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SolarPACES Task III Project: Analyze Heliostat Field:

Results of Methodologies Comparison, Gaps to be Filled and Next Steps to Further Improve the Solar Central Receiver Technology

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Abstract. In recent years, great efforts have been made to reach a consensus on heliostat testing best practices. A specific SolarPACES task was launched to provide a Heliostat Testing Guidelines document for single heliostat evaluation with a focus on prototype validation and qualification. Such guidelines are not well-suited for heliostat evaluation in operating commercial heliostat fields. The commercial implementation of the Central Receiver technology is burdened by the lack of a demonstrated cost-effective methodology to test solar fields, particularly during the commissioning and operation phases of the plant.

To address heliostat characterization challenges, the SolarPACES funded Project "Analyze Heliostat Field" aims to set the basis towards a SolarPACES guideline for Heliostat Field Performance testing under a common framework. This is by means of a review of the existing methodologies, R&D and industrial stakeholders information sharing and preparation of a future quantitative comparison and validation plan.

As part of the development of this project, several meetings and a workshop involving the SolarPACES community was organized to share knowledge and experience in the measurement and characterization of heliostat fields using a range of technologies and procedures. Research centers and companies from 5 different and distant countries have actively participated in these meetings, sharing their experiences, needs and interests. This paper summarizes the outcome of this international collaborative effort and the prospects for future close collaborations sustained over time.

Keywords: Heliostat Performance, Heliostat Field, Testing Guideline, Measurement, Characterization, Commissioning, Reliability

1. Introduction

The heliostat field and the receiver are critical components for performance and reliability of central receiver systems. The receiver is the entrance gate for absorbed energy to the thermal cycle, and the heliostat field is the highway that drives radiation to the door. Poor knowledge of heliostat fields results in underperforming plants, while presenting a high risk of damaging the receiver, or other components downstream with significant negative economic consequences.

Regarding the SolarPACES Heliostat Performance Testing Guideline, the basis for single heliostat and prototype testing was defined. However, except for the design of new heliostats, industry has to address the monitoring of operating fields. Some of the commercial fields operate excellently while others have room for optimization.

Heliostat fields typically consist of thousands of heliostats, scattered over very large areas of land, which introduce tough technical and economic constraints. Installed heliostat field monitoring and operation challenges cannot be met with current proposed testing guidelines since overall conditions, requirements and expected results differ from single heliostat and prototype testing. For instance, heliostat-receiver distances can be much larger, the number of heliostats is enormous, the evaluation of the complete field must be performed periodically, remarkably fast, automated and with low labour efforts.

To achieve this goal, R&D centres, supported by the most relevant industrial stakeholders, have developed and released innovative methodologies during the last few years. Their developments result in a range of different technologies, sometimes making direct comparison between methodologies difficult. Consequently, these methods cannot be verified and/or validated easily, which negatively affect their prospects for implementation.

The Analyze Heliostat Field project seeks to launch the work on addressing this challenge by creating a collaboration framework that facilitates the exchange of knowledge and experiences in the solar community, between technology centers and companies. The common long-term goal is to improve the quality control of heliostat fields under real operating conditions, through the appropriate use and comparison of existing and future characterization techniques.

2. Qualitative comparison of techniques

In recent years, research centers and related companies globally have developed tools and techniques to test the performance of central receiver solar fields. This work has led to different metrology techniques, but the lack of standardization for the various approaches and terminology makes it difficult for the industry to find the best fitting way to introduce them in planned or existing solar tower power plants. Taking this issue into account, a comparison of heliostat metrology techniques was proposed as part of this project, so guidelines or recommendations could be proposed for solar field testing. The expected consequence of this effort is the de-risking of the new techniques, helping the industry make the most of the central receiver CSP technology.

2.1 Comparison methodology

During this project, an initial qualitative comparison of the metrology approaches has been performed. This first analysis has revealed the difficulties associated to the comparison of such diversity of techniques. This task has been carried out by defining a series of comparison attributes, shown in Table 1.

Table 1. *Lists of attributes identified for the performance analysis of the different methodologies framed into each of the subtasks related to solar field testing.*

Concentrator surface characterization	**Tracking accuracy**	**Flux mapping**
Format of the measurement	Format of the measurement	Format of the measurement
Required instrumentation	Required instrumentation	Required instrumentation
Accuracy/uncertainty of the measurement	Accuracy/uncertainty of the measurement	Accuracy/uncertainty of the measurement
Direct or indirect measurement	Purpose of measurement	Direct or indirect measurement
Scope	Scope	Scope
Time per measurement process per heliostat	Time per measurement process per heliostat	Time per measurement process
Degree of intrusiveness	Degree of intrusiveness	Degree of intrusiveness
Application to a complete heliostat field	Application to a complete heliostat field	
Distinguish between contour and canting errors	Measurable heliostat orientations and further restrictions	
	Operational requirements and limits	
	Number of normal vectors per heliostat	
	Basis for the measurement	

As the three categories are referred to measurement and qualification of heliostat or solar field parameters, the basic attributes that define the quality of a measurement are present in all three of the subtasks. In addition to these attributes, some of the subtasks, mainly the one devoted to tracking accuracy, count on extra parameters that are specific to the corresponding heliostat parameter to be characterized.

The methodology tables resulting from this preliminary analysis will be included in the final report of the project that is currently under development. This document will also include a brief review of the results obtained from a CSP industry survey about the penetration of solar field metrology tools in commercial plants and a summary of the workshop discussions at PSA (Almería) on this topic and will be published in the Task III section of SolarPACES website.

As one of the outputs of this project, a near future collaboration between the project participants is being discussed to produce an exhaustive technical comparison of the different systems developed to analyze the solar field. In this planned comparison and validation exercise, the application of these methods was divided in the following heliostat technology development stages (see Figure1):

- A. Heliostat R&D:
  - A1. Components. This stage covers initial knowledge/resource preparation and conceptual analysis/justification for design of a heliostat and a heliostat field. It also includes the preparation for commercial project development. This stage includes

the research, development, and performance validation of components of a heliostat and heliostat field prototype.
    - A2. Integrated Heliostat & On-Site Assembly. This requires the research, development, validation, and performance projection of an integrated heliostat to prepare for commercial deployment.
- B. Mass Manufacturing & Qualification. This stage includes the design and development of mass production lines as well as the quality control of mass-produced heliostats under various conditions such as indoor assembly and outdoor efforts for pre-installation.
- C. Solar Field:
    - C1. Deployment & Commissioning. This stage includes heliostat field construction and quality control.
    - C2. Full Operations & Monitoring. This stage includes quality control, O&M, commercial project management, and end-of-life treatment.

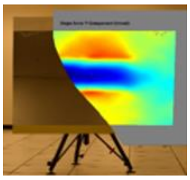
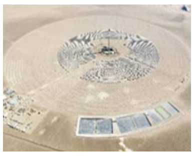
Heliostat Analysis Development Cycle	A1. Heliostat R&D: Components	A2. Heliostat R&D: Integrated Heliostat & On-Site Assembly	B. Mass Manfacturing & Qualification	C1. Solar Field: Deployment & Commissioning	C2. Solar Field: Full Operations & Monitoring
					

***Figure 1**. Proposed development stages for which each technique would be analyzed.*

2.2 Qualitative comparison of techniques

A series of devices, 19 methodologies and systems were discussed and analysed. A preliminary qualitative analysis of each one has been performed. Those systems and the main stakeholders involved in its development organized by testing area, are:

- Concentrator surface characterization: PSA-HPCS (CIEMAT/PSA) [1], NIO (NREL) [2], Helioschar+ (CENER) [3], SOFAST-BCS (SANDIA), ANU's BCS+, CyI technique [4], QDEC-H (CSP Services + DLR) [5] and TEKNIKER's Autocollimator technique [6].
- Tracking accuracy: PSA-HPCS (CIEMAT/PSA) [1], Helioschar+ (CENER) [3], ANU's BCS+, IMDEA's BCS+, SHORT (CENER + TEKNIKER) [7], HelioPoint (CSP Services + DLR) [8], NIO (NREL) [2], UFACET (SANDIA), HelioControl (FRAUNHOFER-ISE) [9], SOFAST-BCS (SANDIA), QDEC-H (CSP Services + DLR) [5] and HFACET (SANDIA).
- Flux mapping: Flux mapping without moving bar for industrial scale receivers (DLR) [10], 3-D flux mapping (ANU) [11], HolisticFLUX (CENER + US + IMDEA), a second method from DLR and Hybrid high irradiance measurement system (CIEMAT/PSA).

The reader can note that some of the methodologies are present in Concentrator surface characterization and Tracking accuracy testing areas. Those techniques, due to the data that are obtained from the measurement process, are able to provide information about the state of the heliostat reflective surface and the tracking accuracy by implementing different processing algorithms depending on the desired output.

As previously stated, the analysis performed during this project has been defined as preliminary and qualitative, defining an initial classification that sorts the methodologies by their similarity, to help establish the starting point for the collaboration that is currently being promoted. That is because the information available during the project does not yet allow direct comparisons for the output of all methods surveyed. The lack of standard vocabulary and approach to heliostat testing methods makes it difficult to propose anything that fits all methods. Therefore, one of the proposals moving forward is to regroup the identified techniques into several categories in a way that allows to test them together.

One of the common points of most of the techniques presented in this project is the usage of cameras. Although most of the techniques include images as part of the inputs to their processing algorithms, the images required depend on the technique: some techniques require images of a reflected pattern or a distant object. Others take direct or indirect images of different beams, scattered through the field or mounted on UAVs, etc. The required sensitivity, definition and camera accessories are technique dependent. Although the raw output of all these systems is based on images, it is not trivial to establish a basic parameter to define accuracies. In addition, currently there is no data about the sensors that each technique has integrated during the different testing phases that they have been subject of.

2.2.1 Concentrator Surface Characterization

The concentrator is usually characterized by the difference between the shape of its design surface (paradigm) and the actual surface resulting from its characterization at a given instant. The resolution of the measurement is usually system-dependent for a particular time, i.e., at a determined heliostat orientation, temperature and wind speed.

A good reference for heliostat characterization is the SolarPACES Heliostat Performance Testing Guideline, see e.g. [12, 13, 14]. Since 2018 it has been applied several times in research and industry. The version 1.0 was launched and provided to be included into the IEC-TC-117 62862-4-3 standardization process.

Some of the techniques presented during this project to characterize the heliostat surface are based on the state-of-the-art, the BCS system [15]. They capture the projection of the heliostat light beam on a white Lambertian target using cameras, or directly use detectors placed on the proper projection plane. Then, these techniques model the heliostat being tested and iteratively alter the surface in the model until the simulated light beam produces results similar enough to the flux distribution obtained from testing the actual heliostat.

On the other hand, the SolarPACES Heliostat Performance Testing Guideline recommends using slope deviation measurement techniques. The bulk of these techniques are based on deflectometry. They compute the reflection direction caused by a surface normal variation from its theoretical orientation at discrete points of the mirror by imaging the reflection of discrete objects (punctual light sources, projected images or patterns). While the imaging is typically done projecting the reflection on Lambertian targets, it can also be performed using cameras looking into the facets to directly intercept the reflection.

There are other techniques, that produce a direct measurement of the heliostat surface shape, such as photogrammetry or laser scanners, which are not represented in the list of techniques to be compared in this project, as they were not contributed by any participant in the current project. Another reported technique is using an array of autocollimators to measure the deviation of a light beam reflected at discrete points on the analysed facet.

2.2.2 Heliostat Calibration and Tracking Accuracy

The tracking accuracy is defined as the deviation of the average concentrator normal vector to the desired orientation to focus the beam spot onto the set point. This parameter should be assessed with numerous samples considering both motion axes across a wide enough range of the useful working envelope of the heliostat in its configuration space. More information on definitions and calibration techniques is given in [16].

The techniques in this category create a model of the heliostat kinematics and estimate the necessary tracking corrections. Each heliostat design requires its kinematic model. There are several kinematic models in the literature, but at the current stage of the comparison, there is no data about the models implemented in each technique.

As it is the case in concentrator surface characterization, some of the identified techniques are based on state-of-the-art BCS [17], whose biggest issue for tracking calibration is the time needed to process the data for each heliostat. This is facilitated by imaging their reflection on an independent and isolated white Lambertian target (note that multiple measurements are needed throughout the year to identify the errors for all orientations of interest). In addition, they often require a good quality heliostat focal spot measurement to accurately determine a reliable pointing direction and, therefore, are typically dependent on them.

To address the slow process that involves the use of the BCS to determine the kinematic model of heliostats, various techniques covering different approaches have been developed:

- Multiple cameras/targets to speed up the acquisition process.
- Moving cameras to scan reflections (UAV).
- Identification of single heliostats on the receiver in operation (tracking excitation).

2.2.3 Flux Measurement

The evaluation of the joint performance of the whole solar field can help to avoid unwanted distribution of solar radiation that can cause accelerated aging of the receiver, led to high heat losses, increased maintenance expenses and economic losses due to reduced operating time. This is usually done through flux mapping, ie. Measuring the incident flux on the receiver or receiver vicinity. Flux mapping provides feedback information about the suitability of the selected aiming strategy and a reliable measure of the net incident power in the system. This is necessary to evaluate the efficiency of the optical subsystem of a plant.

The state-of-the-art in this category is the moving bar, which is very challenging to scale-up for solar field that extends across vast areas, and add complexity because it requires a water-cooling system, actuators maintenance, the use of radiometers, etc. An overview of approaches to measure the flux density on large-scale receivers was given in [18]. Radiometers are typically fragile, difficult to instal and quickly de-calibrate, but currently no real alternative has been suggested so far.

In large plants, the fluxmap is typically estimated using indirect methods, based on optical modelling and/or stored heliostat fluxmaps information. The BCS can be used to perform full-filed flux measurements on a receiver. In this case, a camera takes images of a receiver when irradiated by the solar field and a calibration of the receiver optical response (reflectance and potentially emittance) is established using radiometers or other sensors.

New developments have been suggested in this topic, and overall, all of them are upgraded versions of the modification of the BCS with additional sensors and/or advanced modelling to serve as feedback to the measurements by simulating the solar field behaviour. In addition, spillage flux measurements have been extended through raytracing simulations, especially suitable for smaller, high-temperature receivers as proposed in [19]. Further developments are mainly focused on:

- Overcoming the limitations imposed by the use of a Lambertian target and be able to measure the flux directly on the receiver. This requires significant knowledge to correct the optical properties of receivers, e.g. [20, 10].
- Combine measurements from several sensors and sensor types to reduce uncertainty.

2.3 Heliostat Field Performance Testing Guideline

SolarPACES task III works currently on three different guidelines, each having its own level of completeness, see also [14]:

- SolarPACES Heliostat Performance Testing Guideline (version 1.0 launched, provided to IEC-TC-117 62862-4-3) [13].
- SolarPACES Heliostat Field Performance Testing Guideline [21] (draft version being sent to task III in Oct. 2023).
- Heliostat Wind Load Design Guideline (first calculation sheet downloadable [22]).

All guidelines aim to increase stakeholder confidence in commercial Concentrated Solar Power projects through universally accepted protocols, establishing a standardized framework for heliostat and heliostat field performance testing and wind load calculations.

The total energy provided to the receiver is facilitated by the interaction of all heliostats acting together as a heliostat field. Factors like positioning, blocking/shading, light attenuation in the path to the receiver, quality control issues during manufacturing or transport to the field, and operational aspects like reliability, availability, communication, and easy calibration are of importance. An existing guideline from 2013 [23] do not distinguish between heliostat field and tower performance in the acceptance test procedure which may cause difficulties in the case heliostat provider and owner are unable to validate the contractually agreed performance requirements. To solve this gap, the Heliostat Field Performance Testing Guideline is under development. It addresses the challenge of objectively and practically assessing large-scale heliostat field performance for industrial acceptance tests. It is accessible as a German draft (national draft v1.0) and will undergo international revision within the SolarPACES community in autumn 2023. This guideline needs reliable, accurate and fast measurement techniques for heliostat characterization which have been described in the chapters before.

Further guidelines are identified as necessary. One outcome of the final project workshop was to establish a guideline of best practices for heliostat manufacturing quality control. This is because, in some projects, the quality control during the manufacturing process of a heliostat field can still be enhanced. Frequently, not all available quality control measurements in the whole heliostat production chain are used. This heliostat manufacturing quality control should prevent mediocre heliostat fields. In addition to those guidelines, the HelioCon roadmap also identified the need for standards in other characterization areas [24].

3. Ongoing work and future collaboration

The current collaboration initially proposed a technical in-depth comparison of the different techniques devoted to solar field testing; however, it was found that it was not feasible with the time and budget available. The community however is engaged and has prepared follow-up work to progress on that front. Based on this project, a joint effort has been proposed whose first step will be the definition of the different methodologies characteristics to be shared among the participants and the definition of a common scenario to ensure they are comparable.

The future comparison efforts are planned to demonstrate the capabilities of the evaluated and compared methodologies against a standard case and help to pave the way towards a technical recommendation on solar field performance analysis applicable at the industrial level.

The best way to perform a comparison exercise is via round-robin testing, ideally in the same installations and using the same heliostat or group of heliostats. This can be costly and challenging. As an alternative, the comparison can be successfully built based on hardware verification, using setups that do not depend on heliostats specifically, and software verification, using heliostat-specific data.

As previously mentioned, one of the main difficulties found was the ability to compare all methodologies since there is a wide variety of approaches for each of the categories, so a standard taxonomy used universally to classify the methods developed is needed. This taxonomy will point towards:

- A base case for verification purposes
- A set of parameters that need to be obtained from the measurements for inter-comparison in a round-robin setup.
- The type of hardware verification that should be performed on the system components.
- The possibility to perform software verification independently of hardware verification and what dataset to use.

This is a non-negligible effort that requires some commitment from the participants. In order to define how much resources are needed, the group is defining technical requirements, costs, time and resources available and needed for a round-robin testing program at heliostat field research facilities (eg. Sandia, PSA, IMDEA Energy, CSIRO, CyI, PROMES, Julich, etc.). As it would require the coordination of 11 research centers from 5 different, and more importantly, very distant countries, the team will search for continued funding to continue working on enabling the CSP technology to take a truly significant step forward in its journey towards the important role in the decarbonisation that it is yet to play.

4. Conclusions

This project is a coordinated work carried out by 11 research centers from 5 different and distant countries, with the collaboration and support of 8 companies from 4 different countries, showing that the CSP community can work together to bring our energy generation technology to higher levels of reliability.

This common effort has resulted in a qualitative analysis of different techniques devoted to testing the solar field of central receiver systems, showing the difficulty to make them comparable. During the workshops and discussions for this project, several gaps were identified.

There is common agreement for the need of the CSP Industry to face quality control and monitoring of operating fields in actual operating conditions, to ensure reliability, durability and long-term performance of solar tower technology.

Although there are many methodologies to perform quality control on heliostat at the different stages (heliostat development, mass manufacturing & qualification, solar field development, commissioning, operation & monitoring), the implementation of these techniques by industry needs to be improved. Additional collaboration efforts should be facilitated between R&D Centers & Industry to increase and improve quality control. Only by doing this it will be possible to ensure solar towers reliability and long-term performance, while increasing the confidence of investors and the general public in the technology.

This will pave the way to facilitate the deployment of solar towers as a confident, dispatchable and environmentally friendly renewable energy option.

The basis for a further collaboration beyond the end of this project have been established. The efforts are now focused on the development of protocols dedicated to the evaluation and validation of metrology tools together with the industry. This also includes transversal aspects and shared commonalities between tool sets and approaches.

Data availability statement

All the information accessed to produce this review and comparison article has been provided by the project participants and is accessible mainly in the referred articles of each methodology, listed as part of the References section.

Author contributions

The authors confirm contribution to the paper as follows: project administration: Marcelino Sánchez; conceptualization: Marcelino Sánchez; data curation: Kenneth M. Armijo, Charles-Alexis Asselineau, Guangdong Zhu, Cristóbal Villasante and Rafael Monterreal; writing – original draft: Adrián Peña-Lapuente; Kenneth M. Armijo; Charles-Alexis Asselineau; All authors have participated in data collection, reviewing the results and approving the final version of the manuscript.

Competing interests

The authors and all the project participants have contributed the information about the methodologies developed by their respective institutions, which are the owners of the intellectual property of said methodologies and/or beneficiaries of the revenues generated by the commercialization of the associated devices or services.

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