Technical Gap Analysis of Heliostat Components & Controls

Kenneth M. Armijo[1], Matthew Muller[2], Dimitri Madden[1] and Daniel Tsvankin[2]

[1] Sandia National Laboratories, Albuquerque, NM, USA
[2] National Renewable Energy Laboratory (NREL), Golden, CO, USA

Abstract. In this investigation, concentrating solar power (CSP) heliostat components and controls (C&C) technical gap analysis was facilitated as part of a U.S. department of energy (DOE)-sponsored Heliostat Consortium (HelioCON) program. This work assesses key gap areas within heliostat subcomponent design for both performance and reliability challenges. This research investigated the following key areas within heliostat development: 1. Conceptual Design, 2. Individual Component Development, 3. Heliostat Integration, and 4. Deployed Field. Here, approaches are proposed for addressing engineering and programmatic gaps. Additionally, this work also assesses controls architectures within heliostat fields that employ both wired and wireless systems, and the key technical challenge areas that impact the levelized cost of electricity (LCOE) and heat (LCOH). As components and controls degrade or have issues, the accuracy degradation impacts CSP plant revenue as well as other opportunity costs. Here, HelioCON survey results are also presented to review key concentrating solar power (CSP) plant operational challenges related to C&C that consider both distributed control elements and central control systems. Finally, this work also reviews the consortium's findings and recommendations related to C&C CSP safety and security.

Keywords: Heliostat, Components and Controls, CSP

Heliostat Components & Controls Overview

Heliostats are dynamic systems that require precision controls to provide accurate solar flux pointing during CSP field operation. Heliostats are systems have have a reflective surface, open or closed-loop control system, and a mechanical structure/tracking system. Heliostat fields can comprise near 50% of the total cost of a CSP plant [1], requiring further cost reductions to enable CSP more competitive in the energy market. To reduce overall costs of CSP facilities while improving reliability, optimization is required of component designs to lower costs, such as the drive system, which can account for up to 30% of total cost [2]). In a cost study by NREL [3], a typical commercial heliostat is compared against an advanced design with alternative approaches to cut costs to address the DOE/SETO target of $50/m^2. Both designs share a commonality that a large cost can be attributed to key components such as drives, mirrors/facets, and supporting structures/foundations. The authors provided a breakdown of C&C state of the art elements from the perspective of gaps attributed to cost reduction. Consideration is provided for key overarching criteria such as performance requirements under operational wind loading. Furthermore, state of the art heliostat O&M, degradation, and reliability were also discussed as they are a complex interaction that results only after combining various components with a controller.

To further reduce heliostat component costs, while increasing heliostat surface area, curved facets were introduced [4]. However, larger reflective surfaces and their respective supporting structures are exposed to higher wind loads and can have the drawback of increasing optical losses and mechanical stress levels [5]. Therefore, there have been trends to utilize single, smaller-facet heliostats to optimize heliostat size with respect to receiver geometry, field layout, and costs. Additionally, to further reduce these costs, newer materials or designs have been considered, such as sandwich mirror facet, polymer reflector subcomponents, and coatings to improve reliability or reduce soiling losses. Regardless of design, maximum wind conditions are a primary design consideration that impacts heliostat components and controls. Additionally, maximum operating torques of the drive train and stiffness of structure are primary factors that determine the interplay between wind speed and pointing accuracy.

Accurate heliostat drive train control is required for heliostat structural movements during solar tracking to reflect concentrated sunlight toward a receiver. Wireless and closed-loop controls have become increasingly attractive for new installations as they offer potential cost savings and enhanced performance. While there are potential cost and performance benefits of closed-loop controls, research by Collins et al. [6] has shown that industry has not come to a consensus on a preferred approach, thus requiring further design, optimization and validation for adoption. However, various closed loop control options are not well understood with respect to cost, difficulties in implementation, limitations in optical accuracy, and long-term field performance and maintenance requires. To achieve bankable benefits of closed-loop control and calibration, more research and development is required to come to a consensus on the most beneficial implementation techniques.

Various performance design standards are a typical pathway most industries use to ensure durability, reliability, and to achieve expected performance. Some tracking system standards development has taken place for both concentrating solar photovoltaics (CPV) [7] as well as CSP [8], [9], but these standards need to be expanded to fully cover the needs for heliostat components and controls. Additionally, a deficiency of accepted CSP heliostat standards prevents the industry from rapidly validating new durable and bankable designs that enable reducing costs and becoming a mature industry.

For this investigation, a literature review and survey were facilitated with CSP heliostat designers, plant operators, and those involved in CSP commercial adoption. A gap analysis is presented for heliostat C&C to determine approaches for further cost reduction, with improved performance and reliability.

Heliostat C&C Gaps Identification

For this investigation a gap analysis was developed that focused on the barriers to affordable, capable, and bankable components and controls for heliostats. This gap analysis was based on both a literature review and a survey of current practices in modern, grid-scale heliostat fields. The following topic specific areas were considered: drives, mirrors/facets, structures, wireless control (and power), closed-loop control, and whole-heliostat integration. In support of gap analysis, this task produced a survey that was circulated to CSP heliostat designers, plant operators, and those involved in bankability. Respondents were asked about the primary problems affecting heliostat field operation. Calibration and alignment were the most common answers to all questions concerning causes of heliostat downtime. Drives were the most noted components that had challenges concerning reliability and high replacement costs. When it came to ongoing operational challenges, three categories received the bulk of responses: calibration, soiling, and pointing errors. Issues with pointing error in the field underscore the concept that meeting SunShot objectives with cheaper drives, structures, and mirrors cannot occur at the expense of performance.

The results of the C&C survey pertaining to technical gaps are summarized in Table 1. Respondents were asked about the primary problems affecting heliostat field operation. Calibration and alignment were the most common answers to all questions concerning causes of heliostat downtime. Drives were found to have the highest component issues with regard to reliability, with the highest replacement cost. When it came to ongoing operational challenges, three categories received the bulk of responses: calibration, soiling, and pointing errors. Issues with pointing error in the field underscore the challenge in meeting U.S. DOE SunShot objectives with cheaper drives, structures, and mirrors, which cannot occur at the expense of performance. The survey results suggest a need to address design and fabrication standards for heliostats, with 85% of respondents agreeing that heliostat-specific standards are necessary. Specific requests for standards spanned the heliostat life cycle from design (wind loads) to deployed fields (site acceptance testing), reflecting the relatively custom and ad hoc nature of current field implementation. A larger proportion, 88%, experienced issues with soiling. Here, coatings can help mitigate soiling [10] and the LCOE burden throughout a plant's lifetime.

Table 1. Identified Gaps Related to Components and Controls Under HelioCon
a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

Components and Controls						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important)						
C1	Lack of lightweight composites or other advanced structures (e.g., torque tubes, pedestals, foundation) for hitting cost targets. Material selection needed for rigidity, wind load, and weight reduction.	x	x	x	x	
C2	Lack of lower-cost mirror designs with comparable performance.	x				
C3	Wireless systems approaches are needed to capitalize on lower plant cost, while wireless risks and technical issues must be avoided. Standardized requirements and testing capabilities are needed.	x	x	x	x	x
C4	Lack of closed-loop systems that are applied to: • Automate calibration and reduce commissioning time • Reduce costs • Reduce drive requirements • Improve performance to achieve field error less than 1 mrad.	x	x	x	x	x
C5	Missing design qualification standards for heliostats to enable bankable components and controls, improve heliostat long-term performance, and shorten design improvement cycles.	x	x	x		
Tier 2 Gaps						
C6	Alternatives are needed compared to drive design being decided by worst-case wind loads, as this is a significant barrier to cost reduction.	x	x	x		
C7	Alternate drives for cost reduction have not been fully explored.	x		x	x	x
C8	Coatings for mirrors are needed to improve performance and reliability.	x	x	x	x	x
C9	Mirror quality should be adaptable to environmental conditions, but there are no standards or guidance on how to do this.	x	x			x
C10	Need performance standards for heliostats.			x		x
C11	Need CSP-centric durability standards for glass and mirrors.		x			
C12	Design and O&M are not well coupled (especially problematic with drives/mirrors).	x	x	x	x	x
C13	Reliability/degradation/aging is not well defined, yet this can impact pointing accuracies and system performance over time (especially problematic with drives/mirrors).	x	x	x	x	x
Tier 3 Gaps (Least Important)						
C14	Flexible communication and controls interconnections are needed.			x		x
C15	Heliostats are automatic mechanisms that can exert dangerous forces and create fire hazards; this is not currently being considered.			x		x
C16	Safety is especially important for wireless systems. Redundancies within the controls will be critical especially for SCRAM operations.			x		x
C17	Concerns over cybersecurity attacks on a heliostat field could create a variety of high-consequence events.					x

Using Table 1 the Heliocon C&C investigators categorized the gaps in terms of priority for cost reduction and performance. The five most significant gaps that were determined to have the most impact to heliostat performance were C1, C2, and C3, while C4 and C5 target both costs and reliability improvements, allowing plants to achieve an error less than 1 mrad. Although not included in the Tier 1 category, C7 was also identified as a significant Tier 2 gap since drives do comprise a significant cost for heliostats [11].

Based on input from the comprehensive literature review, survey results and a techno-economic analysis (TEA) assessment of the various components and controls for varying heliostat designs (in terms of levelized cost of electricity (LCOE) and heat (LCOH)), the team prioritized the results within three tier categories where Tier 1 items had the strongest importance for development. This analysis was conducted using the System Advisory Model (SAM) [12].

Table 2. Gaps are categorized in different tiers for components and controls

Dev. Cycle	Conceptual Design	Components	Integrated Heliostat	Deployed Field
Tier 1 (Highest Priority)	(C2) Lower cost mirror designs are needed with comparable performance to existing glass mirrors.	(C1) Composites or other advanced structures (e.g., torque tubes, pedestals, foundation) are necessary for hitting cost targets.	(C3) Wireless systems approaches must be broadly introduced to capitalize on lower plant cost while wireless risks and technical issues must be avoided. Standardized requirements & testing capabilities are needed.	(C4) Closed loop control must be more broadly applied to achieve higher flux performance and auto alignment/calibration processes. (C5) Need design qualification standards for heliostats to enable bankable C&C's, heliostat long term performance, and shorten design improvement cycles.
Tier 2	(C6) Alternatives are needed to impact design being driven by worse case wind loads as this is a significant boundary to cost reduction.	(C8) Coatings for mirrors needed to improve performance & reliability. (C7) Alternate drives for cost reduction have not been fully explored. -Design and O&M are not well coupled (especially problematic with drives/mirrors).		(C9) Mirror quality should be adaptable to environmental conditions but there are no standards for this. (C10) Need performance standards for heliostats. (C11) Need for CSP-Centric durability standards for the glass and mirror. (C13) Reliability/degradation/aging not well defined yet this can impact pointing accuracies and system performance over time.
Tier 3 (Lowest Priority)			(C14) Flexible wired communication & controls interconnections needed. (C16) Safety is especially important for wireless systems. Redundancies within the controls will be critical especially for SCRAM operations.	(C15) Heliostats are automatic mechanisms which can exert dangerous forces and create fire hazards. (C17) Concerns over Cybersecurity attacks on a heliostat field could create a variety of high consequence events.

Heliostat C&C Gaps Assessment

Within the Tier 1 gaps, the C&C team concluded that additional development was most needed for closed loop controls, standards development and use of more reliable and lower cost materials, such as that of composite materials. Techno-economic analysis results indicated that employment of composite structural materials could reduce structural costs by as much as 50% to $10/m^2$, while LCOH could be reduced by 3.0%. Further development of closed loop controls was found to reduce installation time and costs, enhance performance, and reduce calibration time. The sum of the cross-reaching benefits of closed loop control could reduce LCOH by as high as 11.1%. Finally, Heliostat-centric standards were found to provide better guidance for how to compare tradeoffs between alternate components, structures, and heliostat size. Heliostat-centric standards were also found to be critical for the industry to grow and reduce manufacturing errors and improve reliability. Based on this assessment, standards development was predicted to reduce LCOH by as much as15%.

Within the Tier 1 gaps, further down-selection concluded that C4 and C5 had the highest ranking. This recommendation was based on the need to address these gaps to facilitate cost reduction and performance improvements. Per current designs, steel and foundations costs of approximately $24/m^2$ [3] were found to be significant since relatively large steel beams are used for construction of pedestals and torque tubes. Additionally, commodity prices of steel has also had significant fluctuation between 2020 and 2021 of approximately 200% [13], further necessitating the need for alternative designs that either use less steel or other materials that are at a lower and more stable cost. In addition, alternate designs are needed that also support addressing wind loading challenges. Design and material selection for rigidity, wind loading, and weight reduction must also consider quality control and assembly hours in order to achieve cost targets. It was also found that mirrors/facets could also benefit from cost reductions due to composites using novel materials and construction techniques tailored to site-specific environmental conditions. However, there are no standards or guidance on how to improve adaptability. New designs developed by industry could be bankable if site-specific performance and reliability were well-understood. NREL conducted a multi-year and multi-site data collection effort to understand how different environmental conditions change mirror degradation 14]. Further research would be necessary to characterize degradation of composites as well.

Wireless system approaches reduce up-front capital expenditure through reduced wire and conduit use as well as labor reductions per elimination of trenching and wire pulling/assembly. Cost savings are only achieved if wireless systems do not create new modes of failure or safety issues. Development/demonstration of wireless control architecture, signal communication, and methods of hardware integration are needed for industrial-scale heliostat applications. Wireless technical and resiliency issues, tracking error, ease of integration, safety during a potential signal drop, ease of operation, and cybersecurity issues are all of concern. Standardized requirements and testing capabilities need to be created for rapid development of robust wireless systems.

Many older heliostat field designs use variations of open-loop controls, and such systems require countless hours in calibration in the commissioning process and throughout the life of the plant as heliostats require O&M. The slow calibration process surrounding O&M reduces plant availability and overall energy production. Open-loop control provides no mechanism to compensate for degradation of heliostat drives, and therefore drives must be overdesigned to compensate or optical performance will degrade with time. Alternatively, researchers and industry players claim the ability to use closed-loop controls for automated calibration, reduction of commissioning time and O&M hours, reduction of drive requirements, and overall cost reduction. Existing research and plant hardware demonstrate a direction for closing the gap of broadly applied closed-loop control while proprietary motivations slow the process. There must be further research, development, validation, and publication of closed-loop methods that can be supported through a synergistic closing of key metrology gaps. C4 is a high priority as costs can be specifically reduced through lower cost drives and fewer labor hours (commissioning and throughout plant life). Optical performance is increased through improved initial alignment and automatic response to drive wear, pedestal shifting, or other factors that change over the plant life.

Finally, in mature industries, standards serve as a backbone for producing safe, reliable, high-quality products. Standards allow new features, cost reductions, or other design iterations to be seamlessly introduced without quality problems. A qualification standard for heliostat design, covering individual components and overall integration and performance, would improve project bankability, reduce commissioning time, enhance performance, and allow lower-cost designs to more rapidly move from R&D to the field. IEC 62817 (design qualification for solar trackers) contains most of the necessary tests but needs certain amendments to be fully applicable to heliostats. Specific needs are a procedure for measuring performance accuracy of heliostats and specific tests for wireless controllers. Task groups within SolarPACES have been working on such heliostat specific tests, so completing existing SolarPACES work and merging these efforts with the existing IEC 62817 provides a clear path to closing gap C5.

Heliostat Component Integration

In addition to the prioritized gaps identified through the survey results, another challenge that was highlighted was heliostat component system integration. Improvements in modeling capabilities have allowed for extensive computational fluid dynamics (CFD), wind modeling and optimization modeling that could be used to significantly improve heliostat assembly design, field design and component integration. In 2018, Wang et al. developed a high dimensional genetic algorithm toolbox for optimizing entire heliostat fields [15]. The toolbox was used to optimize the Gemasolar plant. The toolbox was used to optimize multiple factors at once by row. The spacing between the tower and the first row of heliostats was optimized, the distance between one row and the subsequent row, the spacing of heliostats in the row, and the height of pedestals in a given row were all optimized. The paper showed that the model could be used with great success for optimizing a specific power tower plant. In the example case given in the paper of optimizing the Gemasolar plant, the optical efficiency could be increased to almost 64% and the annual insolation weighted efficiency could be increased to 57%.

Alternate heliostat integration systems have also been described in literature, such as ganged heliostat systems. Amsbeck et al. optimized a ganged facet torque tube heliostat system in 2008 [16]. The torque tube heliostat system has all facets mounted on single torque tubes which are coupled in rows. When the coupled torque tubes are rotated, the facets in a single row all have the same elevation angle. The system was modeled with a simulated 210 MW_{th} tower plant with a 12-m by 14-m receiver. The heliostat field had a reflective area of 120 m^2, modeled with the heliostat field tool HFLCal. The distance between rows of torque tubes, the distance between the first row and the tower, and the facet distances were all optimized. The weight of the system was also optimized. The system would potentially be far cheaper to build and install, with a simpler control system, and only had a 3% yield reduction when modeled against a traditional tower and heliostat field of the same size and output.

Extensive wind tunnel and computational fluid dynamics wind modeling have increased the available information for heliostat field design significantly. Reactions of both individual heliostats and heliostat fields are better understood, and designs could be improved with this information. Research by Emes et al. on pressure distributions across heliostats also looked at design wind speeds [17]. The paper did conclude that, based on peak hinge moments, maximum design wind speeds could be increased for a 36 m^2 heliostat. The hinge moment data showed that wind speeds of 29 m/s in a desert, 33 m/s in a suburban terrain, and 40 m/s at stow were all possible for a heliostat with proper drives. However, operating loads decreased by up to 70% for the same conditions when the elevation angle was greater than 45°. The overturning moment occurring at the base of the pedestal was also determined, and to stay below the overturning load at angles elevation angles less than 45°, design wind speeds would be 18m/s for a desert and 21 m/s in a suburban terrain.

Conclusions

To reach the current DOE SETO cost target of $50/m^2 for heliostats, further development is required to reduce costs for components and controls with in large CSP facilities. A comprehensive technical gaps assessment was conducted across the heliostat development path from concept design to field deployment where three tiers of prioritized gaps were identified. These gaps were based on an extensive literature review, survey results of various CSP stakeholders and a TEA of LCOE and LCOH with respect to C&C. The current results indicated that while closed loop controls with automation could reduce LCOH by as high as 11.1%. heliostat-centric standards could potentially reduce LCOH by as much as 15%. Three other Tier 1 gaps were also identified, which included the use of composite materials, advanced wireless communication employment and lower cost mirror designs. Finally, in addition to the Tier 1 gaps, survey results also determined that component integration within heliostats was also a significant challenge, which also should be considered for improving manufacturability and deployment.

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