So, the reduced collector thermal output model based on the collector's total area is obtained with the formula (1).

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} K_b(\theta_{LS}, \theta_T) G_b - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_5 \frac{d\vartheta_m}{dt} \quad (1)$$

The gross areas were measured by CENER based on ISO 9806 and standard IEC 62862-5-2 requirements. The width and the gross length were considered as the maximum distance between the extreme facets when the sun is at zenith, and without discounting the possible gaps between facets.

Once the physical model of the collector is defined, and sufficient data is obtained, the parameter identification is performed to obtain the collector characteristics for the Quasi Dynamic Test method (QDT). A Multiple Linear Regression (MLR) has been performed which is a fast matrix method that allows non-iterative parameter identification. The identification of the parameters and the estimation of the uncertainty of each parameter has been calculated with a matrix calculation according to Annex D of the standard ISO 9806 [1].

For now the Solar KEYMARK (SKM) European quality label [19] and within the SRCC American quality label [20] only very few concentrating tracking solar collectors are certified to date.

3.2 Optical simulation and correction calculation

According to SolarKeyMark annex for In-Situ certification [17] "*If a sufficient range of incidence angles cannot be provided, the IAM shall be evaluated by analytical means and incorporated in the efficiency test as fix values*". And according to standard IEC 62862-5-2:2022 [2] "*Alternatively to measuring experimentally the IAM in the range of incidence angles $\boldsymbol{\theta_T}$ and $\boldsymbol{\theta_{LS}}$ accessible for the location of the test, it is possible also to calculate the complete two-dimensional range of IAM from ray tracing, using the geometry of the collector and the optical properties of mirror and receiver materials*". So in both cases, ray-tracing optical simulations with Tonatiuh software [21] and validation procedure were defined to ensure that the on-site measurements for the optical efficiency and the IAM are corrected.

Tonatiuh is open-source Monte Carlo-based ray-tracer program which was developed and maintained by CENER. One of the great advantages offered by Tonatiuh is the versatility to simulate different concentration systems, including those with multiple reflections. For these two scenarios, the capability to develop a specific tracker for each solution is also valuable.

The Tonatiuh model of both collectors for the optical simulation has been developed internally by CENER from the data (dimensions, geometry, optical properties of main components, etc), and the reflectors tracking strategy and CAD files provided by the customers.

In both cases, the optical simulation values were adjusted to the experimental values, minimizing the sum of the errors weighted by the uncertainty of measurement RMSE, in order to obtain a correction factor. The final optical efficiency and IAM between 0º and 90º were therefore a combination of experiment results and simulations.

For Rioglass LFR, to obtain the optical efficiency value $\eta_{0,b}$ at normal incidence the experimental values obtained during the test campaign at different angles were determined separately, $\eta_{0,b}K_b^{exp}(\theta_{LS},\theta_T)$, and the values simulated by the raytracing software Tonatiuh $\eta_{0,b}K_b^{sim}(\theta_{LS},\theta_T)$, using the model supplied by the customer. For the simulated values, for each sun position defined by each pair (θ_{LS},θ_T) a simulation of more than 10 million rays were performed to complete a matrix of efficiency values.

Subsequently, the simulation values were adjusted to the experimental values, minimizing the sum of the errors weighted by the uncertainty of measurement RMSE, according to formula (2), in order to obtain a correction factor C between the simulation values and the experimental ones [22]. The weighting w_k is defined for each group of incidence angles (θ_{LS},θ_T) from 1 to N from its measurement uncertainties u_k , according to formula (3).

$$RMSE = \sqrt{\sum_{k=1}^{N} w_k \left(\eta_{0,b}^{sim}(\theta_{LS},\theta_T) * C - \eta_{0,b}^{exp}(\theta_{LS},\theta_T)\right)^2} \quad (2)$$

$$w_k = \frac{\frac{1}{u_k^2}}{\sum_{k=1}^{N}\frac{1}{u_k^2}} \quad (3)$$

The final optical efficiency value is the value obtained by simulation at normal incidence $(\theta_{LS} = 0º, \theta_T = 0º)$ applying a correction factor C between experiment and simulation as formula (4).

$$\eta_{0,b} = \eta_{0,b}^{sim}(0º,0º) = \eta_{0,b}K_b^{sim}(0º,0º) * C \quad (4)$$

For Seenso collector, for technical reasons of the installation it was not possible to obtain longitudinal incidence angles θ_L greater than 36º and transverse incidence angles θ_T greater than 51º. Longitudinal incidence angles less than 30º were set to 0º.

4. Results

In both cases, the testing campaign consisted of a wide range of sunny testing days, with a variability in fluid temperature and incidence angles.

For the Rioglass LFR, the testing campaign was the result of 1582 data series, averages of 10-minute intervals, using 59 sunny testing days between 6th June 2020 and 15th February

2021, with an inner temperature variability between 80 ºC and 180 ºC and longitudinal incidence angles up to 60º and transversal incidence angles up to 70º, as seen in Figure 3a. The optical efficiency was obtained from data with a temperature difference between 47 and 165 K. The customer's test facility did not allow stable inlet temperatures below 80 ºC.

For the Seenso collector, the testing campaign was the result of 223 data series, averages of 10-minute intervals, using 12 sunny testing days between 6th May 2022 and 2nd July 2022, with an inner temperature variability between 17.3 ºC and 111.8 ºC and longitudinal incidence angles up to 36º and transversal incidence angles up to 51º, as seen in Figure 3b. The longitudinal IAM values throughout the range were obtained by optical simulation. The values of the transverse IAM from 0º to 50º were obtained experimentally. In the range from 60º to 90º it was obtained by optical simulation, correcting them with the experimental values in the range from 0º to 50º.

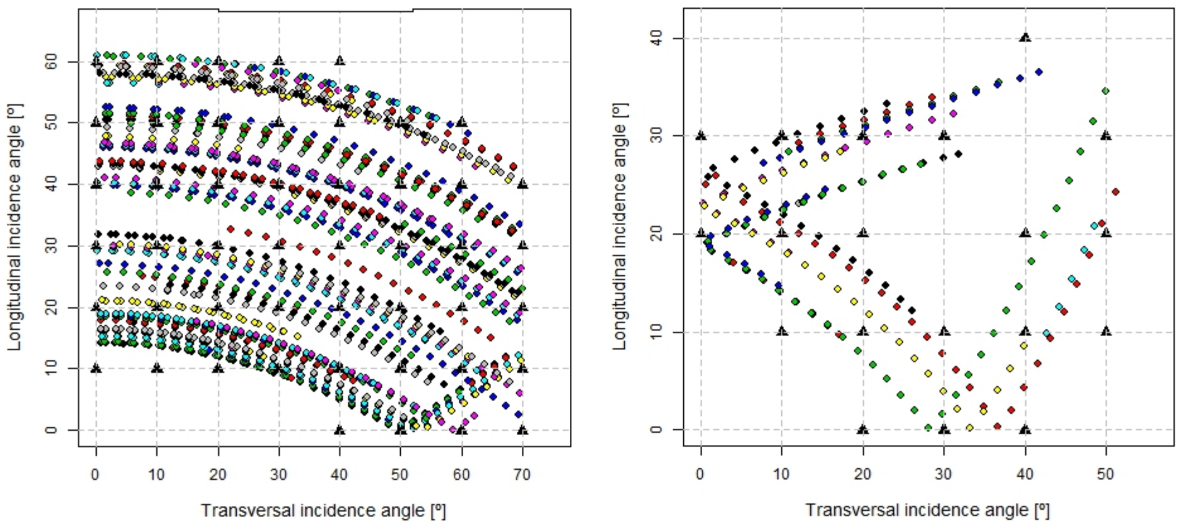


Figure 3. *Incidence angles obtained during the testing campaign (circles) and rounded incidence angles for dummy variables (triangle) (a) Rioglass LFR [23] (b) Seenso collector*

Figure 3b shows that the number of the data series for the Rioglass LFR is much higher than for a standard test, the testing campaign was extended along more than 10 months which allowed to obtain most of the possible incidence angles in this location. For the Seenso collector the incidence angles obtained were the minimum possible for a normal testing campaign.

The optical simulations with Tonatiuh were obtained as specified previously. See Figure 4 shows Tonatiuh models.

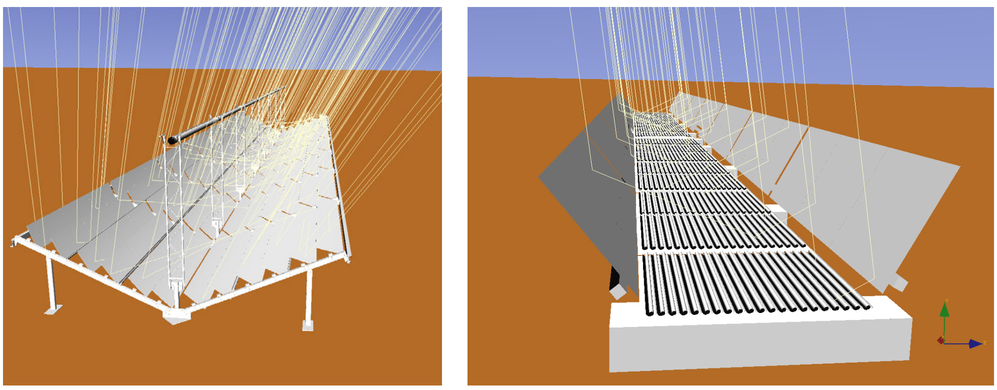


Figure 4. *(a) Rioglass LFR [20] (b) Seenso collector*

For the Rioglass LFR, the correction factor obtained between experiment and simulation as formula (5) was C=0.941 [-].The average expanded uncertainty for the IAM is ± 0.009 [-]. The mean absolute error between IAM obtained from the simulation and the experiment was 0.03 [-]. The IAM results will be published more in detail in ref. [23].

For the Seenso collector, using the dummy method grouping the incidence angles in groups of 10º for the longitudinal incidence angle (greater than 30º) a maximum longitudinal angle of 40º is obtained and a maximum transverse angle of 50º is obtained. For the optical simulation, it was verified that the influence of the longitudinal IAM is not more than 2% up to 30º according to section 26.3.1.1 from ISO 9806. So the longitudinal incidence angles less than 30º were set to 0º. Then, the simulation results were then used to obtain the transverse IAM from 50º to 90º and the longitudinal IAM from 0º to 90º. Figure 5 shows the difference between simulation and experimental results.

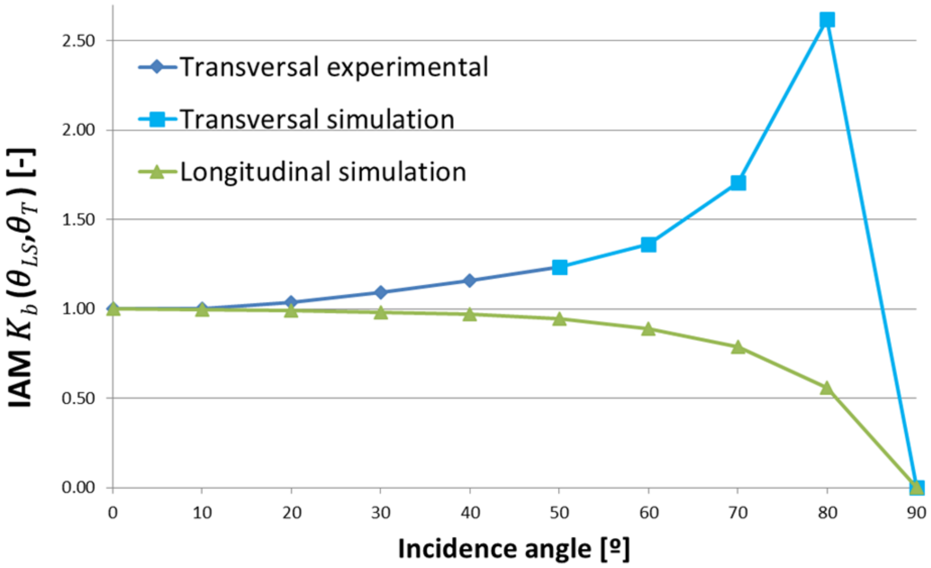


Figure 5. *Seenso IAM*

5. Conclusion

Process heat in industry is a large potential market for solar thermal energy. But it needs more quality controls. The ISO 9806 standard currently contemplates the testing of concentrated solar collectors, although with some limitations. CENER has a wide experience in testing concentrating tracking solar collectors, and is actively participating in all international standardization committees.

A testing methodology for testing large-size LFR and variable geometry collector has been presented in the case that the normal incidence is not possible. One large-size LFR, designed manufactured by Rioglass company and one concentrating solar collector composed of 16 ETC and lateral reflectors with solar tracking on one axis manufactured by Seenso company were tested. The ISO 9806 quasi-dynamic testing (QDT) methodology was used. Optical efficiency and the Incidence Angle Amplifier (IAM) were characterized during a certified testing campaigns. In this study, a methodology of testing, using simulation from a ray-tracing software to determine the optical efficiency at normal incidence, when it is not possible to measure, and also using the experimental results, were validated. It shows that different solutions to determinate the optical efficiency at normal incidence and IAM exist depending on the degree of compliance of the standard requirements.

Data availability statement

The data are not publicly available for confidentiality of the companies Rioglass and Seenso.

Author contributions

Fabienne Sallaberry: Conceptualization, Methodology, Data curation, Formal Analysis, Writing – original draft. **Alberto García de Jalón**: Project administration. **Amaia Mutuberria**: Investigation, Software. **Ignacio Bernad**: Methodology, Visualization. **Josep Ubach**: Investigation. Funding acquisition, Writing – review & editing. **Jose Ajona**: Investigation. Funding acquisition, Writing – review & editing. **Marcelino Sanchez**: Supervision, Project administration.

Competing interests

The authors declare no competing interests.

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