SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Operations, Maintenance, and Component Reliability
https://doi.org/10.52825/solarpaces.v1i.652

Published: 07 Mar. 2024

Pathways to IEC Standards for Heliostat Design Qualification and Site Acceptance in Central Receiver CSP Applications

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Abstract. This paper surveys the existing landscape of standards relevant to heliostats, identifies their gaps, and proposes a path forward to a comprehensive set of heliostat guidelines, technical specifications, and standards under the framework of International Electrotechnical Commission (IEC) TC 117. Gaps in existing guidelines and standards are surveyed using a three-tiered taxonomy: component-level, heliostat-level, and field-level. At each level, the gap analysis is followed by a proposal for a coordinated path forward on the development of standards. At the component level, advances in the understanding of wind loading should inform a technical specification for drives and structures. Reflectors require consolidation of measurement guidelines into existing standards documents. Communications & controls require technical standards to inform their selection and secure implementation. At the heliostat level, IEC 62817 (solar trackers) adequately characterizes drive systems, structures, and electronics, but requires adaptation to heliostats' use patterns, operating modes, and expected life cycles. IEC 62817 does not address heliostat beam quality and pointing accuracy, but the process for determining both is elaborated in the SolarPACES Guideline for Heliostat Performance Testing. This SolarPACES document requires two main modifications: adaptation to IEC language and inclusion of testing after heliostats which have undergone accelerated weathering and mechanical cycling (to understand performance degradation). At the field level, IEC 62862-4-2 addresses the function and control of heliostat fields but does not cover the statistically rigorous testing of heliostat groups, or field performance factors like security and soiling. The addition of documents under IEC-62862-4 is proposed to address this gap.

Keywords: Heliostat, Standard, Specification, IEC, Beam, Tracking, Qualification

1. Introduction to CSP Standards

A mature network of standards is important to the development of CSP as an industry. Solar PV provides an example of this effect. By the year 2000, IEC 61215 was already a mature design qualification standard for PV modules, building on three decades of work in the PV reliability space [1]. As feed-in tariffs created burgeoning demand for PV modules (particularly in Europe), IEC standards enabled a large ecosystem of suppliers to meet this demand without greatly compromising the quality, and therefore reputation, of PV. The same can be accomplished in CSP with a well-designed standards ecosystem.

Internationally, standards for concentrating solar power (CSP) are developed by the IEC (International Electrotechnical Commission) within a dedicated technical committee: TC 117 [2, p. 11]. CSP topics within TC 117 include power tower, parabolic trough, and thermal energy storage technologies. All documents produced by TC 117 are sub-numbered under

IEC 62862 (e.g. IEC 62862-3-5). Current standards which explicitly include heliostats for central receiver plants under TC 117, either in development or published, cover reflector performance, reflector degradation, general field requirements, and field communication and controls performance.

Where standards are not yet appropriate, IEC technical specifications (TS) and publicly-available specifications (PAS) offer another means of issuing guidance and consolidating industry best practices [3]. For heliostat fields in central receiver concentrating solar power (CSP) applications, the scope of applicable standards ranges from the subcomponent level (e.g. bearings, raw steel tubing) up to the installed heliostat field. These can broadly be grouped into three categories: component level, heliostat level, and field level.

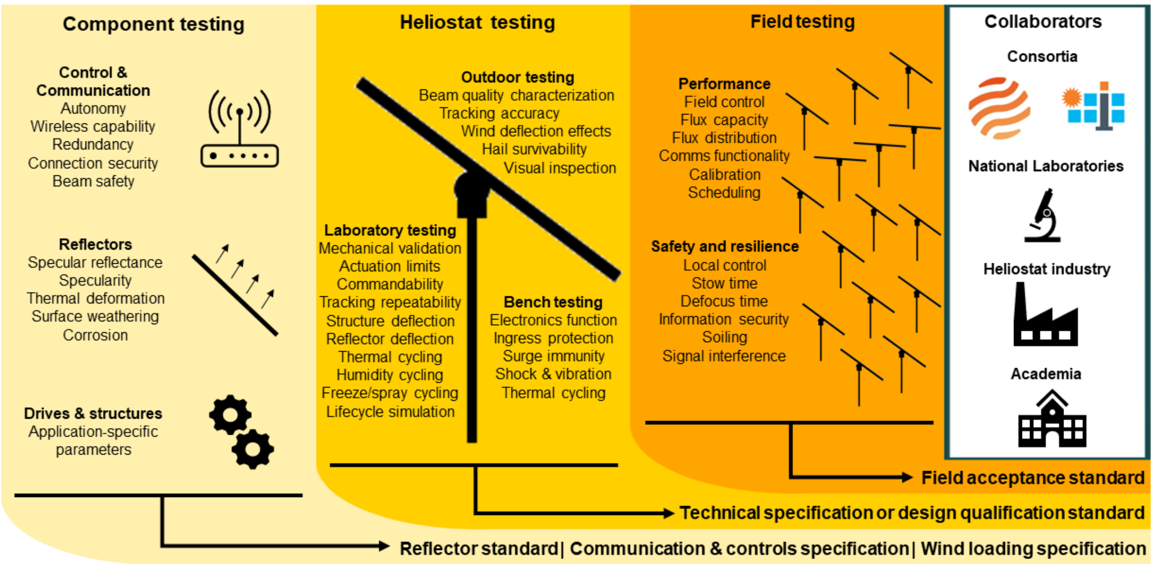

Figure 1. The three levels of testing which would comprise a comprehensive set of heliostat standards. In each section, the reportable outcomes of standardized or guideline-driven testing are described, followed by the proposed documents that would facilitate measurement, reporting, and comparison of those results. The development of guidelines and standards requires input from experts across research bodies (state and academic), industry, and the consortia that coordinate them.

Component level includes not just physical components (drives, mirrors, structure), but control systems and communications protocols. Subcomponents are generally already made to accepted standards (e.g. ASTM standards for the steel used in pylons and torque tubes), with no value to be added from heliostat-specific criteria. These component-level standards are met by suppliers. In these instances, heliostat developers are responsible for the selection of appropriate components and the development of sound designs for their implementation. In other instances, heliostat-specific component standards and specifications are necessary. This includes the testing of reflector weathering and performance, and the testing of communications equipment to ultimately prove secure, safe and effective control of a heliostat field.

There is currently no design qualification standard for complete heliostats. Heliostat level standards are intended to detect infant mortality risks and other design liabilities while characterizing the performance of the heliostat as a system. By accomplishing these goals, a heliostat design qualification standard will a) enable EPCs to compare heliostat designs, b) set targets the design of heliostats, including the selection of components, and c) guarantee the minimum functionality of a viable heliostat.

Field level standards are the basis of equipment and site acceptance and full system performance characterization. While testing the entire heliostat field is the direct precursor to site acceptance of the system, group heliostat tests can contribute meaningful data and reduce the testing burden upon full system installation [4].

2 Standards Survey & Gap analysis

At the component, heliostat, and field levels, this paper surveys documents spanning from draft guidelines to published standards (see Table 1). This work has been conducted under the Components & Controls subtask of HelioCon, a multi-year program led by NREL and Sandia National Laboratory to reduce the cost of heliostat fields.

Table 1. Summary of standards levels, current work, and this paper's proposals.

Level	Ongoing or Complete Work	Proposed IEC Work
Component: drives	- Application-specific tests	- TS 62862-3-X: Technical specification - design loads and component sizing
Component: structure	- Wind load characterization	- TS 62862-3-X: Technical specification - design loads and component sizing
Component: control & communication	- IEC 62862-4-2	- Movement of single-heliostat-level content to TS 62862-3-Y: Technical specification - closed loop control schemes, security, and wireless implementation
Component: reflectors	- IEC 62862-3-5 & -6 - XALE measurement guideline - SolarPACES measurement guidelines	- Completion of IEC 62862-5 & -6 with content additions
Heliostat	- SolarPACES Guideline for Heliostat Performance Testing - IEC 62817 (design qualification for solar trackers)	- IEC 62862-4-X: heliostat design qualification standard
Field	- HELIODOR initiative - IEC 62862-4-1 & -2	- Conversion of 62862-4-2 to complete heliostat field performance standard

2.1 Component-level testing

Heliostats comprise components which are typically either purchased off the shelf or produced as heliostat-specific variants of off-the-shelf components. For this reason, many components do not have heliostat-specific guidelines or standards to qualify their designs. The selection of heliostat components, materials, geometries, and manufacturing techniques is typically left to the developer.

As shown in Figure 2, heliostat-specific IEC standards do not exist for drives and structures. The industry-agnostic ecosystem of tools, guidelines, and standards in these categories obviates the immediate need for heliostat-specific documents. However, continuing heliostat-specific wind loading research has improved the industry's understanding of wind loads on heliostat drives and structures, setting the stage for potential creation of a technical standard concerning this topic. Controls & communications may need heliostat-specific standards and guidelines addressing specific concerns (security, safety, and capability), which IEC 62862-4-1 and -2 begin to address. Reflectors have concrete need for IEC heliostat-specific guidelines or standards. IEC draft documents 62862-3-5 and -6 will serve to fill the full scope of the gap [5],[6]. However, to do so, they will benefit from thorough incorporation of existing guidelines in their execution.

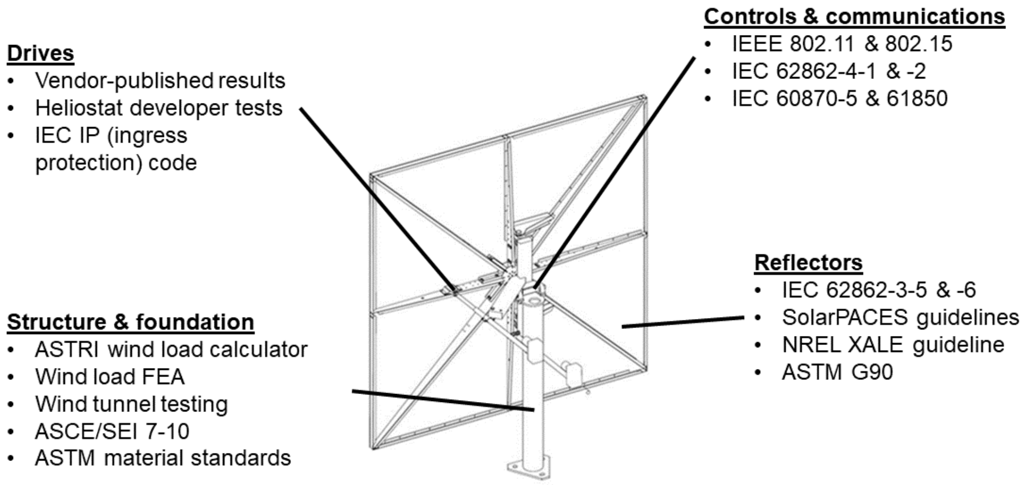

Figure 2. The four main component-level groups being considered are drives, structure & foundation, controls & communication, and reflectors. Existing (draft and published) documentation currently pertaining to each are listed. Heliostat diagram from CSIRO in Coventry et al. [7]

2.1.1 Structure & foundation

Studies on wind loads for solar trackers and heliostats has been conducted for several decades [8],[9],[10]. Heliostat developers can size structures to heliostat-specific wind loads using the ASTRI wind load tool [11], and typically perform advanced simulation or real wind tunnel testing on mature designs. While there is significant data in this area, research is still ongoing and suggests that standards could be further updated or improved considering wind load variation across a heliostat field.

Heliostat structures and foundations can be subjected to codes, such as ASCE/SEI 7-10, or others worldwide [12]. While these codes can ensure sound designs to wind, snow and other loading, they often result in overdesign and higher-than-necessary cost. Major structural design flaws can be diagnosed with torque tests at the heliostat design qualification stage. These include static load-induced deflection, torsional loading, and wind-simulating bending moment testing under IEC 62827 sections 8.4.3, 8.4.4, and 8.4.5 respectively [13].

2.1.2 Drives

There is substantial variation in drive selection as a function of heliostat size and kinematics. No heliostat-specific drives guideline or standard exists. Testing of drive performance can be accomplished with relatively low cost by heliostat developers and a heliostat level standard is expected to be able to adequately test drives' performance as part of a complete heliostat. HelioCon industry partners have developed test regimens for both worm gear and linear heliostat drives. Both drives are tested according to a 25-year lifecycle at forces simulating wind loads, with linear drives separately subjected to an additional 10 drive cycles against 100% survival wind loads. These tests, along with drives sizing criteria for handling wind loads, would be effective within a technical specification regarding wind loads on heliostat structures.

2.1.3 Controls & communication

Two draft standards from TC 117 touch on controls & communication: IEC 62862-4-1 and -2 [14], [15]. IEC 62862-4-1 is a whole-plant standard. Its heliostat-specific sections describe some basic functionality (e.g. stow capability in the absence of communication to central control) and prescribes adherence to additional communications standards, specifically IEC 60870-5 and IEC 61850. However, it does not describe any specific tests or enumerate passing criteria for heliostats.

IEC 62862-4-2, *Heliostat Field Control System*, details required functionality of heliostat controls & communication. The standard tests that functionality at the individual, group, and full field levels. Data security is covered by reference to IEC 62443. As a draft, this document will benefit from additions and clarifications to fill its main gaps:

1. Wireless communications are not explicitly covered, so issues specific to wireless heliostat control are not tested, e.g. interference from high-density signal traffic or functionality limits from onboard heliostat traction battery degradation. Implementation standards are also not given, although local area network (LAN) protocols are fully described under IEEE 802; IEEE 802.11 (wireless local area networks) and 802.15 (wireless specialty networks) are of particular note to heliostat developers [16].
2. Given that dozens of viable closed-loop heliostat control schema are available [17], the standard should provide a method of evaluating the suitability of any particular method to fulfilling individual or field-level heliostat performance objectives.
3. The document requires incremental testing throughout the entire development process of a heliostat field, from single production heliostats to the already-installed solar field. This raises the cost of testing and creates redundancies with standards which specifically cover either the whole field or single heliostats.
4. Environmental conditions for evaluation of performance are rigid, as is the envisioned control architecture for the heliostat field. These both need flexibility for use across sites, developers, environments, and EPC requirements sets.

2.1.4 Reflectors

A variety of guidelines exists from SolarPACES, in published and draft stages, covering reflector testing. *Parameters and Method to Evaluate the Reflectance of Reflector Materials for Concentrating Solar Power Technology Under Laboratory Conditions* covers the instrumentation, measurement parameters, and calculation methods for CSP-relevant reflector variables [18]. *Accelerated Aging Testing of Aluminum Reflectors for Concentrated Solar Power* proposes accelerated aging regimens tailored to three types of environment (coastal, desert, extreme desert) and the mirror measurements required after aging [19]. *Recommendations for Reflectance Measurements on Soiled Solar Mirrors* describes field measurement of reflectors after soiling has occurred [20]. In addition, NREL's *Measurement and Reporting Guidelines for Solar Mirror Aging Test by Using Xenon Arc Lamp Exposure (XALE)* detail the development of indoor accelerated aging test plans and execution of subsequent reflector performance measurements [21].

In the absence of published standards, HelioCon industry partners have used their own suite of reflector tests to validate designs. In some cases, the IEC draft standards above reflect industry practice (e.g. performance of salt spray testing per ISO 9227). In other cases, correspondence with HelioCon industry partners has indicated that tests have gone beyond the scope of existing guidelines of draft standards. Reflectors have been mechanically cycled with oscillating point loads across their surface (~1/m^2) at forces exceeding design load. Individual facets' construction has been tested with 2000N adhesion shear tests. Outdoor accelerated UV exposure testing has also been conducted per ASTM G90 using Atlas EMMA (Equatorial Mount with Mirrors for Acceleration) hardware.

IEC 62862-3-5 & -6, both currently drafts, will form a complete standards infrastructure for the testing of heliostat reflectors. Document -5 covers laboratory testing of heliostat reflectors; -6 concerns the accelerated aging procedures that precede mirror measurement. IEC 62862-3-5 and IEC 62862-3-6 have two primary gaps. First, their scope currently does not include the full scope of methodologies available to developers, e.g. destination environment-specific test regimens (as per SolarPACES guidelines), or outdoor accelerated aging using EMMA or similar hardware. Second, these documents do not yet encompass the full breadth of testing already being successfully used by heliostat developers to validate their designs.

2.2 Heliostat level testing

Two documents individually contain much of the content required for an IEC technical specification or a heliostat design qualification standard: SolarPACES Guideline for Helisotat Performance Testing [22] and IEC 62817: Photovoltaic systems – Design qualification of solar trackers [13].

2.2.1 SolarPACES Guideline for Heliostat Performance Testing

This document comprehensively covers measurement of two criticial heliostat-specific performance parameters: beam quality and tracking accuracy. Beam quality is assessed via ray-tracing simulation, using a variety of measured inputs (self-weight deflectometry, slope deviation measurement, heliostat motion kinematics). Tracking accuracy is measured using photogrammetry to track deviation of beam centroid on a target.

While ray-tracing simulations of beam quality can rely on publicly-available software and standardized software parameters, no standard setup and calculation methodology exists for defining the slope error of an entire heliostat's reflective surface when installed outdoors, nor for evaluating its self-weight deflection across a range of elevation and azimuth positions. These two inputs are critical for accurate simulation.

Regarding slope error measurement tools, Sandia National Laboratory's Optical Fringe Analysis Slope Tool (SOFAST) performs phase measuring deflectometry and may be licensed for use at other test facilities [23]. Similar testing has been performed at the German Aerospace Center‘s Jülich site as part of SolarPACES guideline validation [24]. Measurement of self-weight deflection has been accomplished on medium-scale heliostats at the Jülich site but is not scalable to large heliostats in its current form. However, it is not clear how the methodologies compare when applied to identical setups. NREL's NIO (non-intrusive optical) characterization system is another potential solution [25]. This tool uses photogrammetry and can provide near-equivalent data to phase-measuring deflectometry but is still in development.

Per the guideline, tracking error is calculated by using photogrammetry to find the intensity-weighted centroid of the heliostat's beam on a target while tracking throughout a day-long measurement period. This error effectively encompasses the deviations associated with the heliostat drives‘ performance and the beam's deviation due to wind and weight-induced deflection of the reflector surface itself. As with slope error measurement, one common tool is not available to analyze data and compare heliostat designs or data between installation sites. The Guideline's current language leaves room for interpretation. A variety of hardware setups and software implementations can accomplish the ray tracing and photogrammetry needed to execute the guideline. Standardization and collaboration are therefore necessary to enable various test laboratories to achieve consistent results.

2.2.2 IEC-62817: Photovoltaic systems – Design qualification of solar trackers

This published standard already provides comprehensive set of tests for functionality of heliostat structure, drives, electronics, etc. Mechanical testing (section 8) and electronics testing (section 9) on a heliostat per this standard reveals design deficiencies in every subsystem and component with the exception of reflector performance. Section 7 offers a valid method of assessing a helistat's tracking accuracy without photogrammetry. This method would effectively ignore effects of self-weight reflector deflection on beam shape and therefore its centroid, isolating effects of drivetrain error and structural deformation on tracking accuracy. The merits of isolating these effects requires further discussion. Accuracy thresholds, movement cycle definitions, and cycle counts must be adjusted for heliostats‘ typical operation.

2.3 Field level testing

IEC 62862-4-2, though notionally a controls document, does cover some aspects of field performance and functionality. Its gaps are covered in the Controls & Communication subsection. While rigorous whole-field testing is the immediate precursor to site acceptance, it is a major liability to only test beyond the individual heliostat level after a field has already been installed. Testing groups of heliostats offers an intermediate solution. DLR's HELIODOR project is currently laying the groundwork for a statistically-rigorous field-level standard [4].

3. Proposal for IEC Testing Documents

3.1 IEC 62862-3-5 and IEC 62862-3-6 (component level standard for reflectors)

While drafts have been formed, more work is still needed to complete these documents. In particular, the following require development:

1. Consolidation of specular and hemispherical reflection methodologies between SolarPACES, NREL, and draft IEC methodologies
2. Inclusion of outdoor accelerated aging
3. Mechanical testing, including adhesion and wind loading.

3.2 IEC 62862-3-X (technical specification for communication and controls)

A working group is recommended to focus on creating guidance for the implementation of communication and controls. On the controls side, this would focus on methodologies for closed loop control of heliostats (at the individual and field level). The guideline would effectively consolidate existing knowledge from academia and industry into a valuable resource for heliostat deveopers. In addition, it would give guidance for the development of fully-wireless heliostats by elaborating the redundancy and robustness of wireless power solutions.

On the communications side, this document would include a list of all the minimum functions of a heliostat control system, in addition to a baseline set of security considerations (e.g. UNIDs for all wirelessly-controlled heliostats. This document would also aggregate knowledge on wireless communications as a means of accelerating development of heliostat-specific solutions by industry. In addition, it would clearly enumerate requirements about data security, communication security, safety, redundancy, and performance for heliostat fields which are currently distributed among general IEC documents.

3.3 IEC 62862-3-Y (technical specification for drives and structures)

HelioCon industry partners have used in-house definitions of design loads and coupled them with rigorous FEA. Some of this engineering burden can be removed from future heliostat developers while helping to validate designs by incorporating lessons learned in wind load characterization and testing into an IEC technical specification. This document would include adaptations of calculations in the ASTRI wind load spreadsheet, in addition to prescriptions for sizing main heliostat components (azimuth drive, elevation drive, pylon, torque tube) and the accelerated life test cycles to validate the selection of specific components and structural geometries.

3.4 IEC 62862-4-Y (heliostat level design qualification standard)

This standard does not exist, but a working group is needed to create a heliostat technical specification or design qualification standard under the umbrella of IEC 62862. Two methods of characterizing beam quality may be standardized: simulation and photogrammetry, as described in this paper's discussion of the SolarPACES Guideline for Heliostat Performance Testing. Similarly, two methods of tracking accuracy characterization may be standardized: a laser-based method adapted from IEC 62817, or a novel photogrammetry method based on SolarPACES guidelines. The proposed standard pathway for evaluating both of these variables is shown in Figure 3.

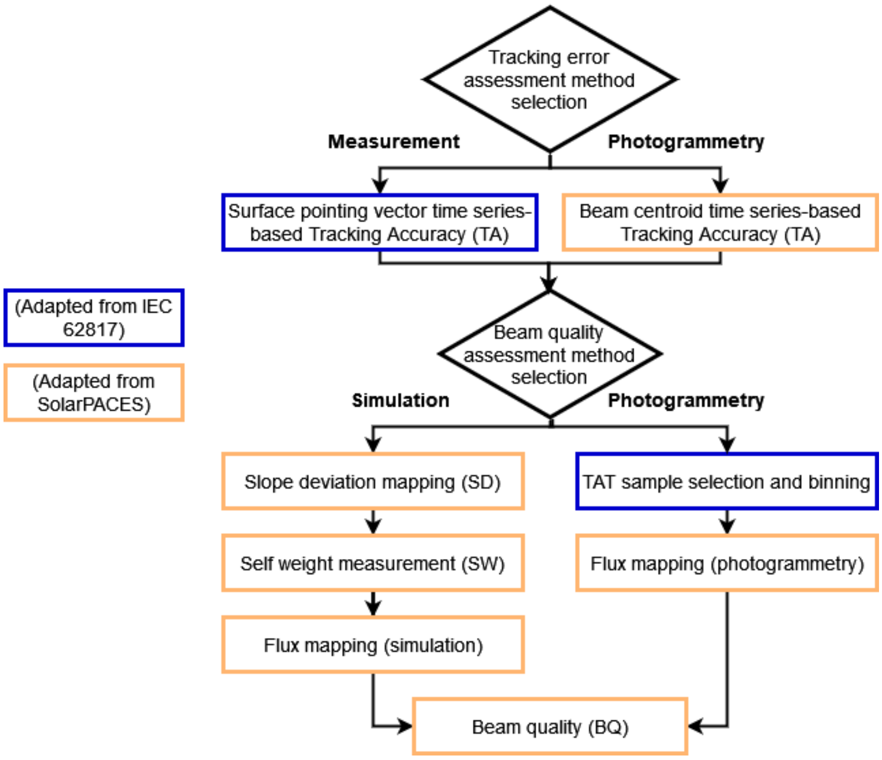

Figure 3. Tracking accuracy (TA) and beam quality (BQ) can each be evaluated using one of two methods.

The standard methods of evaluating beam quality and tracking accuracy would join a variety of tests adapted from the solar tracker standard, IEC 62817, thereby forming a comprehensive document for the evaluation of heliostat designs (see Figure 4).

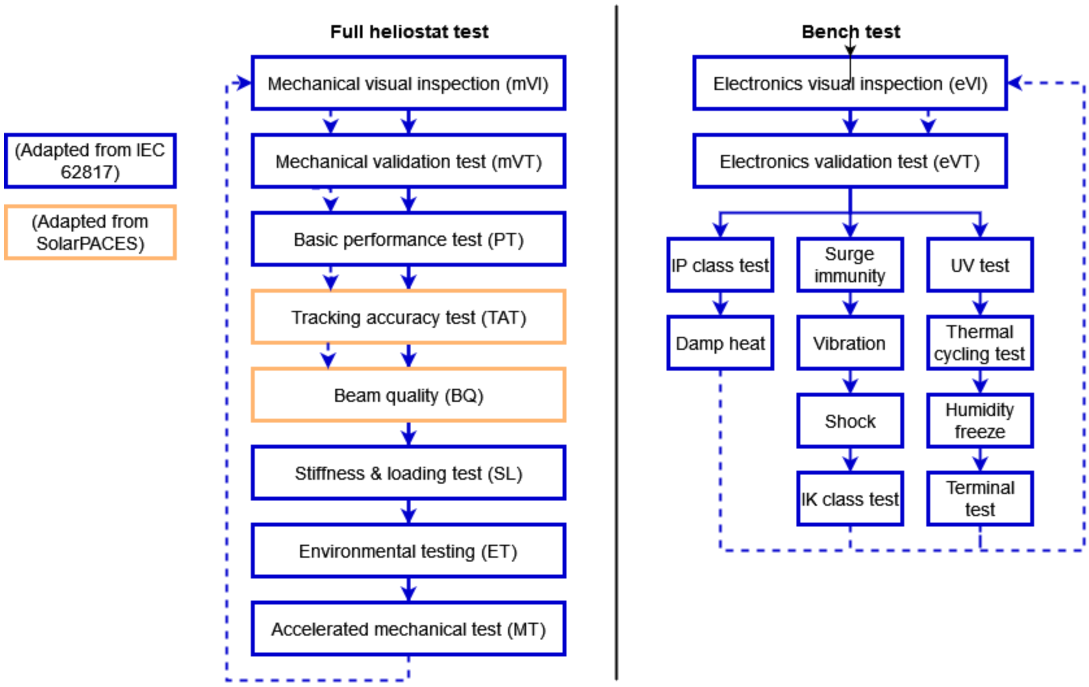

Figure 4. A summary flowchart of the proposed heliostat design qualification standard.

3.5 IEC 62862-4-2 (heliostat field test standard)

Reconfiguring this document as a field level testing standard would allow it to function as a direct lead-in to site acceptance while fulfilling the original task of gauging the effectiveness of the field's control systems. The path to do so is as follows:

- Include significant discussion of group heliostat testing. This will allow for some field performance validation to complete after only a subset of a heliostat field has been built. This should allow for quicker transition from field construction to acceptance, as functionality has been tested on a statistically valid subset of heliostats already.
- Remove laboratory testing of single heliostats and include these procedures within IEC 62862-4-Y (the single-helisotat testing document)
- Include environment-specific adaptations to testing regimens and acceptance criteria. This can be done either by giving guidance on adapting to site-specific environmental conditions, or by creating broad categories of site types in a fashion similar to SolarPACES aluminum reflector aging guideline, where three different types of environmental service conditions (coastal, desert, severe desert) are included to help tailor tests to heliostats' installed environment
- Add interference and packet loss testing specific to wireless heliostat communications.
- Add validation of self-powered heliostat functionality.

3.6 Software

To measure tracking accuracy according to existing SolarPACES guidlines and the proposed IEC 62862-4-Y heliostat standard, images of beams on targets must be taken. They are also required for beam quality (BQ) measurement if photogrammetry is chosen. The image set is guaranteed to be at least 360 images and may include several thousand, depending on the frequency of images at a certain test site. Images will also vary in composition, resolution, and clarity.

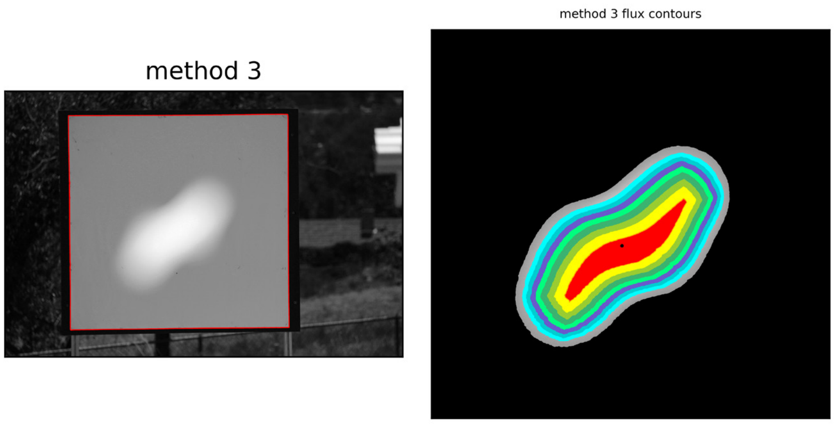

Figure 5. Sample graphical output from standard software being developed at NREL. The subplot on the left shows the target boundaries, as found using one of eight available target identification methods in the software. The subplot on the right shows flux contours (each color is 10%), with a black dot representing the intensity-weighted beam centroid.

Photogrammetry is a variable processes and must be kept consistent if tracking accuracy and beam error are to be evaluated and reported in a manner which allows quantitative comparison between heliostats. Rigorously-documented, publicly-available ray tracing software exists; this kind of photogrammetry-based beam characterization software does not. It must therefore be developed and made publicly available.

Data availability statement

The contents of this submission are qualitative.

Author contributions

Writing – original draft: Tsvankin. Writing – review & editing: Muller

Competing interests

The authors declare no competing interests.

Funding

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided as part of the Heliostat Consortium (HelioCon) by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Acknowledgement

Additional thanks to Kenneth Armijo, Dimitri Madden, Guangdong Zhu, and George Kelly for their feedback on this paper.

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