SolarPACES Task III Project: Analyze Heliostat Field

Project Conclusions, Results of a Qualitative Comparison of Solar Field Evaluation Methodologies and Next Steps to Further Improve the Solar Central Receiver Technology

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Abstract: This report summarizes the conclusions reached along the SolarPACES funded project called "Analyze Heliostat Field", framed into the "SolarPACES Task III: Solar Technology and Advanced Applications", This investigation funds the basis for the development of a necessary Commercial Solar Field Testing Guideline and offers a comprehensive protocol for evaluating and validating metrology tool prototypes and techniques for heliostats. This work provides a wide-ranging overview of various optical metrology techniques and technologies employed to improve heliostat performance. This review is intended to expose the state-of-the-art in optical metrology tools within each step of a heliostat development cycle: A. heliostat research and development (R&D), B. Mass manufacturing and qualification and C. Solar field deployments. This report is intended to provide a reference document representing the current consensus among experts, and guidance for the entire heliostat community. The ultimate goal of this effort is to contribute to address the optical metrology gaps to further reduce commercial risks for CSP technologies. It will support the industry and research communities to develop competitive future heliostat technologies. The project work summarized in this document contributes to this goal via: 1. Characterization and development guidelines and standards information, 2. Contribution of a comprehensive reference document that will be publicly available, and easily accessible for the CSP industry and 3. Federation of an engaged, active heliostat community to further advance heliostat optical metrology technologies.

Keywords: Heliostats, Characterization, Calibration, Flux Mapping, Guidelines

1. Introduction

Optical metrology of individual heliostats and collective heliostat fields requires the application of measurement techniques for performance assessment and quality control. The use of accurate aiming strategies for single or collective groups of heliostats on a concentrating solar power (CSP), or thermal (CST) receiver, is critical for the economical and safe operation of any CSP/T system. High concentration and temperature CSP/T technologies require high optical accuracy. Techno-economical trade-offs generally lead to large CSP/T heliostat fields for commercial applications and many metrology techniques are confronted with a variety of challenges, which include dynamic and localized environmental impacts. Among the challenges faced by heliostat metrology systems are:

- **Scale:** measuring heliostat field systems that are distributed over expansive land areas exceeding multiple square kilometers, with long optical focal lengths of over a kilometer.
- **Environmental factors:** accurately operate under challenging environmental conditions such as dust, wind loads and temperature fluctuations; with overhead solar flux hazards.
- **Challenging performance requirements:** Heliostats must deliver optical accuracy of order of milliradians magnitude to allow acceptable system performance. This performance is subject to dynamic factors such as soiling light scattering, atmospheric attenuation or gravity loading for large heliostats,
- **Reliability:** to achieve overall CSP/T commercial plant service lifetimes of at least 30 years, reliability of components and that ability to maintain consistent metrological quality is important. Reliable inspections of hundreds to thousands of heliostats to detect optical errors and defects, requiring maintenance and replacement, ultimately impact operations and maintenance (O&M) costs.

To achieve this goal, R&D centers, supported by industrial stakeholders, have developed and released innovative methodologies during the last few years. Their developments result in a range of 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.

This document provides a review, comparison, and discussion about the advantages and disadvantages of a comprehensive number of optical metrology technologies and characterization procedures for commercial heliostat fields. The short-term objectives of this effort are to review, discuss and analyze existing problems and concerns in current heliostat fields with a strong participation of industrial stakeholders. In this sense, a common framework, parameters to measure and figures of merit have been proposed during the first stages of the project. Additionally, a questionnaire has been developed to inquire about the state of the Central Receiver Solar technology to actors of different segments of the industrial and research fields of this technology. The results of this survey will lead to a better knowledge about the actual needs and feelings of those who oversee final deployments of this technology. This survey serves as a support for the conclusions obtained from the panel discussion held during the meeting celebrated in Almería as part of this project as the participation of the industry was encouraged, and some interesting feedback content was generated.

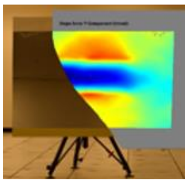
2. Heliostat Development Metrology

2.1 Industrial Tools & Techniques

Heliostat analysis tools and metrology techniques are used to calculate and validate errors and optical quality during different stages of the heliostat development cycle. Zhu et al. provided an analysis of heliostat metrology and technological gaps impacting heliostat field costs and bankability as part of the DOE Heliostat consortium (HelioCon) gap analysis exercise [1]. However, a more detailed review with specific focus on of optical metrology tools and techniques is still needed particularly with regard to standardization and qualification at the various stages of the heliostat development cycle. The tools reviewed are at varying technology readiness level (TRL) design and address several stages of the heliostat development cycle, from R&D development to later stage field deployments and monitoring. To adequately classify the current optical metrology tools, as well as the state-of-the-art techniques to qualify errors and performance, this study has identified three primary stages below: A. Heliostat R&D, B. Mass Manufacturing and C. Solar Field. Both Heliostat R&D and the Solar Field topic areas have multiple subcategories due to further detailed, unique requirements of optical metrology characterization.

- **A1. Heliostat R&D: 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. Heliostat R&D: 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.
- **C1. Solar Field: Deployment & Commissioning.** This stage includes heliostat field construction and quality control.
- **C2. Solar Field: Solar Operations & Monitoring.** This stage includes heliostat field O&M, commercial project management, and end-of-life treatment.

Table 1. Heliostat development cycle breakdown for optical metrology tools and techniques.

	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
Heliostat Analysis Development Cycle					

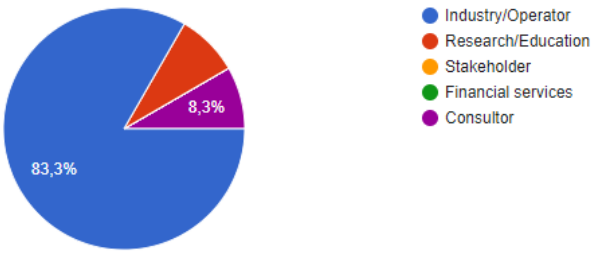
Within this framework, the various tools as well as analytical and qualification techniques are regrouped in four primary topic areas: 1. Guidelines & Standards, 2. Heliostat Characterization, 3. Flux Measurement and 4. Heliostat Calibration. This overall metrology assessment can then help identify gap areas for improvement and allow more detailed techno-economic analysis (TEA) costing of qualification impacts for improved bankability and industry adoption.

2.2 Workshop Industrial Survey

As part of this SolarPACES Task III “Solar Technology and Advanced Applications” effort, an international workshop was held at the Plataforma Solar de Almería (PSA) on 13 June 2023. For this event, the project partners invited relevant actors from the CSP industry to held an open discussion about the state of the CSP technology and their point of view about the difficulties that this technology is having to penetrate in the global energy mix.

As part of the workshop a complimentary survey was facilitated to members of the industrial CSP community. The main idea of this survey was to gather thoughts by non-research community members about the state of heliostat technology as a whole, and in particular, about the state of the solar field analysis technologies. A breakdown of the surveyed groups can be seen in Figure 1 where a majority of respondents from the CSP industry or were operators of commercial sites. Although the target of this survey was the industrial sector of the CSP community, and almost all the surveyed companies responded the survey, most of those companies being main players in the European and Arab CSP industry, the resulting sample is low. Since this group aims to publish a quality journal paper with impactful results of the project and collaborations, it is planned to increase the sample of respondents, and subsequent value of the survey. Results from survey questions can be seen in Appendix A.

Question
What is your background?
Results



Responses to the survey: 10

- Industry/Operator: 8
- Research/Education: 1
- Stakeholder: 0
- Financial services: 0
- Consultants: 1

Figure 1. Breakdown of Survey Responders

Findings from the survey results in Appendix A will be described as follows: One of the main concerns that the CSP industry have is the large CAPEX and OPEX costs of solar tower power plants (Figure A3). Although the survey results states that large investments and poor performance and reliability are slightly more important factors to explain the low central receiver technology deployment (see Figure A1), the conclusions obtained from the discussion held during the workshop points towards that the main problem encountered for investor adoption and deployment of new tower plants is that the component costs are very high. This makes it difficult for CSP companies to make the commitment to build new plants. With this, it is noted that in order to facilitate the integration of new systems in the plants (such as those developed by the members of this consortium), the impact that heliostat characterization challenges have on the costs on plants must be emphasized. The survey results also highlight the difficulties for companies to rely on systems whose impact on costs has not been practically demonstrated in plants. However, risks in a plant also increase costs due to higher financing costs and higher safety margins that move the operations of the plant away from its optimal design points. Then, improving the reliability of the different subsystems that form the whole plant and their joint interaction can improve the operation of the plant, increasing electricity production and subsequent potential revenues. Furthermore, cost reduction is not easy due to the price of materials (steel, foundations, etc.) which may not be reduced. Therefore, to reduce costs of subsystems, component designs may have to be modified to make them lighter (for example), which would potentially make them less accurate and less robust. The approach for improving the efficiency of the plant is focused on trying to increase the economic return of the plant from the same investment/cost.

Another fact related to costs is that each plant is different, and consequently plant components are specifically designed for each individual project. This entails a series of costs that are incurred again and again with each design being performed in a systematic way, and where economies of scale for manufacturing critical components cannot be applied. It is noted that one option that may reduce costs is the design of multi-tower plants, as they allow for greater standardization of designs and reuse of the same design several times by having several towers. In addition, due to more reduced solar fields, multi-tower facilities could lower the optical demand for heliostats and therefore their cost.

An important amount of the plant cost is dedicated to the construction and commissioning of the solar field, which amounts between 40-50% of the total cost of a solar tower power plant. This makes it crucial to find ways to reduce this, because this would have a major impact on the total cost of a plant (Figure A3). But during the different discussion forums/modalities (mainly survey, workshops and e-mail reactions to the survey), industrial companies stated that the heliostat field for a power tower is not considered to be a priority for investigation (Figure A2), as it is a reliable component today that is close to the physical limit of accuracy it can achieve, and basically only the development of methods to calibrate the heliostat pointing of a field in a reduced time, mainly for the assembly and commissioning phases of the plant, should be matter of study, but just a secondary one.

When speaking about methodologies intended to characterize the reflective surface of heliostats, an important feature would be the ability to characterize the solar field in a quick way, in addition to being non-intrusive for the rest of the plant operation task (Figure A9). The same conclusions can be obtained for the tracking accuracy measurement techniques (Figure A10), but in this case, the overall quality of the measurement seems to have a role nearly as important as the speed and intrusiveness of the measurement technique for the respondants of the survey.

In addition, some respondants to the survey questions appeared to not perceive CSP power towers the market as a reliable technology, not only because of previous plant failures generally, but specifically because of the issues with salt tanks, so it is absolutely essential to do more research on the design of hot tanks of power tower plants. Some survey respondants considered this to be more of a priority than the heliostat field. It was commented that the future of CSP is indubitably linked to its capacity to dispatch energy on demand thanks to the storage. Therefore, the recurring reported failures on the molten salt tanks and other systems in contact with the HTF should be thoughtfully addressed in order to demonstrate that CSP can offer a robust and reliable energy storage buffer to the system.

With respect to the collaboration between all the CSP field research institutions and industrial, survey results indicated that large companies are typically the ones who would have to take on risk burdens to introduce new developments in the CSP market, since they are the ones who have the financial capacity to assume risks. But they are not the ones who decide whether to implement new devices or methodologies in commercial plants; it is the final operator of the plant who should be convinced by the developers of novel devices and methodologies to implement those new functionalities.

In order to boost the collaboration between companies and research centers, it would be important to involve the CSP industry in the forums that the research community organizes, such as that of the SolarPACES Task III group at the PSA in 2023. But it is difficult to involve companies due to their own inertias. For example, it is difficult for CSP companies involved in the deployment of power plants to advise technology laboratories about the problems, failures, difficulties, etc. that they really encounter due to their information management policies. It is therefore sometimes difficult to evaluate the situation and promote new solutions by these centers.

Following this line, the possibility of a public database with plant operation data was raised, with measurements taken by different systems, which the companies operating the plants could make available (anonymously) to the research centers so that they could carry out system development tasks more efficiently. It would also serve to provide centers that do not have access to neither testing nor commercial facilities, with data on which they could work to develop new equipment/methodologies/systems.

Finally, results also indicated that the size of heliostat field today is primarily focused on large sizes, however multitower is an option not much explored. This could lower the optical demand for the heliostats and also the cost. Not directly related to the heliostat field, but worth mentioning, the recurring problems with the plant subsystems in contact with the high temperature molten salt. The future of CSP is indubitably linked to its capacity to dispatch energy on demand thanks to the storage. Therefore, the recurring reported failures on the molten salt tanks and other systems in contact with the HTF should be thoughtfully addressed in order to demonstrate that CSP can offer a robust and reliable energy storage buffer to the system.

3. Guidelines & Standards

The SolarPACES task III currently works on three different guidelines, each having its own level of completeness, see also [2]:

- SolarPACES Heliostat Performance Testing Guideline (version 1.0 launched, provided to IEC-117) [3]
- SolarPACES Heliostat Field Performance Testing Guideline [4] (draft version being sent to task III in Oct. 2023)
- Heliostat Wind Load Design Guideline (first calculation sheet downloadable [5])

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 heliostat performance testing guideline defines parameters and proposes methods to measure them. It standardizes the content of test certificates issued by different qualification centers, thereby enhancing the bankability of heliostats in the industry. The Heliostat Performance Guideline has been applied several times in research and industry. After an international review phase starting in 2012, version 1.0 was launched on 30.05.23. It is currently being integrated into the IEC-TC-117 62862-4-3 standardization activity.

The total energy provided to the receiver is generated 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 [6] 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 underwent international revision within the SolarPACES community in autumn 2023.

The Heliostat Wind Load Design Guideline will improve and unify heliostat wind load design methods as a basis for a heliostat specific engineering code. Both wind-tunnel testing and currently in-situ measurements on real-scale heliostats have been and are being performed, e.g. [7, 8, 9, 10]. A first draft calculation sheet based on wind-tunnel testing of the University of Adelaide is available for download [11].

Both the Heliostat Performance Testing Guideline and the Heliostat Field Performance Testing Guideline require reliable, accurate and fast measurement techniques to characterize individual heliostats or whole heliostat field in an efficient manner. During the last few years, R&D centers, with the consensus of the most relevant industrial stakeholders, have developed and released innovative methodologies to properly monitor the solar field of a plant during its operation. These methodologies were compared and the results were discussed during a workshop celebrated the 13th and 14th of June 2023, in which industry stakeholders were actively participating with the intention to determine weaknesses and technology gaps left by current CSP system developments that still have to be addressed or improved.

Additional guidelines related to heliostat metrology are identified as necessary, such as a guideline of best practices for heliostat manufacturing quality control, which appears to be sometimes lacking in the industry. Enhanced heliostat manufacturing quality control should contribute to avoid underperforming heliostat fields. In addition to these guidelines, the HelioCon roadmap also identified the need for standards in other characterization areas [1].

4. Heliostat Surface Characterization

The heliostat concentrator has been traditionally characterized by comparing 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 and given for a particular time-dependent configuration, i.e. at a determined heliostat orientation, temperature and wind speed. The heliostat characterization tools and techniques evaluate din this project are presented in Table B1 in Appendix B.

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. Such flux map-based methods are labelled “Inverse methods” in the table in appendix.

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. This requires discrete objects to be imaged (punctual light sources, projected images or patterns) to identify the light path between a source and a target and infer the normal deviations at these points. While this is typically done with Lambertian targets, it can also be realized using cameras looking into the facets to directly intercept the reflection. Additionally, direct measurement of a surface shape is also possible, for example using photogrammetry or contact probes, however this is not directly covered in Table A1.

During the development of this project, a series of 8 techniques have been proposed to be included in the comparison: PSA-HPCS (CIEMAT/PSA) [16], NIO (NREL) [17], Helioschar+ (CENER) [18], SOFAST-BCS (SANDIA), ANU’s BCS+, CyI technique [19], QDEC-H (CSP Services + DLR) [20] and TEKNIKER’s Autocollimator technique [21].

The techniques that are heavily based on the BCS system working principle (PSA-HPCS and ANU’s BCS+) obtain the heliostat beam image, process it and then simulate iteratively the solar beam of heliostat surfaces with different errors until they reach a good solar beam approximation. Then, the surface that has produced that solar beam is defined as the best approximation to the actual heliostat surface. Other techniques (Helioschar+, through a scanner-based process and direct detection of flux, and SOFAST-BCS, in a similar way as the BCS system) obtain the heliostat beam and the heliostat surface separately, using the information of the heliostat beam to reduce the uncertainties in the estimation of the normal through the heliostat surface. Most of the remaining techniques are based on deflectometry (NIO, SOFAST-BCS, CyI and QDec-H) and obtain the heliostat surface normal deviations by measuring the deformation of known patterns, objects and/or light sources directly (looking into the heliostat with a camera) or indirectly (looking at the reflection on a target). Finally, there is another technique based on autocollimators that measures the deviation of different discrete points of the surface of the facet specially focused on the characterization process integrated in the assembly lines to measure the geometry of the facets.

5. Flux Measurement

The evaluation of the joint performance of the whole solar field can help to avoid uneven distribution of solar radiation that can cause accelerated aging of the receiver and lead to high heat losses, increased maintenance expenses and economic losses due to reduced operating time. This is usually done through flux mapping, i.e. measuring the incident flux on the receiver or receiver vicinity, leading to evaluation of possible hotspots and uneven flux distributions. This then provides information about the suitability of the selected aiming strategy and provides a reliable measure of the net incident power on the receiver, so that the efficiency of the optical subsystem of a CSP system can be reliably assessed.The state-of-the-art in this category is the moving bar, which is very challenging to scale-up for large receiver sizes, and adds 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 [22].

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-field 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), established previously using radiometers or other sensors, is used to determine the incident flux. Known issue of flux measurement with a BCS is that radiometer materials and thermal management systems can be fragile and challenging to accurately calibrate, however presently there are no real practical alternatives to date. In addition, measurement precision can be challenging with respect to camera selection, pixilation and light attenuation, among others.

New developments have been suggested in this topic, and overall, all of them are upgraded versions or modifications 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 [23].

A review of several novel flux measurement techniques is presented in Table B1 in Appendix C. In the area of flux measurement, the recommended R&D focus is as follows:

- 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 model in the loop to understand the optical properties of receivers.
- Combine measurements from several sensors and sensor types to reduce uncertainty. This could also include the convolution of infrared (IR) imaging.
- Advanced predictive modelling based on machine learning data of beam profiles, used to upgrade BCS imaging.

6. Heliostat Tracking Accuracy

Tracking accuracy is defined as the standard deviation of an experimental probability distribution describing the angular deviations of the heliostat reflected beam from its nominal aiming set point direction, during a certain time period of the day. This parameter should be assessed with numerous samples considering both motion axes across a wide enough range of the heliostat's useful working envelope in its configuration space.

Measuring tracking errors is the key to correcting them and improving heliostat performance. The BCS is the method commonly used at industrial scale plants to acquire heliostat pointing errors, then used to calibrate the heliostat tracking actuators, but it has significant drawbacks. Using the BCS for tracking calibration purposes is slow since individual heliostats need to be processed one-by-one on an independent and isolated beam target to define the actual heliostat orientation for each day and hour of interest. Furthermore, determining the error for a particular orientation only allows correcting an offset that will be valid for that orientation but not necessarily for all other orientations of the heliostat. To calibrate the tracking system, measurements must be made in multiple orientations and a model of the heliostat kinematics must be defined and tuned using all the actual orientations measured.

Within this project, several alternative techniques that allow the determination of the actual kinematic model with higher accuracy and shorter time were reviewed and outlined in Table D1 in

Appendix D, where the colour of the columns try to organize the different techniques by the similarity of their measurement basis. Detailed information on definitions as well as descriptions of a number of calibration techniques can be found at [24]. There are several heliostat kinematic models used, however, the details were not investigated in the framework of this project. In the literature, artificial intelligence (AI) has recently been used for this successfully.

Some of the techniques discussed are based on the BCS but attempt to overcome some of its limitations. For example, using the BCS system for heliostat tracking calibration usually requires a good quality flux map measurement to accurately determine a reliable pointing direction, but this is not always possible, especially for heliostats far from the target. The ANU´s BCS+ [25] method addresses the problem of flux map overflow on the screen using a technique that stitches together several images, while the Heliochart+ method proposes the measurement of the flux map by means of a highly sensitive array of photosensors and cameras. IMDEA´s BCS+ technique uses an additional sensor (inclinometer) to add information in the post-processing stage.

Recently, non-flux-map based methods have been proposed to facilitate the calibration of heliostats faster than with BCS, each using a unique approach and different equipment.

The SHORT method (TEKNIKER + CENER) [26] uses low-cost cameras mounted on each heliostat which are used to observe a number of targets with known positions distributed throughout the solar field. During the calibration, the heliostat is moved to sequentially capture such targets with the camera. Once sufficient observations are made, the actual parameters of the kinematic model of the heliostat are adjusted through an iterative optimization process.

HelioPoint (DLR) [27] uses the law of reflection to determine the heliostat's orientation using a powerful LED and a camera, which are installed on a drone (UAV). When the drone is positioned close to the optical axis of a heliostat, the reflection of the LED on the heliostat surface is seen by the camera. The local orientation of the heliostat surface at the detected reflection point is then determined by known positions of the heliostat, and of the drone (which determines the position of the camera and LED). By sampling several local orientations distributed over the heliostat surface, the orientation of the reflector can be deduced. For a fast calibration, the heliostats can be measured in groups.

The HelioControl (Fh-ISE) [28] method introduces a small periodic movement with different frequencies on a number of heliostats during normal operation and observes the receiver with a high dynamic range camera. The system tries to identify the slight focal spot fluctuations around the actual aiming point using frequency analysis.

The NIO (NREL) and UFACET (SANDIA) methods capture with a drone-mounted camera the reflection of an object (typically the central tower) on the heliostat and apply image post-processing techniques to determine the actual orientation of the heliostats.

Other methods referred to earlier, such as SOFAST or QDEC could give information on the orientation of the heliostat using a fixed camera on the tower but they would in principle only provide information for one orientation and could therefore only correct the offset in one position.

7. Continued Optical Metrology Development

7.1 Discussion

From this investigation further effort is still required to directly compare the output of all methods surveyed. A gap identified here was a lack of standard vocabulary and a standardized process for assessing all heliostat characterization methods. Work is on-going to regroup the described methodologies into several categories that can potentially be able to be tested together, either individually as part of round-robin investigations.

It was also determined that for varying characterization and calibration approaches, camera types and techniques can differ significantly. Different camera types perform very differently in different conditions. A first step of this inter-comparison exercise would be to cross validate the usage and response of the sensors used. Presently, there is no readily available information about the specific sensors required for some of these techniques and there is no standard dataset that could be used to validate data processing routines.

The BCS i.e. the "camera-image" method, is the standard tool for both heliostat tracking calibration and flux mapping. There are a number of BCS limitations identified by the proponents of new methods, which have indicated that operations can be relatively slow and inaccurate for distant heliostats, and sensitive to atmospheric environmental conditions which can introduce error. Additionally, it can only be used when the conditions are met for a plant in operation, requiring potential downtime of heliostats during daylight conditions.

The standard method for heliostat shape deformation is deflectometry which is accurate and efficient but requires specific equipment and can only work in the dark (at night typically). Inter-comparison for this system is needed, which could be facilitated through round-robin testing. However, for heliostat fields and the necessary equipment mentioned, this can be costly and challenging. An alternative for successful intercomparison could be built on two aspects: 1. Hardware verification and 2. Software verification. For hardware verification, all sensors used can theoretically be verified using setups that do not depend on heliostats specifically. There are certainly some standards related to camera and flux sensor calibration. For software verification, (i.e. post processing of data) this step would require heliostat-specific data, which could be leveraged in the form of training data and machine learning. A need was also identified in this work for a standard taxonomy developed to universally classify the methods developed. This taxonomy would help provide a set of parameters for standardized measurements and inter-comparisons. A standardized taxonomy would also support hardware verification that should be performed on the system components, and the ability to perform software verification independently of hardware verification and what dataset to use. Examples of items for a proposed standardized taxonomy may include:

- Tasks performed: Tracking calibration, surface characterization and flux-mapping categories.
- Hardware used: Light-source, Cameras (including sensor type, resolution requirements, optics, filters and metadata necessary, etc.) and other sensors (e.g. Gardon thermopile sensors). Specific installation and/or mounting tolerances.
- Target-based method (indirect imaging) or heliostat image-based method (direct imaging).
- Post-processing requirements: software and hardware. Open or closed software.

For this effort, the team plans to continue to determine technical requirements, costs, time and resources needed for a round-robin testing program at heliostat field research facilities (e.g. Sandia, PSA, IMDEA Energy, CSIRO, CyI, PROMES, DLR Julich, etc.). This effort would establish results requirement tables for each task, considering round robin testing limitations. Work is still needed to for hardware verification to establish a detailed list of the types of sensors, filters, light sources and other equipment used by the methods proposed, and look for relevant standards related to performance and calibration testing, or calibration references. This would be particularly necessary for the cases where there are no suitable standards to determine adapted methodologies. This would allow for suitable testing protocols pertaining to all heliostat measurement components and configurations. Additionally, further software verification will need to be facilitated. For flux map-based methods the BCS and other flux map-based post-processing techniques will need to be compared by sharing standardized flux map data and all necessary information for a few down-selected test cases. Additionally, flux map-based options can be tested against synthetic datasets generated from raytracing. Sun reflection imaging methods may also be used to assess sun of heliostat nearest-neighbor reflections by using strategically placed cameras to perform the intercomparisons. The utilization of pattern/artificial light source reflection methods can also be employed that rely on specific patterns, objects or light sources reflected by the heliostat. These are typically difficult to inter-compare based on standard data and will most certainly require physical round-robin testing. Another approach would be the use of synthetic experimental datasets, which would use raytracing to generate simplified synthetic datasets that can be used for the purpose of software development and verification. Overall, a need for further scientific research and development is required for the development of optical metrology characterization techniques and tools.

8. Conclusions

A detailed Heliostat Performance testing guideline report has been developed that offers a comprehensive review of current optical metrology tools and techniques and provides the current consensus among experts on the topic. This review specifically distinguishes between heliostat metrology guidelines, characterization, flux measurement and tracking calibration. This document also reports on an initial survey to industrial stakeholders on the topic of heliostat metrology, highlighting several key aspects hindering CSP technologies development. Among these, heliostat metrology does not appear as a general priority for the surveyed industrial actors, however, the link between heliostat metrology and overall plant performance, financing and reliability is not clearly expressed either. This link is better understood at the research and R&D level and its impacts appears underestimated. Although the main concerns that the CSP industry have is the large CAPEX and OPEX cost of Solar Tower power plants, there is a great consensus from the R&D community regarding the crucial importance of improving quality control on commercial CSP power plants to improve reliability and performance while attracting investors and reducing costs.

Reliability is a cornerstone of any successful energy project, and CSP is no exception. Quality control processes ensure that components, such as mirrors, receivers, and thermal storage systems, meet stringent standards. Consistent manufacturing quality and adherence to design specifications are essential for minimizing downtime and maximizing the lifespan of CSP plants. Reliability is not only about maintaining consistent output but also mitigating the risks associated with equipment failure, which is crucial for fostering investor confidence.

Performance optimization is another key aspect tied to quality control. By ensuring that every component operates at its peak efficiency, quality control measures contribute to the overall performance of the CSP system. This optimization not only increases energy yields but also enhances the economic viability of CSP projects, making them more attractive to investors.

There are several methodologies available for analyzing the actual quality and performance of heliostat fields, although these methodologies are at different development stages, their practical implementation can effectively contribute to improve quality control in actual commercial power plants. However, there are several barriers that make difficult, and even sometime impossible, to implement these technologies specially during the phases of construction, deployment, commissioning, operation, and monitoring under the real boundary conditions facing by EPC constructors and owners along CSP project development.

Within these barriers we can highlight: the very tight execution schedules and, the lack of clear protocols that facilitate the implementation of these methodologies along CSP Project development in an easy way. Heliostat field analysis methodologies should provide EPCs and owners with useful and accurate information in time. In time to be able to make relevant decisions to ensure the quality of the plant, not only during its construction but throughout its lifetime. This information must include not only quality control, but also corrective measures to improve quality and performance.

Future work would lead to the development of processes to evaluate and validate metrology tool prototypes and techniques for heliostats. This would also include transversal aspects and shared commonalities between tool sets and approaches.

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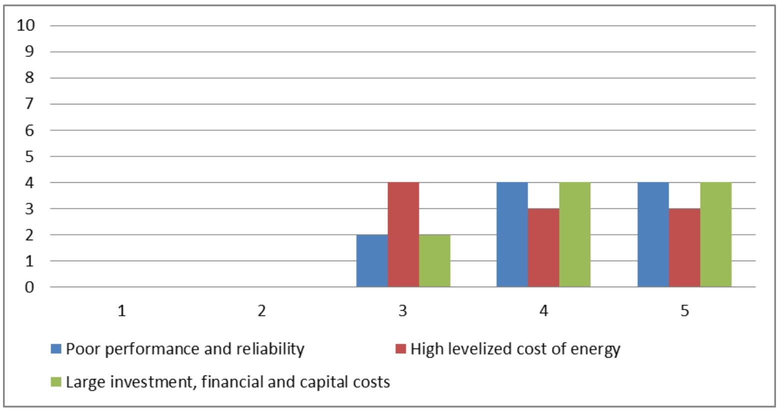
Appendix A. CSP Survey Question Results

Question

The generation of energy by CSP technologies is below the estimations made by the IEA to achieve the Net Zero power generation in 2030. Specifically, the deployment of central receiver technology, technology that has always been shown as the most promising one, does not end to take off.

From your point of view, rate the following factors as the causes of that.

Results



Mean:

- Poor performance and reliability: 4.2
- High levelized cost of energy: 3.9
- Large investment, financial and capital costs: 4.2

Others:

- Too many problems on the existing plants generated very low confidence.
- Too large-scale systems.
- Long implementation (construction schedule), low redundancy (receiver, steam generator, turbine...), no capital attraction (mass scale production/fabrication).

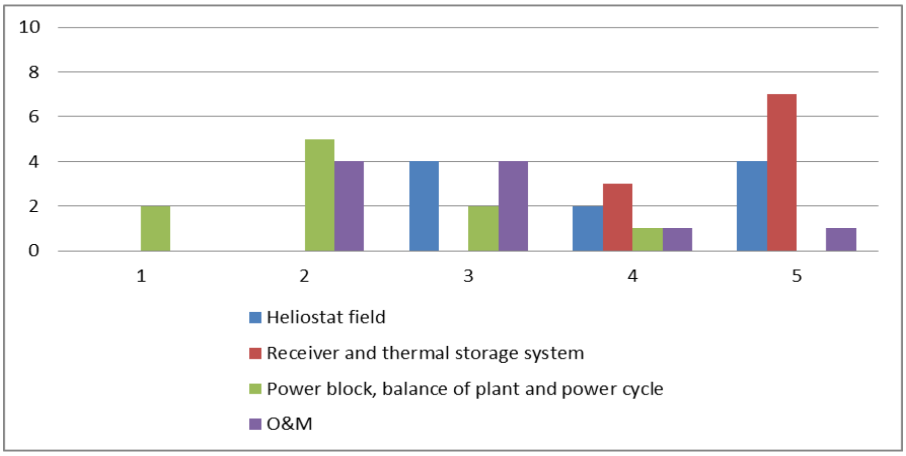
Figure A1. Survey Responses – CSP Adoption Factors

Question

In the central receiver technology, there are many systems that work all together to gather the sun's energy and transform it into electricity. In the pathway to make this technology more competitive.

Rate which of the following of those systems the efforts should be more focused on.

Results



Mean:

- Heliostat field: 4
- Receiver and thermal storage system: 4.7
- Power block, balance of plant and power cycle: 2.2
- O&M: 2.9

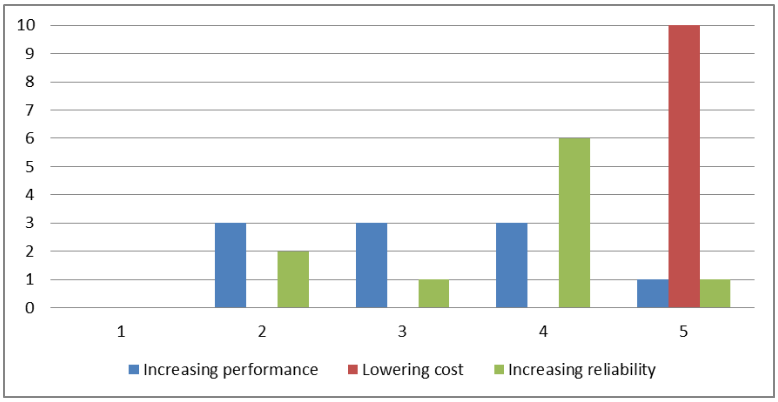
Figure A2. Survey Responses – CSP Competitive Factors

Question

The heliostat field accounts for a major part of the cost of a central receiver plant (around 40%) and is one of the key actors involved in the overall performance and efficiency of the plants. There are several features that are leading the development and setting the pathway of the heliostat technology.

Rate them by their importance.

Results



Mean:

- Increasing performance: 3.2
- Lowering cost: 5
- Increasing reliability: 3.6

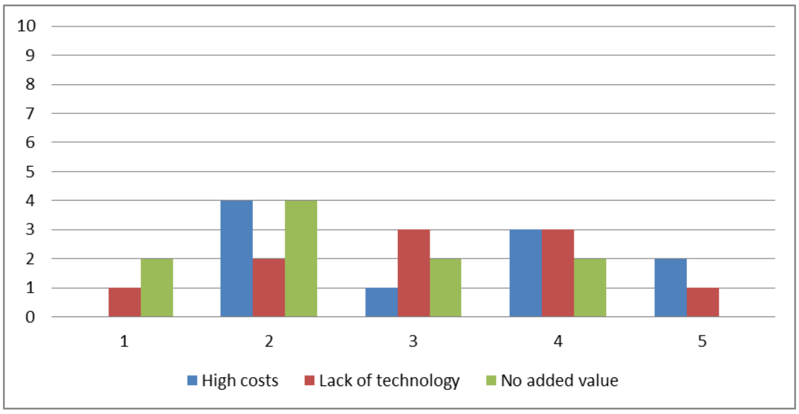
Figure A3. Survey Responses – CSP Adoption Features

Question

The heliostat field is poorly monitored. There is no knowledge about key metrics that directly affect the performance of the field and the generated density flux map over the receiver during operation, e.g. the reflectance of the heliostats, their aiming points, the canting of the facets, etc.

From your point of view, rate the following factors as the causes of that situation.

Results



Mean:

- High costs: 3.3
- Lack of technology: 3.1
- No added value: 2.4

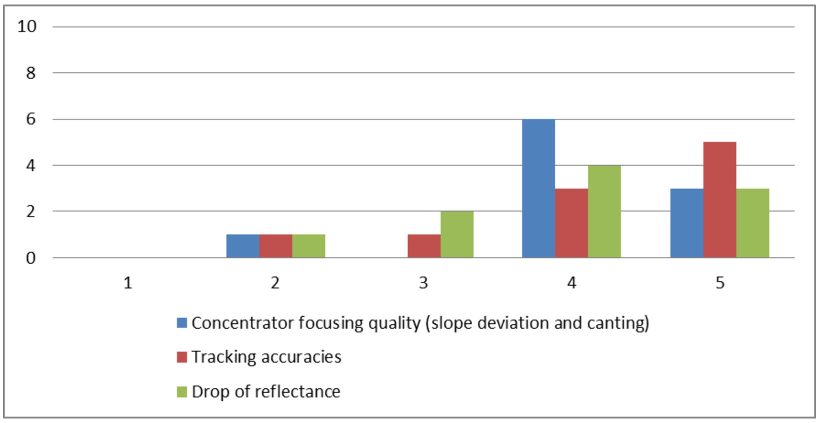
Figure A4. Survey Responses – Heliostat Monitoring Challenges

Question

The key metrics that usually characterize a heliostat are the concentrator focusing quality, the tracking accuracies and the drop of reflectance by soiling or degradation.

Rate them by their priority to be measured and under control in a heliostat field of a plant.

Results



Mean:

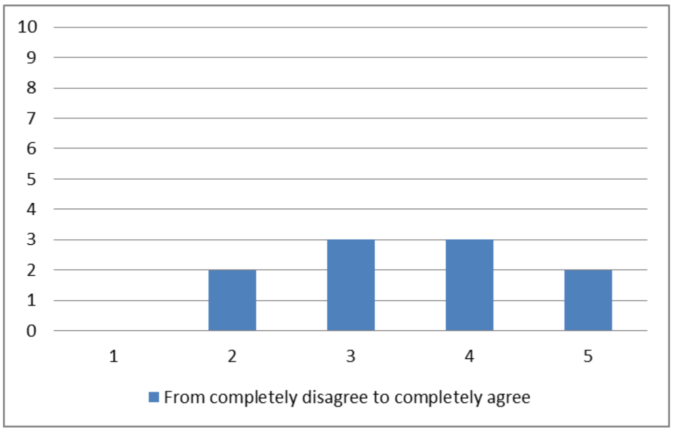
- Concentrator focusing quality (slope deviation and canting): 4.1
- Tracking accuracies: 4.2
- Drop of reflectance: 3.9

Figure A5. Survey Responses – Heliostat Characterization Priorities

Question

The operation of the heliostat field is a very challenging task due to the fact that it is influenced by many external and non-controllable conditions such as wind, DNI variability, etc., and by the uncertainties in the performance of the heliostat field. As consequence, it is not automatized and usually relies on human expertise and decisions.
Rate the degree of agreement with this sentence.

Results



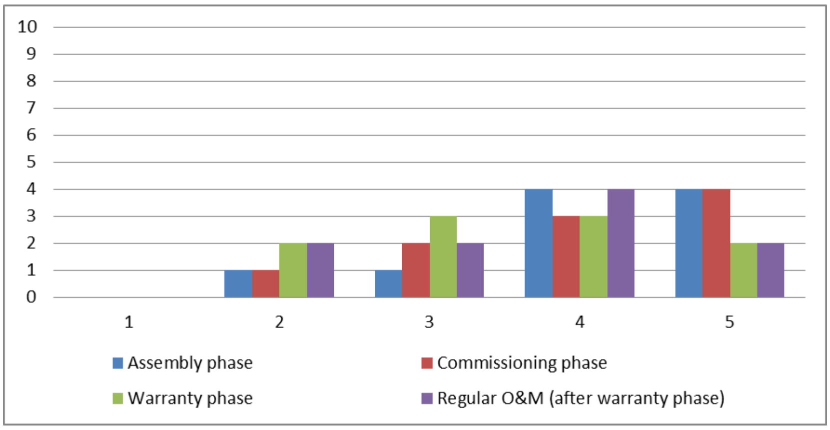
Mean:
From completely disagree to completely agree: 3.5

Figure A6. Survey Responses – Heliostat Monitoring Challenges

Question

The correct assessment of the heliostat field is very important during operation for running the plant close to the maximum performance point; however, it could be even more important during assembly and commissioning phases to accelerate and boost the deployment of the solar field.
If a system to measure the key metrics was available, rate how interesting would be to apply it in the following stages.

Results



Mean:

- Assembly phase: 4.1
- Commissioning phase: 4
- Warranty phase: 3.5
- Regular O&M (after warranty phase): 3.6

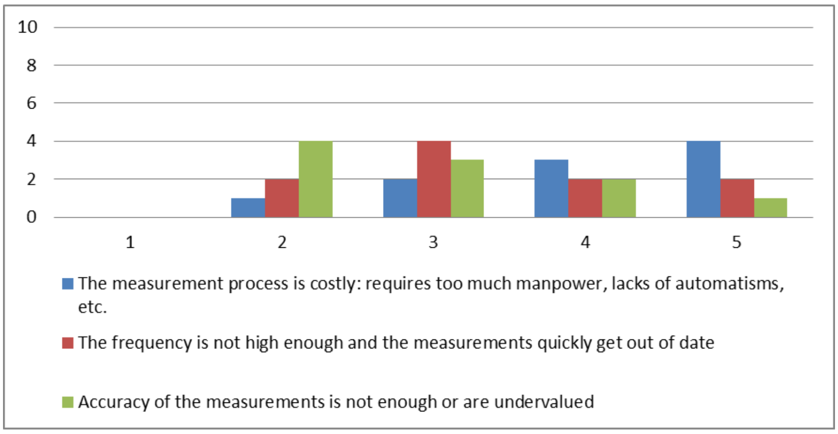
Figure A7. Survey Responses – Heliostat Measurement System Stages

Question

The overall methodology to obtain relevant and useful measurements of the heliostat field is both a technical and operative challenge.

Rate the following difficulties encountered in central receiver plants according to your judgment.

Results



Mean:

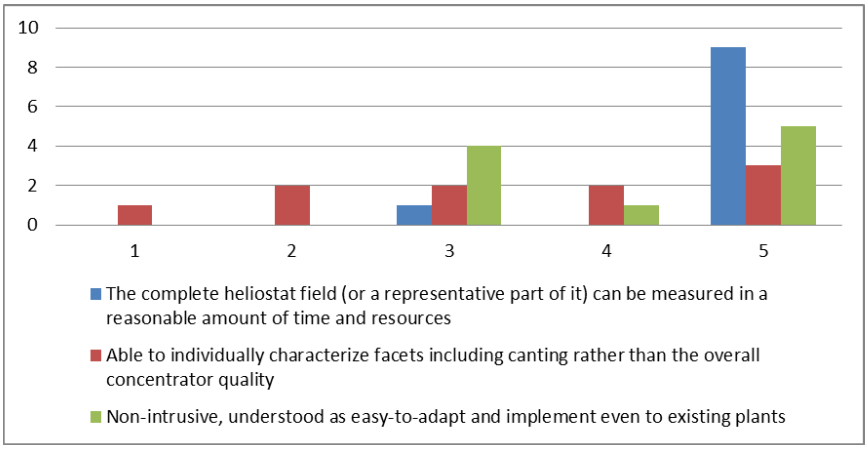
- The measurement process is costly: requires too much manpower, lacks of automatisms, etc.: 4
- The frequency is not high enough and the measurements quickly get out of date: 3.4
- Accuracy of the measurements is not enough or are undervalued: 3

Figure A8. Survey Responses – Heliostat Measurement Challenges

Question

Rate the degree of attractiveness of the following features of a system that measures the optical quality of the heliostats of a plant.

Results



Mean:

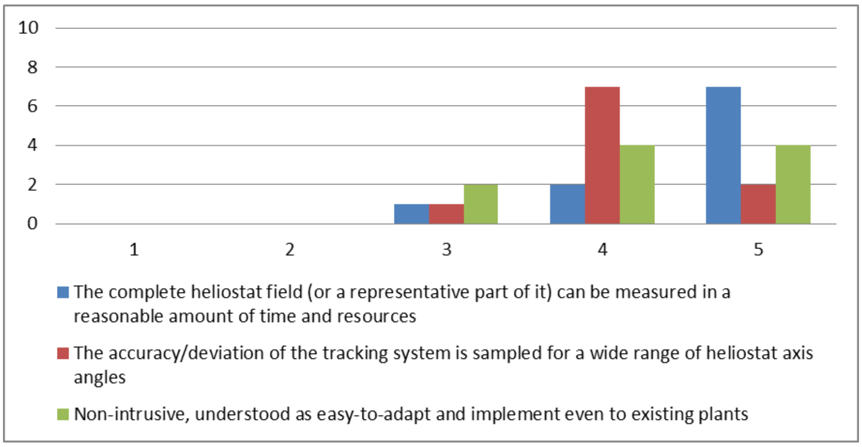
- The complete heliostat field (or a representative part of it) can be measured in a reasonable amount of time and resources: 4.8
- Able to individually characterize facets including canting rather than the overall concentrator quality: 3.4
- Non-intrusive, understood as easy-to-adapt and implement even to existing plants: 4.1

Figure A9. Survey Responses – Heliostat Measurement Attractive Qualities

Question

Rate the degree of attractiveness of the following features of a system that measures the tracking accuracy of the heliostats of a plant.

Results



Mean:

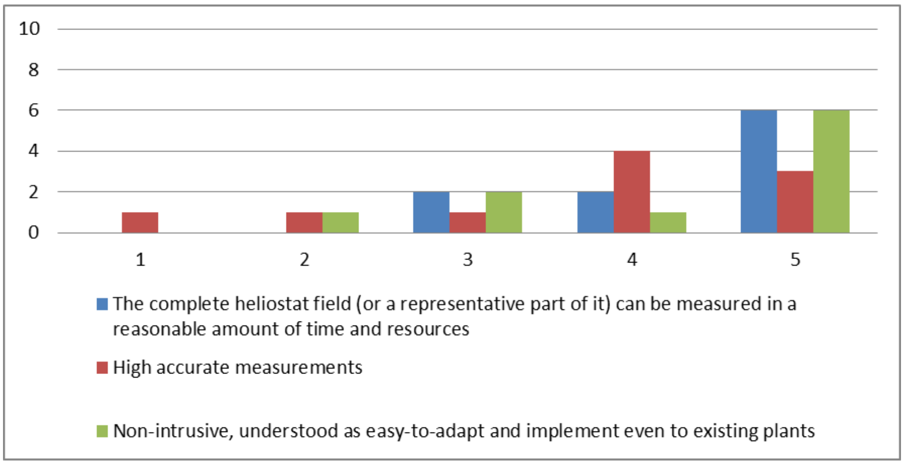
- The complete heliostat field (or a representative part of it) can be measured in a reasonable amount of time and resources: 4.6
- The accuracy/deviation of the tracking system is sampled for a wide range of heliostat axis angles: 4.1
- Non-intrusive, understood as easy-to-adapt and implement even to existing plants: 4.2

Figure A10. Survey Responses – Heliostat Tracking Accuracy Considerations

Question

Rate the degree of attractiveness of the following features of a system that measures the drop of reflectance of the heliostats of a plant.

Results



Mean:

- The complete heliostat field (or a representative part of it) can be measured in a reasonable amount of time and resources: 4.4
- High accurate measurements: 3.7
- Non-intrusive, understood as easy-to-adapt and implement even to existing plants: 4.2

Figure A11. Survey Responses – Heliostat Features Impacting Reflectance Measurements

Appendix B. Heliostat Surface Characterization Tools/Techniques

Table A1. Heliostat Characterization Measurement Systems Overview

Measurement System:	PSA-HPCS	NIO	HELIOSCHARPLUS	SOFAST-BCS	ANU	Cyl	QDec-H
Description:	Heliostat reflected beam analysis by camera-target methodology for optical&tracking characterization of heliostat prototypes	Uncrewed-aircraft system (UAS)-based tool that characterizes heliostat tracking, facet canting, and surface slope errors	Simultaneous mesurements of beam quality and slope error assessment along the concentrator surface	Fringe deflectometry using an active optical target facing the mirror, and a camera viewing the target's reflection in the mirror	Software to process partial sun images reflected from heliostats to estimate optical errors	Airborne, drone-based system for continuous characterization of CST reflector fields	Non-contact optical measurement and digital image processing technique based on the deflectometric measurement
ATTRIBUTE	PSA-HPCS	NIO	HELIOSCHARPLUS	SOFAST-BCS	ANU	Cyl	QDec-H
Measurement type	Indirect	Direct	Direct (beam) / Indirect (surface)	Indirect/Direct	Indirect	Direct	Direct
Data source	Heliostat beam	Heliostat surface	Heliostat beam&surface	Heliostat surface-beam	Heliostat beam	Heliostat surface	Heliostat surface
Distinguish between contour and canting errors	yes	yes	Partially, able to estimate the orientation of the facets and the error along each facet	yes	no	yes	yes
Accuracy/uncertainty of the measurement	Under evaluation	-	Error below 0.1% in light detectors	Full evaluation of accuracy, precision, and uncertainty in progress	NA	Still under investigation	Measurement uncertainty of local spot <0.3 mrad (RMS); Measurement uncertainty of global heliostat slope error <0.1 mrad
Scope	Test and commercial Solar Tower Plant heliostat commisioning and evaluation	-	Commissioning, ordinary operation, maintenance, etc. possible to applicate	Prototype design, high-volume manufacturing process design, field installation, field calibration, field monitoring.	It is applicable to all project phases: assembly, commissioning, ordinary operation, maintenance, etc	Operation and maintenance phases.	Commissioning, ordinary operation, maintenance, etc. possible to applicate

Time per measurement process per heliostat	Data acquisition 5' per heliostat. Processing time for optical quality under testing	For 1D slope error, a 5 second scan and approximately 5-minute post-processing per heliostat is required. These can be done in parallel after the first data collection flight.	Approx. 5-15 min, depending on the size of the spot produced by the heliostat and distance.	SOFAST data capture time: 10 sec. BCS data capture time, 1 sec. Data processing	5-15 min per heliostat, depends on number of sun positions, and speed of the tracking actuators	Approximately 30s. Depends on the size of the heliostat.	Measurement time <60 seconds; Evaluation time <60 seconds (both need to be multiplied in case several image series have to be taken to cover entire heliostat surface) Multiple heliostats can be measured in parallel to reduce measurement time.
Application to a complete heliostat field	Yes	Yes	Yes	Yes	Yes	Yes	Yes -
Required instrumentation	High resolution digital camera + computer + lambertian surface (target).	Method requires a UAS capable of automated flight planning and videography	String of cameras and photodetectors.	SOFAST component: Active optical target (display or projector/screen), camera, computer. BCS component: Passive optical target, camera, computer, heliostat control system.	BCS	A multi-copter drone system equipped with at least two cameras, each sitting at their own gimbal, a processing unit on the drone, a drone positioning system	a digital projector; two digital cameras (one with motorized zoom-lens and pan/tilt head); a control unit; wireless communication or cables
Degree of intrusiveness	Medium	Low	Low	Medium	Low	non-intrusive	Low
Sunshape measurement required	Yes	No	No, but desirable	No	Not compulsory but improves method accuracy	No	No

Appendix C. Metrology Flux Measurement

Table B1. Flux Measurement Current Techniques and Methodologies

Technique	Methodology	Measurement Parameters
DLR flux mapping without moving bar for industrial scale receivers - POC: Marc Roeger	CCD Cameras + Surface characterization + radiometer	Direct measurement on gray-scale of flux reflection, translating into irradiance - Derive the flux distribution by combining surface directional reflectance distribution.
ANU 3-D flux mapping - POC: Ye Wang	Using CCD camera measuring directional and spatial radiosity distribution	Direct measurement of gray-scale of flux reflection from multiple directions - Derive flux distribution-based surface reflectance - Applied to cavity receivers and external receivers
CENER +US+IMDEA - POC: Marcelino Sanchez	Combination of available optical sensors, thermal sensors, CCD camera, infrared cameras, ray-tracing software - In-situ (??) calibration of point sensors (fiber optic based) by using radiometer - calibration of CCD Cameras and IR Cameras by measuring their properties at lab and afterwards on site - validation of computer optical models and thermal models with solar field information - characterization and receiver thermal test - validation of all systems by cross comparison among them.	Direct measurement on gray-scale of flux reflection, translating into irradiance - Uncertainty calculated by the overlapping of all uncertainties found in every method, and where combination IA will be used to get the best possible combination according to the available information in each case Direct measurement of temperature distribution - delay may happen between instantaneous flux and its impact to receiver temperature.
CIEMAT/PSA hybrid high irradiance measurement system - POC: Jesus Ballestrin	Using radiometers and digital cameras (lenses and filters)	Direct measurement of gray-scale of flux reflection, translating into irradiance. - Using radiometers as reference irradiance

Appendix D. Heliostat Calibration Tools/Techniques

Table D1. Calibration Tools Overview

	BCS (Reference)	ANU (BCS +)	IMDEA (BCS +)	Heliochar+ (BCS +)	SHORT	HelioPoint	NIO	UFACET	HelioControl	SOFAST/QDEC, HFACET
Format of the measurement	**Sun reflection on screen**	Partial sun reflection on screen + stitching	Sun reflection on screen	Direct sun reflection	Image of a light (direct)	Image of a reflected light	Reflected object (e.g., tower)	Reflected object (e.g., tower)	Multiple sun reflections on the receiver during operation	Reflected Object/Pattern
Basis for the measurement	**Camera in the field**	Camera in the field	Camera in field + inclinometer with heliostat	Array of light detectors and cameras	Camera on each heliostat	Camera on a drone	Camera on a drone	Camera on a drone	high dynamic range camera + tracking excitation	Fixed camera on the tower
Accuracy/uncertainty of the measurement	**Reference**	Like BCS + scanning pattern tracking accuracy: TBD	Improved accuracy between calibration orientations	Assured accuracy even for small or distant heliostats	A few mrad. Validated 0.25	A few mrad. Target <0.2 Validated ~0.5	TBD	TBD	<20 mm Depending on distance (0.01-0,002 mrad)	
Scope (Result)	**Actual Kinematic model**	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Actual Kinematic model	Only Offset
Time per measurement process per heliostat	**Different measurements required over the year**	Like BCS	Like BCS	Like BCS	Some minutes	Some minutes	Some minutes	Some minutes	Goal: 64 spots in 32s 0.5s per orientation	
Application to a complete heliostat field	**Many months**	Like BCS	Like BCS	Like BCS	Few hours	Few weeks	100-200 heliostat/day? weeks/field	100-200 heliostat/day? weeks/field	7400 spots in 45min / in 26 min using multiple cameras	---
Required instrumentation & Associated costs	**One camera in the field + ambertian target in the tower (screen)**	Like BCS	BCS + one inclinometer per heliostat	Like BCS. A screen is replaced by some bars-HELIOSCHAR	One camera on each heliostat + lights/targets on the field	One drone + light	One drone + camera	One drone + camera	High dynamic range-camera, computer (pref. GPU) for evaluation	One camera + Projector + Screen (BCS

Degree of intrusiveness	**Low One heliostat off**	Low. One heliostat off	Low. One heliostat off	Low. One heliostat off	Low. Preferred night calibration	Low. A group of heliostats is off. Possible night calibration	Low-medium. A group of heliostats is off. Sunlight required	Low-medium. A group of heliostats is off. Sunlight required	Low. Small spot deviations, little adaption in heliostat control	