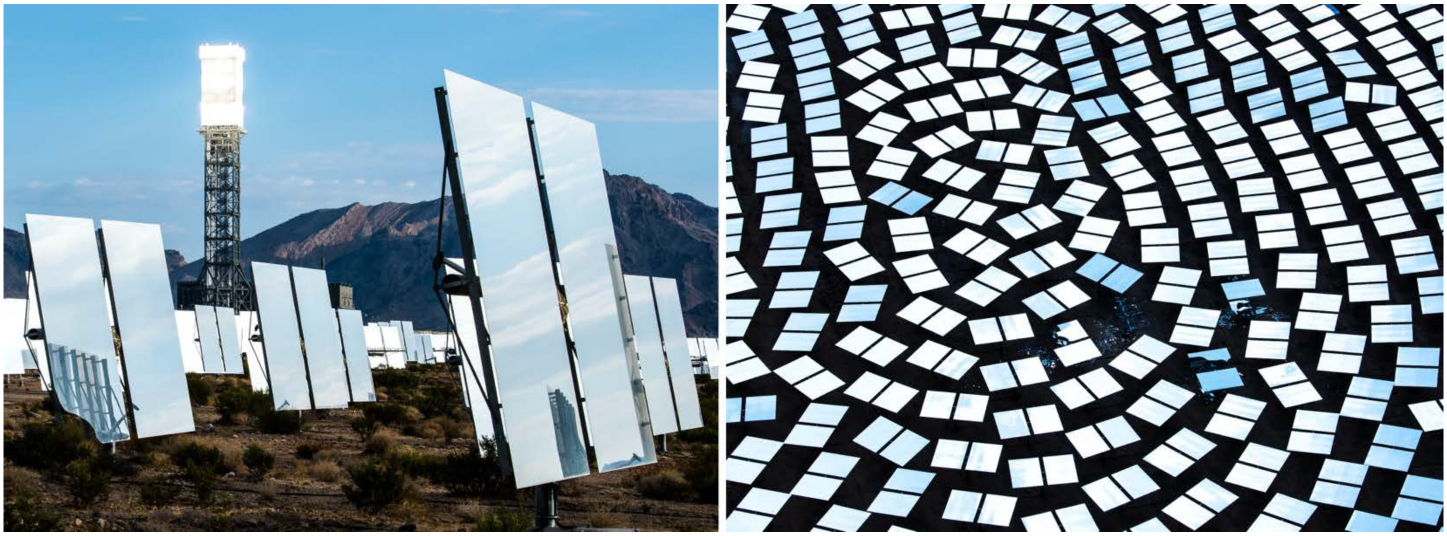

Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power

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3c Queensland University of Technology
3d University of Adelaide

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List of Acronyms

ASTRI	Australia Solar Thermal Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	concentrating solar-thermal power
DEI	diversity, equity, and inclusion
DNI	direct normal irradiance
DOE	U.S. Department of Energy
IEC	International Electrotechnical Committee
IER	investment energy return
IPH	industrial process heat
LE	large electric
LCOE	levelized cost of electricity
LCOH	levelized cost of heat
ME	modular electric
NG	natural gas
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PPA	power purchase agreement
PV	photovoltaic
RFP	request for proposal
RTE	Resources, Training, and Education
SAM	System Advisor Model
sbp	Schlaich Bergermann und Partner, a German company
SETO	Solar Energy Technologies Office
TEA	techno-economic analysis
TES	thermal energy storage
TMY	Typical Meteorological Year

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Thank you to all these supporters for their help making the HelioCon roadmap report a reality.

Executive Summary

Heliostat-based concentrating solar-thermal power (CSP) systems can offer immense potential to provide low-cost, dispatchable renewable thermal and electrical energy to help achieve 100% decarbonized energy infrastructure in the United States. Heliostats are a major determinant of both capital cost and performance of state-of-the-art commercial molten salt towers and Generation 3 CSP systems.[1] In 2021, the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) launched the Heliostat Consortium (HelioCon), a five-year initiative to advance heliostat technologies. The HelioCon mission is threefold: (1) establish strategic core testing and modeling capabilities and infrastructure at national labs; (2) support heliostat technology development in relevant industries; and (3) serve as a central repository to integrate industry, academia, and other stakeholders for heliostat technology research, development, validation, and deployment. In this report, HelioCon presents a roadmapping study on advancing heliostat technologies, intended as a central reference for the entire CSP community.

A Roadmap to Identify and Address Gaps to Heliostat Development

As heliostat-based CSP systems are deployed around the world (current total installed capacity is roughly 2.3 GW), removing commercial risks and improving economic competitiveness is key to attracting additional investors. As such, HelioCon's first step was to conduct a thorough roadmapping study to identify and address technical and nontechnical gaps that limit the development of low-cost, high-performance heliostat technologies with minimized annual operation and maintenance expenses. Gaps are defined as the difference between current state-of-the-art technologies and a future scenario where heliostat-based CSP systems are fully competitive and ready to occupy a substantial market share in the decarbonized energy infrastructure, including electricity, industrial process heat, and solar fuel.

This report summarizes the findings of the HelioCon roadmapping study. The consortium identified gaps, performed detailed analysis to prioritize among three levels ("tiers") of gaps, and recommended pathways to address those gaps. In order to achieve this, HelioCon first organized a workshop to gather industrial stakeholders, subject matter experts, and representatives from relevant sectors. HelioCon also conducted in-depth interviews with heliostat developers. After compiling the gap analysis results, a number of external reviewers were invited to review the results and their feedback was further incorporated into this roadmapping report.

The major technical barriers and recommended strategies are:

- Installation cost reduction:
    - Because the final product in the market is a heliostat field with necessary energy generation units (such as receiver, thermal storage system, and power cycle), cost

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[1] More information on Gen3 technologies can be found at https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp.

  reduction relies on design of both the individual heliostat and the heliostat field. The key performance metric is overall performance of a fully integrated field.

  - Compatibility with high-productivity manufacturing processes is a major design consideration even at the early stage of individual heliostat design.
  - The whole industry would benefit from standard designs of some essential components dominating either performance or cost, such as innovative mirror facet/array manufacturing and low-cost durable drives.
  - Wind load is a dominating factor for heliostat design and heliostat field operation, so a high-fidelity wind load characterization model and a wind load characterization standard are needed.
  - Wireless heliostat field control systems have shown promise in initial commercial deployments. It is expected that the market will continue this trend, maturing in future deployments.

- Performance assurance: Heliostat opto-mechanical errors are still a dominating factor in heliostat performance. Validation of existing metrology techniques and development of new metrology techniques, especially for in-situ outdoor measurement, are needed.
- Operation and maintenance (O&M) optimization: O&M costs are a significant component of energy prices, and mirror cleaning is often the predominant O&M cost for existing power plants. Thus, initial characterization of soiling, as well as mitigation strategies to be used over performance periods of up to 30 years, need to be addressed for commercial heliostat-based projects.
- Commercial risk mitigation: Commercial risks in heliostat-based projects may come from every stage of the project deployment process, from site selection to financing strategy, supply chain establishment, quality control, and end-of-life disposal. In each stage, disagreement from multiple involved stakeholders/parties may create additional risks in achieving a commercial success at the end. Risk mitigation approaches include a third-party quality assurance platform, a high-fidelity heliostat field performance prediction model, a suite of necessary industry standards (such as site characterization, component durability tests, solar field acceptance tests, wildlife deterrence/avoidance), a central database documenting best practices and lessons learned, and expansion of a currently limited workforce. For decarbonization of process heat industries, application of heliostat-based systems lacks precedent, which requires that CSP communities work closely with relevant industry partners through the whole project deployment process.

One other major overall barrier to advancing heliostat technology is the lack of a steady market—meaning a market with a consistent year-to-year deployment rate—to enable capital investment and continuous improvement. This interrupts the development of advanced manufacturing techniques, the establishment of a sustainable supply chain, further cost reduction of heliostats, required workforce expansion, and almost all aspects of heliostat technology improvement. It may be to the advantage of the heliostat industry to develop and explore markets that can accept relatively small-scale projects, rather than focus exclusively on conventional, large-scale power production, with intensive capital risks and long development periods.

HelioCon's detailed gap analysis was carried out under six technical topics:

- Metrology and standards
- Components and controls
- Advanced manufacturing
- Resources, training, and education (RTE)
- Field deployment
- Techno-economic analysis (TEA).

Two special subtopics, wind load and soiling, were also analyzed. Major gaps are highlighted for each topic and subtopic below.

Metrology and Standards

Appropriate measurement techniques and industry standards are fundamental for product design, prototyping, engineering, and improvement.

Gaps in metrology: Opto-mechanical metrology (mirror slope error, mirror facet canting error, and heliostat tracking error) is complex, error-prone, and requires high optical precision, necessitating rigorous validation of different technologies using the same measurement parameter(s). Current metrology gaps include:

- Lack of at least two viable metrology techniques for a given measurement parameter (such as heliostat tracking error, available for the global CSP industry)
- Insufficient or missing validation of any viable metrology technique against a different, trusted metrology technique or ground-truth article.

Gaps in standards: Gaps in community-wide standards for site characterization and heliostat design, testing, field design, and field acceptance test protocols result in significant barriers for new developers, extended design cycles, lower investor confidence, and more complicated arbitration between project parties. Gaps include:

- Heliostat terminology
- Heliostat design guidelines
- Heliostat solar field design/simulation guidelines
- Heliostat test guidelines
- Heliostat solar field acceptance test guidelines
- Site characterization guidelines (e.g., wind, topography, soiling characteristics).

Recommended pathway forward: Addressing these gaps requires continuing development of new metrology tools and round-robin tests of existing/to-be-developed tools. More importantly, one or more globally available third-party evaluation platforms possessing a full spectrum of validated metrology tools would be of critical value in providing an independent performance assessment of pre-commercial heliostat products or newly proposed metrology techniques.

Although the development of standards can be time consuming and require collaborative efforts from the entire international community, a strategic collaboration mechanism can be developed to integrate the whole community to address the gaps in standards. Addressing the gaps in metrology and standards is necessary to develop next-generation heliostat products and remove potential commercial risks for new project validation and deployment.

Components and Controls

Heliostats comprise static and dynamic components operating in a highly controlled manner to provide accurate solar flux pointing. The general composition includes a reflective area, a control system, and the mounting and tracking mechanism. Alternative materials and components are being considered to reduce heliostat weight, while improving rigidity and control and reducing costs. Additionally, resilient control of the heliostat is required for adjustment of heliostat structure so it can accurately track sun position to reflect 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. Heliostat durability and reliability are not well characterized but are of key importance to ensure high performance and safe operation over the designed lifetime. Component degradation and failure, particularly for drives, mirrors, and electronics, are also not well documented in literature but are critical for predicting long-term system performance and planning, as well as financing system O&M.

Gaps in components and controls:

- Lack of lower-cost mirror designs with comparable performance to existing glass mirrors
- Lack of lightweight composites or other advanced structures (e.g., torque tubes, pedestals, foundation) to achieve cost targets and reduce dynamic component costs (e.g., drives)
- Lack of closed-loop controls to achieve higher flux performance and auto alignment/calibration processes
- Missing wireless systems approaches, including standardized requirements and testing capabilities, to capitalize on lower plant costs while avoiding associated risks and technical issues.

Recommended pathway forward:

- Assess composites or other advanced structures; lower-cost mirror designs are needed with comparable performance to existing glass mirrors
- Assess technical ability of drives and promote new drive designs to reduce costs and improve reliability
- Analyze heliostat advanced controls for wireless closed-loop configurations
- Design standards development for heliostats to enable bankable components and controls, increase heliostat long-term performance, and shorten design improvement cycles.

Advanced Manufacturing

Heliostat manufacturing directly influences both solar field cost and revenue and is a major contributor to overall CSP economic performance. Efficient manufacturing begins with initial product design; continues through supply chain, procurement, component manufacture, factory assembly, transportation, and field installation; and ends when a functional heliostat is installed in the field.

Gaps in advanced manufacturing:

- A lack of innovative heliostat mirror facet/array designs with low cost and high performance
- Insufficient facet/array fabrication process knowledge for high economic performance
- Heliostats are not designed for high-productivity manufacturing
- Lack of heliostat developers' experience designing high-productivity manufacturing lines.

Recommended pathway forward:

- Pursue advanced facet and mirror array designs. Consider extensions of past research developing composite mirrors
- Advance both self-supporting facet design concepts and simultaneous facet/array construction concepts
- Establish direct collaboration between heliostat developers and manufacturing solution partners, starting early in the design phase
- Ensure heliostat designs include factory productivity estimates, input assumptions, factory capital cost, and factory operating cost.

Resources, Training, and Education

The heliostat workforce community in the United States is currently very small, with knowledge and expertise not widely available. To address this, RTE encompasses resources, practices, programs, and opportunities to provide newcomers with an adequate knowledge base and training to conduct R&D efforts; help newcomers join the workforce; and foster a productive, healthy, and fulfilling environment for all workers.

Gaps in RTE:

- Little public awareness of heliostat technologies and little exposure to the industry among students
- Lack of publicly accessible resources, such as institutional knowledge like best practices and lessons learned, education/training resources, industry/plant data, and reference materials
- Lack of communication/collaboration between universities and industries/research institutions, and little CSP- or heliostat-focused research in universities

- A lack of guidance and resources for promoting diversity, equity, and inclusion (DEI) in the heliostat workforce and for engaging underserved communities.

Recommended pathway forward: Addressing these gaps will require creating needed resources for the existing workforce community and developing strategies and practices to draw outsiders into the industry. A public relations campaign through social media and university outreach through curriculum development and collaboration opportunities will need to be conducted to increase awareness and interest for heliostat technologies among students and the larger public. To enable the workforce to possess the knowledge and skills necessary to progress the industry, fundamental training and education materials should be developed, and industry knowledge and tools should be compiled in a centralized web-based resource database. Critically, these paths must be pursued while simultaneously broadening the existing workforce through DEI efforts.

Field Deployment

This topic covers all activities required to establish a functioning solar field including site selection, power production modeling, capitalization, permitting, supply chain management, heliostat top-level assembly and installation, and field O&M. The overarching difficulty in field deployment is that each deployment is site specific and heliostat specific, and there have not been enough deployments in a representative time frame or environment to clearly identify the most impactful needs for cost reduction.

Gaps in field deployment:

- CSP projects have relatively high cost for the amount of risk posed by developing technologies and are therefore difficult to capitalize. Key areas of risk include permitting challenges attributed to environmental and land use disputes, power production models that lag behind actual production, and higher than expected costs associated with deployment and O&M costs. Diversification can potentially lead to more deployments and associated cost savings from economies of scale, but industries that could most benefit from industrial process heat (IPH) are often not familiar with CSP. In consort with efforts to develop the other solar thermal components, resources that help industrial plant owners conceptualize heliostats as a solar collector are not readily available and new industry-centric tools to quickly provide first order field layout archetypes, performance models, and TEA for new and retrofit industrial field layouts are needed.
- Costs specific to field deployment and O&M are not well understood due to the uniqueness of each deployment, making it difficult to quantify the impact of technological cost reductions such as automated washing systems, wireless communications, wireless photovoltaic power, and towerless calibration methods.

Recommended pathway forward:

- Reduce actual and perceived investor risk related to production shortfalls, reliability issues, environmental remediation, or permitting barriers by identifying and solving key sources of modeling uncertainty, leading the development of a set of reliability standards for components and manufacturing, developing technology to protect endangered species, and avoiding community opposition by establishing guidelines and best practices for engaging with neighboring communities
- Accelerate adoption of CSP using heliostats in high-carbon industries by developing industry-centered tools that improve familiarity and readiness of CSP as a source of energy. Work with IPH partners in one or more thermal energy-intensive industries such as glass, steel, hydrogen, or cement to develop intuitive software tools that quickly assess the requirements, costs, and opportunities for heliostats in new and retrofitted plants
- Work with operators, developers, and engineering, procurement, and construction firms of existing CSP plants to consolidate and analyze financial records for deployment-specific costs and field-specific O&M costs. Identify the contributing factors with the highest impact such as location, geology, and heliostat design.

Techno-Economic Analysis

TEA uses models and analysis to quantitatively assess the benefits of heliostat design, manufacturing, and operation concepts. A central objective of this topic is to relate the cost and performance of heliostats and heliostat components to the overall system performance.

Gaps in TEA: Most of the TEA gaps identified are related to developing models or data. These include:

- Lack of a validated model for (1) solar field O&M costs and for (2) high-temperature IPH applications
- A poor understanding of (1) the linkage between heliostat research and model inputs, and (2) the impact of construction and commissioning costs on project economics.

Recommended path forward:

- Develop a heliostat field O&M model that accounts for the cost of mirror washing and heliostat repairs and replacements, and their impact on heliostat field performance
- Develop a CSP model that creates and incorporates correlations for tower and receiver costs for IPH applications
- Coordinate work with other HelioCon topics, perform sensitivity analysis in models, and engage industry to improve knowledge gaps.

Special Subtopic: Wind Load

Wind loads are a major driver of heliostat cost. Standardized methods and tools are needed for a more detailed understanding of the static and dynamic loads of a heliostat design. This will increase field efficiency and reliability to reduce the risk of component failures due to high-wind events and, when applicable, enable cost reduction of wind-dependent heliostats to avoid unnecessarily conservative heliostat designs.

Gaps related to wind load:

- Lack of site characterization for wind measurements
- Insufficient critical load cases for heliostat design
- Insufficient understanding of turbulence impacts on heliostat tracking error
- Lack of knowledge on wind load under various heliostat array configurations
- Underexplored heliostat field wind load reduction and operating strategies.

Recommended pathway forward:

- Develop wind load and site characterization guidelines for heliostat design
- Develop heliostat field wind load models with optical performance impacts.

Special Subtopic: Soiling

Heliostat soiling is a major detrimental factor in CSP plants because it limits overall energy input to the receiver. High soiling rates may dramatically decrease revenues and can expose CSP projects and investors to high risk of failure. More studies are required to reliably assess the reflectance state of a whole solar field and to boost both active and passive innovative cleaning methods, including issues related to water scarcity in arid locations.

Gaps related to soiling:

- A lack of accurate characterization of soiling losses during site selection
- Design and automation of new cleaning systems are underexplored
- No established standards or test data to assess anti-soiling coating performance and durability
- A poor understanding of trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, stow strategy, solar multiple), and heliostat reliability.

Recommended pathway forward:

- Create a soiling database to develop a common understanding of the airborne dust and soiling characteristics for relevant sites
- Develop soiling assessment methodologies and analysis tools to characterize soiling during site selection and initial plant design
- Review existing mitigation (e.g., cleaning) practices/technologies, characterize their performance, and develop baseline practices
- Develop standards and tests for optical performance of coatings in CSP applications
- Refine methods and develop software for optimizing cleaning strategies to integrate with existing design optimization tools. These tools will be used to understand the effect of design choices on soiling losses and cleaning costs.

HelioCon's Path Forward

This report is intended as a guiding reference for the entire heliostat community, with a goal of fulfilling gaps to enable the success of the CSP industry as a whole, rather than a single project or entity. HelioCon will use the roadmap to guide its work plan for its performance period. Major anticipated outcomes from HelioCon include:

- A fully validated third-party performance assessment platform for an integrated heliostat and its components
- A series of modeling and testing guidelines and standards
- A publicly available, easily accessible suite of tools, models, and resources for the public
- An engaged, active heliostat community to further advance heliostat technologies.

We aim to utilize the developed capabilities and infrastructure to help reduce commercial risks and support the CSP industry to develop more competitive heliostat technologies in the future energy market.

HelioCon cannot achieve this alone—let's work together. We call on the entire international community to collaborate to address the most impactful gaps and advance heliostat technologies into a fully mature product on an accelerated timeline.

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1 Introduction

Concentrating solar-thermal power (CSP), typically coupled with low-cost thermal energy storage (TES), is a renewable technology that can provide dispatchable electricity or heat to our transforming energy infrastructure and contribute to 100% decarbonization [1]. CSP uses a large volume of tracking reflectors (such as heliostats) to concentrate sun rays to a receiver at the focal point, which can provide direct heat at a temperature over 1,000°C with a point-focus CSP technology (power tower or dish engine). In the commercial market, the operation temperature is determined by techno-economic system optimization for a given application. The produced heat can be used for a variety of industrial processes, or be used in a thermodynamic cycle to produce electricity to the grid.

Power tower is one type of commercial CSP technology, along with parabolic trough, linear Fresnel, and dish engine. Heliostats are the very core element of CSP power tower technology [2]—they are two-axis tracking mirrors that direct the sun's rays toward a receiver at the top of the tower (illustrated in Figure 1). Power tower technology has been used to produce heat at a temperature of approximately 550°C in several utility-scale electricity generation plants deployed around the world. It has also been identified, by the U.S. Department of Energy (DOE), as the most promising Gen 3 CSP technology, with a target of achieving temperatures above 700°C [3]. The high-temperature heat generation of power tower systems can result in: (1) a high-energy-density (and therefore low-cost) TES system; (2) a higher thermodynamic cycle efficiency for electricity generation; and (3) a potential renewable source for decarbonizing heavy-duty industries requiring high-temperature process heat, such as cement, steel, and chemical production.

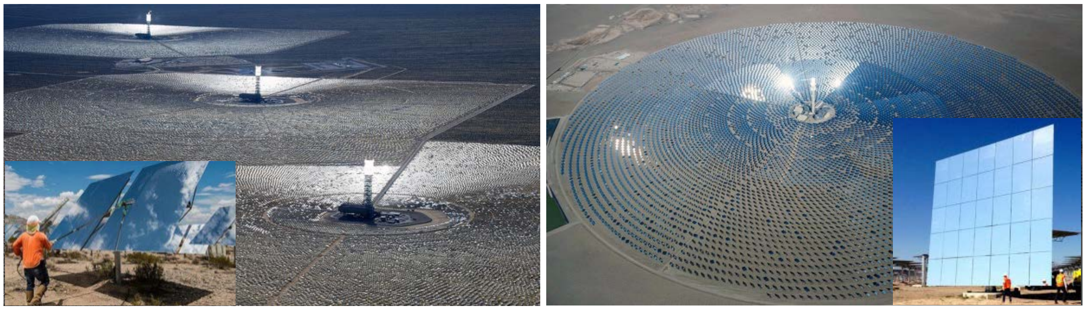


Figure 1. Heliostat size varies widely at deployed U.S.-based utility-scale power tower plants—ranging, for example, from 14 m^2 at Ivanpah (left), to over 100 m^2 at Crescent Dunes (right). HelioCon will advance an established heliostat design and manufacturing approach within the United States.

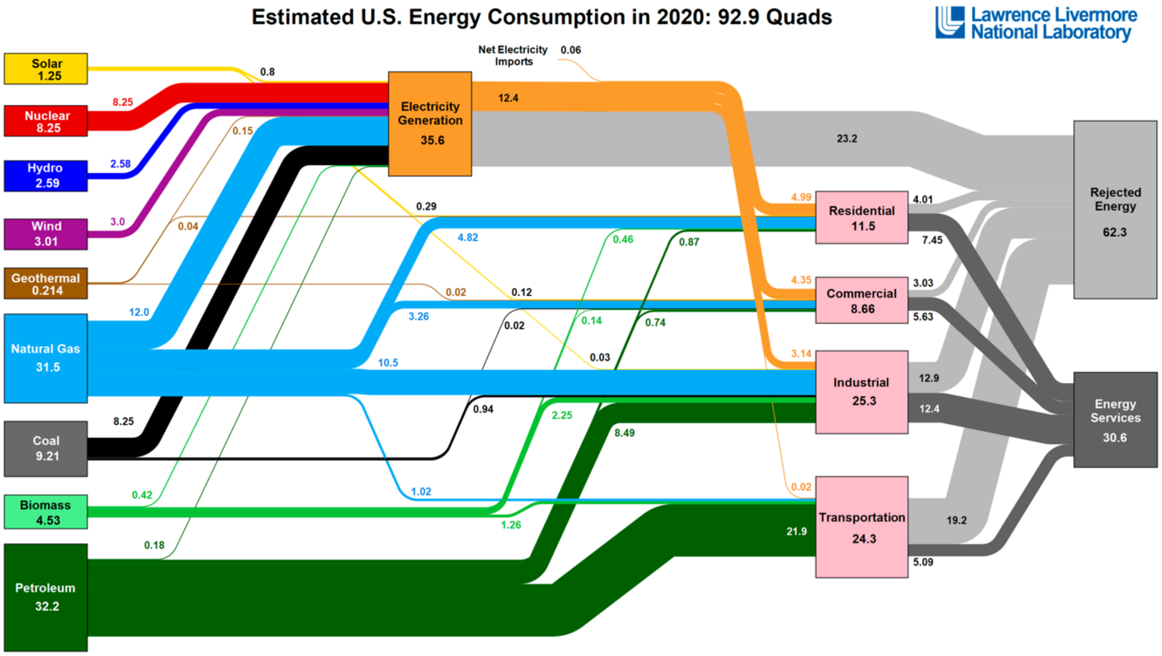
Photos from Getty Images, DOE, and NREL

Substantial challenges and opportunities exist in advancing heliostat technologies for lower cost and/or higher performance. A heliostat consortium, called HelioCon, was established in 2021 to integrate all types of stakeholder input to address these challenges. Funded by DOE's Solar Energy Technologies Office (SETO), HelioCon is led by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia). The U.S. national labs are partnering with the Australian Solar Thermal Research Institute (ASTRI) [4], and are closely working with developers, utilities, and other experts. HelioCon plans to expand its membership through a future request for proposal and award process.

In this report, HelioCon intends to identify and prioritize the technical and nontechnical gaps in the research, development, validation, and deployment of state-of-the-art and next-generation heliostat technology systems. This report will serve as a general reference for HelioCon to plan work for the remaining performance period and as guidance to engage additional relevant entities for productive collaboration.

1.1 Background

CSP can play a significant role in the future decarbonized energy infrastructure. Total estimated U.S. energy consumption in 2020 is illustrated in Figure 2. Though a majority of commercial CSP systems have contributed to electricity generation, CSP also shows strong potential for industrial process heat, fuel generation for transportation (such as hydrogen), and heating and cooling for district and commercial buildings.

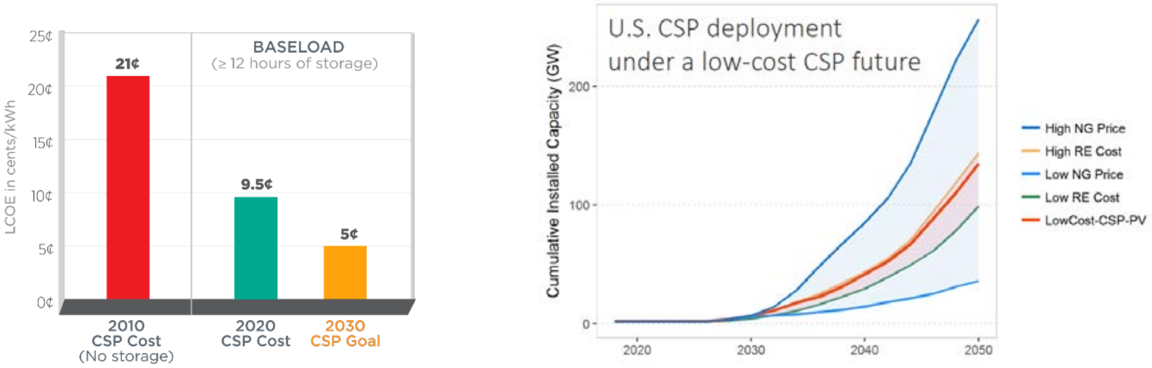


Source: LLNL March, 2021. Data is based on DOE/EIA MER (2020). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 2. Estimated U.S. energy consumption in 2020

Figure from Lawrence Livermore National Laboratory/DOE [5]

In particular, heliostat-based CSP systems could be competitive in dispatchable electricity generation, solar fuel, and heavy industry process heat applications once its economic performance can be further improved. Taking electricity as an example in Figure 3, it is projected that, if a baseload heliostat-based electricity generation system with a storage of 12 hours or more can achieve a cost target of 5 cents per kWh, its commercial deployment may reach a total commercial scale of 35 to 200 GWe by 2050 and may account for 3.5%–20% of national electricity generation for a given scenario [6].



(a) (b)

Figure 3. Projection of performance (a) and U.S. deployment (b) on CSP Gen 3 heliostat-based systems

Figures from [7], [8]

Additionally, when the 2030 performance goal for the heliostat-based CSP systems is met, it would have great potential in non-electricity sectors as well.

1.2 Roadmap Vision and Objectives

HelioCon envisions that competitive heliostat-based CSP systems will contribute to the future energy infrastructure in more than one sector:

- Utility-scale electricity generation systems with dispatchability [3], [8]
- Heavy-duty industrial processes requiring high temperature (500°C or above) [9]
- Solar fuel production with solar heat [10], [11].

In order to achieve commercial competitivity of heliostat-based CSP systems in the future energy market, the consortium will be focused on all major aspects of heliostat fields, which include:

- Heliostat installation cost [12]
- Heliostat technical performance, which includes a variety of metrics such as solar field layout, heliostat optical performance, heliostat degradation, and control strategy [13]
- Heliostat field operations and maintenance (O&M) [14]–[16]
- Minimized commercial deployment risks.

Levelized cost of energy (LCOE) or heat (LCOH) has been adopted by DOE to assess economics of renewable energy technologies. The target value for heliostat-based CSP systems is 5 cents/kWh$_e$ for LCOE or 0.8 cents/kWh$_t$ for LCOH, which would enable sufficient competitivity of CSP systems in the future renewable energy market.

The consortium aims to develop a roadmap of strategic technology development to address the gaps between the state-of-the-art technologies and the future scenario where heliostat-based CSP systems are fully competitive and ready to occupy a substantial market share in the future decarbonized energy infrastructure. The gap analyses are categorized into six topic areas:

- Techno-economic analysis
- Metrology and standards
- Components and controls
- Advanced manufacturing
- Resources, training, and education
- Field deployment.

In addition, we review two special subtopics:

- Wind load
- Soiling.

Specifically, the HelioCon roadmap objectives are:

- To provide a reference on heliostat technologies to the entire CSP community and synchronize the relatively small community to address the most critical gaps/barriers that prevent CSP technologies from becoming commercially competitive.
- To guide the HelioCon work plan for the remainder of the performance period and maximize the projected value of the HelioCon resource to advance heliostat technologies.

1.3 Report Organization

Section 1 provides an introduction to the role of CSP in future energy infrastructure and the objective of the roadmapping study. In Section 2, the baseline heliostat systems are carefully defined to illustrate various application scenarios of heliostat technologies and underpin later techno-economic analysis (TEA) of identified gaps. Section 3 describes HelioCon's approach to conducting the gap analysis and roadmap study. Sections 4–11 provide detailed gap analysis and roadmap study for six major HelioCon topics and two special subtopics. Finally, Section 12 concludes the report.

2 Starting Point: Heliostat Baseline Performance

As of the end of 2021, CSP had a total commercial deployment capacity of 6.8 GWe around the world [17]. While the United States has world-class CSP resource conditions, the Middle East/North Africa (MENA), Morocco, and China are the most promising regions and have plants both deployed and under construction, most of which are heliostat-based power tower technologies. Overall, heliostat-based power tower systems compose about 2.3 GWe (including plants currently operating and those under construction), while parabolic trough is the current dominating technology in commercial deployment.

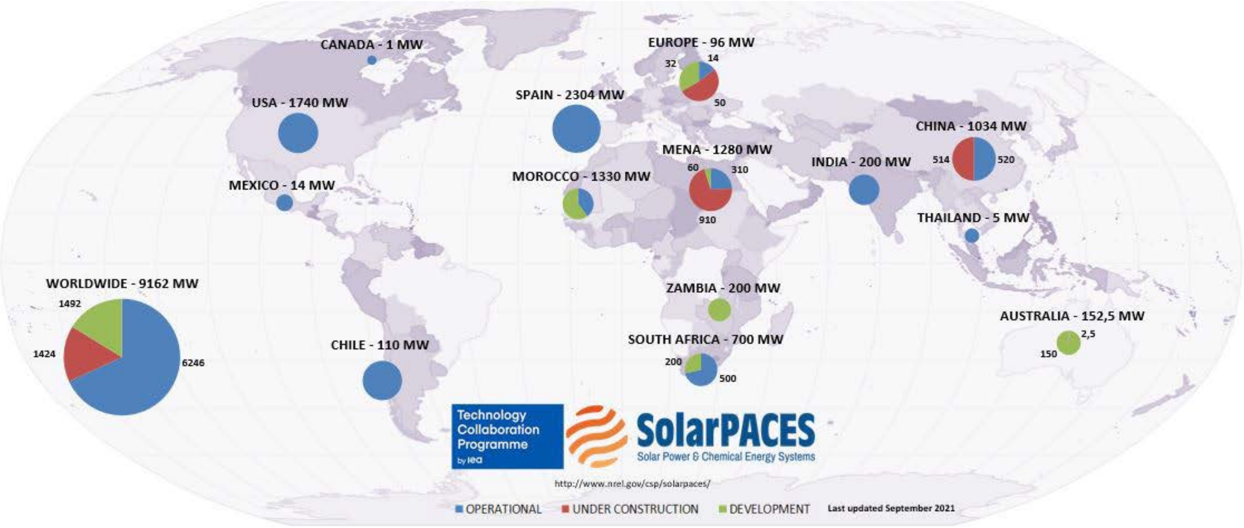


Figure 4. Commercial CSP projects around the world

Figure from [17]

Per HelioCon's initial survey as of 2022, 14 different heliostat designs have been adopted in commercial sites around the world, as summarized in Table 1. The majority of field layouts in the commercial sector are radial. The size of heliostats varies from 14.1 m^2 to 178.5 m^2; the number, shape, and size of facets for each heliostat vary as well. Most back structure designs utilized struts arranged in either one-dimensional or two-dimensional patterns.

There is no consensus in the CSP community regarding the optimum size of a heliostat, as seen in Table 1. The reasons for selecting either larger or smaller size heliostats are as follows:

- Larger heliostats seek to maximize the use of expensive subsystems, such as drives and control systems. Cost of drives and control systems can be a key factor determining overall cost of a heliostat and a heliostat field.

- Larger heliostats imply fewer heliostats for a given heliostat field capacity, leading to less field trenching and shorter power/communication lines. Smaller heliostats are moving toward wireless power and control systems, seeking to eliminate the trenching and wiring altogether.

- Larger heliostats, being farther off the ground, may have less soiling accumulation over time, thus reducing O&M cost.

- Smaller heliostats may offer higher optical performance and improve solar field efficiency.

- Smaller heliostats are subject to smaller wind loads, which increase non-linearly with heliostat height, and also smaller gravity loads.

- Smaller heliostats are more compatible with high-volume automated production processes and reduce/eliminate on-site intensive assembly efforts. In addition, transportation of smaller heliostats becomes easier and of lower cost.

- Smaller heliostats can be more conducive to automated in-line quality-control.

The optimum size of a heliostat will be a balance between installation cost, performance, and O&M. Following are recommended design considerations:

- Heliostat field size has a large impact on the design requirements. For example, a large diameter field may require multiple facet focal lengths. In addition, a larger field might have heliostats up to 1,500 meters from the receiver. This distance reduces the allowable error for the heliostat's optical performance. Requirement of multiple focal lengths for a single project may lead to additional design complexity.

- Mass production capability and efficiency of a heliostat design relies on specific design characteristics and is crucial to eventual success of the final heliostat product.

- Supply chain can have a strong impact on cost of components and may vary with time. An optimum design should have design flexibility to accommodate the ever-varying supply chain situation.

- Wind load varies with heliostat size and is a major load requirement for heliostat design. A high-fidelity wind load calculation model will be valuable.

- Availability of metrology is essential to heliostat design, mass production, installation, and operation. However, metrology has been insufficient in past heliostat design processes. Sufficient metrology techniques must be employed in future heliostat development.

- Wireless control with stand-alone PV power supply can eliminate field trenching, power lines, and communication lines at a solar field. This has been implemented at the Ashalim solar power tower plant in Israel. While wireless control technology is projected to be maturing in future, it may drive the optimum heliostat size to be smaller.

- Local site characteristics can have a strong impact on heliostat design. Site variation may include, but is not limited to, topographic characteristics, wind load, local labor market, weather conditions (such as solar irradiation and extreme weather conditions), soiling and soiling mitigation techniques, local policies that affect project development, site preparation, plant construction, and plant operation.

With the observations above, HelioCon foresees that maturing wireless control technology, availability of design-specific drives, and maturing mass production techniques will have a strong impact on the optimum size selection of next generation heliostats. Additional discussion regarding heliostat size and its implications for design and production can be found in Section 7.1.

Table 1. Summary of Commercially Operational Heliostat Designs Around the World[2]

Title	Country	Heliostat Dimensions (Xm x Ym)	Number Heliostat Facets	Heliostat Facets (col x row)	Heliostat Mirror Area (m^2)	Heliostat Back Structure	Generating Capacity (MW)	Total Facets	Solar Field Developer
Shouhang Dunhuang 100-MW Phase II	China	10.8 x 10.8	35	7 x 5	115.7	stamped	100	420,000	Beijing Shouhang IHW
Hami 50-MW CSP Project	China	~7.9 diameter	10	pentagon	48.5	pentagons	50	145,000	sbp sonne
Luneng Haixi 50-MW Molten Salt Tower	China	-	32	4 x 8	138.0	xy-struts	50	140,800	Luneng Qinghai Guangheng New Energy Co., Ltd
POWERCHINA Gonghe 50-MW CSP Plant	China	5.8 x 3.5	4	2 x 2	20.0	y-struts	50	120,064	Supcon Solar
SUPCON Delingha 50-MW Tower	China	5.8 x 3.5	4	2 x 2	20.0	y-struts	50	108,540	Supcon Solar
Shouhang Dunhuang 10-MW Phase I	China	10.8 x 10.8	35	7 x 5	115.7	stamped	10	52,500	Beijing Shouhang IHW
Ashalim Plot B	Israel	4 x 5.2	4	2 x 2	20.8	y-struts	121	202,400	BrightSource Energy
NOOR III	Morocco	13.4 x 13.4	54	9 x 6	178.5	stamped	134	399,600	ACWA
Khi Solar One	South Africa	13.1 x 10.7	16	2 x 8	140.0	xy-struts	50	65,920	Abengoa Solar - IDC
Gemasolar Thermosolar Plant	Spain	11.5 x 10.4	35	7 x 5	120.0	stamped	19.9	92,750	Torresol Energy
Planta Solar 20	Spain	12.9 x 9.6	28	4 x 7	120.0	xy-struts	20	35,140	Abengoa Solar
Planta Solar 10	Spain	12.9 x 9.6	28	4 x 7	120.0	xy-struts	11	17,472	Abengoa Solar
Crescent Dunes Solar Energy Project	United States	10.3 x 11.23	35	7 x 5	115.7	stamped	110	362,145	SolarReserve, LLC
Ivanpah Solar Electric Generating System	United States	4.55 x 3.0	2	2 x 1	14.1	y-struts	377	347,000	BrightSource Energy

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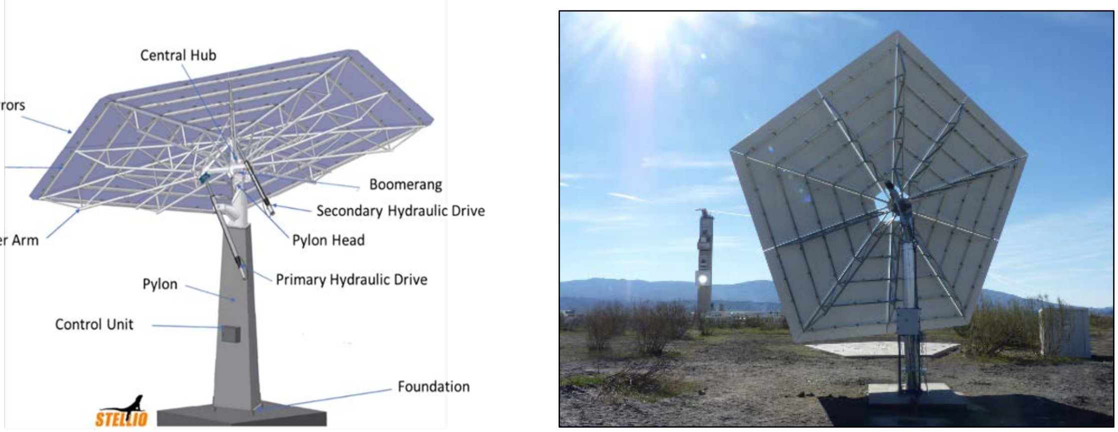
[2] Heliostat size parameters were estimated by approximate methods such as manual measurement of satellite imagery. Back structure assessments were made by viewing images in various documents available on the internet. Therefore the information in this table should be viewed as rough estimates for comparison purposes, but not detailed analysis.

Market competitiveness of a commercial design largely relies on its installation cost before deployment, as well as its long-term performance and additional O&M costs. The installation cost is a collective cost of all components and their assembly. It accounts for costs of parts, associated labor, transportation to site, site preparation, site foundation, and solar field infrastructure. The long-term performance is largely the optical precision of heliostats in the field, and it will determine whether the amount of power reaching to the receiver would meet the design point of a deployed system. The dominating factors are opto-mechanical errors such as mirror slope error, facet canting error and heliostat tracking error, and soiling. A full list of contribution factors is given and elaborated in Section 5. The O&M cost is required to maintain the solar field performance and occurs at a daily basis at a given commercial field. It can be a substantial, but often neglected, contributor to the final cost of delivered energy.

2.1 Example Heliostat Design

Detailed review of commercial heliostat designs can be found elsewhere [13]; however, performance and O&M experiences of commercial heliostat designs are usually not available in the public domain. Here we present cost analysis of an example heliostat design to illustrate the cost formation of a given commercial heliostat design.

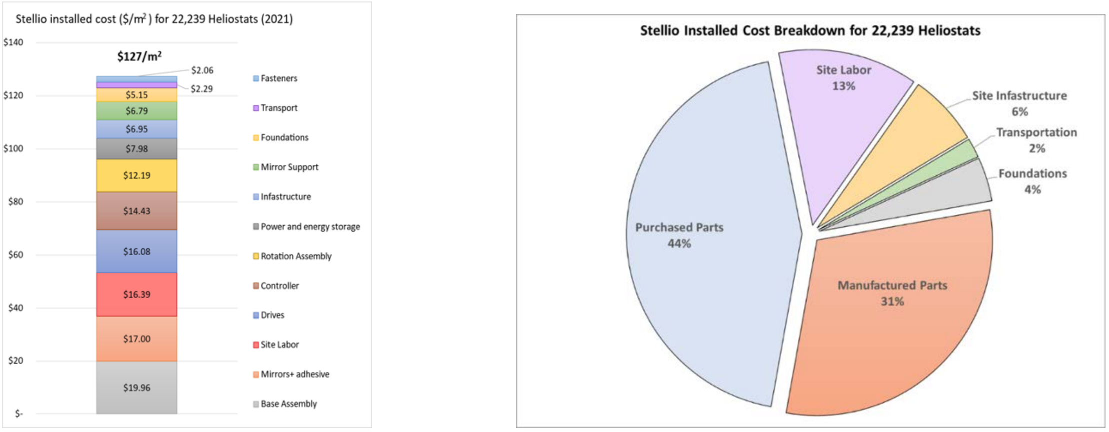
The Stellio design, developed by sbp sonne [18], is employed in a newly constructed 50-MW Hami pilot plant in China [19]. NREL has conducted a bottom-up analysis of the design and verified projected costs against sbp's assessment [20]. A design schematic and an installed heliostat are illustrated in Figure 5. The design uses a pentagon shape to mimic a desirable circular edge of a heliostat, although most commercial designs adopt a rectangular shape. A radial strut is used for the back structure. Its installation cost at a mass production of over 22,000 units is broken down into two cost categories, as given in Figure 6. Base assembly, mirror and adhesive, site labor, drive, and controllers are the dominating cost factors in this case. To reduce the installation cost, these factors would be the potential focus areas for improvement as detailed throughout Section 6.



(a) Design schematic (b) The installed heliostat in field

Figure 5. sbp Stellio design

Images from [20]



(a) Cost breakdown of a single heliostat (b) Cost breakdown of a utility-scale heliostat field

Figure 6. sbp Stellio heliostat cost breakdown

Data from [20]

2.2 Baseline Heliostat Systems

We developed three hypothetical baseline cases that may be used to evaluate the impact of various improvements to cost, efficiency, or both on a measure of the fully burdened cost of the CSP plant's solar collection system, such as LCOH, via TEA. Table 2 summarizes key characteristics of the baseline systems that serve as inputs to NREL's System Advisor Model (SAM) [1], the tool we use for our TEA assessments. The costs that serve as inputs to these cases are sourced from the 2021 CSP baseline costs available in SAM.

We developed three case studies with plants of varying sizes, in which the power rating of the receiver for the first two electric cases is derived using the electric power rating and solar multiple of the plant. The three baseline cases we adopt are: (1) a large, commercial-scale electricity plant with a 727-MWt receiver (about 100 MW_e equivalent); (2) a smaller, modular electricity plant with a 100-MWt receiver (about 20 MW_e equivalent); and (3) a small, modular plant used for industrial process heat with a 30-MWt receiver. We refer to these cases as large electric (LE), modular electric (ME), and industrial process heat (IPH), respectively. The LE and ME are assumed to have hot-side temperatures of 575°C similar to currently operating plants, while the operating temperature of the IPH case focuses on high-temperature industrial applications and is assumed to have a nominal temperature of 1,000°C to reflect a future industrial application such as a solar fuel production process [21]. The three baseline cases are all analyzed and developed using optimization modeling in SAM and Solar Power Tower Integrated Layout and Optimization Tool (SolarPILOT) [22] to minimize LCOH, but the specific parameters that are optimized vary by the case. Table 2 summarizes key parameters and costs for the baseline cases in SAM. Note that while heliostat and plant sizes vary widely, cost curves and cost rates are common for all three cases, and are taken from the baseline costs from the 2021 version of SAM.

Heliostat Size

Each case has a heliostat size that changes with the power rating of the receiver. The dimensions were selected to maintain a similar ratio between the receiver height and the heliostat height across cases. We found that this scaling tended to avoid excessive spillage, especially for the IPH case, which assumes a single facet per heliostat. The LE plant utilizes the SAM baseline parameters for heliostat dimensions of 12.2 m each for length and width; the ME plant has heliostats with length and width that are half those of the LE case; and the IPH case's heliostat length and width are obtained via optimization in SolarPILOT using a starting point of half the length and width of the heliostats in the ME case.

Receiver, Tower, and Solar Field

All three cases obtain solar fields optimized using the radial stagger layout with the default settings in SolarPILOT, with heliostat locations chosen according to power delivered to the receiver using 950 W/m^2 direct normal irradiance (DNI) with solar angle at the summer solstice in Daggett, CA. For the two electric cases, the receiver dimensions and the tower height were concurrently optimized in SAM. We adopted a different approach for the IPH case due to the importance of a high concentration ratio and known power rating, which suggest a certain receiver size. Specifically, we assumed a receiver aperture that had equal width and height and used the guidance from Li et al. [23] indicating that a concentration ratio of approximately 1,250 suns would be sufficient and cost-effective for a potential future IPH application of up to 1,400 K. For a 30-MW thermal receiver and a design point of 950 W/m^2 DNI, this leads to an aperture with height and width of 4.776 m. Then, the heliostat dimensions, receiver elevation orientation, and tower height are optimized in SolarPILOT.

Validation via SolarPILOT Performance Simulation

Once the dimensions of the tower, receiver, and (in the IPH case) heliostats have been obtained, a performance check is conducted in SolarPILOT by replicating the parameters of the solar field, tower, and receiver obtained from the optimization and running a performance simulation at the summer solstice and ensuring the thermal power delivery to the receiver meets or exceeds its rated power. The performance simulation in SolarPILOT assumes a flat plate, so we assume that all flux delivered to the aperture is delivered to the cavity receiver in this performance estimate. As cavity receiver model development continues in SAM and more feedback is obtained, these estimates may be updated.

Table 2. Input Parameters for the LCOH Calculations of a Given Heliostat Baseline System, Assuming the Heliostat Design and Field Layout Are Determined

Impact Category	Input Parameters	Large Electric (LE)	Modular Electric (ME)	Modular Industrial Process Heat (IPH)	Source
Heliostat Field					
	Total reflective surface area (m^2)	1,469,158	207,864	78,086	LE: Optimized in SAM ME, IPH: Optimized in SolarPILOT
	Reflective surface area per heliostat (m^2)	144.37	36.09	10.16	LE: Baseline 2021 SAM values ME: Reduced LE dimensions by half for height and width IPH: Optimized in SolarPILOT
	Field layout	Surround, cylindrical receiver	Polar, cavity receiver	Polar, cavity receiver	LE: Optimized in SAM ME, IPH: Optimized in SolarPILOT
	Aiming strategy	Multi-aimpoint, heuristic aiming strategy from SolarPILOT “Image size priority” setting in SolarPILOT			SolarPILOT heuristic aiming strategy
	Land cost	$10,000/acre			2021 SAM Baseline
Heliostat Design					
Installation Cost	Site improvement ($MM)	23.5	3.3	1.2	Expenses related site preparation (e.g., roads and grading) and other equipment not covered in the heliostats category below. Cost of $16/m^2 taken from SAM Baseline assumptions for 2021.
	Heliostats ($MM)	205.7	29.1	10.9	Expenses related to installation of the heliostats, including heliostat parts, field wiring, drives, labor, and equipment. Cost of $140/m^2 taken from SAM. Cost of $140/m^2 taken from SAM 2021 Baseline.
	Contingency ($MM)	22.9	3.2	1.2	10% contingency costs assumption taken from SAM 2021 Baseline.
	Indirect costs ($MM)	40.3	5.7	2.1	Includes engineering, procurement, and construction and owner costs, such as permitting, royalty payments, consulting, management or legal fees, geotechnical and environmental surveys, interconnection costs, spare parts inventories, commissioning costs, and the owner's engineering and project development activities. 17.6%

Impact Category	Input Parameters	Large Electric (LE)	Modular Electric (ME)	Modular Industrial Process Heat (IPH)	Source
					of installation costs assumption taken from SAM 2021 Baseline.
	Total ($MM)	**292.4 (\$199/m^2)**	**41.4 (\$199/m^2)**	**15.5 (\$199/m^2)**	\$140/m^2 install cost plus \$16/m^2 site improvement, plus 27.6% contingency and indirect costs
Performance	Solar reflectance design value	90% reflectance			2021 SAM Baseline; includes impact of base reflectivity and average soiling
	Cleanliness factor as a function of time within a washing cycle	63 washes/year (approx. 1 per 6 days)			2021 SAM Baseline
	Degradation rate as a function of time (%/month)	No degradation assumed			2021 SAM Baseline
	Optical error (single-axis slope error equivalent)	2.0 mrad			Given by industry feedback as a measure of conservatism beyond the SAM 2021 baseline of 1.53 mrad. Single-axis slope equivalent error is calculated using the following equation: $\sigma_{tot}^2 = \frac{\sqrt{4(\sigma_a^2+\sigma_e^2+\sigma_{sx}^2+\sigma_{sy}^2)+\sigma_{rx}^2+\sigma_{ry}^2}}{2\sqrt{2}}$ in which σ_a^2 and σ_e^2 are azimuth and elevation pointing errors, σ_{sx}^2 and σ_{sy}^2 are horizontal and vertical slope errors, and σ_{rx}^2 and σ_{ry}^2 are the horizontal and vertical reflected beam errors, respectively. For example, single-axis slope equivalent error of σ_{tot}^2 =2.0 mrad is analogous to $\sigma_{sx}^2 = \sigma_{sy}^2 = 2.0$ mrad, with all other components equal to zero. No optical degradation is assumed in the baseline cases.

Impact Category	Input Parameters	Large Electric (LE)	Modular Electric (ME)	Modular Industrial Process Heat (IPH)	Source
	Degradation of overall optical error as a function of time within a maintenance cycle (if applied)	No degradation in optical error is assumed			2021 SAM Baseline
Heliostat O&M					
Costs	Fixed O&M cost ($\$/\text{kW}_e$/year)	27.1	13.1	16.5	SAM 2021 Baseline: $3.5/MWh electric variable, $66/kWe/yr fixed for total system Assumes O&M costs are proportional to installation costs
	Variable O&M cost ($\$/\text{MWh}_e$/year)	1.4	0.7	0.9	
Downtime	Maintenance downtime schedule	Constant solar field availability of 94%			Informed by interviews with currently operating plants
Tower and Receiver					
Operating Parameters	Operating temperatures (inlet and outlet)	Inlet: 290°C Outlet: 575°C		Operating temperature range of 575°C-1,127°C (1,400 K)	LE and ME: SAM 2021 Baseline IPH: Pitz-Paal et al. [21] and Li et al. [23]
	Design average concentration ratio (suns)	726	767	1,549	There is a maximum flux limit of 1,000 kW/m^2 as a default in SolarPILOT; this was removed for IPH
	Receiver aperture width (ME, IPH) or diameter (LE) (m)	19.1	11.8	4.8	Optimized in SolarPILOT (LE, ME); assumed square aperture (ME, IPH); fixed according to desired power rating and concentration ratio (IPH)
	Receiver aperture height	18.8	11.8	4.8	
	Tower height (m)	209.1	102.8	70.5	Optimized in SolarPILOT
Installation Costs	Tower ($MM)	30.7	9.2	6.3	SAM 2021 Baseline Tower Fixed: $3MM Tower scaling exponent: 0.0113
	Receiver ($MM)	68.8	21.6	6.1	Receiver reference cost: $87MM Reference Area: 1,571m^2 Scaling exponent: 0.7
	Contingency ($MM)	10.0	3.1	1.2	10% contingency costs assumption taken from SAM 2021 baseline
	Indirect ($MM)	17.5	5.4	2.2	Includes engineering, procurement, and construction and owner costs, such as permitting, royalty payments, consulting, management or legal fees, geotechnical and environmental surveys,

Impact Category	Input Parameters	Large Electric (LE)	Modular Electric (ME)	Modular Industrial Process Heat (IPH)	Source
					interconnection costs, spare parts inventories, commissioning costs, and the owner's engineering and project development activities 17.6% indirect costs assumption taken from SAM 2021 baseline
	Total ($MM)	**127.0**	**38.9**	**15.9**	
O&M Costs	Fixed O&M cost ($\$/\text{kW}_e/\text{year}$)	11.74	20.0	21.1	SAM 2021 Baseline: $3.5/MWhe variable, $66/kWe/yr fix for total system Assumes O&M costs are proportional to installation costs
	Variable O&M cost ($\$\text{MWh}_e/\text{year}$)	0.6	1.1	1.1	
Site Resource Characterization					
	DNI as a function of time	Annual average DNI: 7.67 kWh/m^2/day			Daggett, CA Typical Meteorological Year (TMY) file (taken from EnergyPlus™ via the SAM library)
	Wind speed as a function of time, operation speed criterion, survival speed criterion	Annual Average Wind Speed: 2.3 m/s Wind Stow Speed Threshold: 15 m/s Survival speed not specified			Daggett, CA TMY file Wind Stow: SAM 2021 Baseline

Table 2 includes several baseline SAM assumptions that are consistent across the three cases but are likely to change with the size of the field, including the normalized O&M costs, land costs, and heliostat capital costs. Normalized O&M costs for the tower and receiver are smallest for the LE case due to its relatively small contribution to the total project cost. Understanding O&M costs for currently operating plants will help to improve the estimates of these costs as the size and application of the project changes, and is a focus of future research.

2.3 Initial Parametric Study

To illustrate the potential impact of various improvements to heliostat costs on the economics of the three baseline cases, we developed a parametric study on each case in which we determine how different performance and cost factors impact the levelized cost of heat (LCOH). This is an analogous term to the levelized cost of electricity (LCOE) in SAM but estimates a time-discounted cost estimate for thermal energy produced, rather than electrical energy. As a result, we adopt an LCOH measure that is agnostic to the presence of a power cycle, which allows for a similar comparison to be made for each of the technologies.

Here, we define the heat term in LCOH as the thermal energy delivered to the receiver from the solar field, which accounts for optical losses (e.g., image intercept, attenuation, cosine) but not reflection and reradiation at the receiver. We chose this measure of heat instead of the “useful” heat into the system, such as the thermal input to a power cycle, because the focus of HelioCon on heliostats. By choosing this measure, we limit the scope of our study to the heliostat field and the tower and receiver, which interact with the heliostats and impact how much thermal energy from the field can be delivered to the receiver. Using the thermal energy delivered to the receiver maintains a consistent measure between the IPH and electrical plant cases but underestimates the true unit cost of useful heat.

All LCOH estimates were conducted in SAM using the following method for each baseline case:

1. Optimize the solar field and receiver dimensions using SolarPILOT, which attempts to obtain a minimum-LCOE plant design. In the IPH case, the receiver design is fixed to preserve a desired concentration ratio, and the heliostat dimensions are optimized instead.

2. The solution obtained by the optimization model is validated via a performance simulation to ensure the thermal power delivery to the receiver is met at the design point of 950 W/m^2 DNI with a solar angle equivalent to the summer solstice, the default single design point in SAM. If required, the receiver’s nominal power rating is increased and Step 1 is repeated until this threshold is met.

3. For the IPH case, set all power cycle startup requirements and minimum power threshold to zero to avoid errors related to parasitic losses in the SAM performance model.

4. Use the performance simulation in SAM to vary inputs and obtain estimates of LCOE.

5. Multiply each LCOE estimate by the ratio:

$$\frac{Electricity\ produced}{Thermal\ energy\ delivered\ to\ the\ receiver} \cdot \frac{Capital\ cost\ of\ receiver\ and\ solar\ field}{Capital\ cost\ of\ plant}$$

to obtain the estimate of LCOH.

Step 2 is employed to address an artifact of the SolarPILOT optimization algorithm that sacrifices power rating to achieve an LCOE reduction in certain cases. This estimate of LCOH removes the costs of the power cycle and TES and assumes that operating expenses are proportional to the capital costs of each subsystem in the plant.

2.3.1 Results

Using the procedure described in Steps 1–5 above, we obtain LCOH estimates of 2.05, 2.42, and 3.33 cents/kWh$_t$ for the LE, ME, and IPH cases, respectively. As expected, the LCOH of each case study increases as the rating of the plant's receiver decreases. The estimates are also significantly higher than the calculated LCOH for the 2030 SunShot Target of 0.8 cents/kWh$_t$ (converted from 5 cents/kWh$_e$); this is due to several significant differences in cost assumptions that include but are not limited to: heliostat installation cost (\$50/m^2 SunShot 2030 vs. \$140/m^2 baseline); engineering/procurement/construction (EPC) and owner cost ratio (9% vs. 17%); and the receiver cost function (~19% lower for SunShot 2030 case).

In what follows, we present preliminary results of our parametric study. Specifically, we evaluate the impact of changes to (1) optical error, (2) installation cost, (3) field reflectance, and (4) O&M costs. While we vary one parameter at a time in the analyses that follow, some technology updates can impact multiple components; for example, thinner glass may reduce installation cost and increase both reflectance and O&M costs. Figure 7, Figure 8, and Figure 9 display the LCOH estimates as each of these parameters vary for the LE, ME, and IPH cases, respectively. In each case, the baseline assumption is at the centerline of the horizontal axis. Parameter sensitivity is assessed from 50% lower than the baseline to 50% higher than the baseline, using reflectance losses from an ideal image as a proxy for field reflectance when determining the range for that parameter. The results show that for each case, across the range of values assessed, optical error and installation costs tend to be more sensitive to changes than reflectance and O&M costs; however, the reasonable range of values by parameter is likely to vary both by parameter and by project (for example, locations with high soiling are likely to incur larger O&M costs related to washing and may have both a higher baseline for O&M and a lower baseline for reflectance).

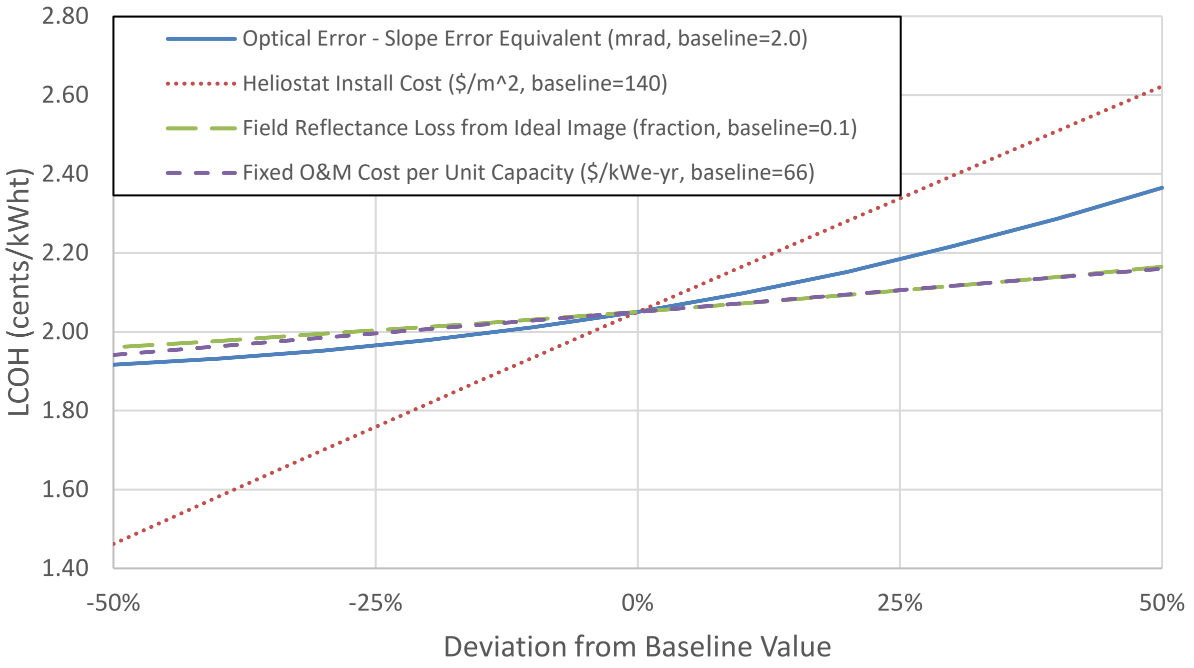


Figure 7. LCOH parametric analysis for the large electric plant case. Baseline case of 2.05 cents/kWh$_t$ is located on the centerline of each horizontal axis

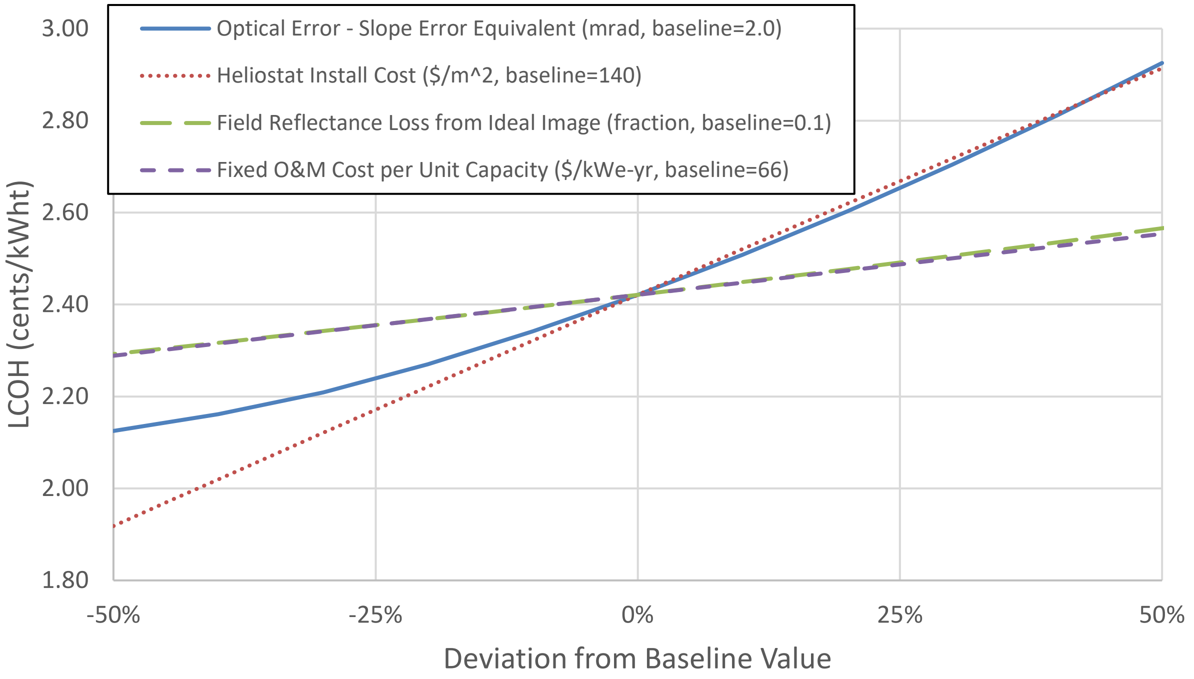


Figure 8. LCOH parametric analysis for the modular electric plant case. Baseline case of 2.42 cents/kWh$_t$ is located on the centerline of each horizontal axis

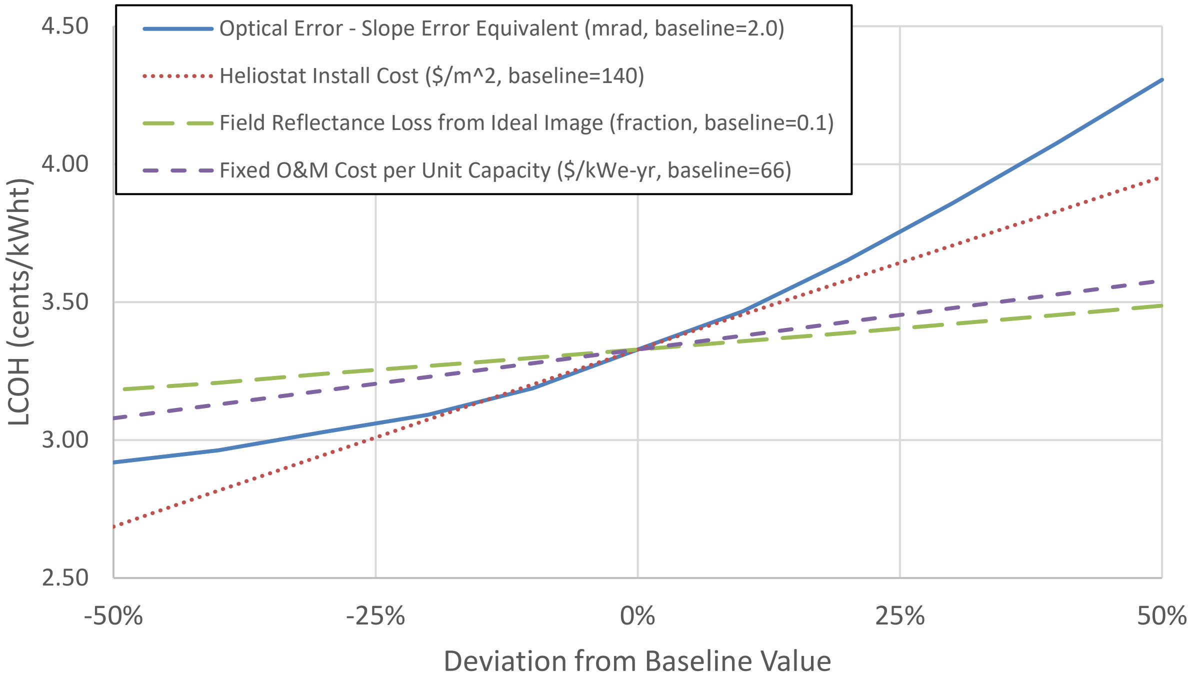


Figure 9. LCOH parametric analysis for the modular IPH plant case. Baseline case of 3.33 cents/kWh$_t$ is located on the centerline of each horizontal axis

2.4 Discussion: How Heliostat Cost Can Impact LCOH

One measure that can utilize the parametric analyses above includes the calculation of an equivalent breakeven capital cost for a given change in parameter values. Figure 10 recasts the parametric LCOH analysis on optical error as breakeven capital costs by determining the installation cost required to obtain the same LCOH as the baseline case. For example, to obtain a reduction in reflected image of 1 milliradian from the baseline IPH case (2.0 mrad), an increase in installation cost from \$140/m^2 to approximately \$185/m^2 yields the same LCOH as a plant with the same optical error, whereas an *increase* of 1 milliradian cannot achieve the same LCOH unless the heliostat cost was lower than the \$50/m^2 target using the same design. Meanwhile, the LE case could achieve the same LCOH as its baseline case with a 1-milliradian increase in slope-equivalent optical error if the capital cost could be reduced by approximately \$40/m^2. This analysis highlights the nonlinear nature of optical error's diminishing returns as incremental improvements take place, as a 1-milliradian improvement in optical error for the LE case would have a budget of ~\$15/m^2 or less to obtain an improvement to LCOH over the baseline. The results show that the smaller plants are subject to greater losses as the optical error increases; the most likely cause is the ratio of the heliostat size to the receiver aperture, which is largest in the modular IPH case and smallest in the LE case.

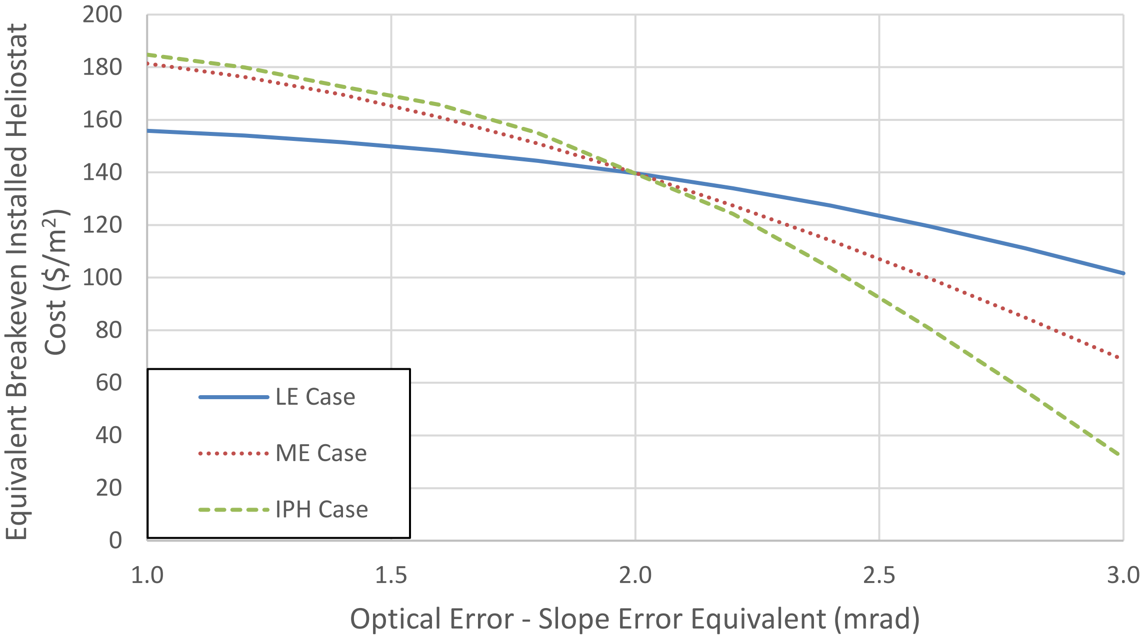


Figure 10. Equivalent breakeven installation costs summary, as a function of single-axis slope-equivalent optical error. The baseline of $140/m^2$ is located at the center of the horizontal axis, at 2 mrad

Figure 11 displays equivalent breakeven installed heliostat cost as a function of field reflectance with identical vertical axis scaling to Figure 10 and shows that over the same range of tested values, heliostat reflectance improvements would require smaller capital budgets. For example, an improvement of 3% reflectance over the baseline for the LE, ME, and IPH cases would need to cost at most $6, $11, and $9, respectively, more than the baseline of $140/m^2$ to yield an improvement to LCOH.

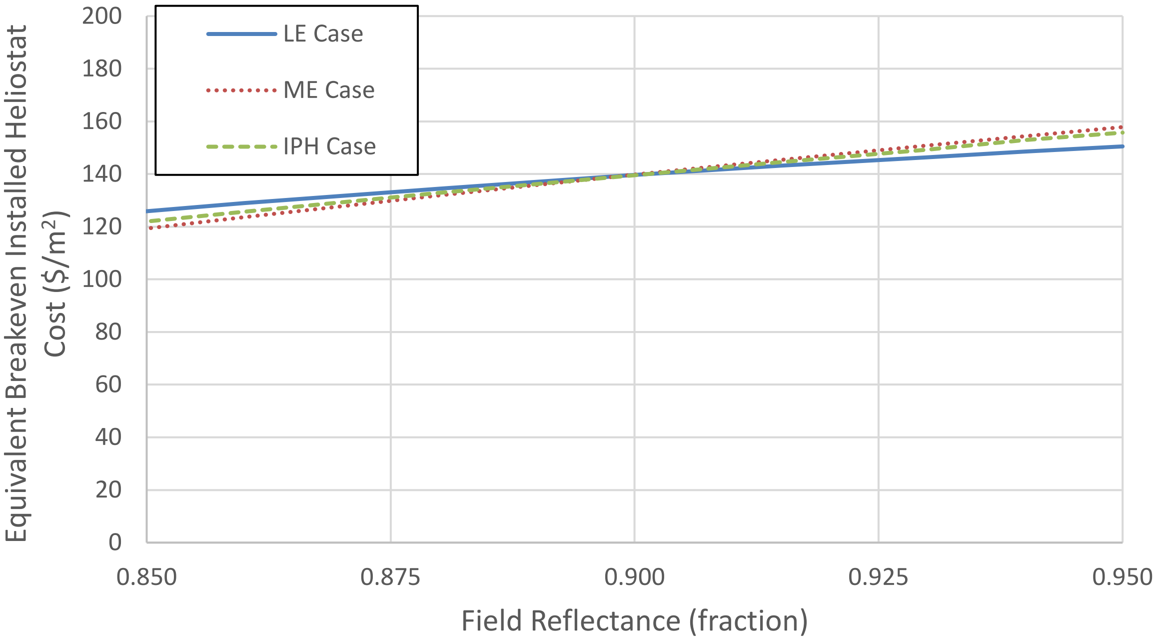


Figure 11. Equivalent breakeven installation costs summary, as a function of field reflectance. The baseline of $\$140/m^2$ is located at the center of the horizontal axis, at 90% reflectance

Figure 12 shows similar analyses to the preceding figures, but for fixed O&M costs. While all three cases exhibit a linear relationship between annual O&M costs and the equivalent breakeven installed heliostat cost, there is a greater sensitivity to the IPH case versus the others, likely due to the greater contribution of solar field, tower, and receiver costs to the total capital cost of the plant than the LE and ME cases (which include TES), and the same total-system baseline of $\$66/kW_e$-year. Incremental improvements to O&M costs are generally more impactful than reflectance across the range of values displayed, though reasonable ranges of parameter values will vary by plant. Note that variable O&M costs contribute a much smaller proportion of project costs than fixed costs, and so we focus on the fixed costs in this study.

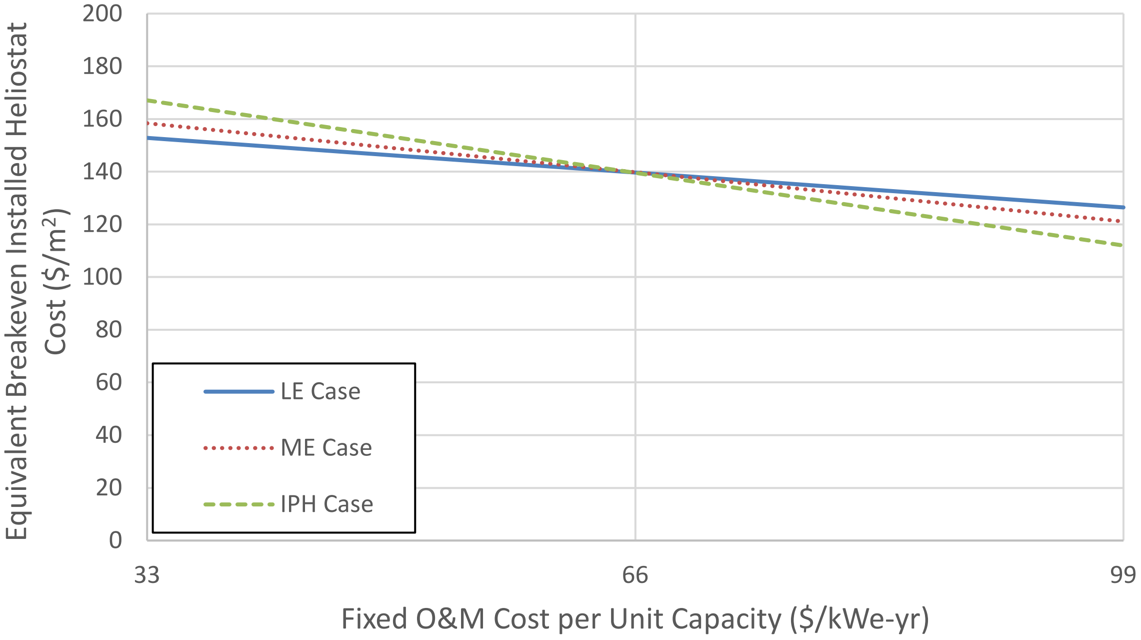


Figure 12. Equivalent breakeven installation costs summary, as a function of fixed O&M cost. The baseline of $140/m^2$ is located at the center of the horizontal axis, at $66/kW$_e$-year

Although the effects of performance differences in the parametric analysis are likely to change as cost assumptions for the baseline cases change, the general trends and curvature of the functions are likely to be similar.

3 Setting Out: Gap Analysis and Roadmap Study Approach

HelioCon first gathered gaps through a series of outreach activities with representatives and experts from industries and research institutes. Detailed gap analysis and roadmap study on high-priority gaps were then conducted for a predefined list of topics and subtopics.

As observed from the CSP global deployment distribution and trend in Section 2, the biggest gap across all topics for heliostat technology (CSP in general, arguably) is the lack of a steady market enabling continuous improvement. A steady market would have a consistent and predictable business volume, rather than stops/starts affecting the whole CSP supply chain. Then, a predictable business volume would help justify capital investment and enable industry management of continuous improvement. Particularly with respect to heliostat-based CSP systems, a utility-scale electricity generation system (50 MWe or larger) is typically adopted in a commercial deployment project and such a system typically requires an intense initial capital investment and an elongated project development time. In the future, a series of smaller-scale projects spreading at constant rate over a sequence of years (such as was achieved in the deployment of CSP trough systems in Spain in the prior decade) may be of help to enable a sustainable cycle of learning, fostering, and maturing of heliostat technologies.

3.1 Assembling the Experts: HelioCon Outreach

The HelioCon project team held several meetings, interviews, and events to solicit feedback from stakeholders, including:

- The HelioCon Roadmap Workshop, held on Nov. 8–10, 2021. Breakout sessions specific to each topic area were carried out and directly contributed to the generation of the initial list of gaps for each area
- Multiple follow-up HelioCon topic-specific subteam meetings from Nov. 2021 to March 2022, and two board of advisors meetings held on March 23 and 28, 2022
- A series of follow-up meetings with leading developers and experts in each topic area
- Individual stakeholder meetings/discussions held with the leading companies as noted in each topic area
- Thorough literature reviews conducted by the HelioCon subteam members
- HelioCon conducted a site visit to the BrightSource Energy research and engineering office and the Ashalim power tower plant.

Additionally:

- The advanced manufacturing team drew upon a prior separate survey of CSP experts, which asked them to estimate the relative value of various CSP autonomy applications[3] [24]

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[3] This was performed under other funding, prior to HelioCon.

- The components and controls team conducted a survey from CSP heliostat designers, plant operators, and those involved in bankability. Respondents were asked about the primary problems affecting heliostat field operation.

3.2 Surveying the Landscape: HelioCon Gap and Roadmap Analysis Topics

HelioCon categorized the gap analysis and roadmap study into the following topic areas along with specific objectives of each topic area:

1. Techno-economic analysis (TEA)
    - Develop model validation tools (e.g., ray tracing, heliostat field layout, annual simulations) and empirical data (e.g., heliostat performance curves, detailed metrology data) that industry can use to compare and validate their proprietary models against
    - Develop standard definitions for heliostat components and performance (e.g., field optical efficiency)
    - Improve representation of heliostat image error in models
    - Develop or modify models to include probabilistic inputs and outputs.
2. Metrology and standards
    - Publish standard operating procedures, guidelines, and white papers
    - Develop and characterize new tools for advanced characterization of heliostats
    - Benchmark existing measurement tools.
3. Components and controls
    - Determine priority of components and controls R&D to support CSP bankability
    - Develop advanced characterization for performance and reliability limitations that impact costs
    - Develop approaches and test beds for characterizing components/subsystems, and new tools for confident deployment of components and controls
    - Publish components and controls standard operating procedures, guidelines, and publications
    - Identify existing gaps for components and controls necessary for advancing heliostat technologies.
4. Advanced manufacturing
    - Catalog knowledge for product design
    - Catalog knowledge for process design
    - Document standard designs
    - Develop metrology and calibration techniques.
5. Resources, training, and education (RTE)
    - Develop a heliostat workforce pipeline
    - Establish heliostat training and education programs
    - Create a centralized resource database
    - Establish programs and practices to promote diversity, equity, and inclusion.
6. Field deployment
    - Standardize site selection

        - Permitting
        - Design layout of the spatial configuration of the heliostats relative to the receiver and the terrain
        - Design validation
        - Capitalization
    - Improve efficiency of installation and assembly
    - Ease commissioning process
    - Optimize O&M
    - Standardize the end-of-life process.

In addition, the team analyzed two special subtopic areas:

7. Wind load (most related to the topic of field deployment)
    - Develop wind load and site characterization design guidelines for heliostat design
    - Develop computational fluid dynamics and TEA models assessing wind load and its impact to impact to a solar field.
8. Soiling (most related to the topic of metrology and standards)
    - Develop a soiling database for potential project development sites
    - Develop high-fidelity soiling characterization methodology/standards for site selection
    - Develop soiling mitigation methodology or techniques.

For each topic and special subtopic, the gaps and roadmap analysis are organized as follows:

- **Scope:** defines the focus areas of the given topic.
- **State of the art:** establishes the current status of the given topic as a reference.[4]
- **List of gaps with ranking:** summarizes a comprehensive list of gaps with a three-tier ranking structure, with Tier 1 as the most important.
- **Gap analysis and recommended pathways:** performs detailed analysis and provides a summary of recommended pathways for the CSP community to address Tier 1 gaps.[5]

3.3 HelioCon's Three-Tier Approach to Categorizing Gaps

For each topic/subtopic, identified gaps are classified into three categories per the following principles, based on expert opinions within and outside of HelioCon:

- Tier 1:
    - Gaps identified as "must address" gaps. If not addressed, the sustainable product development cycle of heliostat technology would be broken, which would fundamentally prevent heliostat technology from being improved generation by generation. Or,

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[4] Detailed literature reviews for selected topics can be found in the appendices.

[5] Detailed analysis on Tier 2 and 3 gaps for selected topics can be found in the appendices.

  - Gaps with a high-probability potential to result into a high techno-economic impact (LCOH) to all three pre-identified heliostat baseline systems.
- Tier 2:
  - Gaps with a potentially high or medium techno-economic impact (LCOH) to any pre-identified heliostat baseline system(s)
  - Gaps that can be addressed with relatively small effort but with low techno-economic impact to all heliostat baseline systems.
- Tier 3:
  - Gaps with a potential low techno-economic impact to all heliostat baseline systems.

After the three-tier categorization, more in-depth analysis will be conducted on the Tier 1 gaps to lay out the solution requirements, address strategy, and provide an initial quantitative impact analysis considering resource constraints.

3.4 Capturing Every Opportunity: Full Development Cycle Analysis

For each given topic, a gap analysis is conducted through the full heliostat development cycle, as illustrated in Figure 13:

- **Conceptual design:** 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.
- **Heliostat components:** This stage includes the research, development, and performance validation of components of a heliostat and heliostat field prototype.
- **An integrated heliostat:** This requires the research, development, validation, and performance projection of an integrated heliostat to prepare for commercial deployment.
- **Mass production of heliostats:** 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.
- **A heliostat field:** This stage includes heliostat field construction, quality control, O&M, commercial project management, and end-of-life treatment.

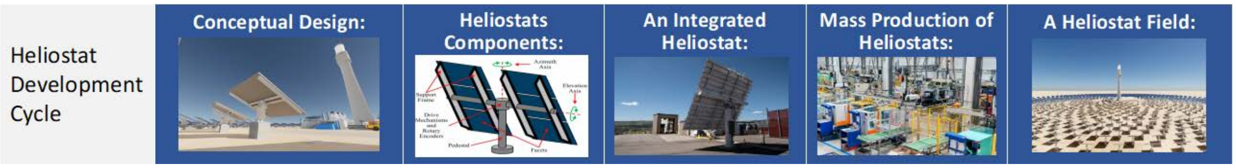

Figure 13. Full heliostat development cycle

Figure by NREL

In next eight sections, a gap analysis and roadmap study are presented for each given topic.

4 Techno-Economic Analysis

The TEA topic uses models and analysis to quantitatively assess the benefits of heliostat design, manufacturing, and operation concepts considered by other topics. The TEA topic will work to provide analysis on a "total system" level to identify the tradeoffs and interactions of proposed concepts. The objectives of this topic include:

- Model economic viability of new heliostat designs and concepts
- Perform analysis on fundamental problems that would promote heliostat economics in general
- Provide analysis and support to guide the HelioCon R&D directions and portfolio.

4.1 Scope

One of the main objectives of the TEA topic is to relate the cost and performance of heliostats and heliostat components to the overall system performance. The thermal energy collected from CSP systems can be used for different end uses, such as electricity generation or IPH. Overall plant performance is affected by things such as the power cycle chosen, the type of cooling used, or the temperature of the end-use application.

In this study, we limit our scope to the analysis of heliostat solar field. An individual heliostat's performance is affected by its position in the solar field, so our scope must include the entire field to capture this. Further, heliostats interact with the tower and receiver. The size and type of the receiver (external or cavity) determines how much of the sun image reflected by a heliostat intercepts the receiver and is collected by the heat transfer fluid in the receiver. The receiver also has a limit to the heat flux it can tolerate before being damaged. The tower height also impacts how the reflected sunlight from the heliostats intercepts the receiver, with the optimum tower height generally increasing with field size.

Once the heat transfer fluid leaves the tower, it does not interact with heliostats anymore, regardless of whether it goes into a TES tank, a power cycle, or some other end use. Therefore, we limit the scope of this topic to the heliostat field, tower, and receiver as shown in Figure 14. We assess the heliostat field, receiver, and tower performance based on the thermal energy collected by the heat transfer fluid compared to its installed and operating costs, using the levelized cost of heat (LCOH) as the key metric in our analysis. We assume that the thermal energy can be used for any range of applications so that the analysis can focus on the heliostats used to collect solar energy. We recognize that the economic value of thermal energy depends on its temperature, with higher temperatures having more electricity generation potential and a greater number of potential applications. Therefore, comparisons of LCOH should only be made between systems with similar heat transfer fluid temperatures.

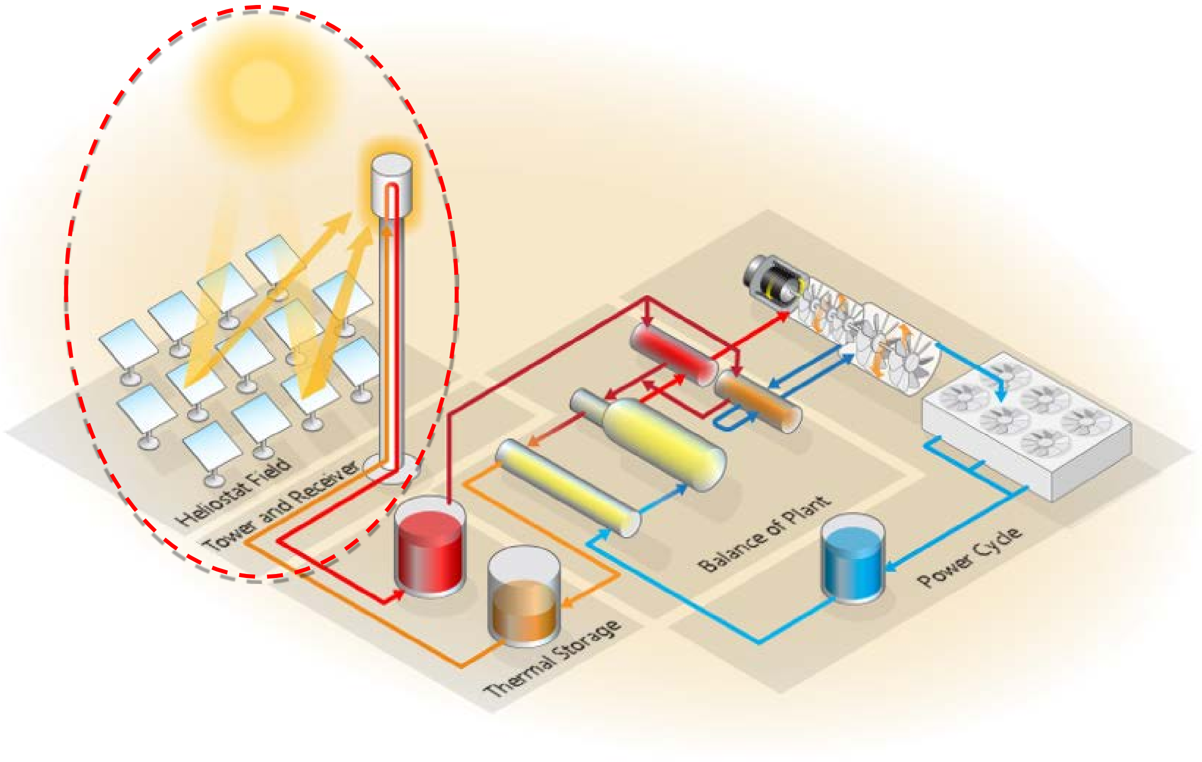

Figure 14. Scope of CSP system considered in the HelioCon TEA

Figure adapted from [25]

4.2 State of the Art

This section presents the state of the art in open-source TEA (Table 3) and ray-tracing (Table 4) models used to characterize the economic and optical performance of CSP plants.

Table 3. Summary of Modeling Capabilities for Open-Source TEA Tools for CSP Tower Plants

	System Advisor Model (SAM) https://sam.nrel.gov/	**SolarPILOT https://www.nrel.gov/csp/solarpilot.html**	**SolarTherm**
Accepts TMY Weather Files	Yes, but not a perfect representation [26]	Yes, with the same reformatting as is required in SAM [26]	Yes: Accepts TMY3 format and Modelica tabular text files.
Annual Performance Metrics	Yes: Annual performance measures and levelized cost metrics are available through SAM's graphical user interface.	Yes: This can be obtained by stepping through the entire year in the parametric analysis simulation.	Yes: Based on a time-stepping solver throughout the whole year. SolarTherm propagates field layout parameters from Modelica to Solstice, allowing full annual-performance-based optimization of field layout parameters.
Ray Tracing Capability	Limited: While the annual performance measures in SAM's user	Yes: SolarPILOT integrates the SolTrace ray-racing engine to allow cross-	Yes: Ray tracing is done for a grid of sun positions, then interpolated throughout the

	System Advisor Model (SAM) https://sam.nrel.gov/	**SolarPILOT https://www.nrel.gov/csp/solarpilot.html**	**SolarTherm**
	interface uses the computationally efficient Hermite method, ray tracing via SolTrace can be accessed through SAM's link to the SolarPILOT API.	comparison of results and analysis of complex geometries.	year. At each sun position and for each DNI at that sun position, the aim-point strategy (and defocusing factor) can be varied to ensure combined optical-thermal performance.
Types of Cost Models	LCOE and power purchase agreement, with full financial inputs that include discount rates for various costs, interest rates and financing terms, and depreciation schedules.	Calculates solar field cost and optimized the heliostat field layout and receiver dimensions to minimize expected cost of energy.	Capital costs for each component are calculated based on physical costing models in most cases, with empirical relations for some for complex components (e.g., typically for the tower cost). O&M costs are estimated. LCOE is calculated based on the combination of annual output and total annualized costs.
Types of Financial Models	Wide collection of financial parameters available for fixed and variable plant costs. These can be used to perform an LCOE or net present value analysis, depending on the market context.	SolarPILOT is an optical modeling tool with some rough approximations of cost aspects to support field layout optimizations. More detailed financial modeling is typically handled in SAM, and can be done via scripting using a link to the SAM API.	Can evaluate plants in a fixed-electricity price context (LCOE analysis) or in a market price context (optimal dispatch). The optimal dispatch solver uses a simplified linear model to decide the best strategy over a two-day forecast horizon. SolarTherm has no implementation of power purchase agreements (PPAs), tax credits, depreciation, etc. That has not been a part of our work up to now.
Additional Capabilities	Includes ability to optimize solar field, receiver, tower dimensions; also includes similar performance and financial modeling of a large collection of other renewable technologies.	SolarPILOT can generate field layouts in a variety of patterns or land constraints, conduct detailed optical performance simulations down to the level of each heliostat facet, perform optimization of key system variables, and conduct parametric analyses.	Optimization of any design parameter and sensitivity analysis, via wrapping with DAKOTA. Performance-based contingency analysis SolarTherm provides component-level surrogate models of power block, heliostat field, receiver, and storage, which are very helpful in model speedup, but require an expert user.

Table 4. Summary of Ray-Tracing Tools for CSP Tower Plants

Name	Description	Source
SolTrace	SolTrace is a software tool developed at NREL to model CSP systems and analyze their optical performance. Although ideally suited for solar applications, the code can also be used to model and characterize many general optical systems.	https://www.nrel.gov/csp/soltrace.html [27]
Sunntics	Sunntics is a commercial toolset for optimized design and operation of CSP plants. The toolset helps drive LCOE down. It enables all parties involved in the project life cycle to create optimized solar field designs, optimize solar field operations, and assess expected plant performance at all stages of development.	https://www.sunntics.com/ [28]
HelioSim	HelioSim is an integrated model for the optimization and simulation of power tower CSP facilities.	https://doi.org/10.1063/1.5067213 [29]
sbpRAY	sbpRAY is a software framework to simulate and optimize the performance of CSP plants, with underlying ray-tracing technology that can run in parallel on a graphics processing unit, or GPU.	https://doi.org/10.1063/1.5117674 [30]
TieSOL	TieSOL is a commercial software suite that simulates and optimizes CSP tower plant design and solar field operations. It utilizes GPU resources to run ray tracing in parallel to make flux mapping computationally tractable.	https://doi.org/10.1016/j.egypro.2014.03.259 [31]
Tonatiuh	Tonatiuh is an open source, freeware, Monte Carlo ray tracer suitable for CSP tower applications. Tonatiuh includes a graphical user interface, is capable of multi-threading computing, and is under development by CENER.	https://doi.org/10.1063/1.5067212 [32]
STRAL	STRAL is a fast and precise ray-tracing tool that includes tool coupling capabilities to allow for co-simulation of plants in multiple environments, allowing for software- or hardware-in-the-loop testing, development of control algorithms, and more.	https://elib.dlr.de/78440/ [33]

Name	Description	Source
Tracer	Tracer is a Python-based open-source ray-tracing package. It has parallel processing capabilities for faster simulations. Tracer was developed to provide a ray-tracking engine with programmability and extensibility but currently lacks a general user interface.	https://github.com/anustg/Tracer [34]
Solstice	Solstice (SOLar Simulation Tool in ConcEntrating optics) is a free, open-source software. It has parallel processing capabilities and uses a Monte Carlo algorithm to achieve a faster convergence rate than collision-based algorithms. It is a command-line tool made for coupling with other programs.	https://www.meso-star.com/projects/solstice/solstice.html [35]

4.3 Ranked Gaps

We developed an initial list of gaps for the TEA of heliostats. Industry developers and experts were asked to name gaps in TEA during the HelioCon Roadmap Workshop in 2021. Additional gaps were identified through conversations with other topic members, literature review, and during the development of the heliostat field base cases described in Section 2.

The initial list of gaps for the TEA topic is summarized in Table 5. Each gap is briefly described, and the heliostat development cycle stages (Figure 11) that the gap impacts are indicated. To facilitate later analysis, each gap is numbered, with "T" identifying it as a TEA gap. All of the TEA gaps impact stage "a"—conceptual design of the heliostat development cycle. This is because TEA is an essential part of the decision-making and evaluation processes during the design and development of heliostats and CSP projects in general. All identified TEA gaps also affect stage "e" (deployed field) because TEA is used to evaluate operating CSP projects to compare actual performance to expectations, identify cost and performance improvement opportunities, and evaluate operation, maintenance, and capital improvement decisions. Some gaps impact additional heliostat development stages, primarily when the gap is associated with heliostat components.

The characterization of tiers described at the beginning of Section 3.3 was used to rank the initial list of TEA gaps. The gaps were grouped by the heliostat development stage where they are considered to have the largest impact. The resulting rankings are shown in Table 5. Four gaps were identified as Tier 1 (most important), five as Tier 2, and one as Tier 3 (least important). Gap T1 (linkage between model inputs and actual components) spans all heliostat development stages because component models from each heliostat development stage can be used to inform TEA models.

Table 5. Initial List of Gaps Identified for Heliostat Consortium TEA

Techno-Economic Analysis						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important)						
T1	The linkage between heliostat component research and its impact on TEA model inputs is poorly understood	x	x	x	x	x
T2	Lack of validated and widely accepted model for solar field O&M costs • Need to split plant and field O&M out (in SAM, specifically) • Need data on mirror washing (as function of soiling) • Need data on warranties for heliostat components, as well as facet degradation rate and replacement frequency	x	x			x
T3	Insufficient knowledge of construction and commissioning costs, and the impact of delays on financing costs • What is impact of heliostat field commissioning time on project economics? • How do construction and commissioning time requirements affect project bankability?	x		x		x
T4	Lack of validated CSP models for IPH applications	x				x
Tier 2 Gaps						
T5	Typical ranges for TEA model inputs are not fully validated, especially for inputs that can vary significantly by location	x				x
T6	Lack of fidelity in receiver cost models, especially for cavity receivers	x				x
T7	Lack of fidelity in tower cost models, especially for shorter towers, IPH/modular systems	x				x
T8	TEA models lack the capability to estimate the impact of wind loads at a given site on heliostat cost and performance • Hourly averages in TMYs; gusts not considered • Impact of wind on aiming	x	x	x		x
T9	Lack of standard criteria for site selection • What is the cutoff for minimum DNI? • Hourly averages in TMYs; gusts not considered • Impact of wind on aiming: what is the cutoff for maximum continuous wind speed/gusts? • What is cutoff for mirror soiling rate?	x				x
Tier 3 Gaps (Least Important)						
T10	CSP industry lacks historical data, tools, and cases that industry can use to assess and validate their models.	x				x

4.4 Gap Analysis and Recommended Pathways

Table 6 summarizes the solution functionality, justification and benefits, and proposed strategy for addressing each TEA Tier 1 gap. Most of the gaps are related to developing models or data. Strictly speaking, none of these gaps are essential for heliostat development, but all would aid in the heliostat development process.

Gap T1, poor understanding of linkage between model inputs and actual components, is listed first and is considered the most important gap. Completely addressing this gap by developing models for all heliostat components and subcomponents is likely not possible due to the large number of models that would be needed to cover all potential designs and technologies. Instead, the TEA will be used to identify which gaps and research could be most impactful and then focus on developing models and inputs for those high-impact areas.

Gap T2, lack of a model for solar field O&M costs, could be considered a subset of Gap T1 but we list it separately because this is a gap that spans several field activities, and a concerted effort is needed to better understand field O&M and the trade-offs between O&M costs and system performance. Gap T4, lack of CSP models for IPH applications, is similar in that we require this model to proceed with the proposed HelioCon work. Gap T3, impact of construction and commissioning labor costs and time frame, is actually an analysis gap and was included due to difficulties in getting projects commissioned on time in recent projects that have impacted the perceived bankability of CSP projects.

Table 6. Top-Ranked Gap Analysis for TEA

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
T1: Link between heliostat component research and its impact on TEA model inputs is poorly understood	• Models of components and subcomponents that relate heliostat performance to manufacturing and installation cost • Generate metrics needed in systems-level models to assess overall impact on LCOH	• Develop better understanding of cost and performance drivers for components • Increased accuracy of performance model's forecasted LCOH, relative to true plant costs	• Work with HelioCon topics to identify and develop component models • Industry engagement to develop and refine component models
T2: Lack of validated and widely accepted model for solar field O&M costs	• Split total project O&M costs in plant-specific and solar field-specific portions • Models that estimate mirror washing cost • Models/data on heliostat component replacement cost and frequency	• Needed to focus on O&M related to heliostat field only • Needed to balance washing costs with performance impacts	• Work with field deployment topic • Data from RTE topic • Literature search
T3: Insufficient knowledge of construction and commissioning costs, and the impact of delays on financing costs	• Relate time required to install and calibrate heliostat field with impact on revenue and overall project financials	• Reduce project risk and uncertainty • Inform developers and investors	• Work with field deployment topic • Sensitivity analysis in TEA models
T4: Lack of validated CSP models for IPH applications	• Model that includes cavity receiver performance as a function of temperature	• Current TEA models not developed for evaluating IPH • Needed to evaluate heliostats for IPH applications	• Work with SAM team at NREL to add these capabilities

5 Metrology and Standards

Metrology, in the context of heliostat, is the application of measurement for performance assessment and heliostat quality assurance. It is a fundamental requirement of successful wide-scale CSP deployment. The nature of CSP, particularly achieving high temperatures via high solar concentration ratios, implicitly requires high optical accuracy. Traditional optical metrology techniques fall short due to the very large size of CSP solar field, complicated by their outdoor setting. Further, CSP incurs special metrology challenges, such as measuring systems distributed over very wide land areas exceeding multiple square kilometers, long optical focal lengths of up to 1.6 km or longer, assessment of optical accuracy under varying gravity loads and temperatures, high production volumes, and operation in a harsh environment with overhead solar flux hazards. Despite these challenges, heliostats must demonstrate optical accuracy of a few milliradians in slope error (or slope-error-equivalent), implying that their metrology systems must deliver sub-milliradian accuracy. In addition, the harsh environment typical of CSP plants brings additional metrology needs, such as prompt recurring assessment of mirror soiling, to support optimum mirror washing management. Lastly, the long service life of CSP plants mandates recurring inspection of thousands of heliostats to detect defects needing maintenance or repair.

Standards are equally important for any given product development, and the heliostat is no exception. Standards can serve as a fundamental basis for the heliostat community to communicate; when it comes to comparing different heliostat technologies, a consistent platform can be adopted to ensure fairness and promote healthy unbiased competition. More importantly, when the heliostat technology is placed in a market with other available technologies such as PV, wind, and fossil fuel, sufficient standards (to be defined) would be a critical reference for investors to examine the bankability of a given commercial system. At the same time, the development of standards needs to be a collective effort across the entire global heliostat community. It would involve a series of rigorous necessary steps such as gathering a dedicated working group, regular technical meetings, initial draft guideline, collection of comments/edits, revision, various stages of voting, and organization-specific requirements on standards. Thus, development of final standards is typically time-consuming, and it is always suggested to start as soon as possible.

5.1 Scope

Metrology of heliostats includes any techniques to measure technical performance of heliostats, a heliostat field, and other devices/equipment involved in heliostat manufacturing. It is considered a critical step to complete a sustainable product design/refinement cycle.

For a commercial heliostat field, the ultimate performance assessment would be the beam (flux) control on the receiver surface with respect to:

1. **Maximized efficiency:** The ratio of the amount of solar flux reflected to the receiver surface and the theoretical limit of total solar flux striking on the total mirror surface (total mirror surface area multiplied by DNI).
2. **Minimized failures:** The frequency of receiver failure due to unexpected flux distribution control on the receiver.

Contributing factors to the flux control requiring the direct performance measurement include [36]:

- Sun shape
- Incidence angle (sun position relative to individual heliostat)
- Heliostat shape
- Attenuation
- Solar-weighted specular reflectance
- Opto-mechanical errors
  - Mirror surface slope error
  - Mirror facet canting error
  - Heliostat pointing error
  - Heliostat tracking error
- Soiling (a separate subtopic discussed later in this report)
- Structural/wind load (a separate subtopic discussed later in this report)
- Receiver coating properties (excluded from HelioCon)
- Receiver geometry (excluded from HelioCon).

Standards for heliostats and large-scale systems will define the fundamental terms for the development of metrology techniques and synchronize the measurement metrics out of relevant techniques so that the CSP society can communicate on a common platform.

5.2 State of the Art

Because metrology and standards are fundamental to heliostat technology, researchers have already conducted substantial research in this area. The state-of-the-art metrology technologies and standards available and under development are summarized in Table 7. Here, the following criteria are first established to determine whether the requirements on metrology for a given technical parameter are fully satisfied:

- At least two viable metrology techniques for a given measurement parameter are available for the whole CSP industry
- Any viable metrology technique is validated against a different trusted metrology technique or ground-truth article.

The first criteria is a result of the following: (1) most measurement parameters related to heliostats are not a single measurement value (such as mirror slope error), and their measurement results cannot be duplicated 100%; (2) a given metrology technique can be prone to many operational uncertainty and errors, and two or more available techniques can greatly enhance the validation of a given technique and the measurement results. By using the criteria above, the majority of technical areas have gaps in metrology, which is to be further discussed in the next section.

Table 7. State-of-the-Art Metrology and Standards Techniques for Heliostats

Measurement Parameters	Metrology Techniques	Maturity
Sun Shape		
Metrology	Charged-couple device (CCD) camera-based techniques [37]	Available
	Pyrheliometer [38]	Commercial
	Rotating Shadowband Irradiometers [39]	Commercial
Incidence Angle		
Metrology	Accurate ground survey on heliostat position [40]	Available
Standards	Sun position algorithm [41]	Open-source
Heliostat Shape		
Metrology	Laser scanning techniques [42]	Available
	Photogrammetry, deflectometry and reflectometry techniques [43]–[46], [47]	Available
Attenuation		
Metrology	In-field measurements [48], [49]	Under development
	Hybrid attenuation measurement combining in-field measurement and advanced correction models [50], [51], [52]	Available
Solar-Weighted Specular Reflectance		
Metrology	Reflectometers [53]	Commercial
	S2R2 instruments for direct measurement of specular and solar-weighted reflectance [54], [55]	Available
Standards	Solar specular reflectance model [56]	Under development
Opto-Mechanical Errors		
Metrology	Laboratory techniques (slope error): QDec-M [57]	Commercial
	Laboratory techniques (slope error and/or canting error): - Deflectometry-based: SOFAST [58] - Laser-scanning techniques [42], [59] - Phase-measuring deflectometry [60]	Available
	Laboratory techniques (slope error): - VISproPT by ENEA [61]	Under development
	In-situ techniques (tracking error) [62]: - Beam characterization system [63],[64],[65] - Camera-based heliostat-scanning method by BrightSource Energy [66], [67]	Deployed
	In-situ techniques [62]: - NIO by NREL [68]–[70] - UFACET by Sandia [71], [72]	Under development

Measurement Parameters	Metrology Techniques	Maturity
	- HELIOSCHAR by CENER [73], [74] - Airborne-based system by CYI [75] - HELIOPOINT by DLR [75] [76] - QDec-H by DLR [77] - SHORT by TEKNIKER and CENER [78] - Heliostat pointing calibration methodology by IMDEA Energy [75] - Retroreflector-based calibration method by CSIRO [79] - Camera-array-based calibration method by CSIRO [80] - Inverse-analysis-based heliostat tracking calibration method by the Australian National University [75]	
Standards	SolarPACES guideline on heliostat performance testing [81]	Under development
	SolarPACES Heliostat Field Performance Acceptance Test Guideline [82]	Under development

5.3 Ranked Gaps

The full list of technical gaps in metrology and standards for the heliostat technologies is summarized in Table 8. Each technical gap is briefly described and its impact to different stages of heliostat development cycle is also marked. To facilitate the subsequent analysis, each gap is numbered with respect to each individual topic. For example, the gap M1 on measurement of heliostat shape deviation would have an impact on the heliostat development stages: c (integrated heliostat); d (mass production); and e (deployed field). At the same time, S3: heliostat field layout design guideline would be critical at stage a (conceptual design).

All gaps will have an impact to heliostat technology development. With the pre-established categorization principles, they are categorized in three different tiers first. Among all twelve gaps on metrology, six are identified as Tier 1; five as Tier 2; one as Tier 3.

Among all eleven gaps in standards, five are identified as Tier 1; three as Tier 2; three as Tier 3. Detailed justifications for the Tier 1 gaps will be given in the next section.

Table 8. Identified Gaps Related to Metrology and Standards Under HelioCon

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

Metrology						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important)						
M1	Opto-mechanical error measurement in laboratory: there are no fully validated metrology techniques on opto-mechanical error measurement in the laboratory, which is typically performed on an integrated heliostat under loads (structural load and additional simulated load). Current available metrology techniques have not been validated against each other and their operation often involves a complex, error-prone process.			x		
M2	Opto-mechanical error measurement in outdoor environments: there are missing metrology techniques on opto-mechanical error measurement in outdoor environments that can test one or multiple integrated heliostats under realistic impact factors, such as • Wind load • Temperature • Full range of orientation. While a measurement in an outdoor environment may be prone to additional unpredicted uncertainty, a direct verification using reflected beam assessment would also become necessary.			x		
M3	Opto-mechanical quality assurance tools for mass production: there are missing opto-mechanical quality assurance tools for heliostat mass production. The tools need to be adapted/optimized for specific heliostat design in order to achieve required accuracy, efficiency, and reliability.				x	
M4	Opto-mechanical quality calibration after installation: there is missing metrology for opto-mechanical quality calibration after installation.					x
M5	Opto-mechanical error in-situ monitoring tools: there are missing in-situ monitoring tools for the full spectrum of opto-mechanical error including surface slope error, mirror facet canting error, and heliostat tracking error. The in-situ tools should be applicable to commercial-scale heliostat fields.					x
M6	Receiver flux quality real-time assurance tools: there are missing validated receiver flux quality real-time assurance tools that can accommodate aiming strategies based on the knowledge of full field heliostat opto-mechanical performance.					x
Tier 2 Gaps						
M7	Heliostat shape deviation: there are missing metrology tools to measure heliostat mirror shape deviation due to - Structural load - Wind load - Structural degradation.			x	x	x
M8	Opto-mechanical error measurement for mirror facets in laboratory: various mirror facet metrology tools are not fully validated against each other.		x			
M9	Opto-mechanical quality pre-calibration before installation: there are missing metrology tools available to ensure opto-mechanical quality of heliostats before installation.					x
M10	Monitoring tool of cloud passage: there are no high-fidelity metrology tools to monitor the passage of clouds and project their impact to solar field operation due to the safety of receiver operations.					x

Metrology						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
M11	On-site measurement and monitoring tool of attenuation: there are no-fully validated metrology tools for real-time attenuation of a large-scale heliostat field.					x
Tier 3 Gaps (Least Important)						
M12	Monitoring tool of solar field flux glare					x
Standards						
Tier 1 Gaps (Most Important)						
S1	Definition of optical attributes for heliostats: there are missing standards in defining the fundamental optical attributes for heliostats at a rigorous mathematical formation, which includes, but is not limited to: - Sun shape - Solar reflectance and impact of soiling - Opto-mechanical error • Slope error, canting error, pointing error, tracking error - Comprehensive description • Distribution, mean, root mean square • Single heliostat vs. whole field - Impact factors • Load (wind, gravity) • Heliostat orientation • Degradation over lifetime • Ambient conditions - Beam quality • Metric to characterize beam quality and overall characteristics • Beam glare.	x	x	x	x	x
S2	Heliostat design guideline: there is no heliostat design guideline to summarize key factors for a commercial heliostat design, including: - Design and safety factors to consider - Lifetime performance of components and the integrated product - Performance test requirements - Performance prediction over a lifetime for a given commercial system.	x	x	x	x	x
S3	Heliostat solar field design guideline: there is no heliostat solar field design guideline that provides a complete reference on a full spectrum of factors to consider, including: - Target metrics - Contributing factors • Technical performance • Cost • Financial structure • Energy pricing structure • Energy prediction model.	x				
S4	Heliostat testing guideline: there is no heliostat testing guideline for specifying the heliostat tests to ensure performance for commercial deployment, which defines: - Measurement scenarios: laboratory vs. in-situ - Under loads (static and dynamic) - Reporting format.		x	x	x	x
S5	Heliostat solar field acceptance test guideline: there is no heliostat solar field acceptance test guideline to assess the solar field construction quality, which specifies:					x

Metrology						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
	- Heliostat actual performance vs. target performance - Measurement uncertainty - Projection of annual performance with a given confidence level					
S6	Site characterization with high-fidelity: there is no guideline/standard to clearly survey all local factors to assess techno-economic feasibility/performance of a commercial project at a given deployment location. The local factors may include, but are not limited to: - Sun shape - Temporal solar irradiance file - Soiling characterization - Attenuation characterization - Cloud patterns - Extreme events - Weather forecasting.	x				x
Tier 2 Gaps						
S7	Heliostat field performance monitoring guideline: there is no guideline to define the metrics and methods to monitor a commercial solar field. The monitoring metrics include: - Heliostat performance: whole field vs. sampling ○ Optical errors ○ Soiling measurement and characterization ○ Aiming quality - Beam quality - Beam glare - Cloud passing - Receiver temperature - Wind and wind load - Structural degradation.	x				x
S8	Correlation of opto-mechanical performance with design, production, and deployment defects: there is no correlation between the opto-mechanical performance and various defects such as design, production, and deployment, so that a heliostat product can be improved through engineering iteration.			x	x	x
S9	Receiver aiming strategy development guideline: there is no guideline for receiver aiming strategy development, which should consider (but is not limited to): - The performance assessment - Receiver safety operation requirements - Required metrology system for solar field and receiver - Weather condition monitoring - Receiver heat transfer fluid flow rate control.	x				x
Tier 3 Gaps (Least Important)						
S10	Heliostat field safe operation guideline: there is no guideline/standard for heliostat solar field safe operation for the industry, which should cover: - Potential operation hazards - Impact of beam glare - Environmental impacts.	x				x
S11	Assessment and monitoring of environmental impacts of solar field: there is no standard or guideline on assessing and monitoring the environmental impacts of solar fields; this would help expedite the project permit authorization process required by local and federal regulations and policies.	x				x

During the HelioCon Roadmap Workshop, valuable feedback was collected, some of which is highlighted below:

On Metrology

- High-quality flat mirror facet may be valuable to serve as a reference for metrology system assessment
- Metrology needs may vary from one design to another
    - Coupled with trade-offs of a specific heliostat design
- Redundancy is always good but depends on the cost to develop metrology
    - It is expensive to develop a metrology system; need to prioritize efforts
- Practical requirements are hard to define
    - Vary with specific designs; coupled with the design process
- Round-robin tests are needed for metrology systems within the same category.

On Standards

- Standards (e.g., terminology) are critical for effective communication
    - Fundamental technical communication
    - Third-party assessment at a consistent platform
    - Especially those directly related to project financing
- Identify the specific value of standards through a commercial project development procedure (toward permitting)
- Identify partnering organizations to actually support project permitting in the United States, such as the Occupational Safety and Health Administration (OSHA), American Society of Mechanical Engineers (ASME), the International Electrotechnical Commission (IEC), SolarPACES, and others
- Leverage standards from other industrial sectors such as PV, common material production
    - Such as soiling, trackers, electronics, wind load, sun shape, high precision level attenuation
    - Need to consider unique features of CSP.

5.4 Gap Analysis and Recommended Pathways

Table 9 summarizes the required functionality of the proposed solution, justification, and benefits by addressing the given gap, and includes the recommended pathway for the Tier 1 gaps on metrology. As seen in the table, all six Tier 1 gaps on metrology are fundamental to the development of viable heliostat technologies. Opto-mechanical errors of heliostats dominate optical performance of a commercial-scale solar field and the solar field efficiency. Per a past study [83], an additional opto-mechanical error of 2 mrad (slope error equivalent) may result into an annual energy reduction of 20% for a given 100-MWe solar tower plant. In addition, in comparison with other CSP technologies such as parabolic trough and linear Fresnel, heliostat power tower system is most sensitive to the increasing opto-mechanical errors [83]. Though heliostats have been under development for a few decades and a number of heliostat designs were adopted in existing commercial power tower plants, metrology to characterize and measure opto-mechanical errors under various conditions and development stages is still largely missing.

Five of the six Tier 1 gaps on metrology are related to measurement of opto-mechanical errors. For each of measurement scenarios, the opto-mechanical error measurement requirements vary, and therefore the metrology design principles can be dramatically different as well. Two key observations regarding the top-ranked gaps on metrology are:

- Most available metrology techniques are singular technology for a given measurement condition. In most cases, they are not mutually validated against other technologies. Based on the limited round-robin test results, the differences between metrology techniques may be substantial.
- The development of a commercial metrology technique can be very time-consuming. It typically requires multiple rounds of refinement.

The recommended pathway proposed to address the gaps takes into account the key observations above but also the importance of required participants in the metrology development. It calls for the global community to:

- Develop new tools to fulfill the top-tier gaps
- Carry out round-robin tests to assess the metrology techniques measuring the same set of parameters
- Develop a validated third-party evaluation platform(s) for the validation of newly proposed tools.

Table 10 summarizes the required functionality of the proposed solution, justification, and benefits by addressing the given gap, and the recommended pathway for the six Tier 1 gaps on standards. The development of all top-ranked gaps on standards would require the engagement of the international society. For almost any guideline or standard development, an international work group with a comprehensive representation from key stakeholders, such as relevant industrial players and independent subject matter experts from different countries, is necessary to organize the efforts from the beginning. It is truly a mission for the international society.

The overall goals of HelioCon on the topic of metrology and standards are to (1) achieve the most-advanced metrology technologies identified in selected Tier 1 gaps; (2) establish a validated third-party evaluation capability within HelioCon for heliostat performance assessment and new metrology technology assessment; (3) develop and document the Tier 1 guideline and standards for heliostat technologies; and (4) promote the development of high-tier metrology technologies and standards by working with international community.

Table 9. Top-Ranked Gap Analysis for Metrology

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
M1: Not Fully validated metrology for opto-mechanical error measurement in laboratory	• Able to measure an integrated heliostat • Able to measure the shape deviation, slope error and canting error (if applicable) • High surface resolution • Easy operation • Accommodating various orientations • Low measurement uncertainty • Verification of results	• Fundamental step to the product development • Provide performance assessment of an integrated heliostat to (1) improve the design; (2) ensure the quality of the final design product; (3) serve as the third-party evaluation.	- Develop new tool(s) - Perform round-robin tests of available techniques on the market - Make the most advanced technologies available (or licensable) in the market - Establish third-party test labs possessing more than one metrology techniques to support the industry needs for product prototyping and engineering optimization
M2: Missing metrology for opto-mechanical error measurement in outdoor environment (a few heliostats)	• Able to perform in-situ measurement of one or more fully functional heliostats • Able to measure the full spectrum of opto-mechanical error • Easy operation • Accommodating various orientations • Accommodating various weather conditions • Low measurement uncertainty • High-resolution measurement • Verification of results	• Fundamental step to the product deployment • Provide performance assessment of a final heliostat product under realistic operation conditions before field deployment.	• Develop new tool(s) • Perform round-robin test of available techniques on the market for validation • Make the most advanced technologies in the market available (or licensable) to the public • Establish third-party in-situ performance assessment platform possessing more than one metrology technique to support the industry needs to evaluate pre-commercial products
M3: Missing metrology for opto-mechanical quality assurance tool	• Able to measure shape deviation, slope error, and canting error • Automatic operation • Fast assessment speed	• Fundamental step for mass production • Provide quality assurance for mass production line before field deployment	• Develop new tools specific to individual mass production line design • Make third-party evaluation platform available for new tool validation • Make proven quality assurance tools available to the global industry

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
M4: Missing metrology for opto-mechanical quality calibration after installation	• Accommodating in-situ conditions during construction • Minimal manual operation or automatic operation • High-precision calibration • Fast calibration process	• Provide quality assurance of installed heliostat field to achieve the target performance at the design point	• Develop new tools or adapt other types of tools for quality calibration for installation of specific heliostat designs • Make third-party platform available for new tool validation • Make proven calibration tools available to the whole industry
M5: Missing metrology for opto-mechanical error in-situ tools (full commercial-scale field)	• Able to measure full spectrum of opto-mechanical errors • Automatic operation (or minimal manual interruption) • Able to survey a large volume of heliostats within a short time (to be defined) • Accommodate the need of either high-speed or high-resolution measurement • Verification of results	• Fundamental to know solar field performance and its change with time and environmental conditions • Fundamental to conduct any solar field performance improvement • Fundamental to maximize solar field optical efficiency and minimize receiver failure • Fundamental to gather the reference performance of deployed technology so as to develop the next generation technology	• Develop new tools • Perform round-robin tests among available technologies • Make proven calibration tools available to the whole industry • Make third-party platform available for new tool validation.
M6: Missing metrology for receiver flux quality real-time assurance tool	• Able to measure flux distribution on receiver geometry in real time • Able to correlate flux distribution with solar irradiance and solar field operation • Automatic operation • Able to be directly integrated into solar field control for hazard mitigation	• Fundamental to solar field safe operation	• Develop new tools with a partnership from an operational power plant for technology benchmark • Develop open-source function-specific modules

Table 10. Top-Ranked Gap Analysis for Standards

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
S1: Missing definition of optical attributes for heliostats	• Clearly define mathematical and physical representation of optical attributes of heliostat technologies	• Fundamental for the whole heliostat technology (and CSP) community to communicate • Will greatly facilitate comparison of metrology technologies, different heliostat designs, different heliostat system performance	• The whole community should review and agree on the draft guideline under development • The community should develop a standard under the IEC CSP track.
S2: Missing heliostat design guideline	• Clearly summarize the contributing factors impacting technical performance • Make recommended steps on concept development, prototyping, and performance validation • Summarize available modeling tools and test tools available to assist heliostat design	• Will serve a fundamental basis for heliostat developers to refine the design process and not neglect any important factors • Will shorten the learning curve for any newcomers	• An international work group from different countries including leading heliostat developers, third-party performance evaluation entities, and subject matter experts should be formed to lead and coordinate the effort • Heliostat test guideline and a third-party performance evaluation platform should be available ahead of time.
S3: Missing heliostat solar field design/simulation guideline	• Clearly summarize the contributing factors impacting solar field performance • Clearly summarize the solar field performance assessment metrics and accompanying uncertainty • Summarize a recommended procedure capturing and correlating the analysis uncertainty of each step • Categorize required measurement/survey data on-site for a given project deployment location and assumption taken at discretion	• Will serve a fundamental basis for project developers to optimize solar field with respect to its economic return • Will facilitate the project financing with synchronized high-fidelity energy production projection	• An international team of subject matter experts should be formed to lead the effort of the guideline draft • A partnership with stakeholders from the industry would be needed for practical validation of the developed guideline • IEC should be engaged for converting the guideline into an IEC standard.

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
	• Summarize the requirements for developing a high-fidelity solar field design/simulation model • Summarize available solar field design/simulation models		
S4: Missing heliostat test guideline	• Clearly define a full set of tests required to certify technical performance of a given heliostat design	• Fundamental to determine an objective and complete performance of a given heliostat • Will facilitate the financing of a commercial project	• Develop after metrology technologies are ready • An international team with subject matter experts in the area will lead the draft test guideline development with available metrologies available in-house • A validation test campaign should be planned for the guideline validation/demonstration • IEC should be engaged for converting the guideline into an IEC standard.
S5: Missing heliostat solar field acceptance test guideline	• Explicitly define a procedure to evaluate technical performance of a newly constructed solar field in a quantitative fashion • Provide a recommended list of modeling and testing tools as references	• Fundamental for a seamless transition between a solar field EPC and the owner • Will eliminate the ambiguous part of heliostat field performance assessment • Will facilitate the project financing and shorten the project deployment time	• It will be developed after metrology technologies are ready and the heliostat test guideline is completed • A validation campaign will require a partnership with a heliostat system developer • An international working group should be formed to convert the guideline into a standard under IEC.
S6: Missing site characterization guideline	• Establish a procedure to survey the weather and other conditions so as to collect sufficient information to (1) ensure a high-fidelity plant performance prediction analysis, and (2) identify potential risks of major failure points of a project	• Fundamental for determining the economic viability of a project • Fundamental for the solar field layout and size optimization at a given site	• A validated high-fidelity plant performance prediction model should be available to assess the impact of various site characteristic factors • A task force partnering with a project developer should be formed to address the immediate need of the site characterization guideline

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
	• Scope of site characterization should cover: ○ Weather conditions, solar irradiation, sun shape, soiling, wind, extreme events ○ Ground condition ○ Local ecosystem ○ Local labor market		• An international working group should be formed to convert the guideline into a standard under IEC.

6 Components and Controls

6.1 Scope

Heliostats comprise static and dynamic components required to operate within a highly controlled manner to provide accurate solar flux pointing during CSP operation. The general composition includes a reflective area, control system, and a mounting and tracking mechanism. A reflective area is typically made up of one or more mirrors (also called facets), with a surface area that, on some heliostats, has reached to 178.5 m^2, as shown in Table 1. According to Coventry et al. [84], Gen 1 and 2 heliostats have a size range of 1.14 m^2 (eSolar) to 120 m^2 (Abengoa), with various sizes in between, e.g., 15.2 m^2 (BrightSource), 62.5 m^2 (Pratt&Whitney), and 116 m^2 (Sener) [85], [86], [87], [88], [89]. These efforts have required optimization of the component designs to lower costs of customized components (such as drive system, which can account for up to 30% of total cost, primarily for the azimuth drive [90]).

To further reduce fabrication costs while increasing heliostat surface area, curved facets were introduced [91]. 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 [92]. 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 the primary forces that dictate choices within heliostat components and controls. Additionally, maximum operating torques of the drive train and stiffness of structure are primary factors that determine the relationship between wind speed and performance.

Electronic control of the heliostat drive train is required for adjustment of the heliostat structure so it can track sun position 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. Heliostat durability and reliability are not well characterized but are of key importance to ensure high performance and safe operation over the designed lifetime. Component degradation, particularly for drives, mirrors, and electronics are also not well documented in literature, but are critical for predicting long-term system performance and planning, as well as financing system O&M.

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 PV [93] as well as CSP [94], [81], 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.

6.2 State of the Art

In NREL's most recent cost study [12], a typical commercial heliostat is compared against an advanced design with alternative approaches to cut cost and move toward 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. Hereafter, a breakdown of the state of the art of these key components and system controls is provided from the perspective of gaps toward cost reduction. Consideration is provided for key overarching criteria such as performance requirements under operational wind loading. Furthermore, state of the art of heliostat O&M, degradation, and reliability are discussed as they are a complex interaction that results only after combining various components with a controller.

6.2.1 Drives

Heliostat drives represent one of the most expensive components in a heliostat, as demonstrated by the commercialized Stellio drive (in Section 2) comprising 22% of the design's total cost. The specific drive and rotational assembly costs associated with this design would account for 57% of SETO's \$50/m^2 cost target for heliostats, demonstrating the need for further cost reduction. Appendix B provides a literature review on a variety of existing and proposed drive system design options for heliostats cost reductions.

While many conceptual designs and prototypes have been considered, there are few alternative drive types at current commercial scale in the field. Of the 15 CSP tower facilities to enter operation worldwide (per SolarPACES' database) since 2013, all but one use a pedestal configuration with an azimuth slew drive and linear actuation for elevation. These projects comprise a wide range of locations and heliostat developers: Ashalim, Israel; Delingha, China; and Calama, Chile (by BrightSource, Cosin Solar, and Abengoa). BrightSource's current two-facet pedestal heliostat design is shown in Figure 15. Early-construction installations continue this trend: all six under-construction grid-scale installations use pedestal-type heliostats. This includes sites in Golmud, China (CGDG Qinghai New Energy) and Redstone, South Africa (ACWA Power).

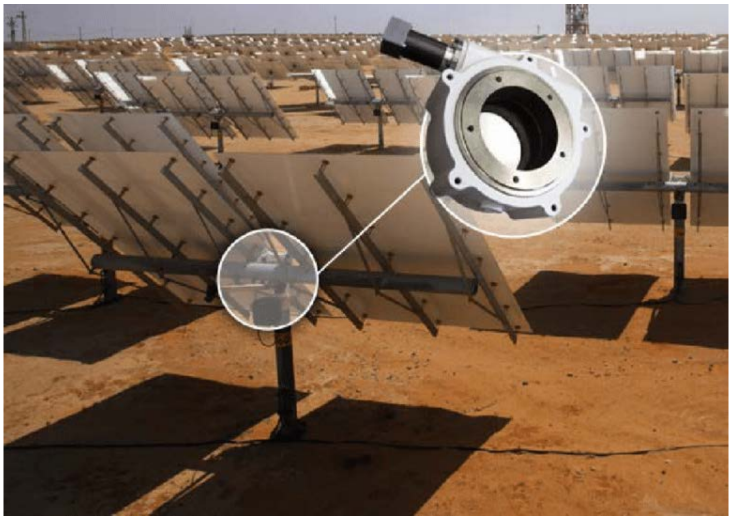

Figure 15. Typical for current state of the art, the production BrightSource heliostat at Ivanpah uses a worm gear-driven azimuth drive

This particular unit was developed specifically by the firm Cone Drive for BrightSource heliostats. Custom solutions like this must be large scale (which BrightSource can achieve as the heliostat provider for multiple CSP facilities) to be cost-effective. Photo from [14].

One exception is the Hami, China, project that uses the Stellio heliostat, which makes use of two linear actuators per a slope drive configuration (a sloped primary axis). Separately, CSIRO has partnered with Chinese company Thermal Focus to license their own cost-cutting heliostat design that implements a tilt-and-roll system with two linear actuators.

Drive costs must be reduced, but there are three primary barriers in the process. First, drives are generally overbuilt per current understanding of wind loads. In order to advance alternative low-cost designs or downsize existing drives, research is needed to better characterize high-frequency wind speeds at heliostat heights as well as how wind loading changes throughout a heliostat field design. For small format heliostats, linear drives escape some overbuilding issues though mechanical advantage of off-axis attachment, although other issues (primarily dust and water ingress) exist. Second, the heliostat market volume is too low to support ongoing development and improvement of drives or other components. Current projects must select slew drives or linear actuators that already have volume in other industries.

6.2.2 Mirrors/Facets

Heliostat facets represent a high proportion of both heliostat component cost and designs that could be improved to reduce LCOE and LCOH. Commercially available heliostat mirrors (including adhesives and supports) represent $24/m^2 of the total cost [12]. Most commercially installed heliostats use second-surface mirrors constructed with 3- to 4-mm glass. One exception is Abengoa's ASUP 140 (used in the LuNeng Haixi 50-MW plant), which uses a 2-mm glass reflector. Some variations exist in the means of supporting the reflector. The ASUP 140's relatively thin mirrors are supported by foam in a sandwich-type construction. Material and weight reductions for large heliostats have been achieved by replacing facets' typical solid backing with stamped, lattice-type facet supports. Heliostats installed at Noor III in Morocco (Figure 16) use this style of construction.

Figure 16. SENER's HE54 heliostats at Morocco's Noor III facility (operational since 2018)

At 178.5 m^2, this is the largest heliostat in commercial CSP use [95]. Each facet uses a latticed support. This reduces the material usage of the facet itself, a weight reduction which can lower design loads on the drives and heliostat structure. Photo from [96].

Although sandwich- and stamped back sheet-supported facets have been used in commercial installations, further work is needed. The slope error of these facets can reach 0.05 mrad/°C operating deviation from as-manufactured temperature [97]. The Eurostars2 PHOTON ("High Performance Thermosolar Plants based on PV-Hybrid Autonomous Heliostats and Tailored Receivers") project has addressed this with thermally balanced sandwich "bi-facets" that reduce this error down to 0.005 mrad/°C, but these are not yet implemented at field scale.

Previous work showed that heliostat field performance can have more than twice the impact on LCOE as cost and design [14]. For this reason, alternate facet materials and construction techniques must provide either substantial savings or negligible performance penalties to become viable. These alternatives include polished metal, coated metal, and automotive-style coated plastic mirrors, although none have thus far been used for heliostats at commercial scales. While glass mirror alternatives have demonstrated similar specular reflectivity, it has been challenging to prove similar outdoor durability of these materials [98]. Glass holds the status quo as a durable and bankable first surface reflector against outdoor weathering, and therefore it is challenging for any new material to displace glass mirrors.

This reliability challenge is further complicated because there is not a clear understanding of environmentally specific weathering factors. For example, a mirror surface will be subjected to very different weathering in the Middle East (multiple intense sandstorms in a year) compared to the desert southwest United States where sandstorms are much less frequent. There is also a lack of systematic data demonstrating how glass mirror performance changes over time with existing mirror cleaning methods and frequency. Sandstorms, ultraviolet dose, humidity levels, salt exposure, temperatures, and cleaning methods/frequencies are weathering factors that can vary site-to-site but are not necessarily fully characterized. IEC 62788-7-3 has recently been published and includes a set of durability tests that can be applied to mirrors to characterize changes in performance in response to blown sand or various cleaning methods. While this standard provides a starting point, it does not specify pass/fail criteria or any means to link number of test cycles to the environment at a specific heliostat site.

In close relation to alternate mirror materials, there has been significant work to develop anti-soiling coatings for glass and other surfaces. A more in-depth discussion of anti-soiling coatings is presented in the soiling section of this document (Section 6.2.6) but these coatings require techno-economic justification through both the durability testing described above and additional standardized tests demonstrating anti-soiling efficacy.

As with heliostat drives, a greater understanding of wind loads (and mitigation measures for those loads) presents an opportunity for lowering the cost of mirrors. Feedback from a HelioCon workshop indicated that mirror facets are overdesigned with respect to different heliostat orientations that may not occur simultaneously, and robustness against worst case wind loads as well as other environmental conditions. Current research has considered a wide variety of solutions to wind loads on facets; this is presented in Appendix B and covers facet gaps, aspect ratios, stretched membranes, overall size alterations, and all-glass reflectors.

Cost reduction of mirrors/facets represents a significant gap, with current prices being nearly double the DOE/SETO heliostat cost target of 50/m^2. There are multiple pathways to cost reductions, including material selection, facet design, mirror gap, aspect ratio, and reduced design requirements through additional wind loading research. Soiling is known to reduce mirror performance over time, affecting O&M costs and ultimately LCOE. Anti-soiling coatings provide the potential to maintain higher mirror performance at a lower cost, but standards are necessary to demonstrate both efficacy and durability of such coatings.

6.2.3 Structure

Nearly all commercial heliostats use a pedestal that supports a rotating torque tube. These structures tend to be fabricated from structural steel and are therefore material-intensive. The mass of steel in a heliostat structure can range from 59 kg/m^2 for a pedestal design to 15 kg/m^2 for an optimized spaceframe [99], [100]. A large mass of raw material inputs into assemblies (e.g., steel into the heliostat's structure) is not only a significant cost, but one that is inherently susceptible to large fluctuations in commodity prices.

Some variegated geometries that potentially reduce material usage are in commercial use. Heliostats manufactured by eSolar, in use at the agriculture firm Sundrop Farms' South Australia CSP facility since 2016 and pictured in Figure 17, use a ballasted truss to support each heliostat, largely eliminating pedestals and concrete foundations in the process. CSIRO has developed a heliostat comprising glass directly bonded to a formed sheet steel frame in use since 2011 in a research application [14]. The Stellio heliostat, installed at the CEEC Hami 50-MW plant, reduces wind loads with a pentagonal shape and circumferential purloins supporting its facets.

Figure 17. eSolar trussed and ballasted heliostat

24,000 mirror modules mounted on shared trusses are used at the SunDrop facility. The diminutive heliostat represents a design approach that focuses on minimizing cost of installation at the site; according to eSolar, installation used local unskilled labor, with only one size of wrench needed for complete assembly [101]. Photo from [85].

Torque tubes have been eliminated entirely in several recent applications. At Atacama I (operational since 2021), the mirror facet support structure is entirely trussed. The Abengoa ASUP 40V3 heliostats used at Atacama I are shown in Figure 18. Facets may also be suspended from a central pylon, rather than supported from underneath. Suspension-style solar trackers are being developed by Solaflect and Skysun LLC. Originally developed for heliostat applications in collaboration with NREL, suspension structures can reduce steel consumption by two-thirds relative to a standard pedestal design [102].

Figure 18. Abengoa trussed heliostat at Atacama I

This design eliminates torque tubes entirely. This can lower the structure's cost in two ways. First, less material (by mass) is used. Second, there is no need to separately procure and process a small quantity of one specific tube/pipe size for the torque tube. Photo from [103].

Cost reduction of heliostat structures is primarily a question of steel usage and respective frame coatings (paint, hot dip process, etc.). There are three complementary pathways for reducing the cost of heliostat structures. First, greater understanding of wind loads can lead to a more informed structural design specification. Heliostat-specific tools like the wind load spreadsheet developed by ASTRI and the University of Adelaide [104] can enable developers to size heliostat structures appropriately for applications, rather than overdesigning to generic building codes. At a field level, this may lead to heterogeneity of heliostat designs within a single field. As noted in ASTRI's heliostat costing report, wind loads in well-protected inner rows may experience only 10% of highly loaded outer rows [14]—a much lower design load, which could enable lighter structures in shielded areas of the field. Second, alternative designs with less steel can meet existing design targets. This is seen in the trussed and suspension heliostats discussed in this section. Third, alternative materials can be considered. Plastics and composites can greatly reduce mass and create more design possibilities. Although they are not currently used in commercial heliostat or PV tracker applications, their structural use in cyclically loaded structural applications by the automotive and aerospace industries indicates suitability for heliostats.

The pedestal foundation can also be optimized for strength or low cost. Pfahl et al. have extensively studied heliostat cost reduction methods including the use of a prefabricated concrete ground anchor foundation [105]. Traditional concrete foundations typically use rebar, steel anchors, and concrete to secure the pedestal to the ground. According to Pfahl et al., such foundations for heliostats typically contribute about 10% of the total heliostat cost. To reduce this cost, Pfahl et al. consider a prefabricated concrete foundation block, which is built to accept natural material such as sand or rock.

Pedestal foundations can also be eschewed with carousel-style rim drives. One such example is the Solar Dynamics SunRing, which accomplishes azimuthal rotation with a geared ring riding on ground anchors. Kurup et al. showed that the foundation cost is \$2.07/m^2 higher than that of a heliostat with a traditional single foundation [12]. However, site labor costs were reduced by \$8.60/m^2, partially as a result of a semi-automated piledriving procedure replacing the laying of a standard foundation. Labor costs can vary significantly between, and within, countries. Exploration of foundations that require less labor to install are therefore twofold: (1) cost reduction of the heliostat, and (2) cost certainty across sites.

6.2.4 Controls Design

Heliostat control systems ensure that each individual heliostat in a field tracks the angle bisector between the sun and the solar receiver [62]. Control systems also manage the flux on the receiver by varying the number of heliostats in use. For every CSP system, the number of heliostats pointed at the receiver needs to be adjusted depending on the sun's position in the sky. For example, at noon in the middle of summer fewer heliostats need to be pointed at the receiver than late in the afternoon on a winter's day.

Control of each individual heliostat may be open- or closed-loop. As elaborated by Sattler et al., this is not a binary distinction [62]. Fully closed-loop systems possess a beam characterization system, which provides feedback data based on where each heliostat's beam hits the receiver. Partially closed-loop systems use measurements beyond data from the heliostat's drive encoders—tracker-mounted cameras, for instance. Using specific definitions, Sattler et al. identify 30 unique closed-loop calibration schemes as the current state-of-the-art, sorted into five classes [62].

Simple illustrations, as shown in Figure 19, help to explain the five different classes (A1, A2, B, C, D) of techniques that have been explored for closed-loop calibration systems.

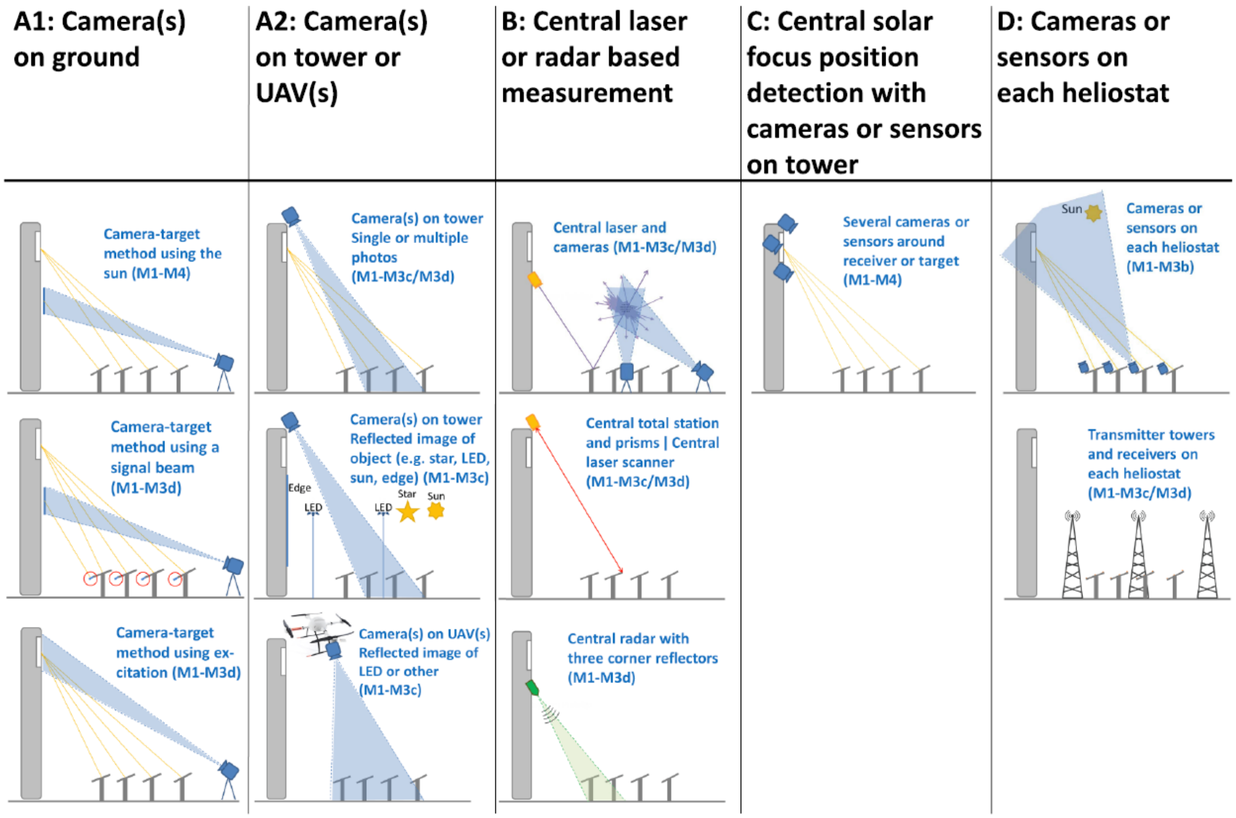

Figure 19. Five classification schemes for automatic calibration of heliostats [62] demonstrate that methodologies vary, and there is currently no broadly accepted strategy for closed-loop calibration and control

Note that UAV stands for unmanned aerial vehicle.

Closed-loop control can enable automatic rough calibration as part of commissioning and fine calibration on a daily or even more frequent basis. The goal is to decrease commissioning and O&M cost and increase long-term plant performance. For example, the National Renewable Energy Centre of Spain demonstrated that 0.6 mrad directed beam direction error is achievable with heliostats using consumer-grade 5-megapixel CMOS cameras for calibration [78]. Some form of closed-loop control is implemented in heliostats from Abengoa, BrightSource, and Supcon (Cosin) Solar, comprising the majority of central receiver facilities that have been online since 2013. The hardware to enable closed-loop heliostat control is also capable of providing feedback for plant-level control. At Ashalim, for instance, the PV panel mounted to each BrightSource heliostat provides irradiance data back to field management software. This software is able to therefore decide, in real time, which heliostats to aim at the central receiver to maximize flux in, for instance, partially cloudy scenarios [106].

While the potential cost and performance benefits of closed-loop control are obvious, Figure 18 demonstrates that the industry has not come to a consensus on a best technique. The differing options are not well understood for variation in cost, difficulties in implementation, limitations in optical accuracy, and long-term field performance and maintenance requires. In order to achieve bankable benefits of closed-loop control and calibration, more research and development is needed to come to a consensus on the most beneficial implementation techniques.

6.2.5 Wireless Controls

A truly wireless heliostat is not only controlled, but powered, wirelessly. Traditionally, heliostats have been controlled by buried copper or fiber optic wired networks, but in recent years there has been movement toward wireless communications. Wireless communications offer simplified plant design and cost reduction due to both material reduction and reduced labor hours at construction. In the heliostat space, Solar Dynamics, Trinamic, BrightSource, and others have introduced wireless heliostats. At Ashalim (operational since 2019), BrightSource equips each wireless heliostat with a PV panel—see Figure 20. The need for cabling is thereby reduced by 85% or more [107]. The PV panel provides not only power but heliostat-level irradiance data—feedback that enables field management software to fine-tune receiver flux [106]. Glatzmaier assessed the cost and performance benefits of a wireless system for heliostat power and control. Through an extensive survey, analysis, and model development, his project quantified and compared the cost of their shared-node wireless system to be 42% less than the cost of a fully wired system that is representative of the state-of-the-art technology for commercial power tower plants [108].

Figure 20. Wireless BrightSource heliostat at Ashalim with top-mounted PV panel

A small heliostat is estimated to consume less than 1 kWh per day [109]. Heliostat-attached PV panels can therefore provide feedback data and eliminate power cabling. Image from [106].

Heliostat fields present an opportunity for deployment of Low Power Wide Area Networks, which are already heavily utilized for Internet of Things solutions. PV tracker systems have in recent years operated with wireless communications, where lessons learned can be utilized for CSP heliostats. For example, Nextracker (a single-axis PV tracker company) was founded in 2013 and begin installing utility-scale PV plants with solar trackers controlled by Zigbee wireless communications and small PV panels and batteries for power. Nextracker now has over 50 GW of installed trackers operation on Zigbee wireless networks [110]. While single-axis trackers are simpler to control than two-axis heliostats, such installations have proven the possibility for cost reduction using wireless control.

Although wireless systems offer cost reductions, various approaches could introduce significant technical, cybersecurity, and other safety issues. There are currently no standardized requirements and testing capabilities to validate both functionality and safety as the CSP industry transitions to fully wireless control.

6.2.6 Operations and Maintenance, Reliability, and Degradation

Heliostats represent one of the primary impact drivers of CSP plant O&M costs through items like calibration/alignment, mirror cleaning, mirror replacement, and drive replacement. Historically the largest part of O&M costs came from mirror replacements, but newer designs have reduced failure rates for receivers and currently field labor, as well as cleaning costs. These can be viewed as high impact drivers with regard to O&M costs. The International Renewable Energy Agency estimates that O&M costs per operating facilities in 2020 range from USD 0.02/kWh to $0.04/kWh [111]. Zhu demonstrated that O&M costs can have a significant influence on LCOE, especially for higher internal rates of return [15]. The most recent ASTRI cost study concluded that O&M must be accounted for in heliostat design, especially when targeting USD 0.05/kWh [14].

Alternatively, it is not as simple as targeting designs with the lowest O&M costs, because long-term LCOE determination is based on a complex assessment that must include cost for up-front capital, finance rates, O&M reserves, maintenance schedules, and system performance with respect to time. As noted earlier, the ASTRI cost study stated that solar field performance has 2.3 times the impact on LCOE than the cost, which demonstrates the danger of overly focusing on cost reduction and not adequately accounting for higher plant degradation with time, which may result in undercutting O&M spending.

The PV industry has experienced a race to the bottom of O&M costs, and the NREL PVfleets project has found many case studies where plants have degraded at higher-than-expected rates without sufficient O&M. The CSP literature is limited in terms of understanding expected plant degradation of various components of heliostats. Relevant questions arise:

- How does the degradation rate of mirrors vary with respect to climate?
- Are degradation rates included in long-term plant performance and TEA forecasts?
- How does tracking accuracy change with time and with degradation of gears/backlash in slew drives or other drive systems?
- Is downtime for replacement of components like mirrors or drives accounted for in long-term performance models?

All of these questions support ASTRI's conclusion that O&M costs must be considered within heliostat design, but they also make clear that complete information is not available to make all of these trade-off decisions. Furthermore, a heliostat's performance is not simply based on the reflector performance, or the controller performance, or the drive performance; it is based on the integration of all the components into a system. This system is then impacted by climatic variables like humidity, salt-particulate aerosols, wind, airborne dust, and other factors.

In other industries, standardization provides an infrastructure for handling issues around O&M, reliability, and degradation. There is ongoing work through SolarPACES and there are currently relevant IEC standards (for example IEC 62817, design qualification for solar trackers), but currently heliostats are in need of a number of standards covering topics such as quality assurance, design validation, durability, and reliability.

6.2.7 Relative Component Impacts on Cost

In context of SETO's 2030 goals, it is important to understand the relative contribution of a respective component's cost to the overall cost of the heliostat. Large gaps in relatively costly components present the clearest targets for technical and financial focus. The most contemporary analysis in this area was conducted by Kurup et al. [12]. For a commercially available heliostat costing \$127/m^2 overall, the authors found that the top six categories driving cost were the base assembly (\$19.96/m^2), mirrors and adhesives (\$17.00/m^2), site labor (\$16.39/m^2), drives (\$16.08/m^2), controllers (\$14.43/m^2), and rotation assembly (\$12.19/m^2). These key components and field labor total \$96, or nearly twice the current DOE/SETO heliostat cost target of \$50/m^2. It is also worth noting that rotation assembly and drives can be grouped as the drivetrain with a total of \$28.27, or greater than half of the target cost.

The same study analyzed an advanced/emerging heliostat costing \$99/m^2 overall. While the emerging heliostat made a significant improvement by reducing site labor (\$16.39/m^2 to \$7.79/m^2) some of the key components costs remained challengingly high: mirrors and mirror supports \$23.99/m^2, drive train \$23.47/m^2, and base assembly \$11.12/m^2 (or \$17.70/ m^2 when the increase in fastener cost is included). This analysis clearly demonstrates that there are gaps to reduce the cost of the drive train, mirrors, and tracker structure, and that field assembly must be considered to avoid high labor costs.

6.3 Ranked Gaps

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 commonly flagged components for unreliability and high cost of replacement. 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 survey exposed 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%, had experienced issues with soiling. While soiling is traditionally considered an O&M domain, coatings can play an important role in mitigating soiling's LCOE burden throughout a plant's lifetime.

Through the literature review of the state of the art, communication in the HelioCon workshop, and the industry survey, technical gaps in components and controls for heliostat technologies were developed as summarized in Table 11.

Table 11. 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

6.4 Gap Analysis and Recommended Pathways

Using the tier-based criteria, the components and controls team categorized the gaps into three discrete tiers. Position within a tier does not indicate the priority of a gap within that tier. The five most significant gaps were determined to have the most impact to heliostat performance and cost: C1, C2, and C3 are specifically focused on cost reduction, while C4 and C5 target both costs and long-term performance improvements, allowing plants to achieve an error less than 1 mrad.

Within the Tier 1 gaps, the components and controls team considered further prioritization and concluded that C4 and C5 (closed loop controls and IEC standards respectively) were highest ranking. This recommendation is based on of the need to address these gaps to facilitate cost reduction and performance improvements. The team also believes there are also existing pathways to closing both gaps.

C1: Composites or advance structures

It is clear that existing heliostat structural and foundation costs must be reduced in order to achieve the DOE/SETO cost target of $\$50/m^2$. Per current designs, steel is a large portion of heliostat cost, and therefore cost targets are very sensitive to steel price variation. Large, heavy steel beams are used for construction of pedestals and torque tubes. Alternate designs are needed that either use less steel or use alternative materials that are lower cost. In addition, alternate designs that are better optimized can be achieved in conjunction with the closing of gaps surrounding wind loading (for example the need for high-frequency wind data, understanding of wind loads throughout the heliostat field, or wind-mitigating designs). 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.

C2: Lower-cost mirrors/facets

At current prices, mirrors would be a large portion of the target $\$50/m^2$. Costs can be reduced by 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 would be bankable if site-specific performance and reliability were well-understood.

Some data exist, which can potentially be leveraged to help close this gap. NREL conducted a multi-year and multi-site data collection effort to understand how different environmental conditions change mirror degradation [98]. Data were compiled into a Solar Mirror Material Database. Inquiry into additional sources of data may also be warranted.

C3: Broad application of wireless controls

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.

C4: Broad application of closed-loop control with auto calibration

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.

C5: Need for an IEC heliostat design qualification standard

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.

Table 12 summarizes the Tier 1 gaps, the outcome of addressing them, the justification for the gaps' selection, and the inputs necessary for progress on closing the gaps.

Table 12. Tier 1 Gap Analysis for Components and Controls

Tier 1 Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
C1: Lack of lightweight composites or other advanced structures (e.g., torque tubes, pedestals, foundation) are necessary for hitting cost targets.	Lighter-weight construction; increased reliability and lifetime; lower costs of fabrication, transportation, and deployment	Steel and foundations cost ~$24/m^2 per 2020 in the most recent NREL cost analysis. Steel costs jumped 200% in 2021, demonstrating the high sensitivity to this commodity cost. These numbers demonstrate the need for drastic change if $50/m^2 is going to be achieved.	Funding to research initiatives focused on alternate materials and structural designs outside the typical pedestal heliostat design. Funding to support testbeds for examining alternate designs coming from industry. Publication of a proven heliostat design qualification standard that would provide industry the necessary tool for validation of new designs outside the status quo.
C2: Lack of lower cost mirror designs with comparable performance to existing glass mirrors.	Mirror facets are designed for optimal performance and manufactured at volume to achieve cost reduction.	Mirrors and their supports cost $24/m^2 per 2020 commercial heliostats. This would account for nearly 50% of a $50/m^2 target and therefore does not leave sufficient dollars for the remainder of the heliostat.	Funding provided to research and develop composite/sandwich or other mirror designs that can achieve cost reductions.
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.	IEC standards are published that enable the safe and effective use of wireless controls.	Robust signal communication R&D needed for resilient wireless controls. R&D needed for wireless advanced controls architectures and hardware for facilitating single node or mesh networking.	Develop wireless testbeds to characterize signal abatement/loss and networking architectures. OR Adapt current wireless testbeds for heliostat field operations, size, and configurable topologies.
C4: Lack of closed-loop systems that are applied to achieve higher flux performance and auto alignment/calibration processes.	Closed-loop controls and various feedback sensors are a well understood, bankable solution to automated calibration, reduced drive requirements, and maintaining long-term heliostat performance.	More robust closed-loop communication needed for all operations within a heliostat field, such as with calibration and general commissioning.	Closed-loop communication R&D funding and testbeds for evaluating novel sensors and controls architectures. This includes R&D to address automation for calibration and commissioning as well as costs, while reducing field error.

Tier 1 Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
C5: Missing design qualification standards for heliostats to enable bankable components and controls, heliostat long-term performance, and shorten design improvement cycles.	IEC design qualification standards are validated and published. Any new heliostat design is subjected to this standard to prove market entry.	Bankable design qualification standards allow for rapid feedback on new designs that target cost reductions. This feedback enables further improvements in design and a real pathway to achieve $50/m^2 cost targets. Without such standards a new design may never be given a chance or may be installed in the field and failures are found after millions of dollars of expenditures.	IEC 62817 is a design qualification standard for solar trackers and was intended to also cover heliostats. At the time of writing there was not sufficient support from the heliostat industry to include several key sections related to heliostats. It is a low-hanging fruit to develop 62817-X, which includes the additional language specific to heliostats. This approach will take advantage on a number of appropriate existing tests as well as shorten the development process.

7 Advanced Manufacturing

The manufacturing process for heliostats begins with product design; proceeds through supply chain, procurement, component manufacture, factory assembly, transportation, and field installation; and ends when a functional heliostat is installed in the field. This comprehensive perspective allows optimization of the entire process and design tradeoffs between component manufacture, subsystem assembly, full heliostat assembly, and field installation. Manufacturing, assembly, and installation processes occur throughout this process, presenting multiple opportunities for reducing cost to achieve DOE/SETO's \$50/m^2 goal.

Heliostat functional capabilities such as automatic field calibration enable choices in the manufacturing and installation processes to further optimize the goal of achieving a functioning heliostat. For example, automatic field calibration could relax tolerances on heliostat kinematic parameters and field installation location. Similarly, high-quality process control is needed at all steps, so metrology is fundamentally intertwined with advanced manufacturing. Additional examples include measurement of production tooling such as molds, and control of the facet-truss assembly process to meet optical canting tolerances while operating at a production pace. Several examples are listed in Section 5.

Successful heliostat manufacture begins with a supply chain of qualified materials, followed by fabrication operations to transform those materials into parts and assembly operations to combine parts into layers of subassemblies, culminating in a final complete installation. Quality control is essential at all steps, and production pace must meet volume requirements. For context, the Crescent Dunes plant has over 10,000 heliostats, each comprising 35 facets mounted with four bolts. Considering only these elements, constructing this field within a one-year period would require one mirror facet to be manufactured every 90 seconds, one bolt to be assembled every 20 seconds, and one full heliostat to be manufactured every 52 minutes. This simplistic calculation is misleadingly optimistic; actual production will be much more demanding due to practical issues such as work stoppages for various reasons and operational constraints such as weather and daylight.[6] Meeting a one-year overall lead time would further accelerate production pace owing to the need to reserve time for calibration and commissioning. Smaller heliostat designs lead to even higher required production rates. For example, the Ivanpah facility includes over 170,000 heliostats; constructing such a facility in one year would require an average rate of at least one full heliostat every three minutes.

7.1 Scope

The goal of the heliostat enterprise is to design, manufacture, and operate heliostats to maximize economic return. In this topic we consider issues related to design and manufacture, leaving operation issues for Section 5. We will focus on heliostat design, production process, and calibration.

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[6] Individual factory line cycle (or takt) times, which are the "heartbeat" of the assembly line, may be longer than these time intervals if multiple lines operate in parallel. This incurs increased manufacturing cost, which is why speed is a premium.

- *Product design.* The design process is the most influential phase of the heliostat life cycle. For example, reducing a heliostat facet glass thickness from 4 mm to 3 mm for a solar field[7] of 1,200,000 m^2 will reduce the total glass content[8] by 3,000,000 kg; if glass costs[9] 1.35 \$/kg, this seemingly small design choice may reduce solar field material cost by \$3 million, or 5% of the total cost for a hypothetical heliostat achieving the \$50/m^2 DOE/SETO cost goal. Further, reflectivity will also increase due to decreased optical path length,[10] possibly increasing revenue. But at the same time, this thickness reduction might allow mirror deformation under wind or gravity loads, deteriorating solar performance and costing much more over the life of the plant. There are other implications as well, such as increased breakage risk due to hail and cold water shock; design decisions are often complex.

  Fundamental design choices can have an even greater influence. For example, is the heliostat facet self-supporting, enabling only three mounting points, or supported by multiple points to compensate for a lack of rigidity? The facet rigidity, backing structure, and mounting hardware required for these two cases may result in very different costs, and potential performance differences. Heliostat designers consider such decisions, and have arrived at a wide variety of conclusions. This is evidenced by the variation in both size and construction type for heliostats.

  Optimum heliostat size is a remarkable outstanding problem. A previous study [90], [92] indicated that a large heliostat size is optimum, prompting construction of some heliostat fields with large heliostats up to 178 m^2. However, this view was not unanimous; other contemporary researchers calculated a smaller optimum size [112]. Recently, designers in many cases have selected significantly smaller size, approaching 2 m^2. Factors influencing this decision include:

  - As heliostats become smaller, the number of drives and control units required increases. This has implications for both cost and reliability.
  - As heliostats become smaller, they become more numerous, which requires an increased number of control and power wires and increased trenching. However, if they become small enough to be powered by PV and wireless control is provided, then these may eliminate inter-heliostat wiring altogether.
  - As heliostats become smaller, they are lower to the ground and spaced more tightly, reducing wind loads; further, the movement arm of wind loads becomes smaller. However, being lower to the ground may increase soiling.
  - As heliostats become smaller, their reduced wind load may enable selection of drives that are already manufactured in high volume for other applications.

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[7] 1,200,000 m^2 is roughly the total mirror area of the Crescent Dunes plant.

[8] Several sources list glass density in the range 2,400–2,800 kg/m^3. If we assume 2,500 kg/m^3, then the weight of a sheet of glass 1 mm thick is 2.5 kg/m^2. Thus, glass has an areal density 2.5 kg/m^2 per millimeter thickness.

[9] From https://web.mit.edu/course/3/3.11/www/modules/props.pdf.

[10] See A. Pfahl, et al, "Heliostat Innovation in Detail to Reach Challenging Cost Target," SolarPACES 2020, and C. Holze, et al. "Laminated Solar Thin Glass Mirror Solution for Cost Effective CSP Systems," SolarPACES 2012.

  - As heliostats become smaller, the number of manufactured units increases, making efficient automated production more economical.
  - As heliostats become smaller, fully assembled mirror arrays become feasible to transport from a central factory to the installation site.
  - As heliostats become smaller, their attachment to the ground becomes less expensive.
  - Further, small single-facet heliostats do not require multi-facet canting, eliminating several assembly, metrology, and maintenance steps.

  The selection of optimum heliostat size is tightly coupled to the heliostat design, the solar field design, and the heliostat manufacturing process, making the notion of an "optimum size" elusive.

- *Process design.* The processes that manufacture heliostats are also a significant factor determining both cost and performance. As with design, cost can be greatly affected by seemingly innocuous parameters such as curing or cooling hold time. A standard technique is to identify bottleneck process steps, and seek to optimize associated process parameters to reduce cycle time. The next bottleneck is then identified and improved, repeating in a process of continuous improvement.

  Fundamental process choices can have an even greater impact on manufacturing cost. For example, consider assembling the housing of a drive component. One approach using screws may require multiple operations to pick up a screw and drive it into place, while a snap fit approach can be accomplished with a single assembly operation. Part fabrication is full of example processes that increase productivity, including stamping, casting, injection molding, roll forming, and more. Several process approaches for heliostat manufacture have been proposed and pursued by industry.

  Process details can have a significant impact. For example, consider a system that uses heat or adhesives to achieve facet curvature. The associated cooling or curing time determines the number of molds that are required. In our previous example where a facet must be manufactured every 90 seconds, an adhesive curing time of one hour would imply that 40 copies of the mold would be needed. This increases tooling cost, increases required floor space, and introduces process control challenges to ensure that product coming off all 40 molds has consistent quality. Additionally, a commercial-scale heliostat field may adopt two or more focal lengths, thus adding design complexity.

  Concurrent engineering of heliostats and their production system can establish an important feedback loop between them, reducing the cost and increasing the performance of both. Establishing accurate and detailed cost models of components and assemblies is paramount to driving cost to the minimum. Backing design decisions with a cost model helps to keep things grounded in the unique design problem that heliostats represent. For example, part consolidation is often used to reduce cost, but with stamped sheet metal designs consolidation can increase the offal/scrap associated with each part. Such consolidation makes sense at low volumes but is likely suboptimal at high volumes. A cost model is a useful tool to determine that threshold.

- *Transportation.* Materials must flow from their initial point of manufacture to the final installed heliostat location. Parts must be delivered to a factory, partially or fully assembled heliostats must be transported to the site, in some cases to a local factory for further assembly, and then heliostats must be transported to their final destination in the field. Optimizing this process to maximize productivity and minimize damage is an important part of process design.
- *Field installation.* A final installed heliostat is fully assembled. How much assembly is performed in a central factory, a local site factory, or directly on the field varies with the selected heliostat design; heliostats have been built spanning the range from installing mirrors in the field to placing fully assembled heliostats, including foundation, in place with a forklift. Because of the wide range of scales in the size of current heliostats, and the variation in foundation design that results from different ground conditions, conceiving of a single universal general-purpose solution to automated field installation is difficult. However, as with primary manufacturing, considering installation during the design phase can lead to design choices that achieve more efficient or even automated field installation.
- *Calibration.* Once a heliostat is fabricated, assembled, and installed, it may need additional adjustment to achieve required optical performance. In some past instances this has required per-facet canting adjustments, requiring expensive labor. This expensive and error-prone process is best avoided. Whether or not manual canting adjustment is required, full-heliostat calibration is typically required to achieve desired pointing accuracy, due to variation in actual as-built heliostat geometry from the ideal design specification. The necessary corrections can generally be implemented by software, but the necessary adjustment parameters must be measured. We include calibration as an important step in achieving a final functioning heliostat. See Section 5 for further discussion.
- *Control.* Closed-loop control of heliostat pointing is achieved by using sensor feedback to sense and correct pointing errors. This can greatly simplify heliostat production and operation by eliminating the calibration step. Because manufacturing optimization is often accomplished by eliminating material, parts, or steps, closed-loop control is relevant to advanced manufacturing. However, this topic is addressed in Sections 5 and 6.
- *Supply Chain.* In some cases, available materials or components can constrain or improve design. For example, a designer may desire a particular type of thin glass, but suppliers might not be sufficiently diverse. Conversely, heliostat designer might exploit certain available components supplied in volume to other applications; an example would be selecting drives already manufactured for automation applications.

7.2 State of the Art

At first look, approaches to improving heliostat manufacturing are not immediately obvious. Consider the components of a typical heliostat:

- Foundation or ground mount
- Pylon
- Kinematic axes and drives

- Mirror array backing structure
- Mirror facets
- Control electronics
- Power supply (in some cases).

The bulk of these are produced from standard materials using standard manufacturing processes. The ground mounting, pylon, kinematic axes, drives, backing structure elements, and glass facets are all instances of products that have been made for many decades at volumes far exceeding CSP production volumes. Table 13 lists processes used in manufacturing various heliostat designs.

Table 13. State-of-the-Art Advanced Manufacturing for Heliostats

Component or Feature	Manufacturing Techniques	Maturity
Mirror Facet	Flat glass fabrication	Commercial, widely available [e.g., low-iron glass for PV]
	Curved glass fabrication	Commercial CSP [e.g., trough mirrors produced in high volume]
	Reflective coating application	Commercial, widely available [e.g., mirrors for multiple applications]
	Environmental seal coating application	Commercial solar [e.g., trough mirrors, PV sealing]
	Anti-soiling coating	Under development with current poor results (over years), probably site dependence, introducing different types. See Section 11.
	Adhesive bonding	Commercial, widely available [architectural adhesive suppliers]
	Mounting pad fabrication with integral fasteners	Commercial, widely available [injection molding companies with insert capability]
	Linear structure forming (hot or cold rolling, roll forming, extrusion)	Commercial, widely available [steel suppliers, roll form equipment vendors, aluminum suppliers, extruders]
	Metal stamping	Commercial, widely available [steel stamping equipment and tool suppliers]
	Honeycomb core fabrication	Commercial, widely available [honeycomb material manufacturers]
	Sheet substrate forming and cutting (monolithic or composite material)	Commercial, widely available [sheet slitting, chopping, stamping equipment providers]
	Sandwich facet construction	Commercial CSP Successfully achieved by multiple companies
	Mold fabrication	Commercial, widely available [blow mold, vacuum form mold, injection mold suppliers]
	Variable focal length mold fabrication	Commercial CSP

Component or Feature	Manufacturing Techniques	Maturity
		[achieved by exiting heliostat developers]
	Glass slumping	Commercial CSP [e.g., trough mirrors]
	Glass deformation during assembly	Seems successfully achieved by at least one company; needs confirmation
	Springback correction	Seems successfully achieved by at least one company; needs confirmation
Mirror Array	Raw structural material	Commercial, widely available [steel suppliers]
	Pre-coated structural material	Commercial, widely available [steel suppliers]
	Chopping process	Commercial, widely available [chop tools]
	Hole-making processes (drilling, stamping)	Commercial, widely available [machining and stamping tools]
	Manual welding	Commercial, widely available [welding equipment suppliers]
	Automated spot welding	Commercial, widely available [robot vendors, robot spot welding end-effector vendors]
	Threaded fastener assembly	Commercial, widely available (both manual and automated) [manual tool vendors, automated assembly work cell vendors]
	Deformable through-rivets	Commercial, widely available [example: Huck bolts and structural blind fasteners]
	Rivetless deformation fastening	Commercial, widely available [examples: Stanley self-piercing rivets, Tucker Products]
	Mirror array construction	Commercial CSP Successfully achieved by multiple companies
	Simultaneous assembly, facet shape, and canting of facet array	Successfully achieved by at least one company; requires significant expertise
Drive	Drive meeting all heliostat technical specifications	Commercially available for small to medium heliostats. However, size must match current mass-produced product to achieve a good price. At the time of an earlier cost study [113], high precision drive positioning (to a fraction of milliradian) was relatively inexpensive for elevation drive and extremely expensive for 360° azimuthal drives. Today, industrialized manufacturing allows small size at affordable costs.

Component or Feature	Manufacturing Techniques	Maturity
Pylon	Galvanized steel tube	Commercial, widely available [steel suppliers]
	Stock with structural cross section	Commercial, widely available [steel suppliers]
	Stock for anti-rotation vane	Commercial, widely available [steel suppliers]
	Manual welding	Commercial, widely available [welding equipment suppliers]
	Automated welding	Commercial, widely available [automated welding work cell suppliers]
Foundation	Concrete	Commercial, widely available [concrete suppliers]
	Rebar	Commercial, widely available [steel suppliers]
	Post hole drilling	Commercial, widely available [ground drilling auger suppliers]
	Pouring	Commercial, widely available [foundation suppliers, EPC companies]
Assembly	Low-volume manual assembly	Commercial, widely available [common method for small volumes]
	Medium volume automated assembly	Commercial, widely available [e.g., flexible assembly work cell providers]
	High volume automated assembly	Commercial, widely available [e.g., synchronous assembly machine providers]

7.3 Ranked Gaps

Certain aspects of heliostats distinguish them from ordinary manufactured objects:

1. The combination of very tight optical tolerances, large size, harsh environmental conditions, long design life, and a very low-cost target for both construction and O&M.
2. Mirror coating that must maintain high reflectance over decades of outdoor use including soiling and washing. Requires a layer structure which protects the silver on the mirror from corrosion.
3. Large glass facets, which must be curved with low curvature to very high optical accuracy, with design curvature varying across the solar field.
4. Backing structures which, when combined with mirror facets to form an ensemble mirror, must achieve very tight optical tolerances and not have greatly disparate thermal properties[11]

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[11] Single-facet heliostat designs have the advantage of eliminating the need for the backing structure to achieve an optically accurate assembly. In that improved situation, the backing structure must be designed in such a way that it does not inadvertently deform the facet—a simpler goal to achieve.

5. Optical prescription (sometimes called focal length), which varies from heliostat to heliostat.

With these observations in mind, we gathered information using several approaches. The first of these was a survey of CSP experts asking them to estimate the relative value of various CSP autonomy applications [24]. In addition, we hosted Advanced Manufacturing breakout sessions in the HelioCon Roadmap Workshop and conducted multiple subsequent interviews with industry leaders. These interactions and the resulting responses are further explained below. The relevant potential gaps that emerged were:

- Easy field transportation, installation, and calibration
- Metrology (see Section 5)
- Wind load data to enable mass reduction, customized for location in the solar field
- Methods for fabricating high-quality, low-cost mirror facets
- Reliable market certainty enabling capital investment and continuous improvement
- Heliostat manufacturing automation
- Heliostat "mobile factory" that can be re-used at multiple sites
- Field installation automation with automated quality assurance
- Standard baseline heliostat and facet designs
- Low-cost, high-quality drives for CSP, especially for small heliostats
- Collaboration with other industries, e.g., high-volume, automotive, precision mirrors
- Rules of thumb for fabrication, material, and component costs
- Quality control, including supply chain, statistical process control
- Access to expertise in early design phases; state-of-the-art manufacturing know-how
- Mold fabrication and metrology, including multiple focal lengths
- CAD tolerance analysis.

Additional suggested gaps include:

- Lack of knowledge of typical ground conditions for foundation design assessment
- Method for low-cost production of concrete elements for pylon foundations
- Lack of knowledge of the creep behavior of adhesives and polyurethane foams.

Manufacturing is accomplished by executing manufacturing processes. As noted, many heliostat components are made by well-understood processes with no special features associated with heliostats. Heliostat facets and mirror array assemblies are an exception, due to their large size, shallow curvature, and tight optical tolerances. The mirror array assembly may be another such candidate, for similar reasons. We note that the industry that produces parabolic trough collectors is closely related, and positioned to produce heliostat mirrors, but heliostat optical tolerances are tighter, on both facets and full mirror arrays.

We also note the diversity of processes used to manufacture heliostat facets. Example facets we have seen indicate the following processes have been employed for various facet designs:

- Glass slumping or molding
- Metal stamping
- Glass sandwich assembly
- Injection molding
- Adhesive bonding, for either backing elements or sandwich construction.

A full list of gaps in advanced manufacturing, prioritized among three tiers, is given in Table 14.

Two additional important gaps are addressed elsewhere in this report:

- Lack of a steady market enabling continuous improvement.
- Insufficient wind load data to enable location-specific mass reduction.

The first of these is addressed in Section 3, and the second is addressed in Section 10.

Table 14. Gaps Related to Advanced Manufacturing Under HelioCon

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

Advanced Manufacturing						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important)						
AM1	Innovative heliostat mirror facet/array designs needed ○ Example: composite designs	x	x	x	x	x
AM2	Insufficient facet/array fabrication process knowledge, including: ○ Injection molding ○ Wide-area adhesive application ○ Laminated mirrors ○ Sandwich construction ○ Frame attachment ○ Canting control ○ Knowledge and use of fastening technologies ○ Material alloy and thickness selection for efficient manufacture ○ Composite structures	x	x	x	x	
AM3	Heliostats not designed for high-productivity manufacturing, due to: ○ Lack of access to expertise in early design phases (for example, high-volume, automotive) ○ Developers don't know how to find automation providers	x	x	x	x	
AM4	Lack of heliostat developers' experience designing high-productivity manufacturing lines, due to: ○ Lack of access to expertise in early design phases ○ Difficulty finding automation providers ○ Risks from lack of automation experience ○ Perception of required capital is not sufficient	x	x	x	x	
Tier 2 Gaps						
AM5	Trade-off between face-up and face-down stow not fully understood[12]	x	x	x		x
AM6	Variable focus heliostats and their economic benefit not understood[13]	x	x	x	x	x
AM7	Lack of field installation and quality assurance automation support	x	x	x		x
AM8	Specialized metrology tools not mature enough for factory use ○ Not compatible with factory environment ○ Calibration checks ○ Statistical process control				x	
AM9	Lack of knowledge about creep behavior of adhesives and PU foams (used for sandwich constructions)		x	x		x
AM10	Lack of knowledge of typical ground conditions for foundation design	x				x
AM11	Lack of low-cost production method for concrete foundation elements				x	x
AM12	Lack of a standard baseline design	x		x		
Tier 3 Gaps (Least Important)						
AM13	Lack of rules of thumb for fabrication, material, and component costs	x				
AM14	No CAD-based tolerance analysis for mirror array backing structures	x		x		
AM15	Lack of a standard facet specification	x		x	x	
AM16	No standard facet production methods, including multiple prescriptions				x	
AM17	Metrology for molds not widely understood				x	
AM18	Metrology for mirror array backing structures not widely understood				x	

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[12] This is highly related to soiling, where face-down stow may be advantageous in dusty areas.
A reviewer comment: There was a DOE study of this in the 1970s [114]. The effects of lack of capability to invert were investigated in three principal areas: 1. Dust buildup effects, cleaning frequency, and costs. 2. Increased

We also collected industry comments during the survey, workshop, and subsequent discussions. Key comments that emerged from these discussions are listed below (paraphrased and edited for clarity):

- It's hard to find accurate wind load data, which shows the reduction in wind loads with respect to position within the field. This problem is more complex for heliostats than it is for parabolic troughs. Current work is a start, but it does not meet the needs of a solar field designer seeking to reduce mass in the field.

  See the DOE 10 MW Solar One project for previous studies comparing heliostats on the boundary of the field compared to the interior of the field.

- A key way to reduce cost is to increase production volume. Then we can achieve continuous improvement. This requires a reliable, predictable continuous market. Current spot projects make this difficult. A reliable market enabling continuous improvement would cause substantial cost reduction.
- There are two fundamental design approaches to heliostat design which we have seen succeed. In one approach, facets are designed as self-supporting structures that are responsible for achieving optical tolerances as a stand-alone unit. These are then assembled into an array, and canting angles set to achieve overall heliostat optical shape. In the second approach, individual mirror facets are not self-supporting, and do not achieve their final optical shape until included in a mirror array which simultaneously determines the facet optical shape and overall heliostat canting and optical shape. Among these, the second method can achieve the lowest cost, but it requires very rigorous execution of the final assembly step.[14]
- Support structures may be constructed from pre-galvanized material, which can arrive in pre-galvanized rolls and then formed and punched to produce required part geometry.
- Select a drive which matches an existing high-volume production instance. For example, consider drives used in automation applications, and then select the size that is already the size mass-produced for a large-volume automation customers. This reduces prices, and also increases likelihood of long-term future support. Also purchase from a long-term credible supplier. Note that this approach obviously influences the choice of heliostat size, since the heliostat size must match the drive.[15]
- Our future vision of heliostats is facet mirrors that are composite structures, with 1.1 mm commercial glass mirrors supported by a rigid backing structure. This would bring about several advantages: Reduced cost (capital expenditures, or CAPEX, and operating

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heliostat damage probabilities due to hail effects. 3. Reflected beam safety issues. The conclusion was that vertical stow was the most cost-effective.

[13] Reviewer comment: This may be most relevant for industrial process heat applications, since these may utilize smaller heliostat fields. For large heliostat fields, the most distant heliostat dominates, and for its low curvature, the difference may be negligible.

[14] Reviewer comment: See the previous work of Arnold Goldman, who proposed a tiny heliostat approach.

[15] Reviewer comment: Solar field configuration also influences drive selection. For industrial process heat fields with a polar configuration, azimuth ranges <180° are suitable. But a surround field requires either 360° azimuth rotation or heliostat flip.

expenditures, or OPEX), reduced weight, and reduced structural support, all of which reduce cost, and increased reflectivity (from 94% to 96%),[16] increased stiffness, and increased operation in wind, all of which increase energy production, plus additional cost reduction due to decreasing the solar field size by 2%.[17]

- Assembling mirror arrays in the mirror factory allows the entire process to be controlled, and then heliostat installation is merely fastening the array onto a torque tube and pylon.
- Soiling conditions, rates, and required washing procedures vary from site to site.
- Past heliostats have generally not been designed to optimize manufacturing or assembly.
- Heliostat developers do not have relationships developed with automation providers. Engaging automation developers early in the heliostat design process is important for achieving high automation performance. Heliostat production risk is increased due to lack of heliostat developer experience with automation.
- Heliostat developers have sometimes had an unrealistic perception of what capital investment is required for automation. Tens of millions of dollars can be required to achieve a good automated production line.
- Some heliostat developers do not have a strong understanding of fastening technologies. Examples include spot welding and self-piercing riveting.
- Some heliostat developers do not have experience designing with material alloys and thicknesses that are customized for high-volume manufacturing. This is common practice in the automotive industry.
- A standard engineering practice with automotive unibodies is to first design for stiffness objectives. I believe car bodies likely have that in common with heliostat structures. Also, because of the production speed/volume and the performance requirements of heliostats, I have a strong instinct to apply automotive unibody methods to the design, manufacture, and assembly of heliostats. This includes automotive materials: the steel and aluminum alloys that might not be in heliostat engineers' tool belts. In my experience, heliostat designers usually stick to fairly conventional materials like A500 steel tubing, A36, A572 grade 50 plate/sheet, A512 plate/sheet, etc.

  Automotive Advanced High Strength Steels (AHSS) can offer significantly higher strength but retain good weldability and formability. Automotive steel grades that come in coil form are also typically readily available with galvanized coatings. Automotive aluminum grades are available with pretreatments for adhesive bonding so surface prep, which is critical in adhesive bonding of aluminum, isn't a necessary step in manufacturing. In both cases, these aluminums and steels are available in many thicknesses; often in increments of only 0.1 to 0.2 mm.

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[16] Compared to mirrors that are 4 mm thick.

[17] Reviewer comment: McDonnell Douglas manufactured over 900 facets using 0.7 mm glass and did not have a glass breakage problem. Their mirrors had a very small surface waviness (0.6 mrad), short focal distance, and held their optical parameters. They were tested over 15 years later and still met optical performance. See K. Stone, H. Braun, T. Clark, "Status of The SES Solar Dish Reflective Surface," ASME International Solar Energy Conference, June 13-18, 1997, Albuquerque, New Mexico.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

These higher grades do have a higher cost per unit of mass but the strength increases often outrun the cost. Stress-limited parts can be significantly thinned, lowering the weight and gravity-related deflection of heliostats, while the overall stiffness should be driven mostly by truss size and shape rather than individual member thickness.

For example, see https://matmatch.com/resources/blog/advanced-high-strength-steel-stronger-lighter-safer-cars/.

- It is advantageous to use mature glass suppliers, because they can achieve large production volumes, their large volumes enable them to achieve low prices, and their established market position increases the likelihood that they will remain in business long into the future to provide support and replacement parts.
- Specialized technologies needed for heliostat production have historically not been mature enough for factory use, and are sometimes not compatible with the factory environment (for example, the computer operating system).
- Collaboration between suppliers through some quasi-standardization in heliostat or component design may enable higher volumes and continuous improvement prior to wide-scale deployment. Optimization of a fundamental design may be less critical than making selections that are widely adopted among developers, increasing the production volume in a limited market due to commonality, so that the cost of each unit produced decreases as a function of the cumulative number of units produced because of small, incremental, continuous product and process improvements. An increase in cumulative production may be a more powerful economic driver than selection between fundamentally different, though well executed, designs.

7.4 Gap Analysis and Recommended Pathways

For the Tier 1 and Tier 2 gaps, Table 15 and Table 16 provide a detailed discussion of the functionality required to address each gap, justification of each gap's importance, and a discussion of potential approaches to addressing each gap.

The recommended pathway forward for the CSP community described these tables may be summarized as follows:

- Pursue advanced facet and mirror array designs. Consider extensions of past research developing composite mirrors [14], [115].
- Advance the (1) self-supporting facet concept, and the (2) simultaneous facet shape/canting assembly concept.
- Support direct collaboration between heliostat developers and manufacturing solution partners, starting early in the design phase.
- Heliostat designs should include factory productivity estimates, input assumptions, factory capital cost, and factory operating cost.
- Compile a catalog of manufacturing processes relevant to heliostat manufacture, with ways to find professional solution providers.
- Characterize all issues affecting stow up/stow down decision.
- Evaluate variable-focus heliostat designs and their economic trade-offs.
- Evaluate adhesive and foam material properties for creep and other effects.

- Develop methods for providing ground condition data for potential CSP sites.
- Develop accelerated, cost-reducing concrete foundation fabrication methods.
- Select a representative baseline heliostat and characterize its cost and performance.

Table 15. Top-Ranked Gap Analysis for Advanced Manufacturing

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
Tier 1			
AM1: Innovative heliostat mirror facet/array designs needed AM2: Insufficient facet/array fabrication process knowledge	Mirror facet and full heliostat designs that employ thinner high-reflectance glass or alternative reflector materials suitable for high volume manufacturing methods, combined with lighter and less expensive materials to achieve both improved performance and cost reduction. Associated proven manufacturing processes which demonstrate that high-productivity manufacturing can be achieved. Comprehensive testing verifying both optical performance and durability, including optical performance under varying temperature and operational wind load conditions.	Heliostats with composite facet/array may be able to significantly reduce cost and increase performance by simultaneously: Reducing material content of expensive glass, thus reducing cost. Reducing mirror weight, thus enabling elimination of additional mass in the supporting structure. Increasing solar reflectance and thus energy production. Increasing mirror facet stiffness, and thereby expanding the envelope of wind conditions allowing energy production.	Develop research plans that build on past research developing composite facets and resolve remaining questions [14], [115]. Develop research plans which advance the (1) self-supporting facet concept, and (2) simultaneous facet shape/canting assembly concept.
AM3: Heliostats not designed for high-productivity manufacturing	Established collaborative relationships between heliostat developers and professional manufacturing solution providers, with interactions beginning at the design stage. High-productivity manufacturing includes efficient manual production, efficient automated production, or hybrids combining both.	Designing heliostats for high-volume manufacturing will improve factory productivity and reduce cost, including both manual, semi-automated, and fully automated methods. Feedback loop between product design and process design will reduce cost and increase performance of both.	Encourage projects with a direct collaboration with both heliostat developer and manufacturing solution partners, considering both human and automated manufacturing technology. Measure and report results to ensure design improvements for manufacturing were achieved. Support multiple cycles of learning.

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
Tier 1 (continued)			
AM4: Lack of heliostat developers' experience designing high-productivity manufacturing lines	Below achieved by direct collaboration between a heliostat developer and manufacturing solution provider: Full factory designs for two scenarios: production volume 150,000 m^2/year (one shift), and volume 1,500,000 m^2/year. Designs may consider alternative approaches to centralizing manufacturing within fixed factories, and or distributed manufacturing performed on-site. Critical processes identified, with detailed work cell designs. All quality-critical work cells implemented and demonstrated, producing a meaningful test production volume operating at faster than 1.5x their final design cycle time, and with defect-free yield exceeding 90%. Full factory cycle time, supply chain, and buffer analysis. Realistic expectations for required capital.	If heliostat industry gains experience with high-volume factory design, it will be better able to achieve economically efficient mass production. Demonstrating critical work cell function achieves learning required for success and reduces risk. Designing for very high production rates such as 1,500,000 m^2/year will drive detailed studies of how to manufacture a given heliostat with high-performance automation systems.	Competitive stages-and-gates process addressing all items in functionality column. Above, possibly with mid-term down selection and increased funding to support further hardware development. Support direct collaboration between a heliostat developer and a manufacturing solution provider. Input from a CSP plant operator may also be beneficial. Ensure designs are concrete enough to include factory productivity estimates, input assumptions, factory capital cost, and factory operating cost. Require full documentation of design and performance predictions and lessons learned. Compile a catalog of manufacturing processes relevant to heliostat manufacture, with ways to find professional solution providers.

Table 16. Second-Ranked Gap Analysis for Advanced Manufacturing

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
Tier 2			
AM5: Trade-off between face-up and face-down stow not fully understood	Full analysis of the trade-offs between face-up and face-down stow, considering drive/linkage cost, hail resilience, and soil rate, with associated economic ramifications. Understanding of the probability and economic impact of hail events likely at CSP plants over operational life.	Correct understanding will lead to design choice with highest economic performance.	Characterize all issues affecting stow up/stow down decision, including drive/linkage design, structure impacts, hail robustness, and soiling rate. Quantitatively assess trade-offs, prepare design trade-off curves as appropriate. See the previous study on this topic, [114]
AM6: Variable focus heliostats and their economic benefit not understood	Practical designs identified which maintain focus despite changing sun incidence angle. Analysis identifying resulting increase in flux intensity under realistic operating assumptions for multiple scenarios. Analysis of resulting economic benefit. Target cost analysis, comparison to current design.	Fixed-focus heliostats are known to reduce focus as sun position changes. Variable-focus heliostats have the potential to increase flux intensity and therefore temperature, while reducing spillage. This may increase plant generated value, for example for high-temperature IPH applications with real estate limits.	Demonstrate variable-focus heliostat with low-cost design and evaluate its performance. Perform ray-tracing and TEA to determine its added value, and compare to cost.

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
Tier 2 (continued)			
AM7: Lack of field installation and quality assurance automation support	Achieve by direct collaboration between a heliostat developer and a field automation provider: Identify critical installation tasks that are candidates for automation, either for economic, quality, acceleration, or safety reasons. (Candidates include mirror array installation, canting verification and adjustment, and calibration.) <u>For manipulation-oriented:</u> Identify and document candidate automation concepts. Downselect. Demonstrate critical tasks. Field-ready system, robust and working at design speed. <u>For information-oriented:</u> Determine fundamental information requirements. Identify best measurement approaches (accuracy, speed, cost). Field-ready system, robust and working at design speed.	Well-chosen and well-designed field automation may reduce both cost and lead time before plant operation can begin. Accelerating plant startup increases revenue, and provides earlier return on investment, reducing risk.	In a stages-and-gates process, identify candidate problems, assess their value, and select the most beneficial for further development. For selected task(s), demonstrate key technology. Achieve robust implementation of key technology. Require direct collaboration between a heliostat developer and a field automation provider. For information-oriented, candidate tasks and approaches: • As-installed optical shape measurement (e.g., LiDAR, Goldberg + Zisken) • Calibration and accelerated calibration (e.g., beam characterization system with extensions, high-speed calibration)
AM8: Specialized metrology tools not mature enough for factory use	Tools to solve factory metrology problems that meet all requirements for factory application. Should include physical context, all functional needs, operating system and communication requirements.	For specialized CSP metrology tools to achieve a positive impact, they must be compatible with the production environment.	Identify existing or new tools that could meet factory metrology requirements, and invest further effort to produce versions that meet factory requirements.

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
Tier 2 (continued)			
AM9: Lack of knowledge about creep behavior of adhesives and PU foams	Data predicting long-term effects such as creep and degradation for adhesives, foams, and other materials relevant to advanced heliostat construction. Determined by rigorous tests executed by a trusted source.	Lack of knowledge of long-term performance increases risk and reduces bankability. Performance degradation resulting from creep or other long-term effects could reduce CSP plant economic production.	Evaluate material manufacturer data for material properties to identify gaps in creep or other parameters needed for robust CSP heliostat design. Design and execute accelerated test procedures to determine values.
AM10: Lack of knowledge of typical ground conditions for foundation design	Site survey methods effective at efficiently deducing required ground parameters. Ideally a database of such conditions readily available for potential candidate sites.	Uncertainty in soil conditions leads to difficulty making heliostat deign decisions, delays foundation design, introduces risk, and may impede capital acquisition.	Determine the ground parameters required, and associated measurement techniques. Evaluate the feasibility of public gathering and dissemination of such data for potential CSP locations.
AM11: Lack of low-cost production method for concrete foundation elements	A cost-efficient field concrete fabrication method.	Reducing foundation costs will reduce solar field capital cost.	Determine the range of concrete fabrication problems requiring solutions, develop accelerated, cost-reducing solutions.
AM12: Lack of a standard baseline design	Detailed characterization of a baseline design for CSP community reference.	A baseline design would enable developers to assess whether potential new concepts are likely to yield an improvement.	Select a heliostat that is representative of the state of the art, and characterize its cost and performance. Publish the resulting findings for reference.

8 Resources, Training, and Education

Resources, training, and education (RTE) encompasses resources, practices, and programs to ensure that (1) newcomers to the heliostat development community have an adequate knowledge base and training to conduct R&D efforts, (2) outsiders to the field are provided with resources and opportunities to join the workforce, and (3) the workforce community is a productive, healthy, and fulfilling environment for all workers.

8.1 Scope

The RTE topic seeks to create and expedite pathways for new employees to join the heliostat workforce and to build their knowledge base. The scope of the RTE topic includes four main areas:

- **Online Database:** A web-based resource database will serve as the primary tool to compile all developed RTE resources, facilitate information sharing among the workforce, and disseminate information to the public. Resources will be compiled to support heliostat focused education, R&D, and industry development, such as introductory or onboarding training materials, institutional knowledge among industry experts, standards, materials, and procedures, available software and hardware tools, and case studies of lessons learned from previous/existing plants.
- **University Involvement:** Opportunities and education support will be provided to the academic community to increase accessibility and exposure of the heliostat and CSP industries to students. These efforts include curriculum development, internship opportunities, education outreach events, and funding opportunities for university students to collaborate on heliostat research projects.
- **Training Resources:** Training resources will be developed to introduce and market heliostat technologies to those outside the community and to provide training on fundamentals and institutional knowledge that provide new workers the knowledge base to conduct their work effectively.
- **Diversity, Equity, and Inclusion (DEI):** DEI must be at the heart of all RTE initiatives. The workforce must be provided with resources, training, and expert guidance to facilitate a diverse, equitable, and inclusive working environment in R&D and industry projects. Prioritizing DEI is necessary to produce the most innovative energy solutions that shrink equity gaps between well-served and underserved communities rather than exacerbate them. All RTE programs will incorporate DEI planning to ensure the project solutions are accessible and beneficial to all communities, including minority, underrepresented, and underserved ones.

Following these areas, the main objectives of this topic are to:

- Create an up-to-date database of heliostat R&D resources and training materials.
- Build a reliable pipeline of workforce talent by engaging the higher education system
- Compile knowledge and create introductory heliostat training materials for new employees entering the workforce

- Plan and implement initiatives to promote DEI in the workforce and educational institutions and to benefit underserved communities

8.2 State of the Art

A newcomer seeking to enter the heliostat development business will face a lack of resources for heliostat R&D, systematic training materials to enhance their employee knowledge base, and ready talents to carry out required R&D efforts. In addition, those outside the heliostat field generally have little or no exposure to heliostat technologies or solar thermal applications.

Table 17. State of the Art of RTE for U.S.-Based Heliostat Workforce

RTE Area	RTE Item	Status
Online Database		
	Web-based resources	• SolarPACES website offers resources on standards and current research • Heliostat reference material often found based on internal knowledge and general literature searches • Heliostat specific-resource database under development in Zotero
University Involvement		
	Heliostat research	• Small number of university mechanical engineering programs have students/faculty that conduct heliostat research
	Heliostat education	• Some renewable energy courses contain introductory information on heliostats, but programs vary widely in scope
Training Resources		
	New R&D workers	• Trained using journal publications and expertise of individual research mentors • Techno-economic training not standard for all workers
	New heliostat industry/plant workers	• Generalized power plant training/manuals • Training varies from plant to plant • Heliostat technology developers often publish at industry venues and conferences
DEI		
	DEI in the heliostat workforce	• DOE requires DEI planning in funded projects • Labs provide resources, training, and contacts to support DEI development • Minority-serving institutions and DEI contacts identified for partnerships
	Projects that benefit underserved communities	• Many universities have programs to support underserved/minority students and larger underserved communities, but not specific to heliostat technology

8.3 Ranked Gaps

The following efforts were made to gather information on the gaps in heliostat RTE:

- **HelioCon Workshop:** Stakeholders from national labs, industry, and academia participated in an RTE-focused breakout session of the workshop and discussed questions on the major components of RTE. Feedback highlights included:

    - The heliostat industry requires many skills, and heliostat outreach and education for universities should strive to be broad
    - Student interest is driven by career opportunities presented by industry; there is lots of interest for renewable energy but not specifically for heliostats or CSP
    - Social science/DEI experts must be engaged at early project stages to drive solutions
    - Cross-over workers should be identified that have appropriate skills in other industries.

- **University outreach interviews:** We interviewed faculty from 11 university programs to gather information on DEI programs, funding needs, preferred collaboration mechanisms, and best ways to develop the workforce pipeline. Highlights include:
    - A multidisciplinary approach to expanding heliostat interest among students is key. Renewable energy courses are already popular among students, and inserting heliostat educational material into them as opposed to creating heliostat-specific coursework will reach students with a diverse set of skills. Supporting students' overall STEM development sets them up for more career options.
    - We must expand exposure of students to the CSP industry by supporting academia's access to industry plant data and networking opportunities, and providing more general CSP problems that are accessible to university research.
    - There is a strong preference for direct project funding supplemented with student internship opportunities as the collaboration mechanism between labs and universities. Faculty want to maintain control over the project and serve as the main advocates for students while allowing students the opportunity to work on large-scale industry-level problems through internships.

- **Meetings with DEI staff and experts:** We met with the director of NREL's DEI office and the minority-serving employee resource group leadership. Highlights include:
    - DEI planning must follow building blocks: (1) DEI on project team, (2) DEI in research and implementation partners, and (3) involving and benefiting underserved communities
    - NREL's University Partnership Program facilitates partnerships with minority-serving institutions
    - We identified DEI contacts to partner with for the design heliostat projects to benefit underserved communities.

The gaps identified from the RTE information gathering efforts are given in Table 18. Gaps are sorted into the four main areas: online database, university involvement, training resources, and DEI. For some gaps it is necessary or more advantageous to address them not just in the sphere of heliostats but expanding to CSP or, more broadly, to solar energy. For example, a public relations campaign will need have some focus on introducing CSP before providing information about heliostats to a broad audience. DEI gaps also apply to solar energy more broadly, and it may be more advantageous to address them as such.

All gaps will have an impact on developing the heliostat technology workforce. With the pre-established categorization principles, they are categorized in three different tiers. Of the nine gaps, four are identified as Tier 1, three as Tier 2, and two as Tier 3.

Table 18. RTE Gaps and Ranking

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field.

HelioCon Topic: Resources, Training, and Education						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important)						
R1	Heliostat technology resources are not accessible in a centralized web-based format • Need for a heliostat reference library that is accessible to newcomers • Lack of documentation and accessibility of current institutional knowledge, including knowledge on industry standards, materials, procedures, and case studies of lessons learned • Need for a centralized database to find information on available software/hardware tools and methods • Need for a centralized database of training/education materials	x				
R2	Lack of heliostat research projects in universities • Small number of university students/faculties performing heliostat-related research • Very few students masters/PhD thesis projects related to heliostats/CSP • Need for CSP/heliostat research funding accessible to minority/underrepresented students	x				
R3	Little public awareness of CSP/heliostat technologies • Awareness of CSP/heliostat technologies is not widespread across students or the public • Lack of informational videos and documents introducing heliostat/solar thermal technologies to a general audience • Lack of CSP/heliostats social media content	x				
R4	Lack of resources and guidance for promoting DEI in CSP workforce • Lack of DEI training resources and guidance for heliostat workforce • Need resources for project leaders to prioritize DEI in project planning • Need for more partnerships with minority-serving institutions	x	x	x	x	x
Tier 2 Gaps						
R5	Lack of engagement of underserved communities in CSP projects • Need for more funding/hiring opportunities for minorities/underrepresented groups • Must identify heliostat industry development projects with energy, hiring, and leadership benefits to underserved communities	x	x	x	x	x
R6	Little exposure of STEM students to CSP • Lack of heliostat-focused curriculum/school projects within renewable energy coursework • Lack of events for student engagement, such as workshops, conference events, or seminars • Lack of collaboration/communication between heliostat researchers/industry leaders and students/faculty • Lack of access of CSP industry contacts and CSP plant information/data for students and faculty	x				
R7	Insufficient training materials for new workers in heliostat R&D • Lack of introductory training resources for new workers being onboarded in heliostat R&D	x				

HelioCon Topic: Resources, Training, and Education						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
	• Workers often do not receive training on TEA aspects of heliostat technologies					
Tier 3 Gaps (Least Important)						
R8	Lack of CSP or solar thermal degree programs • Lack of CSP or solar thermal certificate or specialties for engineering/renewable energy students • No CSP or solar thermal masters programs currently exist	x				
R9	Insufficient training resources for new CSP plant workers • Lack of CSP plant operations manuals • Need for course modules for CSP plant workers/operators					x

8.4 Gap Analysis and Recommended Pathways

Table 19 summarizes the required functionality of the proposed solution, justification and benefits, and proposed strategy for addressing each gap. Tier 1 gaps are fundamental steps toward expanding RTE and addressing the Tier 2 and Tier 3 gaps, and this factors into the rankings. The HelioCon team will seek to address Tier 1 and Tier 2 gaps over the course of the project, beginning with Tier 1 and moving to Tier 2. Tier 3 gaps may be addressed in the final stages of the project based on the success level of addressing Tier 1 and Tier 2 gaps. Of the four top-ranked gaps, one is focused on building a web-based resource database, on is focused on DEI, one is focused on university outreach, and one is on public awareness of CSP/heliostats technologies. Each of these gaps are related to each other and reinforce Tier 2 and Tier 3 gaps.

A web-based resource database is a key tool needed to address all RTE gaps. To effectively promote university outreach, training priorities, and DEI, the workforce requires a mechanism to easily share information among the research community, disseminate information to the public, and market the industry to a broader audience. A public relations campaign is needed to grow awareness of the industry in the public, including a social media presence.

Supporting heliostat research projects within universities must be the priority in university outreach because it will establish connections between the workforce and academic communities, establish heliostats as a viable research path for students and faculty, and be the first step toward establishing a sustainable workforce pipeline. The collaboration of faculty and students with researchers on projects will facilitate addressing Tier 2 and Tier 3 university outreach gaps of expanding exposure of the industry to a broader STEM student audience and could form the foundation for degree programs. Efforts need to be made to connect to students and faculty from adjacent fields such as machine learning, artificial intelligence, robotics, optical materials, etc. to ensure that the industry is benefiting from cutting edge technological developments. DEI planning noted above will guide efforts to promote heliostat research projects in universities.

Promoting DEI within the current heliostat workforce is a crucial step that must occur early in the project effort because it will impact all other project efforts. All heliostat technology development and outreach efforts must incorporate DEI priorities, which requires DEI planning, leadership, and resources at early planning stages. The heliostat workforce cannot seek to benefit underserved communities without first establishing DEI principles within the workforce and partnering with DEI experts and minority-serving institutions to ensure that solutions benefit these communities in a meaningful and positive way. This DEI planning will guide how all other RTE gaps in university outreach, training, and resource database development are addressed.

The proposed addressing strategies consider feedback from internal DEI staff and experts, stakeholders who participated in the workshop, and interviewed university faculty with experience with solar thermal research and education.

Table 19. RTE Top-Ranked Gap Analysis

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathways
R1: Heliostat technology resources are not accessible in a centralized-web based format	• Searchable web-based introductory heliostat information and references • Information on project, funding, and hiring opportunities • Lists of industry standards, available tools, manufacturers, industries, plants, and labs • DEI policy and program information	• Facilitates information sharing and communication among heliostat workforce community • Allows public dissemination of information addressing all other RTE gaps	• Compile institutional knowledge, such as manufacturing and plant O&M best practices and lessons learned through interviews and surveys • Compile available resource materials including industry data/knowledge, references, training and educational resources, and available tools • Organize resource materials and data into web database
R2: Lack of heliostat research projects in universities	• PhD/master's students with heliostat thesis projects • Graduate programs able to sustain funding support for heliostat projects	• Sustainable pipeline of graduate students to workforce pipeline • Foundation for future expansion of heliostat programs in universities	• Establish connections between students/faculty and researchers/industry leaders through internship opportunities • Identify and support PhD/masters students to purse heliostat-focused thesis projects • Pose industry problems to universities to innovate solutions
R3: Little public awareness of CSP/heliostat technologies	• Introductory videos and documents that market the industry to a broad audience	• Familiarizing a large audience of students to the industry could increase their likelihood to seek out future opportunities • Communities may be less likely to oppose CSP if they are familiar with the technology and informed on the potential benefits to the environment and economy and dispel myths	• Create short introductory/informational videos targeted at a general audience • Create social media accounts for CSP/heliostat technologies and enlist researchers and students to generate content • Create public events, such as seminar series or workshops to educate a broad audience of heliostat fundamentals • Partner with universities to create annual fundamental CSP trainings open to the public

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathways
R4: Lack of resources and guidance for promoting DEI in CSP workforce	• Project team creates an inclusive working environment • Opportunities for minorities/underserved groups for meaningful roles on project team • DEI contacts and experts available to coordinate project planning • Partnerships with minority-serving institutions for implementation of future projects	• A variety of viewpoints and backgrounds are needed to devise the most innovative and effective strategies to industry gaps • Required step to address R2: to effectively plan projects that benefit underserved communities, the project team must have DEI expertise • Project proposals that can effectively engage with diverse communities are less likely to receive opposition from neighboring residents	• Consult with DEI staff/experts establish resource and training materials • Partner with minority-serving institutions on CSP projects • Identify organizations and contacts to partner with that work with underserved communities
R5: Lack of engagement of underserved communities in CSP projects	• Heliostat projects that benefit underserved communities with energy, hiring, and leadership opportunities	• Delivering energy solutions to underserved communities is key step toward delivering clean energy broadly • Underserved communities are often left out of the planning phase and often do not benefit from the industrial activities that affect them	• Engage community leaders of underserved populations in industry development opportunities • Partner with university programs targeted at underrepresented/minority students • Increase accessibility of funding, training, and hiring opportunities to underrepresented groups • Consult with sociology and DEI experts at early stages of project planning
R6: Little exposure of STEM students to CSP	• Renewable energy courses contain heliostat curriculum and projects • Opportunities for students to learn about CSP industry	• Students with variety of skill sets and backgrounds will seek out graduate work/career opportunities in heliostats if their interest is piqued in	• Develop heliostat/CSP curriculum modules to be inserted in existing renewable energy and engineering coursework to reach a broad student audience • Create capstone or senior design projects in

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathways
	• Heliostat workshops and conference events	standard coursework • Renewable energy courses are very popular among students; introducing heliostat curriculum would reach large diverse audience	CSP/heliostat technologies • Lead CSP/heliostat focused workshops and seminars • Work with authors to add examples or problems that feature heliostats to illustrate fundamental concepts such as mechanics, optics, or heat transfer into standard textbooks • Organize tours of plants for students
R7: Insufficient training materials for new workers in heliostat R&D	• Education materials on heliostat fundamentals accessible to workers entering R&D workforce • Education on broad heliostat topics, technical and economical	• Expedite learning curves of new workers • Workers will have more complete understanding of heliostat technology, make decisions with economics in mind	• Create introductory training materials, such as videos or documentation to onboard new workers • Create a publicly accessible reference library
R8: Lack of CSP or solar thermal degree programs	• CSP certificate or master's programs offered to students at universities with solar thermal faculty and coursework	• Heliostat workforce can identify and recruit students who graduate with CSP specialty	• Collaborate with universities with critical mass of solar thermal faculty/courses to build online master's program
R9: Insufficient training resources for new CSP plant workers	• Operations manual for CSP plant • Training on heliostat fundamentals for plant O&M workers	• Broader knowledge among plant workers will result in fewer mistakes and better decisions in plant O&M • Help disseminate lessons learned from industry, so they are less likely to be repeated	• Collect information on plant needs for worker training and hiring through surveys and interviews. Compile basic statistics on how many people a plant employs at each stage of the development cycle • Create CSP course modules and resource material such as video lectures/documentation • Create a professional certificate program for solar field maintenance and repair

9 Field Deployment

9.1 Scope

Field deployment captures all activities required to establish a functioning solar field. Figure 21 depicts the broad scope under the field deployment subtopic. Pre-deployment activities include site selection, field layout modeling, and activities supporting capitalization, and permitting including power production models, DEI and environmental impact studies, and reliability/performance evidence. Once approved, early activities pertain to supply chain management, delivery/inspection, and logistics. On-site deployment activities include site preparation: leveling, trenching, installing foundations, and often environmental remediation procedures such as relocation of protected animals or plants. Then an assembly line is constructed for heliostat top-level assembly. Heliostats must then be transported to position and mounted in field. Calibration and O&M activities related to mirror washing and field operations up to end-of-life disposal are also included under the topic heading of Field Deployment.

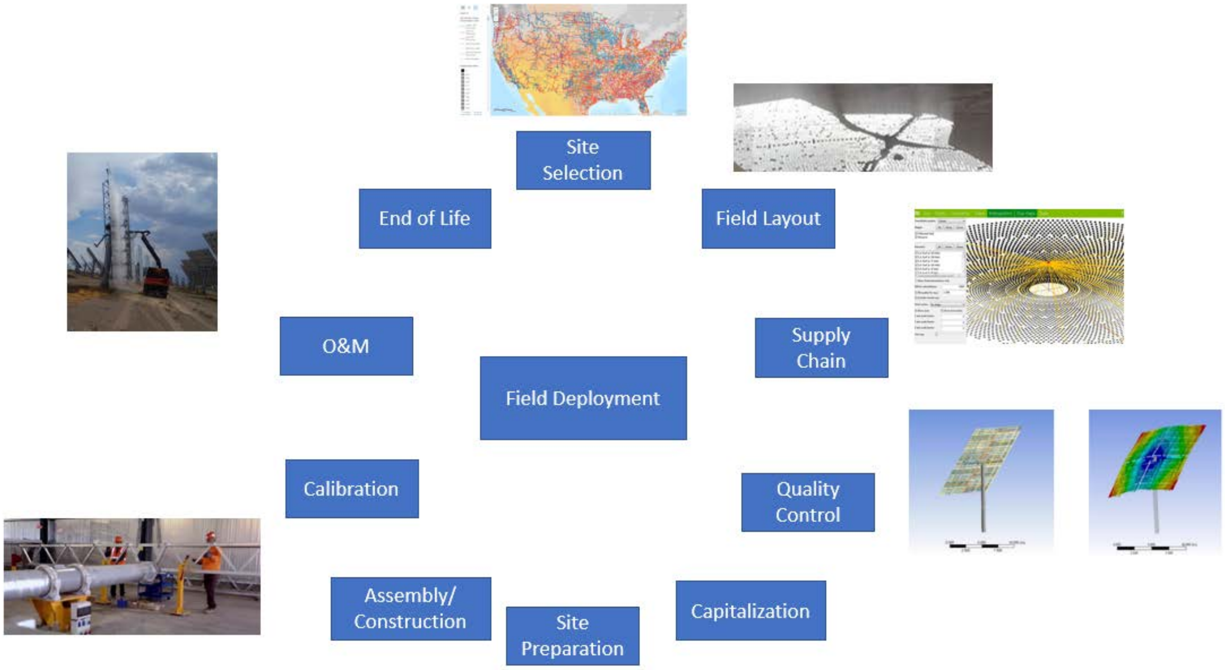

Figure 21. Diagram of field deployment scope

Field deployment has substantial overlap with other topic areas. This section first considers the broader context and then narrows the solution space to a more focused set of problems to be solved by field-specific efforts as well as leveraging activities within the other subtopics. Deployment considerations naturally inform component designs for ease of top-level assembly, installation, and maintenance; the costs of wireless controls or photovoltaic power supplies may be offset by eliminating trenching for communication and power lines. Metrology and controls can potentially remove calibration from the critical path schedule if pre-tower calibration can be developed, quality control methods in the manufacturing process can not only improve receiving and inspection requirements on-site, but can help in the capitalization process by assuring investors of a high likelihood of performance and reliability. Efforts within the RTE subtask can potentially reduce local opposition by bringing a diverse understanding of community concerns with large heliostat fields to developers and helping to improve familiarity of the technology and the economic opportunities it presents. TEA models can be improved with a more rigorous understanding of deployment related costs as often only total plant costs or total field costs are available and deployment costs must be inferred as a percentage of the whole. These same TEA models are being redesigned to serve an audience of manufacturers who use IPH. In addition to refined cost figures on deployment steps, this audience may be served by enhanced field layout options that provide visualization tools for retrofitting existing plants with heliostat fields or combined power with other fossil or renewable sources.

The roadmapping process will evaluate the current state of the art, identify improvement opportunities (gaps), and prioritize them. The remaining work within the consortium will then seek to close these gaps while working closely with the other subteams in areas of substantive overlap.

9.2 State of the Art

Figure 22 gives an overview of currently deployed commercial fields around the world and the associated heliostat technology developers. LCOE, total plant costs, and total field area data are available from an NREL/Solar PACES database, CSPguru [116]. Figure 22 is intended to convey the types of heliostats (heliostat size and design are assumed to be more or less consistent within a developer) that are deployed in various regions around the world. (The details of the terrain in which heliostats were deployed is proposed for study in future work.) LCOE data can imply that costs are generally trending downward with time—consistent with learning rates that would be expected of any industry. An important caveat is that heliostat costs, and more specifically, field deployment costs, could not be directly obtained at the time of writing (a gap to be discussed below), and therefore, while the heliostat developer is associated with the LCOE, the reader should not insinuate that the heliostat developer is the primary driver of LCOE, which includes all other components in the plant as well as fixed and variable O&M costs.

The diversity of site conditions, including DNI, geology, atmospheric clarity, proximity to resources, governmental policy and incentives, labor rates, profit margins for the heliostat developers and manufacturers is confounded in the data and likely explains some of the deviations from the linear fit. This highlights a gap in that it is difficult to identify technological solutions to deployment processes that will work across the board. It is assumed that companies likely keep records of deployment cost data, but this data is not widely accessible.

Air quality can also affect the optimal size of heliostats by constraining the distance from the receiver that a heliostat can be. It is also important to note that over the same time frame, the cost of wireless communication and photovoltaic technologies and additive manufacturing have dropped dramatically, so plants from 2010 may include different components than plants built in 2020.

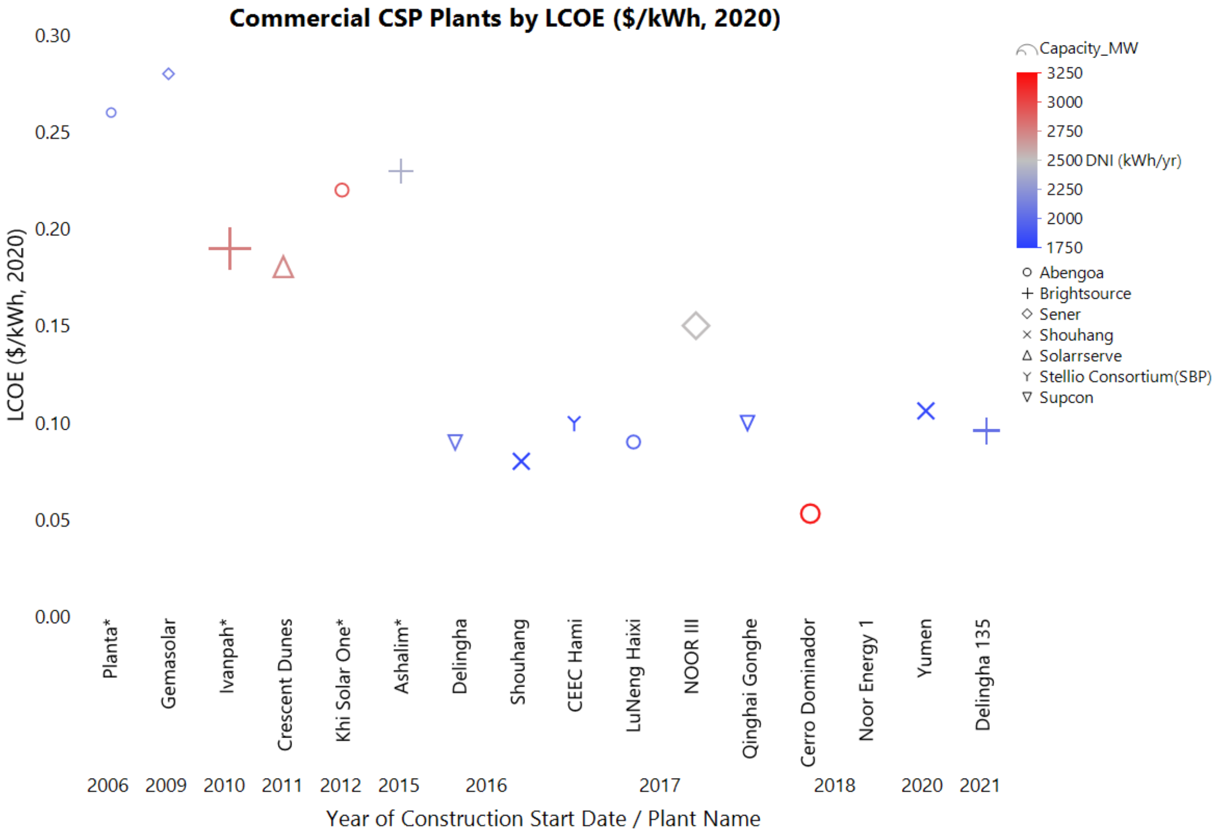

Figure 22. Estimated LCOE costs of existing plants with heliostat fields by year of construction start, and with heliostat technology developers identified

The symbols are color coded for DNI and sized for plant capacity ranging from approximately 20–377 MW_e. Plants have medium (6–7 hr) to long-term (10–17.5 hr) storage in molten salt, except those indicated with an asterisk.

Table 20 summarizes the state of the art in field deployment for each step, from financing and site selection to O&M and degradation.

Table 20. State of the Art in Heliostat Field Deployment

Field Deployment Stage	State of the Art
Financing	The lowest LCOH has been achieved in large systems (100–200 MW) which maximize the utility of single high-dollar components such as the receiver, tower, and power block and scale up the heliostat field. These systems can approach $1 billion, and so financing typically must pull together several entities. U.S. fields have used government incentives such as the loan guarantee program and production and investment tax credits. These incentives often come with requirements on labor and environmental standards.
Site Selection	Ideally, sites are selected that have the richest solar resources and clear air, with proximity to transmission lines, a labor force, water, and egress by road/rail. Often the site is predetermined by the governing body and utility for reasons that may have little technical merit; for example, a desire to create jobs in a certain district, or to build out civil infrastructure (roads, gas pipelines,

Field Deployment Stage	State of the Art
	etc.) in a low populated area. Additionally, candidate CSP plants would be placed at or near existing plants to retain the labor force and operational permits.
Permitting	California and Nevada have established conventions for permitting. Impact studies on humans and the environment have been performed, though it is uncertain whether these studies capture the reasons for the rise of opposition groups on social media who can have a major influence on county and municipal governments in rural areas. Permitting on federal land requires compliance with the National Environmental Protection Act, Migratory Bird Treaty Act, and the Endangered Species Act. Millions of dollars have been spent studying migratory patterns of birds, and translocation programs for desert tortoises, and rare shrubs.
Solar Field Layout	A developer will design a field layout using optical ray-tracing software to determine the minimum-cost arrangement that achieves the designed power requirements. Some developers preserve the natural terrain, which reduces paving costs, preserves natural habitats, and may inhibit vehicles within the field requiring manual washing. Unlike photovoltaics which are often deployed over existing infrastructure such as parking lots, rooftops, and open fields, there may be a dearth of tools targeted to the needs of plant operators that allow users to perform similar overlays of heliostat fields in industrial retrofit scenarios that could serve as a barrier to potential adopters of the technology.
Supply Chain	The supply chain for the entire project will often be pre-selected up-front to reduce the risk of a bid. The receiver and heliostat designs are usually predetermined at the time of the bid. Contrary to the intentions of these risk reduction efforts, it can also be difficult for the engineering team to make changes in heliostat or component choice because supplier relationships are often carefully pursued and protected once established, and the required reanalysis can be system-wide and time consuming.
Assembly	The heliostat components are manufactured to the farthest practical extent that can be transported to the site; an assembly line is then created on-site to finish building the heliostat. Assembly procedures are optimized for each site and trade studies determine to what extent the heliostat is pre-assembled in a remote factory.
Site Preparation and Construction	Field preparations begin with trenching to run power and/or data lines. Newer plants have been deployed with PV panels and wireless communication systems on individual heliostats which offset costs associated with trenching and wire. Roads must be cleared for construction and maintenance vehicle access. Ground leveling, where performed, can ensure uniform layout and simplify O&M but can also result in increased erosion, and the removal of natural vegetation can result in increased dust that causes soiling and atmospheric attenuation. Paving is usually restricted to a main access road to the power cycle at the center of the plant.
Operations and Maintenance	Facet washing is the number one O&M cost in the plants interviewed. Wash crews either operate vehicles or clean the mirror facets by hand, depending on heliostat size and field density. A continuously operating hand washing crew as small as two can typically cycle through the field 20 to 25 times a year. By comparison a truck can wash about 300 heliostats per day and a fleet of 3-4 trucks and 5 people per shift can typically cycle through the entire field every

Field Deployment Stage	State of the Art
	week. Automated washing trucks have been deployed and cycle through the field every 7 days with a fleet of 6 trucks [117]. Truck washing operations are susceptible to erosion. Individual heliostat-mounted waterless cleaning systems have been designed and tested [118]. Repairs are done by a team of (usually 3 to 12) technicians, prioritizing troubleshooting and straightforward repairs over replacement of facets and assemblies that are more costly and time-consuming. Inner-ring heliostats are prioritized for maintenance due to higher efficiency. Large-scale events (e.g., hailstorms, dust storms) usually are addressed by hiring temporary contracted labor.

9.3 Ranked Gaps

Field deployment gaps were gathered during a roadmapping workshop attended by CSP researchers, developers, and heliostat designers in addition to literature reviews and expert interviews. Gaps are summarized in Table 21. During the roadmapping workshop, the point was raised that impacts due to delays are difficult to quantify. While costs related to increased financing charges are straightforward, delays have also led to project cancellations on several occasions. The hidden costs associated with cancellations are likely significant because cancellations disrupt the industry and suppliers and hinder learning rates.

Field deployment may not affect the overall plant deployment time if deliveries are on time and the assembly line is operating smoothly. Ivanpah installed 650 heliostats per day during the height of construction [119]. The field's installation time is related directly to the number of employees available to install heliostats. However, because locations are often very remote, there may be insufficient skilled labor resources needed to install the pedestals and heliostats, and steep learning curves for assembly can cause further delays. It was mentioned that because heliostat design technology has not yet converged, a slightly new design is used for each deployment within a given developer, which limits the applicable learning from previous installations. Some of the longest lead items associated with field deployment were tunneling for power and communication lines. Opportunities to make wireless and PV technologies more prevalent in heliostat fields may be explored in HelioCon as a means to reduce costs and boost the heliostat industry.

Continuity of projects can be a major contributor toward meet the DOE 2030 cost targets. Published studies show evidence that cost reductions due to economies of scale may amount to over 30% [120]. Figure 22 shows a downward cost curve over time within most major developers. It was mentioned that deployment costs decreased significantly between the first and last of three towers in the Ivanpah plant [119]. Facilities and automation technologies for assembly are often only useful for a single project in part because projects are so spread out in space and time that the same heliostat is not reused, adding to the cost and lead time of the project.

The attendees also mentioned that calibration is time- and labor-intensive, and overly reliant on the tower being erected, causing a stack-up of scheduling that might be compressible with the right technical resources such as non-tower based UAV and PV calibration methods.

Soiling mitigation is a major expense with dependencies to the field deployment process, because construction generally changes the environment. The clearing and paving process and the cleaning process have been observed to increase erosion and pedestal stability as watershed through the field carves new pathways. Attendees mentioned that wind mitigation strategies should be considered during the design and deployment phases. Small fields are more amenable to wind mitigation techniques, such as fencing, than large fields.

There was also discussion of technological solutions. Automation of pedestal construction, heliostat assembly, and installation seems feasible and may cut labor costs significantly. This is covered in Section 7. However, a significant increase in standardization, or commitments to multiple projects, would be required to justify the cost of developing and manufacturing the automation equipment.

Wireless communications and distributed PV power on heliostats may be able to help with deployment timing and reduce wiring and trenching costs. As mentioned earlier, companies are developing or have deployed wireless and PV systems. There is still a lack of wireless protocols and standards for solar fields, and there is also a cost associated with outfitting each heliostat with a reliable wireless system.

A major concern in the workshop was that costs could be lower if there were some degree of standardization in the heliostat industry. It was suggested that smaller modular systems would be funded more frequently, accelerating learning curves and decreasing deployment times and costs. Innovative systems are being developed to make this approach economically viable. Small field penetration into the IPH market may also accelerate learning rates.

In addition to the workshop, a literature review was performed to discover gaps. A *Concentrating Solar Power Best Practices Study* performed a similar series of interviews and identified several gaps in field deployment [21]. Key gaps identified in that report related to deployment include the following:

- Lack of thought put into maintenance access in many solar field designs in an effort to maximize optical efficiency.
- Miscalculations of the water quantity needed and water quality issues where the groundwater was much more mineralized than anticipated.
- Lack of industry consensus on optimal heliostat sizes, which hinders standardization.
- Lack of consensus on power supplies, though individual solar power supplies on each heliostat are becoming much more prevalent.
- Lack of access to testbed facilities and standards for reliability testing in extreme environments and accelerated aging testing, which would help heliostat manufacturers make a case for reliability when there are few examples of plants operating over 30 years to serve as a basis.
- Erosion due to watershed has created ruts in the roads between heliostat rows, making cleaning difficult particularly for wash trucks. Wash truck designs have also been impacted by the lack of standards because a unique design is required for each type of heliostat and, in some cases, field layout.

The study also noted that heliostats were assembled with good precision in the assembly line but temperature changes as well as bumps and vibrations along the road to the field would result in canting/focus errors prior to placement on the field. Power predictions should account for dew and frost that cuts into production time in the mornings but can perform natural cleanings of the heliostats by sloughing off accumulated dust. Certain stow positions may be more resistant to frost than others.

Another paper with valuable insights into field deployment gaps was the *Commercial and Advanced Heliostat Collectors Cost Update* by Kurup et al. [17]. This study looked at the Stellio heliostat by sbp Sonne and the SunRing heliostat by Solar Dynamics. It was found that site labor and base foundation costs were lower in the SunRing. While this study is not intended to discuss optical performance or to identify a preferred heliostat in the context of the overall plant performance, it does break down the costs of process steps and illustrates the relative cost reduction potential of field deployment processes. TEA shows that cost-cutting methods need to be significant if they come at the expense of optical quality; see, for example, the baseline case parametric studies in Section 2.3.1.

The project team held conversations with the System Advisor Model (SAM) development team to determine what gaps exist in field deployment matters as they relate to techno-economic modeling. The model captures the financing charges accumulated without revenue streams in the form of accumulated interest over deployment time assumed to be 12 to 36 months but cannot account for externalities of lost bids due to the changing priorities of key stakeholders over the same period from impairing industry from making the investments in automation and standards from too much time lapsing between subsequent tower system deployments. Another gap is that it is uncertain what portion of this time is related to heliostat deployment, which may not be the longest lead item as the tower and receiver also have long lead times. This can make it questionable whether efforts to shorten heliostat deployment time are economical if other components with long lead times, such as the receiver, tower, and power block are not installed as quickly as the heliostats. It was noted that the default site preparation assumption is $16/m^2.

Interviews were held with CSP industry experts. The most promising potential for cost reductions may be in the assumption of O&M, which scales proportionally to the size of the field. However, the O&M for the field vs. the other components of the plant is not itemized. Mirror washing is generally stated to be the most expensive part of the O&M budget. Future work could seek to understand O&M costs in a highly detailed manner to facilitate a better understanding of how O&M costs are impacted by labor, water, soil type, surface type (flat/natural etc.), and heliostat type the easiest and most impactful to address. Heliostat availability is not well understood. Some models assume 99% when designing fields. Interviews with plant owner/operators indicated the value may be closer to 92%, with solar fields oversized to account for this target availability. In the SAM model, field layout is assumed to have a good layout and aiming strategy, but actual deployments might use three or fewer focal lengths (close, middle, far), resulting in significantly greater spillage and less power produced than modeled.

CSP models often predict the optimal LCOE point with a single-tower system over 100 MW$_e$. A plant of this scale may require more than $1 billion to construct. A comment was made that it may be premature to optimize LCOE and the benefits of a greater number of smaller, modular projects on the order of $200–300 million would be less risky and more likely to get accepted and thus gradually mature the technology, leading to the economies of scale and standardization that drive costs toward the LCOE goal over several years. The lack of standards may weaken the reliability case and deter investors due to difficulty in certifying that the product/project has been correctly built/delivered. Furthermore, the tax incentives and loan guarantees in 2011 that justified the creation of Tonopah and Ivanpah as well as the net price of retail electricity on which PPAs are based have since been reduced, making the prospect of CSP less likely in the U.S. market, though prices for CSP have come down considerably over the same period.

Approach to Gap Ranking

Field deployment is a process that is entirely dependent on the system. The receiver constrains the field layout, and the choice of heliostat and land condition determines the field deployment process. The approach for distilling the broad and variable scope into focused research areas is illustrated in Figure 23. Activities that reduce investment risk such as improving power production models, reliability, and permitting barriers or penetrate into new thermal energy markets could lead to more fields driving learning rates that could amount to 20% cost reductions (informed by Lilliestam et al.). Then there are design innovations that directly reduce deployment costs such as wireless communications or mounted PV power that eliminate trenching and wiring costs or balasted heliostats that eliminate the pouring of foundations could amount to 24% cost reduction if optical performance could be held constant (informed by Karup et al.). Additionally, deployment and O&M process innovations could reduce field costs (informed by comparative simulations in SAM). These gaps could address mirror washing or field preparation. It is acknowledged that solutions will leverage activities in other topic areas of HelioCon.

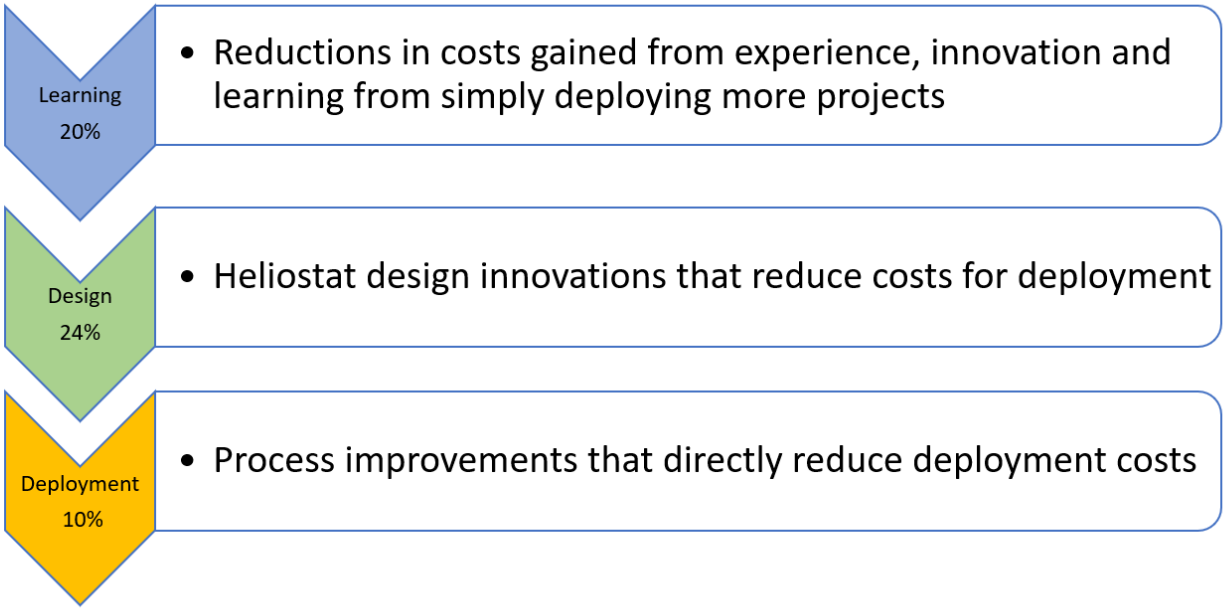

Figure 23. Quantitative ranking criteria for field deployment

Table 21 shows the ranking of the gaps into the tiers and indicates which phase in the heliostat's life cycle the gap in question would impact.

Table 21. Tier 1 Gaps Related to Field Deployment Under HelioCon

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

Field Deployment						
No.	**Gaps**	**a**	**b**	**c**	**d**	**e**
Tier 1 Gaps (Most Important):						
F1	Reasons behind the underperformance of operational plants relative to modeled performance are not well understood			x		x
F2	A lack of precedent demonstrating full plant service life and multiple early-life setbacks lead to a higher reliability risk profile than conventional generators	x	x	x	x	x
F3	The large land requirement and possible environmental impact of heliostat fields lead to higher permitting risk than conventional generators					x
F4	The large land requirement and possible social and cultural opposition of heliostat fields lead to higher permitting risk than conventional generators					x
F5	Industrial plants are often located closer to populated areas and owner/operators lack clarity on how a heliostat field, glare, and beam would impact traffic, workers, structures, and processes within and around an operating plant					
F6	CSP researchers and developers lack data on plant processes, layouts, thermal duty cycles, and the related variability that would be required to optimize the best heliostat choice and field layout for multiple industries of interest					
F7	There is a lack of cost data on the specific field deployment processes of interest. Field costs are typically rolled into overall plant costs.				x	x
F8	There is a lack of data on the time duration of field deployment processes of interest. Historic data may not be informative because the timing of these processes in many cases was intentionally spread out to coordinate with the tower and receiver timelines. Deployment times are 3–6 times greater for CSP than other renewables.					x
F9	Strategies for minimizing plant shutdown during wind and cloud events lack test data on wind shielding effects, turbulence, and partial shading over real fields					X
F10	Water usage for facet cleaning strains resources in desert climates and costs for facet cleaning systems are the major expense of many operational fields.					
Tier 2 Gaps:						
F11	The effect of dew accumulation on start-up times has not always been considered					x
F12	Degrading optical performance of solar field may not be reflected in techno-economic power models		x			x
F13	Pre-tower calibration methods may not reflect deflection, creep, or thermal effects during actual use			x		x
F14	TMY data are inadequate. Extreme events such as fires or polar storms may not be included in TMY data.					x
F15	Transient cloud passages are represented as a DNI reduction in an hourly average, as is the format for the TMY files that serve as input to performance assessment tools, but may require a shutdown of the receiver in actual operations					x
F16	Measurements required to prove quality are not known until deliveries are accepted			x	x	x
F17	Water treatment plant sizing can be difficult to assess accurately					x
F18	Land use policy and transmission routes can face jurisdictional challenges and even small opposition can stall or cancel projects					x

Tier 3 Gaps:						
F19	Solar resource modeling has been inaccurate due to increased forest fires and jet trails					x
F20	Uncertainty in the costs associated with implementing emerging technologies is not captured in baseline heliostat costs		x	x	x	x
F21	Heliostat designs have required difficult or labor-intensive procedures due to inaccurate predictions of what maintenance procedures are most likely			x	x	
F22	Cost/value of life extension programs is not built into initial design			x		x
F23	Recycling and disposal processes lacks specification			x		x
F24	Skilled labor cannot find a consistent enough stream of work to remain effective between deployments		x	x	x	x
F25	Assembled heliostats changed on the way to site due to vibration and temperature change			x		x
F26	Removal of native vegetation may impact ecosystem and public relations; no consensus on benefits for using vegetation for dust control and erosion mitigation					x
F27	Models that assume heliostats are focused correctly may not reflect actual spillage from only a few discrete focal types across the field					x
F28	Complete systems analysis is time consuming and costly when changes are made, which tends to lock in early designs to the detriment of better options that come up later					x
F29	Quality checks must be performed intermittently as it is too costly to check every heliostat. Lack of comparable demonstration in time makes reliability testing more necessary					x

9.4 Gap Analysis and Recommended Pathways

The general problem with reducing costs in field deployment is that companies have had few opportunities to deploy heliostats, relative to other renewables, which has hindered learning and innovation in these processes. To break this overarching problem into manageable scope, the recommended pathways strive to identify the main cost and risk factors that make heliostat field deployments less likely. Risk factors should focus on the following:

- Historically, field deployments have been delayed and cancelled in the permitting phase, so activities should focus on technical means of mitigating the environmental impacts and reasons for community opposition. In the past these challenges have focused on violations to the Endangered Species Act and Migratory Bird Treaty Act—specifically environmental impacts on birds, terrestrial animals, and plants. Other challenges have focused on community activist groups voicing opposition to real or perceived impacts. HelioCon can lead new studies leveraging ongoing efforts in how best to engage tribal and rural communities about the impacts and opportunities the come with CSP deployments. The outcome could be a blueprint for community-led deployment solutions and the social and environmental considerations during site prospecting.
- Projects have also failed to garner the capital needed from investors because less risky options may exist. Recommended pathways should strive to quantify the reasons for shortfalls in power prediction models and offer improved models as well as lead on the development of standards that can ensure bankable quality and reliability.
- Diversifying into solar-thermal applications could lead to more frequent opportunities, but unfamiliar technologies may be perceived as too risky. Other programs are underway to develop the thermal technologies for providing heat to industry. For the part of heliostats, recommended pathways should not underestimate the importance of giving interested newcomers a quick look at how a solar field might fit into an industrial site. Technical work should leverage existing field layout applications, and add features that simplify the ability of a potential plant owner to explore the techno-economics of CSP as well as visualize the integration of fields with existing property lines and the impacts of glare on traffic and nearby establishments that are more likely in populated settings where retrofitted plants are likely to be.

In addition to risk reduction, the driver for increasing the likelihood of additional deployments is cost reductions. Large cost reductions can come from innovations that reduce the costs of facet washing (labor and water usage) and innovations that reduce the financial impact due to wind induced tracking error. A major gap in field deployment is the lack of statistics on the costs of various deployment and O&M processes. The HelioCon effort could provide a much more impactful result if companies contribute existing plant data. The recommended pathway is to consolidate field deployment data across several companies in a way that protects the trade secrets of the participants while enabling trans-industrial learning opportunities. This way, one company that has deployments in certain regions can gain virtual knowledge on deployment considerations in other regions from another company.

The Tier 1 gaps, if solved, potentially increase the frequency of field deployments by addressing three key areas of investor risk and by aiding in the diversification of the heliostat market into CSP. Reducing investor risk is approached by leveraging work in the other subtopic areas including techno-economic analysis, metrology, wind, and soiling to improve the power prediction modeling. Model improvements will also come from combining efforts in the TEA and existing plant support to perform a "post-mortem" analysis on previous or existing projects to understand the difference between model assumptions and actual plant operations and reconcile predicted versus actual production. Investor/utility risk is also reduced by leveraging the standards and advanced manufacturing topic areas to develop a set of reliability standards that touch on the entire development cycle: design, testing, production, quality control, and life cycle monitoring, shown in Figure 24.

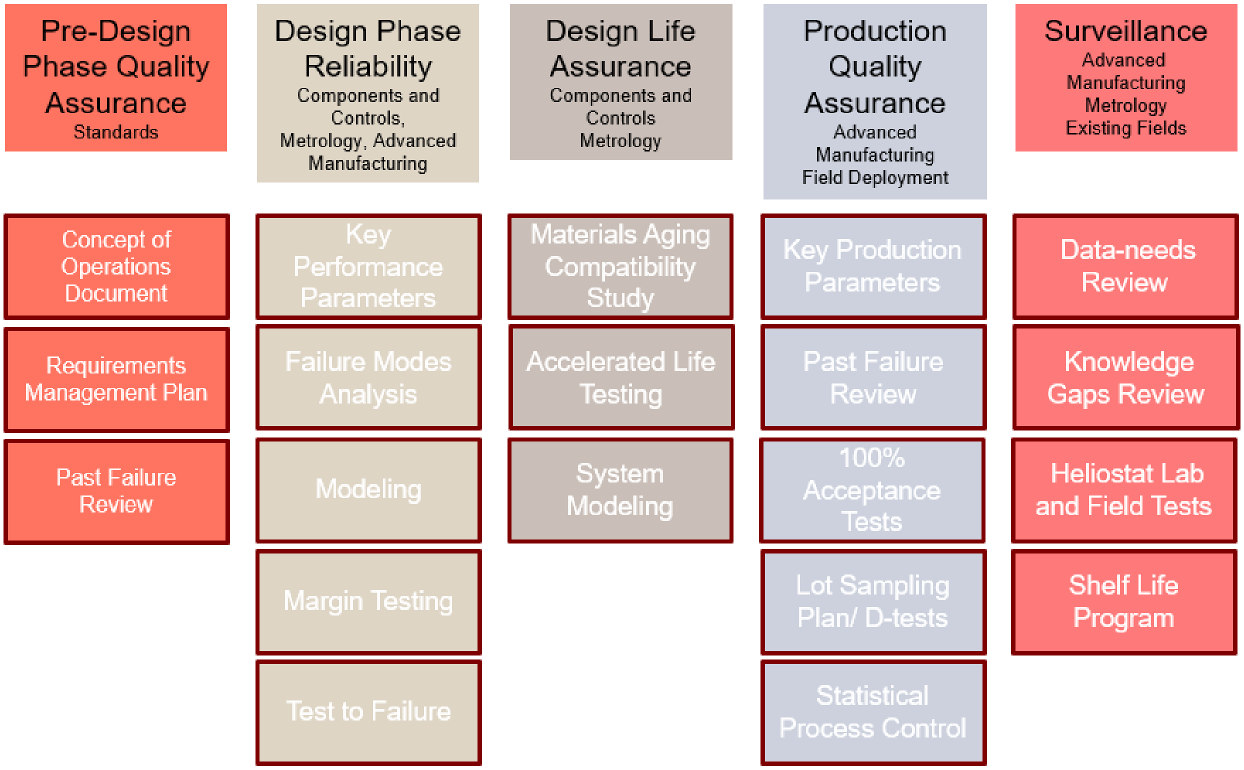

Figure 24. Example of topics across the life cycle for systematically assuring reliability

Table 22 shows the tier ranking criteria for the gaps itemized in Table 21. Many of the gaps were identified by professionals at electric utility companies, plant developers, and owner/operators as discussed in Section 9.2.

Table 22. Gap Analysis and Recommended Pathways for Field Deployment

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
F1. F2. F3. F4.: Heliostat fields have higher risk than other power investments	Investors and utilities have high confidence that CSP project proposals will perform as advertised and assurance that past issues with production, reliability, and permitting have been adequately de-risked. **Field Performance** • Improve the accuracy of power production models • Develop standards evidence and methods for assuring heliostat reliability **Cultural and Environmental** • Eliminate danger to endangered species and migratory birds • Identify reasons for community opposition to heliostat field deployments and solutions **Standards:** • Standards for modeling, reliability, deployment and reliability may build confidence in CSP projects	Easing investor concerns about profit and risk may lead to more projects and costs trend lower with each subsequent deployment. Discontinuities in demand for CSP systems have hindered the cost reductions that would be associated with learning rates in an otherwise stable and regular sequence of deployments. These efforts focus on key hurdles to project approval. • CSP plants have produced less energy than proposed. • Several CSP projects were cancelled due to environmental concerns, archeological concerns or community opposition. Many that survived to address these concerns did so at great cost to the project. • Standard build and inspection points will ensure that EPCs and investors can write contracts and inspection routines that ensure if standards are met that the heliostats will work as designed once in the field.	• Identify primary contributors to model inaccuracy and refine power predication and economic models ○ Wind, atmospheric attenuation, reflectivity degradation, mechanical creep, soiling (MS, CC, TEA) • Develop a reliability assurance framework and develop test facilities as necessary to accommodate • Develop standards for wildlife detection and deterrence/avoidance (CC) • Develop best practices for early community engagement and inclusion (RTE, TEA)

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
F5, F6: Heliostat field integration with industrial thermal processes lacks precedent	<u>Objective</u>: Industry leaders have a clear and confident conceptualization of plant layout and operations with incorporated heliostat fields **Likely Industry Questions** • Field deployment cost • Field layout for retrofitted sites and solar resource requirements • Safety and logistics of glare and beam **Key Field Design Questions** • Thermal duty cycles • Human and mechanical interfaces • Industrial labor routines	Industry is more likely to adopt CSP if the economics and logistics are familiar and well-conceptualized.	Other CSP components are being developed for adoption by industry. HelioCon can develop field layout tools optimized for rendering layout and cost analysis for new and retrofit scenarios that are more accessible to industry users. <u>Approach</u>: Work with industry partners to develop field layouts that meet the technical, safety, and logistical needs of industrial plant operators. Leverage ongoing efforts for heat transfer components ○ Research thermal requirements for target industries and size concept fields ○ Present concept fields utilizing existing land features such as fields or parking lots ○ Work with industry to understand gaps to deploying heliostats fields in new and retrofit industrial plants ○ Determine CSP centered industry-informed details on the key interfaces, power requirements and variability, and overall functionality of plants in target industries ○ Perform TEA of field deployment in model plants in target industries ○ Determine the limitations of location and weather on the feasibility of heliostat powered CSP <u>Industry Partners</u>: • Industrial plant tours for HelioCon members to document layout and operations • Plant tours with heliostat technology developers to tour and document approach to IPH • Cement, steel, glass, and/or hydrogen <u>industrial partner(s) leads</u> team with CSP co-PI to perform gap analysis and create model field design and TEA for new plant and for retrofit.

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
F7, F8: The site-specificity of O&M and field preparation/ installation procedures limits the opportunity for incremental improvements that span multiple sites	Objective: Statistics on field deployment and O&M costs informed by operating plant data are available and the most promising cost-cutting innovations have been identified and developed. The solution should pursue innovative solutions to some of the known high-cost/labor-intensive areas of O&M such as washing and trenching while consolidating and analyzing quantitative data from deployed commercial scale fields to determine the relative value of investments in innovation	There are numerous opportunities to pursue technical solutions to cost reductions, but without accurate information on the cost and cost sensitivities, it is difficult to know whether the investment is going to be justified.	Approach: Work with industry partners to compile data on past deployment and O&M costs while pursuing technology for known high-value solutions • Itemize costs for deployment steps from records of past deployments from multiple companies in multiple locations with different heliostat types • Itemize costs for field O&M from records of past deployments from multiple companies in multiple locations with different heliostat types • The relationship between ground conditions and deployment processes (specifically foundations) is not well understood • The relationship between soil type and washing requirements is not well understood • Consolidate cost information to identify opportunities for automation and technical development • The value of technical innovations for field O&M is difficult to justify EPCs • Field preparation, assembly line building, mounting and installing, delivery costs, labor costs Operators • Parasitic power losses, mirror washing, breakage rate and mirror replacement costs, drive replacement costs Technology Developers • Autonomous low-water washing systems • Towerless, self-calibration systems • Low cost, secure and reliable wireless communication systems

10 Special Subtopic: Wind Load

10.1 Scope

Heliostats are exposed to atmospheric wind that imposes unsteady loads on the drives, torque tube, pylon, foundation, and mirror support components. The wind-bearing heliostat components shown in Figure 25 are designed for two conditions: (1) serviceability with sufficient stiffness to minimize local deformations of the mirror surface, typically with a maximum slope error of the order of 1 mrad during operation at all orientations [121], and (2) survivability with sufficient strength to resist the maximum loads in operation and during high-wind events when the heliostat surface is aligned horizontally in the stow position. Operating heliostats are characterized by maximum drag forces with increasing surface area with respect to the approaching wind, whereas stowed heliostats are characterized by maximum lift forces in a highly turbulent flow generated by upstream roughness in the atmospheric boundary layer. Static wind loads on heliostats [122] are conventionally defined using nondimensional aerodynamic coefficients that account for the heliostat shape depending on the structural design and atmospheric boundary layer turbulence characteristics depending on the surface roughness of a field site. Wind load coefficients are used in combination with stow and survival design wind speeds to estimate the bending and torsional loads at the hinge and base of the heliostat pylon resisted by the torque tube, pedestal, and foundation. Dynamic wind loads induced by coupling between the temporal variations of the wind loads and the dynamic properties of the heliostat structure lead to unsteady pressure distributions and oscillations of the heliostat surface that impact the tracking accuracy and optical performance of the heliostat field [123]. Detailed understanding of the static loads and dynamic response of a heliostat design with respect to the local wind conditions at field sites are critical to: (1) reduce conservative manufacturing tolerances and material cost, and (2) increase field efficiency and reliability and thus reduce risk of component failures due to high-wind events. Determination of accurate heliostat design loads for site-specific low-altitude wind characteristics are important to reduce uncertainty and increase confidence of heliostat performance measures with a potential to reduce finance risk and O&M repair and replacement costs. However, such favourable outcomes may be offset by repeated non-reoccurring engineering costs and component validation if each site requires different designs or components.

The layout of heliostat fields in power tower plants have been optimized primarily with respect to the optical efficiency of the field and disregarding of wind load. Within a heliostat field, the mean flow and turbulence characteristics can be significantly different from the incoming atmospheric flow. The wind loads on heliostats in the field therefore vary from those on a single heliostat conventionally adopted for uniform field design to counter increases in manufacturing cost and quality deviation of multiple heliostat designs in a field. Static wind loads on heliostats are strongly dependent on the heliostat field density, or the non-dimensional spacing between the heliostats with respect to the mirror chord (windward) length. Shielded inner rows at high field density can be subject to considerably lower mean wind loads while simultaneously facing less stringent pointing and beam quality requirements due to their proximity to the tower. This may allow the design of lighter in-field heliostats with a larger allowable deflection under reduced wind loads while delivering adequate performance. However, the peak wind loads in high-density field regions can be increased above those on a single heliostat, such as a 30% increase in lift forces on a heliostat in stow [124] and a 40% increase in maximum operating hinge moment.

Such load amplifications for limiting cases are likely to be caused by the increased unsteadiness of flow in the wake of upstream operating heliostats at distances up to 8 chord lengths [125] and increased center of pressure movement further from the central elevation axis than in the case of a single heliostat [126]. Variation within heliostat fields is not well understood and difficult to characterize. Nevertheless, through measurements on instrumented heliostats in field sectors and analysis of their deflection based on spatial relationships to other heliostats (and the tower), analytical models on wake flow interactions and load distributions can be developed and combined with dynamic performance impacts.

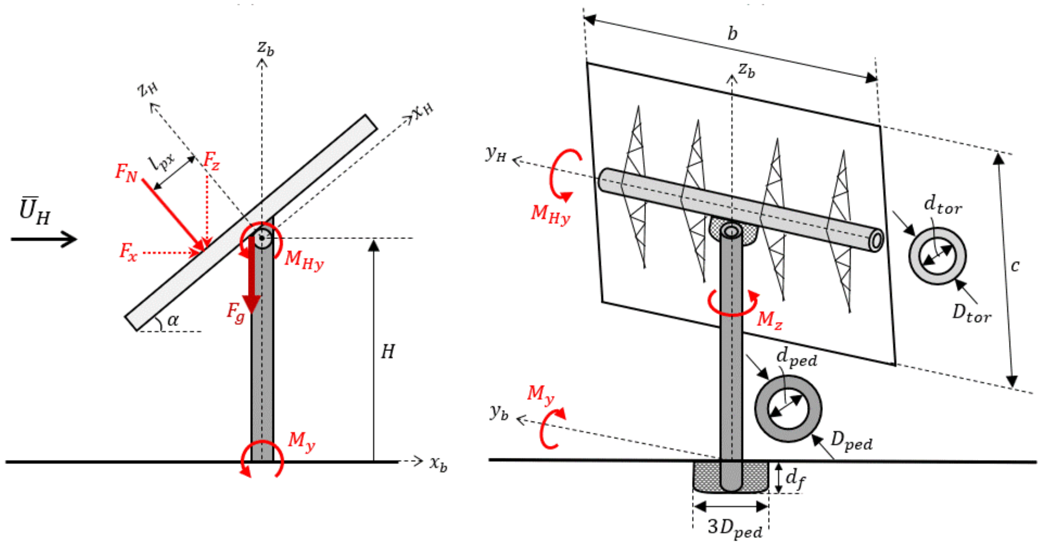

Figure 25. Schematic diagram showing the wind loads on a heliostat (left) and the characteristic dimensions of the wind-bearing structural components of a T-shaped azimuth-elevation heliostat with elevation axis height H and aspect ratio b/c (right)

Figure from [127].

Determining the dimensions of the structural components of a heliostat relies on understanding the effect of external loads due to wind and gravity on deflections and mirror shape for optical performance during plant operation, and survivability in stow position under extreme wind conditions. Spillage losses associated with beam misalignment due to wind-induced heliostat tracking errors can significantly affect the operational performance of power tower plants, particularly with increasing distance from the tower in large solar fields [128]. Kolb et al. [113] showed that the cost of wind-dependent heliostat components followed a three-halves power law with the heliostat area, based on scaling of material costs of thin tubing with a constant maximum stress. As wind loads increase with heliostat area, the required diameter and thickness of the pedestal, torque tube, and mirror support trusses increase to ensure the combined bending and torsional stresses remain below the ultimate tensile stress of the material within an acceptable limit of safety [129], [130]. Emes et al. [127] showed that the increasing mass of steel required to satisfy material stress limits in the structural sections of T-shaped heliostats increases from 18% to 34% of the total direct cost of manufacturing a heliostat with increasing size from 25 m^2 to 150 m^2.

The maximum wind loads are highly sensitive to the variation of turbulent wind fluctuations with surface roughness and height in the lowest 10 m of the atmospheric boundary layer. A sensitivity analysis by Emes et al. [127] estimated that the total heliostat cost increased by approximately $20/m^2 with increasing turbulence from a low-roughness desert terrain to a high-roughness suburban terrain. This has significant implications for designers and manufacturers due to: (1) the significant variability of local wind conditions at different field sites, and (2) the large range of heliostat sizes currently being deployed, from larger heliostats ($A \geq 120$ m^2, $H \leq 6$ m) developed by Abengoa Solar and Sener, to smaller heliostats ($A \leq 20$ m^2, $H \leq 3$ m) developed by eSolar, Vast Solar, and BrightSource Energy [131].

10.2 State of the Art

Wind characterization and loading of heliostats due to wind has been identified by various stakeholders as a critical area of importance in the *CSP Best Practices Study* [132]. Currently, static and dynamic load measurements on scale-model heliostats in boundary layer wind tunnels are used to characterize wind loading and influence design of heliostats as inputs to Finite Element Analysis (FEA) models and analytical approaches based on wind codes for buildings with fundamental natural frequencies smaller than 1 Hz [133], [134]. Full-scale prototype testing also exists for dynamic load analysis but is scarcely published in the literature. Development of computational fluid dynamics (CFD) models to complement wind tunnel and field measurements is ongoing. They are computationally expensive with limited capability to accurately reproduce atmospheric wind conditions at the relevant heights of heliostats in CSP plants and simulation of wind loads on a complete field.

Table 23 summarizes the current best practices for both wind characterization and loading of heliostats, which are separated on the basis of the underlying techniques.

Table 23. State of the Art in Characterizing Wind Conditions and Loading for Design of Heliostats

Techniques	Current Practice	Maturity
Characterizing Wind Conditions at Heights Relevant to CSP Fields (Measurements)	• TMY data in annual CSP field efficiency models conventionally input hourly or daily averaged wind data. • In practice, during operation of a CSP central receiver field; however, heliostats are stowed based on a 3-second gust wind speed [132]. The moving average gust speed over 3 seconds at a 10-m height, defined by the World Meteorological Organization, is adopted by most national weather services and measured by cup anemometers (1 Hz) at automatic weather stations. • Second-generation heliostats defined with a maximum operational design gust wind speed of 22 m/s and a stow survival design wind speed of 40 m/s at a 10-m height based on a 100-year mean recurrence interval [135]. • At the heliostat design stage, design wind speeds for maximum operating and stow configurations are specified using local/regional wind maps in national wind codes with limited frequency and resolution of historical wind measurements at the proposed field site [123]. • Strategies for stowing heliostats are conventionally applied to the whole heliostat field based on point measurement of wind gust velocity at or near the field site [136].	Available and used commercially
Wind Loading on CSP Structures (Measurements)	• Design wind pressures and loads in standards for slender low-rise buildings of mean roof height less than 18 m and fundamental natural frequencies smaller than 1 Hz [133], [134]. • Heliostat design methods for aerodynamic load coefficients established by Peterka [122] and considered the effect of longitudinal turbulence intensity on peak wind loads [137]. • Integral length scales of the turbulent eddies in the atmospheric surface layer relative to the heliostat structure characteristic length correlates strongly with maximum wind loads in stow position and at 90 degrees elevation [123], [138], [139]. • Square-mirrored heliostats are subject to smaller torsional loading than PV arrays, but azimuth moments and lift forces increase with increasing heliostat mirror aspect ratio [140]. • Strain gauges, load cells, and accelerometers are robust and can be mounted on full-scale heliostats in atmospheric conditions to characterize loading cases. • Load cells (at up to 1 kHz) provide three-dimensional force and moment measurements and offer robust operation in outdoor conditions. • Dynamic strain gauges offer high sensitivity (500 mV/g) measurements of strain with accurate frequency and damping characteristics even at low wind speeds [141]. • Tri-axial accelerometers identify vibrational mode shapes and frequencies of a heliostat structure and dynamic response through hammer-excited and wind-excited testing [142]. • Multi-camera dynamic photogrammetry techniques offer increased resolution of wind-induced dynamic response of Stellio heliostat at low frequencies [43].	Used sparingly

Techniques	Current Practice	Maturity
Wind Tunnel Testing for Wind Conditions and Loading	• Part-depth atmospheric boundary layer simulations in wind tunnels established for small structures based on dimensional analysis and similarity of turbulence spectra and force balance techniques [143]. • Matching of turbulence spectra in the reduced frequency range corresponding to the full-scale load distributions provide similarity in maximum load distributions [143]. • Geometric scaling ratios of heliostat models with larger dimensions (e.g., 1:20) show similarity of longitudinal spectra for operating loads, and smaller dimensions (e.g., 1:60) show similarity of vertical spectra for stow loads [143]. • High-frequency force balance method (at up to 1 kHz) established for measurements of overturning moments and drag forces. • Integration of surface pressure distribution through pressure taps on upper and lower surface (at up to 1 kHz) established for lift forces, hinge moments, and dynamic load analysis [144], [145].	Used extensively
Characterizing Wind Conditions at Heights Relevant to CSP Fields (Simulations)	• Mesoscale simulations performed using a numerical weather prediction model, such as weather research and forecasting, typically contain all the key atmospheric flow physics and are designed to reproduce all the dynamic features in the atmosphere [146]. Mesoscale simulations have been advanced significantly in the last couple of decades and are being used to predict synoptic and mesoscale processes associated with extratropical cyclones, fronts, and jets. These mesoscale weather models also include techniques to assimilate a wide range of direct and in-direct observation types, from traditional in situ surface and upper-air data to satellite-based measurements [146]. • Microscale simulations (RANS/LES) of atmospheric boundary layers usually focus on modeling small-scale and high-frequency turbulent flow behavior close to the ground. These microscale high-fidelity simulations are commonly used by the wind energy community to characterize wind and turbulence near the ground to provide critical information for siting and operation of wind plants [147]. • The meso-micro coupled algorithms force the microscale simulations using the weather and atmospheric features typically included in the mesoscale simulations. Dynamic input from mesoscale weather models can provide important meteorological, topographical, and other environmental drivers of microscale variability [148]. These techniques are now being used increasingly to study flow characteristics around wind farm sites.	Used extensively in wind energy community
Wind Loading on CSP Structures (Simulations)	• Single heliostat structure simulations in field/wind tunnel are increasingly being performed to study rigid/static behavior of structures. These are mostly steady RANS based simulations with computational mesh resolving the geometry [149],[150],[151],[152],[[153]. • Unsteady simulations with complex array configurations are computationally expensive and are being used sparingly to study deep array effects on collector structures [13], [154], [155].	Used sparingly
Economics of Wind-Load Reductions	• The shielding effect for wind protection and dust mitigation has been investigated and adopted using perimeter fences in heliostat fields. • Reductions in wind speed and turbulence of the incoming atmospheric boundary layer can be achieved using fences; however, the porosity and height of fence required to be effective in a field of heliostats requires further investigation [156]. • Retrofit devices mounted to the edge of a heliostat present an alternative method to reduce loads and thus mass of heliostats on the inner field with feasibility and TEA.	Not used in the CSP industry

10.3 Ranked Gaps

Table 24 lists the critical gaps in the area of wind loading. Following the convention used in this report, each technical gap is briefly described and its impact to different stages of heliostat development cycle is also marked. These gaps are separated in terms of underlying techniques, measurements, and modeling used for characterizing wind conditions and loading. Using the tier-based criteria, the gaps are classified and ranked in Table 24. Position within a tier does not indicate the priority of a gap within that tier. Four gaps are identified as Tier 1 to have the most impact to heliostat performance and cost: WL1, WL2, WL3, and WL4. There are five gaps categorized into Tier 2 and one gap into Tier 3.

Table 24. Identified Gaps Related to Wind Loading

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

No.	Gap Description	a	b	c	d	e
Tier 1 Gaps (Most Important)						
WL1	**Insufficient wind measurement and characterization at heliostat field sites** • Need to identify sufficient temporal and spatial resolution of measurements for full characterization of wind loads on heliostats, cost, and risk evaluation of a CSP plant. • Need for high-frequency instruments such as ultrasonic anemometers (at up to 32 Hz) to provide three-dimensional wind measurements with robust operation in outdoor conditions. • Characterization of impact of ground roughness and terrain on wind conditions approaching a heliostat field. • Characterization of impact of correlations between stow and survival gust and mean wind speeds with changes in heliostat size is crucial to reduce uncertainty of heliostat wind load predictions and material cost.	x				
WL2	**Lack of understanding on the impact of atmospheric turbulence on dynamic loading and tracking error** • Impact on optical effects from dynamic wind loading not well understood. • Wind loading data exist for single heliostats and very few tandem configurations in wind tunnels. • More investigations are needed to better understand the field layout on overall optical performance of the field.		x			
WL3	**Lack of understanding on wind load on heliostats in array configurations** • Traditionally, wind tunnel studies have been used to characterize wind loading on collector structures. • Wind tunnels inherently cannot reproduce the large-scale flow features observed in field measurements. • There is a strong need to investigate static and dynamic wind load variations on arrays of heliostats in wind tunnels and field environments to further optimize heliostat field design for wind load in combination with optical considerations.					x
WL4	**Missing design standards for determining heliostat wind load coefficients and safety factors** • Need to develop specific design standards for heliostat wind loads instead of slender body building codes currently being used.	x				

No.	Gap Description	a	b	c	d	e
	• The combinations of tracking angles for the application of dynamic amplification factors and safety factors to the critical load cases in heliostat design are not well understood. • The uncertainty of safety factors with alternative heliostat designs (e.g., spinning axis, tilt-roll, carousel, umbrella) to a conventional azimuth-elevation tracking configuration and with changes in height of a mirror closer to the ground in stow position needs to be investigated.					
Tier 2 Gaps						
WL5	**Insufficient computational modeling accuracy of dynamic wind loads on heliostats** • Higher fidelity simulations of dynamic loading on multiple structures in complex configurations are computationally expensive. • This capability will be complementary to the field and wind tunnel measurements. • Few validation studies of static loads against experimental measurements and very limited fluid-structure interaction simulations published in the literature.		x			
WL6	**Lack of TEA of heliostat wind load reduction methods** • The economic benefit of reduced mass due to shielding effect has not been itemized for a proposed power plant in the field. • Need for feasibility analysis of wind load reduction methods leading to increased operation, improved load mitigation strategies such as wind fencing to reduce plant downtime and thus increased revenue.					x
WL7	**Lack of understanding of dynamic loading on heliostat structures** • Need to more accurately characterize dynamic loading on heliostat components using both measurements and simulations. • Studies focusing primarily on resonance frequency of structures have limited applicability due to dependence on specific design of heliostats and installation configuration.		x			
WL8	**Insufficient computational modeling accuracy of atmospheric turbulence** • Unsteady higher fidelity simulations of flow and turbulence in atmospheric boundary layers in the field are needed. • Accurate characterization of turbulence close to the ground (relevant to collector heights). • To investigate atmospheric stability effects on wind loads, need to reproduce diurnal cycles or multi-day cycles of mesoscale weather models, coupled to microscale (close to the ground but without atmospheric dynamics) simulations.	x				
WL9	**Missing characterization of heliostat wind loads in tropical areas** • Wind tunnel and computational studies needed to develop methods to model wind loads on heliostats, with respect to extreme tropical wind conditions and micro-scale weather events such as dust devils and downdrafts. • Need to develop multipliers for turbulence profiles and regional wind speeds based on micro-scale wind events in non-tropical and tropical weather conditions, following conventions in design wind standards for buildings (ASCE 7-02, AS/NZS 1170.2), PV panels (ASCE/SEI 7-16), and wind turbines (IEC 61400-1).	x				
Tier 3 Gaps (Least Important)						
WL10	**Missing approach in characterizing local wind impacts due to field and tower installation**					x

No.	Gap Description	a	b	c	d	e
	• Need wind tunnel and computational studies of the increase in localized surface roughness due to construction of heliostat field. • Need to characterize impact of increased surface roughness generated by heliostat field on atmospheric boundary layer velocity and turbulence profiles and loads within the field.					

10.4 Gap Analysis and Recommended Pathways

Table 25 summarizes the required functionality of addressing the solution, justification, and benefits by addressing the gap and the proposed addressing strategies for the four Tier 1 gaps on wind loading from Table 24. Among these identified gaps, WL1, WL2, and WL4 are critical for enhancing the performance of CSP plants and reducing risk for investors. WL3 offers a great opportunity for reducing heliostat costs through improved tools for wind loads, but requires extensive research for thorough performance assessment and improvements.

Table 25. Top-Ranked Gap Analysis for Subtopic of Wind Load

Gaps	Functionality of Addressing Solution	Justification/Benefits	Recommended Pathway
WL1: Insufficient wind measurement and characterization at heliostat field sites	• Able to measure atmospheric boundary layer turbulence at relevant heights, resolution, and frequency • Able to increase field operation through smart stowing strategies during windy conditions	• Fundamental step to site selection and characterization (together with DNI, soiling, etc.) • Needed to improve accuracy of heliostat wind load predictions based on gust wind speeds that are site dependent • New methods/tools will provide improved estimation of heliostat costs to reduce risk and conservative heliostat designs	• Provide recommendations and guidelines for the required equipment and data collection and processing techniques • Access historical wind data collected in heliostat fields for analysis • Work with metrology and standards topic and soiling subtopic in SolarPACES Task 3 to develop wind characterization techniques for prospective and operational heliostat field sites
WL2: Lack of understanding of the impact of atmospheric turbulence on dynamic loading and tracking error	• Measurements that relate tracking error and atmospheric boundary layer turbulence during windy conditions • Field efficiency models on spillage losses that incorporate dynamic	• Needed to improve tracking performance of plant • Needed to balance heliostat costs with performance impacts	• Investigate the correlation between tracking error, the field layout, and terrain roughness • Obtain funding to instrument dynamic load sensors on heliostats in an operating field

Gaps	Functionality of Addressing Solution	Justification/Benefits	Recommended Pathway
	loads and heliostat position within a field		• Collaborate with CSP plant operators through prototype testing and refined testing
WL3: Lack of understanding on wind load on heliostats in array configurations	• Instrumenting heliostats in an array to investigate sensitivity to heliostat wake effects and atmospheric boundary layer turbulence effects • Models of wind load distributions in field sectors due to surface roughness and upstream heliostats	• Reduce project risk and uncertainty of heliostat design wind loads • Needed to improve field operating strategies during windy conditions	• Perform wind tunnel experiments and computational fluid dynamics modeling to develop correlations between heliostat wake and load data on array configurations • Access historical wind data collected in heliostat fields for analysis • Perform sensitivity analysis in TEA models
WL4: Missing design standards for determining heliostat wind load coefficients and safety factors	• Guidelines for industry to apply testing procedures for deriving ultimate wind loads on different heliostat designs • Safety factors for static loads and dynamic response of heliostat with respect to site wind speed and turbulence conditions	• Needed to identify critical load cases for prototype testing by industry • Reduce project risk and uncertainty of heliostat design wind loads • New methods/tools will provide improved estimation of heliostat costs to reduce risk and conservative heliostat designs	• Investigate the relationship between gust factor and wind speed standard deviation, and peak loads on heliostat structures • In collaboration with industry, review and develop procedures through initial design and prototype testing • Perform sensitivity analysis in TEA models

11 Special Subtopic: Soiling

Maintaining high reflectance of a CSP solar field is of paramount importance for the economics of the plant. One of the key reasons for degradation is the loss of reflectance due to the accumulation of dust on the surface of the heliostats. Reports have indicated that these soiling losses can vary significantly from site to site—from a few tenths of a percentage point to a few percentage points per day, depending on the site characteristics [157], [158]. These losses have led CSP operators to periodically clean heliostats using a number of different cleaning apparatus [159], but these operations can be expensive and have been identified as a key opportunity to reduce costs [160]. Moreover, the disparity in soiling rates across different sites has made the planning of soiling mitigation measures (e.g., cleaning resources, schedules) difficult, particularly at the time of site selection.

11.1 Scope

The soiling subtask is concerned with the development of soiling measurement, modeling, and techniques to characterize soiling and plan mitigation measures for existing and planned CSP plants. This includes:

Measurements:

- Assessment of deposited and airborne dust characteristics (e.g., amount, size distribution, composition, concentration) and their variation across different CSP-relevant sites
- Development of standard methodologies to assess and report reflectance losses of soiled heliostats
- Establishment of strategies and technologies for monitoring soiling losses of large solar fields

Modeling and Characterizing Soiling Processes:

- Identification of the key mechanisms within each of the soiling processes (e.g., deposition, adhesion, removal)
- Development and validation of models describing the key mechanisms
- Improvement and development of new techniques for predicting soiling losses

Mitigation:

- Development of methodologies for optimizing mirror washing resources and deployment
- Assessment and development of passive mitigation techniques (e.g., coatings).

Enabled by these developments, the subtask seeks to provide tools to assess soiling characteristics during site selection. These tools will also be useful for existing plants and will allow improvements and cost/benefit analyses of potential mitigation strategies.

11.2 State of the Art

The soiling of solar collectors is a complex process that involves a number of subprocesses, as depicted in Figure 26. *Generation* refers to the loading of the atmosphere with dust from various sources while *deposition* refers to the settling of is airborne dust on a (typically horizontal) surface. The balance of different *adhesion/removal* mechanisms then determine which of the deposited particles remain on a surface. Finally, the deposited dust results in a loss of collected irradiation (i.e., reflectance loss for CSP).

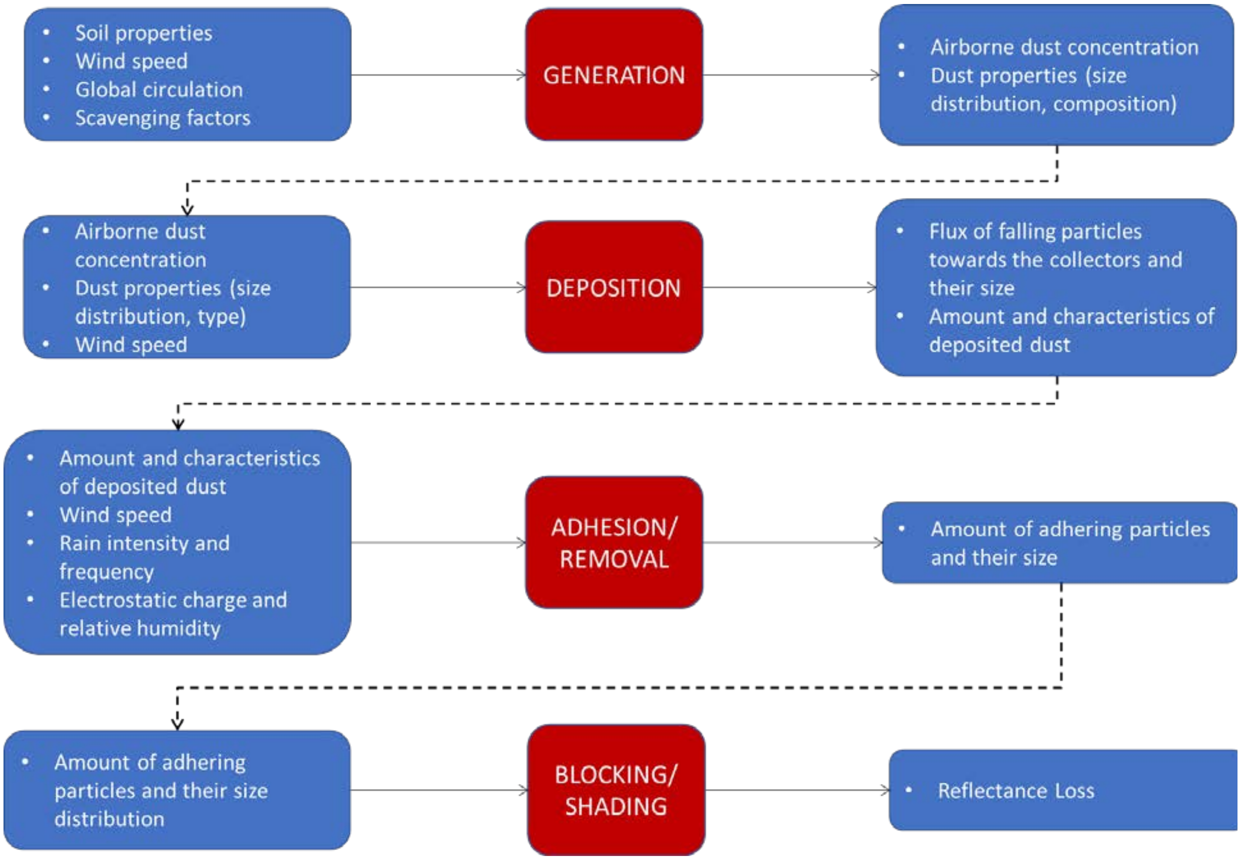

Figure 26. Conceptual diagram of the overall soiling process including the main involved parameters

Figure adapted from [161]

Airborne dust contributions come from a variety of sources, including: (1) dust particulate from stirred up and blown ground, (2) road dust due to friction of vehicles on a road, (3) salt aerosols from wave action and sea-spray or road salts, (4) anthropogenic pollutants (power plant exhaust), (5) biological particulates, such as spores or pollen, (6) photochemical particulate such as nitrates or sulfates, and (7) soot from forest fires, vehicle emissions, or volcanic eruptions [162]. The entrainment of particles in the atmosphere is usually characterized by the evaluation of particles sources and sinks, and commonly dealt with in atmospheric sciences. The relative prevalence of each source has a strong impact on airborne dust composition. Yet, it is common in solar soiling studies to assume that ground soil composition is similar to the local airborne dust [161], [163]. In geological sciences, dust is usually described as particles whose diameter is smaller than 62.5 µm [164], although some studies include particles up to 100 µm [165] or 500 µm [166]. The size distributions of airborne particulates are usually described by a tri-modal distribution. Particles with diameters >3 µm are classified as coarse, those with diameters from 0.1 µm to 3 µm belong to the accumulation mode, while the ultrafine mode refers to particles with diameters <0.1 µm

[165]. A few examples of typical tri-modal dust size distributions exist in literature and can be exploited to approximate local dust characteristics [165].

The overall description of each soiling subprocess is complex and prone to approximation errors. In solar-related literature, the generation phase is commonly neglected, since measurements of airborne dust concentration can be obtained with locally deployed dust samplers (e.g., Protinus 1000, Dust Master Pro 7000) or through satellite techniques [167]. Data can also be obtained regarding dust composition and size distribution with additional instrumentation. Moreover, measurements of dust deposition density on the collectors' surfaces, and eventually reflectance measurements can also be achieved with a range of devices. Reflectance measurements are typically obtained via handheld reflectometers (A-1) on a sample set of mirrors, or automatically measure mirror samples placed within the field environment (e.g., TraCS [168]).

Regarding mitigation of soiling losses, the most relevant technique adopted to diminish the detrimental effect of soiling is washing the heliostats. The costs related to cleaning activities may be significant and need to balance the otherwise incurred production losses due to soiling. Few cleaning methods are currently deployed to wash heliostats [169], whose characteristics and costs may affect the optimal cleaning strategies. Despite interest in automation, most currently deployed CSP tower plants use staffed washing trucks that traverse the solar field and manually wash the heliostats using a solution of demineralized water and detergent. Some studies claim that although effective, heliostats washing may leave some amount of dirt on the surfaces that eventually lead to long-term soiling-induced degradation [170]. Recently, a number of studies have dealt with optimization of cleaning strategies as well (e.g. [171]–[173]), which are discussed in Appendix A.

A summary of the state of the art regarding the three mentioned topic areas is reported in Table 26, while a more thorough literature review for these areas is detailed in Appendix A.

Table 26. State of the Art for Soiling Measurements, Modeling, and Mitigation

Category	State of the Art
Measurements	○ Use of handheld reflectometers to assess reflectance across field ○ Some automated reflectance measurement devices have been proposed (including drones) but are rarely utilized commercially (e.g., TraCS in Figure 28) ○ Techniques are available to characterize composition and size of both airborne and deposited dust ○ Satellite reanalysis databases are available for surface dust concentration and dust deposition on the ground
Modeling and Characterizing Soiling Processes	○ Soiling losses during site selection and plant design are highly uncertain ○ Soiling loss studies are mostly conducted for PV systems using regression analysis ○ Motivated by the site specificity of regression analysis, a few physical models of soiling phenomena have been developed ○ Most studies estimate soiling losses for fixed collectors ○ Model predictions typically are deterministic (i.e., no prediction of confidence interval) ○ The few physical soiling models have examined only dry deposition with limited experimental studies on effects of moisture ○ Existing studies rarely model adhesion/removal balance

Category	State of the Art
	○ Soiling models mostly assume particles to be spherical and made of a single compound
Mitigation	○ Studies addressing cleaning technologies and their effectiveness are typically limited to small studies on prototype systems ○ Anti-soiling coatings are assessed in laboratories or under controlled conditions ○ Economics of cleaning solar fields have been addressed, where the key variables are soiling status, cleaning trucks and crews, schedules/routing, and thresholds ○ Methods seek to maximize profit for a given plant design, but LCOE impact is not typically computed.

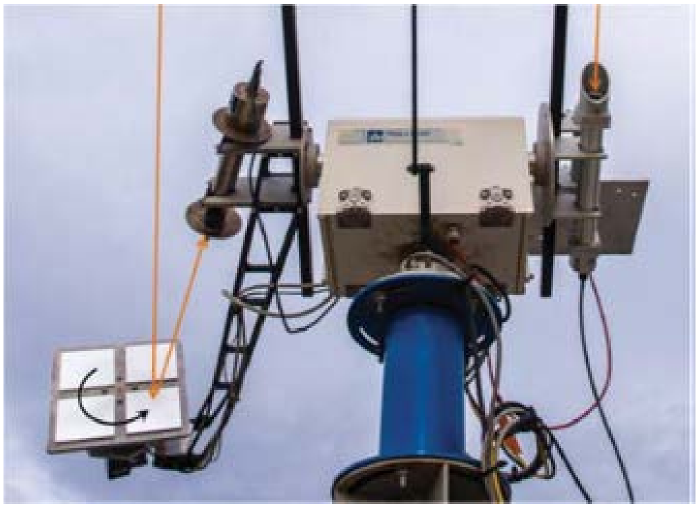

Figure 27. TraCS automatic soiling monitoring system using measured DNI via reflected sample

Adapted from [168]

11.3 Ranked Gaps

The summary of the state of the art and the initial list of gaps can be found in Table 27. Each technical gap is labeled with an “So” number and categorized into different activity areas for the soiling subtask (measurement, modeling and characterizing soiling processes, and mitigation). The resulting opportunities for HelioCon to make an impact are summarized as well.

The main gaps can be summarized as follows:

- Measurements are typically taken using handheld reflectometers. Procedures are laborious and are weakly standardized. Automated systems are available, but industry uptake has been poor.
- Although there are systems to measure a variety of dust characteristics (e.g., size distribution, composition), these measurements are rarely exploited to understand heliostat soiling.

- Some CSP-relevant soiling prediction models are available, but they omit some potentially relevant mechanism and are yet to be validated with data from an operational field.
- Soiling rates are typically understood only after the plant is built and so there is a significant risk of unexpectedly high productivity losses due to soiling. Moreover, there is an opportunity to mitigate the impact of soiling through plant design (e.g., oversizing the field), which can only be conducted if soiling losses estimates are available during design.
- There are a number of understudied aspects in mitigation, including:
    - Improvement of cleaning systems and methodologies (e.g., equipment, spraying technique, robotics, better brushes, cleaning solutions, automation);
    - Using the soiling state of the solar field to inform O&M decisions (e.g., cleaning priority, aiming).
- There are no standard methods to assess the CSP performance (optical, durability) of coatings.

Approach to Gaps Ranking

The identified gaps are classified and ranked in Table 27. According to the sections defined in Table 26, four gaps belong to Measurement, eight gaps to Modeling and Characterizing Soiling Processes, and four gaps to Mitigation. Four gaps are identified as Tier 1, one from Modeling and three from Mitigation. Although qualified as Tier 2, some gaps would be relevant to achieve some of the Tier 1 objectives, while their stand-alone relevance is considered Tier 2 or 3 (e.g., So7 and So11 for So1, or So12 for So4). The gaps are also categorized depending on the heliostat development stage they belong to: So1 is listed under Conceptual Design phase, while So2 and So3 under Deployed Field and Components, respectively. Eventually, So4 belongs to both Conceptual Design and Deployed Field, given the wide range of themes involved.

Table 27. Soiling Subtask Gaps and Ranking

a = conceptual design; b = components; c = integrated heliostat; d = mass production; e = deployed field

No.	Gap Description	a	b	c	d	e
Tier 1 Gaps (Most Important)						
So1	No systematic evaluation of soiling is performed at site selection stage.	x				
So2	Design and automation of new cleaning systems are underexplored.					x
So3	There are currently no established standards or test data to assess anti-soiling coating performance and durability for a particular application.		x			
So4	Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood.	x				x
Tier 2 Gaps						
So5	No standard method for solar field reflectance sampling has been adopted.					x
So6	Typical processes for assessing field reflectance are labor-intensive and the value of automated ones is yet not well understood.					x
So7	The effect of composition, size distribution, and other dust characteristics on heliostat soiling rates is not well studied.	x				
So8	Only few physical soiling models are currently available, and they have yet to be validated on actual solar fields.					x
So9	Direct application of models developed for PV soiling-induced efficiency loss is yet not mature to provide heliostat reflectance losses estimates.	x				
So10	Uncertainty of model-predicted soiling losses has not been assessed.	x				
So11	The impact of different adhesion and removal mechanisms on soil deposited on tracking heliostats is not yet well understood.	x				
So12	The knowledge of the solar field’s soiling state is not properly exploited to inform O&M decisions (e.g., cleaning, defocusing, aiming strategy).					x
Tier 3 Gaps (Least Important)						
So13	Accuracy and usability of satellite-derived dust estimates for soiling estimation has not yet been established.	x				
So14	Moisture effects on adhesion and removal are not well understood.	x				
So15	Models neglect actual particle shape.	x				
So16	No methodology is available to estimate CSP soiling losses from satellite reanalysis-derived dust estimates.	x				

11.4 Gap Analysis and Recommended Pathways

Table 28 summarizes the required functionality of the proposed solution, justification, and benefits by addressing the given gap, and the proposed addressing strategies for the four Tier 1 gaps on soiling. Among these gaps, So1 and So4 are paramount for enhancing the performance of CSP plants and reducing the risk for investors, whereas So2 and So3 offer great opportunity for reducing cleaning and soiling costs while requiring extensive research for thorough performance assessment and improvements.

Table 28. Soiling Subtask Tier 1 Gap Analysis

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
So1: Soiling evaluation at site selection	• Able to provide accurate soiling estimates for a given location and plant design • Requires limited (if any) experimental campaign • Models and analysis incorporated into software tools • Result uncertainty assessed with experiments • Evaluate impact of sand storms on overall solar field performance	• Fundamental step to site selection • Soiling losses and cleaning costs are a key O&M cost • New methods/tools will provide (1) estimation of cleaning costs to diminish risk; (2) inclusion of soiling assessment (together with DNI, wind, etc.) as part of site characterization	• Develop and refine physical models for soiling predictions • Develop tools to assess expected plant performance that include soiling and optimal design of cleaning systems • Development of standard site characterization measurements/ experiments • Field validation of models using targeted experiments • Create a “soiling database” that includes soiling data available for different areas of the world.
So2: Design and automation of new cleaning systems is underexplored	• Clearly defines effectiveness and costs of cleaning systems • Able to adapt cleaning system design to the field • Able to identify solar field design parameters that influence cleaning system design • Able to adapt cleaning design to local environmental and economic condition (e.g., labor costs, skill of labor force) • High reliability, low maintenance • Identify and tailor anti-soiling coatings for specific locations	• Improve design and selection of cleaning systems may significantly reduce lifetime cost of the plant • Potentially large reduction in cleaning costs by automation	• In close collaboration with industry partners, review existing technology and characterize their performance • Develop functional requirements and cost models for cleaning systems • Develop new cleaning designs that address these functionalities • Include collaboration with CSP plant operators through initial design, prototype testing, and refined testing

Gaps	Functionality of Solution	Justification/Benefits	Recommended Pathway
			• Develop a best practices manual about suggested methodologies and techniques for optimal heliostats washing
So3: No standard or data to assess anti-soiling coating durability/performance	• Clearly define performance criteria for coatings • Able to provide recommendation and procedure for testing the durability of coatings in CSP-relevant environments	• Enable evaluation/ understanding of economic impact of coatings	• Coordinate with similar efforts in PV to characterize durability of coatings • Develop standards and tests for optical performance of coatings in CSP applications
So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	• Able to directly assess the economic impact of changing key design parameters, plant location, and cleaning regime • Able to provide adequate figure of merit for plant financing • Verified through case studies with industrial partners	• Accurate costs and revenues estimates are fundamental parameters for plant financing and risk reduction • Enables co-optimization of capital and O&M expenditures to minimize plant lifetime costs	• Develop and verify heliostats reliability models • Identify key design parameters that interact with optimal cleaning regime • Continue to develop cleaning optimization methods/tools to include revenue and costs associated with key design choices and heliostat reliability • Collaborate with industry partners to refine and deploy above tools on existing plants to understand accuracy and ease of use • Conduct studies on using tools for new sites

12 Conclusions

Heliostat-based CSP systems have great potential to play an increasing role in the future energy sector transformation for electricity generation, process heat, and solar fuel. HelioCon was formed to advance heliostat technology with respect to installation cost, performance, and O&M in order to increase CSP's commercial competitivity in the future energy market. As part of this work, HelioCon categorized heliostat R&D into six technical areas along with two special subtopic areas. For each area, the HelioCon team first established the state of the art, collected and ranked gaps in each topic with inputs from leading industrial developers and key stakeholders of the CSP community, and then conducted detailed gap analysis and developed recommended pathways to address top-tier gaps.

This roadmap report intends to provide a reference for (1) HelioCon to plan the future work that would be most valuable in the improvement, validation, and deployment of heliostat technology; (2) the global community to integrate the efforts where it can address the most impactful gaps to promote heliostat technology advancement and remove deployment barriers.

Thus, HelioCon calls for international collaborations to address the Tier 2 and Tier 3 gaps, in addition to the Tier 1 gaps that HelioCon is unable to address alone. HelioCon recognizes that the gap and roadmap analysis will need future improvement, and other stakeholders would be at a better position than HelioCon in leading the effort to resolve some gaps. In particularly, a given Tier 2 or 3 gap may not be high priority for the industry as a whole, but may be critical for a given technology developer or stakeholder, so HelioCon would be interested in supporting where it can.

HelioCon will plan to recruit additional members through an annual competitive request for proposal (RFP) process to tackle the identified high-priority gaps. HelioCon anticipates updating the gap and roadmap analysis on an annual basis so that necessary adjustments can happen to maximize the value of the collaborative effort.

12.1 Gap Analysis Summary

All Tier 1 gaps are summarized in Table 29. Addressing them will directly contribute to either improving economic performance of heliostat or heliostat systems, such as installation cost, energy production efficiency (opto-mechanical performance) and O&M, or reduce commercial risks. For example, addressing gaps in TEA would help facilitate heliostat-based CSP system designs with a flexible scale, thus reducing commercial risks to promote commercial deployment; addressing gaps in metrology and standards would improve performance and reduce commercial risks; addressing gaps in advanced manufacturing and components and controls would help reduce heliostat installation cost; addressing gaps in RTE would help expand required workforce for research, development, and overall CSP industry, thus resulting in less commercial risk of a project development; addressing gaps in field deployment would reduce commercial risk and increase bankability.

Of all the top-tier gaps, here are a few for particular emphasis:

- **Installation cost:** This involves all gaps on advanced manufacturing (AM1, AM2, AM 3, and AM4) and components and controls (C1, C2, C3, C4 and C5). In particular, utilization of composite materials for heliostats (AM3 and C1) may have a great potential in lowering the cost of next-generation heliostats.

- **Energy production efficiency:** Particularly important are gaps in metrology (M1, M2, M3, M4, M5 and M6) and manufacturing (AM2, AM3, and AM4) to ensure the performance of a commercial system.
- **O&M:** This includes gaps in soiling characterization and cleaning techniques (So1, So2, So3, So4).
- **Commercial risk:** Most important are gaps in standards (S4, S5, S6), field deployment (F1 - 8), TEA (T1, T2, T3, T4) advanced manufacturing (AM2, AM3, AM4), and RTE (R1, R2, R3, R4). Development of smaller-scale heliostat-based projects would have a great potential to reduce commercial risk with less capital investment and less construction time.

In particular, S6 (missing guideline and standard on site characterization) and R4 (heliostat technology resources are not accessible in a centralized-web based format) will have an impact on all key aspects of heliostat economic competitivity.

Table 29. Summary of Tier 1 Gaps and Their Impact Areas

Cost = Installation Cost; Energy = Energy Production Efficiency; OM = Operation & Maintenance; Risk= Commercial Risk.

Gap ID	Description	Impact			
		Cost	Energy	OM	Risk
Techno-Economic Analysis					
T1	Missing linkage between model inputs and actual components				X
T2	Lack of validated and widely accepted model for solar field O&M costs			X	X
T3	Insufficient knowledge of construction and commissioning costs, and the impact of delays on financing costs	X			X
T4	Lack of validated CSP models for IPH applications				X
Metrology and Standards					
M1	Not fully validated metrology on opto-mechanical error measurement in laboratory		X		
M2	Insufficient metrology on opto-mechanical error measurement in outdoor environment (a few heliostats)		X		
M3	Missing metrology on opto-mechanical quality assurance		X		
M4	Missing metrology on opto-mechanical quality calibration after installation.		X		

Gap ID	Description	Impact			
		Cost	Energy	OM	Risk
M5	Missing metrology on opto-mechanical error in-situ measurement (full commercial-scale field)		X		
M6	Insufficient metrology on receiver flux quality real-time assurance tool		X		X
S1	Missing standard on optical terminology for heliostats		X		
S3	Missing guideline and standard on heliostat design	X	X		
S4	Missing guideline and standard on standard heliostat solar field design/simulation				X
S5	Missing guideline and standard on heliostat solar field acceptance test				X
S6	Missing guideline and standard on site characterization	X	X	X	X
Special Subtopic: Soiling					
So1	No systematic evaluation of soiling is performed at site selection stage			X	X
So2	Design and automation of new cleaning systems is underexplored			X	
So3	No standard or data to assess anti-soiling coating durability/performance			X	
So4	Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood			X	
Components and Controls					
C1	Composites or other advanced structures (e.g., torque tubes, pedestals, foundation)	X			
C2	Lower cost mirror designs with comparable performance to existing glass mirrors	X			
C3	Wireless systems, with standardized requirements & testing capabilities	X			
C4	Closed loop control and auto alignment/calibration processes	X	X		
C5	Design qualification standards for heliostats to enable bankable C&C's, heliostat long term performance, and shorten design improvement cycles	X	X		X
Advanced Manufacturing					
AM1	Innovative heliostat mirror facet/array designs needed	X	X	X	
AM2	Insufficient facet/array fabrication process knowledge	X	X		X
AM3	Heliostats not designed for high-productivity manufacturing	X	X		X
AM4	Lack of heliostat developers' experience designing high-productivity manufacturing lines	X	X		X

Gap ID	Description	Impact			
		Cost	Energy	OM	Risk
Resources, Training, and Education					
R1	Heliostat technology resources are not accessible in a centralized-web based format	X	X	X	X
R2	Lack of heliostat research projects in universities				X
R3	Little public awareness of CSP/heliostat technologies				X
R4	Lack of resources and guidance for promoting DEI in CSP workforce				X
Field Deployment					
F1. F2. F3. F4	Heliostat fields have higher risk than other power investments				X
F5, F6	Heliostat field integration with industrial thermal processes lacks precedent				X
F7, F8	The site-specificity of O&M and field preparation/installation procedures limits the opportunity for incremental improvements that span multiple sites				X
Special Subtopic: Wind Load					
WL1	Insufficient wind measurement and characterization at heliostat field sites	X			X
WL2	Lack of understanding of the impact of atmospheric turbulence on dynamic loading and tracking error		X		
WL3	Lack of understanding on wind load on heliostats in array configurations	X			
WL4	Missing design standards for determining heliostat wind load coefficients and safety factors	X			

12.2 The HelioCon Roadmap: Anticipated Outcomes

HelioCon will use the gap analysis in this report to guide future work. HelioCon aims to address high-impact gaps by developing capabilities and infrastructures and make them available to the entire community, so that commercial risks of the heliostat-based project deployment can be reduced. At the end of the HelioCon performance period (September 2026), HelioCon plans to make progress toward the following capabilities and infrastructures:

- Develop all capabilities under: advanced manufacturing, metrology, components and control, and field deployments.
- Develop all modeling capabilities, which may include solar field O&M optimization model, solar field aiming control optimization model, solar field performance projection model, and others.

- Make a capable TEA model accessible to the public, which can allow effective evaluations of heliostat-related innovations under flexible scenarios (at varying system scale and applications).
- Create a centralized database that compiles all available knowledge base related to heliostat RD&D, training materials, and educational programs.
- Create a list of licensable models and tools developed and acquired under the consortium.
- Create a list of accessible services using the developed consortium capabilities.
- Create a projected roadmap for future heliostat development in the United States and in the world.
- Provide a full assessment of the success and lesson learned through the consortium.
- Provide a summary on remaining gaps the consortium has yet to address.
- Perform a feasibility study on whether the consortium may maintain operation with projected revenues from licensable tools, user services, and established fund-in partnership.

HelioCon also hopes to initiate international momentum to advance heliostat technologies. Only with an international collaborative effort, can CSP systems have the opportunity to realize their technical and commercial potential in the future 100% decarbonized energy sectors, including electricity, industrial process heat, and solar fuel production.

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Appendix A. Soiling Measurement, Modeling, and Mitigation Literature Review

In this appendix, a thorough literature review on main soiling topics is reported. The appendix is divided into three subsections that recall the state-of-the-art summary depicted in Table 26: measurements, modeling, and mitigation.

Measurements

Measurements in the area of CSP soiling are related to both the characterization of airborne and deposited dust (e.g., size distribution and composition) and the assessment of the reflection of the soiled surfaces. Following is a state-of-the-art analysis for both dust properties and reflectance measurements.

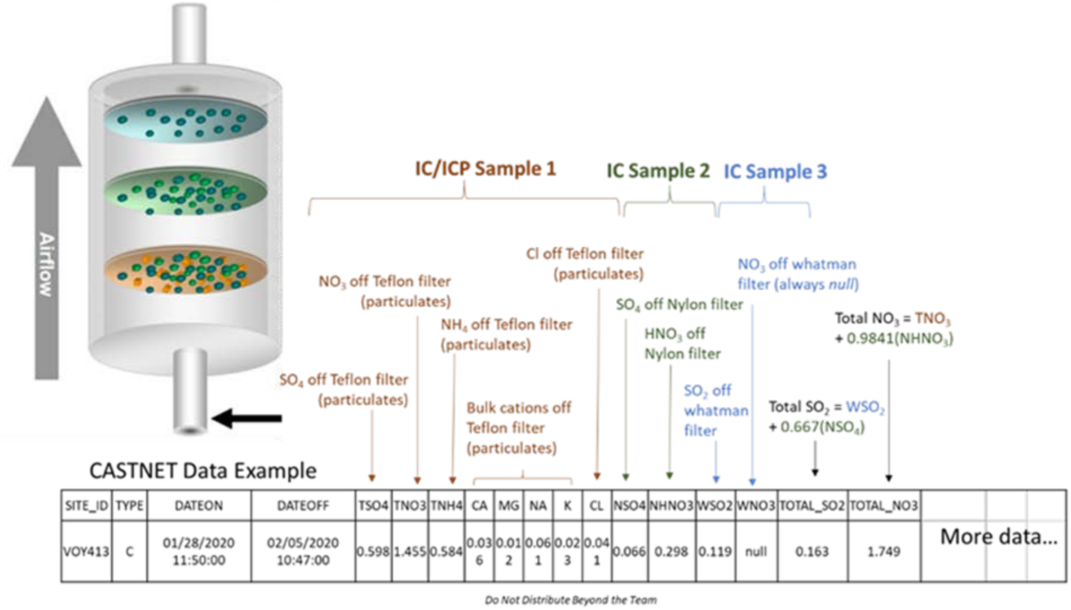
Measurement of Dust Properties

To both capture and fully characterize the particulate at a site, measurement techniques need to span the ranges and compositions of particulate under consideration. Various characteristics of the dust also necessitate characterization, including size distribution, deposition density, composition, as well as potential changes to these during weather events (e.g., humidity-induced deliquescence or wash-off).

Real-time particle sizing can be done using different methods (e.g., light scattering laser photometry). Laser aerosol particle spectrometers can size particles from 0.2 µm to 40 µm. In some cases, a dual measurement mode can be applied to sample particle sizes in the ambient condition (under deliquesced conditions) or after dry-out to measure particle sizes in the dried dust condition. It should be noted, however, that laser scattering spectrometers measure a “scattered light equivalent diameter,” which assumes a spherical particle with the same light scattering characteristics as the actual aerosol particles. Thus, this parameter is strongly affected by particle shape. Outdoor soiling microscopes have also been developed and applied for real time measurement (as short as two minute intervals) of particle deposition and resuspension for particles larger than 10 μm^2 [174], [175]. It has been found that the outdoor soiling rates from outdoor soiling microscopes can be correlated to the particle measurements, as well as other environmental factors such as wind speed, relative humidity, and dust storms [176].

Dust deposition densities can be quantified through a variety of methods. One common method is through mass accumulation (measurement of dust on a known substrate area) [177], [178]. This can be performed as direct measurements from the panel surface [176] or from weighting smaller test coupons [179]–[181]. Other methods, such as hand sampling or robotic sampling (through use of a remote crawler with a venturi sampler) of dust from known surface areas can be applied to measure relative dust loads [182].

Retention of samples for chemical analysis to differentiate salt or brine aerosols from detrital silicate mineral grains can also be desirable [182]. Cascade impactors can discriminate between different particle sizes and collect the particles for later analysis, allowing assignment of particle mineralogy/composition as a function of particle size. Some limitations include particle size measurements (<10 µm) and the necessity to operate in non-condensing conditions, <90 %RH. Additional tools for chemical analysis include chloride candles (ASTM G140-02) [183], which are a widely used method to determine the chloride deposition rates onto a wet wick. While quantitative deposition rates can be determined to compare across sites with seasonal variations, they are dependent on the geometry of the candle, and thus cannot be compared directly across various methods. Another option for potential dust composition characterization is the Clean Air Status and Trends Network (CASTNET), a long-term atmospheric monitoring program that is managed and operated by the U.S. Environmental Protection Agency in cooperation with the National Parks Service, Bureau of Land Management, and many local partners [https://www.epa.gov/castnet]. CASTNET comprises ~100 sites across the United States that use filter packs to measure the ambient concentrations of total suspended particle bulk compositions (no size discrimination) and acid gas concentrations via analysis of the filter pack collection system. The sample analytes for the CASTNET system are commonly the bulk cations (Ca^{2+}, Na^+, Mg^{2+}, K^+, NH_4^+), bulk anions (Cl^-, NO_3^-, SO_4^{2-}), acid gases ($HNO_{3(g)}$, $H_2SO_{4(g)}$, $SO_{2(g)}$), and ozone. Example output is shown in Figure A-1. For sampling, the filter packs, which are situated on a 10-meter-high tower with a rain shield, are collected and changed weekly.



SITE_ID	TYPE	DATEON	DATEOFF	TSO4	TNO3	TNH4	CA	MG	NA	K	CL	NSO4	NHNO3	WSO2	WNO3	TOTAL_SO2	TOTAL_NO3	
VOY413	C	01/28/2020 11:50:00	02/05/2020 10:47:00	0.598	1.455	0.584	0.036	0.012	0.061	0.023	0.041	0.066	0.298	0.119	null	0.163	1.749	More data…

Figure A-1. CASTNET output shown with sample analyses

Figure from [184], [185]

Measurement of Soiling Losses

Measurements characterizing soiling losses for CSP reflectors can be captured by measuring the reflectance in-situ or in a laboratory setting. Methods have been proposed that use handheld reflectometers on a sample set of mirrors, or automatically measure mirror samples placed within the field environment. Additionally, automatic methods using image-processing on high resolution photographs have been investigated and tested on small scales.

SolarPACES published a list of available reflectometers and measurement devices under a Task III deliverable "Portable reflectometers to measure soiled reflectors in solar fields"; see Table A-1, summarizing the instruments, measurements, and optical properties [53].

Table A-1. Summary of Commercial Reflectometers

Adapted from [53]

Manufacturer	Surface Optics	Devices & Services Co.		Aragon Photonics	Konica Minolta	CSP Services GmbH	PSE AG
Developer	Surface Optics	Devices & Services Co		Abengoa & University of Zaragoza	Konica Minolta	DLR	Fraunhofer ISE
Model	410 Solar	15R-USB	15R-RGB	Condor	CM-700d/600d	TraCS	pFlex 2.1
Measurement principle	Integrating sphere unit where the specular port can be opened	A source lamp and a detector positioned in incidence and outgoing angles, lenses to focus the reflected beam onto an aperture stop, which defines the acceptance angle		6 different beam sources and 6 detectors	Integrating sphere unit where the specular port can be opened	One pyrheliometer for measuring DNI and another measuring the DNI reflected at a mirror sample	3 light sources with different wavelength and 1 detector
Measurement type	Hemispherical and diffuse reflectance (specular calculated)	Monochromatic specular reflectance at selected acceptance angles. RGB model provides above at selected of 5 wavelengths		Monochromatic specular reflectance and solar-weighted specular reflectance (from the six wavelengths)	Hemispherical and diffuse reflectance and color	Specular reflectance	Monochromatic specular reflectance and cleanliness factor
Light source	Tungsten	LED		LED	Xenon	Sun	LED
Incidence angle (deg)	20	15		12	8	15	8
Beam spot size (diameter, mm)	6.35	10.00		Six spots with variable diameter (depending on mirror thickness and curvature) are aligned and cover a 230mm^2 area in the mirror	3 (700d model) 8 (700d and 600d models)	16.00 measurement area is 40 cm^2 with rotating mirror	10
Wavelength range (nm)	7 bands between 300 and 2500	Peak at 660	Band red, green, blue, white and IR filters: 460 (±50) 550 (±50)	435, 525, 650, 780, 940 and 1050, solar-weighted according to ISO 9050	400-700 (10 nm steps)	Integrated full solar spectrum	470 (±25) 525 (±25) 625 (±25)

Manufacturer	Surface Optics	Devices & Services Co.		Aragon Photonics	Konica Minolta	CSP Services GmbH	PSE AG
			650 (-40, +150) 720 (-40, +100)				
(Half) acceptance angle (mrad)	52.4	3.5 7.5 12.5 23.0	2.3 3.5 7.5 12.5 23.0	145.0	*	13.6	67

Several reflectometers have variable or ranges of applied wavelengths. Incidence angle is fixed, and only the Device&Services instrument provides variable acceptance angles. The variable acceptance angles are crucially important to accurately describing a specularity profile [186].

Few automatic characterization methods have been investigated and tested. They can be separated into two approaches:

1. Direct measurement of the soiled mirror
    - QFly, photography, and other drone-based methods [187], [188]
    - Calibration cameras [189]
2. Measurement of a mirror sample placed in the solar field environment
    - TraCS [168] and AVUS [190]

TraCS and AVUS have both been experimentally validated automatic methods for monitoring soiled samples in the field. They each use a reflector sample placed within the field environment, assumed to soil at the same rate as the operational reflectors. The TraCS system DLR utilizes a pyrheliometer and derives a cleanliness metric from the received DNI reflected off a reflector sample.

The AVUS system utilizes a moving arm to periodically assess the reflectance of the exposed sample mirror and compare it to the one kept clean inside the device. Measurements are taken automatically, moving the sample to an optical port, and reflecting an incident beam onto an Si-based sensor. Both instruments are shown in Figure A-2.

Automatic methods for directly measuring field reflectors have used photography and image processing approaches. One proposed method uses QFly and a novel image processing algorithm [187], which was experimentally validated on a trough plant. Another aerial method uses a similar pixel-gradient analysis technique to correlate grey-scale pixel values with mirror soiling, with the added capability of identifying corrosion [188]. Both methods cite the potential of radiometric imaging in future work, as well as increasing method accuracy. At the time of writing, QFly reported a root-mean-square deviation of 2.9%, stating this value was far higher than uncertainties associated with handheld reflectometers.

(A) TraCS (TraCS4 variant shown) (B) AVUS

Figure A-2. TraCS automatic soiling monitoring system using measured DNI via reflected sample (A) [168] and AVUS automatic monitoring system using a rotating arm to assess the mirror sample reflectance (B) [190]

Estimating a field-wide reflectance loss due to soiling has been proposed in few studies [191] [192] [193]. There are very few automatic collection systems, with only TraCS being commercially adopted. As a result, much of the proposed work describes sampling methods using the portable reflectometers listed above combined with manual measurements and varies from study to study. No standard method for representative solar field sampling has been adopted.

In addition to measurements taken in the solar field environment, portable reflectometers can be used in a laboratory setting in soiling and accelerated aging tests [194]. The laboratory has the added benefit of high-resolution, bench-mounted reflectometers and spectrophotometers such as the PerkinElmer Lamda 1050 and Surface Optics HDR-100. The concern in laboratory soiling measurements is the disturbance to samples during shipping or the accuracy of soiling induced artificially.

Findings in dust size and composition indicated larger particles (>500 um) do not readily adhere to glass surfaces and may be irrelevant for modeling and simulation [195]. Data were collected via a 2-meter pole collector and analyzed in a lab via microscope.

Modeling and Characterizing Soiling Processes

A number of studies have modeled the soiling of solar collectors' surfaces [174], [196]–[198]. Most of these studies are related to PV, and only few dealt with CSP technologies (despite the fact that the impact of soiling is more severe for CSP [199]). A common approach in soiling studies is to exploit regression analysis/machine learning to establish correlations between reflectance losses and environmental parameters like airborne dust concentration, air temperature, wind speed, and relative humidity [173], [176], [197], [200]–[207]. These studies, although accurately identifying the dependance of reflectance losses to the parameters considered in the correlations, are likely very difficult to generalize to gain insight into soiling rates at different sites.

Other models in both PV and CSP have sought to exploit simplified physical models to explain and predict soiling losses. In these studies, a model for each of the soiling processes (see Figure A-3 and Figure A-4) is typically developed [161], [163]. The available models for each subprocess will be briefly reviewed below.

Deposition

The deposition mechanisms are mainly derived from atmospheric studies that assess how airborne particles deposit on surfaces. The same approach can be applied to both PV panels and heliostats, so the available literature is plentiful. Deposition includes both dry deposition and wet deposition, the latter referring to material scavenging happening due to wet precipitation processes [165]. The removal rate of particles from the atmosphere due to precipitation is commonly modeled as a decay model where a scavenge coefficient is computed to approximate the pollutant transfer rate into raindrops [208]. Regarding dry deposition, fundamental models for gravitational settling and the combined action of inertial impaction and diffusion are used to estimate a deposition velocity [165], [174], [196], [209]–[212], as depicted in Figure A-3. The relative importance of each of these mechanisms depends strongly on their size (quantified by their aerodynamic diameter): larger particles are greatly influenced by gravitational pull and inertial effects, while diffusion is more relevant for smaller ones. The deposition velocity v_d for a flat surface is commonly modeled as:

$$v_d = v_s + \frac{1}{r_a + r_b}, \tag{1}$$

where v_s is the settling velocity due to gravity, and the term $\frac{1}{r_a + r_b}$ accounts for inertial and diffusion effects.

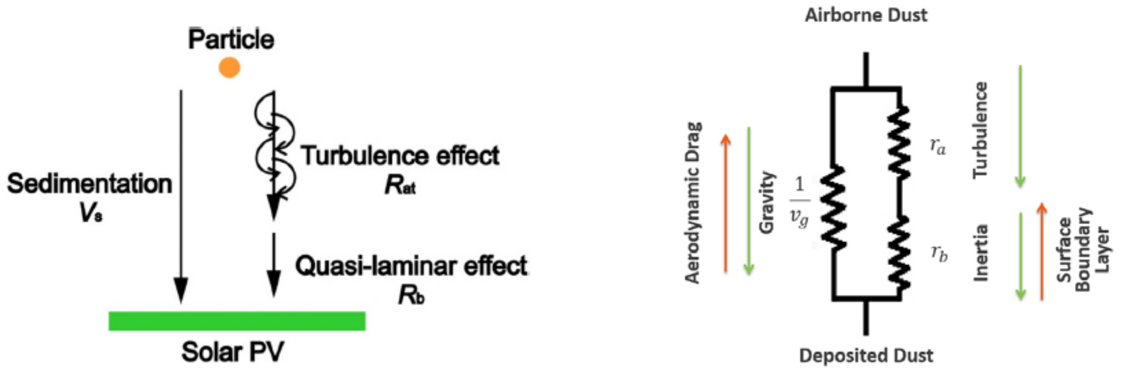


Figure A-3. Deposition velocity models for a study in PV (left) and a study in CSP (right)

Figure from [196] (left) and [209] (right)

The total deposition flux is computed as:

$$F_d = C_d \cdot v_d \tag{2}$$

where C_d is the concentration of dust. To account for the tilting of heliostats deployed around the field, Eq. (2) has to be multiplied by the cosine of the heliostat tilt angle α_{tilt}. In some studies, only the settling velocity v_s is multiplied by such quantity, acknowledging the omnidirectionality of the other terms. Note that the dust flux is size dependent due to both the different concentrations and the dependence of deposition velocity on size. By integrating this deposition flux in time, the amount of dust (at each diameter) that falls on the surface of the heliostat may be calculated [209].

Adhesion and Removal

After deposition, the balance between forces of adhesion (e.g., van der Waals forces, gravity, capillary force) and removal (e.g., gravity, wind, rain) determine whether a particle remains on the reflective surface [161], [163], [213]–[217]. This balance is of much greater relevance for tracking heliostats than for the typically studied fixed collector PV systems. For tracking collectors, the tilt and azimuth angle (and therefore removal forces) are a function of the time of day, time of year, and position of the collector in the field, even for constant environmental conditions. Furthermore, the impact of potential removal factors like wind or dew are significantly influenced by the position of the heliostats, and may have significantly different impact depending on the location of the heliostats within the field (e.g., shielding effect of external rows with respect to wind).

Figure A-4a shows some of the main competing adhesion and removal forces acting on a spherical smooth particle on a flat surface. Van der Waals interaction is always present when a particle adheres on a surface. Few expressions of the corresponding adhesion force exist, although among the most commonly adopted is the so-called JKR model from [218]:

$$F_{vdW} = \frac{3}{4}\pi W_A D_p \tag{3}$$

where W_A is the work of adhesion and D_p is the particle diameter. Different expressions exist also for rough particles, where the right end side of Eq. (3) is further multiplied by the number of contact bumps N_c and the bump radius β [213]. Electrostatic forces may also arise when dust particles gain charge. Although many solutions exist for different geometries and approaches, a commonly accepted simplified equation is the following [219]:

$$F_{el} = \frac{1}{4\pi\epsilon_0}\frac{Q_1}{(2s)^2}\left[\frac{Q_1(1-k_2)}{(1+k_2)}\right] \tag{4}$$

where Q_1 is the net charge of the particle, ϵ_0 is the permittivity of vacuum, k_2 is the dielectric constant of the surface, and s is the distance between particles and surface. At high relative humidity values, water vapor condenses and can form water bridges between particles and surfaces. This strongly enhances adhesion through the capillary force [220], which is usually expressed as the sum of two terms: the capillary pressure force and the surface tension force. In most practical cases, the overall capillary force can be approximated by the following [161], [221]:

$$F_c = 4\pi\gamma R cos(\theta) \tag{5}$$

where γ is the surface tension of the liquid, R is the particle radius and θ is the contact angle. Although still object of debate, dew plays a relevant role in both the enhancement and the mitigation of heliostats soiling [222]. While it can cause runoff of particles, it is also likely to promote caking and cementation, which causes strong adhesion between particles and surfaces [175], [223]. Removal mechanisms include rolling, sliding, and lift off due to wind [161], [213], [216], [224]. For tilted surfaces, gravity also acts as a removal force on particles [209]. Wet removal phenomena are left for further discussion in the mitigation section. Regarding removal due to wind effects, the related mechanisms result in particle detachment when:

- The removal moment due to wind is larger than the resistant moment due to adhesion forces
- The removal force acting parallel to the surface due to wind is larger than the friction force due to the adhesion forces
- The lift off force due to wind is larger than the adhesion forces in the vertical direction.

Figure A-4b depicts a comparison among adhesion and removal mechanisms as a function of particle size, which was studied by Ilse et al. [163] using adhesion mechanisms found throughout literature. Ibrahim et al. [224] performed some experiments on microspheres detachment from surfaces, identifying a threshold wind velocity depending on particles diameter and surface material, with a clear decreasing trend from ∼10 μm to ∼100 μm. Ahmadi et al. [220] identified rolling as the most effective removal mechanisms, and capillary and the most adhesion-enhancing process.

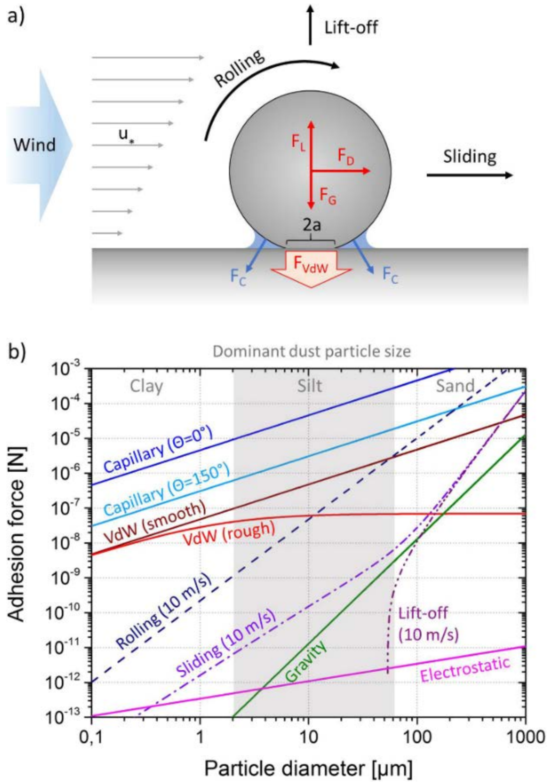


Figure A-4. Adhesion and removal mechanisms

Figure from [163]

It should be noted that these removal mechanisms can be affected by the tilt angle α_{tilt} and orientation of the surface relative to the wind direction [209], [211]. Due to their continuous movement throughout the day, this implies that the evaluation of removal mechanisms must consider the history of tilt and orientation angles when evaluating the relevant removal mechanisms.

Reflectance Loss Models

The deposition and the adhesion and removal models will provide a distribution of particles on the surface of the heliostat that hinder the reflection of incoming solar irradiation toward the receiver. Given a distribution of particles on the surface of a heliostat, reflectance loss model estimates the power lost. The nature of this model is very different for PV and CSP, owing to the fact that CSP can only make use of specular reflection at relatively small acceptance angle [163].

Following the approach of [209], [225], the reflectance loss due to a deposited particle is assessed through the shade it casts on the reflective surface (shading area, A_s), and that portion of the reflective area where sun rays would intercept the particles after reflection (blocking area, A_b). This approach inherently implies that any beam that is not specularly reflected constitutes a loss, due to the exploitation of direct irradiation only (diffuse radiation is not useful, in contrast with PV), and the requirements of small acceptance angles in large solar tower plants [199]: any deviation from the defined path would result in the reflected radiation missing the target. The sum of shading area and blocking area determines the non-reflective area A_{nr} and hence the magnitude of reflectance loss. Those areas strongly depend on the incidence angle, meaning they vary significantly throughout the day and around the solar field at a given time. Finally, the reflectance loss can be computed as the ratio between A_{nr} and the overall area of the heliostat. The reflectance loss can also be computed as in [226], where the deposited dust particles are expected to cause similar blocking and shading area effects, but are modeled as a turbid medium. The resulting reflectance then depends on both the incidence angle and an empirical soiling attenuation parameter, which accounts for the dust virtual layer thickness and its properties.

Satellite Reanalysis

Recently, some studies have attempted to establish soiling-induced efficiency reduction for PV panels deployed in different areas using satellite reanalysis databases (e.g., MERRA-2) [167]. These databases exploit techniques that allow estimation of the dust load from aerosol optical depth measurements and subsequently estimates of both the surface dust concentration and the yearly dust deposition on the ground (or on a flat solar collectors' surface). This total deposition is used as an input to some established loss models for PV [162], [174], [227]. A study by Micheli et al. [228] exploited the measurements obtained from MERRA and the deposition model developed in [212] to assess PV soiling losses in a few location within the United States, and attempted to create a "soiling-induced performance loss" map for such locations. However, these studies do not assess the size distribution and the composition of particles, which are likely more relevant for CSP than PV technologies since specular reflectance (strictly required for CSP) is more sensitive to particles' size then diffuse reflectance (exploited by PV). Indeed, models derived for PV panels may not be directly applicable to CSP, and more specifically to heliostats. Also, yearly average soiling rate are not able to provide information regarding soiling variance and seasonality, which may have a strong impact on mitigation measures (e.g., cleaning resources) [229]. Furthermore, the soiling rates provided by the reanalysis are computed for flat surfaces and would need to be adapted to account for heliostat tracking systems that vary tilt and orientation angles continuously during the day.

Mitigation

The most relevant technique adopted to diminish the detrimental effect of soiling is washing the heliostats. The costs related to cleaning activities may be significant and need to balance the otherwise incurred production losses due to soiling. A few cleaning methods are currently deployed to wash heliostats [169], [230], whose characteristics and costs may affect the optimal cleaning strategies. Despite interest in automation, most currently deployed CSP tower plants use staffed washing trucks that traverse the solar field and manually wash the heliostats using a solution of demineralized water and detergent. These trucks generally spray water at a high pressure and may include brushes that further clean the mirror. Trucks with low-pressure sprayers that provide a "deluge" wash are also commonly deployed; these trucks use more water and are less effective at cleaning the mirror facets but travel through the field and wash heliostats more quickly than the other options. Plants with smaller heliostats may deploy crews that travel by foot and wash the facets using a squeegee. While alternative cleaning methods to manual or vehicle-based washing exists, such as the automated systems discussed in [162], these systems can be expensive to build and maintain, and so their deployment in plants is limited to locations with very high soiling. The authors are aware of several anecdotal remarks from solar field operators that automated washing trucks have been attempted, but fell into disuse either because of mechanical failures, maintenance complexity, or a mismatch between operation complexity and operator capabilities. Mirror breakage has also been caused by these systems. It is clear from operator interviews that washing process details need to vary from site to site due to varying soil conditions. Despite these challenges, interest in automated washing systems persists, as documented in these two videos [117], [231]: SUPCON washing system, Heliogen Icarus.

Several studies in the literature developed optimized cleaning strategies that minimize revenue losses plus washing costs for PV systems, parabolic troughs, and heliostats [171], [172], [204], [229], [232]–[235]. The heliostat cleaning literature is composed of studies that obtain either (1) long-term decisions, such as cleaning timing, frequencies or thresholds [171], [204], [232], [233], or staffing levels [172], [229], or (2) short-term decisions, such as route selection of the solar field sections to prioritize over the next few days [234]. The preferred model may depend on the fidelity of soiling data available on-site and the number and types of wash trucks that are available either for purchase or already at the plant. The objective of the optimization may also play a pivotal role in the choice of the preferred model, since in some cases focus may be given to collected energy, heat generation, electricity generation, or total revenues. Studies on PV systems included soiling and cleaning optimization in LCOE and net present value computations, including these for assessment of the most suitable technology [236]. LCOE and similar indicators have also been used to evaluate soiling effects on CSP plant simulations [237]. To provide investors with the required tools to reduce the risk through reliable evaluations of the impact of soiling and cleaning costs, their impact on the LCOE (or, in the case of an IPH application of CSP, LCOH) should be carefully assessed.

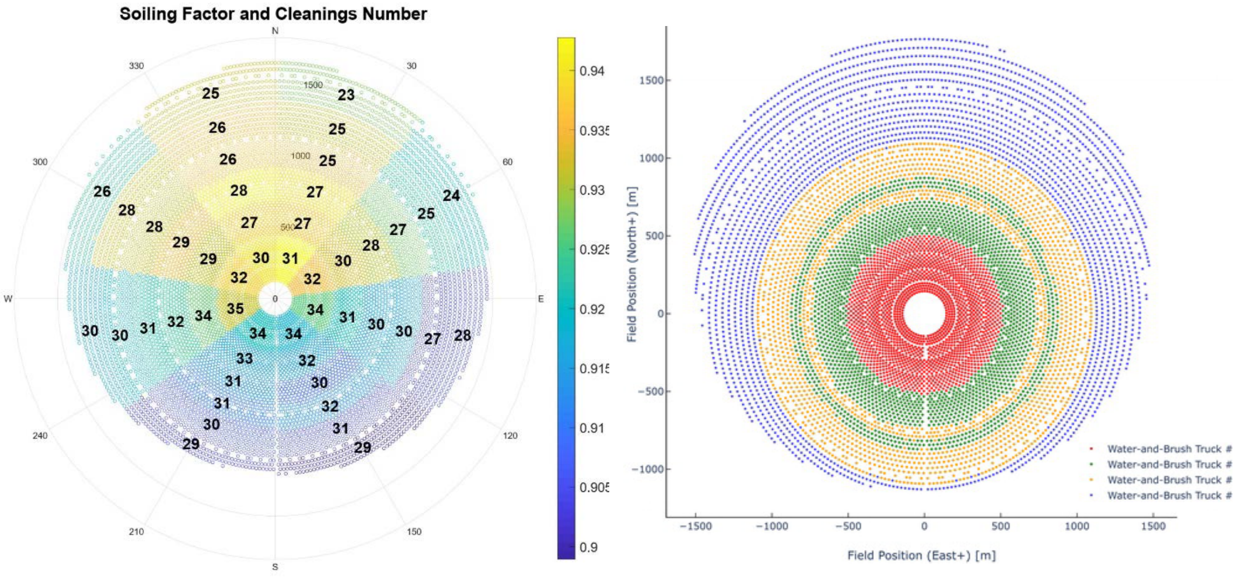


Figure A-5. Two examples of cleaning policies from the literature: one in which the timings of the sectorial cleanings are varied explicitly using identical trucks (left), and one where they are varied implicitly through the selection of different technologies (right)

Figures from [171] (left) and [172] (right)

Anti-soiling coatings offer a path to both recovering lost revenue and reducing O&M costs. Over the last decade there has been numerous research efforts across academia and industry to develop anti-soiling coatings for both CSP mirrors and PV glass surfaces [238]. While there are various chemistries, microstructures, and approaches such as hydrophobic, hydrophilic, and photocatalytic, all these options face the challenge of proving long-term outdoor durability as well as long-term functionality. While there are publications that claim durability as well as both indoor and outdoor testing that demonstrate anti-soiling benefits, these results must be taken in careful context [239], [240], [241], [242], [243], [244], [245]. Although a coating may exhibit durability and efficacy in one set of conditions, it can very easily fail in another set of conditions. There are currently no state-of-the-art standards for the PV or CSP industry to distinguish if a given coating has the durability or functionality for a given site. NREL initiated a 5-year outdoor study that included four manufacturers, nine coatings, three cleaning methods, and five test locations to help understand both of these issues [246], [247]. Accelerated indoor durability testing in conjunction with this effort led to the recent publication of IEC 62788-7-3 [248]. This standard provides repeatable tests that can be used to evaluate coating durability, but it does not provide the means or pass-fail criteria to align testing to a particular geographic site. Further work is necessary to provide the CSP industry with the tools necessary to readily evaluate site-specific performance gains for a given anti-soiling coating as well as to understand how long the coating will provide said gains given site cleaning processes and local environmental conditions.

Appendix B. Components and Controls: Literature Review

Overview of Actuation Styles

- Azimuth-elevation
    - This is the most common setup in grid-scale CSP plants. This axis arrangement results in a T-shaped heliostat. The primary axis of rotation is azimuthal (about a vertical axis). The secondary axis of rotation is elevation (about a horizontal axis) using a torque tube. This section will typically refer to heliostat components (e.g., pedestals, azimuth drives) in context of an azimuth-elevation heliostat.
    - Some azimuth-elevation heliostats are able to eschew a traditional azimuth drive for a large carousel at their base.
- Horizontal-first (elevation-azimuth)
    - This setup uses a primary elevation and secondary azimuthal axis. The German Aerospace Center's experimental heliostat uses rim drives to accomplish this style of actuation.
- Target-aligned
    - One axis of rotation forms a line from the heliostat to the receiver. The secondary axis runs perpendicular to this one. Heliosystems' PATH heliostat uses this control scheme.
- Swiveled
    - The mirror surface is fixed by a U-joint at one point and actuated at two others. This eliminates primary and secondary rotational axes in favor of combined translation/rotation of the mirror surface plane.

Drives

Téllez et al. described two common drive types for heliostats: traditional rotary electromagnetic motors and hydraulic actuators [26]. These drives can be used with several different mechanical transmissions for transferring mechanical energy from the drive to azimuth or elevation axes. These transmissions include worm, spur, chain gears, harmonic, capstan, planocentric drives, rack and pinion systems, spindles, and friction wheels. For azimuth drives, expensive, high precision gears with minimum backlash are required.

While traditional drives are incredibly well built for the purpose, the cost is prohibitive, and some studies show that integration into the heliostat could be improved. Typically, a heliostat with standard elevation and azimuth control has one linear slope drive for elevation and one slew drive for azimuth. Specifically, azimuth drives responsible for rotating the pedestal about the foundation represent a significant heliostat technology gap. Azimuth drives manufactured by Winsmith have been a previous standard in heliostat design [8]. These drives generally use five gears, one central gear for rotating the pedestal surrounded by three idler gears and one motor driven gear. The combined five gears are able achieve a gear reduction for control. However, Winsmith azimuth drives are very expensive. A cost reduction report by Gregory Kolb et al. states that for both large and small heliostats, drives are the most expensive component [10]. Drives make up approximately 27% of the cost for large heliostats and 30% of the cost for small heliostats. This report also confirms that azimuth drives are typically the most expensive drive type. As stated in the report, conservative or completely alternate designs to the Winsmith drive are needed. Conservative redesigns of the Winsmith azimuth drive may be a solution, as even according to Winsmith current drives are likely over-built, especially on heliostats located in the inner field [27].

A significant problem with the traditional Azimuth drive design is the location of the drive at the pedestal base. Emes et al. discussed the pedestal and hinge bending moments that occur in unsteady pressure distributions of a turbulent atmosphere [28]. In their study, simulations confirmed that turbulence and changing pressure distributions can impose significant moments on the pedestal. Turbulence increases in fields containing a large number of heliostats, making pedestal mounted drives even less optimal for heliostats at certain positions within a field. The required pedestal height for optimal performance also increases farther back from a tower as some optimization studies have found, which would cause an increased moment on the pedestal base. As such, excessive loading to pedestal mounted drives can pose a risk for wear and damage.

Another significant challenge with azimuth drives is complexity. This has pushed many researchers to study alternatives to the standard azimuth drive. A heliostat cost optimization study by Finn von Reeken et al. assessed slew and slope drives for azimuth control [29] and stated that linear slope drives which use lever arms for azimuth control can provide lower tracking error than traditional azimuth slew drives. Linear slope drives were also stated to be cheaper. As a result, it was found that linear slope drives consistently resulted in a lower LCOE. Free axis arrangements of the slope drive were stated to have additional requirements, however. T-shaped heliostats could have the issue of the corners touching the ground with a linear slope drive, though can be avoided by increasing pedestal height. In a review by Pfahl et al. it was also noted that pedestal mounted heliostat drives may be more expensive than linear drive systems [30]. Alternate drive systems such as rim drives with cables may also be cheaper than the pedestal mounted systems

A cost reduction study by Kolb et al. evaluated cost reduction techniques for heliostats [10] where several drive mechanisms were discussed. The study did state that with current understanding of wind loads and torques on heliostat drives, a lower cost drive could easily be used to replace the azimuth drive. The study also mentioned that a lack of production-line manufacturing techniques makes the azimuth drive more expensive than it needs to be. One concept for cost reduction of drives was to use a pipe in pipe azimuth drive, where a pipe rotates within the fixed pedestal to achieve azimuth rotation. This concept has been used at the White Cliffs plant and is useful for smaller dishes of approximately 7 m^2. A driving motor at the base of the pedestal rotates the pipe within the pedestal where wind loads are distributed along the length of the pipes rather than on the drive. A 33% cost reduction from conventional azimuth drives was determined feasible with this drive method.

Hydraulic azimuth and elevation drives were discussed for use with relatively large (>60 m^2) heliostats. While large heliostats can be expensive to manufacture and have optical penalties due to worse optical quality, a net cost reduction could still be achieved. Hydraulic drives require more maintenance and are complex but for a large heliostat could offer net cost reduction of \$18/m^2. An analysis of spb's commercially available Stellio heliostat by Kurup et al. found that hydraulic drives were ultimately responsible for \$16.08/m^2 of the heliostat's ultimate cost—11.63% [17].

Finally, a water ballasted heliostat motion system was discussed, which would eliminate the need for drives entirely. In this system, water would be pumped between chambers on the back of the facets to change the balance of the heliostat and track the sun. This system would entirely eliminate the need for any gear drives and could bring significant savings.

Pfahl et al. has studied heliostat cost reduction methods with rim drives [13], [105], [249]. In a conceptual two rim design, the first rim intersects the pedestal and mounts to a vertical or horizontal support beam. This drive provides changes to the elevation angle. The second rim rests on the first rim and is fixed to the mirror facets to change the azimuth. The drives are designed to be used with winch wheels. In this design, the loads on the drives would be significantly reduced and the long lever arm would allow for the use of low-cost drives. There would be a reduced load on the bearings, mirror panel, and upper pedestal during stow. The energy consumption of the drives would be low as well. However, the drawbacks include increasing the height of the pedestal, which increases the wind load on the base of the pedestal, higher mounting and installation effort requirements, and potentially low stiffness against wind loads in certain mirror panel orientations.

Cable actuation systems are another low-cost alternative to current heliostat drives. One such example is a Google heliostat, which used cable pulley drive systems for elevation and azimuth control [31]. This cable actuation system would require cables to be in constant tension. Google created this condition by mounting the facet panel at the top of a tripod frame. A single U-joint served as the connection between the panel and the tripod frame, acting as a dual hinge which allowed the panel to vary both azimuth and elevation angles. The hinge system was not mounted perfectly centered on the facet panel. Instead, the panel was mounted such that its center of gravity of is farther forward than the center of the frame, causing the panel to lean forward. A dual pulley system is then mounted behind the panel with two cables running to the top left and right corners of the panel. The cables pull back on the panel so that it no longer leans forward, keeping the cables perpetually in tension. This system uses an electric pulley winch system to reel in the cables and change the angles of the panel. Pulling both the left and right pulleys at the same time will change the elevation angle. Pulling one cable disproportionately to the other will cause a change in the azimuth angle. In this system, low-cost, low-power motors can be used such as the Google worm drive with anti-backdrive design characteristics that will limit the holding torque requirements of the motor. The use of a cable pulley system such as this would drastically reduce the drive system and motor costs of a heliostat. However, it was noted by Google that their motor pulley system, especially with the low power motor, would not be able to quickly move the heliostat into stow position for protection from unexpected high winds or threats to the heliostat.

Mirrors/Facets

Many parts of mirror and facet design can be improved, ranging from material construction to reliability over a range of environmental conditions. Heliostat mirrors and supports are heavy, adding significant weight to the pedestal and supports and contributing to heliostat cost. The mirror face of a heliostat acts as a sail in the wind, resulting in the significant wind loads on the pedestal and hinge. Both the gaps between mirrors and the overall aspect ratio of the mirror face play key roles in the wind loading.

Reducing the load on heliostat components from high wind could significantly reduce overall heliostat cost by reducing structural design requirements. Multiple studies have already been conducted in literature on reduction of wind load through mirror face modification. Wu et al. studied the effect an increasing gap between heliostat facets has on the wind load [32]. This study was conducted both experimentally and numerically. The experimental heliostat was a polymethyl methacrylate 1:10 scale heliostat placed in a wind tunnel. The heliostat facets had variable gap sizes of 0-40 mm. The experimental study found that increasing the gap size did not significantly change the mean wind load coefficient. The numerical study found that increasing the gap size increases the wind load, but only slightly. The gap size does not have a significant enough effect on wind load to be considered in heliostat design for reducing structural requirements. However, this study also found pressure coefficients, lift coefficients, drag coefficients, and moment coefficients on a heliostat at different incidence angles of wind, data which is very useful in heliostat design.

Pfahl et al. studied the wind loads on heliostats and compared the moments resulting from the wind load at various aspect ratios of the facet panel [33]. It was determined that for reliability of the foundation and pedestal, a higher aspect ratio is favorable. The moment on the base of the pedestal is significantly reduced when the aspect ratio is higher. The elevation drive, which is exposed to a high moment at the hinge of the heliostat, also benefits from a higher aspect ratio as this moment is reduced. However, a high aspect ratio of the panel is not advantageous for azimuth drives.

Engineering for both cost reduction and optimized reflectivity represents another significant gap in mirror design that has been researched in literature. A survey study by Pfahl in 2014 considered cost reduction methods for heliostats including using aluminum mirrors [34]. Aluminum mirrors would be light weight with good rigidity and handling, low breakage, and would be suitable for monocoque constructions. However, they would have reduced reflectivity and extra costs for protective coatings against abrasives. This paper referenced a study by Almanza et al., which looked at aluminum surface solar mirrors over a 12-year duration in Mexico City. The mirrors were exposed to aggressive weather and abrasive particles in the atmosphere yet only had a reflectance decrease of 3%. Two types of aluminum solar mirrors have been studied primarily, mirrors with integrated first and second surfaces and first surface compound mirrors. Aluminum first surface mirrors are considered an excellent candidate for heliostats.

A cost reduction study conducted in 2006 by Kolb et al. evaluated cost reduction techniques for heliostats [14]. Two cost reduction methods for heliostat facets were proposed. The first cost reduction method considered the use of a large stretched-membrane facet. This facet would be developed for integration into a pedestal type heliostat with a surface area of up to 150 square meters. However, the analysis found that the stretched membrane type heliostat may not decrease heliostat cost or increase LCOE, so the concept was removed from consideration. Another stretched membrane facet was considered that would replace welded stainless steel strips of traditional heliostats with a single large fabric. The method would remove the need for expensive stainless steel strips and expensive welding techniques as the fabric would be mounted using press-fit concentric hoops. The fabric would be impregnated with a sealer to avoid air leaks into the facet plenum environment. However, rough calculations in the study suggested that heliostat cost per square meter could be reduced by $7 with this method alone.

Additionally, Bhargav et al. considered heliostat faces of size 8, 32, 64, 96, 120, and 148 square meters for cost analysis [35]. The study considered the component costs for pedestal and truss structures, drives, mirror modules, drive control systems, field electronics, and design overhead for each size. Overall, 8 m^2 heliostats were the most expensive. Prices decreased at 32 m^2 and bottomed out at 64 m^2. From that size on, the price increased again. However, even at the considerably large size of 148 m^2, the cost never exceeded that of the 8 m^2 heliostat. The 8 m^2 was more costly in almost every category except for the pedestal and truss system, which predictably increased in cost for increasing size, and the mirror module cost which was the same for all sizes. The most expensive component for the 8 m^2 size was the drive.

The Google prototype heliostat explored the use of a custom reflector made entirely of glass to keep manufacturing costs down and to keep the system lightweight [36]. The system used a matrix of rectangular optical quality glass mirror sheets, mounted on a glass honeycomb back board. The honeycomb was constructed from segments of glass bonded to glass backboard on the back and the optical quality glass mirror on the front. The glass sheets were annealed glass instead of tempered glass, which kept costs low but reduced strength. The system was cheap and light weight and eliminated thermal expansion issues, all factors which translated to a cheaper frame and truss support system. The reflector was slightly curved to increase concentration ratio. The system was designed to be lifted with vacuum lifters. A hail gun was used to fire an ice ball at the reflector to simulate 25 mm hail in accordance with IEC 61215A, which the reflector survived. However, the mirror was only tested via FEA in standard load conditions. High wind scenarios were not tested on this entirely glass reflector.

Torque Tubes

Torque tubes are an important component of T-type heliostats but do not vary significantly between heliostat designs. Traditional torque tubes in heliostat designs are constructed out of steel round tube or pipe. For a T-type heliostat design, a torque tube acts as a central horizontal rotational axis and is a key part of the facet support structure. The single axis can be used for rotation to vary elevation angles and mounting of welded truss systems for support of mirrors. Torque tubes also effect heliostat stow position. Mammar et al. conducted computational fluid dynamics and wind tunnel studies on heliostats to evaluate the effect of wind speed on torque tube heliostats [37]. It was found that the torque tube design has a significant effect on the choice of stow position that will result in minimized moments. With respect to most torque tubes, the optimum stow position cannot be perfectly horizontal at high wind speed. The inclusion of a torque tube was also shown to reduce the vertical force component in wind. Their results showed that vertical forces were reduced at all elevation angles between 0-90° with the use of a torque tube and computational fluid dynamics validation experiments. Torque tubes are large and heavy, which may unnecessarily contribute to the $/lb. of a heliostat and the mass loads on the pedestal. The mass and volume of materials used could be optimized while still maintaining adequate strength to prevent bending under high loads.

Some torque tube optimizations have been performed in literature. In particular, Samir Benammar and Kong Fah Tee modeled heliostat components and analyzed the structural reliability at high wind speed. The torque tube was modeled considering gravity and wind as the main loads which could cause deformation. The torque tube was modeled with the center of the tube jointed at the top of the pedestal, eliminating deformation at the center of the tube and maximizing points of bending deformation as the end points of the tube. The maximum wind load was applied to the center based on the accepted assumption in literature that wind loads are centered on heliostats. Two torsion loads were considered, generated by wind and by mirror weight. Based on this model, it was determined that the torque tube element is a critical component that needs to be improved. Recommendations are that for small heliostats at sites with low wind speed, a thick torque tube with a small diameter is most reliable. However, at locations with high windspeed, a thin torque tube with a large diameter will be most reliable. It was also found that in the stow position, heliostat torque tubes can have the relatively low reliability, especially as compared to the pedestal and truss system, as wind speed increases.

Pedestal

The pedestal is typically a vertical support, which like the torque tube, is often a large round, square, or rectangular steel tube. The pedestal is firmly secured to the ground with the use of anchors and a relatively large foundation. The use of large and rigid mechanical bodies is necessary for when a load is applied on the pedestal and the pedestal foundation during high wind conditions. As with torque tubes, the pedestal and foundation cost, strength, and weight are functions of raw material cost since these components are often made of concrete and standard steel components. However, these components can also be optimized for the most cost and weight efficient dimensions while maintaining high strength and bending resistance. Benammar and Tee [250] modeled heliostat components and analyzed the structural reliability at high wind speed. In their model, the total bending stresses on a pedestal were stated with respect to applied wind loads, mirror weight, and compressive stress [38]. Pedestal reliability was found to be lowest with mirrors in the vertical position and highest in the horizontal stow position. Maximum bending moments occur at the base of the pedestal. The study attempted to optimize the reliability of the pedestal given these bending moments and wind load conditions, using a round steel tube as the pedestal. The study increased the inner and outer diameter simultaneously or the wall thickness, but not both at the same time. It was shown that both increasing pedestal diameter and thickness increased the reliability in these models. However, increasing the thickness had a significantly greater impact. Increasing the pedestal diameter only had a small impact on reliability.

The pedestal foundation can also be optimized for strength or low cost. Pfahl et al. have extensively studied heliostat cost reduction methods including the use of a prefabricated concrete ground anchor foundation [16]. Traditional concrete foundations typically use rebar, steel anchors, and concrete to secure the pedestal to the ground. According to Pfahl et al., such foundations for heliostats typically contribute about 10% of the total heliostat cost. To reduce this cost, Pfahl et al. considers a prefabricated concrete foundation block which is built to accept natural material such as sand or rock. The material is removed from the foundation installation site and then placed back on the foundation, partially burying it in rock or sand. The addition of site material to the foundation block would decrease costs. It would also make transportation easier, as the pre-installed foundation would be lighter. Significant cost reduction is expected for this method. To improve soil characteristics, stabilization and exchange methods that are standard in coastal protection could be applied.

Pedestal foundations can also be eschewed with carousel-style rim drives. One such example is the Solar Dynamics SunRing, which accomplishes azimuthal rotation with a geared ring riding on ground anchors. Kurup et al. showed that the foundation cost $2.07/m^2 higher than that of a heliostat with a traditional single foundation [17]. However, site labor costs were reduced by $8.60/m^2, partially as a result of a semi-automated piledriving procedure replacing the laying of a standard foundation.

While the pedestal, like the torque tube, does not represent a significant gap outside optimizing the design for material usage and reliability, the pedestal foundation has more room for improvement. Numerous methods exist for fixing a large structure such as a heliostat to the ground, and an optimal methodology could be developed that allows for ease of transportation, optimization of material usage, and good rigidity and resistance to wind and mass loads.

Structure and Truss System Components

Truss systems vary between heliostat designs such as large T-shaped heliostats with torque tubes or small heliostats with single U-joint connections. The truss system also involves bolts, welds, and adhesives that may be used as attachment and pinning methods. These attachment methods must take into account material rates of thermal expansion. Glass and steel mirrors use different pinning methods due to different facet weights and facet rates of thermal expansion. Facets are typically fixed with pins that allow flexing and rotation. These pins are mounted above the torque tube and must be capable of holding the weight of the facets. These pins are often mounted to the facets using glue and pads for increased surface area and to avoid damaging the facets. This is another potential gap area that could be improved and studied, though it is dependent on other components of a specific heliostat such as mirror design.

As with many components of heliostats, wind loads can impact the mechanical integrity of the truss system. The widespread availability of wind load data may better demonstrate what components of the heliostat structure are over built and what components require reinforcement. For example, Emes et al. have studied pedestal and hinge bending moments that occur in unsteady pressure distributions at a turbulent atmospheric boundary layer [28]. Pressure distributions on heliostat faces can be non-uniform due to turbulence and can cause significant bending moments at the base of the pedestal and at the hinge. Their study found that at the hinge the bending moment is strongly correlated to the center of the pressure distribution and movement of this center. It was also found that the bending moment at the hinge is highly correlated with turbulent energy. This study is significant as turbulence in heliostat fields can be high. As found by Peterka et al., heliostats increase turbulent kinetic energy as wind flows through a field [39]. Studies like this demonstrate turbulent movements of center of pressure distributions could significantly improve heliostat support structure engineering.

While extensive FEA is typically involved in the construction of a truss system, reliability analysis is needed. Benammar and Tee modeled heliostat components and analyzed truss structural reliability at high wind speed [38]. In their model of the heliostat truss system, a heliostat with four identical truss systems was considered. This is difficult to model for reliability since truss systems can vary greatly. However, useful reliability information was still gained. Wind and mirror weight loads were considered as external forces were applied on the truss. The assumption was made that wind loads concentrated at the center of the heliostat as well as the center of the individual truss systems. In most models of the truss system, reliability did not change. However, it was noted that in one case where the cross-sectional area of the truss system was increased, reliability of the truss system across a range of wind speeds was improved.

Many alternate support systems have also been designed that differ from traditional truss systems built around a vertical pedestal and horizontal torque tube. The Google prototype heliostat developed in 2010-2011 used a simplified tripod truss system to mount the entire heliostat [40]. The system had a single large beam at the front making a 90° angle with the ground, supported by two 45° cross members running from the top of the vertical beam to the ground. Horizontal beams were mounted in between these members for additionally rigidity and support. The system used ground anchors which would run through holes in the frame and screw into the ground. The specific frame was designed to be small, lightweight, and even foldable for easy shipping and delivery to a target plant site. The specific frame was built for a 6 m^2 heliostat panel and contributed just \$11.70 to the \$/m^2 cost of their heliostat, though the design could easily be scaled up for larger heliostats. The frame was made out of galvanized steel C-channels and was rivetted together instead of welded.

Space frames have effectively reduced material usage (and therefore cost) in non-commercial applications. A prototype space frame design documented by Davila-Peralta et al. reduced steel usage to 15kg/m^2, a mass elimination of two-thirds from a conventional T-type heliostat [15]. The use of space frames, however, typically also necessitates use of rim drives or other actuation methods.

Trusses can be avoided entirely with a membrane-type mirror panel approach. This suspends the entire mirror surface from a central pylon using cables, using the mirrors themselves as structural members in compression. Coventry et al. note that this can reduce overall material usage by 60%–65% [41]. In heliostat applications, Solaflect's William Bender calculated a \$25/m^2 reduction in installed cost for the suspension heliostat, of which nearly two-thirds stemmed from reduced material usage [42]. Solar-tracking PV arrays, manufactured by Solaflect Energy, are commercially available using this style of construction and actuation.

Controls

When a heliostat's reflected light spot is pointed toward the target, control of the heliostat must transition from rough aiming using accelerometer data to precise, on-target position control. There are two important components of this transition: capture strategy and capture detection. Capture strategy is lining up the heliostat angle with the target so the on-target position control can sense it and "capture" it. The heliostat accelerometer has an accuracy of a degree, while the on-target position control has a tighter resolution of 1/200 of a radian (about 0.25 degrees). Because of these differences, it's possible that the heliostat could think it's pointed directly at the target, while the target is unable see it. In our testing, the accuracy of the accelerometer was sufficient most of the time. If it misses, the heliostat could move in a spiral pattern—tight, widening circles—until the light spot is captured.

Capture detection happens when the on-target positioning system detects the location of a light spot from a specific heliostat in its field of view. At this point, the heliostat's control system switches from relying solely on the accelerometer to relying on the on-target spot position sensing system, which has far higher precision and accuracy.

When a heliostat field tracks the bisector and directs sunlight, tracking error can occur. As described by Sattler et al. in their review paper, heliostat tracking error has very low tolerance, and is usually measured in units of mrad, equivalent to 0.057° [18]. An example of this tolerance is given with a heliostat 1 km away from a target, where a 1mrad tracking error would put a beam 2 m away from the desired aim point. Tracking errors can source from gravity bending, gear ratios and backlash, pivot point offset, dust refraction, angular offset, levelling and other installation errors in the heliostat, poor installation of the torque tube relative to the pedestal, poor heliostat design relative to wind and mass loads, low encoder resolution, and even disagreements between unit systems used by different engineering groups [18], [43], [44], [45]. Of these errors, gear ratios, back lash, and encoder resolution are some of the major contributors [46]. Tracking errors alone represent a significant gap in heliostat design, as errors above 1 mrad can easily account for 10%–20% losses in expected energy collection [47].

Strachan and Houser monitored heliostat beam quality, mirror module performance, durability, and tracking accuracy in the wind from 1986–1992 at Sandia National Labs and compared ATS and SPECO heliostats [48]. In winds ranging from 11–27 mph, the ATS heliostat had a maximum beam deviation of 3.7 mrad, average deviations of 0.92 mrad, and average maximum beam centroid deviations for all observations of 1.9 mrad. The SPECO heliostat had a maximum beam deviation of 4.7 mrad, average deviations of 0.86 mrad, and average maximum beam centroid deviations for all observations of 1.9 mrad. The study found that overall, for the course of 6 years of observation, both heliostats were structurally rigid enough to perform within their design specifications in real-world wind scenarios.

To account for tracking errors and maintain accuracy in a heliostat field, further control systems must be in place. Many heliostat systems use open-loop tracking to accomplish these goals. They stay on target by following a preset course given their known positions in the field and the known course of the sun in the sky. This requires heliostats to be placed precisely on level, graded land on a firm foundation. Other control systems are closed loop, measuring and recalibrating the field based on input data every few seconds.

Traditionally, many heliostat field systems employ open-loop controls tracking (which doesn't require sunlight to operate), where heliostats stay on a receiver target by following a preset trajectory based on their known positions within a respective field layout, the time of year/day, and based on their geographical location. This has traditionally required heliostats to be located on level, graded land with a firm foundation. For closed-loop heliostat control, coarse and fine motion refinements are accomplished using sensors located on the heliostat as well as those on the receiver; see Figure B-1. Communication between the two sets of sensors through the field computer and individual heliostat computers allow for course orientation control. Here, multiaxis accelerometers as well as employment of a precise, target-mounted light spot position sensor can be used for alignment within few degrees of accuracy [49]. Additionally, on-target position control using a photometry system to position light spots around a target calibration panel or receiver can be used more fine refinements. Depending on the receiver geometry, pointing accuracy would need to be sufficient to allow precise control of the heat distribution [49].

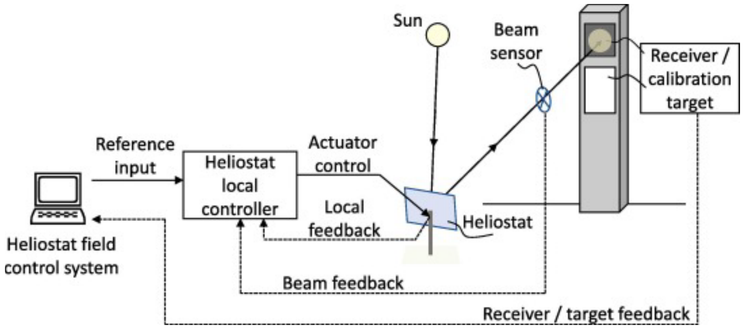


Figure B-1. Closed-loop heliostat control configuration example [18]

For closed-loop control systems, generally the goal is three-fold:

- Rough orientation control of the heliostat using a reflector-mounted 3-axis accelerometer for alignment within few degrees of accuracy.
- Capture of the heliostat's light spot by a precise, target-mounted light spot position sensor—in our case, a multi-scopic photometry system.
- Precise, on-target position control using a photometry system to position light spots around a target calibration panel or receiver. The pointing accuracy would need to be sufficient to allow some control over heat distribution across a specific target such as a heat exchanger in a receiver down to 10–50 cm resolution [50].

During operation when a heliostat's reflected light is pointed toward a receiver, control of the heliostat must transition from coarse to fine resolution refinement, which requires both on-board sensors (e.g., accelerometers) as well as on-target or receiver position control. To make the transition seamless, one must consider the capture strategy and capture detection. The capture strategy is lining up the heliostat angle with the target so the receiver spot position control can sense it [49]. Capture detection occurs when the on-target positioning system detects the location of a light spot from a specific heliostat in its field of view. At this point, the heliostat's control system switches from relying solely on heliostat sensors to relying on receiver spot position sensing system or photometrics, which can have a significantly higher precision and accuracy [49].

Closed and open loop control systems must be 5–10 times more accurate than the desired tracking error, meaning 1 mrad tracking error requires 0.1 mrad error in the control system [18]. This requirement alone represents a significant gap in heliostat design. However, important distinctions must be made between closed loops and open loops in heliostat control, as the distinction is not always clear and there is significant overlap. Examples and definitions are provided in Sattler et al., Malan et al., and Swart et al. for open and closed heliostat control loops

[18], [51], [52]. Given examples state that a typical signal or effect in a control loop may flow through components starting from the control room, to the controller, then to an actuator, an encoder, a sensor on the heliostat, mirror and surface normal influencers such as drives, to the target. Measuring devices in this loop may include computers, encoders, sensors, cameras, beam characterization systems, and other devices for measuring heliostat and mirror normal. Closed loops will use the measuring devices for feedback to input into the loop of the signal and effects. Heliostat closed loop systems will typically use the beam characterization system for feedback to input into the control system. However, partially closed loops also exist, which use feedback from individual heliostat and mirror normal measuring devices as input into the control loop [18]. Even open loops are not always pure open loop systems, as closed loops will still exist between the control room, drives, and encoders.

An important distinction between open and closed loop systems in heliostat design is that, while closed loops use feedback, an open loop will compute the heliostat normal vector based on simple model estimations. These models consider the coordinates of the field, the coordinates of the target, the time of year, and the time of day to estimate the vector of sunlight reaching the field and the proper pointing angles to reflect that light to a target coordinate. Many heliostat control systems will stop at this point without verification that the beam has reached the target [53]. Some have integrated a closed loop component by adding a beam characterization system which can be used for simple verification by the operators or can actually close the loop with feedback.

Open-loop control systems for heliostats represent a significant gap that could be improved. Adding measurement devices for flux at the receiver, spillage, aiming errors, with feedback, could significantly reduce tracking error. While open loop tracking has errors up to 1–2 mrad, closed-loop tracking systems with simple measurement devices can easily reduce error to 0.1 mrad [53]. Though more error can still be accounted for, such as shifting foundations or warpage from wind, devices that can measure heliostat parameters such as perpendicularity of the torque tube relative to the pedestal or foundation level could be integrated. Along with heliostat pointing vector measurements or even mirror normal vector measurements, control loops could be further improved.

For deployed CSP system, heliostat receiver pointing requires timely and accurate adjustment depending on the sun’s position in the sky. A field controls management algorithm is employed to actively determine which specific heliostats should be pointed at a given receiver, as well as which should be held in reserve. Heliostat field control systems are designed to direct sunlight at a specific target within 1–2 milliradian accuracy [54]. Controls algorithms, along with heliostat operators, leverage feedback from a heliostat computer to track sun movement; however, adjustments over time are required for simultaneously correcting externalities such as wind, foundation shifting and thermal expansion. In addition, control systems employ tools, such as a beam characterization system to monitor and adjust the amount of thermal power reaching a receiver to a predetermined thermal envelope. Here, control systems are designed with dynamic optimization algorithms to operate within the integrated CSP system at the most profitable points of power generation depending on the time of day and year.

Component Integration

Component integration and overall heliostat field design represents another gap. Improvements in modeling capabilities have allowed for extensive computational fluid dynamics wind modeling and optimization modeling that could be used to significantly improve heliostat field design and component integration. In 2018, Wang et al. developed a high dimensional genetic algorithm toolbox for optimizing entire heliostat fields [55]. 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 [56]. 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 [28]. 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.

CSP Industry Survey

Following are bulleted questions and their most common responses. Response quantities are in parentheses at the end of each response. Unique answers (those only given by one respondent) are generally not listed.

- What are the top problems you have encountered with heliostat components and controls during the installation and commissioning phase of CSP plants?
    - Alignment to receiver (5)

    - Excess focus and slope errors (3)
    - Drive encoder errors (2)
    - Mirror corrosion and delamination (2)
- What are the top reasons for heliostat downtime in the operational phase of CSP plants?
    - Calibration issues (3)
    - Controller failure (2)
- What are the most expensive repairs (including labor hours) for heliostat O&M?
    - Repair/replacement of drives (4)
- What are the most unreliable components for heliostats (including controller components)?
    - Drives (3)
    - Programmable logic controllers – PLC (2)
- What are the most significant challenges in maintaining heliostat performance, including desired targeting alignment?
    - Calibration (6)
    - Soiling (5)
    - Pointing error (4)
    - Facet canting in the field (2)
- Have you had significant issues with soiling and cleaning of heliostat mirrors? If so, please describe the issues and the cleaning methods used. (Note: all described issues are presented below. Of respondents who answered this question, seven answered yes and one no.)
    - Rapid accumulation of dust during weather events.
    - Facet damage from brush-based cleaning methods.
    - Terrain roughness impacting speed and usability of cleaning tools.
    - Limited water resources in arid climates.
    - Soiling rates exceeding prediction.
    - Reduced morning performance due to ice.
- Do you see a direct need for codes or standards to improving commissioning or operations of CSP plants? If so, please list specific areas you see the need for codes or standards. (Note: of respondents who answered this question, 11 answered yes and two no).
    - Commissioning, e.g., a Site Acceptance Test (SAT) standard, including communications and overall performance (4)
    - System alignment (3)
    - Drive performance (2)
    - Controls performance (2)
- Is Heliostat resiliency and security a concern?
    - Yes (7)
    - No (5)
- Describe other issues or concerns regarding heliostats. (This question elicited a variety of responses with no overlap between respondents.)
- With respect to cost, reliability, and operability of heliostat components (and their control systems), what are the most important areas of R&D?
    - Mirror cost reduction and quality improvement (4)
    - Improved resilience of all components toward weathering (3)
    - Automation and wireless control (2)
    - Mirror focusing and slope error reduction (2)
    - Calibration and automatic monitoring (2)

Further Breakdown of Gaps for Components and Controls

Following is a detailed breakdown of Tier 2 and 3 gaps that was too detailed for the main report body.

Table B-1. Tier 2 Gap Analysis for Components and Controls

Gaps – Tier 2	Functionality of Solution	Justification/Benefits	Addressing Strategy
C6: Alternatives are needed to impact design being driven by worse case wind loads as this is a significant boundary to cost reduction.	Lower torque drives can be used Variable drive sizing between inner and outer field locations Wind fences or other field modifications to minimize wind loading	Cost reduction in drives and heliostat structure can be achieved with more detailed wind data or field design to reduce forces due to wind.	Funding provided to wind research specifically to the problems indicated for CSP.
C7: Alternate drives for cost reduction have not been fully explored.	Alternative drives such tip-trackers with two linear actuators are installed at scale and achieve bankability	In the most recent NREL cost analysis drives cost $\$28/m^2$ and this must be reduced to achieve $\$50/m^2$ for the entire heliostat cost.	Funding for better wind data per C6 opens opportunity for different drives, publication of proven heliostat design qualification standard enables bankable testing of alternate drives, or funding directly to drive development or drive test beds.
C8: Coatings for mirrors needed to improve performance and reliability.	Durable anti-soiling coatings are applied to mirrors and result in less cleaning and higher effective reflectivity	Mirrors must maintain high reflectivity and reliability for 30 yrs.	Funding provided to develop advanced coatings. Utilization of coatings formulations and R&D best practices from PV industry.
C9: Mirror quality should be adaptable to environmental conditions but there are no standards for this.	Environmental testing standards are linked to degradation-based climate zones. Optimization is achieved by pairing mirror design to installation environment.	CSP plants are being installed in differing environments and mirrors are being overdesigned to handle all these environments. This means that cost reduction is left on the table for some sites.	DOE funding past work to gather mirror performance and degradation data in various locations. These data were assembled in a database for further analysis to help determine environment specific accelerated testing for various environments. The database was never used due to funding cuts and therefore is a low hanging fruit.

Gaps – Tier 2	Functionality of Solution	Justification/Benefits	Addressing Strategy
C10: Need performance standards for heliostats.	IEC heliostat performance standards published, and heliostats are tested to these standards through design phases, commissioning, and as needed throughout a plant's life cycle	Without clear performance tests for heliostats systems can end up underperforming in the field and drive up the cost of electricity for CSP systems.	IEC 62817-X as mentioned in C5 offers an efficient way to take advantage of an existing standard while including the necessary performance testing. SolarPACES has already written some language around performance testing that could be included in 62817-X
C11: Need for CSP-centric durability standards for the glass and mirror.	IEC durability standards, including pass fail criterial, are published for CSP mirrors. The standards are applied to new mirror designs, coatings, and in manufacturing quality assurance	Materials differences for various heliostat mirrors needs to be evaluated for developing more robust and accurate designs.	Research studies and tools needed for evaluating construction materials and reflective surfaces both from performance and reliability. Evaluation of best practices, test beds, and trade studies needed from other industries to further develop current mirror durability and performance evaluation capabilities.
C12: Design and O&M are not well coupled (especially problematic with drives/mirrors).	O&M is planned within a heliostat design enabling cost and financing models to include maintenance costs/reserves necessary to achieve modeled plant performance	When design and O&M are not well coupled systems typically degrade faster than intended and underperform expectations (resulting in higher LCOE). By coupling these variables system performance can be upheld over the life of the plant, reducing LCOE.	Development of a heliostat design qualification standard (including testbed development where necessary) and reliability standards for mirrors is the first necessary piece to connecting design and O&M. The data/results from such standards help inform how a system will degrade per accelerated lifetime testing. Mean time between failures and other reliability data must be gathered on key components.
C13: Reliability/degradation/ aging not well defined yet this can impact pointing accuracies and system performance over time.	Reliability/degradation of various components and controls are well understood. Designs to reduce cost include reliability/degradation trade-offs and therefore new designs are optimized for lowest LCOE over the life of a plant.	Without reliability/ degradation models for components and controls, CSP system O&M is not appropriately planned. System downtime and system underperformance are the likely outcomes.	Data must be collected and made readily available for degradation of components and controls as well as mean time between failures for various components. Funding appropriate test beds as well as design qualification standards will help to generate necessary data.

Table B-2. Tier 3 Gap Analysis for Components and Controls

Gaps – Tier 3	Functionality of Solution	Justification/Benefits	Addressing Strategy
C14: Flexible wired communication and controls interconnections needed.	Confident controls communications through a CSP field for varying operational modes. Ability to modify heliostat set configurations without signal transmission interruptions/attenuation concerns.	Robust communication hardware needed to ensure reliable signal quality between heliostat and field computer.	Reliability research of current interconnection hardware with respect to signal distribution under varying controls scenarios. OR Utilization of best practices for large wired controlled systems from other industries.
C15: Heliostats are automatic mechanisms that can exert dangerous forces and create fire hazards.	Safety standards are published for heliostats and pass/fail testing to the standards are conducted on individual heliostats and heliostat plants.	Controls signals to heliostats will cause a heliostat to move, regardless of if there are objects or personnel in the proximate vicinity. Additionally, unintended movement could facilitate hazards including fire.	Engineering controls safety criteria, feedback and hardware needed for addressing design and operations to ensure reliable movements that do not cause injury or damage.
C16: Safety is especially important for wireless systems. Redundancies within the controls will be critical especially for SCRAM operations.	Safety standards are published for heliostat wireless controls.	Signal loss or abatement within wireless systems could facilitate hazards, particularly for automated systems. Safety redundancies and immediate feedback needed within controls to guard against unintended movements or consequences.	R&D funding for assessing feedback architectures with a variety of sensors and wireless controls software/hardware. Research for leveraging resilient safety engineering controls to operate reliably during contingencies and SCRAM operations.
C17: Concerns over cybersecurity attacks on a heliostat field could create a variety of high consequence events.	Heliostat specific cyber security standards are implemented	Detrimental impacts of hacking of controls systems could pose issues related to plant power production or hazards from unintended heliostat motion.	Funding for R&D to address cybersecurity within the field and single-heliostat level controls for guarding against unintended control. Administrative controls development to also provided additional safeguards.

Appendix C. Techno-Economic Analysis

Capital and O&M Costs

It is important to understand how costs vary over time with respect to heliostat performance and reliability considerations, such as O&M, reliability, and lifetime for small and large multi-facet heliostats. O&M cost can determine longitudinal costs of heliostats. The results from such a gap study could demonstrate that up-front costs may be more, but the overall cost per lifetime is more cost effective.

In Figure C-1, from Zhu et al. [15], data points show that O&M costs have a dramatic impact on LCOE. There is an increased leverage of O&M costs on LCOE as the cost of the plant is reduced. Zhu defines the annual investment energy return (IER) as the ratio of the annual net generated electricity of a solar power plant to the direct system cost of the plant. Figure C-1 shows the LCOE as a function of annual IER for different variable O&M cost assumptions. The major takeaways from the empirical LCOE plot below are:

- LCOE shows an asymptotic behavior as a function of annual IER, instead of a linear behavior as one speculates without detailed analysis. It drops quickly when the annual IER increases at a low annual IER (such as 0.5) but becomes flatter with increasing annual IER at a fairly large value (such as 1.5).
- O&M cost has a dramatic impact on LCOE. For a high O&M cost of $30/MWh, by looking at the horizontal line of the SunShot Initiative goal of 6 cents/kWh, it seems impossible for LCOE to achieve 6 cents/kWh, no matter how much the annual IER is boosted.
- For any LCOE objective, one can identify the required performance criterion for the annual IER. For example, by assuming an O&M of $7.5/MWh, the required annual IER is 1.61 kWh/$-yr to achieve a real LCOE of 8 cents/kWh, and 2.22 kWh/$-yr for 6 cents/kWh. Once an annual IER is determined, one can work on the physical system performance and the related simple “hard” system cost values.

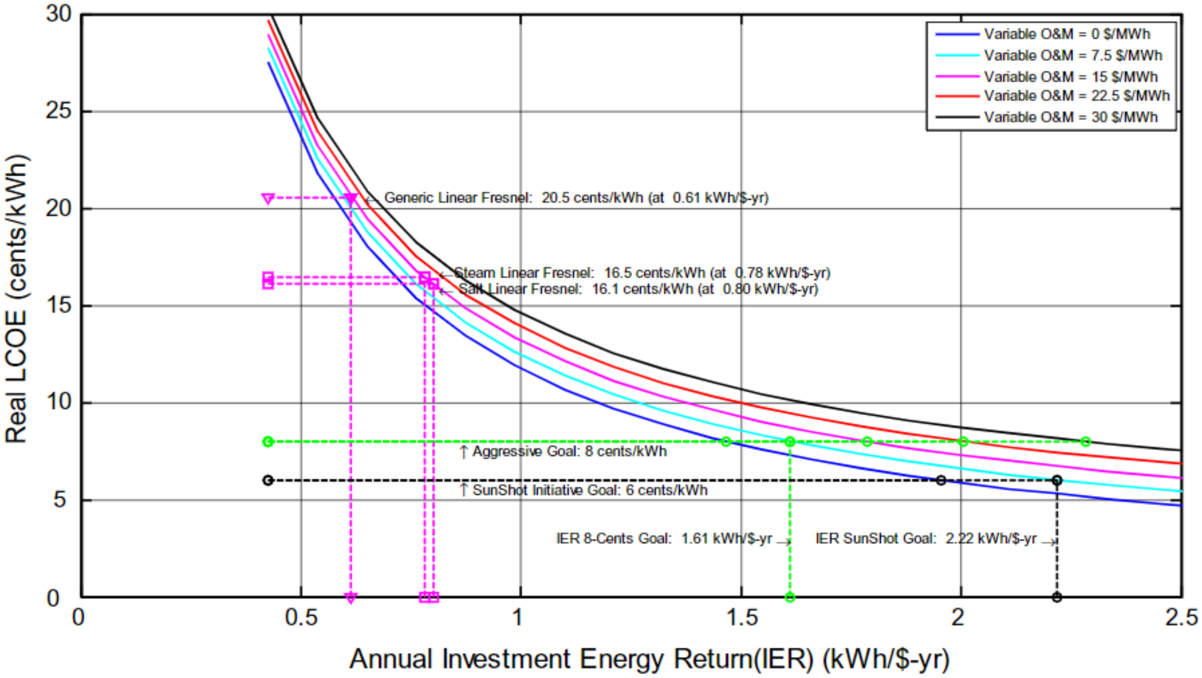


Figure C-1. LCOE as a function of annual IER for different variable O&M cost assumptions

Figure from Zhu et al. [15]

In a recent paper by Kurup et al. [12] the System Advisory Model (SAM) was used to highlight key cost categories for TEA. Table C-1 shows the results of the SAM cases with the Default, Commercial, and Advanced costs, assuming the remainder of the CSP plant and the financial assumptions stays the same. To ascertain the impact of the heliostat cost on the overall plant cost and LCOE, researchers created a SAM simulation with three scenarios: Default heliostat (2013 cost), Commercial heliostat (Schlaich Bergermann und Partner “sbp” cost), and Advanced heliostat (SunRing cost). The default SAM financials in SAM 2020.11.29 were used. As of 2021, the investment tax credit, which is a key financial incentive for large solar projects, has been extended for commercial solar projects starting construction up to December 31, 2023. We used the 26% investment tax credit, assuming the CSP projects modeled start construction in 2021 or 2022 [251]. The investment tax credit is currently expected to decrease to 10% after 2023 [251]. As seen in Table C-1, the 26% investment tax credit benefit significantly impacts the LCOE; for example, in Tucson, Arizona, in the default cost case, the LCOE drops by 20.2% with the investment tax credit applied. We assumed any CSP project starting construction in 2021 and 2022 uses the full investment tax credit. At Location 1 (Tucson, Arizona), with the investment tax credit applied, the reductions in heliostat field costs from $140/m^2 to 127/m^2 and 96/m^2 in the Commercial and Advanced cases could lead to reductions in LCOE of 3% and 10% respectively. For Location 2 (Daggett, California), which has slightly higher DNI than Tucson, Arizona, changing the costs from the default $140/m^2 for the heliostats to $127/m^2 and $96/m^2 has almost the same LCOE reductions as Arizona.

Table C-1. Default, Commercial, and Advanced Cost Cases in SAM and the Impact on LCOE [12]

SAM System Cost Category	Default Heliostat	Commercial Heliostat	Advanced Heliostat
Other Cost Categories for Locations 1 and 2			
Contingency on direct CAPEX (7% default, $)	27.3 million	26.3 million	24.0 million
Indirect: Engineering procurement and construction cost and owner costs ($)	54.3 million	52.3 million	47.7 million
Indirect: Total land cost ($)	9.5 million	9.5 million	9.5 million
O&M fixed cost by capacity ($/kW$_e$-yr)	66	66	66
Total Direct Costs for Location 1 and 2	$498.2 million	$480.7 million	$367.0 million
Total Installed Costs for Location 1 and 2 ($/kW)	6,920	6,676	6,095
Finance Assumptions			
Analysis period (years)	25	25	25
SAM LCOE real for Tucson, Arizona (¢/kWh)—without investment tax credit (ITC)	11.83	11.47	10.61
SAM LCOE real for Tucson, Arizona (¢/kWh)—ITC at 26% (DOE EERE, 2021b; SEIA, 2021)	9.44	9.16	8.50
SAM LCOE real for Daggett, California (¢/kWh)—without ITC	11.48	11.13	10.29
SAM LCOE real for Daggett, California (¢/kWh)—ITC at 26% (DOE EERE, 2021b; SEIA, 2021)	9.16	8.89	8.25

Levelized Costs

LCOE is a key metric used by the DOE/SETO with regard to TEA to assess CSP parity against fossil and other traditional power generation sources. The LCOE is defined as the sum of the annualized costs, C_c, of each component over the annualized electrical energy produced E_e (Eq. 1)

$$LCOE = \frac{\sum_c C_c}{E_e} \qquad \text{Eq. (1)}$$

Although LCOE is a fundamental TEA metric to establish the total electrical energy produced, there are other modes that can be beneficial to reducing cost of CSP systems. Levelized cost of coating (LCOC), levelized cost of heat (LCOH), levelized cost of mirror optics (LCOMO), net present value, and internal rate of return (IRR) are all key financial performance parameters, yet there are few comparative studies of these parameters with respect to CSP within the current literature.

LCOC is the ratio of the annualized cost of the coating (and associated costs such as labor and number of heliostats required) to the average annual thermal energy produced by the receiver, Eq. 2 [252]. This is a new metric that can be used to evaluate and compare alternative materials against a baseline coating (e.g., Pyromark 2500), yet limited research has been done using this metric. According to Boubault et al. [253] the LCOE can be reduced by selecting the most cost effective coating. The application of a receiver coating is generally profitable and enables a lower LCOE. LCOC is given by Eq. 3 where $C_{coating}$ is the annualized cost of coating and C the annualized cost of all other components. $E_{e,coating}$ and $E_{e.ref}$ are the annualized electrical energy that would be produced with and without coating, respectively. C does not include any benefits or revenue due to the plant. $C_{coating}/E_{e,coating}$ is the marginal LCOC as described in [252] Units of LCOC consists of \$/MWhth.

$$LCOC\ (Levelized\ Cost\ of\ Coating) = \frac{C_{annual}}{E_{thermal}} \qquad \text{Eq. (2)}$$

$$LCOC = \frac{C_{coating}}{E_{e,coating}} + C\left(\frac{1}{E_{e,coating}} - \frac{1}{E_{e,ref}}\right) \qquad \text{Eq. (3)}$$

LCOH is an economic assessment metric that includes all the costs incurred over the lifetime of a heat-generating system (e.g., CSP). The LCOH is calculated based off Eq. 4. Solar collector cost (e.g., heliostat), indirect costs, fixed charge rate, and O&M costs are essential factors that must be optimized in order to decrease cost of heat (Figure C-5). Literature on LCOH is primarily focused on medium-temperature solar collectors rather than high-temperature heliostats.

$$LCOH = \frac{(Installation\ cost)\times(FCR)+Yearly\ O\&M}{Q_{output}} \qquad \text{Eq. (4)}$$

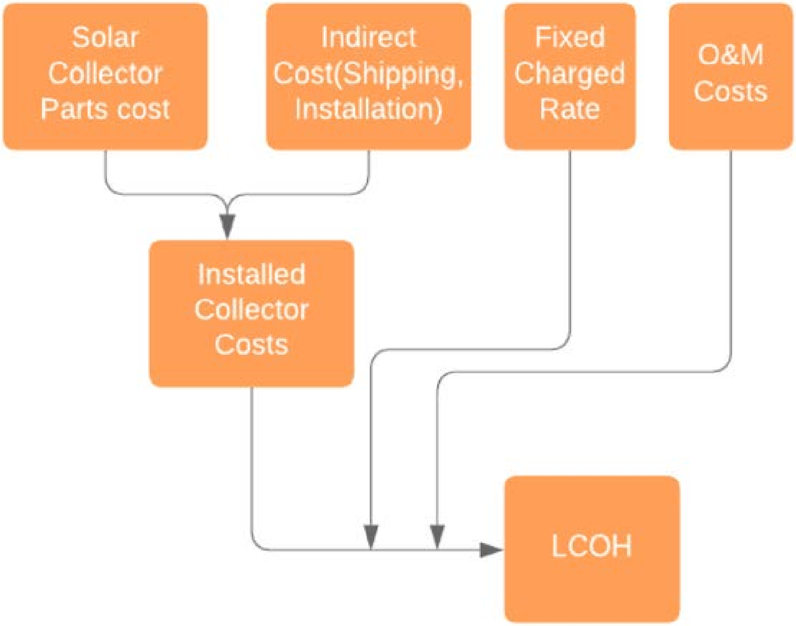


Figure C-2. Process flow diagram to calculate LCOH of a solar collector in \$/kWh [254]

LCOMO is a focused TEA metric with respect to optical performance, physical design, metrology and costs. In literature LCOMO is determined by specific CSP metrology aspects related to concentrating optics, primary optics, low-cost optics, optical performance, and optical efficiency. This novel CSP system cost-performance metric was introduced as LCOMO in Armijo and Yellowhair [255]. LCOMO can be used to evaluate and compare heliostat design parameters and O&M considerations. It is hypothesized that this parameter can be used during heliostat and facet development, with respect to a field layout, to focus on the parameters that have the highest impact on performance and cost. LCOMO can be defined as the difference in LCOE from the baseline LCOE from the initial LCOE.

$$LCOMO = LCOE_i - LCOE_{baseline} \qquad \text{Eq. (5)}$$

Through probabilistic modeling, several heliostat design parameters were investigated (i.e., slope error, heliostat size, focusing strategy). Results demonstrated mirror reflectance having the strongest correlation to LCOMO, this suggests a strong need for clean mirrors through an optimum mirror cleaning schedule [255]. Similar to LCOC and LCOH, LCOMO has limited information on how these parameters can ultimately drive down the total levelized cost of energy within the heliostat technology.

Cost of Heliostats

In this TEA review, the investigators identified empirical evidence of TEA for heliostats that fit within the prespecified subcomponent and field design criteria. A strategy to identify the relevance of literature published between 2007 and 2021 was implemented. Overall, this review investigation assessed specific parity cost metrics for heliostats, such as LCOE, LCOH, and levelized cost of optics. Research was performed over a variety of literature sources as well as discussions with CSP industry entities. Reviews within databases were refined to peer-reviewed articles, conference papers, and survey papers. Government-issued reports and web pages were investigated as well. Each source was scanned for the following topics: scalability, O&M, capital cost, CSP, mirrors, LCOE, LCOH, levelized cost of optics, and SAM TEA assessments. Reviewing articles and all available TEA evidence through this explicit and systematic method minimizes bias, thus providing reliable findings from which substantive gaps can be identified. The following subsections detail key findings of the literature review.

According to the McDonnell Douglas Astronautics Company, a 20% cost reduction can be achieved when the heliostat size is increased to at least 100 m^2 [256]. Bigger was predicted to be better due to the improved economies of scale for the heliostat components. However, more recent studies from Kurup et al. [12] show scenarios with individual heliostat aperture of 27 m^2, 48.5 m^2, and 144 m^2 with similar cost estimates to Kolb et al. [90]. The Kolb et al. study consisted of two heliostat concepts, full-scale glass/metal and subscale stretched membrane prototype with an individual heliostat aperture of 148 m^2 and 150 m^2, respectively, whereas the Kurup et al. study consisted of three models: default, commercial, and advanced scenarios. The default scenario uses the default heliostat performance values from the latest version of SAM (2020.11.29) with an individual heliostat aperture of 144 m^2. This cost was determined through analysis of the global CSP market, deployed projects, and a prior industrial survey [257]. The commercial scenario represents the Stellio heliostat developed by Schlaich Bergermann und Partner (sbp) located in Germany, with an individual heliostat aperture of 48.5 m^2. The advanced scenario represents the SunRing cost, with an individual heliostat aperture of 27 m^2. A summary of these results is shown in Table C-2.

Table C-2. Summary of Heliostat Price Estimates

	148 m^2 Glass/Metal Heliostat Price	150 m^2 Stretched Membrane Heliostat Price	144 m^2 Default Heliostat Price	48.5 m^2 Commercial Heliostat Price	27 m^2 Advanced Heliostat Price
5,000/yr	164 USD/m^2	180 USD/m^2	-	-	-
7,470 one time	-	-	140 USD/m^2	127 USD/m^2	96 USD/m^2
50,000/yr	126 USD/m^2	143 USD/m^2	-	-	-

The number of heliostats per field varied per case scenario, for Kolb et al. the heliostat price was given for 5,000 and 50,000 heliostat units per year. Meanwhile, the three SAM scenarios form Kurup et al. was modeled for 7,470 heliostat units. This was assumed to be a one-time cost rather than a yearly expense. The lower price at the higher production rate is primarily due to economies of scale. A price breakdown for glass/metal, SM, and commercial sbp heliostats is given in Table C-3.

Table C-3. Cost Breakdown of Various Solar Field Sizes

	148 m^2 Glass/Metal Heliostat Price ($/$m^2$)	150 m^2 SM Heliostat Price ($/$m^2$)	48.5 m^2 Commercial Heliostat Price ($/$m^2$)
Mirror module	23.06	42.99	17.00
Support structure	21.21	19.08	19.96
Drive	27.11	26.67	16.08
Drive electrical	1.78	1.76	7.98
Controls	1.94	1.87	14.43
Pedestal	16.96	16.73	6.76
Total direct cost	92.06	109.11	82.21
Overhead/profit (20%)	18.41	21.82	-
Total fabricated price	110.47	130.93	82.21
Field wiring	7.40	7.30	9.01
Foundation	2.28	2.30	5.15
Field alignment/checkout	6.34	2.41	-
Rotation assembly	-	-	12.19
Site labor	-	-	16.39
Transportation	-	-	2.29
Total installed price	126.50	142.90	127.24

The Kolb et al. [90] Sandia study used the 148 m^2 ATS heliostat as its reference and explored a size domain of 53 m^2 to 214 m^2. Figure C-3 shows what happens when the relationship between price and heliostat area are extended for heliostats smaller than 53 m^2. While outside the original domain of the Sandia analysis [90], the general trends are clear: Specific cost escalates strongly as size falls, with the impact particularly noticeable for sizes below 30 m^2. Additionally, as the heliostat area begins to scale upward, the price shows an asymptotic behavior in which the DOE goal of $50/$m^2$ becomes very difficult to reach. The purpose of this HelioCon work is to determine new technical pathways of reducing costs further.

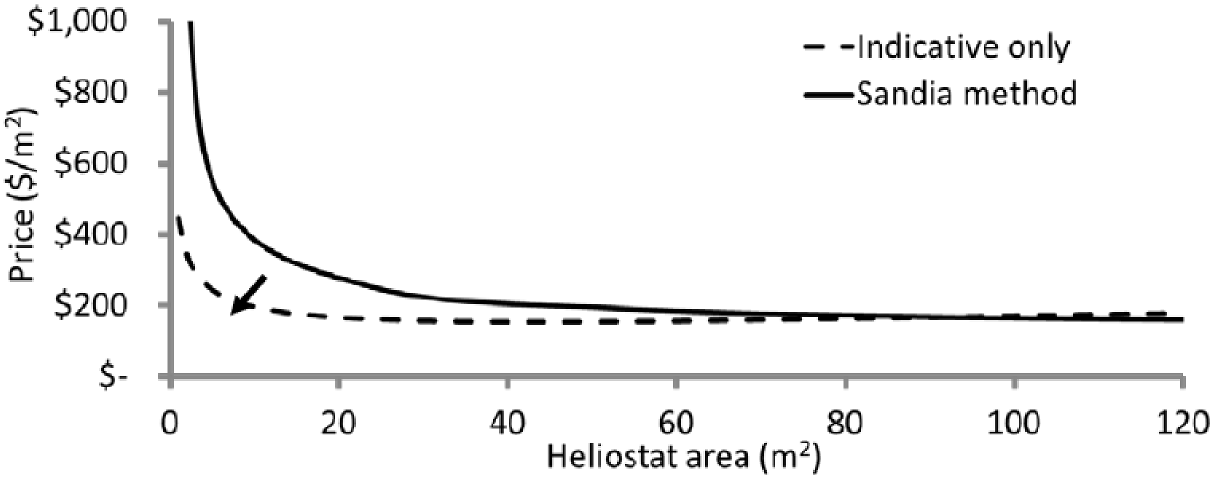


Figure C-3. Heliostat price dependence upon area, using the method of Sandia to extrapolate to smaller sizes (solid line). The dashed line is indicative only, showing forecast impact of cost drivers relating to manufacturing and assembly of smaller heliostats.

Figure from Sandia National Laboratories [90].

Appendix D. Roadmap Workshop Participant List

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