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Outcomes and Features of the Inspection of Receiver Tubes (ITR) System for Improved O&M in Parabolic Trough Plants

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Abstract. Concentrated solar power (CSP) plants based on parabolic trough (PT), after several years since their commissioning, demand new operation and maintenance (O&M) developments. Particularly, the receiver tube´s potential degradation over time is a real challenge. In this paper, the current version of the ITR System's last developments and advanced features are presented together with the main outcomes provided by the system for a real, complete solar field inspection in a commercial PT power plant. Exemplarily, this commercial ITR inspection showed that 0.8% of the tubes were underperforming and thus classified as outliers, while the average relative power of the tubes from the solar field resulted in about 97% of the ideal tubes' power. This paper shows that, thanks to the ITR Inspection System, plant operators can more easily develop and adopt improved O&M strategies, such as corrective and preventive actions in the solar field and even predictive actions in case of periodic inspections.

INTRODUCTION

Concentrated solar power (CSP) plants based on parabolic trough (PT) technology represent the majority of the total operational CSP plants worldwide, accounting for about 4 GW (80% of the total 5 GW installed capacity of CSP plants) [1]. In addition, a number of PT plants are already under construction and commissioning as well as under development or announced. As per today, the planned capacity of PT plants by 2020 will be over 15 GW [1]. Considering these numbers and with some of the new generation of PT power plants already reaching or approaching their 10th anniversary in operation, now is the time when operation and maintenance (O&M) developments becomes crucial to ensure a good performance of current plants and to warrant the reliability of the technology for further deployment of such plants. Suitable and specifically developed O&M methods for PT plants are now essential for maintaining appropriate levels of thermal efficiency and assessing durability of the components during the plant's useful life, thus safeguarding the project's financial performance over time. Particularly, the receiver tube is the most critical component in PT technology plants due to its direct impact on the plant efficiency and due to its potential degradation over time, either caused by vacuum loss, by breakage, by degradation or others. Therefore, the need for accurately and comprehensively assessing the receiver tubes' status in a PT plant is vital and should be of major importance for any plant operator. However, the massive number of receiver tubes in a plant and the difficulty to truthfully measure their performance makes it a challenging and demanding task.

To address this, the National Renewable Energy Centre of Spain (CENER) developed a dedicated methodology [2] and has been continuously improving and upgrading the so-called ITR System for PT plants over the past years. The current version of the ITR System couples the IR inspection of the complete solar field receiver tubes and advanced video-post processing of the images with a reference validated receiver tube model for a robust assessment of each tube's performance. Additionally, all the information gathered and derived from successive field inspections is kept in a historical database for later analysis of periodical inspections. This service constitutes a significant

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breakthrough for conducting the surveillance of the receiver tubes degradation over time, and to adopt improved corrective, preventive and predictive strategies with the aim of optimizing the O&M to ensure appropriate thermal efficiency and final electricity production of the plant. In this paper, the latest developments and advanced features incorporated to the ITR System are presented together with the main outcomes provided by the ITR System for a real, complete solar field inspection in a commercial PT power plant.

METHOD

The ITR System is based on temperature measurement by infrared (IR) thermography of the receiver tube glass surface. The system is composed by different devices for quick massive, but yet fully detailed terrestrial inspection which allows for the analysis of approximately 4000 tubes per day (~ 20-22 loops per day). This means that only four days are typically required to accomplish the inspection of the complete solar field for a 50 MW power plant. Some pictures of the ITR System are shown in Fig.1.

FIGURE 1. CENER ITR System, onsite inspection, tube detection and glass cover temperature measurement.

The measurement method consists in recording IR images (videos) along the half-loops (as recording unit) in a safe way without any interference with the normal operation of the plant. ITR System allows to monitor the receivers in parallel direction, in adequate elevation and orientation, at a maximum distance of 4-5 m and approximately at 15-20 km/h in such way that the receiver tube is always centered on the image. The conditions during the inspection must be stable, avoiding sudden changes in radiation or wind speed. IR videos acquired during field inspection are then processed by the ad hoc ITR software. The ITR processing requires the configuration of certain critical parameters (e.g. glass emissivity), as well as operating load and meteorological inputs, corresponding to the specific inspection instant, in order to enable some of the advanced analysis features out coming from the model based simulations that will be explained later.

The software identifies each receiver tube, processes its glass temperature and classifies each of the tubes in the solar field according to its status. Consequently, tubes with untypical behavior are identified by a combination of both statistical analysis (outliers) and comparison with the theoretical performance according to the actual instantaneous plant operation.

To facilitate O&M decision-making, in addition to tube-based status information, the ITR System provides a number of aggregated indicators on half-loop, loop and solar field basis derived from accurate model based simulations of the impact of the status of the tubes on the solar field performance. Finally, ITR software´s additional features include the historical data base management for periodical inspections surveillance. Figure 2 shows main processing steps on the ITR software scheme.

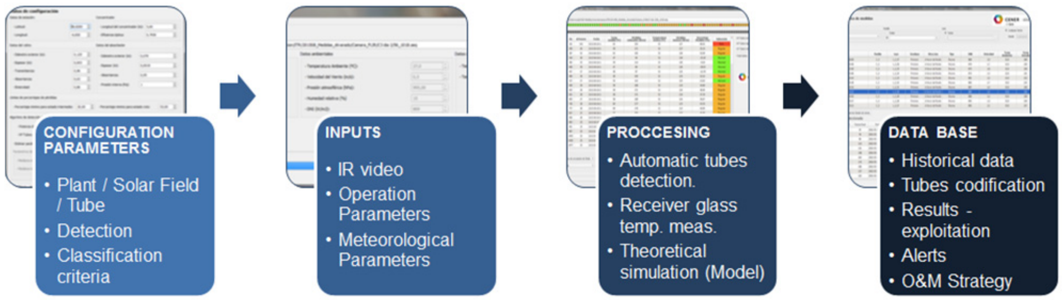


FIGURE 2. ITR Software scheme.

In the following sections further information on the procedures used to classify each receiver tube and to assess the impact of the tubes' status in the solar field performance is provided. Also, an outlook on the ITR system measurements repeatability and reproducibility, essential to any measuring system, is provided.

Receiver Tubes Status – Classification (Outliers Statistical Analysis)

The classification of the status of the receiver tubes is based on a statistical analysis of outliers. This analysis allows the identification of receiver tubes posing an untypical behavior. For this, the first step is to obtain non-seasonal data from each tube's measured glass temperature, as shown in equation (1).

$$\Delta T = (T_{meas} - T_{adjust}) \tag{1}$$

Non-seasonal data ΔT corresponds to the difference between the tube's measured glass temperature, T_{meas}, and an adjusted temperature T_{adjust} which is relative to the linear distribution of the measured glass temperatures for each whole half-loop. The aim of this data is to reduce the dependence on the particular conditions of each inspection. Then, this non-seasonal data is statistically analysed for the identification and classification of outliers, in order to obtain the atypical values and the extremely atypical ones.

The ITR outliers statistical analysis is based on the box-and-whisker plot. This analysis is focused on positive data ($\Delta T > 0$) corresponding to glass temperatures that are higher than the adjusted values, therefore, on tubes posing a worse behaviour than the rest. This analysis belongs to descriptive statistics and allows knowing data distribution with the median, 25th and 75th percentiles (Q1 and Q3) as well as maximum and minimum values. In this plot, the data of a histogram are put in a single dimension, facilitating the analysis of the information by making that 50% of the population rests within the limits of the box (Interquartile Range - IQR). An example of a box-and-whisker plot for a normal distribution and the classification intervals defined for the ITR system are shown in Fig.3.

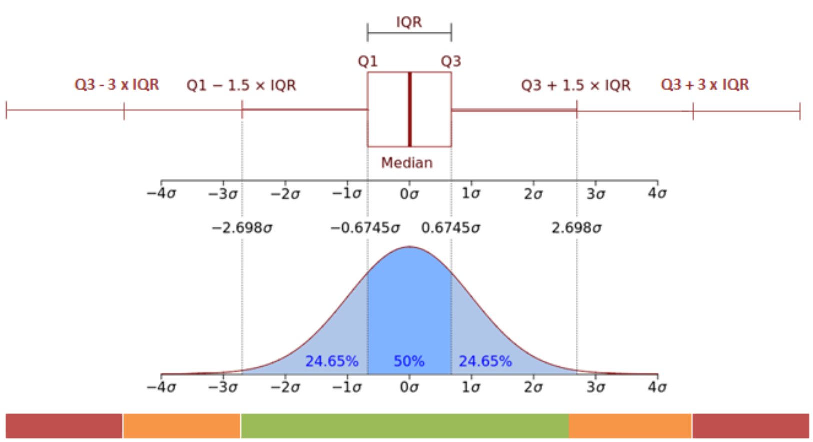


FIGURE 3. Example of a box-and-whisker plot for a normal distribution. Classification intervals marked by the coloured boxes red, orange and green.

The classification criterion is determined by the interval normalized limits for the categories listed in the table 1:

TABLE 1. Tubes Classification Categories and Interval Limits.

Category	Interval Limit
Green (Ok)	$\Delta T < Q3 + 1.5 \times IQR$
Orange (Regular)	$Q3 + 1.5 \times IQR < \Delta T < Q3 + 3 \times IQR$
Red (Not Ok)	$Q3 + 3 \times IQR < \Delta T$

As graphically shown in Fig. 3, and numerically shown in Table 1, the ITR system assumes that tubes with untypical behavior (orange and red tubes) are those which temperature difference, ΔT, is greater than the threshold of (Q3 + 1.5 x IQR). Tubes with temperature differences greater than (Q3 + 3 x IQR) are considered extreme outliers (red tubes). The outliers analysis is carried out considering both the tube's corresponding half-loop as data set and the whole solar field as data set. Then, definitive outliers are considered those which result outliers at both levels.

This tubes classification procedure is based on a tested and robust statistical methodology, regardless of the plant operation circumstances at the inspection time and without the need of any theoretical reference behavior. Considering at the same time the repeatability and reproducibility achieved by the system on glass temperature measurements (see relevant section below), the reliability of the classification approach is guaranteed. As introduced in Table 1, the inspected receiver tubes by non-seasonal data classification are handed out among three different categories. These categories are: red tubes, which are identified as extremely atypical values with the worst behavior; green tubes, those that show an acceptable temperature and behavior; and, lastly, the orange tubes, posing a intermediate situation and considered as regular outliers.

In the ITR system tool, the outliers are displayed in an accurate and traceable outlier's map, where tubes with untypical performance are detected and located as they are in the real layout of the plant that is available and - helpful for plant operators for making decisions regarding O&M strategies, such as a tubes replacement action.

Power Indicator for Plant Performance Evaluation

Additionally to the classification of outliers, a power indicator is defined for the analysis of the impact on the solar field performance derived from accurate model based simulations, developed by CENER, which has been validated against commercial parabolic trough plant performance.

The underlying tube model of the ITR software is a detailed one-dimensional object oriented heat transfer model, which has been thoroughly validated to ensure that it accurately represents the parabolic trough receiver tubes. Initial validation was done at experimental facilities [3] resulting in a very satisfactory model to represent complete operating systems. Additionally, a more detailed validation of the heat loss model has been carried out comparing model simulations with experimental measurements on the testing facility of CENER using different tube manufacturers under nominal conditions. Emissivity values from heat losses tests and from spectral measurements of the reflectivity at far IR wavelengths of absorber samples are also used to fine tune the model. Finally, outdoor, on-field measurement campaigns of the ITR system carried out between 2015 and 2016 were also used to validate the inspection procedure as well as the estimation of the heat loss by the use of the reference tube model and the assessment of the tube status impact on the solar field performance.

On-field measurements of each tube glass temperature as well as operation parameters (each half-loop inlet and outlet temperatures, defocusing signal), collector and absorber geometrical and thermo-optical parameters and meteorological variables (plant location, DNI, ambient temperature, wind speed, ambient pressure, relative humidity, etc.) are inputs for the simulation model. Thus, this model is used to estimate both the actual tube heat losses and useful power and the corresponding theoretical values for the nominal status of the tubes (vacuum nominal pressure condition). Both model results are then compared and the power indicator is calculated as:

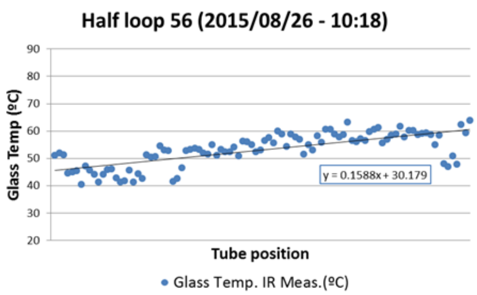
$$PI = \frac{P_{estim} - P_{theo}}{P_{theo}} (\%) \tag{2}$$

Where, the power indicator PI is a percentage value obtained from the difference between the estimated power of the tube P_{estim} and the theoretical power at nominal conditions P_{theo}.

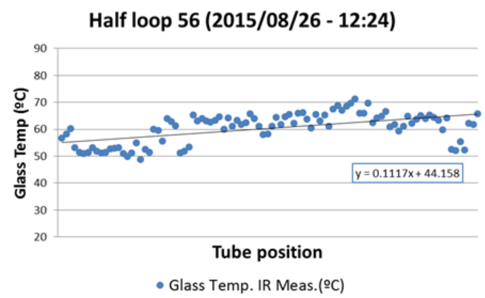
This indicator is mapped, with a gradual color scale for different aggregation levels (tubes, collectors, half-loops and loops) resulting in a friendly "status photo" at the inspection time, which allows for an intuitive and rapid identification of the more relevant and convenient O&M actions.

ITR Measurements Repeatability and Reproducibility

The developed measurement method and post-processing shows the desirable repeatability and reproducibility, as observed in different consecutive inspections during the same day (similar operating conditions) and night, as well as after a longer period of 7 months (and different operating conditions). Figure 4 picks up glass temperature measurements for the tubes of a half-loop in different moments.



(a)



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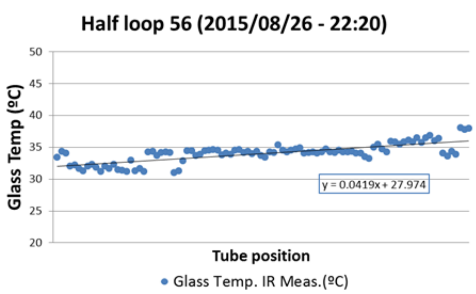

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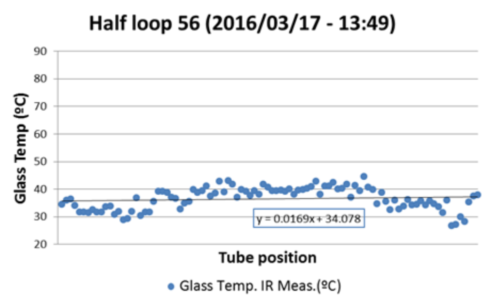

(d)

FIGURE 4. Glass temperature measurement repeatability and reproducibility for inspections during the same day (a,b) or night (c), and after 7 months (d).

RESULTS

As previously mentioned, different on field measurement campaigns were carried out between 2015 and 2016 for the ITR System development. The following results belong to the first commercial service performed in 2017. Figure 5 shows box-and-whiskers plots for every inspected half-loop along the different solar fields (SF) of the commercial plant. As it can be observed, outliers number and distribution is not homogenous for all the solar fields. Likewise, the IQR interval varies for each half-loop. It is worth to mention that only high temperature half-loops were inspected, except for loops of the SF 2 that were 100% inspected.

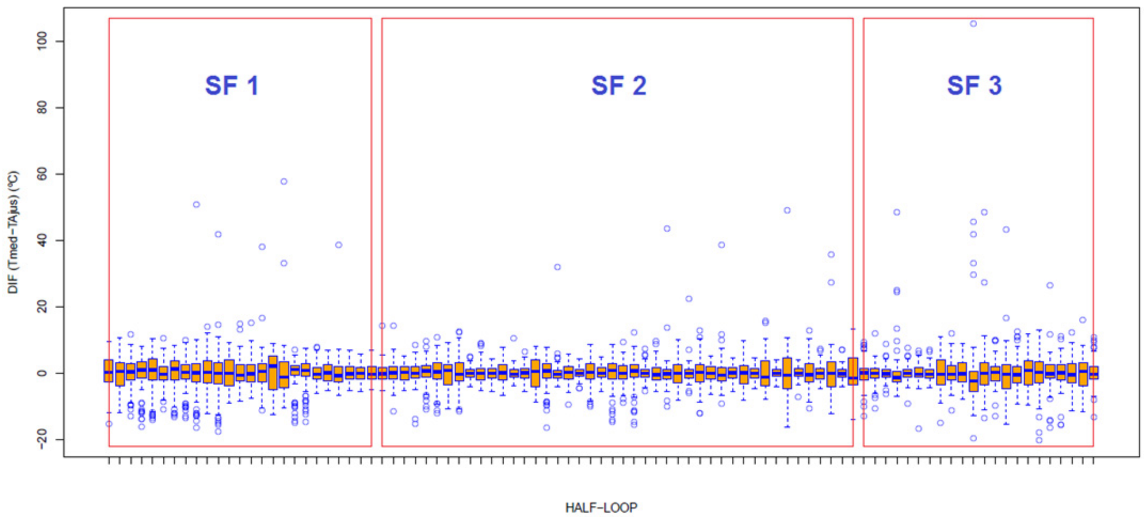

FIGURE 5. Box-and-whisker plot for half-loops inspected in each solar field.

The results of the outliers´ classification are summarized in Table 2. For the total number of tubes inspected in the plant 0.8% of them were identified as outliers (73 tubes of a total of 8,736).

Based on the classification criterion stated before, 45 tubes (0.5%) were identified as atypical in a regular situation (orange colored) with a relatively similar ratio in each solar field, and 28 tubes (0.7%) as extremely atypical with a non-acceptable behavior (red colored).

TABLE 2. Classification Results.

Classification Results	SF 1	SF 2	SF 3	Total
Total of ORANGE outliers	8	18	19	**45**
% of the total of tubes inspected	0,3%	0,4%	0,9%	**0,5%**
Total of RED outliers (Broken glass)	0	3	3	**6**
Total of RED outliers (Correct glass)	7	4	11	**22**
Total of RED outliers	7	7	14	**28**
% of the total of tubes inspected.	0,3%	0,2%	0,7%	**0,3%**
Total number of outliers	15	25	33	**73**
Total % of the total of tubes insp.	0,6%	0,6%	1,6%	**0,8%**

Among the red outliers those tubes that do not present the glass cover are easily differentiated from other red tubes that still conserve the glass cover. ITR System adds value to the solar field diagnostic identifying those tubes which do not have lost the glass cover and, for other reasons, are not showing a good performance according to their nominal specifications.

The distribution and location of outliers on the solar field layout along the half-loops inspected is displayed in Fig.6. Orange and red tubes are identified in an easy way with a quick look at the outliers map. This layout respects the hydraulic functional configuration of the solar field for the best comprehension, maintaining half-loop codification and relative position, with the exception of white gaps in case of no inspected half-loops (out of order half-loops).

This map, together with the thorough list of tubes traceable to the plant´s original nomenclature and the tube cover status (with or without cover), represents a really complete and valuable information (i.e. Table 3) that is supplied to the plant´s operator for the best knowledge about the solar field status in order to adopt new operation strategies or consider maintenance actions concerning to the tubes with the worst behavior, susceptible to substitution.

TABLE 3. Example of Outliers List Information Detail.

Number of Outlier	Solar Field	Half-Loop	Tube	Meas. Temp (ºC)	ΔT (ºC)	Covered (Yes/No)	Classif.
1	1	25	5	--	--	No	Red
2	1	7	63	124.4	62.6	Yes	Red
3	1	9	24	65.2	8.0	Yes	Orange

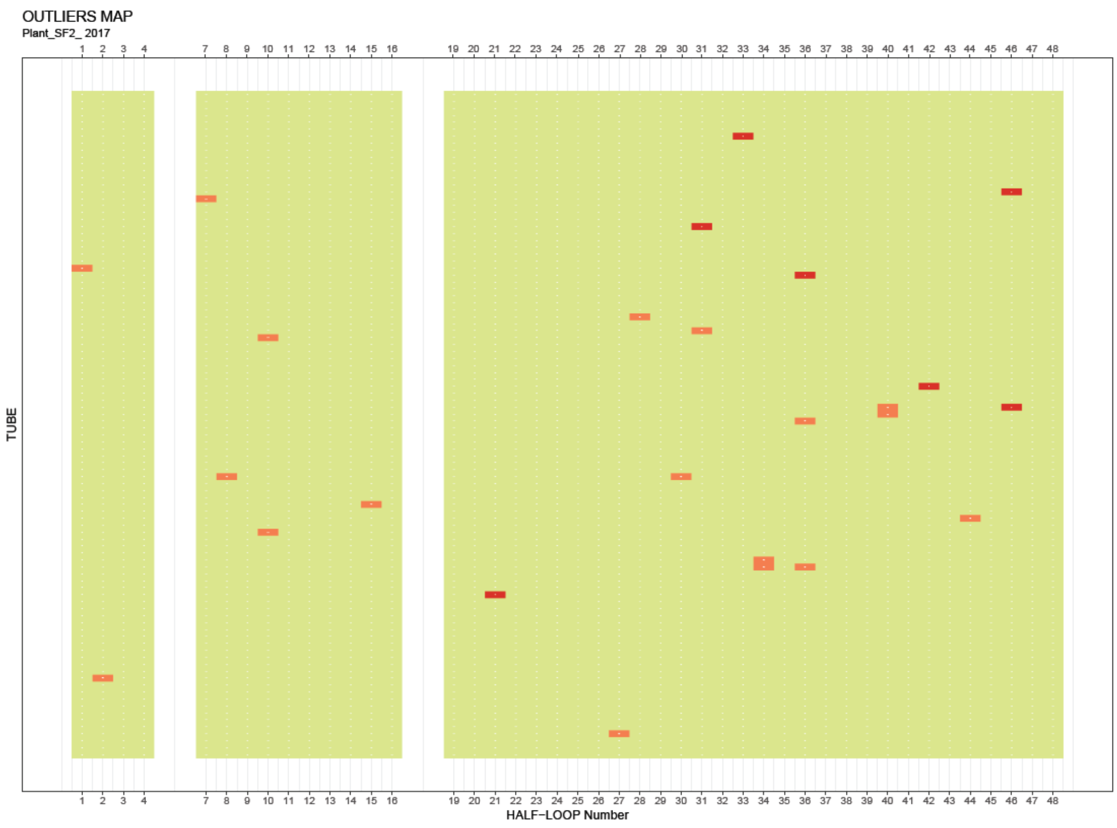

FIGURE 6. Outliers map for the solar field 2 (SF 2).

Once the outliers are located from their measured glass temperature, the power indicator referenced to theoretical values resulting from the simulation model are mapped according to the defined methodology (considering the operation conditions at inspection time). In Fig. 7, the power indicator for every tube is displayed in a gradual scale of colors from ideal tube performance, 0%, shown in green to the maximum negative value -35% shown in red. The power map reveals the performance of the solar field is close to the reference, leaving some areas nearer to intermediate values and showing a great correspondence of the worst tubes shown in Fig.6.

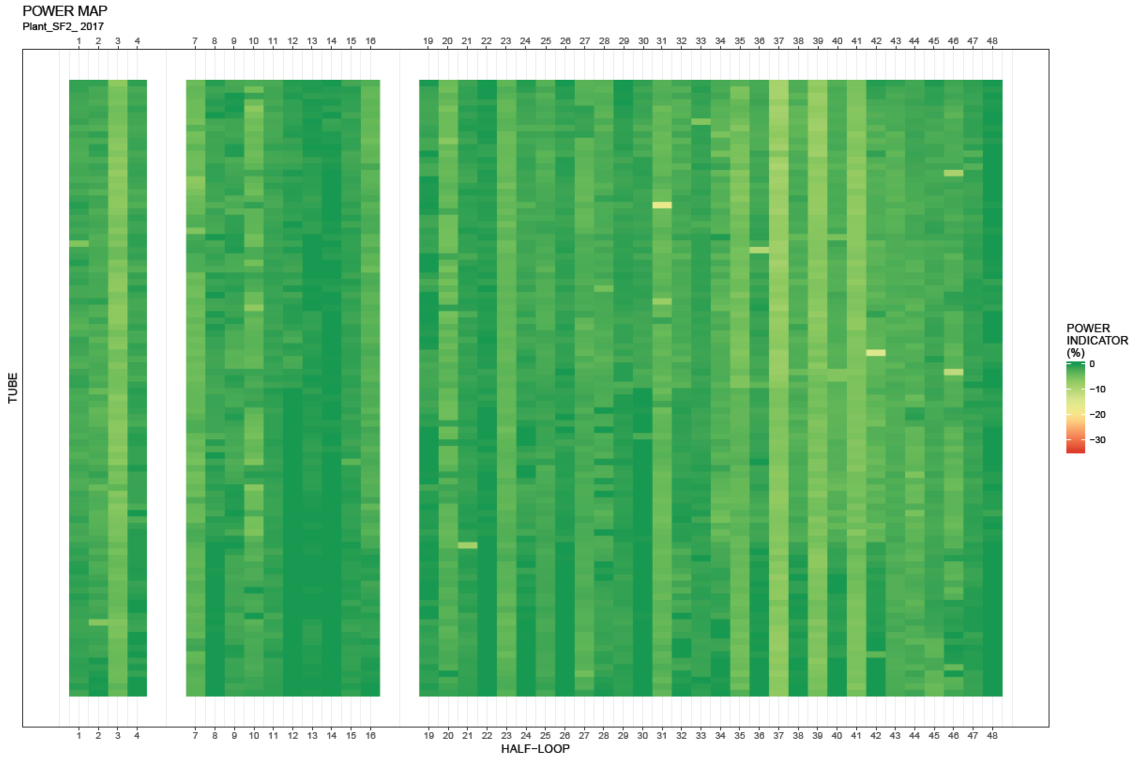

FIGURE 7. Tubes power map for the solar field 2 (SF 2).

Besides the visual feedback of the power map, other key parameters are determined to better quantify and characterize the status of the tubes and the solar field. This way, the cumulative percentage of tubes plotted respect their relative power offers another control criterion that can be adjusted considering different units of analysis: the whole solar field, some-subfields or some loops, half-loops, collectors or tubes). As an example, Fig. 8 summarizes the tubes status for the SF 2 and shows that 99% of the tubes are over the 93% of power performance, with an average relative power of around 98%. Table 4 summarizes results for the three inspected solar fields and for the average of the whole inspected tubes, which results in an average relative power of 97% over the nominal solar field value. This key parameter allows plant operators to fix reference threshold values pursuing the solar field optimized performance.

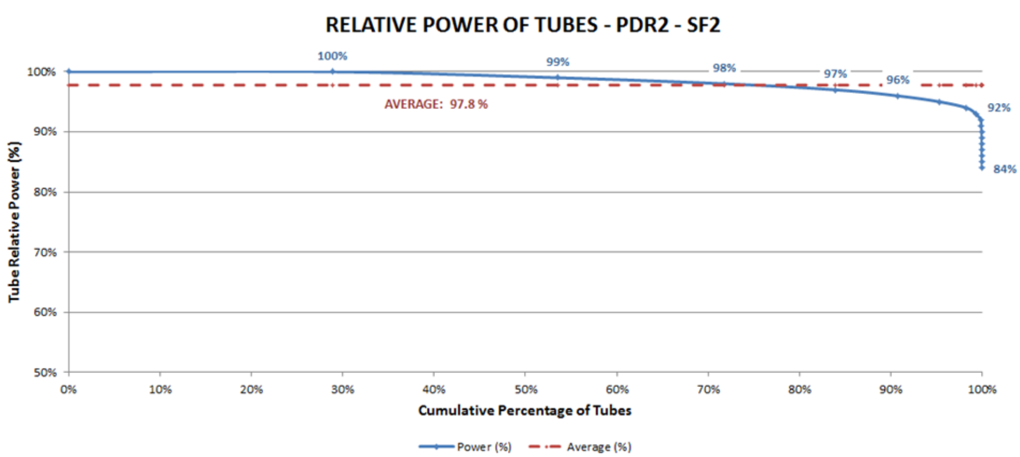

FIGURE 8. Relative power of tubes of the solar field 2 (SF 2).

TABLE 4. Average Relative Power of Tubes Inspected per Solar Field.

SF 1	SF 2	SF 3	Total
97%	98%	97%	97%

Once the power map (Fig.7) and the ratio of relative power of tubes are available (Fig.8), it is possible to analyze the solar field status referenced to the nominal conditions of the receiver tubes. Thus, thanks to periodical ITR inspections, the surveillance of the tubes behavior can be thoroughly monitored and assessed over time.

CONCLUSIONS

CENER has developed a Receiver Tubes Inspection System (ITR) in parabolic trough plants to carry out the surveillance of the receiver tubes degradation and to adopt new O&M strategies with the aim of optimizing the thermal efficiency and final electricity production of the plant. In fact, the inspection service is nowadays being supplied at commercial scale.

The assessment of the tubes status is based on a robust procedure of glass cover measurement from IR images acquired thanks to a terrestrial inspection device. Features such as repeatability and reproducibility provide reliability to the system for periodical inspections and the surveillance over the time of the tubes and solar field performance.

On the basis of contrasted statistical method, a classification of outliers allows to identify and locate the tubes with the worst behaviour in a detailed and traceable way. Through the application of a validated model for the tubes heat losses characterization in nominal conditions, the power indicator is obtained for tubes at operation conditions at inspection time. Power maps and other key parameters like the relative power of tubes versus a cumulative percentage of tubes of the solar field are set out as valuable, qualitative as well as quantitative, outcomes of the ITR Inspection System.

Thanks to the ITR Inspection System, improved O&M strategies, such as corrective and preventive actions in the solar field, and even predictive actions in case of periodic inspections, can be adopted by plant operators.

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