U.S. Department of Energy

HelioCon

Heliostat Consortium for Concentrating Solar-Thermal Power

Heliostat Consortium Annual Report 2024

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Heliostat Consortium Annual Report 2024

Guangdong Zhu,[1] Jeremy Sment,[2] Craig Turchi,[1] Margaret Gordon,[2] Randy Brost,[2] Rebecca Mitchell,[1] Devon Kesseli,[1] Tucker Farrell,[1] Matthew Muller,[1] Kenneth Armijo,[2] Michael Cholette,[3] Matthew Emes,[4] Alexander Zolan,[1] Chad Augustine,[1] Stephanie Meyen,[1] Daniel Tsvankin,[1] Shashank Yellapantula,[1] Parthiv Kurup,[1] William Hamilton,[1] Dan Small,[2] Aaron Spieles,[2] Michael Collins,[5] Joe Coventry,[6] Kyle Kattke,[7] Michel Izygon,[8] Rick Sommers,[7] Eirini Tsiropoulou,[9] Mohamed (Hameed) Metghalchi,[10] J. Roger Angel,[11] Derek Schulte,[12] Laura Schaefer,[13] Mark Ayres,[14] Heejin Cho,[15] Michael Wagner[16]

1 National Renewable Energy Laboratory
2 Sandia National Laboratories
3 Queensland University of Technology
4 University of Adelaide
5 Commonwealth Scientific and Industrial Research Organisation (CSIRO)
6 Australian National University
7 Solar Dynamics LLC
8 Tietronix Software
9 University of New Mexico
10 Northeastern University
11 University of Arizona
12 DKA Design
13 Rice University
14 MarkAyres Engineering
15 University of Nevada, Las Vegas
16 University of Wisconsin-Madison

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-91036
October 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photo by Josh Bauer, NREL

NREL prints on paper that contains recycled content.

Preface

The Heliostat Consortium for Concentrating Solar-Thermal Power (HelioCon) began in 2021 to advance heliostat technologies over the course of 5 years. This report provides an update on the progress the HelioCon team has made in 2024, including sharing research highlights; expanding the number of partnerships with industry, research and educational institutions, and other stakeholders; expanding our HelioCon community; providing information to a growing audience through our web presence; and participating in national and international conferences with industry leaders.

Guangdong Zhu

Guangdong Zhu, Ph.D.

HelioCon Executive Director

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38488/38714.

The authors would like to thank our Board of Advisors, who provide valuable feedback and help prioritize opportunities and capabilities. The full list of advisors is available at https://heliocon.org/advisors.html.

We would also like to thank our advisors from the U.S. Department of Energy, particularly Andru Prescod and David Haas, for their rigorous review and invaluable support of HelioCon.

List of Acronyms

ABL	atmospheric boundary layer
ABLRF	Atmospheric Boundary Layer Research Facility
ADACS	Avian Detection and Collection System
ANU	Australian National University
BACI	before-after control-impact
BCS	beam characterization system
CAD	computer-aided design
CENER	National Renewable Energy Center of Spain
CIEMAT	Centre for Energy, Environmental and Technological Research
CPU	central processing unit
cRIO	compact real-time embedded industrial controller
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	concentrating solar-thermal power
CST	concentrating solar thermal
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPC	engineering, procurement, and construction
FY	fiscal year
GPU	graphics processing unit
HALOS	Heliostat Aimpoint and Layout Optimization Software
HelioCon	Heliostat Consortium for Concentrating Solar-Thermal Power
HFCS	heliostat field control system
IAB	integrated access and backhaul
IEC	International Electrotechnical Commission
IPH	industrial process heat
kWh	kilowatt-hour
LCOE	levelized cost of energy
LCOH	levelized cost of heat
LIDAR	Light Detecting and Ranging
LSAMP	Louis Stokes Alliances for Minority Participation
MBSE	model-based system engineering
MCRT	Monte Carlo ray-tracing
mrad	milliradians
NEPA	National Environmental Policy Act
NIO	Non-Intrusive Optical
NREL	National Renewable Energy Laboratory
NSTTF	National Solar Thermal Test Facility
O&M	operations and maintenance
OSAMS	Operating Surface Angle Measurement System
PV	photovoltaic
PROMETHEUS	Predictive and Optimized Control of Heliostats for Future Solar Fields
R&D	research and development
ReTNA	Reflected Target Non-Intrusive Assessment

RFP	request for proposal
RMS	root mean square
RTE	resources, training, and education
SAM	System Advisor Model
SCADA	supervisory control and data acquisition
SETO	Solar Energy Technologies Office
SFERA	Solar Facilities for the European Research Area
SIPS	Small Innovative Projects in Solar
SOFAST	Solar Optical Fringe Alignment Slope Technique
SolarPACES	Solar Power and Chemical Energy Systems
SQL	structured query language
TEA	techno-economic analysis
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle

Executive Summary

Heliostat-based concentrating solar-thermal power (CSP) systems offer immense potential to provide low-cost, dispatchable renewable thermal and electrical energy to help achieve 100% decarbonized energy infrastructure in the United States. CSP with low-cost thermal energy storage can be used either to produce dispatchable electricity or provide high-temperature heat to difficult-to-decarbonize industries, such as cement, steel, and chemical production. The U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO) is working to improve the techno-economic performance of heliostat-based CSP systems, with a target of $0.05 per kilowatt-hour electricity (kWh_e) or $0.02 per kilowatt-hour thermal (kWh_{th}) for heat generation for next-generation CSP plants with thermal energy storage.

In 2021, SETO funded the formation of the Heliostat Consortium for Concentrating Solar-Thermal Power (HelioCon), a 5-year consortium designed to advance U.S. heliostat technologies by engaging industry, subject matter experts, and general stakeholders for direct project-level collaboration, external consulting, and mission-specific panels and workshops. HelioCon is led by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, in partnership with the Australian Solar Thermal Research Institute.

HelioCon emphasizes the significance of heliostats as a key component of CSP technologies. Heliostats track the sun to reflect sunlight to a receiver, where the thermal energy is captured by a heat transfer medium and transferred to a thermal energy storage vessel. The energy can be stored as heat for hours to days prior to use for industrial heating or electric power generation. There can be more than 10,000 heliostats in a single CSP plant, representing 30%–50% of the cost of system construction and a primary driver of operations and maintenance (O&M) costs.

HelioCon serves as a hub to integrate all DOE-funded efforts that directly advance heliostat technologies and engage the international research community on this topic.

HelioCon Mission and Objectives

The HelioCon mission is to promote the development and commercial deployment of heliostat-based CSP technologies in the United States by advancing the understanding, performance, and overall cost-effectiveness of heliostats and related technologies. To accomplish this mission, HelioCon pursues the following strategic objectives:

- Develop strategic core capabilities and infrastructure to support high-performance heliostat manufacturing, validation, and optimization and facilitate industry's ability to design, manufacture, install, and operate central receiver heliostat fields with higher technical and economic performance.
- Fund research on new technologies with significant potential to improve heliostat field economic performance.
- Form U.S. centers of excellence focused on heliostat technology to restore U.S. leadership in heliostat research, development, and validation.
- Promote workforce development by developing/enhancing training and educational programs in heliostat design, production, and operation.
- Support the growth of the industry with the developed HelioCon resources, capabilities, and expertise.

Completed Work

In 2022, HelioCon released a multiyear heliostat roadmap,[1] which identifies research, development, and deployment gaps in heliostat technologies as well as strategies to overcome them. The report shares recommended strategies to reduce commercial risks and improve economic competitiveness to attract investors to heliostat-based CSP systems. Guided by the roadmap study, researchers from core HelioCon member organizations have been conducting research and development (R&D) tasks that address the most critical gaps identified in the roadmap.

To this end, HelioCon researchers have advanced the commercial readiness of heliostat characterization and design tools, including Reflected Target Non-Intrusive Assessment (ReTNA), the Solar Optical Fringe Alignment Slope Technique (SOFAST), and the Non-Intrusive Optical (NIO) technology, and have worked with HelioCon's industrial partners to assess composite mirror facets. Progress has also been made toward a solar field closed-loop wireless control system, a collaboration between HelioCon researchers, academic institutions, and industrial partners. Additionally, projects based on university partnerships (including Northeastern University, Rice University, and the University of Nevada, Las Vegas) have increased CSP awareness and education in higher education.

HelioCon also issued a second request for proposals (RFP) in fiscal year 2024 (FY24), building on the first RFP that was announced in FY23. Round 2 of the RFP was issued in December 2023, with $3.1 million total awarded to six awardees in July 2024. The awarded projects are aimed at innovating heliostat controls, deployment, and workforce training to lower the cost of CSP and support the expansion of a heliostat-trained workforce. More information on the awardees can be found in Section 1.2.

Members of HelioCon continue to promote work being done in the heliostat industry through website content, outreach, networking at conferences, workshops, a seminar series, and other methods.

Planned Work

As HelioCon completes its third year, it plans to leverage learnings from past years and feedback from stakeholders to update the 2022 roadmap, which would guide HelioCon's future efforts.

Another key effort in the next year is a CSP value promotion campaign, which will include a stakeholder meeting and compile a CSP value study for California and the western United States with third-party validation. The meeting will solicit stakeholder feedback, provide information on current CSP technologies, and promote the value of CSP in future grid scenarios.

In the upcoming years, awards to the six projects from the HelioCon RFP Round 2 will focus on lowering the cost of heliostats and heliostat technologies and creating new market opportunities for the heliostat industry. Projects encompass topics such as heliostat soiling, control, performance, and cost reduction, as well as education and outreach. Projects will be implemented over the next 1–3 years.

[1] Available at https://www.nrel.gov/docs/fy22osti/83041.pdf.

A key component of the projects will be strong collaboration and communication among the HelioCon core member organizations and 11 awardees from the RFPs. Researchers from NREL, Sandia National Laboratories, and the Australian Solar Thermal Research Institute will work with the awardees and connect them to valuable resources at the labs.

HelioCon founding (core) members will continue the R&D efforts identified as highest priority for HelioCon. Detailed research efforts under HelioCon, including HelioCon directly funded projects and projects funded under other funding resources, are summarized in Chapters 2–13. HelioCon publications are highlighted in Chapter 14.

Anticipated Results

Major anticipated outcomes from HelioCon's work 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 heliostat technologies
- An engaged and active heliostat community that advances heliostat technologies.

The consortium will use 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's Impact at a Glance

128
Staff

47
Projects

~100,000
Interactions
(across all outreach efforts)

20
Publications/Seminars

27
Lead Researchers

16
Consortium Members
(by the end of FY24)

19
Partners
(collaborating without direct funding from the consortium)

10
Media Mentions

Table of Contents

List of Figures

List of Tables

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

1

HelioCon Community
2024 Update

1 HelioCon Community 2024 Update

In 2021, the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO) funded the Heliostat Consortium for Concentrating Solar-Thermal Power (HelioCon) to advance U.S. heliostat technologies. Since launching in 2021, the consortium has quickly grown in membership, support, and awareness. HelioCon is led by the National Renewable Energy Laboratory (NREL) in partnership with Sandia National Laboratories (Sandia) and the Australian Solar Thermal Research Institute (ASTRI). The HelioCon team also includes a Board of Advisors that comprises utilities; developers; plant owners; component suppliers; engineering, procurement, and construction companies; academic researchers; standards organizations; and international advisors. In addition, consortium-funded project performers and cost-share providers, as well as non-consortium stakeholders—including subject matter experts from U.S. and international institutions—participate in the consortium. This section describes HelioCon's impact in fiscal year 2024 (FY24) by detailing the people involved in the consortium, the request for proposals (RFP) issued to advance heliostat technologies, and the consortium's outreach activities.

1.1 People

1.1.1 HelioCon Leadership

The HelioCon leadership team consists of the following people:

- **Guangdong Zhu, Ph.D.**, HelioCon Executive Director. Dr. Zhu is the group manager and a senior researcher in the Thermal Energy Systems Group within the Energy Conversion and Storage Systems Center at NREL.
- **Margaret Gordon, Ph.D.**, HelioCon Co-Lead. Since 2021, Dr. Gordon has managed the Concentrating Solar Technologies Group of 30+ members at Sandia and the National Solar Thermal Test Facility, which is the only large-scale high-flux testing facility in North America.
- **Craig Turchi, Ph.D.**, HelioCon Partnership Director. Dr. Turchi's tenure at NREL spans two periods; most recently, he returned to NREL in 2008. Dr. Turchi is the manager of the Thermal Energy Science and Technologies group and he also leads the concentrating solar-thermal power (CSP) program at NREL.

1.1.2 HelioCon Staff

HelioCon's research and administrative staff has grown 13% from the previous year. This growth has allowed HelioCon to quickly increase its research capacity, presence at conferences and events, ability to reach new or potentially new partners, and leadership in the society for women in CSP. Specifically,

- HelioCon participating staff increased to 128 in FY24.

- HelioCon key staff increased to 27 in FY24.
- HelioCon worked with 41 graduate and undergraduate students (including 13 interns hired at national labs) in FY24. HelioCon recruited two undergraduate interns under DOE's Science Undergraduate Laboratory Internships program to support the consortium's research activities. HelioCon has mentored 72 interns since its inception.
- HelioCon also took this opportunity to expand its workforce for heliostat research and development (R&D) and increase its diversity, equity, inclusion, and accessibility portfolio with activities such as:
    - The HelioCon seminar series, consisting of 29 publicly available recorded videos to spread knowledge. This year, we did a seminar highlighting Northeastern University's project on a mirror-washing study that was conducted by two Louis Stokes Alliances for Minority Participation (LSAMP) students.
    - Thirteen interns from diverse backgrounds contributed to HelioCon projects at NREL and Sandia in FY24, and their work will be highlighted in the HelioCon intern seminar in August.
    - We spotlighted Northeastern student capstone projects by featuring them in an article on our website.

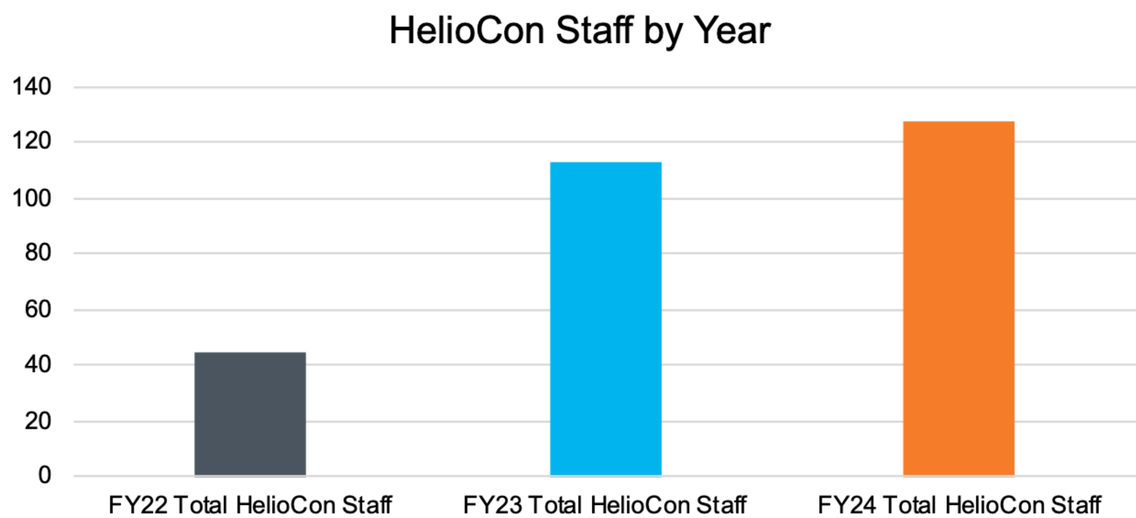


Figure 1. Trends of HelioCon staff growth in the past 3 years

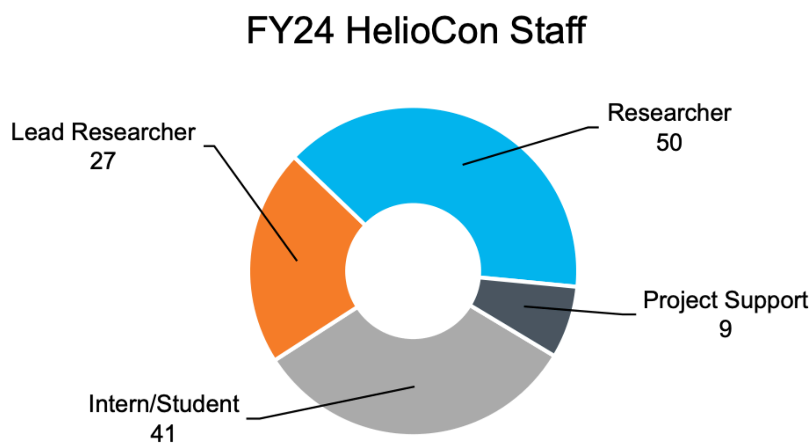


Figure 2. HelioCon 2024 staffing distribution

1.1.3 HelioCon Members

HelioCon members perform research, development, and deployment work that furthers HelioCon's mission. Research, development, and deployment activities are supported directly through HelioCon and/or by non-consortium-funded cost sharing. Members of HelioCon are given access to consortium research facilities and resources, and direct collaborations between consortium members are highly encouraged. Membership in HelioCon has increased from seven to 19 members since 2022, and the consortium has added five new members since last year.

Current members are:

- NREL (lead: Guangdong Zhu)
- Sandia National Laboratories (lead: Margaret Gordon)
- ASTRI (lead: Dominic Zaal)
- Commonwealth Scientific and Industrial Research Organisation (lead: Mike Collins)
    - Australian National University (lead: Joseph Coventry)
    - University of Adelaide (lead: Matthew Emes)
    - Queensland University of Technology (lead: Michael Cholette)
- HelioCon members recruited through RFP Rounds 1 and 2 (listed in Table 2).

1.1.4 Board of Advisors

HelioCon's Board of Advisors is made up of subject matter experts who represent utilities; developers; plant owners; component suppliers; engineering, procurement, and construction companies; academia; standards organizations; and international advisors. Through regular meetings and interactions with the leadership team, the Board of Advisors:

- Provides a knowledge base of existing industrial development and scientific progress
- Assists with the early development and implementation of the consortium roadmap and RFPs, subject to conflict-of-interest procedures
- Promotes collaborations through multiorganization projects
- Provides feedback to ensure that work performed under the consortium maintains industrial relevance.

Table 1. 2024 Board of Advisors

2024	
Joe Stekli (Board of Advisors chair)	Galvanize Climate Solutions
Antonio Luis Ávila-Marín	Centre for Energy, Environmental and Technological Research (CIEMAT)
Yaniv Binyamin	BrightSource Energy
Kaycee Chang	California Energy Commission
Yoel Gilon	Solar Technology Consultant
Michel Izygon	Tietronix
Sarah Kurtz	University of California Merced
Hameed Metghalchi	Northeastern University
Hank Price	Solar Dynamics LLC
Marc Röger	German Aerospace Center
Laura Schaefer	Rice University
Steve Schell	Heliogen
Kimani Toussaint	Brown University
David White	CSP Consultant

1.2 Request for Proposals

HelioCon used an RFP to engage a wide community to advance heliostat technologies. Round 2 of the RFP was issued in December 2023, with $3.1 million total awarded to six awardees in July 2024. The focus of the awarded projects is to innovate heliostat controls, deployment, and workforce training with the goal of lowering the cost of CSP and supporting the next generation of highly trained workers. Researchers need to realize significant techno-economic improvements for heliostats to meet federal electricity cost goals for CSP facilities—5 cents per kilowatt-hour (kWh) for dispatchable CSP configurations or 2 cents/kWh for thermal production. Several of HelioCon's selected projects have the potential to reduce heliostat costs through maintenance and control improvements. Others aim to create new educational programs to prepare the heliostat workforce to bring these and future innovations to industry, which could reduce costs while at the same time providing economic benefits to local communities. The Round 1 and 2 RFP awardees are listed in Table 2.

Table 2. HelioCon Members From RFP Rounds 1 and 2

Applicant	Principal Investigator	Name	Duration (Months)
RFP1			
Solar Dynamics – SunRing	Kyle Kattke	SunRing: Advanced Manufacturing and Field Deployment	12
University of New Mexico	Eirini Eleni Tsiropoulou	HELIOCOMM: A Resilient Wireless Heliostats Communication System	36
Northeastern University	Mohmmad Metghalchi	An Educational Program on Concentrated Solar Power Heliostats for Power Generation and Industrial Process	24
Solar Dynamics – Wireless	Rick Sommers	Demonstration of a Heliostat Solar Field Wireless Control System	12
University of Arizona	J. Roger Angel	Self-Focusing Heliostats With Closed-Loop Tracking	18
Tietronix	Michel Izygon	Digital Twin and Industry 4.0 in Support of Heliostat Technology Advancement	18
RFP2			
DKA Design	Derek Schulte	Soiling on Heliostats Estimated by Shaded and Unshaded Scatterometry	18
Rice University	Laura Schaefer	A Brighter Future: Education and Outreach for Small-Scale Concentrating Solar on Urban Brownfields	24
Northeastern University	Hameed Metghalchi	Advancing University-Level Education on Heliostat Design and Operation	24
University of Wisconsin	Michael Wagner	PROMETHEUS: Predictive and Optimized Control of Heliostats for Future Solar Fields	24
University of Nevada, Las Vegas	Heejin Cho	Precision Angle Measurement System for Enhanced Heliostat Performance and Cost Reduction	24
MarkAyres	Mark Ayres	Solar Field Control Software	24

1.3 Outreach

HelioCon relies on a variety of tactics to share news and information about the CSP industry. In addition to maintaining a website with an expanding suite of resources, HelioCon members regularly speak at national and international conferences, and a virtual HelioCon seminar series has seen significant growth in viewership since it launched in 2021. The HelioCon seminar series now features 29 recorded presentations from experts across the industry. The goal of the series is to increase the accessibly of CSP industry knowledge. Topics range from fundamentals of optical metrology to commercial plant lessons learned to recommended guidelines for standardized reflectance measurements. The HelioCon seminar page is the third-most-visited page on the HelioCon website.

1.3.1 Website Visits

The HelioCon website, www.HelioCon.org, promotes heliostat technology and its applications and shares resources with the public and key stakeholders. HelioCon is intended to serve as a resource to interested persons/entities on heliostat technologies, and the website plays a key role in achieving this goal. Staff members regularly update the website with new content, share content on social media platforms and through DOE and NREL communications channels, and work to increase traffic and visits to the site.

In FY24, the HelioCon website stats showed:

- Nearly 3,000 new users
- The homepage was the most-viewed page, followed by educational videos
- The top three countries in terms of visitors were the United States, Australia, and China.

Additionally, the website now includes a new section for featured HelioCon projects.

Figure 3. The HelioCon website

1.3.2 Conferences

The conferences that HelioCon attended in FY24 are listed below. For more details on HelioCon's presence at these conferences, please visit the HelioCon website: https://heliocon.org/resources/heliocon_workshops_and_conferences.html.

SolarPACES 2023 Conference

HelioCon had a strong presence at the 2023 Solar Power and Chemical Energy Systems (SolarPACES) conference, which was held October 10–13, 2023, in Sydney, Australia. SolarPACES is an international cooperative network that brings together teams of experts from around the world to focus on the development and marketing of CSP systems. HelioCon shared 17 presentations at SolarPACES.

Figure 4. HelioCon at the 2023 SolarPACES conference

Photo by NREL

HelioCon Workshop 2024

HelioCon hosted its annual workshop in Anaheim, California, from July 16–17, 2024. The conference was colocated with the American Society of Mechanical Engineers Energy Sustainability Conference. There were five HelioCon sessions with 21 technical presentations. During the technical sessions, researchers presented detailed information about specific HelioCon topic areas and initiatives. In the summary session of the workshop, the HelioCon team provided a high-level overview of past accomplishments and highlights, introduced recently awarded RFP projects, and led a discussion on progress made on the gaps identified in the heliostat roadmap report as well as future goals. The workshop had options for virtual and in-person attendance, with 35 people attending in person and two participating virtually.

Figure 5. Participants at the 2024 HelioCon Workshop

Photo by NREL

1.3.3 HelioCon Seminar Series

The HelioCon seminar series provides a forum for HelioCon's members to share their latest research and stay up to date on industry trends. Eight HelioCon seminars were hosted in FY24, presented by RFP Round 1 awardees, NREL staff, and an industry presenter.

Table 3. HelioCon Seminar Series

Date	Title	Speaker
September, 18, 2024	Wind Driven Loads on Solar Collectors: Perspectives from Two Field Campaigns	Dr. Shashank Yellapantula (senior scientist, NREL)
August 28, 2024	Intern Projects in Heliostat Technologies at NREL, Sandia	Milo Davis, Kyle Sperber, Justin Kilb, Yu Zhao (NREL); Javier Martell, Madeline Hwang, Taylor Johnson, Nicholas Phelps, Kristina Ji (Sandia)
June 12, 2024	Solar Mirror Reflectance and Standardized Reporting	Tucker Farrell (research engineer, NREL) and Stephanie Meyen (researcher, NREL)
March 20, 2024	HELIOCOMM: A Wireless Communications Autonomous System for Concentrated Solar Power Fields	Eirini Tsiropoulou (associate professor, University of New Mexico)
February 21, 2024	Digital Twin and Industry 4.0 in Support of Heliostat Technology Advancement	Michel Izygon (chief technology officer, Tietronix Software Inc.)
January 17, 2024	Fields of Twisting Heliostats for Direct Air Capture and Making Syngas and Cement	J. Roger Angel (professor of astronomy and optical sciences, University of Arizona)
November 15, 2023	Louis Stokes Alliances for Minority Participation (LSAMP) Summer Experience: A Cleaning Mirror Assessment with Reflectance	Kyla Hampton (dual degree engineering student, Clark Atlanta University and Northeastern University), and Courtney Jackson (dual degree engineering student, Clark Atlanta University and Northeastern University)
October 18, 2023	Calibration and Characterization Systems in Solar Concentration Plants: Field Expertise, Conclusions, and Lessons Learned	Adriana Zurita (senior researcher and project manager, Tewer Engineering), and Marco Carrascosa (CEO, Tewer Engineering)

1.3.4 Other Seminars

Upcoming seminars will include presentations that feature HelioCon RFP winners and experts from across the CSP industry.

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

2

Research at National Laboratories

Metrology

2 Research at National Laboratories – Metrology

Since its creation in 2021, HelioCon has been enabling strategic core testing and modeling capabilities and infrastructure at national labs, supporting heliostat technology development in relevant industries, and serving as a central repository to integrate industry, academia, and other stakeholders for heliostat technology research, development, validation, and deployment. Below are key research initiatives and future priorities for the consortium.

HelioCon researchers have contributed robust research to the heliostat field through a variety of technical reports, publications, patents, lab activities, and an RFP.

2.1 Third-Party Evaluation Platform

Description: Many heliostat-based power tower plants, including Ivanpah and Crescent Dunes in the United States, are underperforming, posing a significant barrier to commercial CSP deployment (Zhu et al. 2022; HelioCon Website n.d.). Establishing a standardized third-party evaluation platform at NREL would address quality control issues and bridge the gap between heliostat developers and investors by providing credible evaluations. This project aims to develop such a platform by acquiring metrology tools, standardizing procedures, conducting demonstrations, and engaging in community outreach to create internationally accepted standards, thereby enhancing the industry's maturity and economic viability.

Project Lead: Rebecca Mitchell and Stephanie Meyen (NREL)

Objectives and Impacts:

The primary objective of the proposed project is to create a measurement platform, provide guidance, and establish standards for the third-party evaluation of heliostats. Anticipated impacts include:

- The fully validated third-party evaluation platform is anticipated to provide accurate in situ performance measurement of commercial heliostat designs, which would result in an annual energy uncertainty of less than 5% for a given commercial system.
- The third-party evaluation platform would greatly reduce the commercial deployment risks of a given commercial design and increase investors' confidence in commercial project deployment.

Approach:

- Acquire and install tools: Install instruments for measuring various heliostat metrology types, as outlined in the HelioCon roadmap, including sun shape, atmospheric attenuation, heliostat reflectance, surface shape, opto-mechanical errors, beam quality, soiling, and wind loads.
- Develop standardized procedures: Establish standardized procedures for third-party heliostat evaluation at the Flatirons Campus.
- Showcase capabilities: Conduct a round robin measurement campaign with 2–3 commercial heliostat prototypes to demonstrate the third-party evaluation capabilities.

- Disseminate information: Publicly report outcomes, conduct outreach with research institutes and industry, and enhance awareness through a student workshop.

Status:

- Beam characterization system (BCS) target installed at NREL Flatirons Campus.
- Ten heliostat prototypes set to be installed in the coming months.
- Comparison testing between BCS, Non-Intrusive Optical (NIO), and Reflected Target Non-Intrusive Assessment (ReTNA) will be conducted in FY24.
- A project starting in FY25 will develop the third-party evaluation platform with capabilities for industry customers.

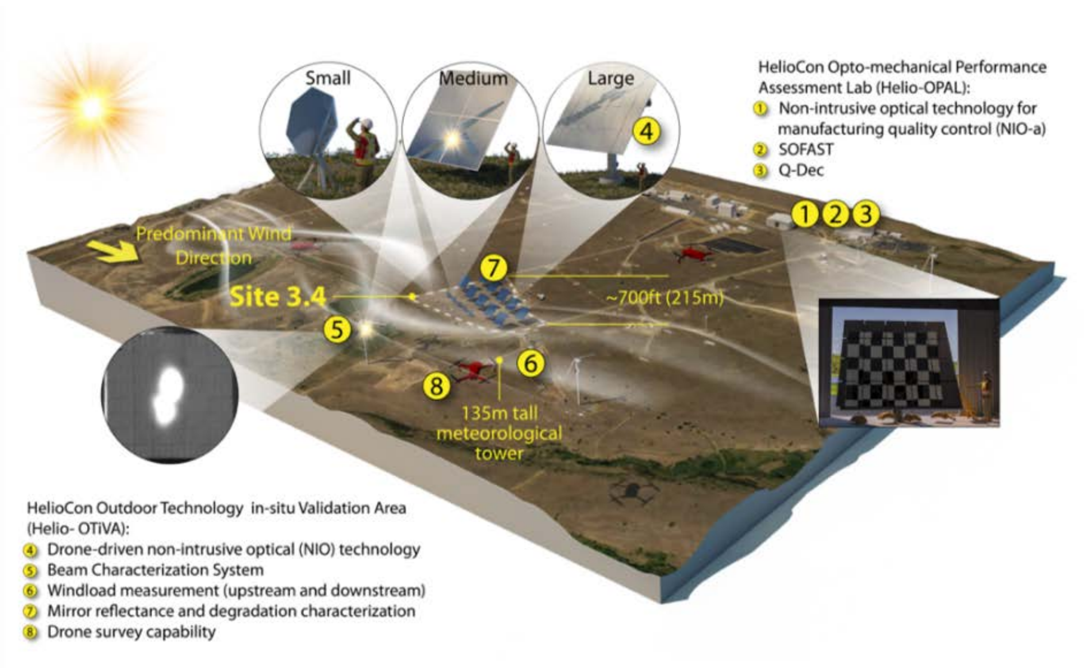


Figure 6. An illustration of the third-party heliostat evaluation platform at NREL's Flatirons Campus

Image by Josh Bauer, NREL

2.2 SOFAST 2.0: High-Fidelity, Flexible Optical Measurement

Description: Solar Optical Fringe Alignment Slope Technique (SOFAST) 2.0 produces high-fidelity measurements of CSP mirrors—both individual facets and multi-facet heliostats. It provides the following three operating modes. (1) Fringe: Using an active display, it produces high-resolution slope maps measuring hundreds of thousands of points across a full CSP mirror in under 15 seconds. (2) Fixed: Using a low-cost printed target, it measures medium-resolution slope maps with thousands of points, with a data acquisition time of a fraction of a second. (3) Hybrid: This includes both fixed and fringe modes, selectable by a simple software switch and no hardware change. For all modes, SOFAST delivers multiple analysis results, including detailed slope maps, error analysis, and built-in ray-tracing to estimate energy performance of an as-measured mirror.

Project Lead: Randy Brost (Sandia)

SOFAST 2.0 (Andraka 2018; Smith and Brost 2022) is also highly flexible. Its open-source architecture and associated computer-aided design (CAD) layout tool allows it to be applied to a wide range of problems, including mirrors with horizontal, vertical, or tilted orientations, with sizes ranging from a small educational system completely contained within a laptop to factory or lab-scale systems to large-scale systems capable of measuring full heliostats.

SOFAST 2.0 is also easy for industry, research, or education partners to implement. Both SOFAST 2.0 and its associated CAD layout tool are released open-source through OpenCSP, and SOFAST 2.0 includes features to streamline calibration using photogrammetry and computer vision techniques.

Objectives and Impacts:

The objective of the Sandia team is to deliver SOFAST 2.0 as a high-quality, high-performance, flexible system to meet a variety of CSP needs, and make it widely accessible to maximize impact. Anticipated impacts include:

- SOFAST 2.0 is anticipated to enable developers of new CSP collectors to produce higher-quality optics, increasing energy production.
- The system will enable manufacturers of CSP mirrors and collectors to achieve higher manufactured product quality through the use of high-speed, high-fidelity inline inspection.
- Due to its free, open-source access and increased flexibility and range of operating conditions, SOFAST 2.0 is anticipated to increase the number of developers and manufacturers enjoying the improvements mentioned above.
- The program is designed to increase knowledge of both researchers and workforce by providing a low-cost, easy-to-access deflectometry capability to support both research and learning.

Approach:

- Directly measure slope—the primary functional aspect of CSP mirrors.
- Include automated correction methods to make the system robust and easier to implement.

- Check accuracy using ground truth standards and methods (in progress).

Status:

- SOFAST 2.0 is operational and integrated with OpenCSP; documentation is nearly complete.
- So far, SOFAST 2.0 has been transferred to two industrial partners, with a third imminent.
- SOFAST has been used for both prototype development and high-volume production at a key industrial partner, successfully measuring thousands of production mirrors.
- SOFAST is part of a new Sandia capability to measure the optical effect of temperature change.
- An initial ground truth check has demonstrated accuracy of 0.08 milliradians (mrad) root mean square (RMS) (still in progress).

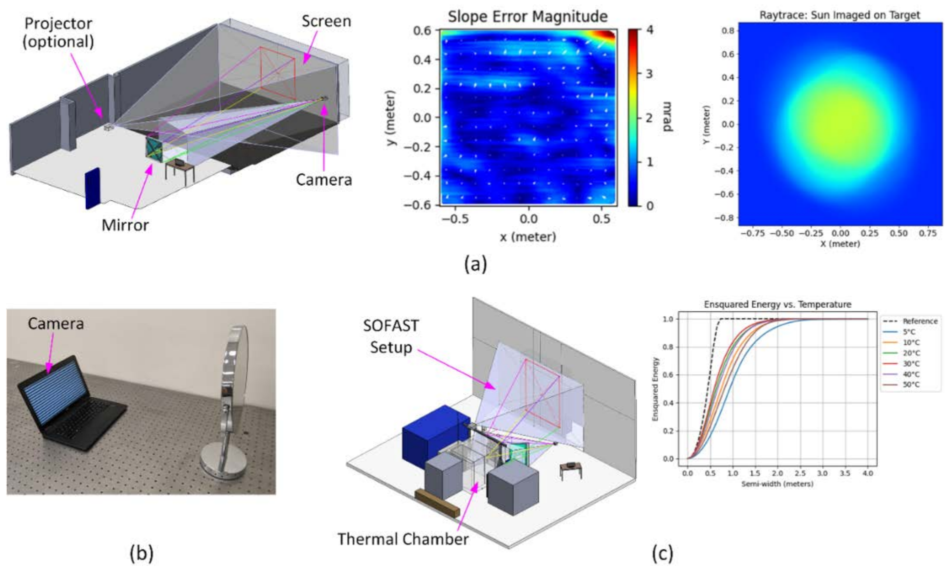


Figure 7. Example SOFAST applications. (a) Single heliostat facet with ray-tracing analysis. (b) Laptop installation for education. (c) Thermal chamber setup and temperature analysis.

Images from Sandia Concentrating Solar Optics Laboratory

2.3 Non-Intrusive Optical Technology

Description: The drone-based Non-Intrusive Optical (NIO) technology developed at NREL allows for in situ characterization of heliostat optical errors at commercial-scale power tower CSP plants (R. A. Mitchell and Zhu 2020a; 2020b; Farrell et al. 2021; R. Mitchell and Farrell 2024). The method will be validated using data collected from commercial solar fields, including Cerro Dominador and Crescent Dunes, and compared against BCS measurements of tracking error at NREL's Flatirons Campus.

Project Lead: Rebecca Mitchell and Tucker Farrell (NREL)

Objectives and Impacts:

The primary objective of this project is to provide a beta version of a commercial NIO tool that will further commercial demonstration and could be licensed by CSP plant operators to conduct efficient measurements and monitoring of the solar field, which can be incorporated into operation practices to improve power output. Ultimately, the team plans to perform a large-scale commercial demonstration of the tool. Anticipated impacts include:

- NIO will provide a feasible method of assessing detailed heliostat surface optical errors in commercial-scale plants.
- This technology will provide CSP plants with crucially needed data on impacts to heliostat slope, canting, and tracking errors over time in different conditions, such as varying temperature, wind, and elevation angles.

Approach:

- Obtain stakeholder data to determine the industry needs that the NIO metrology capabilities must meet.
- Develop a commercial NIO package with a user interface and documentation and training, and capability services to meet stakeholder needs.
- Perform a commercial demonstration of the NIO tool by performing data collection activities and providing optical error data deliverables to a plant partner.
- Develop a business strategy to market and launch a beta version of the commercial tool package at the conclusion of the project.

Status:

- Made significant advancements toward commercialization of the NIO software by streamlining the data architecture and improving the reliability of the automated post-processing of data through testing of collected Cerro Dominador and Crescent Dunes data.
- A BCS has been deployed at the Flatirons Campus, and two types of heliostats have been identified for installation at the site. Heliogen heliostats have been delivered on campus and a purchased Heliuss heliostat prototype is being fabricated.
- An IF1200A hexacopter unmanned aircraft system (UAS) has been acquired for NIO data collection, and test flights were conducted at the Flatirons Campus.

Figure 8. The NIO drone test scene and the BCS target installed at NREL's Flatirons Campus

Photo by Rebecca Mitchell, NREL

2.4 OpenCSP: Collaborative Code and Data for CSP

Description: OpenCSP is an open-source platform including source code, applications, and data to enable collaborative development for the CSP community, supporting industry, research, and education.

Project Lead: Randy Brost (Sandia)

Objectives and Impacts:

OpenCSP aims to accelerate the transfer of state-of-the-art CSP metrology and analysis tools to industry; provide a resource for businesses seeking to support CSP development; and enable the code and data to contribute to education. The platform will provide a community collaborative development environment to enable teams to build new, advanced CSP applications more quickly and speed their deployment. Anticipated impacts include:

- OpenCSP will increase the quality of developed CSP collectors by providing a suite of high-quality, free, easy-to-access tools for improving CSP collector optical accuracy.
- The platform supports improved CSP analysis by providing a set of ready-to-use CSP optical analysis tools.
- An open-source platform would increase the quality and relevance of CSP research by providing substantial real-world datasets to enable researchers to more easily engage with realistic problems.
- OpenCSP will increase the quality of CSP optical metrology by providing detailed design information for a high-accuracy optical calibration reference standard, including both manufacturing and operational guidelines.
- The platform is anticipated to increase the quality and depth of new state-of-the-art CSP metrology and analysis software by enabling multi-institution collaboration and encouraging teamwork, and by reducing redundancy and replicate work.

Approach:

- Establish a strong collaborative code development environment set up to support effective team code development, including automatic testing, document generation, and issue tracking.
- Provide a large corpus of difficult-to-produce CSP research data.
- OpenCSP welcomes all to use its resources and contribute to make it even better.
- The OpenCSP platform will include the following subsections, all of which are provided with an open-source license allowing unlimited use, requiring acknowledgment:
    - *OpenCSP_Code*: Both foundation classes for building new programs and ready-to-run applications, including Sandia's SOFAST 2.0 code, all in Python.
    - *OpenCSP_Data*: Large datasets for research, optical targets for metrology ground truth tests, and test data for OpenCSP_Code.
    - *OpenCSP_Mechanical*: Includes an interactive CAD tool for designing deflectometry layouts, plus a gallery of CAD models to support collaborative CSP research.

- *OpenCSP_Tools*: Non-code tools to aid CSP analysis and understanding.
- *OpenCSP_Documents*: Documents supporting OpenCSP and related topics.

Status:

- As of July 2024, both code and non-code OpenCSP repositories have been operational for months and are being used by the OpenCSP team. We plan to announce the public opening of OpenCSP at SolarPACES in October 2024, with the presentation: "OpenCSP: Collaborative Code and Data For CSP."
- The OpenCSP web portal is under construction; send inquiries to OpenCSP@sandia.gov.

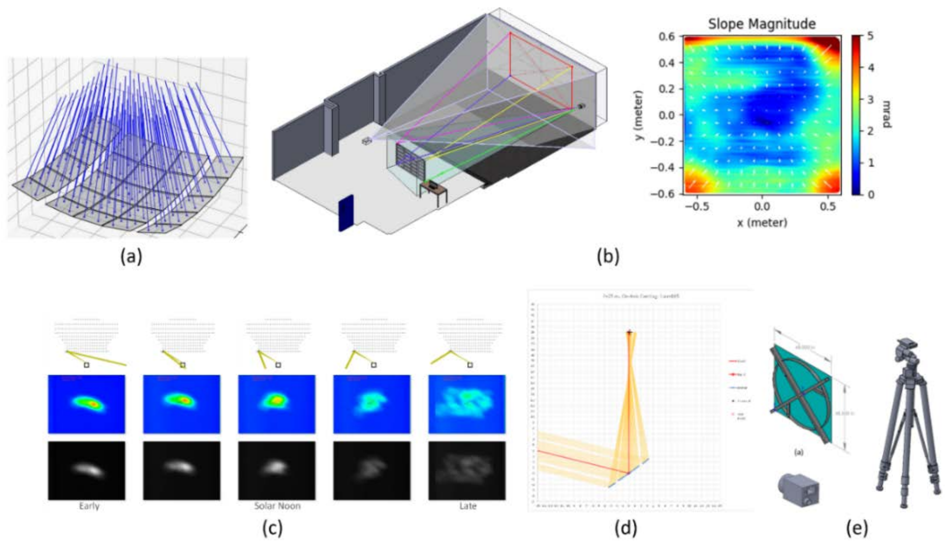


Figure 9. A few OpenCSP examples. (a) Heliostat representation. (b) SOFAST 2.0 deflectometry system. (c) BCS dataset spanning daily and annual variation. (d) Interactive ray-trace tool. (e) CAD examples.

Photo from Sandia Concentrating Solar Optics Laboratory

2.5 ReTNA Technology Development

Description: The Reflected Target Non-Intrusive Assessment (ReTNA) tool measures mirror surface slope and facet canting error for heliostat qualification, R&D, and quality assurance on the heliostat assembly line (Kesseli 2024). It is designed to adopt simple, low-cost equipment, such as modular, lightweight printed targets and off-the-shelf cameras.

Project Lead: Devon Kesseli (NREL)

Objectives and Impacts:

The objective of the ReTNA project is to develop and validate laboratory optical measurement technology to offer the industry a lightweight, low-cost, and portable system capable of fast setup and automated measurement, and to enable accurate measurement of slope and facet canting error for heliostats of various geometries at varied heliostat orientations and with varied loading applied to the heliostat. Anticipated impacts include:

- ReTNA is anticipated to create a new, validated optical measurement system for heliostats in the lab and in industry, with measurement time <1 minute, setup time for a new installation <8 hours, and uncertainty <0.25 mrad.
- The project will develop a standardized protocol for heliostat measurement and a standard measurement output report to add to other measurements available in the heliostat testbed.
- ReTNA aims to complete measurement of at least two commercial heliostats, with the measurement output report reviewed by industry for feedback.

Approach:

- Use target deflection techniques to accurately measure mirror shape.
- Use photogrammetry to reduce the required precision of the setup.
- Leverage advancements in image processing and computer vision to automate measurement.

Status:

- Completed concept-proof stage, and repeated ReTNA testing on a commercial heliostat.
- Built initial ReTNA prototype at NREL, working on second-generation system prototype.
- In next year, complete further rigorous validation campaigns with research and industry partners and collaborate with industrial partners to demonstrate commercial ReTNA layouts.

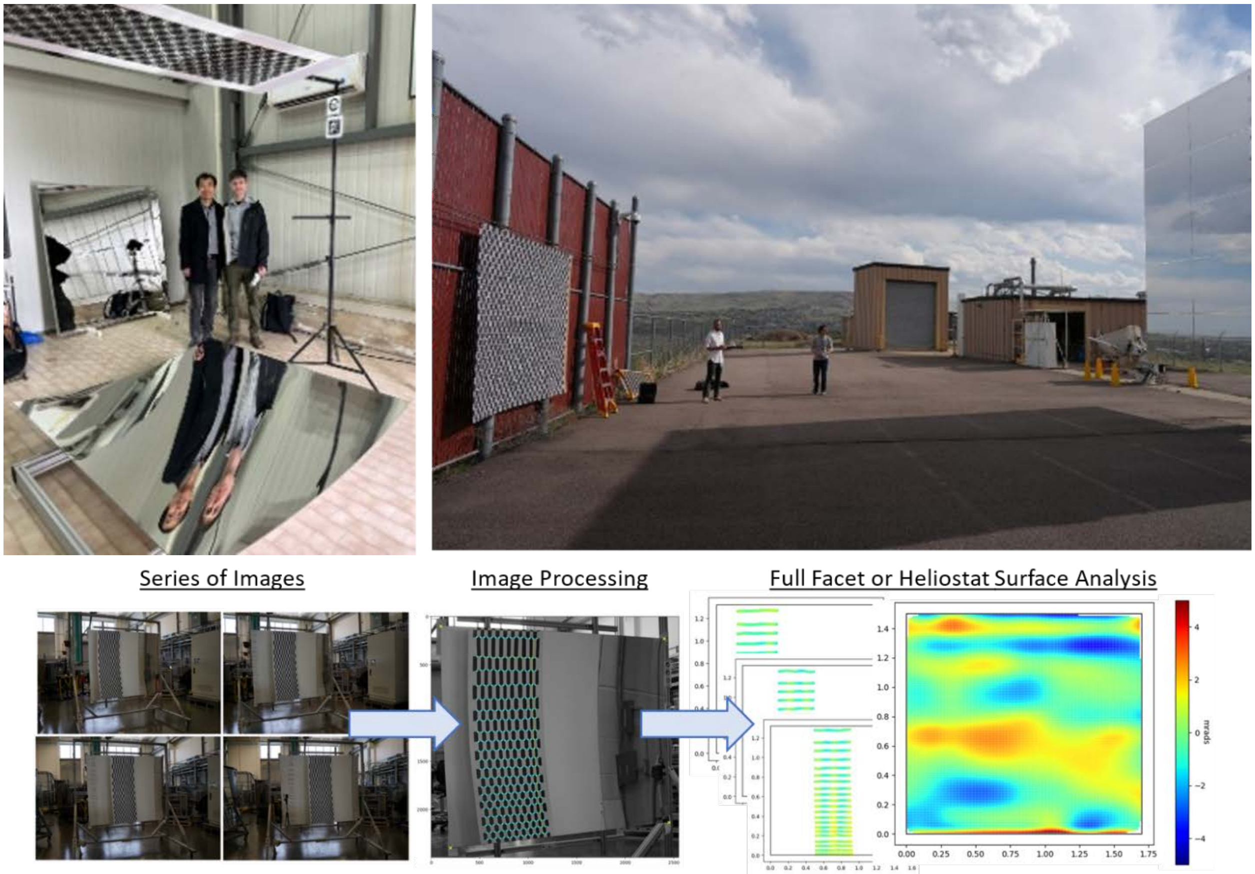


Figure 10. Illustration of ReTNA equipment and setup ease. Top: A ReTNA portable layout (left) and larger stationary setup (right). Several layouts have been demonstrated this year for different applications. Bottom: ReTNA workflow for measurement with a smaller target.

Photos and image by Devon Kesseli, NREL

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

3

Research at National Laboratories

Components and Controls

3 Research at National Laboratories – Components and Controls

3.1 HelioCon Components and Controls: Composites

Description: This project is focused on laminating and testing coupon sandwich mirror facets with 96% reflectivity mirrors (Tsvankin and Muller 2024; Muller 2024). Improving reflectivity from 93% to 96% results in significant field performance gains that offer more than a one-to-one reduction in the CSP levelized cost of energy (LCOE). 96% reflectivity is achieved with 1–2-mm glass mirrors as opposed to the standard 3–4-mm glass. Such thin glass is not structurally robust and therefore requires additional support. Testing with coupons provides the opportunity to learn which adhesive materials and support structures provide the most protection to the silver layer as well as robustness to hail and other damage mechanisms.

Project Lead: Matthew Muller (NREL)

Objectives and Impacts:

The objective of this project is to evaluate the technical viability of composite mirror facet designs. The project's aim is to demonstrate the robustness to hail and the degree of corrosion of the silver layer with added supports. Anticipated impacts include:

- This research is anticipated to offer industry new insights into the expected results of adding materials to mirrors to protect the silver layer. For example, the lamination structure and edge seal on coupon facets have proven no reflectivity degradation under accelerated environmental testing using mirrors with only the lower-cost indoor paint protection of the reflective surface.
- The project also anticipates providing industry and manufacturers with data on supports for environmental protection. For example, there was no damage to 1-mm sandwich mirrors from 1.5-inch hail under a 90° angle of incidence at 45 mph, exceeding International Electrotechnical Commission (IEC) hail testing required for solar panels.

Approach:

- Conduct peel testing for bond strength between the three adhesives and the four adjoining surfaces.
- Measure the performance of thin mirrors from two sources.
- Complete accelerated damp heat, thermal cycling with humidity, UV plus humidity, and condensation testing on 10-cm samples.
- Conduct hail testing on 24-inch samples.

Status:

- Peel testing is complete, resulting in ethylene vinyl acetate providing the highest bond strength.
- Mirror performance characterization is complete.
- 10-cm samples have been laminated with both 1- and 3-mm glass. 3-mm glass is indoor glass and was included because it does not have outdoor protective paint. This provides the opportunity to determine whether adhesive layers and an edge are sufficiently hermetically sealed to protect the silver layer.
- Samples are currently undergoing damp heat, UV plus humidity, and thermal cycling with humidity testing.

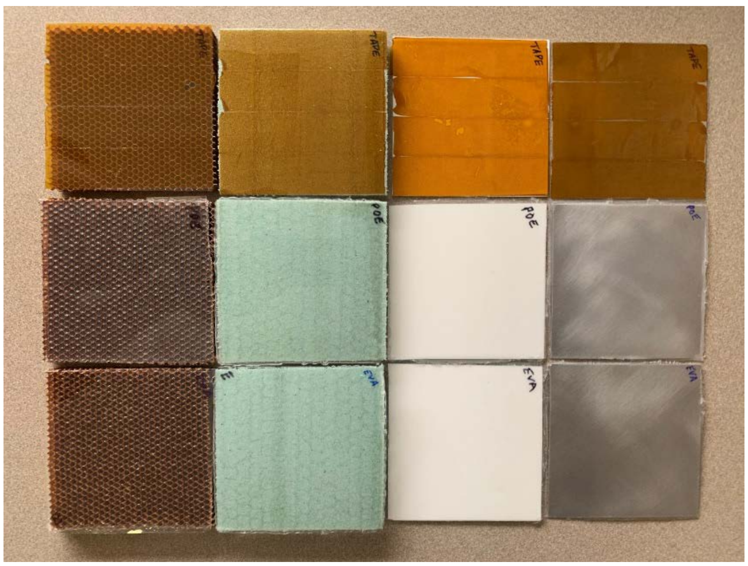


Figure 11. The nine different combinations of surface and adhesive materials subjected to peel testing

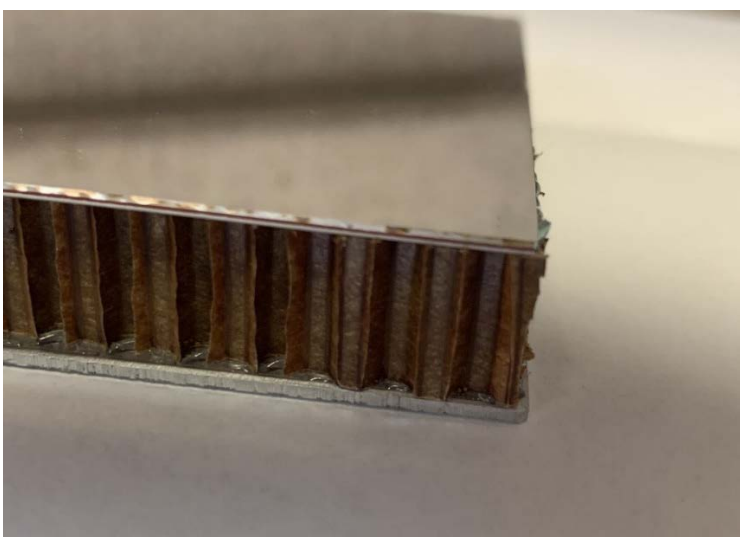


Figure 12. A sample laminate stack with a 1- mm mirror supported by honeycomb before applying and edge seal structure

Photo by Matthew Muller, NREL

3.2 Heliostat Field Closed-Loop Control System Testbed Development

Description: This project is developing a closed-loop controls and wireless communications testbed, which will parallel a DOE SETO heliostat field refurbishment effort (Armijo et al. 2024; Augustine, Zolan, and Armijo 2024). This experimental test system, comprising 218 heliostats, will be flexible. Python closed-loop control architectures will be brought in to demonstrate on-sun with an approximately 200-foot-tall solar tower. This system would also enable testing of wireless controls communications such as Wi-Fi, mesh, and radio platforms. This work is being conducted in a phased approach, with a laboratory closed-loop control testbed used prior to real-time closed-loop control with 4, 16, and the subsequent 218 heliostats (where feedback is tested from one or more measurements of direct optical metrology).

Project Lead: Ken Armijo (Sandia)

Objectives and Impacts:

This system's objective is to create a closed-loop control testbed with highly flexible software and hardware controls and communication and optical sensors that will communicate with both wired and wireless protocols. The project will develop software architectures to determine optimal pointing of each heliostat, accounting for unique metrology considerations. The goal is to decrease commissioning and operations and maintenance (O&M) costs while increasing plant performance for varying solar market flux requirements. Anticipated results include:

- This project will develop new heliostat controls for the laboratories with flexibility across multiple software platforms (e.g., Python).
- The project will explore potential cost/energy savings for commissioning as well as improved pointing for heliostats and the ability to rapidly de-risk technologies before deployments.
- The system offers the ability to rapidly screen advanced control technologies to improve R&D maturities, especially those that are wireless.
- This project aims to develop a novel way to screen control architectures prior to heliostat evaluation.
- The project will develop closed-loop control systems with the ability to de-risk controls that could damage heliostats.

Approach:

- Closed-loop systems have a BCS that provides feedback based on the heliostat's receiver aiming.
- Closed-loop control enables automatic calibration as part of commissioning and fine calibration on a daily or even more frequent basis.
- Hardware to enable closed-loop heliostat control is capable of feedback for plant-level control.
- Python software is integrated within control room architecture and set up to decide which heliostats aim at the receiver to maximize flux and desired pointing strategy distribution.

Status:

- Controls and real-time processing architecture are being completed, with validation work underway.
- Completion of Wi-Fi communications setup, with mesh communications development ongoing.

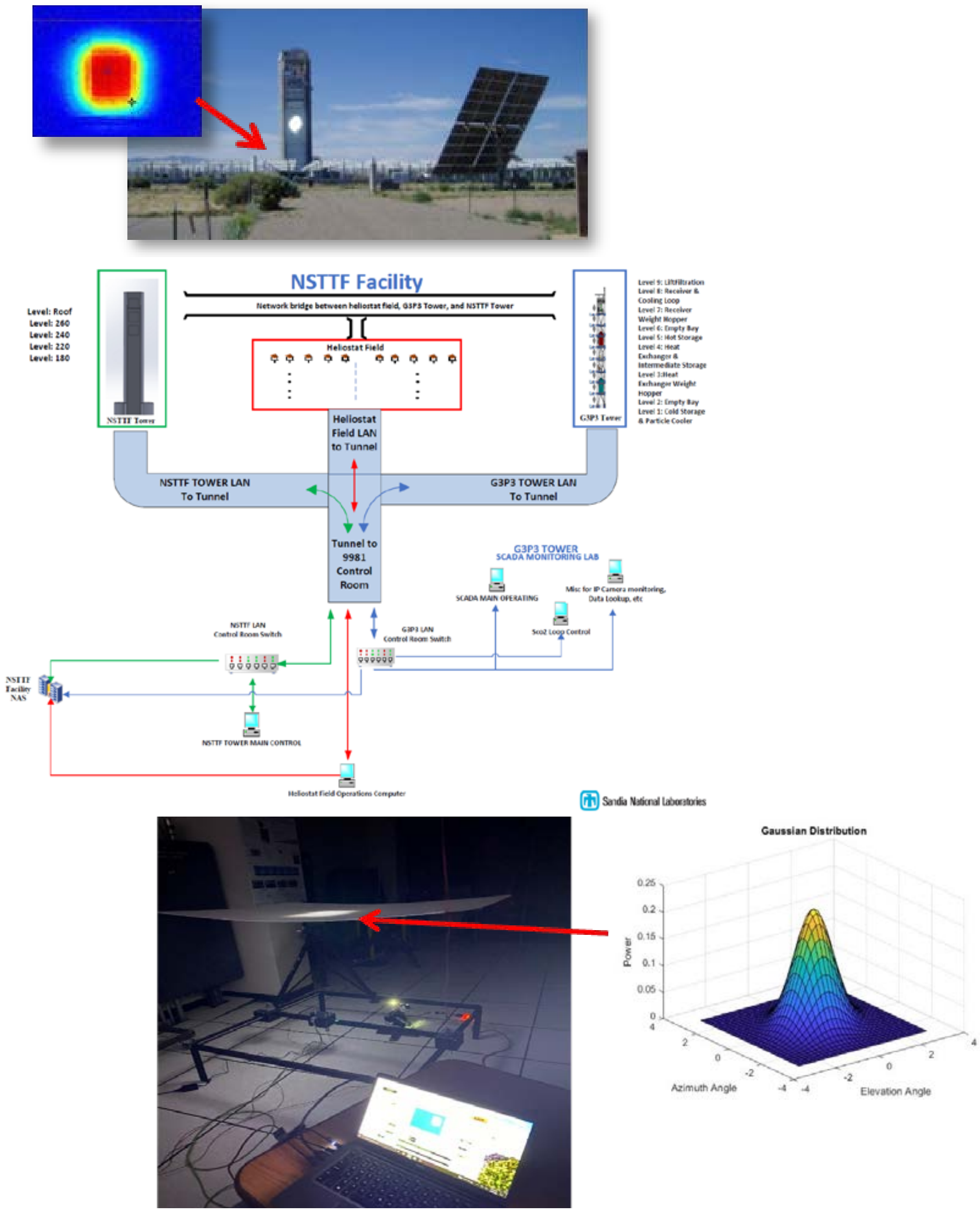


Figure 13. Top: Sandia National Solar Thermal Test Facility (NSTTF) solar tower with on-sun beam and BCS metrology image, used for feedback controls. Middle: Sandia NSTTF closed-loop control system architecture. Bottom: Laboratory closed-loop controls testbed for controls screening with a smaller target.

Images by Luis Garcia-Maldonado, Sandia

3.3 Develop an IEC Design Qualification Standard for Heliostats

Description: Currently, there is no set of standards for heliostats, and this means that each new design and field must go through individual bankability requirements and approvals. This lack of standardization results in additional risks and associated costs. Development and publication of an IEC Design Qualification Standard for heliostats is the intended goal in this subtask as part of a larger development of standards to support cost reduction and maturation of the heliostat industry (IEC 2024).

Project Lead: Stephanie Meyen and Matthew Muller (NREL)

Objectives and Impacts:

The main objective of this project is to obtain IEC approval for a new work proposal and form an international working group with regular development meetings, with a goal to complete a committee draft of 62862-4-3 by the end of 2024. Anticipated results include:

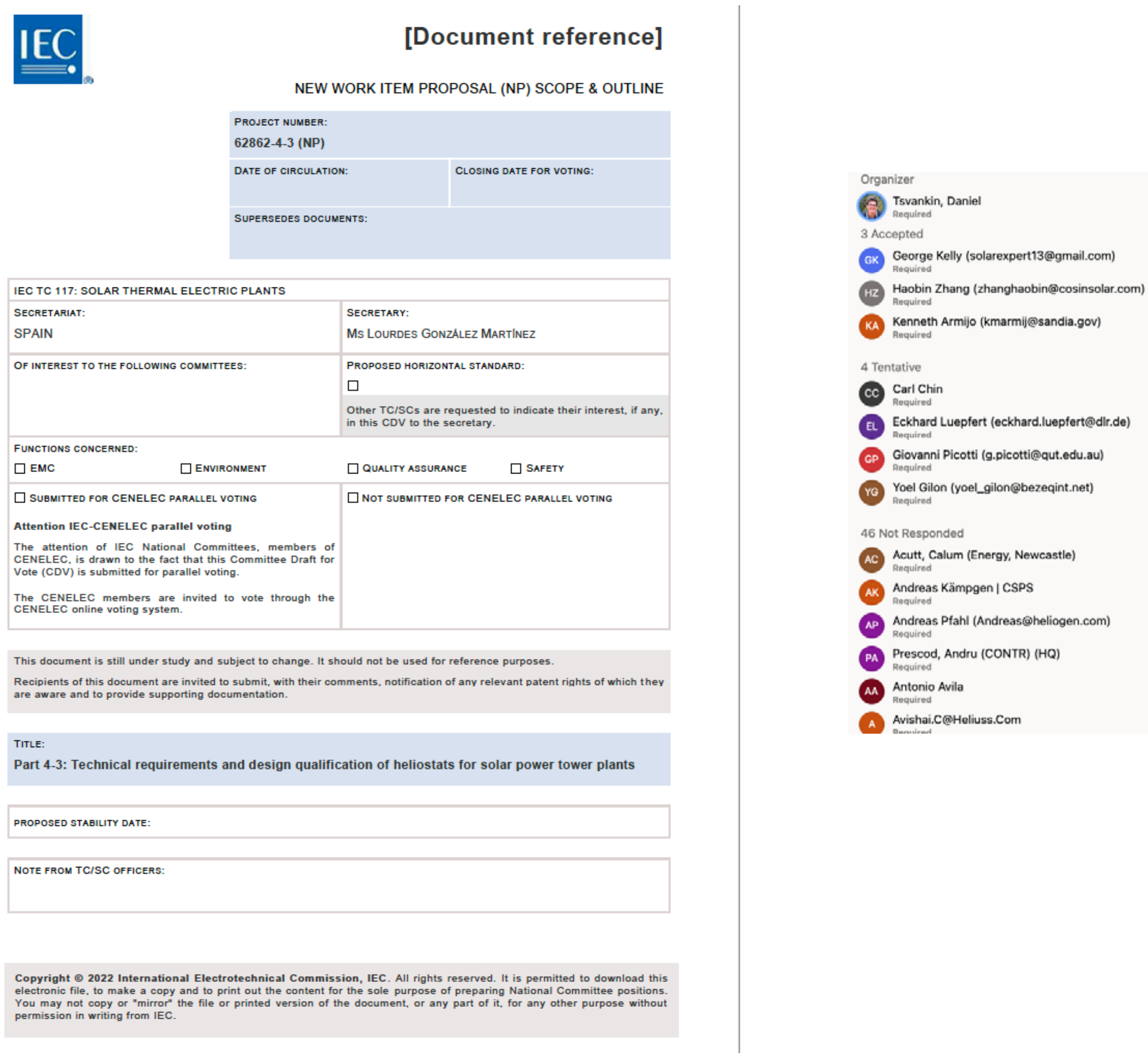
- Creating this standard assures the heliostat operator that the parameters reported in a specification sheet were measured by consistent and accepted industry procedures. This provides customers with a sound basis for comparing and selecting a heliostat.
- The tests within the standard are engineered with the purpose of separating designs that are likely to have early failures from designs that are sound and suitable for use as specified by the manufacturer. This provides confidence for investors that the heliostat meets performance and lifetime requirements.

Approach:

- Submission and complete voting on new work proposal in 2023.
- Convene online meetings every 6 weeks to actively develop the committee draft.

Status:

- The new work proposal was formally approved by IEC voting, and a kickoff meeting occurred in September 2023.
- Working group meetings have been held approximately every 6 weeks. The draft includes scope, purpose, and table of contents, and Sections 1–8.4 have been covered in detail.
- The group is on track to complete a committee draft by the end of 2024 to circulate for comments among TC117 members in 2025.



[Document reference]

NEW WORK ITEM PROPOSAL (NP) SCOPE & OUTLINE

PROJECT NUMBER: 62862-4-3 (NP)	
DATE OF CIRCULATION:	CLOSING DATE FOR VOTING:
SUPERSEDES DOCUMENTS:	

IEC TC 117: SOLAR THERMAL ELECTRIC PLANTS	
SECRETARIAT: SPAIN	SECRETARY: MS LOURDES GONZÁLEZ MARTÍNEZ
OF INTEREST TO THE FOLLOWING COMMITTEES:	PROPOSED HORIZONTAL STANDARD: ☐ Other TC/SCs are requested to indicate their interest, if any, in this CDV to the secretary.
FUNCTIONS CONCERNED: ☐ EMC ☐ ENVIRONMENT	☐ QUALITY ASSURANCE ☐ SAFETY
☐ SUBMITTED FOR CENELEC PARALLEL VOTING **Attention IEC-CENELEC parallel voting** The attention of IEC National Committees, members of CENELEC, is drawn to the fact that this Committee Draft for Vote (CDV) is submitted for parallel voting. The CENELEC members are invited to vote through the CENELEC online voting system.	☐ NOT SUBMITTED FOR CENELEC PARALLEL VOTING

This document is still under study and subject to change. It should not be used for reference purposes.

Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

TITLE:
Part 4-3: Technical requirements and design qualification of heliostats for solar power tower plants

PROPOSED STABILITY DATE:

NOTE FROM TC/SC OFFICERS:

Copyright © 2022 International Electrotechnical Commission, IEC. All rights reserved. It is permitted to download this electronic file, to make a copy and to print out the content for the sole purpose of preparing National Committee positions. You may not copy or "mirror" the file or printed version of the document, or any part of it, for any other purpose without permission in writing from IEC.

Figure 14. Cover page of IEC draft standard on heliostat design qualification and an example of a virtual meeting attendee list

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

4

Research at National Laboratories

Field Deployment

4 Research at National Laboratories – Field Deployment

4.1 High-Fidelity Performance Prediction Model

Description: A high-fidelity, heliostat-based system performance prediction model is needed for commercial project deployment. Our approach uses Monte Carlo simulation to obtain point and interval estimates of plant production and will characterize, then incorporate, several sources of uncertainty to obtain point, interval, and percentile estimates of performance prediction.

Project Lead: Alex Zolan (NREL)

Objectives and Impacts:

The primary objective of building a performance prediction model is to create a way to assess the techno-economic feasibility of developing CSP tower systems for high-temperature industrial heat applications. The model would determine the impact of project size, operating temperature, and heliostat design on the levelized cost of heat (LCOH) and its ability to meet industrial process heat (IPH) demand. Anticipated results include:

- The model will validate the quality of existing performance models such as the System Advisor Model (SAM™) and the Solar Power Tower Integrated Layout and Optimization Tool (SolarPILOT™).
- This project will quantify key sources of uncertainty when developing estimates of CSP solar field performance.
- A performance prediction model will identify key unknowns and opportunities to reduce the range of future estimates through more project experience and better metrology.

Approach:

- Develop a simulation model that leverages existing performance characterization tools (i.e., SolarPILOT (Wagner and Wendelin 2018; Hamilton, Wagner, and Zolan 2022), SAM (Kesseli et al. 2019), and SolTrace ("SolTrace" n.d.)) and incorporates uncertainty in key inputs, including solar field availability, solar resource, optical performance, soiling, and modeling and measurement error.
- Generate a case study comparing historical production to a simulated performance model to compare empirical versus simulated distribution of solar field performance.
- Package the software in a format that is accessible to the research and industry communities.

Status:

- Backcasting of historical Ivanpah plant production for a single year: completed last year
- Characterization of ≥3 sources of variation: completed this year
- Software package release: in progress; a repository on GitHub houses the code and will be released to the public next fiscal year.

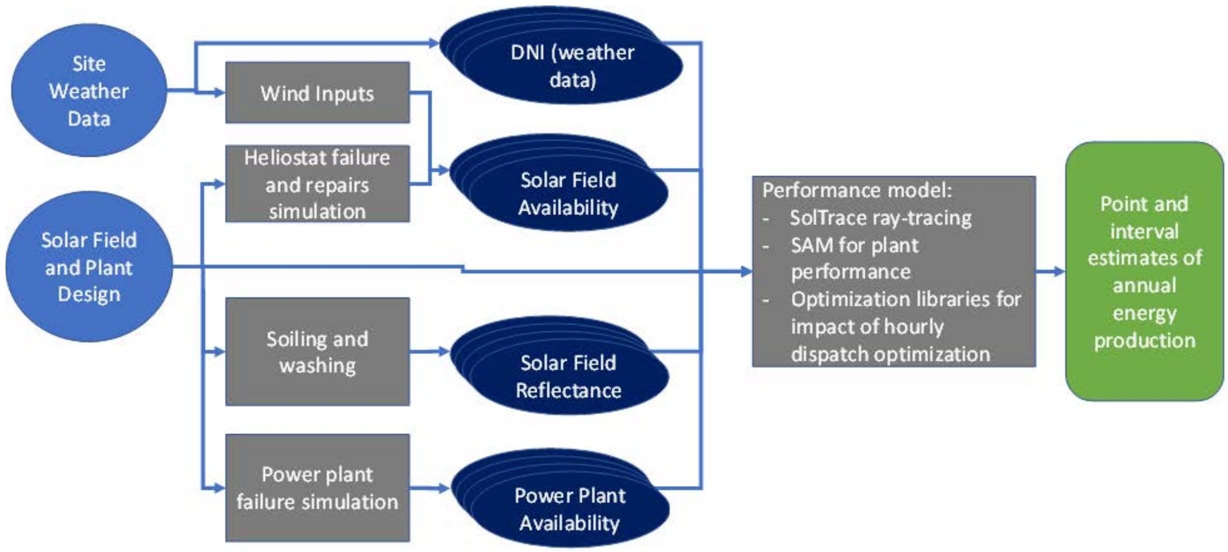


Figure 15. Flowchart describing the performance forecasting methodology

Image by Alexander Zolan, NREL

4.2 Analysis of O&M at Ivanpah

Description: We visited the Ivanpah plant to conduct a reflectance measurement campaign and provided an analysis of mirror-washing activities at Ivanpah (Zolan and Picotti 2024).

Project Lead: Alex Zolan (NREL)

Objectives and Impacts:

The key objective of this project is to develop an analysis of mirror-washing activity at Ivanpah and determine a schedule that balances the trade-off between revenue loss to soiling and the costs of mirror-washing. Anticipated impacts include:

- This project establishes a validation of existing O&M models using measured data rather than contrived data.
- The analysis estimates the value of information, i.e., return on the cost of obtaining field measurements.
- This project improves estimation of O&M costs and performance within performance characterization tools like SAM and SolarPILOT.

Approach:

- Performed on-site reflectance measurements for newly cleaned and soiled mirrors in the field
- Gathered information on the cleaning method and its efficacy, as well as on-site measurements
- Used mirror-washing optimization model developed in prior research to obtain optimal seasonal schedule, using prior reflectance measurements and wash history as a guide
- Characterized mirror non-specularity using measurements obtained via multiple instruments.

Status:

- Provided a report on key insights, including recommendations for a seasonal schedule, to Ivanpah
- We have requested additional mirror samples to investigate mirror non-specularity further as a function of age.

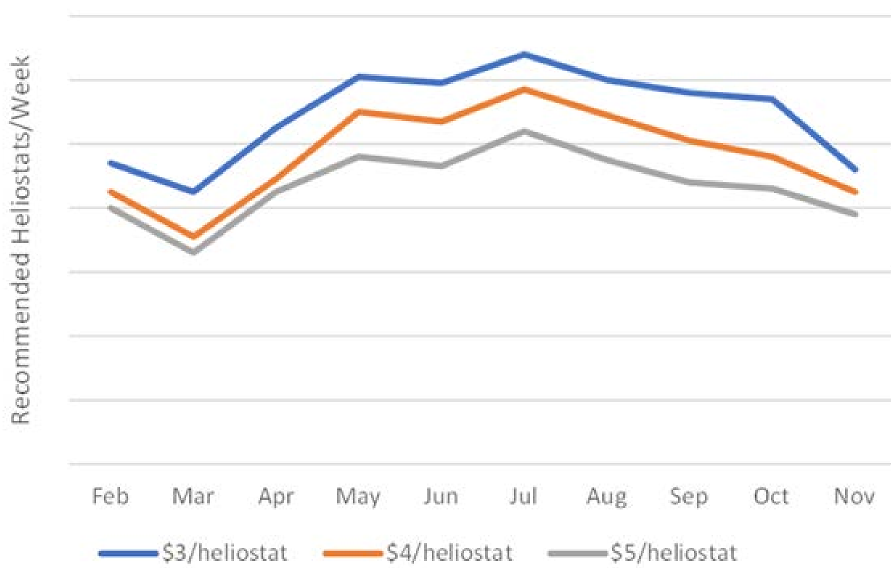


Figure 16. Monthly recommended cleaning schedule, in heliostats per week, for the Ivanpah facility, using the deterministic optimization approach and a fixed soiling rate of 0.1% per week for the field

Image by Alexander Zolan, NREL

4.3 Impacts of Heliostat Shading on Desert Habitats, and a Proposed Methodology for Coexistent Field Deployment and Operations With Desert Flora and Fauna

Description: Both an on-ground survey of the Bonanza Solar site by the team's biologist and a complete unmanned aerial vehicle (UAV) flyover study have been completed (Sment et al. 2024). A comparative report between the two methods and an overall characterization of the results, with a focus on the desert tortoise, is in progress. During these evaluations, it was noted that the area has experienced drought conditions over the past few years, which was speculated to be a contributing factor to a higher than usual number of tortoise carcasses discovered by the drone flyover. Efforts have been made to expand a network of partnership with the Bureau of Land Management, U.S. Fish and Wildlife Service, United States Geological Survey, academic research institutions, and private developers to further develop a large-scale, long-term ecological study. Initial data acquired from a previous NREL project was analyzed to determine whether temperatures inside and outside a deployment of parabolic troughs would be different. Additional data collection opportunities are being explored to further characterize ground conditions inside and outside a solar deployment.

Project Lead: Jeremy Sment and Aaron Spieles (Sandia)

In conjunction with the ecological cost assessment of heliostat, or photovoltaic (PV), deployments on desert habitats, a financial cost assessment of deployment methods is focusing on technologies currently used and evaluated for PV. By specifically focusing on ground screws as a cost-effective foundation support, as they have a drastically reduced environmental impact compared to blade and grade methods, the Sandia team is focused on creating references for ground screw style deployments to effectively support heliostats in a variety of soil compositions. These references are intended to reduce the overall deployment cost for small heliostats (1-m^2 area) by guiding the selection of adequate, but not oversized, ground screw style foundations in different CSP-relevant areas. Preliminary cost modeling of ground screws as a foundation style, based on limited ground screw performance data, suggests that small heliostats can most benefit from reduced foundation costs. A factorial experimental design has been identified as the path toward statistically relevant results for this testing.

Objectives and Impacts:

The goal of the Sandia team is to deliver an initial ecological evaluation based on current results and leverage those findings to scope and propose a full-scale before-after control-impact (BACI) ecological study with identified partners. The team's objective is to deliver a ground screw performance model that better informs a location-specific costing for small (facet area) heliostat deployments. Anticipated impacts include:

- This work strongly signals to stakeholders at the Bureau of Land Management, U.S. Fish and Wildlife Service, and other institutions a clear indication of intent to provide necessary evidence to explicitly include CSP and heliostat field deployment on the next Programmatic Environmental Impact Statements to expedite National Environmental Policy Act (NEPA) compliance.
- This project aims to determine whether burrow temperatures can be correlated to air and ground temperatures inside and outside a heliostat shaded area to lower the cost of environmental impact assessment methodologies and inform whether shading from heliostats affects the temperature-dependent sex determinacy of the desert tortoise.

Approach:

- Evaluation and reporting on the current state of one partner site, Bonanza Solar, to prepare scope for a full-scale BACI ecological study
- Data acquisition of ground conditions in current deployments
- CSP-relevant soil composition data for controlled aboveground testing for ground screws and limited in-ground testing at the National Solar Thermal Test Facility (NSTTF), as permitting allows.

Status:

- On-ground (traditional) and UAV flyover surveys focused on the desert tortoise are complete.
    - Full-scale BACI scope will be informed by the results from completed survey reports and comparison of methods.
- Design of experiment and procedure is in progress. Procurement of necessary testing equipment is in progress.
    - Cost model will be revisited after the ground screw performance testing is completed at the NSTTF.
- Sensor selection and sharing with the NREL team for ground condition data acquisition is in progress.

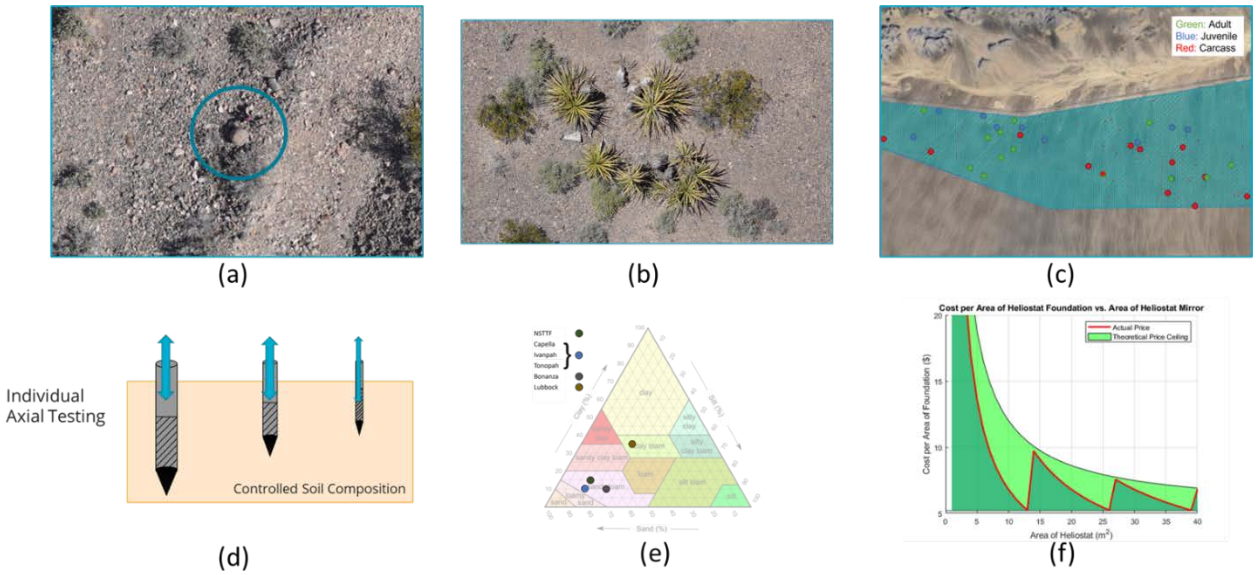


Figure 17. (a) UAV tortoise identification. (b) Full-size UAV image. (c) UAV flyover preliminary results. (d) Controlled ground screw performance test diagram example. (e) Soil texture pyramid for relevant sites. (f) Initial foundation cost model results.

Photos a, b, and c from Matt Bandy, Sandia. Images d and e from Aaron Spieles, Sandia. Image from Kristina Ji, Sandia

4.4 Pedestal and Foundation Cost Analysis

Description: In conjunction with the ecological cost assessment of heliostat, or PV, deployments on desert habitats, a financial cost assessment of deployment methods has evolved to focus on technologies previously used and evaluated for PV (Sment et al. 2024). Many of the impacts of installing PV fields have been studied with previous environmental impact statements as a part of the NEPA process. By specifically focusing on ground screws as a cost-effective foundation support, as they have drastically reduced environmental impact compared to blade and grade methods, the Sandia team is focused on creating references for ground screw style deployments to effectively support heliostats in a variety of soil compositions. These references are intended to reduce the overall deployment cost for small heliostats (1-m^2 area) by guiding the selection of adequate, but not oversized, ground screw style foundations.

Project Lead: Aaron Spieles (Sandia)

Preliminary cost modeling of ground screws as a foundation style, based on limited ground screw performance data, suggest that small heliostats can most benefit from reduced foundation costs. A two-factor, three-level factorial design has been proposed for evaluating ground screw performance, with controlled soil composition and ground screw length as the primary variables. This experimental design will be employed for axial loading directions, transverse loading, and multi-screw style foundations to evaluate ground screw performance, replicated to achieve a minimum statistical power of 80%.

Objectives and Impacts:

The primary objective of the cost analysis is to deliver a ground screw performance model that better informs a location-specific costing for small heliostat deployments. Anticipated impacts include:

- This preliminary performance model, with a minimum statistical power of 80%, will inform a maximum heliostat size based on projected soil composition that can be supported with a ground screw style foundation. This informed heliostat size will directly contribute to understanding the baseline cost of deployment by aligning foundations with NEPA guidelines and direct hardware costing based on the size and number of necessary foundation elements.
- This modeling would expedite the NEPA approval process for heliostat foundation projects that comply with PV-focused BLM Programmatic Environmental Impact Statements 2024 guidance consistent with a $50/$m^2$ SETO goal.

Approach:

- CSP-relevant soil composition data has been extracted to determine soil compositions for testing.
- Experimental design and component procurement are in progress, informed by industry guidelines and relevant standards.

- Controlled soil composition aboveground testing for limited-length ground screws and limited in-ground testing of large ground screws is taking place at the NSTTF, as permitting allows.

Status:

- Design of experiment and procedure is in progress. Procurement of necessary testing equipment is in progress.
- The cost model will be revisited after the ground screw performance testing is completed at the NSTTF.

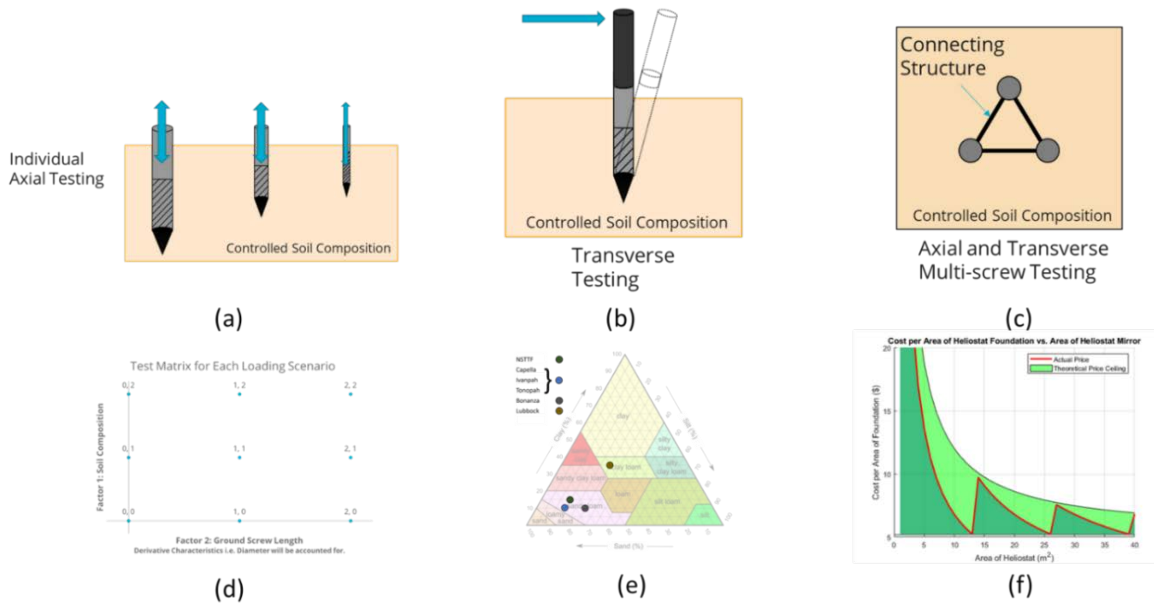


Figure 18. (a) Axial ground screw test diagram. (b) Transverse ground screw test diagram. (c) Multi-screw structure test diagram. (d) Two-factor, three-level factorial design matrix for ground screw testing. (e) Soil texture pyramid for relevant sites. (f) Initial foundation cost model results.

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

5

Research at National Laboratories

Techno-Economic Analysis

5 Research at National Laboratories – Techno-Economic Analysis

5.1 Heliostat Field Optimization for Power Tower Solar Industrial Process Heat Applications

Description: We investigate the impact of a heliostat's design and the layout of the solar field on the performance and cost of the collection system of a power tower system supporting high-temperature industrial heat applications (Zolan et al. 2024).

Project Lead: Alex Zolan (NREL)

Objectives and Impacts:

The primary objective of this project is to assess the techno-economic feasibility of developing concentrating solar thermal (CST) tower systems for high-temperature industrial heat applications and to determine the impact of project size, operating temperature, and heliostat design on the LCOH and its ability to meet IPH demand. Anticipated impacts include:

- This project aims to obtain higher-quality estimates of solar collection system performance in support of high-temperature IPH applications.
- This project would establish a standard for solar field design when performing site assessment via model-to-model validation.

Approach:

- Develop a collection of case studies for IPH applications using the default heliostat designs in SAM, scaled for the size of the project.
- Develop cost correlations for heliostats as a function of heliostat size, number of heliostats, and number of projects.
- Determine the impact of heliostat design and sizing on project costs and performance for IPH applications.

Status:

- Development of three baseline case studies for IPH applications: completed this year
- Journal publication to be submitted: "Impact of Process Temperature on the Cost of Concentrating Solar Thermal Industrial Process Heat"

Heliostat Sizing Optimization Study: currently in progress; gathering cost data available and building the optimization framework.

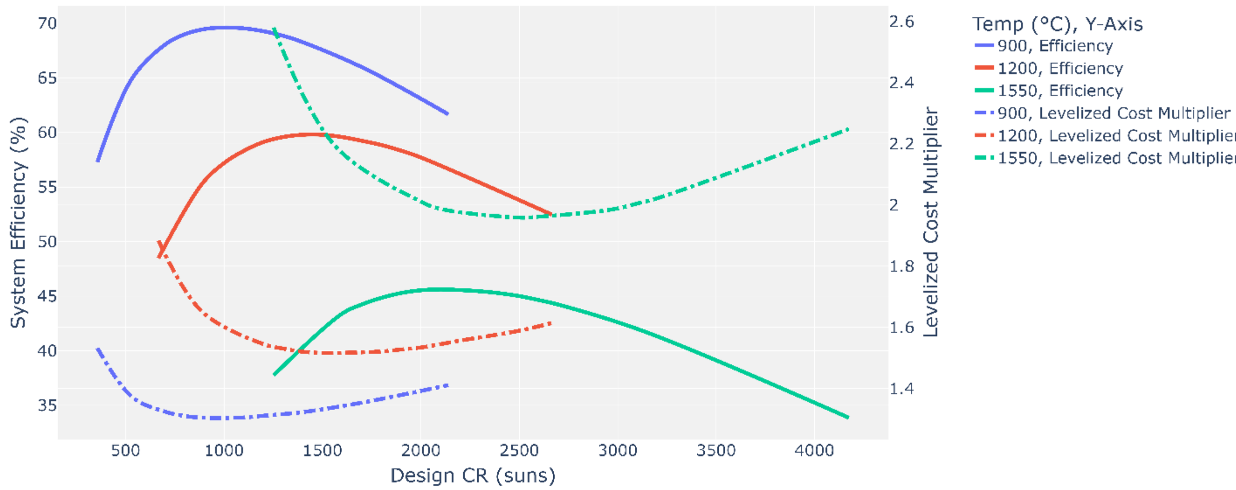


Figure 19. System efficiency and relative LCOH as a function of design concentration ratio for a case study with a 160-MW_{th} receiver operating at 1,200°C

Image by Alexander Zolan, NREL

U.S. Department of Energy
HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power

6

Research at National Laboratories

Resources, Training, and Education

6 Research at National Laboratories – Resources, Training, and Education

6.1 HelioCon Database

Description: HelioCon offers a centralized database for the community to perform advanced R&D activities and project deployment.

Project Lead: Rebecca Mitchell (NREL)

Objectives and Impacts:

The HelioCon database project is designed to increase the public accessibility of CSP knowledge and develop resources, training, and education to support newcomers to the industry. Anticipated impacts include:

- The database would reduce the long learning curves of newcomers to the industry with easy-to-digest learning materials, centralized in one location.
- The project increases public accessibility of heliostat/CSP technology knowledge, which now mostly exists as expert knowledge or within private or research institutes.
- The database provides tools to increase public awareness of the technology area.

Approach:

- Develop heliostat training materials.
- Engage educational institutions to develop a workforce pipeline to the CSP community.
- Promote diversity, equity, and inclusion in the CSP community.
- Create a centralized web-based resource database.

Status:

- The HelioCon seminar series has hosted almost 30 speakers.
- The resource database is complete with lists of metrology tools, software tools, and component suppliers; standards and guidelines; a Zotero reference library; and a plant database.

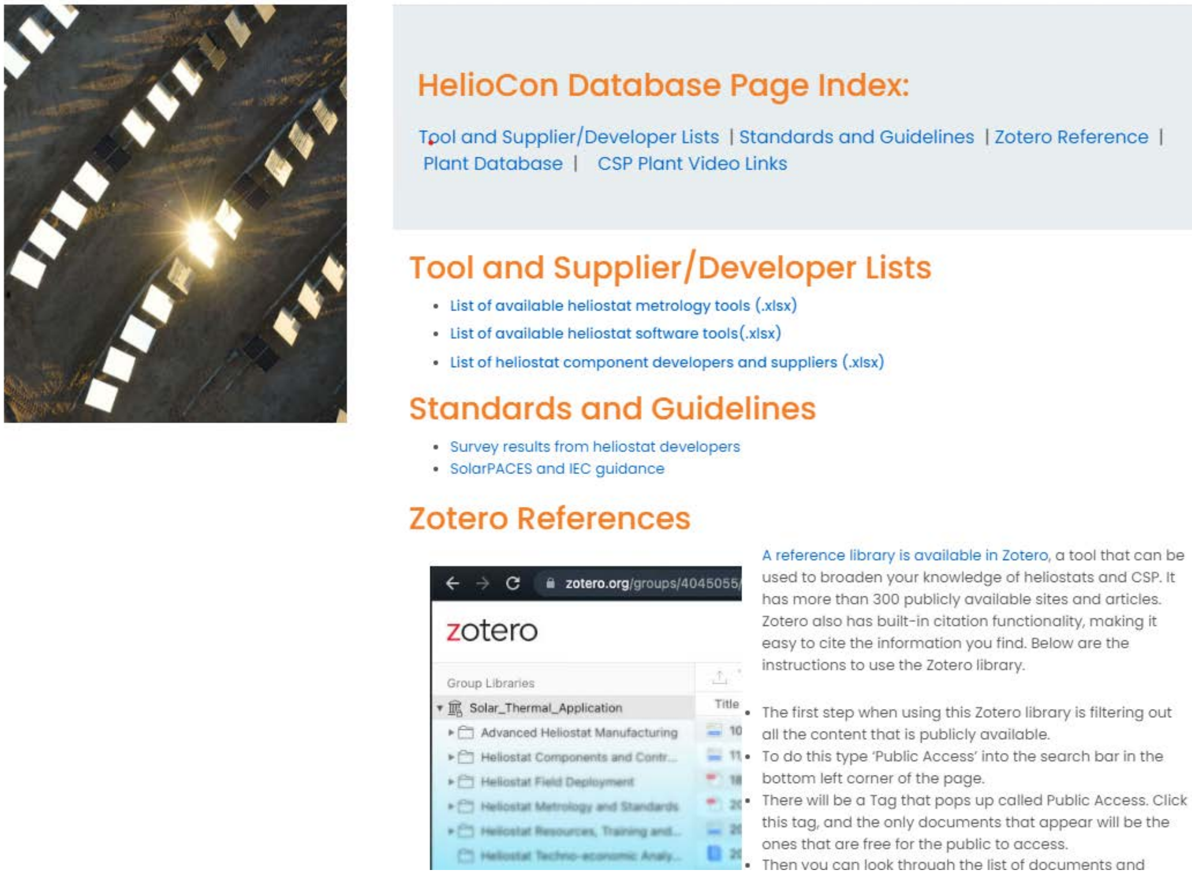


Figure 20. The resource database on the HelioCon webpage, which contains lists of metrology tools, software tools, and supplier contacts; information on standards and guidelines; a Zotero reference library; and a plant database

6.2 Solar Thermal Collegiate Competition

Description: A Solar Thermal Collegiate Competition in which student teams from collegiate institutes compete for prize funds by tackling a solar-thermal technical challenge.

Project Lead: Paul Ndione (NREL) and Kenneth Armijo (Sandia)

Objectives and Impact:

The main objective of this collegiate competition is to ignite students' excitement about solar-thermal technologies and generate interest within collegiate institutes. The competition aims to increase public awareness of solar-thermal technologies while providing students with experiences and skills to pursue research opportunities or careers in the solar-thermal industry. Anticipated impacts include:

- The competition seeks to draw in and expose a larger university/student community to solar-thermal technology development.
- The competition would increase the public visibility of solar-thermal technology through accessible challenges and communications coverage of the competition.
- This program enables students to gain experience in design, fabrication, and testing of a prototype.

Approach:

- Collect feedback from university faculty on how to best design the competition.
- Design the solar-thermal competition, including a technical task, required deliverables, and a rules document.
- Launch and administer the inaugural competition in the 2025–2026 academic year.

Status:

- The project will begin in FY25.

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

7

Research at ASTRI

7 Research at ASTRI

7.1 Standardization of Slope Error Data Reporting

Description: Indirect measurement of slope error is often achieved by measuring discrete points on a 3D surface. The secondary step of converting the point cloud into a surface can influence the result of the analysis. A point cloud analysis method has been developed and is proposed as a new best practice for comment by the CSP community. Commonwealth Scientific and Industrial Research Organisation (CSIRO) software has been refactored into a high-quality Python package to be released under an open-source license.

Project Lead: Mike Collins (CSIRO)

Objectives and Impacts:

The primary objective of this project is to develop software for post-processing (e.g., slope error determination) of point cloud measurements of mirror surfaces such as heliostat facets and share it with the CSP community. The software would remove uncertainty in the method of reporting of slope error when comparing results. Anticipated impacts include:

- The project aims to create and disseminate an open-source standardized analysis and reporting tool.
- The project will standardize plotting and reporting specifications and figures of merit for facet quality.
- This software will decrease confusion or risk of misunderstanding of slope error parameters and will remove significant errors in irradiance and yield predictions.

Approach:

- Develop Python package with well-defined and flexible framework for the following steps:
    - Loading data
    - Preprocessing
    - Meshing
    - Analysis
    - Aggregation.
- Combine fragmented software components into a well-organized software package using Poetry package management.
- Package can be run from the command line, or through Python scripts or Jupyter Notebook.

Status:

- Software package is complete, including example data and code.
  Awaiting final approval for open-source release.

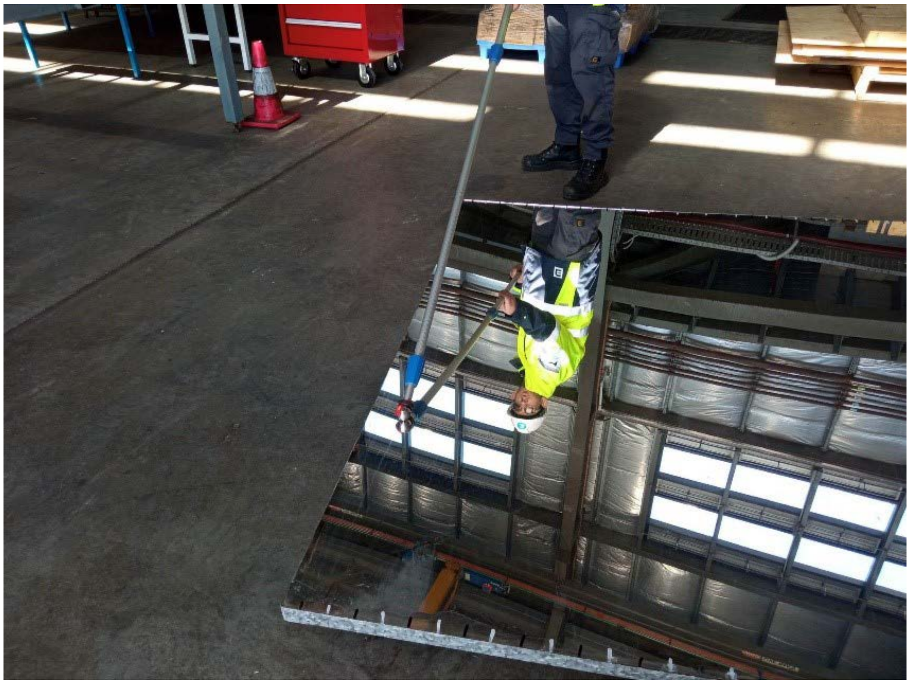


Figure 21. Using a laser tracking coordinate measuring machine (Leica AT901) to measure the heliostat surface point cloud (CSIRO)

Photo from Calum Acutt, CSIRO

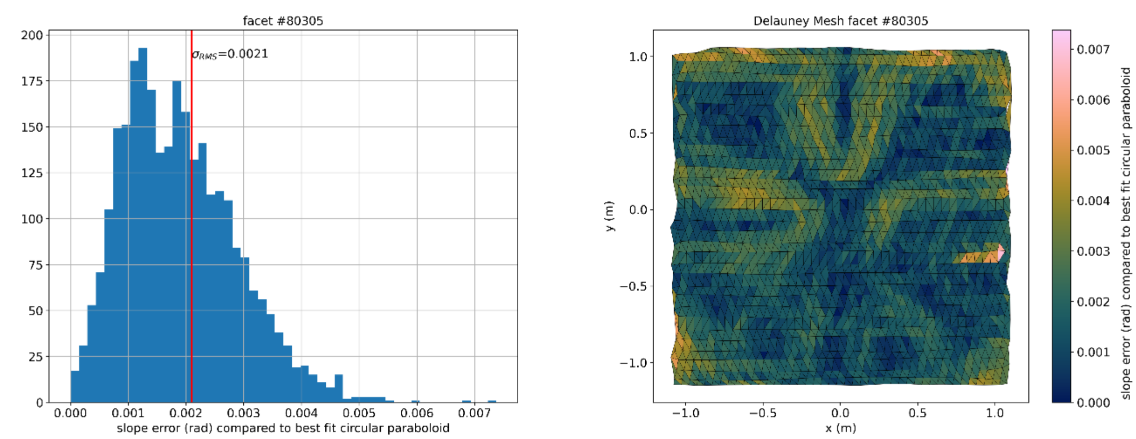


Figure 22. Example of analysis result. Left: Histogram of slope errors and RMS area-weighted slope error. Right: 2D plot of meshed point cloud colored by slope error of each facet, compared with best-fit paraboloid (CSIRO).

Images from Mike Collins, CSIRO

7.2 Heliostat Wind Load Field Measurements

Description: This project develops understanding of wind load design requirements for a single heliostat and heliostat fields through experimental measurements and analysis of heliostat wind loads at the University of Adelaide wind tunnel facility and Atmospheric Boundary Layer Research Facility (ABLRF) (Emes, Marano, and Arjomandi 2024; Bakhshipour et al. 2024). Wind tunnel experiments focus on measurements of 3D turbulent flows between adjacent heliostats in a field array and structural wind loads on instrumented heliostat models. ABLRF field measurements focus on analysis of atmospheric boundary layer (ABL) turbulence parameters and wind loads on a single heliostat at different operating angles in an open country terrain for verification and comparison with wind tunnel ABL physical modeling and wind load characterization techniques.

Project Lead: Matthew Emes and Maziar Arjomandi (University of Adelaide)

Objectives and Impact:

The primary objective of this project is to develop a detailed measurement procedure to reconcile single-heliostat wind load field measurements with wind tunnel experiments and develop a correlation between local turbulent flow and wind load variations in low- and high-density arrays of heliostats for wind load prediction in a heliostat field. Anticipated impacts include:

- Understanding of heliostat wind loading within an array, in this project, will lead to reductions in capital cost and improved efficiency of CSP plants due to the applicability of changes in wind loading throughout a heliostat array. This can result in improved partial stow strategies and cost-effective heliostat design in the field.
- Understanding the change in heliostat wake and flow field, and consequently dynamic loads on heliostats, will improve the efficiency of energy generation. This can be accomplished by ensuring that heliostat vibrations are minimized according to heliostat shape and elevation angles in the heliostat design phase.
- The updated heliostat wind load design parameters in this project will assist in the development of non-square heliostats by improving the accuracy of design loads for specific heliostat aspect ratios.
- The outcomes of the project will support the development of improved wind loading estimates, which can lead to a reduction in capital cost and a reduction in structural failure.

Approach:

- Compare aerodynamic wind load coefficients of a full-scale heliostat model at the ABLRF with a 1:6 scale wind tunnel heliostat model at a range of elevation and azimuth angles to investigate the impact of ABL turbulence parameters on heliostat wind loads.
  Investigate the variation of turbulent flow measured between heliostats in adjacent rows and wind loads on heliostats at different elevation angles in low- and high-density arrays of staggered and linearly arranged heliostat models in the wind tunnel.

Status:

- Single-heliostat load ABLRF field measurements at different elevation angles are overall consistent with wind tunnel data for the prevailing wind direction impacting the front of the heliostat, and show strong dependence on the ratio of integral turbulence length scales to heliostat chord length. See the following publication: Emes, Matthew J., Matthew Marano, and Maziar Arjomandi. 2024. "Heliostat wind loads in the atmospheric boundary layer (ABL): Reconciling field measurements with wind tunnel experiments." *Solar Energy* 277: 112742. https://doi.org/10.1016/j.solener.2024.112742.
- Fluctuating drag and lift forces on heliostats at $\alpha = 15°$ within a seven-row array in the wind tunnel are up to 30% larger than those on a single isolated heliostat, whereas drag and lift forces on heliostats at $\alpha \geq 30°$ in row 3 and beyond are reduced by up to 50% compared to those on a single isolated heliostat.
- In the next year, analyze the effect of wind direction on heliostat wind loads at ABLRF and investigate the turbulent flow profiles within a heliostat array.

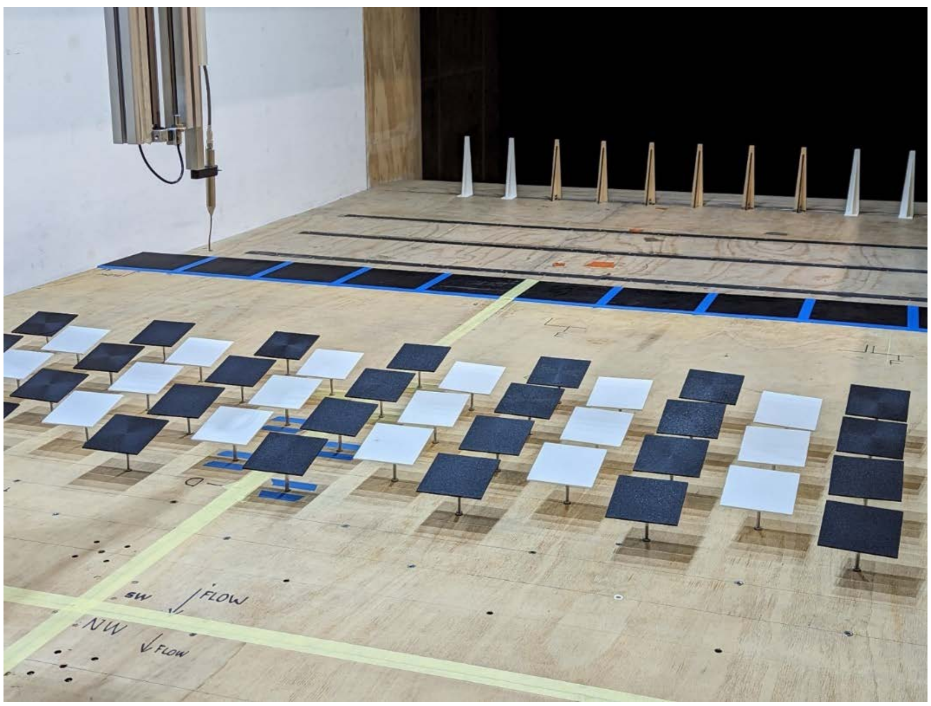


Figure 23. Linearly staggered array of heliostat models instrumented with three-axis load cells and a multi-hole pressure probe and traverse system for flow characterization in the University of Adelaide wind tunnel

Photo from Matthew Marano, University of Adelaide

Figure 24. ABLRF: heliostat model instrumented with a load cell and pressure sensors, and horizontal and vertical arrays of ultrasonic anemometers for ABL turbulence measurements

Photo from Matthew Emes, University of Adelaide

7.3 Heliostat Soiling Characterization and Mitigation

Description: 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 financial risk. More research is required to reliably evaluate the reflectance state of a whole solar field, enable soiling assessment in early design and site selection phases, and boost both active and passive mitigation methods. This project intends to address the challenges resulting from heliostat soiling by developing efficient soiling characterization and low-cost mitigation strategies (Anderson et al. 2024; 2023).

Project Lead: Giovanni Picotti and Michael E. Cholette (Queensland University of Technology)

Objectives and Impact:

This soiling project's main objective is to engage with existing plant operators to understand and improve O&M practices around soiling monitoring and cleaning. The project will develop benchmark soiling prediction approaches, clarify the state of practice in soiling mitigation, and develop and validate techniques to characterize soiling early in the plant design process. Anticipated impacts include:

- This project aims to develop better estimates of soiling losses early in plant design and site selection.
- The project seeks to give site operators the ability to optimize design mitigation measures (e.g., cleaning) to minimize the impact of soiling.
- Soiling mitigation strategies would reduce uncertainty about the impact of soiling on existing and future plants.

Approach:

- Develop a soiling database by:
    - Developing a standard reporting framework and hosting platform
    - Publishing data from Queensland University of Technology studies as well as planning and executing new lab and field experiments
    - Working with SolarPACES task and other partners (e.g., DLR, Fraunhofer ISE) to develop standard measurement and reporting procedures.
- Perform soiling studies with academic and industry partners to:
    - Assess accuracy of soiling models and perform benchmarking studies (using soiling database discussed below)
    - Provide advice and analysis on cleaning plans and other soiling mitigation measures for new and existing plants
    - Refine soiling models to include missing key phenomena.

Status:

- Performed five soiling campaigns in multiple locations in Australia with both industry and academic partners, with two additional campaigns planned in the United States and Europe.
- Carrying out a benchmarking study assessing satellite data accuracy for soiling predictions.
- Engaging international stakeholders to compile a soiling database.
- Participating in a SolarPACES working group to develop guidelines for soiling characterization.
- Finalizing a study into solar field optimization, including soiling at design phase.
- Completed laboratory study and analysis on moisture impact on soiling.

Completed two cleaning optimization studies: one for a future modular solar field and one for an existing solar field (in collaboration with NREL).

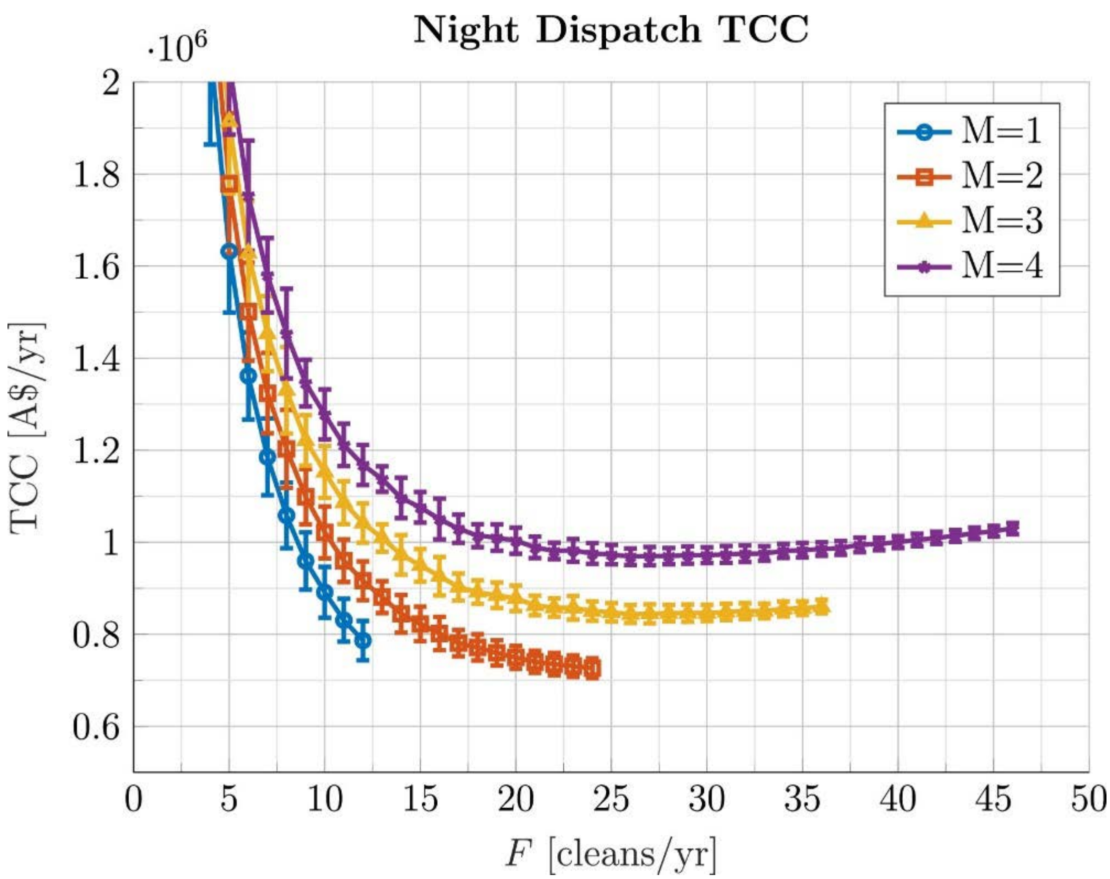


Figure 25. Total cleaning cost for a 56-MW plant equipped with modular solar fields in a nighttime dispatching scenario for varying numbers of cleaning crews

Image from Cody Anderson, Queensland University of Technology

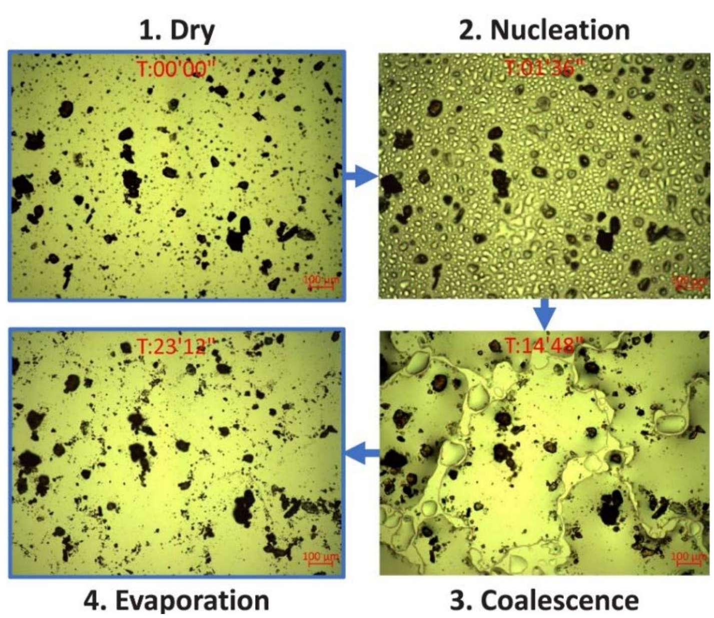


Figure 26. Bright-field microscope images of the four stages of moisture condensation on a cold mirror sample surface, magnification at 10x

Image from Cody Anderson, Queensland University of Technology

7.4 Impact of Heliostat Panel Shapes on Total Effective Slope Error

Description: This project refines the concept of an equivalent slope error, which encompasses all types of optical errors, to improve the accuracy of single-heliostat optical models and full heliostat field models for CSP annual performance analysis, especially in cases where experimental test data is available to be incorporated.

Project Lead: Joe Coventry and Ye Wang (Australian National University (ANU))

Objectives and Impacts:

This project's objective is to use an equivalent slope error to quantify different types of optical errors in a heliostat—and to quantify the whole field's annual performance. Anticipated impacts include:

- This project aims to unify and quantify optical errors using an equivalent slope error model, which integrates various types of optical deviations into a single metric, to improve accuracy.
- Bridging experimental measurements of individual heliostats with optical modeling would enable operators to complete a comprehensive, full-field annual performance analysis.
- Gaining insights into heliostat shape design would lead to optimized performance and improved alignment with optical requirements.

Approach:

- Evaluate the flux distributions of imperfect heliostats using Monte Carlo ray-tracing (MCRT).
- Evaluate the flux distributions of paraboloid-shaped heliostats with varying slope errors using MCRT.
- Obtain the slope error value that matches the radius of energy capture of the paraboloid-shaped heliostats and the imperfect heliostats at design point.
- Validate that the annual energy outputs of the imperfect heliostats and the paraboloid-shaped heliostats with the slope error are equivalent.

Status:

- The equivalent slope errors of different shapes of mirror facets (i.e., spherical, parabolic-cylindrical, and flat) have been evaluated, and the annual performance has been validated.
- The next step is to include other optical errors.

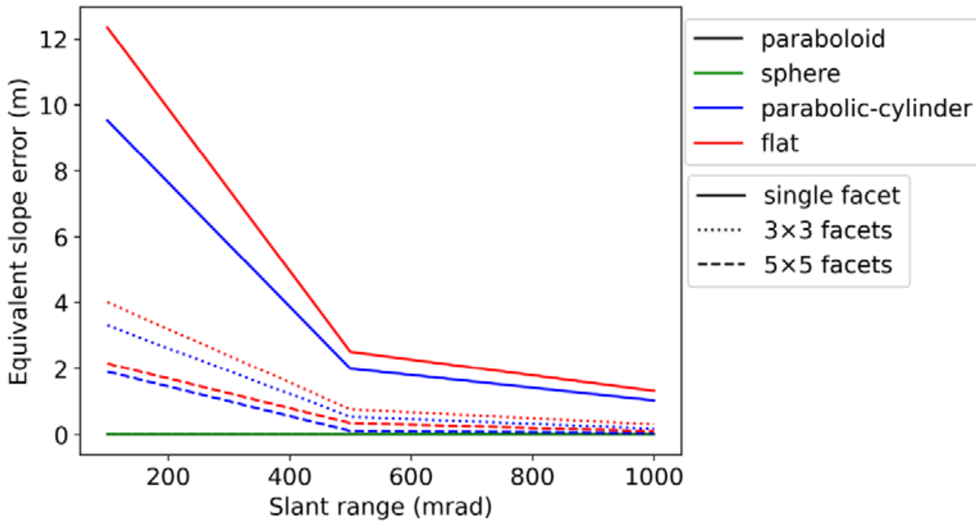


Figure 27. Equivalent slope errors of 12 configurations of heliostats

Image from Ye Wang, ANU

7.5 Techno-Economic Analysis of Heliostat Fields for High-Temperature Heat Supply

Description: Our study is a collaboration with NREL to explore the optimal design of heliostat fields, receivers, and towers in CST systems, aiming to provide heat at 900°C, 1,200°C, and 1,550°C at minimal LCOH.

Project Lead: John Pye and Ye Wang (ANU)

Objectives and Impacts:

The main objective of this analysis is to evaluate the techno-economic performance of heliostat fields for high-temperature heat supply. Anticipated impacts include:

- Revealing the levelized cost of CST technology for high-temperature heat supply would demonstrate its competitiveness compared to PV and wind energy up to specific temperature thresholds.
- Presenting the optimal scale of modular design tailored for commercial and industrial applications would maximize efficiency and cost-effectiveness.
- Identifying the optimal heliostat size and concentration ratio for various temperature applications would ensure peak performance and energy output across different use cases.

Approach:

- Perform annual system modeling to obtain the LCOH of a CST system with a tower, a polar heliostat field, and a cavity receiver (modeling the cavity aperture as a black body).
- Perform sensitivity analysis on the system scale and uncertainties in cost and performance assumptions.

Status:

- The LCOH of small- to large-scale systems has been obtained. The trend of optimal tower, field, and receiver design has been analyzed.
- Initial sensitivity analysis on tower cost has been conducted.
- The next step is to evaluate novel heliostat designs (e.g., target-aligned) for high-temperature applications.

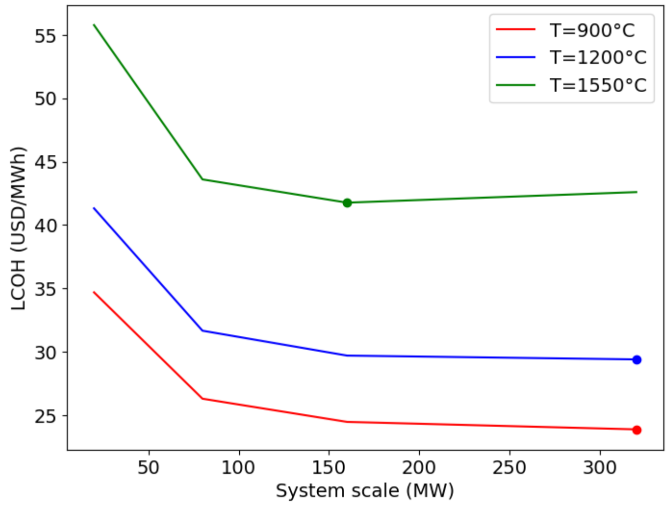


Figure 28. Optimal LCOH as a function of system scale for three high-temperature applications

Image from Ye Wang, ANU

7.6 Using BCS Images To Evaluate Heliostat Shape

Description: The project aims to develop an efficient method for retrieving slope error measurements from commonly used BCS techniques (Wang, Coventry, and Pye 2024).

Project Lead: John Pye and Ye Wang (ANU)

Objectives and Impacts:

This project's objective is to develop the "Helioshape" software package to smoothly process sets of multiple BCS images from a heliostat at different sun positions, estimating the actual shape of the heliostat. The project will develop a robust image stitching technique to obtain a full flux map of a beam size larger than the target. Anticipated impacts include:

- The project will create an open-source software package to process BCS images for heliostat shape estimation.
- This software package will maximize the use of BCS for detailed heliostat optical characterization, enhancing performance assessments.

Approach:

- Acquire beam images of a heliostat at different times of day using BCS.
- Match the flux distributions from MCRT and image data by optimizing the shape of the heliostat, which is governed by a quadratic equation.

Status:

- Improved image stitching by automatically detecting the target from images.
- Developed the Helioshape program to analyze the large BCS datasets shared by Sandia via the OpenCSP project.
- The next step is to validate the heliostat shape obtained from this program with alternative measurements like deflectometry or photogrammetry.

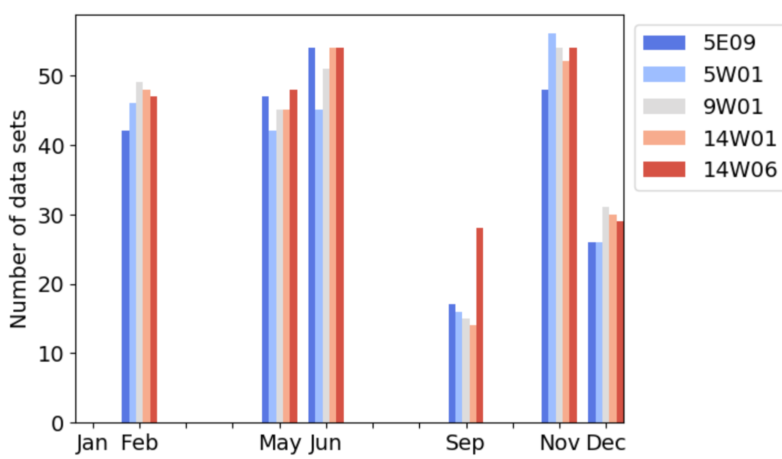


Figure 29. Distribution of the Sandia BCS datasets covering a wide range of sun positions

Image from Ye Wang, ANU

8 Research Through Request for Proposals 1

8 Research Through Request for Proposals 1

8.1 SunRing Advanced Manufacturing and Field Deployment

Description: This project by Solar Dynamics LLC develops an advanced on-site assembly line for its existing heliostat (Kattke and Stegall 2024). The assembly line incorporates a new mirror array workstation that adds 2D focusing to the mirror array. The steps required to deliver a complete heliostat field are also detailed from heliostat installation, commissioning, and O&M, culminating in a comprehensive cost model that captures the heliostat's full life cycle cost.

Project Lead: Kyle Kattke (Solar Dynamics)

Objectives and Impacts:

The main objective of this advanced manufacturing and deployment project is to redesign the mirror array for integration with a workstation that adds 2D focusing and to design an on-site assembly line with automation added where practical. The project will detail the cost and schedule to perform all in-field work, from heliostat installation to lifetime O&M. Anticipated results include:

- The project aims to update the mirror array design to improve the optical performance of Solar Dynamics' heliostat by adding 2D focusing. Focusing is produced during the mirror array assembly process without adding to material costs.
- This project will prototype the new mirror array workstation alongside a deployment of Sandia's SOFAST metrology system at the SolarTAC test facility in Colorado. SOFAST measurements will be used to tune the workstation to realize <1-mrad slope error on the mirror array.
- This project will create a holistic heliostat cost model covering a heliostat's entire life cycle, including materials, assembly, installation, commissioning, and lifetime maintenance. The cost model framework will be shared with the HelioCon community.

Approach:

- Finite element analysis used to optimize mirror array balancing cost and optical performance.
- Mirror array workstation designed to impart a 2D paraboloid shape during the assembly process.
- The mirror array will be built with a workstation prototype, and Sandia's SOFAST will be used to measure the slope error of the mirror array. SOFAST measurements are used to tune the workstation.
- Work with third-party automated assembly vendor to develop on-site assembly line.

Status:

- Prototype mirror array components have been ordered; scheduled to begin prototype construction in August 2024.

- Sandia is performing tests to confirm SOFAST screen details, including the ability to perform measurements in ambient lighting conditions and the use of a low-cost stretched screen.
- Solar Dynamics has developed a conceptual on-site assembly line, and this will be refined by a third-party automated assembly vendor (contract placed in July 2024).

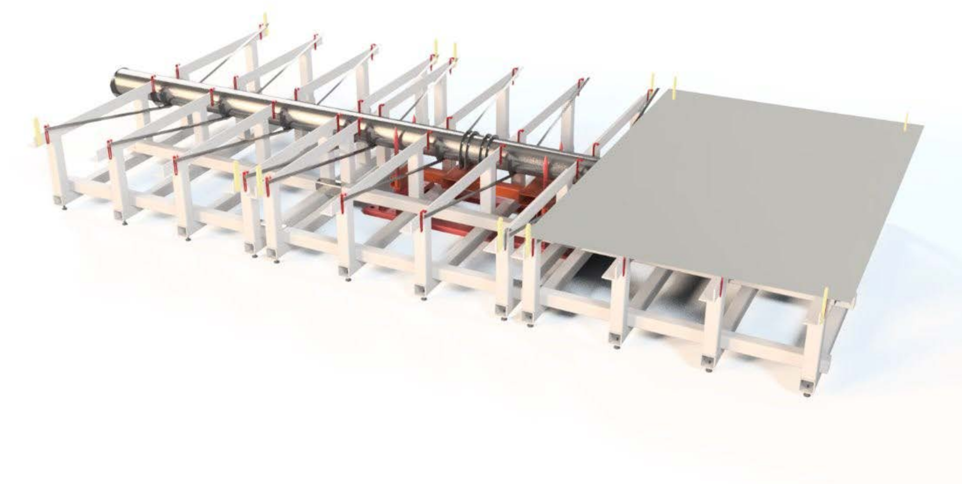


Figure 30. CAD model of mirror array workstation prototype with one facet placed. Sixteen vertically adjustable control points (highlighted in red) per facet allow 2D focusing of the mirror array.

Image from Nathan Stegall, Solar Dynamics

8.2 HELIOCOMM: A Resilient Wireless Heliostats Communication System

Description: HELIOCOMM will introduce a resilient wireless communication system based on the principles of integrated access and backhaul (IAB) technology, entropy-based routing, dynamic spectrum management, and interference mitigation (E. E. Tsiropoulou 2024; E. E. Tsiropoulou, Rahman, and Siraj 2024). At the end of the project, HELIOCOMM aspires to achieve the following performance targets: (i) end-to-end latency on the order of magnitude of milliseconds to support the autonomous autocalibration of the heliostats; (ii) heliostat transmission power on the order of magnitude of MW; (iii) a 50% increase in the energy efficiency by utilizing the IAB technology instead of the mesh networks technology; (iv) a 50%–60% decrease of the heliostats' energy consumption related to the wireless communication functionalities; and (v) network reconfiguration and routing identification on the order of magnitude of milliseconds.

Project Lead: Eirini Eleni Tsiropoulou (University of New Mexico)

Objectives and Impacts:

HELIOCOMM aims to develop resilient wireless communications in large-scale CSP fields. The heliostats' closed-loop autocalibration would be on the order of magnitude of few milliseconds based on a wireless communications system (E. Tsiropoulou, Rahman, and Siraj 2024). The project would create an automated network reconfiguration under any external CSP conditions. Anticipated impacts include:

- HELIOCOMM would develop a fully wireless communication system supporting CSP fields consisting of thousands of heliostats.
- The project creates end-to-end latency on the order of magnitude of milliseconds for closed-loop autocalibration functionalities.
- The project aims to develop network reconfiguration and routing identification on the order of magnitude of milliseconds.

Approach:

- Design of IAB-based network and optimization of energy efficiency and latency
- Dynamic clustering-based network reconfiguration and entropy-based routing
- Autonomous spectrum management in the access and wireless backhaul
- Intra- and inter-cluster interference mitigation.

Status:

- Optimization of energy efficiency and minimization of latency
- Achieved less than 250 milliseconds communication overhead to support closed-loop autocalibration
- Segmentation of the CSP field and least path loss-based routing
- Full wireless connectivity of a CSP field with 7,683 heliostats without any disconnected heliostats

- Publication: Tsiropoulou, Eirini Eleni, Aisha B. Rahman, and Md Sadman Siraj. 2024. "HELIOCOMM: A Wireless Revolution in Concentrated Solar Power Systems." *IT Professional* 26 (3): 73–79.
- Publication: Tsiropoulou, Eirini Eleni, Aisha B. Rahman, and Md Sadman Siraj. 2024. *HELIOCOMM: Wireless Controls State-of-the-Art Report*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-5K00-88431.

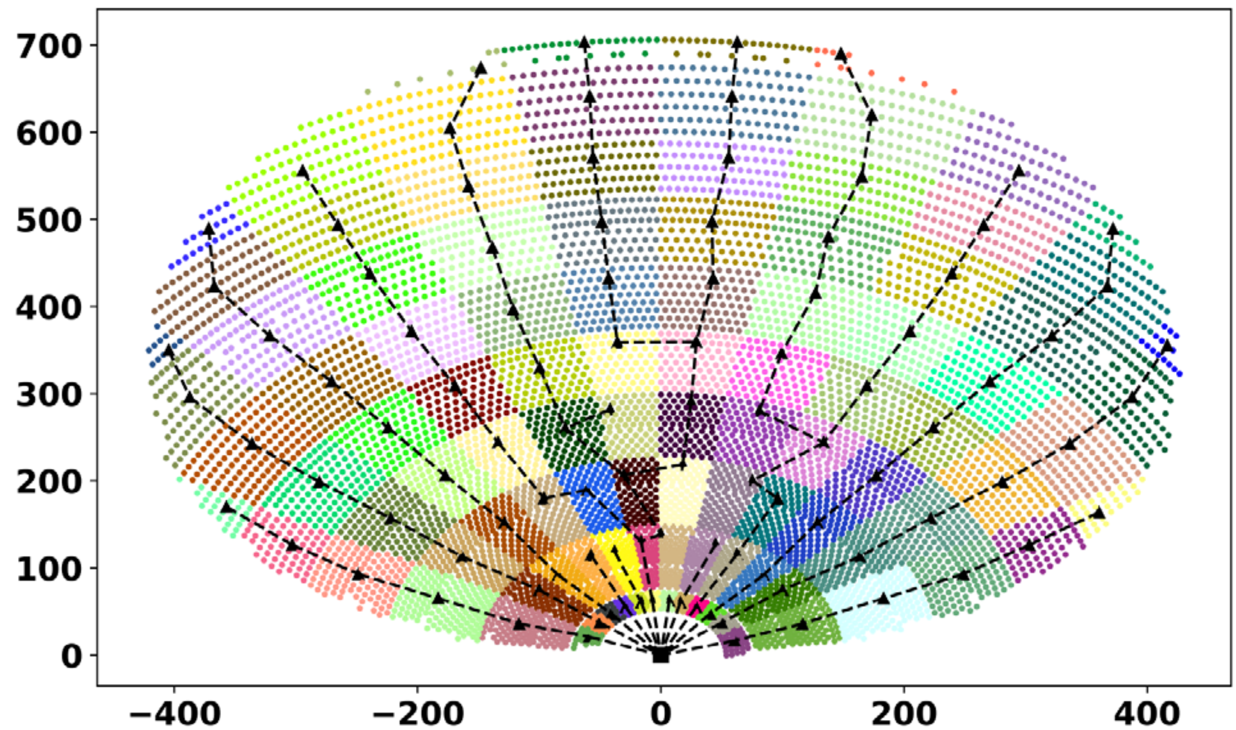


Figure 31. Data traffic routing to the central station based on the least path loss-based routing algorithm for a daylong simulation (Jan. 1, 2020) based on real data.

Image from the University of New Mexico

8.3 Demonstration of a Heliostat Solar Field Wireless Control System

Description: This project aims to engineer, install, and operate a robust, secure, low-cost wireless communication system for controlling an existing heliostat solar field using SmartMesh IP, a commercially available technology. In parallel, the project will develop and validate a computer wireless simulation to predict wireless system performance for large-scale solar fields with tens of thousands of wireless heliostats.

Project Lead: Rick Sommers (Solar Dynamics)

Objectives and Impacts:

This project's primary objective is to eliminate wirelessly controlled heliostat reliability and performance concerns. By developing commercial systems engineering and hardware supply chain partnerships, the project would de-risk the adoption of wirelessly controlled heliostats for commercial power plants and achieve lower-cost heliostat solar field installations. Anticipated impacts include:

- This project aims to reduce the overall installation cost of commercial heliostat solar fields by eliminating the installation costs associated with a typical wired communication system, resulting in estimated heliostat cost savings between $7/m^2 and $20/m^2, with larger cost savings realized for smaller heliostats.
- This project also would confute the CSP industry's perceived risk that a heliostat solar field wireless communication system is less reliable than a conventional wired system.

Approach:

- Install and operate a SmartMesh IP wireless communication system at Sandia's NSTTF, controlling all 214 operational heliostats for all operational scenarios.
- Create a computer wireless simulation using Remcom's Wireless InSite radio frequency simulation software for the NSTTF wireless installation. Validate the wireless simulation with actual data from the operating NSTTF wireless system. Extend the validated NSTTF wireless simulation to predict the performance of a commercial reference plant of 30,000 heliostats.

Status:

- Successfully demonstrated the integration of the SmartMesh IP wireless hardware with the NSTTF heliostat control system.
- Developed initial wireless communication system application-level programming interfaces for both the NSTTF heliostat control system and the solar field control system.
- Created a 30-node computer simulation of the NSTTF wireless system installation and validate with actual test data.

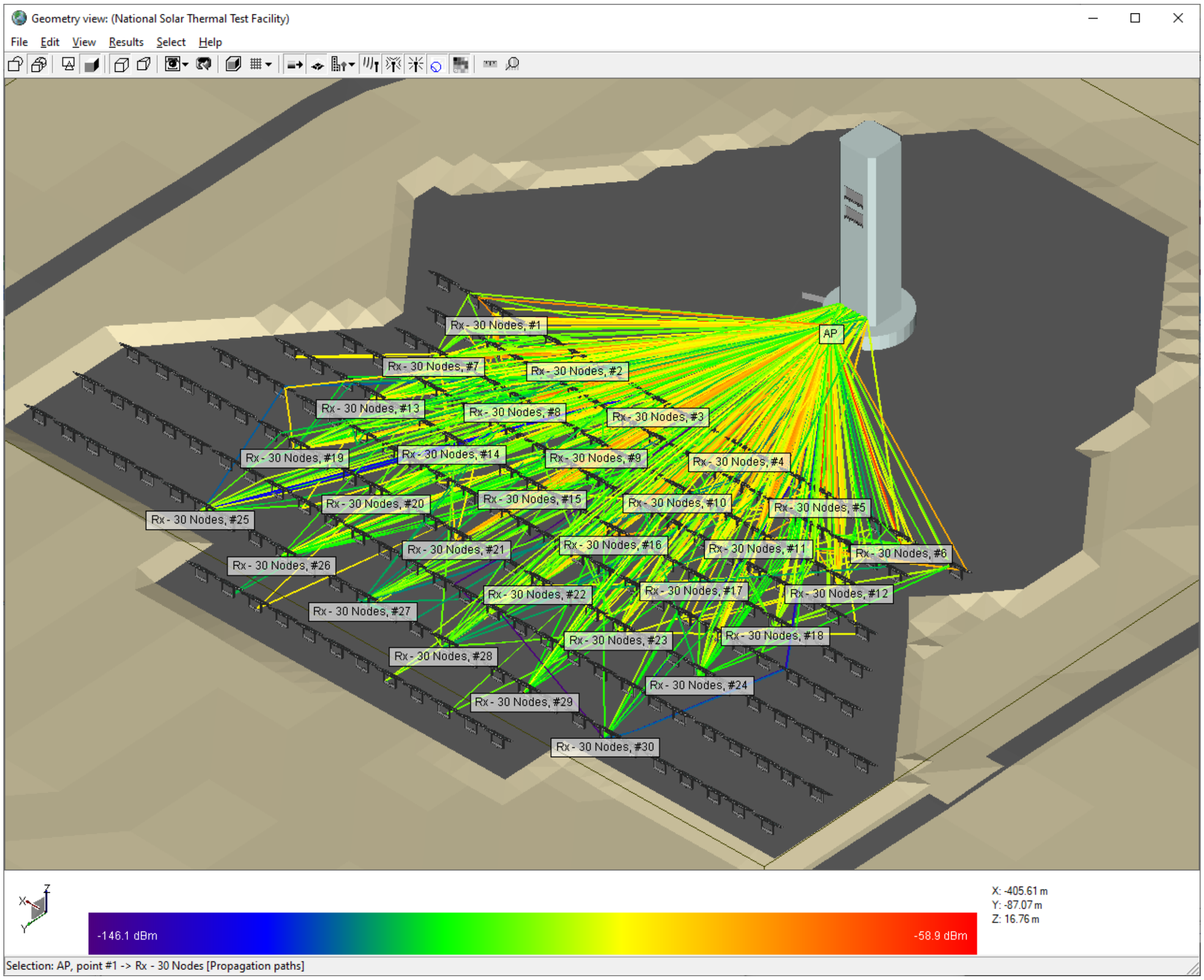


Figure 32. Image of NSTTF 30-node wireless simulation visually indicating wireless signal path lost between access point radio and heliostat

Image from REMCOM

8.4 An Educational Program on CSP and Heliostats for Power Generation and Industrial Processes

Description: The aim of this project is to develop opportunities to explore CSP for undergraduate students in the realms of education, research, and outreach. The primary objective is to develop a graduate-level course in addition to five short courses aimed at educating students and industry professionals. Additionally, CSP capstone projects will be presented to senior undergraduate students for them to develop and expand their knowledge of heliostat and CSP technology (Metghalchi 2024).

Project Lead: Hameed (Mohamad) Metghalchi (Northeastern University)

Objectives and Impacts:

This educational program's main objective is to perform outreach, advertising, and recruitment to generate student interest in CSP research and education opportunities. The aim is to develop university and industry coursework as well as capstone engineering design projects for upper-class undergraduate students. Anticipated impacts include:

- Capstone (Senior) CSP design projects: Three student groups designed and built concentrated solar energy systems for their senior design.
- This project resulted in the development of a new graduate-/senior-level CSP course, which has already been taught. We believe that it may be the only course dealing 100% with CSP.
- This project aims to design five short industry courses to educate industry professionals from various backgrounds.
- New solar receiver: Students designed a new concept for a solar receiver, which is being built, and a provisional patent application for the receiver has been obtained with Northeastern University.

Approach:

- Involve engineering freshman in CSP and heliostat activities.
- Involve interested underrepresented minority students from LSAMP in summer CSP-related activities.
- Develop a graduate course in CSP technology.
- Develop short courses for professional development for industry practitioners and the public.
- Develop capstone engineering design projects for upper-class undergraduate students.

Status:

- All objectives for Phase I completed.

Figure 33. A student group presenting their capstone prototype of a deformable heliostat to the public

Photo from Northeastern University Mechanical Engineering Capstone Project

8.5 Self-Focusing Heliostats With Closed-Loop Tracking

Description: The project has built and tested a new type of heliostat to enable the theoretical maximum concentration (Angel et al. 2022). It incorporates automatic twisting of the concave reflector shape throughout the day, as the sunlight angle of incidence changes, as needed to always form a disc image of the sun. Fields of such heliostats have the potential for commercial application of CSP at temperatures much higher than the current 565°C that is characteristic of commercial fields of fixed-shape heliostats.

Project Lead: Roger Angel (University of Arizona)

Objectives and Impacts:

This project aims to enable commercial CSP at significantly higher concentration as needed to obtain temperatures of 800°C–1,500°C—and enable both the highest-efficiency conversion of solar to mechanical and electrical power and high temperature for industrial processes, such as making synfuel, calcination, and direct air capture. Anticipated impacts include:

- This project has enabled successful demonstration of an 8-m^2 twisting heliostat that, unlike conventional fixed-shape heliostats, focuses sunlight to a disc image of the sun throughout the day.
- The project aims to develop closed-loop tracking accuracy that holds the image on target to an accuracy better than 0.5 mrad RMS.
- This project resulted in the developed design for a commercial field of 400 such twisting heliostats, to deliver 1 MWth at 3,000-sun concentration, throughout the year, for solar industrial heating to >1,000°C.

Approach:

- A new heliostat with a rectangular reflector whose shape is automatically altered by twisting to raise or lower opposite corners, creating astigmatism.

- Use a dual-axis mount of the target-oriented type that allows for a simple mechanical coupling of the twisting mechanism to the cross-axis rotation drive.
- Obtain accurate tracking with a novel closed-loop camera, including a beamsplitter that takes advantage of the target-axis tracking geometry.

Status:

- A full-scale 2.4-m x 3.3-m reflector has been built, incorporating four diagonal back struts for shape change by twisting.
- The prototype incorporates a cam mechanism built for automatic shape change.
- A complete heliostat has been assembled and tested at the University of Arizona.
- The disc image measurements show >85% encircled energy within 11.4-mrad diameter for angles of incidence up to 68°.
- The prototype has now been delivered to Sandia National Laboratories for further evaluation.
- A novel high-resolution deflectometry metrology system was developed to set the reflector surface to 0.5-mrad slope accuracy.
- Novel starlight metrology has been utilized for field measurement of the surface contour to <0.1-mm RMS accuracy.
- Angel, Roger, Nick Didato, and Matt Rademacher. n.d. "Heliostat with Automatic Shape Adjustment for High Concentration Throughout the Day." (R. Mitchell et al. 2024).

Figure 34. A full disk image of the sun is reflected to a target (distant right) from a twisting heliostat

Photo from Roger Angel, University of Arizona

Figure 35. The twisting heliostat is purely mechanical: No computer is required

Photo from Roger Angel, University of Arizona

8.6 Digital Twin and Industry 4.0 in Support of Heliostat Technology Advancement

Description: The project's main objective is to apply multiple technologies from Industry 4.0 to heliostat design, manufacturing, deployment, and operations to realize the cost reductions seen by other industries that have adopted these technologies. Industry 4.0 technologies, such as model-based system engineering (MBSE), virtual and augmented reality, machine learning, industrial Internet of Things, and digital twins, are transforming the manufacturing sector as well as the entire life cycle of complex physical systems. By adopting these technologies to the design, manufacturing, and operations of the heliostat field, future CSP plants will benefit from the same cost reductions, performance increases, lowered risks, and improved reliability that the car and aerospace industries have realized in the past few years.

Project Lead: Michel Izygon (Tietronix)

Objectives and Impacts:

This project's main objective is to demonstrate how Industry 4.0 technologies can help the CSP industry achieve the goals set by DOE and showcase multiple use cases for Industry 4.0 technologies. Anticipated impacts include:

- The project would improve the operational efficiency of the solar field.
- The project breaks down data silos between designers, manufacturers, and operations.
- This project supports predictive maintenance, making operations more predictable and less expensive.

Approach:

- Apply MBSE to a solar field system.
- Develop a digital twin of one heliostat.
- Develop a digital twin of a full solar field.
- Develop a digital twin of a heliostat manufacturing assembly line.

Status:

- Developed a set of MBSE models to capture the design and the behavior of a heliostat.
- Developed a set of MBSE models to capture the heliostat manufacturing line.
- Developed digital twins of various solar field use cases.
- Publication: Izygon, Michel, Soon Ong, and Tatyana Rakalina. 2023. "Applying Model-Based Systems Engineering to Concentrated Solar Power Plants." In *SolarPACES 2023 Conference Proceedings*.

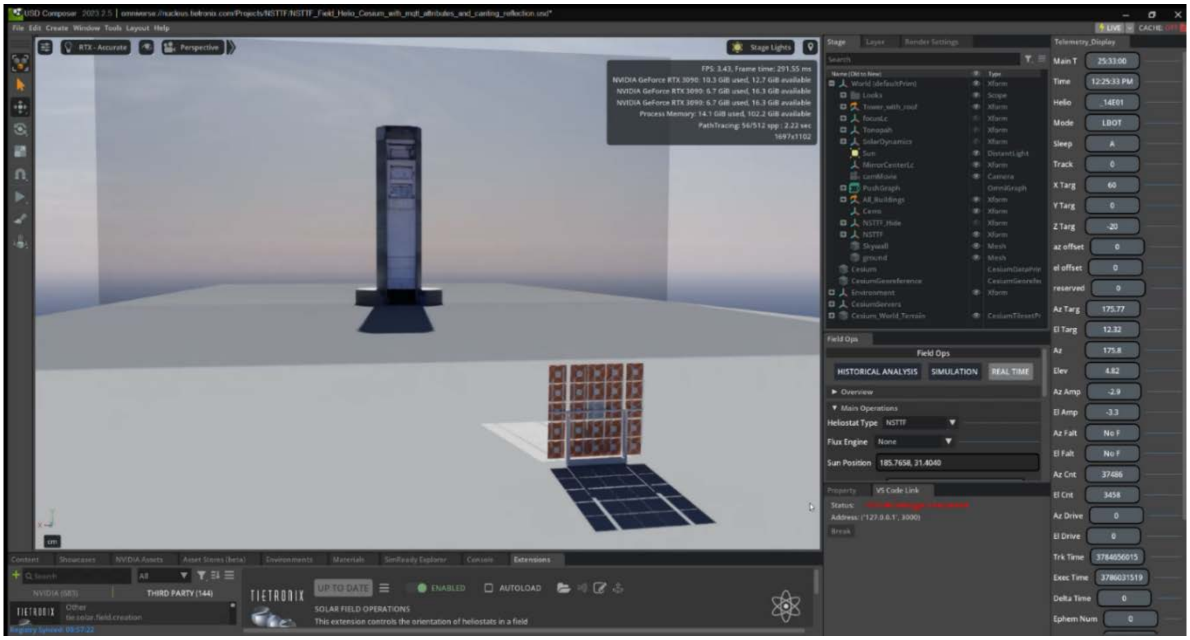


Figure 36. Digital twin of one heliostat at the NSTTF, playing back the log file of an experiment operation. The digital twin provides visualization of the heliostat motion and displays the telemetry data captured during the experiment.

Image from Tietronix

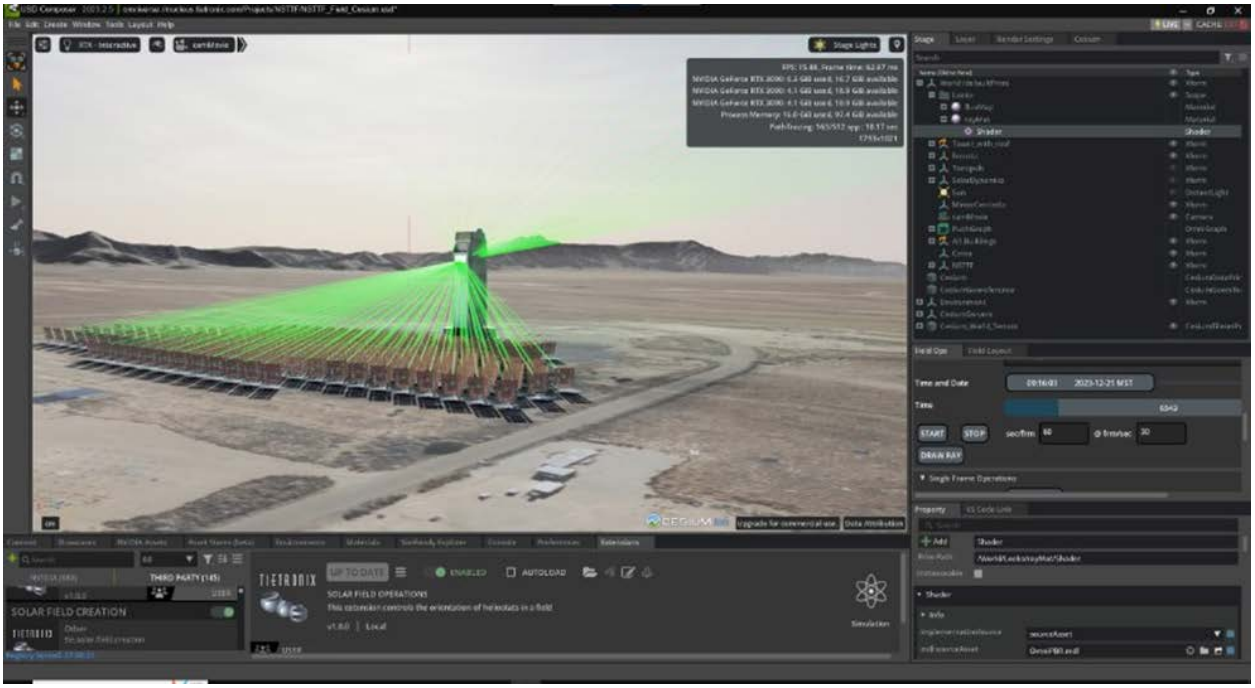


Figure 37. Visualization of the full NSTTF solar field, focusing on the receiver with the flux map computed with the fast ray-tracing simulation software

Image from Tietronix

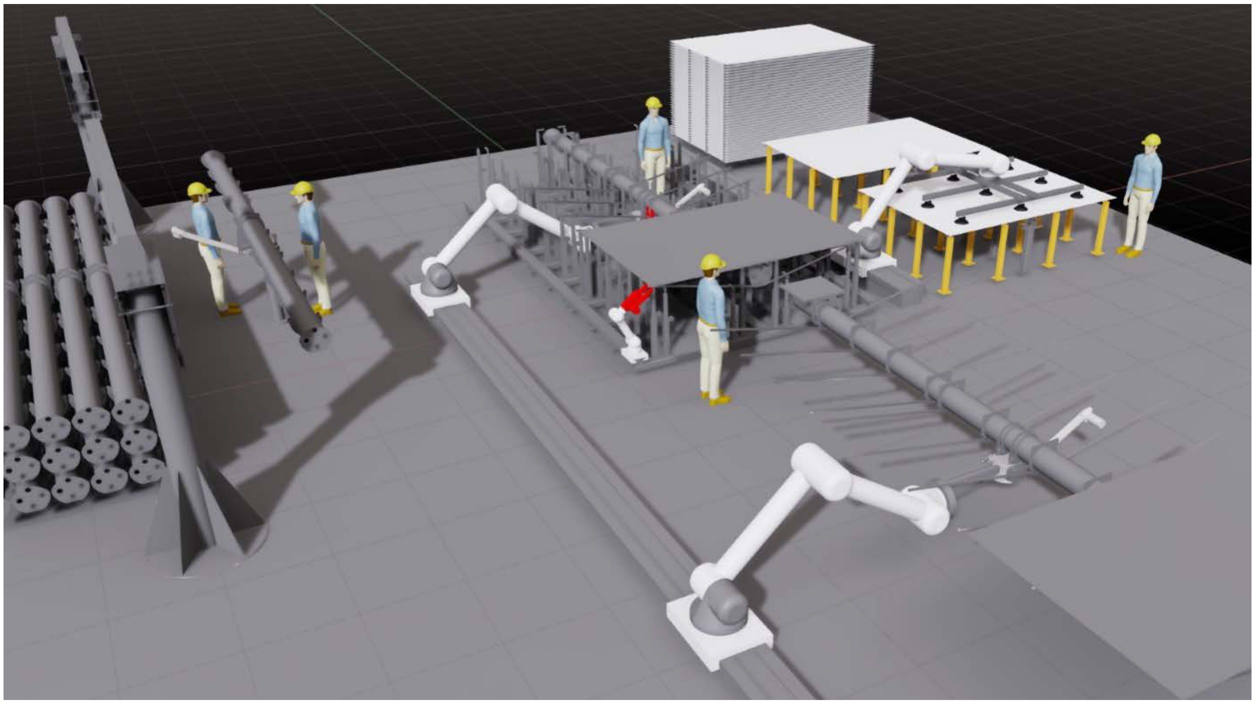


Figure 38. Digital twin of a heliostat manufacturing facility. The digital twin enables the users to view how the humans and robots are performing the assembly with the expected timing. Optimization of the position of each station, robot, and operator can be done with the simulation within the digital twin.

Image from Tietronix

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

9

Research Through Request for Proposals 2

9 Research Through Request for Proposals 2

9.1 Soiling on Heliostats Estimated by Shaded and Unshaded Scatterometry

Description: When clear portions of "blue" sky are viewed from a heliostat mirror, light from the sun is progressively scattered by soiling and is remotely visible as a brighter and less sharp sky reflection when compared to mirror regions that are shaded from direct sunlight (but reflect a similar path of sky).

Project Lead: Derek Schulte (DKA Design LLC)

The project will develop a method to estimate the loss of CSP/CST-useful solar reflectance from remote imaging of shaded and unshaded regions of mirror facets (in conjunction with site, soil, geometric, and other known data).

This method presents opportunities to reduce costly in-field soiling measurement, improve measurement fidelity and density, and enable improved operations and system control.

Objectives and Impacts:

This project aims to estimate applicable (receiver-capturable, specular) mirror reflectance losses due to soiling within ±0.5% and eliminate regular, manual, in-field measurement of mirror soiling. Anticipated impacts include:

- This project would reduce labor costs of in-field reflectance measurement via remote, unattended data acquisition with existing low-cost sensors.
- This project would result in mirror cleaning cost reduction via schedule optimization with higher-density (location and time) and higher-accuracy reflectance data.
- Receiver performance improvements are anticipated when heliostat pointing (control) and aiming (targeting) are refined based on improved reflectance data.

Approach:

- Create an invertible quantitative model to estimate specular and diffuse heliostat mirror reflections as a function of soiling level (as well as other factors).
- Anchor and validate the model by soiling mirror coupons and measuring their spatial reflectance.
- Demonstrate the method's capabilities under the controlled conditions of a subscale testbed.
- Demonstrate the method with heliostats at Heliogen's Lancaster, California, CSP test facility.
- Estimate the potential savings of using the proposed method.

Status:

- Model inputs and methodology established.
- Reflectometer and testbed mechanical design complete; procurement 80% complete.

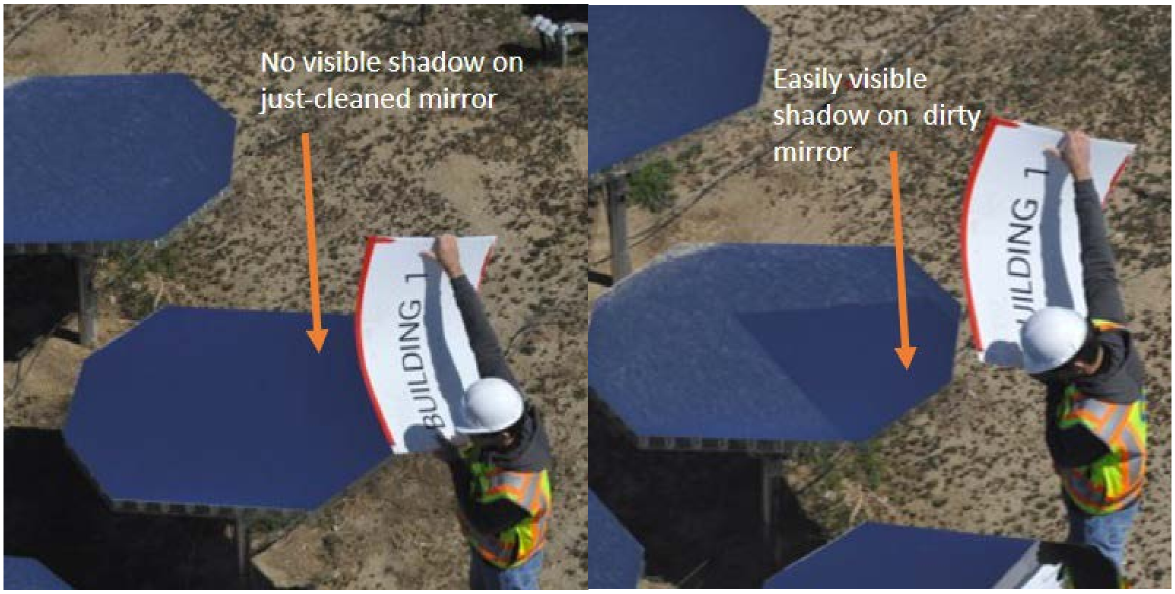


Figure 39. Clean (left) and dirty (right) mirrors. Shadow is visible on soiled mirror but not on clean mirror.

Images from Heliogen

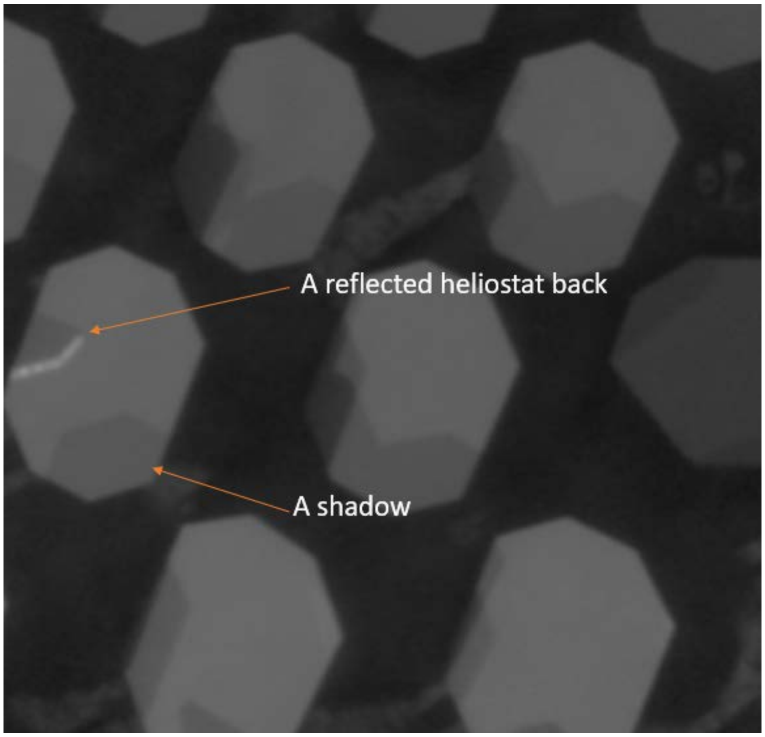


Figure 40. Cropped image from Heliogen field camera of several heliostat mirrors when specifically posed relative to field geometry and solar direction

Image from Heliogen

9.2 A Brighter Future: Education and Outreach for Small-Scale Concentrating Solar on Urban Brownfields

Description: The Brighter Future project is working to uncover and address the root causes of gaps in educational training opportunities in concentrating solar systems, with an emphasis on small-scale systems and community integration. While strong technical skills remain crucial for producing the next generation of the concentrating solar workforce, this project also incorporates economic and sociological elements. Those considerations will increase the field's appeal to a broader population, motivated by the social impact of the work, and to students in 2-year schools, an important source of the solar workforce.

Project Lead: Laura Schaefer (Rice University)

Objectives and Impacts:

Brighter Future's primary objective is to develop educational modules (both for the classroom and through extracurricular activities) that enhance concentrating solar workforce awareness and diversity. The project will evaluate the potential of small-scale heliostats on urban brownfields with combined cycle/storage technologies paired with local industries for IPH and will assess the social dimensions, technology awareness, and acceptance among local communities for locating concentrating solar systems in urban brownfields. The project will also create new capital expenditure/operating expense models. Anticipated impacts include:

- Brighter Future increases awareness of the benefits of CSP in urban communities.
- The program expands the potential workforce for CSP installation, operation, and development.
- The project quantifies capital expenditure/operating expense costs for small-scale CSP installations.

Approach:

- Design, administration, and evaluation of a survey to assess concentrating solar awareness, obstacles, diversity, and opportunities to identify the cause of lack of awareness or interest
- Creation of an undergraduate/graduate research program with (1) computational modeling of stand-alone and combined cycle small-scale systems, and (2) geographic information system tool applications for locating those systems, incorporating sociological and economic considerations
- Development of cross-disciplinary curriculum modules for both introductory-level and advanced students in the social sciences and engineering.

Status:

- Developing the list of educational survey questions and building the target audience, using university resources/partners and outreach through the Energy Sustainability conference.
- Building a cohort of junior- and senior-level undergraduates.

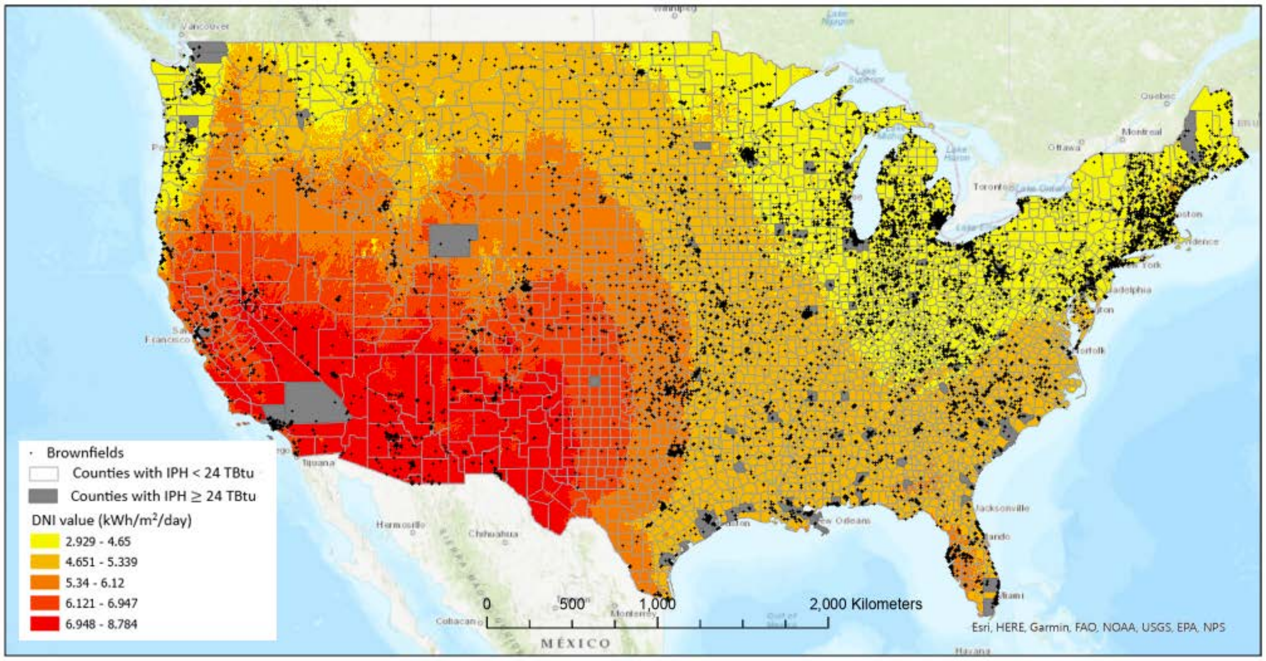


Figure 41. Initial combined assessment of IPH demand by level/county, brownfield locations, and direct normal irradiance levels

Sources: NREL/TP-6A20-77760 by McMillan et al., the U.S. Environmental Protection Agency EnviroAtlas, and NREL's Solar Resource Maps

9.3 Advancing University-Level Education on Heliostat Design and Operation

Description: The goal of this project is to advance education on heliostats via targeted classroom instruction, undergraduate-level research, and development projects. We also plan to institutionalize heliostat education by incorporating examples and homework assignments related to concentrating solar energy into course syllabi. Such courses include Freshman Cornerstone of Engineering I and II, Control, Robotics, Mechanical Design, and Financial Management for Engineers.

Project Lead: Hameed (Mohamad) Metghalchi (Northeastern University)

Objectives and Impacts:

The main objective of this university-level project is to develop and incorporate examples/homework related to heliostats in as many undergraduate/graduate courses as possible. The program also aims to develop ways to conduct research about CSP in undergraduate and graduate courses, design and build devices for use in CSP technology in senior capstone design courses, and offer a senior/graduate CSP course as well as five short courses dealing with CSP. Anticipated impacts include:

- The project resulted in concentrated solar energy projects in an ME 4550 Mechanical Design course.
- The project has resulted in two students designing and prototyping a mechanism capable of emulating the path of the sun in a laboratory. The objective is to make a simple design capable of holding a flashlight and adjusting via input the "azimuthal" and "zenith" angles of the flashlight, with the flashlight's vertical (zenith) angle controlled by a belt drive system. The design has a full SolidWorks 3D model prepared, with 8020 and rail fixtures on order.

Approach:

- Discuss CSP with instructors of many undergraduate courses to develop examples/homework in their courses.
- Invite undergraduate students to get involved in CSP research.
- Engage students in CSP-based senior capstone design courses.
- Offer graduate and short courses in CSP.

Status:

- The project is ready to go, with a full graduate course syllabus completed and short course outlines developed.

Figure 42. A presentation briefing students on the capstone senior project process and guidelines

Photo from the Northeastern University Mechanical Engineering Capstone Project

9.4 Precision Angle Measurement System for Enhanced Heliostat Performance and Cost Reduction

Description: This project focuses on improving the performance of heliostat fields by developing the Operating Surface Angle Measurement System (OSAMS), a precise instrument for measuring heliostat accuracy. OSAMS enables detailed analysis of heliostat performance under real-world conditions, facilitating design optimization and potentially improving tracking accuracy. Additionally, the project aims to educate the public and train new workers in the field through online modules on CSP and heliostat technology.

Project Lead: Heejin Cho (University of Nevada, Las Vegas)

Objectives and Impacts:

This project's aim is to design, fabricate, and test a cost-effective yet highly precise surface angle measurement sensor that will provide detailed data on the mirror surface reflection angle of a heliostat under standard operating conditions and develop publicly accessible online education modules that cover the fundamentals of CSP and heliostats. Anticipated results include:

- The project will achieve a heliostat tracking error of less than 0.01° (0.25 mrad) through the use of OSAMS.
- The program will improve system design and reduce uncertainty in heliostat tracking and performance under operational conditions.
- The project will develop cost-effective, highly precise angle measurement sensors.

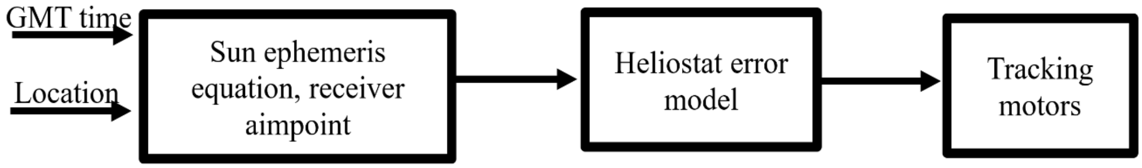
Approach:

- Develop the OSAMS sensors, which are designed to enhance the accuracy and efficiency of heliostat design, prototyping, and field performance by enabling precise measurement of various parameters affecting heliostat accuracy of the reflective beam.
- Use calibrated OSAMS sensors to perform field testing to collect sensor data and analyze the heliostat reflective surface performance.

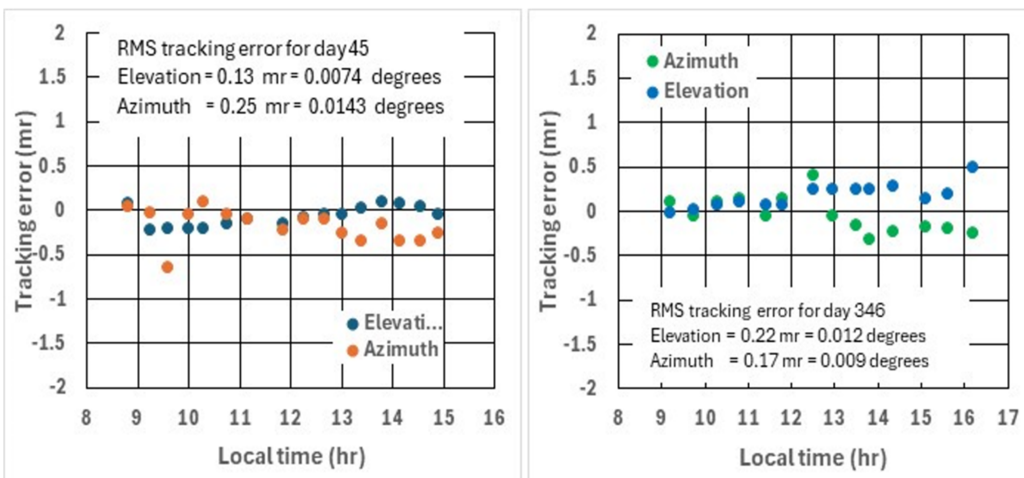
- Develop an analytical software program that can estimate the tracking error model coefficients and characterize the reflective surface angle error.
- Develop online educational modules that disseminate fundamental knowledge about CSP and heliostats.

Status:

- This project has been awarded and is projected to start technical work in FY24.



A heliostat error model was used to modify the tracking angles.



(a) (b)

Figure 43. Sandia tracking tests of McDonnell Douglas heliostat #1 in 1983

Image from University of Nevada, Las Vegas

9.5 PROMETHEUS: Predictive and Optimized Control of Heliostats for Future Solar Fields

Description: The PROMETHEUS project aims to develop an innovative tool to improve real-time heliostat control and aiming in the solar field. The tool will optimize the aiming strategies accounting for flux intensity impact on receiver lifetime, the actual status of the heliostats (soiling distribution, broken mirrors and/or drivers), and required driver power consumption during transient operation. Nowcasting of the solar radiation and its spatial distribution in the short term (5–15 minutes) is incorporated into the solution approach.

Project Lead: Michael Wagner (University of Wisconsin–Madison)

Objectives and Impacts:

The PROMETHEUS project's objective is to create an optimization tool that produces a more favorable flux distribution on the receiver. Improvements will be included in the freely available tools Heliostat Aimpoint and Layout Optimization Software (HALOS) and/or SolarPILOT. The project will develop solar radiation nowcasting and its spatial distribution on the solar field that accurately predicts the solar resource available and then optimizes the aiming strategies, as well as maximizing the harvested energy on the receiver to account for accurate soiling prediction and heliostat failure. These aspects will be implemented in freely available tools for CSP plant modeling as SolarPILOT/SAM, reducing the O&M cost and receiver failure rate in a large solar plant after adoption of the developed tools. The project aims to quantify the potential cost reduction of the generated electricity by model application through empirical studies to existing assets, and to improve solar plant and receiver design with potential cost savings thanks to the adoption of a more accurate flux control. Anticipated impacts include:

- Reduction in O&M costs: The new tool will reduce the solar field's O&M costs by 10%, achieved through a 25% reduction in receiver maintenance and a 15% extension in driver life. This is accomplished by optimizing heliostat aiming strategies to minimize wear and tear on critical components.
- Increased solar energy collection: The project aims to increase collected solar radiation by 3% annually. This is achieved by implementing advanced control methods that maximize the efficiency of solar energy collection.
- Lower LCOE: The project will achieve a 5% reduction in LCOE, contributing to a corresponding 5% reduction in the environmental impact of CSP technology. This is realized through a combination of the bullets above.

Approach:

- The main innovative contribution of the proposal is the development of heliostat aiming strategies that account for the actual heliostat field status and operational impact on the receiver lifetime. The offerors have already developed (Tool 1) heliostat aiming strategies tools focusing on heat flux distribution on the receiver, but it was not applied to real-time operation [1, 2]. Another tool for the prediction of the actual soiling of the heliostats (Tool 2) depending on their position in the solar field and the dust concentration in the air has been developed and available [3].

Status:

- The proposed project starts from the models developed by the partners to optimize the solar flux on the receiver and stress-fatigue analysis [1, 2, 4, 5, 17]. These models will be improved to accommodate the actual solar field status (soiling distribution, uneven direct normal irradiance, heliostat status and driver failure).

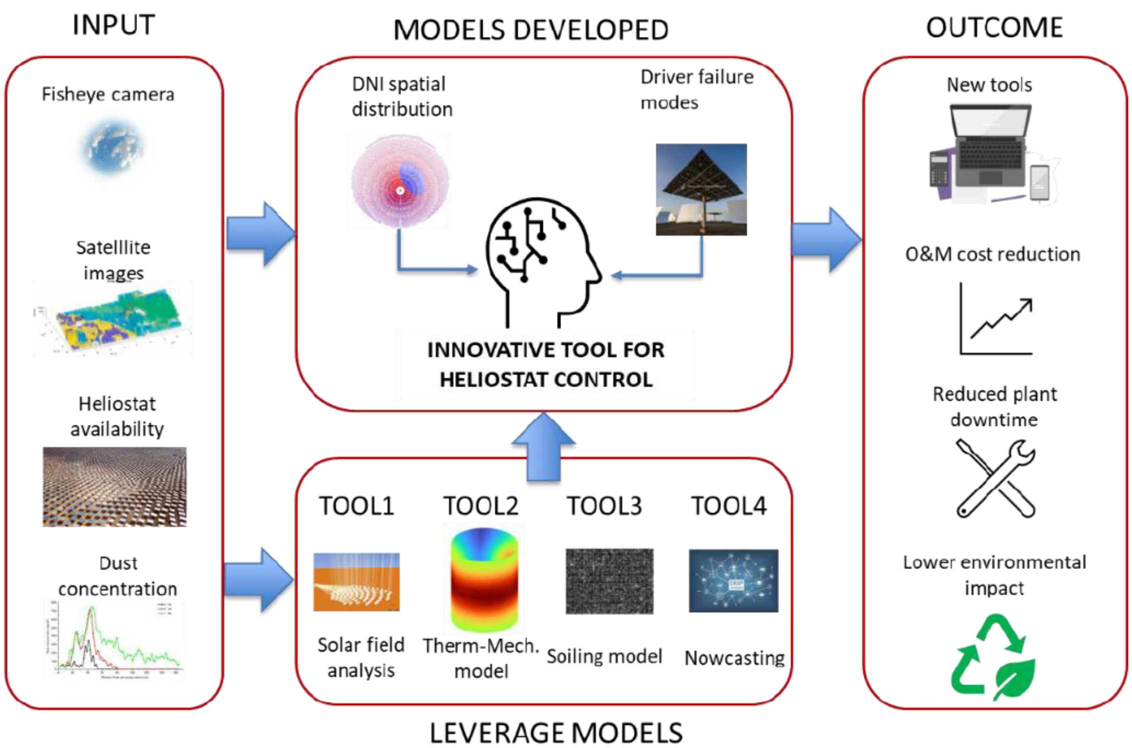


Figure 44. PROMETHEUS proposed approach with different aspects of research

Illustration from University of Wisconsin–Madison

9.6 Generic Heliostat Field Control System

Description: The generic heliostat field control system (HFCS) is based on the Crescent Dunes HFCS. It includes an integrated heliostat field and receiver model. It provides online control and monitoring as well as offline simulation for study and training.

Project Lead: Mark Ayres (Crescent Dunes, MarkAyres Engineering)

Objectives:

The generic HFCS program aims to develop a generic HFCS that can accommodate various heliostat and receiver designs and provide a proven control system for heliostat/receiver projects. The project would enhance the Crescent Dunes field/receiver monitoring and simulation with the TieSOL ray-tracing CUDA technology by providing real-time receiver performance, offline operator training simulation, and offline study simulation to recreate system anomalies and develop remedial actions. Anticipated impacts include:

- The proposed generic control system will offer a low-cost, performance-validated, and commercially ready product in the market that would directly remove technical barriers for heliostat technology developers and greatly reduce deployment risks of commercial-scale projects.

Approach:

- Repurpose the Crescent Dunes HFCS from a proprietary General Electric system to a Microsoft structured query language (SQL) server and an open-source or commercially available supervisory control and data acquisition (SCADA) system.
- Add the TieSOL ray-tracing as an enhanced option to the Crescent Dunes ray-tracing.

Status:

- Dual redundant server 2022 system operational with Microsoft SQL server.
- Selected two candidate commercial SCADA systems for first-stage integration.
- In the next quarter, down-select the commercial SCADA system. Look at possible open-source SCADA systems that can provide comparable capabilities.

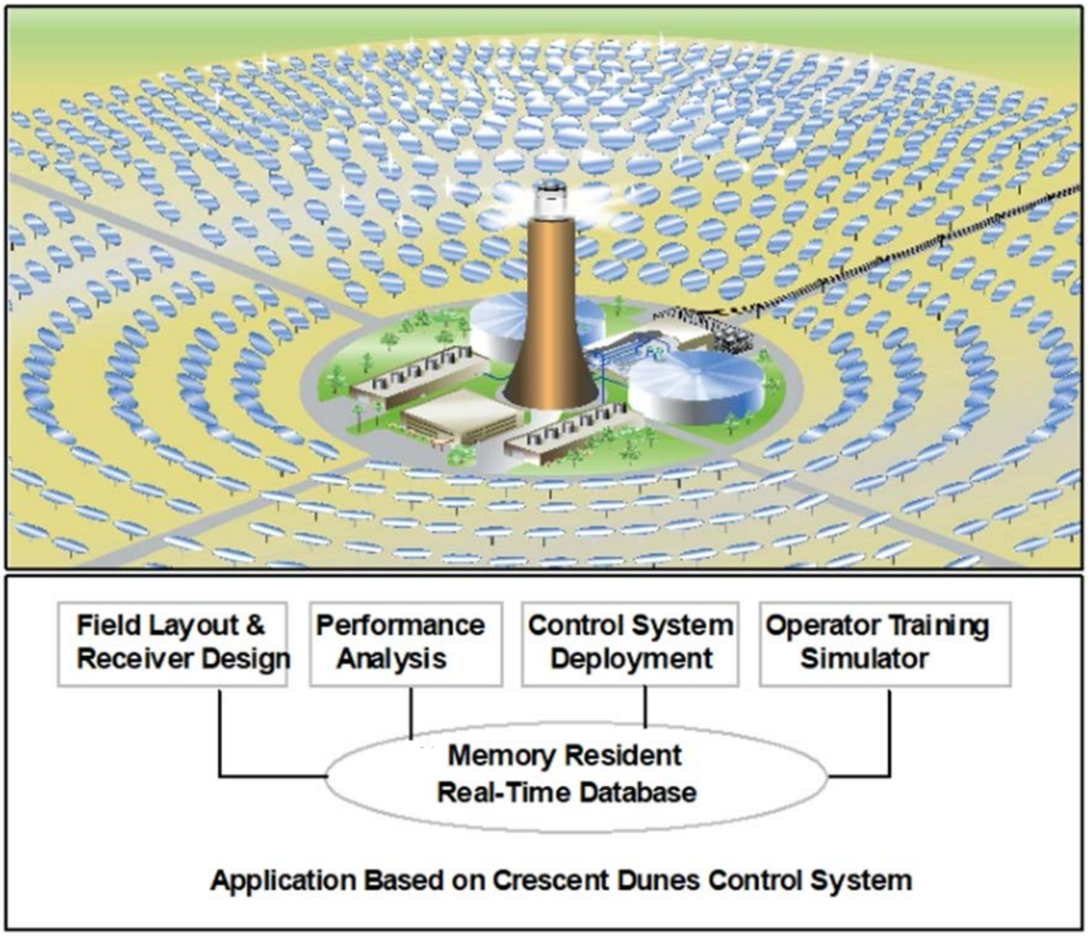


Figure 45. Diagram of generic heliostat field design and control system.

Image from Mark Ayres

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

10

Research Through Partnerships With the Heliostat Consortium

International Collaboration

10 Research Through Partnerships With the Heliostat Consortium – International Collaboration

10.1 Ray-Trace Model Round Robin Test

Description: The solar field of a power tower CSP plant constitutes about a third of the plant costs, and optimizing the design and operation of these systems can be supported by modeling optical systems using ray-trace software tools. This work compares three MCRT software packages—SolTrace, Solstice, and TieSOL—by simulating multi-facet heliostats and commercial-scale solar fields (R. Mitchell et al. 2024). The comparison focuses on assessing the agreement of receiver flux distributions and examining factors like solar hour, heliostat locations, facet and canting focusing, and aimpoint strategies to improve tool accuracy and reliability.

Project Lead: Rebecca Mitchell (NREL)

Objectives and Impacts:

This project's primary objective is to obtain agreement in flux modeling across SolTrace, Solstice, and TieSOL for commercial-scale power tower CSP solar field models and establish benchmark case studies for validation of future ray-trace tools. Anticipated impacts include:

- This project offers case studies to benchmark and verify ray-trace tools with realistic commercial-scale models.
- Creating standards for ray-trace validation will increase confidence in these tools and de-risk the possibility of developing inaccurate models that are used to predict plant performance.

Approach:

- Single-heliostat case studies with a flat rectangular target to benchmark agreement between the three tools for a single-facet and multi-facet heliostat
- Commercial field case studies modeled by a planned plant in Port Augusta, Australia, with single- and multi-facet heliostats, heliostat canting and facet focusing determined according to slant range, and aimpoints at the centerline and with scattering
- Diagnostic case studies using isolated heliostats selected from the commercial field model to troubleshoot discrepancies between the tools.

Status:

- Agreement achieved between the three tools using comparison of flux metrics.
- Draft of paper to be submitted for publication.

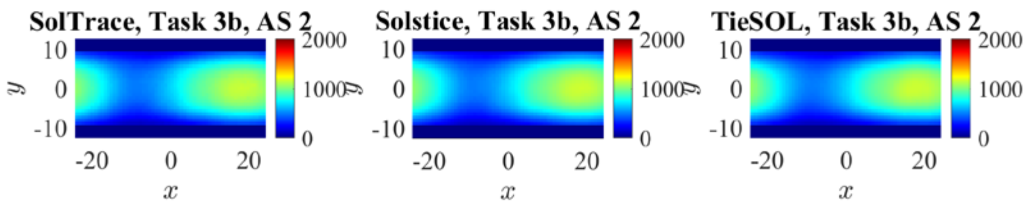


Figure 46. An example flux distribution comparison plot for a commercial-scale case study implemented in SolTrace, Solstice, and TieSOL

10.2 ReTNA and SOFAST Participation in International Optical Metrology Round Robin Study

Description: Both NREL and Sandia have participated in an international optical metrology round robin effort. During this effort, six parabolic trough facets were shipped between participating labs for measurement of each lab's system. Sandia received and measured the panels in the first quarter of FY24 and hosted NREL in December 2023 to measure panels at Sandia using a portable version of ReTNA. NREL and Sandia's participation began under a Solar Facilities for the European Research Area - 3 (SFERA-3) award, but the majority of each group's effort was made possible through HelioCon efforts.

Project Lead: Marco Montecchi (ENEA) – leading the international round robin effort. U.S. leads: Devon Kesseli (NREL), Randy Brost (Sandia), Braden Smith (Sandia), Guangdong Zhu (NREL)

Objectives and Impacts:

The main objective of the optical metrology round robin is to compare optical metrology systems and approaches by measuring the same panels, identify potential differences in metrology systems and their causes, and foster international collaboration and collective improvement of measurement systems. Anticipated impacts include:

- This project builds collaboration and engagement with international experts in the field of CSP optical metrology (ENEA, DLR, Fraunhofer ISE, Sandia, and NREL).
- The project builds on the validation, improvement, and standardization of optical measurement tools used in research and industry by measuring the same parabolic trough mirror facets using five different measurement systems, and comparing results on a standard measurement grid.

Approach:

- Six parabolic trough panels are shipped between participating labs and measured on a specific support structure.
- Participating teams traveled to ENEA under the SFERA-3 project to discuss methodologies and how results will be presented. NREL brought a portable ReTNA system to measure mirror panels at ENEA.

- Sandia: A new SOFAST setup was constructed to measure panels in the round robin orientation, and the support structure was constructed according to specifications from ENEA. The six panels were shipped to Sandia and measured in the first quarter of FY24.
- NREL: A lightweight, portable ReTNA setup was brought to Sandia. This involved a collapsable target stand, adhesive target sticker, camera, and tripod. Measurement of four panels was collected at Sandia over 2 days in December 2023.

Status:

- All five round robin teams completed an initial measurement of the parabolic trough panels and have shared results.
- Ongoing work is being done to diagnose differences between the measurement systems, which are often larger than the reported uncertainties.
- For SOFAST, results were sent to ENEA for comparison. Ongoing investigation to determine the measurement discrepancy.
- In the ReTNA measurement, significant challenges included applying this measurement system to highly curved parabolic trough mirrors, and accurate identification and transformation into the round robin reference frame for comparison. Nonetheless, this collaboration has led to many important ReTNA improvements, in terms of understanding the limits of this system, formalizing testing procedures, and developing software necessary for comparison with other measurement systems, which will be performed under HelioCon.

Figure 47. Right: Measurement of a round robin trough facet at Sandia. Here, a portable ReTNA target is set up underneath Sandia's SOFAST target screen. Left: Participants in the SFERA-3 round robin project at ENEA.

Photo by Devon Kesseli, NREL

10.3 BCS Round Robin

Description: This project is an international effort to develop, compare, and ultimately standardize BCSs. The scope of system comparison includes hardware, image capture methodology, and image processing algorithms. Leading CSP research institutions across three continents are contributing to this effort.

Project Lead: Marcelino Gonzalez (National Renewable Energy Center of Spain [CENER]), Kontxi Etxamendi (CENER), Guangdong Zhu (NREL) and Tucker Farrell (NREL)

Objectives and Impacts:

This round robin aims to develop a common set of BCS procedures covering hardware setup, test execution, and data processing. The project will analyze performance, commonalities, and differences between participating institutions' implementation of the common procedure set and will produce a unified BCS standard aligning with execution of SolarPACES guidelines and IEC standards. Anticipated impacts include:

- This project builds the validation, improvement, and standardization of the BCS used in research and industry by processing at least 20 BCS images from at least three different BCS installations and processing these standard images with at least three different types of BCS software.
- Generalization of BCS: Testing different BCS images with different software will generalize BCS software, lowering the barrier for BCS system deployment at new CSP installations.

Approach:

- Harvest a common dataset and means and methods information from project partners and industry.
- Develop a unified means and methods document by consensus from participating institutions.
- Execute BCS testing at all institutions.
- Draft a comparison analysis and a resulting common standard.

Status:

- Dataset compiled from three primary participating institutions.
- Group BCS means and methods document drafted based on individual institutions' existing BCS processes.
- Image processing and sensitivity analysis on the CENER dataset (largest provided) completed by NREL using Monte Carlo-style processing parameter variation.
- By year's end, have testing at all institutions underway, governed by a common means and methods document.

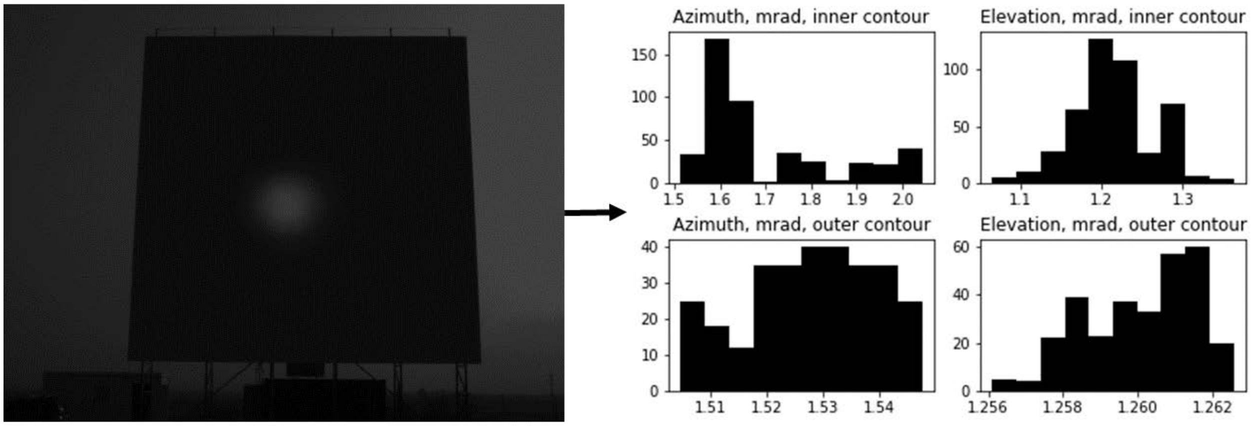


Figure 48. Left: One raw BCS image from a round robin partner institution's contribution to the shared dataset. Right: NREL preliminary sensitivity study result of varying image preprocessing parameters on this particular image, with the y-axis representing the number of preprocessing parameter combinations resulting in the calculated tracking deviation indicated on the x-axis. Two image post-processing methods are used: inner contour and outer contour.

Left image from CENER; right image by Daniel Tsvankin, NREL

U.S. Department of Energy
HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power

11

Research Through Partnerships With the Heliostat Consortium

TCF

11 Research Through Partnerships With the Heliostat Consortium – TCF

11.1 Commercialization of a Non-Intrusive Optical Technology To Measure Heliostat Optical Errors in Utility-Scale CSP Plants

Description: The drone-based NIO technology developed at NREL will be commercialized into a tool package with software, user interface, manual, and training services (R. Mitchell and Farrell 2024). The project team will partner with Tietronix for market assessment, tool development, and data collection to demonstrate its capabilities at a commercial CSP plant. The goal is to advance the technology to a beta version for further demonstration and eventual licensing.

Project Lead: Rebecca Mitchell (NREL)

Objectives and Impact:

This project's main objective is to provide a beta version of a commercial NIO tool that, with further commercial demonstration, could be licensed by CSP plant operators to conduct efficient measurements and monitoring the solar field, which can be incorporated into operation practices to improve power output. The project will perform a large-scale commercial demonstration of the tool. Anticipated impacts include:

- The project would demonstrate the value of the NIO tool for commercial solar field optical assessment to plant customers.
- This project will demonstrate high-volume heliostat drone scan capabilities.

Approach:

- Obtain stakeholder data to determine the industry needs that the NIO metrology capabilities must meet.
- Develop a commercial NIO package with a user interface, documentation and training, and capability services to meet stakeholder needs.
- Perform a commercial demonstration of the NIO tool by performing data collection activities and providing optical error data deliverables to a plant partner.
- Develop a business strategy to market and launch a beta version of the commercial tool package at the conclusion of the project.

Status:

- Made significant advancements toward commercialization of the NIO software by streamlining the data architecture and improving the reliability of the automated post-processing of data.
- Performed an NIO UAS survey of 10% of the Cerro Dominador solar field in the Antofagasta region of Chile (over 1,100 mirrors) to demonstrate the commercial-scale measurement capability.

Figure 49. The NREL NIO team collects drone images of heliostats at Crescent Dunes plant

Image from Miguel Rosales, Tietronix

11.2 ReTNA Technology Project

Description: In FY23, NREL was awarded a Technology Commercialization Fund project to adapt the ReTNA tool developed under HelioCon for commercial use (Kesseli 2024). This work began in FY24, and has been successful, with multiple commercial heliostat developers showing interest in the tool. Over the last three quarters under this project, the ReTNA team traveled to a large-scale heliostat developer's facility to perform two separate test campaigns—the first to demonstrate ReTNA technology and compare with existing tools, and the second to demonstrate a full-scale installation on their heliostat manufacturing assembly line. We have also partnered with a second heliostat developer, Solar Dynamics LLC, to develop a unique ReTNA layout for their assembly platform. This new layout was built and tested for the first time at the end of the third quarter of FY24. The team is working on several software improvements that are essential for commercial deployment.

Project Lead: Devon Kesseli (NREL)

Objectives and Impacts:

The primary aim of this project is to demonstrate the commercial applicability of the ReTNA measurement system and adapt the system to meet the needs of commercial heliostat developers. After validating the ReTNA system in a commercial environment, the project will complete the necessary software development for commercial deployment. Anticipated impacts include:

- The project will redevelop the ReTNA measurement system to meet the requirements defined from commercial heliostat developers.
- Automating ReTNA measurement using computer vision techniques will eliminate manual measurement bottlenecks and reduce measurement time to <30 seconds.
- Validating ReTNA deployment at a commercial partner's facility will demonstrate a lower cost and faster optical measurement compared to state-of-the-art measurement systems, for faster heliostat design cycles and manufacturing QC.

Approach:

- Work closely with commercial heliostat developers to determine their heliostat measurement needs and how ReTNA can be adapted to meet those needs.
- Validate ReTNA in these new environments.
- Remove ReTNA's reliance on other commercial photogrammetry software.

Status:

- Designed and built two unique ReTNA installations at two different commercial partner facilities.
- Fully validated one layout (initial results generated at Solar Dynamics), but there is still significant improvement and validation work to do.
- Completed significant software improvements needed to share code with commercial partners; however, work to remove commercial photogrammetry software has been delayed.

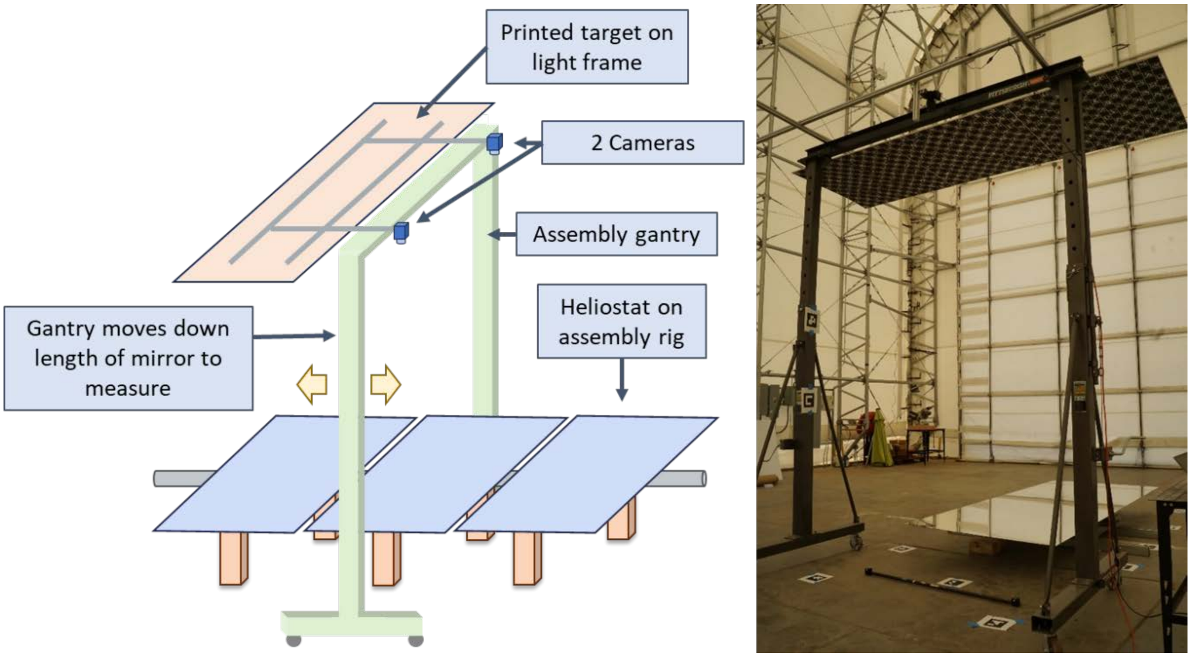


Figure 50. A unique ReTNA layout, specific to Solar Dynamics' heliostat assembly. Diagram of the design (left) and image of initial installed system (right).

Image and photo by Devon Kesseli, NREL

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

12

Research Through Partnerships With the Heliostat Consortium

Small Innovative Projects in Solar (SIPS)

12 Research Through Partnerships With the Heliostat Consortium – Small Innovative Projects in Solar (SIPS)

12.1 Development, Validation, and Testing of High-Reflectance, Cost-Reducing Composite Heliostat Mirror Facets

Description: In this DOE Small Innovative Projects in Solar (SIPS) project, NREL is partnered with Heliuss Solar Industries to manufacture and conduct performance and environmental testing of paraboloid-shaped 1.20-m x 1.35-m composite mirrors that have built-in structural support. These composite mirrors will use ~1-mm low-iron glass supported by honeycomb and a backplate to achieve a ~3% increase in reflectivity. The support structure is intended to create a hermetic seal that can increase field life while eliminating usage of steel and expensive protective paints. O&M costs will be reduced due to the resilience of the facet structure, and overall CSP generation costs will be reduced due to the performance improvements. The project began June 1, 2024, and therefore there are no results yet to share, but all findings of this project will be made publicly available.

Project Lead: Matthew Muller (NREL)

Objectives and Impacts:

This project's primary objective is to demonstrate full-size composite facets with an approximate 3% improvement in reflectivity. The project will demonstrate the durability and resiliency of the composite facets by subjecting the facets to a full set of performance and environmental testing, as well as demonstrating manufacturing methods that are in line with the necessary cost structure to achieve target costs for CSP energy. Anticipated impacts include:

- If successful, the project will demonstrate a manufacturing pathway to higher-reflectance mirrors that are more cost-effective than existing Heliostat facets.

Approach:

- Heliuss will work with manufacturing partners to produce and provide NREL with three waves of varying facet stacks for performance and environmental testing.
- NREL will conduct a full set of performance and environmental testing on the facets provided by Heliuss. The results will be shared with Heliuss and made publicly available. Each phase of testing will guide changes in the production of the next wave to make progress toward goals of low cost, improved performance, and durability.

Status:

- The project began June 1, 2024, and a contract has been signed with Heliuss for first facet delivery to NREL in August–September 2024. First results are expected in October 2024.
- A detailed performance and durability test plan has been developed and approved by DOE.

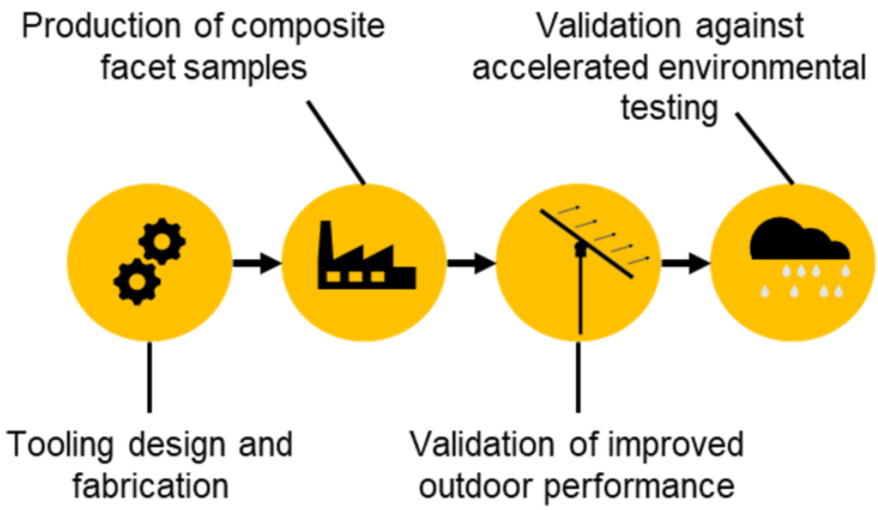


Figure 51. The overall plan for developing and testing composite facets that are consistent with HelioCon goals for low-cost heliostats

Graphic by Daniel Tsvankin and Matthew Muller, NREL

12.2 Development of Flexible Wireless Control Architectures for Heliostat Fields

Description: This DOE SIPS project is intended to provide the U.S. CSP industry with a communication protocol and hardware testbed for the realization of a high-performing, low-cost wireless heliostat control. Wireless controls enable cost reduction of heliostat fields, but off-the-shelf hardware is not designed for the unique needs of heliostat fields. NREL and CaribouLabs will demonstrate wireless hardware that is designed to be low-cost while specifically meeting the most rigorous needs of any heliostat field.

Project Lead: Matthew Muller (NREL)

Objectives and Impacts:

SIPS aims to build out a flexible NREL wireless control testbed with 100 communication nodes for lab, industry, and academia use. The program will test hardware at NREL's Flatirons Campus, demonstrate key wireless performance metrics, and publish cost/benefit analysis, design documents, and test results for novel wireless heliostat communications. Anticipated impacts include:

- The project will demonstrate a low-cost wireless control architecture that is readily available for use for heliostat fields, regardless of heliostat manufacturer.

Approach:

- A 100-node wireless architecture will be installed at NREL's Flatirons Campus.
- The field will be tested against simulations and demonstrated to meet key performance criteria that are needed for closed-loop control and autocalibration of heliostat fields.
- Wireless hardware designs will be provided on an open-source repository, and all results will be published.

Status:

- The project began on June 1, 2024, and a contract is in process with CaribouLabs.
- CaribouLabs will deliver the first wireless hardware to NREL in the summer of 2024.

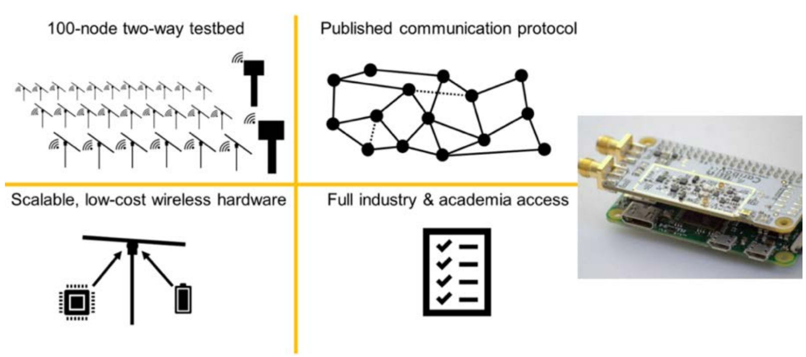


Figure 52. The overall project plan for development and testing of wireless communications for heliostats

Graphic by Daniel Tsvankin and Matthew Muller, NREL

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

13

Research Through Partnerships With the Heliostat Consortium

Lab Call

13 Research Through Partnerships With the Heliostat Consortium – Lab Call

13.1 Wind Loading on Solar Collectors

Description: Wind loading is one of the primary drivers of the structural design costs of CSP collector structures (heliostats and parabolic troughs) (Egerer et al. 2024). To date, the design of these structures has relied on data from wind tunnels that do not adequately capture the dynamic effects observed at scale. This project is conducting a comprehensive field measurement campaign to measure the exact wind conditions and the resulting loading on heliostats at Crescent Dunes. This dataset will be used to quantify the optical performance of heliostats and will also be used to develop and validate computational models capable of predicting the unsteady flow environment and loading in deep-array configurations.

Project Lead: Shashank Yellapantula (NREL)

Objectives and Impacts:

This project has two overarching objectives:

- The project will gather detailed measurements to characterize the prevailing wind conditions and resulting operational loads on parabolic troughs and heliostats.
- The project will develop and validate a computationally efficient, high-fidelity modeling tool capable of predicting wind loading in deep-array installations of solar collectors.

Anticipated impacts include:

- The project aims to offer better quantification of wind-driven loads on life and optical performance of Heliostats, as pursued by the measurements and modeling in this project.
- The data being generated in this project will provide an advanced understanding of wind-driven loads on supporting structures and can eliminate over design allowing the designers to meet $50/m^2 goal for a solar field outlined by DOE.

Approach:

- Install wind and load measurement instrumentation at Crescent Dunes power plant. Measure wind inflow into the plant along with wakes behind the heliostats. The focus will be on characterizing static and dynamic loads on the heliostats at the plant edge and deep in the array.
- A computationally efficient actuator source modeling capability will be used to simulate heliostats in complex deep-array configurations. The focus of the modeling activity in FY24 is to develop techniques for modeling dynamic behavior of heliostats.

Status:

- Wind and load characterization instrumentation was installed at Crescent Dunes. Three heliostats—two at the edge and one in the interior—have been equipped with several load characterization instruments. Installed equipment includes several strain gauges, inclinometers, rotary encoders, pressure differentials, and accelerometers on each of the four corners of the heliostats.
- As expected, the inflow met-tower with four sonic anemometers observed north and northwest as the predominant wind direction with peak wind speeds > 25 m/s (60 mph).
- High-wind events with sustained wind speeds >20 m/s with very high turbulence intensity are also being observed. These wind gusts impose a large variation of wind-driven loads on the mirror surface and supporting structures.

Figure 53. The inflow tower and sonic anemometers installed at Crescent Dunes

Figure 54. Lidar installation at Crescent Dunes

Figure 55. Schematic of the load instrumentation installed on three heliostats at Crescent Dunes, along with some images of the actual installation

13.2 Elevating SolTrace's Capabilities for the Next Generation of Concentrating Solar Thermal Analysis

Description: In this project, we plan to refactor and optimize SolTrace's source code to be computationally efficient and enable graphics processing unit (GPU) parallelization, which will allow users to simulate commercial-scale CST optical problems faster than has ever been possible with open-source software (National Renewable Energy Laboratory n.d.; "SolTrace" n.d.).

Project Lead: William (Bill) Hamilton (NREL)

Objectives and Impacts:

This project's main objective is to improve SolTrace's computational efficiency for both central processing unit (CPU) and GPU parallelization. The project will improve SolTrace's usability, accessibility, and maintainability, and increase SolTrace's usership within the academic community for research projects and teaching CST optical performance. Anticipated impacts include:

- SolTrace would become the first open-source MCRT software for concentrating solar applications that enables GPU parallelization.
- Users will be able characterize CST system annual optical performance within seconds or minutes rather than hours or days; thereby enabling design iteration, optimization, and automation methods.
- CST researchers and developers will be able to use SolTrace, as verification or within their simulation workflows, to conduct ray-tracing for novel collector and/or receiver designs.

Approach:

- Modify SolTrace's existing source code to improve computational efficiency and enable GPU parallelization of its ray-tracing operations.
- Automate SolTrace's simulation processes including but not limited to (1) convergence testing on results, (2) solar tracking geometry, (3) heliostat layout methods, (4) additional sun shape models, (5) design point evaluation, (6) time-series analysis, and (7) post-process ray-tracing results.
- Rebuild SolTrace's graphical user interface to provide users with more visualization of the model's inputs and outputs.
- Conduct three SolTrace user surveys throughout the project with the goal of receiving ideas and feedback from the SolTrace community.

Status:

- The project is currently in negotiations with DOE.
- The project is planned to start October 1, 2024.

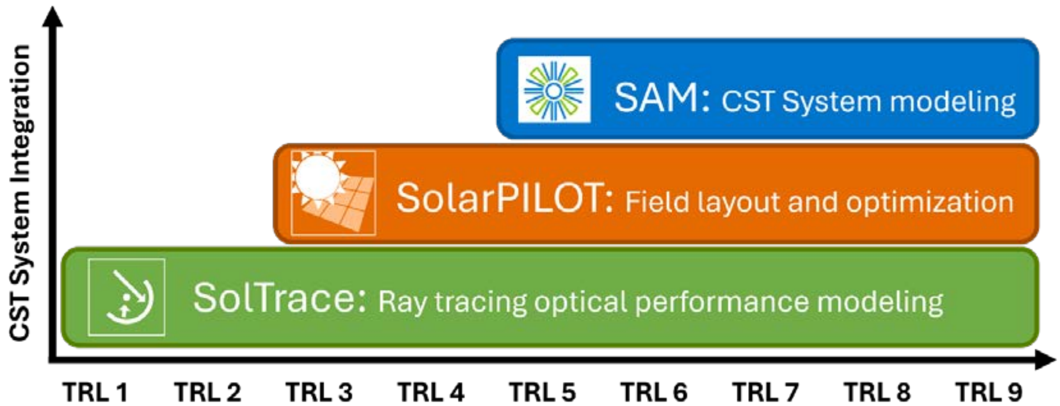


Figure 56. SolTrace MCRT serves as the foundation of CST system performance modeling and enables optical characterization of novel collector and receiver designs

Image by Bill Hamilton, NREL

13.3 Avian Surveillance Within Concentrating Solar Power Flux Hazard Volumes

Description: This project outlines the development of an artificial intelligence (AI)-based avian surveillance system for CSP plants aimed at reducing bird fatalities caused by concentrated sunlight. The system uses stereoscopic imaging, motion detection algorithms, and machine learning to detect and track birds in 3D space near CSP towers. With a goal of processing 30 frames per second, the system aims to initiate mitigation measures before birds enter high-risk areas.

Project Lead: Daniel E. Small (Sandia)

Objectives and Impacts:

Detect and track birds in real time: The system aims to identify and monitor avian wildlife near CSP towers using stereoscopic imaging and motion detection algorithms. The project will let CSP plants initiate timely mitigation measures: By processing data at 30 frames per second, the system seeks to divert birds from high-risk areas before they incur serious injury. The ultimate goal is to decrease bird deaths caused by concentrated sunlight, addressing both environmental concerns and legal compliance with the Migratory Bird Treaty Act. Anticipated impacts include:

- The Avian Detection and Collection System (ADACS) should allow CSP power tower ecological evaluation and siting times to be reduced, as a quantitative method for performing an automated site survey does not exist.
- The ADACS + deterrent capability (when installed at existing CSP power towers) will be able to reduce avian mortality by triggering avian deterrent mechanisms when birds are detected flying toward the high-flux-hazard volumes.
- This combined capability should be a win/win for both solar powered developers hoping to speed approval processes and wildlife ecologists hoping to protect critical natural resources and endangered species.

Approach:

- Stereoscopic imaging and 3D localization
- Motion detection and target identification
- Data association and multi-object tracking.

Status:

- Preliminary results and testing: Various camera configurations tested in Unreal Engine simulations
- Avian mortality study completed: Conducted at Ivanpah Solar Power Facility from October 2013 to December 2021.

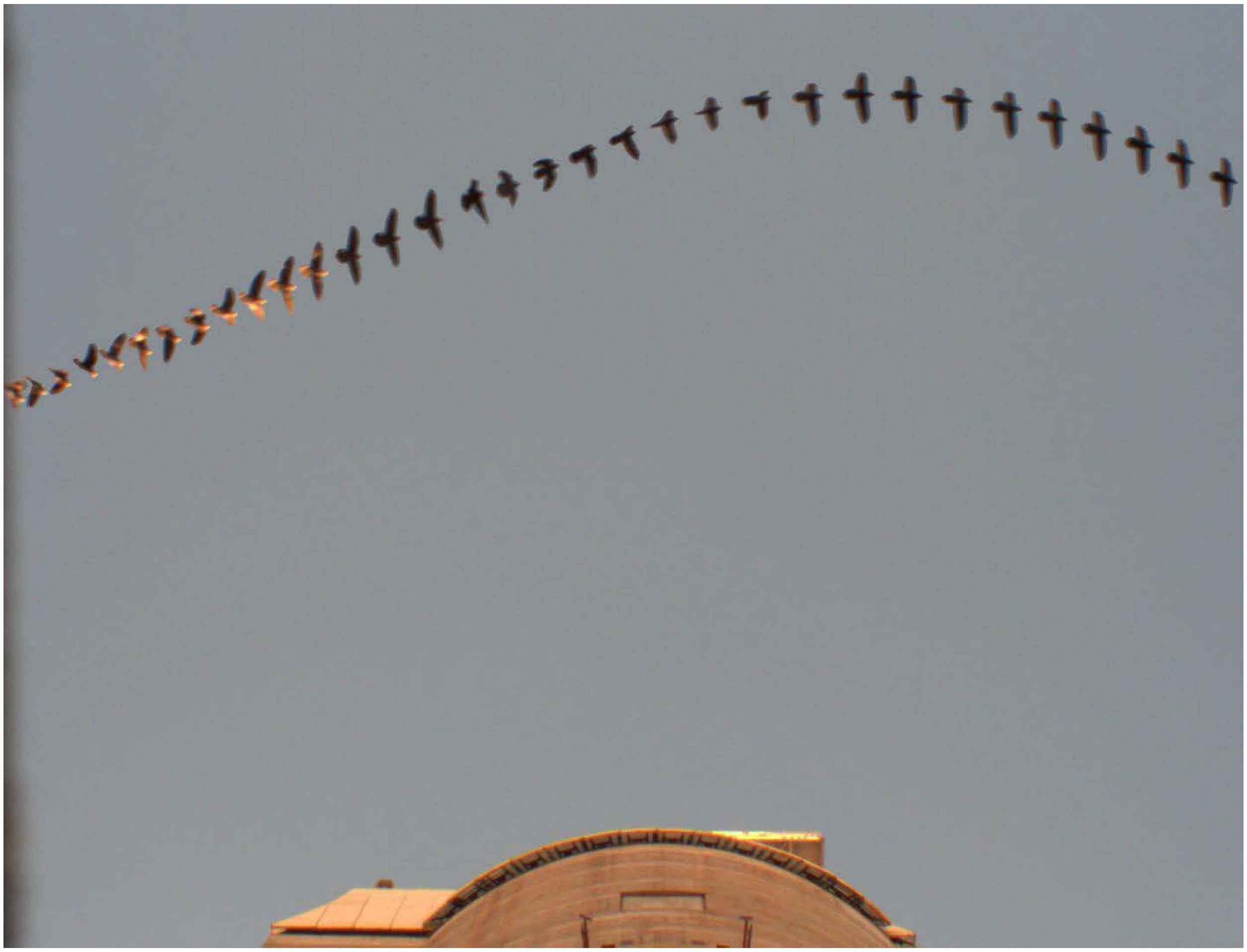


Figure 57. Bird flight at Sandia Solar Concentrating Facility

Image from Sandia National Laboratories

13.4 NSTTF Heliostat Field Refurbishment Project

Description: The NSTTF currently operates an open-loop heliostat field control software with outdated hardware and a software version limited to a fixed 2008 technology. This project seeks to update the hardware to a 15-year operational guarantee with the ability to upgrade the software to a modern version of controls, including closed-loop control capabilities.

Project Lead: Kenneth Armijo (Sandia)

Objectives and Impacts:

This project aims to update open-loop controls capability to closed-loop, update the Heliostat dual-axis controller to guarantee 15 years, and update the Heliostat field control software to a modern version (2023). Anticipated impacts include:

- This project offers a new heliostat comms capability for the laboratories.
- The project brings potential cost/energy savings for deployments, and reliability and confidence for commercial deployments. This testbed resource will de-risk technologies before deployment.
- This project aims to give operators the ability to rapidly screen comms technologies to improve R&D maturities.

Approach:

- New control software will have a queue state machine architecture for easy adaptability and integration.
- Single-engine template software will allow faster integration and changes.
- Develop a user-friendly integration using open-source software for closed-loop controls and heliostat calibration.

Status:

- New compact real-time embedded industrial controller (cRIO) hardware fully updated with modern firmware.
- Benchtop testing of closed-loop controls complete; field testing has begun.
- Wireless system in development; communications stations deployed in the field and at the control tower with clusters of four heliostats wirelessly controlled.
- Host, real-time, and field-programmable gate array have been field tested, running four heliostats from new graphical user interface.

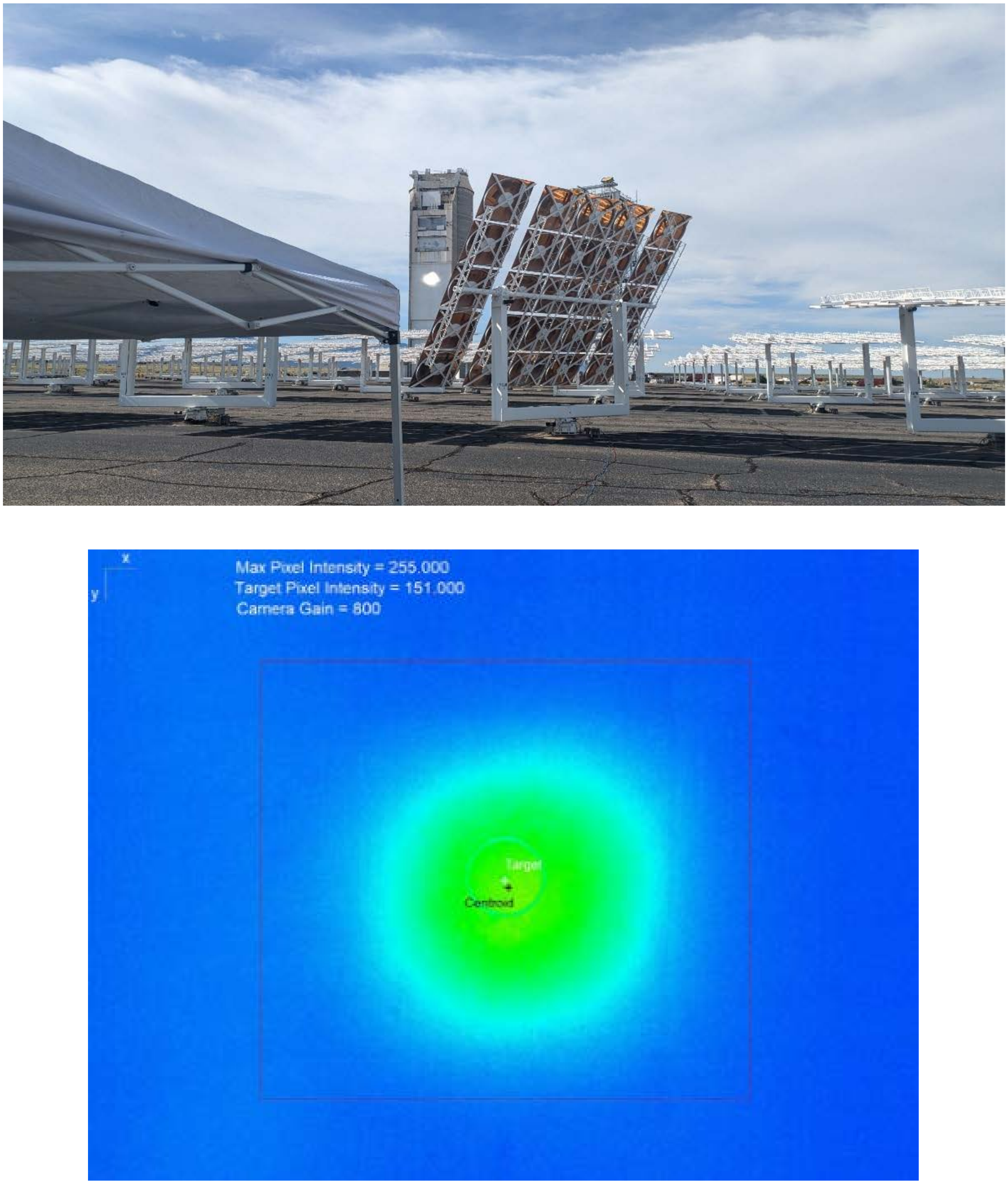


Figure 58. First beam on tower using new software and graphical user interface with updates to minimize vibrations and keep the beam within 0.02 degrees of GPS timer

Images from Ansel Blumenthal, Sandia

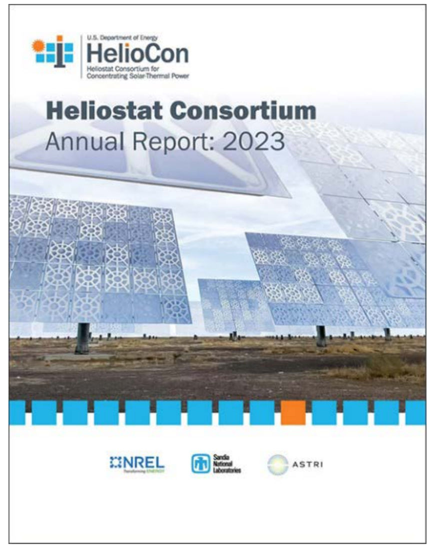
U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

14

Publication Highlights

14 Publication Highlights

14.1 Heliostat Consortium Annual Report: 2023



Citation: Zhu, Guangdong, Chad Augustine, Tucker Farrell, Devon Kesseli, Parthiv Kurup, Rebecca Mitchell, Matthew Muller, Daniel Tsvankin, Shashank Yellapantula, Alexander Zolan, Kenneth Armijo, Randy Brost, Margaret Gordon, Daniel Small, Jeremy Sment, Braden Smith, Mike Collins, Joe Coventry, John Pye, Ye Wang, Michael Cholette, Giovanni Picotti, Maziar Arjomandi, and Matthew Emes. 2023. *Heliostat Consortium Annual Report: 2023*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-87662. https://www.nrel.gov/docs/fy24osti/87662.pdf.

Abstract: The HelioCon Annual Report 2023 provides detailed information on progress the HelioCon team has made since its founding, including expanding the number of partnerships with industry, research, education, and other institutions; increasing staff size; providing information to a growing audience through its web presence; and participating in national and international conferences with industry leaders. In 2023, HelioCon successfully completed its key milestones and further defined goals and objectives for 2024. HelioCon will continue to advance U.S. heliostat technology, capabilities, and the national workforce by:

- Carrying out high-impact R&D and technology validation projects at national labs for strategic core capabilities and infrastructure.
- Engaging relevant industries and research institutes to advance heliostat technologies and minimize commercial deployment risks through new round of RFP.
- Expanding workforce through student internships and collaboration with universities and community colleges.
- Enhancing the impact of HelioCon activities such as participating researchers, students, publications, seminars, and R&D projects.

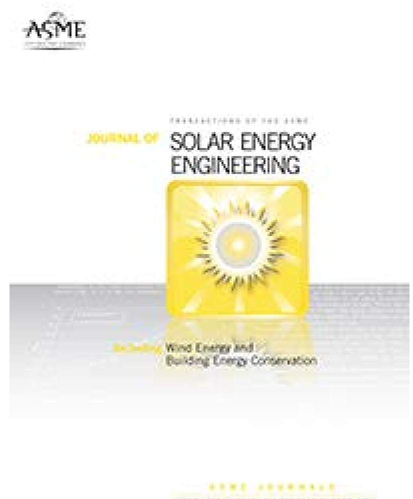
We look forward to engaging with industry and academia through direct partnerships, workshops, conferences, meetings, and other in-person/virtual opportunities in the upcoming years.

14.2 Field Measurements Reveal Insights Into the Impact of Turbulent Wind on Loads Experienced by Parabolic Trough Solar Collectors

Citation: Egerer, Ulrike, Scott Dana, David Jager, Brooke J. Stanislawski, Geng Xia, Shashank Yellapantula. 2024. "Field measurements reveal insights into the impact of turbulent wind on loads experienced by parabolic trough solar collectors." *arXiv.* https://doi.org/10.48550/arXiv.2401.13089.

Abstract: To ensure efficient and reliable operation of a CSP plant, its solar collector field needs to accurately focus sunlight. The optical efficiency and structural integrity of the solar collectors is significantly influenced by wind conditions in the field. In this study, we present insights into dynamic wind loading on parabolic trough CSP collectors. We derive novel conclusions by analyzing a first-of-a-kind measurement campaign of wind and structural loads, performed at an operational CSP plant. Previous research primarily relied on wind tunnel tests and simulations, leaving uncertainty about wind loading effects in operational settings. We demonstrate that the parabolic trough field significantly alters the turbulent wind field within the collector field, especially under winds perpendicular to the trough rows. Our measurements within the trough field show reduced wind speeds, changes in wind direction and turbulence properties, and vortex shedding from the trough assemblies. These modifications to the wind field directly impact both static and dynamic support structure loads. Our measurements reveal higher wind loads on trough assemblies compared to those observed previously in wind tunnel tests. The insights from this study offer a novel perspective on our understanding of wind-driven loads on CSP collectors. By informing the development of next-generation design tools and models, this research paves the way for enhanced structural integrity and improved optical performance in future parabolic trough systems.

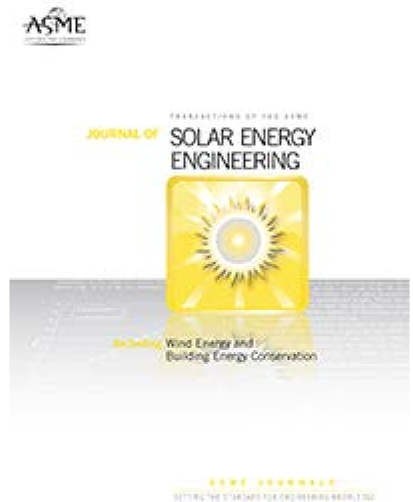
14.3 Status Quo and Gap Analysis of Heliostat Field Deployment Processes for Concentrating Solar Tower Plants



Citation: Sment, Jeremy and Alexander Zolan. 2024. “Status Quo and Gap Analysis of Heliostat Field Deployment Processes for Concentrating Solar Tower Plants.” *J. Sol. Energy Eng.* 146 (6): 061004. https://doi.org/10.1115/1.4065430.

Abstract: Deployment of the solar field of a CSP plant is one of many factors that are integral to the success of a project. Knowledge transfer from outside the industry is limited due to the unique nature of heliostats, which redirect sunlight to a receiver with high precision while maintaining a high level of reflectivity. Moreover, learning from project to project can be limited due to the site-specific nature of projects, as the market includes several developers, each with their own unique design. In this paper, we discuss the state of the art in heliostat field deployment. We cover all the key aspects of deployment from project assessment to a fully functioning system, which include site selection, layout development, supply chain, assembly, site preparation and construction, calibration, and O&M. We then perform a gap analysis on field deployment and recommend priorities for future research.

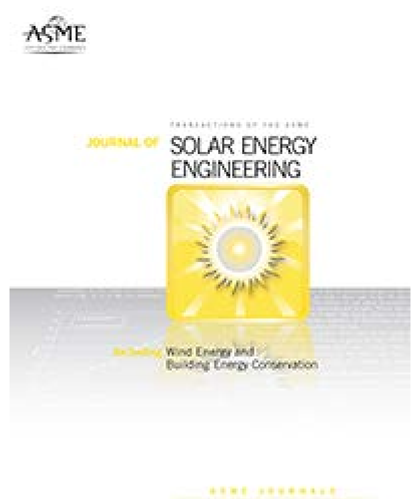
14.4 Analysis of Gaps in Techno-Economic Analysis To Advance Heliostat Technologies for Concentrating Solar-Thermal Power



Citation: Augustine, Chad, Alexander Zolan, and Kenneth Armijo. 2024. "Analysis of Gaps in Techno-Economic Analysis to Advance Heliostat Technologies for Concentrating Solar-Thermal Power." *J. Sol. Energy Eng.* 146 (6): 061002. https://doi.org/10.1115/1.4065431.

Abstract: HelioCon was launched in 2021 to advance heliostat technology. One of its first efforts was to do a detailed analysis of gaps in technology and capabilities in the heliostat industry and complete a roadmap study describing high-priority gaps. HelioCon gathered gaps through a series of outreach activities with representatives and experts from industries and research institutes. This paper discusses the gap analysis for the techno-economic analysis (TEA) topic. 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. In this study, we limit the scope of this topic to the heliostat field, tower, and receiver and do not consider downstream applications or uses of thermal energy. We conducted a thorough review of existing models and compiled a list of the state of the art in open-source tools currently available to researchers. We collected an initial list of gaps for the TEA of heliostats from industry developers and experts. Each gap is briefly described, and the heliostat development cycle stages that the gap impacts are indicated. We ranked the initial list of TEA gaps into tiers depending on their potential impact. For TEA, most of the gaps identified 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.

14.5 Heliostat Consortium: Gap Analysis on State of the Art in Wind Load Design

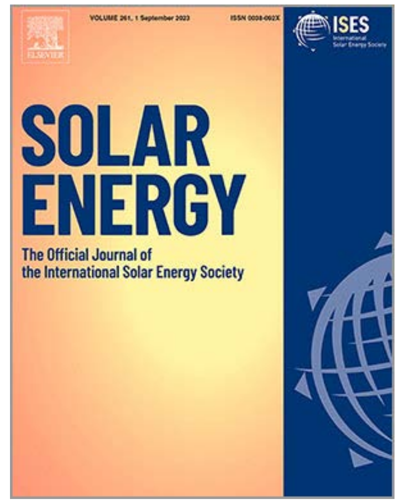


Citation: Emes, Matthew, Shashank Yellapantula, Jeremy Sment, Kenneth Armijo, Matthew Muller, Mark Mehos, Randy Brost, and Maziar Arjomandi. 2024. "Heliostat Consortium: Gap Analysis on State of the Art in Wind Load Design." *J. Sol. Energy Eng.* 146 (6): 061001. https://doi.org/10.1115/1.4065429.

Abstract: 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 enable cost reduction of wind-dependent heliostats to avoid unnecessarily conservative heliostat designs and increase field efficiency and reliability to reduce the risk of component failures due to high-wind events. Gaps related to wind load include 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, and underexplored heliostat field wind-load reduction and operating strategies. The recommended pathway forward is to develop wind load and site characterization guidelines for heliostat design and develop heliostat field wind-load models with optical performance impacts.

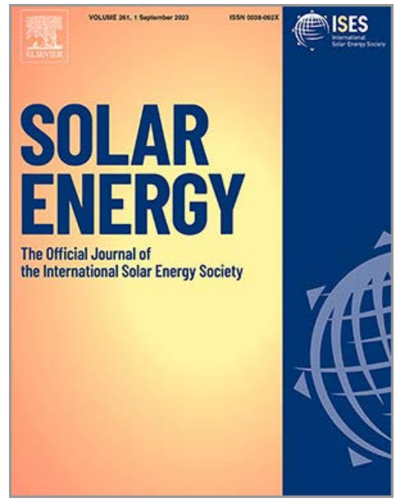
14.6 Effect of Facet Gap on Heliostat Wind Loading



Citation: Marano, Matthew, Matthew J. Emes, Azadeh Jafari, and Maziar Arjomandi. 2024. "Effect of facet gap on heliostat wind loading." *Solar Energy* 271: 112428. https://doi.org/10.1016/j.solener.2024.112428.

Abstract: Multi-facet heliostats are more versatile and advantageous in design compared to single-facet heliostats, while generating new design challenges. Multi-facet designs can reduce manufacturing costs, allow for decentralization of power supply, and bring the option of face-down stow. Addition of a gap between two facets changes the flow structure around the heliostat. The effect of gap between two heliostat facets is therefore investigated on wind loads through experimental investigation in a large wind tunnel. A heliostat model was placed in a simulated ABL at the University of Adelaide wind tunnel. The investigation covered gap ratios between two panels (gap spacing/facet width) from 0 to 2 and panel aspect ratios (facet width/chord length) of 0.35 to 0.65, forming a complete heliostat aspect ratio of 0.7 to 1.3 with no gap. Wind load coefficients were determined using load cell measurements at the base, and application of differential pressure sensors on the surface, of the heliostat model. Findings indicate the presence of a gap, in general, increases the wind load on the heliostat, with the facet aspect ratio exacerbating the results. The maximum load cases shift further into the operating range of heliostats where a change in center of pressure, due to a change in gap ratio, shifts maximum coefficients from an elevation angle of 30° to 45° for lift force and hinge moment, and 90° to 75° for azimuthal moment. Increasing loads on elevation and azimuth drives potentially increase tracking deviations and beam misalignment, reducing CSP plant performance.

14.7 Heliostat Wind Loads: Effects of the Aspect Ratio and Ground Clearance Ratio



Citation: Bakhshipour, Sahar, Matthew J. Emes, Azadeh Jafari, and Maziar Arjomandi. 2024. "Heliostat wind loads: Effects of the aspect ratio and ground clearance ratio." *Solar Energy* 269: 112332. https://doi.org/10.1016/j.solener.2024.112332.

Abstract: The impact of heliostat aspect ratio and ground clearance ratio on static wind load coefficients has been studied in this article. Wind tunnel experiments were undertaken at the Thebarton wind tunnel at the University of Adelaide. A high-frequency load cell was used to measure the forces and moments on heliostat models with five aspect ratios ranging from 1 to 2, four different pylon hinge heights (0.1 ≤ ground clearance ratio ≤ 1) and elevation angles from 0° to 90° at a constant azimuth angle of zero degrees. The results show that increasing aspect ratio does not have a significant impact on drag and lift coefficients, but increases hinge moment, and the overturning moment coefficient by up to 55% compared with a square heliostat. The results also indicate that for an approximately constant ground clearance ratio, increasing aspect ratio causes a reduction in drag and overturning moment coefficients and lift coefficients for aspect ratio ≤ 1.5. The effects of ground clearance ratio show that drag coefficient is approximately constant with ground clearance ratio while the lift coefficient increases slightly. It also indicates that increasing ground clearance ratio causes increased overturning moments coefficient and hinge moment coefficients by up to 40% and 30%, respectively. Finally, increasing the hinge height of heliostat result in increase in lift coefficient, overturning moment and hinge moment coefficients.

14.8 Patent: Light Detecting and Ranging (LIDAR) for In-Situ Heliostat Optical Error Assessment

Citation: Small, Daniel E., Charles Q. Little, and Julius Yellowhair. 2020. Light Detecting and Ranging (LIDAR) for in-situ heliostat optical error assessment. U.S. Patent No. 11,921,215.

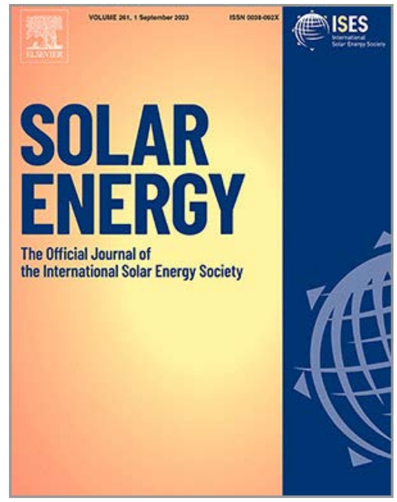
Abstract: A system and method for optical assessment of a heliostat includes obtaining a point cloud data representing an image of the heliostat; isolating the data; filtering and fitting the filtered heliostat data to a bounding box; translating the heliostat data to a plane to aid in segmentation; segmenting a plurality of facets of the heliostat, fitting each of the segmented facets to a respective plane; generating normal vectors characterizing each of the plurality of facets; and calculating a canting angle associated with each respective facet of the plurality of facets. A heliostat with mirrored facets and a scanner are provided. The scanner captures point cloud data representing the heliostat, which is segmented for each facet. Normal vectors characterize the facets and a canting angle is calculated for the respective facet.

14.9 Patent: Heliostat Error Detection

Citation: Zhu, Guangdong and Rebecca Amelia Mitchell. 2022. Heliostat error detection. U.S. Patent No. 11,250,587 B2.

Abstract: The present disclosure describes NIO characterization methods which efficiently measures optical errors (such as mirror surface slope error, mirror canting error, and heliostat tracking error) of a heliostat field. The methods utilize photogrammetry and deflectometry to analyze an image taken of a heliostat to determine optical errors and increase the amount of solar energy delivered by the heliostat to the receiver.

14.10 Heliostat Wind Loads in the Atmospheric Boundary Layer (ABL): Reconciling Field Measurements With Wind Tunnel Experiments



Citation: Matthew J. Emes, Matthew Marano, and Maziar Arjomandi. 2024. "Heliostat wind loads in the atmospheric boundary layer (ABL): Reconciling field measurements with wind tunnel experiments." *Solar Energy* 277: 112742. https://doi.org/10.1016/j.solener.2024.112742.

Abstract: This paper investigates similarity effects of atmospheric boundary layer (ABL) turbulence in full-scale field measurements and wind tunnel experiments on the aerodynamic wind loads on a single heliostat. Two experimental studies were conducted at the University of Adelaide: (1) field measurements of ABL wind turbulence and six-axis load cell measurements on an instrumented heliostat in open farmland at the Atmospheric Boundary Layer Research Facility (ABLRF), and (2) wind tunnel (WT) testing of six-axis load cell measurements on a 1:6 scale model heliostat in a simulated ABL. It was found that mean and peak wind load coefficients at the ABLRF during a high-wind period with steady wind direction showed similar variations with elevation angle as WT study. Load coefficients at ABLRF showed only a small variation with changes in mean wind speed and the streamwise component of turbulence intensity, however, drag and lift force coefficients varied due to the anisotropic turbulence intensities, spectra and integral length scales of longitudinal and vertical wind components at ABLRF that deviated from Engineering Sciences Data Unit (ESDU) and WT data at heights below 5 m. Load coefficient distributions at ABLRF showed increased skewness and non-Gaussian behaviour compared to the corresponding WT distributions. The results of this work found that wind tunnel experiments overestimate drag force coefficients and underestimate lift force coefficients compared to ABLRF field measurement. This is critical for verification of aerodynamic wind load coefficients in wind tunnel experiments and the sensitivity of single heliostat wind loads to ABL turbulence characteristics.

U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

15

Summary

15 Summary

Table 4 summarizes current research efforts mapped to Tier 1 gaps, as identified in the HelioCon roadmap report. Projected outcomes by FY27 (if HelioCon operates for 6 years total) are also given as a reference in the table. Please refer to the HelioCon roadmap report for details on the Tier 1 gaps.[2] With the resources available from HelioCon and elsewhere, HelioCon is taking steady action to address a large portion of the Tier 1 gaps, although there are some Tier 1 gaps (and additional Tier 2 and 3 gaps from the HelioCon roadmap report) that are not being addressed as of today. HelioCon has been making noticeable progress in addressing the Tier 1 gaps on the following topics: TEA, metrology and standards, components and controls, wind loads, and resources, training, and education (RTE). Tier 1 gaps in advanced manufacturing are largely unaddressed, due to the fact that industrial entities are best suited to lead these and there is a lack of a U.S. CSP industry. For the Tier 1 gaps in soiling, the mitigation strategy requires in-field measurement over the long term and learnings through new rounds of demonstration, which are challenging to implement. The Tier 1 gaps in standards require the participation of an international society as well as lessons learned and practical experiences from a larger number of commercial plants; however, the current lack of data and knowledge sharing from existing power plants means that no viable effort can be planned without support from a large number of commercial power plants.

[2] Available at https://www.nrel.gov/docs/fy22osti/83041.pdf.

Table 4. Summary of Tier 1 Gaps and Their Impact Areas

Notes: please refer to HelioCon roadmap (Zhu et al. 2022) on Gap ID; project numbers (Proj.) refer to the section number of each project within this report.

Efforts on Track | Blind Spots | Planned Efforts Not Sufficient

Gap	Progress Made Through FY24	Projected Outcomes by FY27
Techno-Economic Analysis		
Gap T1: Missing linkage between model inputs and actual components - Proj. 5.1	Under the planned project on heliostat field optimization for heliostat-based systems, performance of actual components was collected and incorporated into a system model for system design and optimization.	A framework will be established to accommodate the performance of actual components. Heliostat supply chains are not mature and resilient and have many single-failure points. Performance data on actual components, such as drives and mirror facets, are not available to the public in the foreseeable future.
Gap T2: Lack of validated and widely accepted model for solar field O&M costs - Proj. 4.2; - Proj. 10.1; - Proj. 13.2	A detailed O&M performance model, O&M real-time optimization tool, and solar field digital twin model are under development; comparison and validation with actual solar field data are planned.	The gap is projected to be addressed. Further improvements are also anticipated with learnings from new plants beyond FY27.
Gap T3: Insufficient knowledge of construction and commissioning costs and the impact of delays on financing costs	HelioCon has had difficulty identifying any engineering, procurement, and construction (EPC) or plant developers willing to share their data, best practices, and experience. The HelioCon team will continue to approach relevant stakeholders for information sharing.	Without participation of EPCs and plant developers on this topic, it is extremely challenging to address this gap.
Gap T4: Lack of validated CSP models for IPH applications - Proj. 4.1; - Proj. 7.5; - Proj. 9.5	A high-fidelity performance prediction model has been developed, and a comparison with the performance model by a leading industrial technology developer is planned. Detailed TEA on IPH applications is an ongoing effort. A solar field real-time control optimization tool is also under development.	Validation of the high-fidelity performance model and solar field control optimization tool with at least one leading industrial partner. Validation with additional deployed systems is dependent on new IPH system deployment.

Gap	Progress Made Through FY24	Projected Outcomes by FY27
Metrology and Standards		
Gap M1: Not fully validated metrology on opto-mechanical error measurement in laboratory - Proj. 2.2; - Proj. 2.4; - Proj. 7.4; - Proj. 10.2; - Proj. 11.2	Under HelioCon, SOFAST was adopted by industry and is being upgraded; a new technique, ReTNA, for slope error measurement was developed and is in the commercialization phase with industrial partners. In collaboration with the international community, round robin tests were carried out, and results are under detailed comparison. A standard process for solar mirror specular reflectance has been established. A HelioCon OpenCSP database was established to facilitate international collaboration.	Validation of at least two metrologies on slope error is complete. But no validation work is planned for mirror facet shape measurement and canting error measurement of large heliostats due to the difficulty of setting up large heliostats in a laboratory environment.
Gap M2: Insufficient metrology on opto-mechanical error measurement in outdoor environment (a few heliostats) - Proj. 2.1; - Proj. 2.3; - Proj. 10.3	A third-party metrology platform is under planning and development for measurement of heliostats at one of HelioCon's designated sites. The platform will assemble all available metrology with to-be-established test protocols for performance validation of heliostat designs.	The third-party metrology platform is fully developed.
Gap M3: Missing metrology on opto-mechanical quality assurance	Heliostat optical quality assurance technique is under development with limited industrial partners in the United States.	One optical assurance tool for slope error and canting error has been completed by working with industrial partners. Quality assurance tools/protocols on components such as drives, new structure designs, and new mirror facets will be likely missing, due to insufficient commercial providers.
Gap M4: Missing metrology on opto-mechanical quality calibration after installation	No work is planned due to the lack of required industrial partnerships and new commercial construction.	Validation of existing/new field calibration tools is not planned, as addressing this gap is dependent on new industrial collaboration.

Gap	Progress Made Through FY24	Projected Outcomes by FY27
Gap M5: Missing metrology on opto-mechanical error in situ measurement (full commercial-scale field) - Proj. 2.3; - Proj. 7.6; - Proj. 9.1; - Proj. 11.1	HelioCon is developing new techniques such as NIO measuring slope error, canting error, and tracking error, and the DKA technique measuring soiling. Round robin tests on existing tools such as BCS are planned efforts.	Validation of key techniques such as NIO and BCS is predicted to be completed. A commercial demonstration of new techniques is expected, but with uncertain commercial partnership. Validation of a secondary tool such as BCS or a look-back camera for daily operation is expected, pending commitment from the international society.
Gap M6: Insufficient metrology on receiver flux quality real-time assurance tool	No efforts planned under HelioCon.	The mitigation strategy will require an expansion of scope, including receivers, an extremely challenging innovative technique, and commercial power plant partnership.
Gap S1: Missing standard on optical terminology for heliostats - Proj. 2.4; - Proj. 7.1	HelioCon is participating in the development of the international heliostat optical terminology standard. HelioCon's OpenCSP project has also been initiated for establishing standard code development for CSP research.	A standard on optical terminology is expected to be completed with an international effort. OpenCSP is expected to become a central platform for international research collaboration on knowledge sharing and standard code development.
Gap S2: Missing guideline and standard on heliostat design	No efforts made under HelioCon so far, but new projects will be planned to establish an initial heliostat design process in FY25–FY27.	HelioCon will develop an initial design process to solicit public feedback.
Gap S3: Missing guideline and standard on standard heliostat solar field design/simulation	Some preliminary efforts such as high-fidelity models are ongoing under HelioCon, but no international initiative has been started to form an international working group.	Formation of an international working group, but a standard will not be completed within the FY27 timeframe.
Gap S4: Missing heliostat testing guideline	Preliminary efforts such as third-party evaluation platforms have been planned under HelioCon.	Formation of an international working group and an initial testing guideline draft proposed, but an international consensus will not be completed within the FY27 timeframe.
Gap S5: Missing guideline and standard on heliostat solar field acceptance test	HelioCon proposed to collaborate with another leading institute that has developed an initial draft.	The draft standard obtains consensus with participating members, but the

Gap	Progress Made Through FY24	Projected Outcomes by FY27
		required field tests will be pending on cooperation of plant developers.
Gap S6: Missing guideline and standard on-site characterization	Preliminary efforts, including soiling characterization and wind load characterization, are planned.	Formation of an international working group and an initial guideline proposed, but an international consensus will not be completed within the FY27 timeframe.
Special Subtopic: Soiling		
Gap So1: No systematic evaluation of soiling is performed at site selection stage - Proj. 7.3	HelioCon is leading an international working group of soiling characterization; soiling tests at various sites are ongoing.	The working group is developing a soiling evaluation process and database of available characterization results.
Gap So2: Design and automation of new cleaning systems is underexplored	No efforts are planned under HelioCon.	Some industrial developers are developing automated cleaning systems, but they are limited to specific heliostat design and field conditions.
Gap So3: No standard or data to assess anti-soiling coating durability/performance	No efforts are planned under HelioCon.	Value of anti-soiling coating is still under debate.
Gap So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	Relevant preliminary efforts are planned, such as soiling characterization and O&M model development.	A developed high-fidelity O&M model will be available for assessment. However, the work requires industrial participation, which is uncertain.
Components and Controls		
Gap C1: Composites or other advanced structures (e.g., torque tubes, pedestals, foundation) - Proj. 3.1; - Proj. 12.1	Under HelioCon, initial cost analysis, prototyping, and testing of composite mirror facets are ongoing; prototyping and testing of composite heliostat designs are planned.	An initial analysis of composite heliostat designs will be concluded, and HelioCon will share the findings with the CSP community.
Gap C2: Lower-cost mirror designs with comparable	No work planned under HelioCon.	Efforts under HelioCon are largely dependent on industrial developers. HelioCon has no IP on alternative

Gap	Progress Made Through FY24	Projected Outcomes by FY27
performance to existing glass mirrors		advanced reflectors or resources to develop related IP.
Gap C3: Wireless systems with standardized requirements and testing capabilities - Proj. 8.2; - Proj. 8.3; - Proj. 9.6; - Proj. 12.2	A testbed for a wireless control system, an open-source wireless communication algorithm, and a commercial prototype are planned.	A fully functional testbed for wireless systems is demonstrated with at least one commercial design and ready for validating future commercial designs.
Gap C4: Closed-loop control and auto alignment/calibration processes - Proj. 3.2; - Proj. 13.4	Closed-loop control with BCS is under development and testing at NSTTF.	A prototype closed-loop control system will be tested at HelioCon's test field, NSTTF. A real-time heliostat tracking monitoring technique—an alternative to BCS—is needed for performance validation.
Gap C5: Design qualification standards for heliostats to enable bankable components and controls, enable heliostat long-term performance, and shorten design improvement cycles - Proj. 2.1; - Proj. 3.3; - Proj. 13.4	HelioCon is co-leading the standard development of heliostat design qualification with the international community. Round robin tests will be planned with HelioCon's third-party metrology platform and NSTTF test solar field.	The relevant standard is available for the community to use.
Advanced Manufacturing		
Gap AM1: Innovative heliostat mirror facet/array designs needed - Proj. 8.5	One RFP Round 1 project is developing a self-focusing heliostat design with closed-loop tracking.	HelioCon plans to identify more industrial partners for collaboration on new heliostat designs.
Gap AM2: Insufficient facet/array fabrication process knowledge	No work planned under HelioCon.	Industry is best suited to address this gap.
Gap AM3: Heliostats not designed for high-productivity manufacturing	No work planned under HelioCon.	Industry is best suited to address this gap.

Gap	Progress Made Through FY24	Projected Outcomes by FY27
Gap AM4: Lack of heliostat developer experience designing high-productivity manufacturing lines - Proj. 8.1	One RFP Round 1 project is designing high-productivity manufacturing lines.	Industry is best suited to address this gap, but their work is largely dependent on future commercial projects.
Resources, Training, and Education		
Gap R1: Heliostat technology resources are not accessible in a centralized web-based format - Proj. 2.4; - Proj. 6.1	A HelioCon knowledge database has been developed and will be updated annually. An open-source OpenCSP library has been initiated for collaboration of the international community.	A HelioCon knowledge database and open-source OpenCSP library will be ready for the heliostat/CSP community.
Gap R2: Lack of heliostat research projects in universities - Proj. 6.1; - Proj. 8.4; - Proj. 8.5; - Proj. 9.2; - Proj. 9.3	Seven U.S. universities were awarded research projects under HelioCon.	Multiple universities engaged in heliostat research with established programs.
Gap R3: Little public awareness of CSP/heliostat technologies - Proj. 6.2; - Proj. 8.4; - Proj. 9.2; - Proj. 9.3	HelioCon hosts a regular seminar series, the solar-thermal collegiate competition, and educational program developments at partnered universities. A CSP value promotion campaign is planned.	CSP lessons learned, direct addressing of public concerns about the technologies, and the value of the technologies are shared to a broader audience of stakeholders. Successful demonstration projects would also be critical in addressing this gap.
Gap R4: Lack of resources and guidance for promoting diversity, equity, and inclusion in the CSP workforce - Proj. 6.1	HelioCon established a designated task committed to the promotion of diversity, equity, and inclusion throughout all the HelioCon efforts, including internships and public availability of the HelioCon knowledge database.	HelioCon will maintain a focus on diversity, equity, and inclusion as the community grows.
Field Deployment		
Gaps F1, F2, F3, F4: Heliostat fields have higher risk than other power investments	Efforts include the development of high-fidelity performance prediction models for developers and investors and an examination of the	HelioCon tools support risk mitigation of heliostat fields for demonstration or commercial heliostat projects.

Gap	Progress Made Through FY24	Projected Outcomes by FY27
- Proj. 4.1; - Proj. 4.3	environmental impacts of heliostat fields.	Success requires participation of critical stakeholders, such as other federal agencies, state agencies, and utilities, and proposed CSP projects.
Gaps F5, F6: Heliostat field integration with industrial thermal processes lacks precedent	Relevant efforts under HelioCon include development of optimum heliostat-based system designs for a representative set of system capacities and temperatures.	Recommended heliostat-based system designs will be shared with the public. This effort requires commitment and investment of the industrial process stakeholders.
Gaps F7, F8: Site-specificity of O&M and field preparation and installation procedures limits the opportunity for incremental improvements that span multiple sites - Proj. 4.2; - Proj. 4.4; - Proj. 8.6; - Proj. 13.3	HelioCon efforts aim to support future commercial project development.	The mitigation strategy requires the development of commercial-scale projects, which are largely driven by stakeholders such as federal/state agencies, utilities, and investors. HelioCon will be supporting where needed.
Special Subtopic: Wind Load		
Gap WL1: Insufficient wind measurement and characterization at heliostat field sites - Proj. 7.2; - Proj. 13.1	Wind measurement and characterization were carried out and planned in a laboratory environment and a commercial site.	Initial protocol of measurement and characterization is expected to be developed. Participation of additional institutes and industrial partners is needed, in addition to HelioCon efforts.
Gap WL2: Lack of understanding of the impact of atmospheric turbulence on dynamic loading and tracking error - Proj. 7.2 - Proj. 9.4	Limited efforts planned under HelioCon. One HelioCon member published initial research findings on the impact of atmospheric turbulence on dynamic loading; one RFP Round 2 project is to develop a new instrument for measurements.	Data will be collected for empirical correlation, but a systematic strategy on numerical modeling, experimental tests, and in situ characterization/validation is needed.
Gap WL3: Lack of understanding of wind load on heliostats in array configurations - Proj. 13.1	A test campaign at a commercial site is planned under HelioCon.	Some limited data will be collected, but additional data collection campaigns on various heliostat designs are needed.

Gap	Progress Made Through FY24	Projected Outcomes by FY27
Gap WL4: Missing design standards for determining heliostat wind load coefficients and safety factors - Proj. 7.2	Research findings were published by HelioCon members but not sufficient for development of a standard.	An initial draft is expected to be initiated with collaboration of the international community.

In the coming years of HelioCon, the consortium's priorities will be directed or, when needed, shifted to:

- Metrology techniques and protocols that enable direct performance assessment of heliostats in existing commercial plants and third-party evaluation of heliostat designs and heliostat field designs
- Field deployment efforts to minimize commercial risks of heliostat-based systems and encourage/promote commercial deployment of a series of heliostat-based systems to advance the learning curve for heliostat technologies
- TEA R&D that would help standardize optimum heliostat designs and optimum heliostat system designs
- RTE efforts that would lead to a centralized knowledge base and expansion of potential workforce
- Components and controls R&D that can reduce the cost of heliostat installation and O&M, such as novel component designs and wireless and closed-loop controls
- Advanced manufacturing techniques that would be driven by standard heliostat designs and heliostat system designs
- International movements that would integrate limited resources to a standardized industry with proven performance.

HelioCon's FY25 projects have been planned to address top-priority gaps in Table 4. In addition to the projects summarized in the chapters above, additional projects have been designed to address gaps that have insufficient efforts for FY25. In particular, the HelioCon roadmap study's mid-term update will allow for an update to the HelioCon top-priority gaps based on what HelioCon has learned in the past 3 years, as well as the development of a more effective and cohesive strategy to advance the broader commercial deployment of heliostat-based technologies for energy decarbonization.

Table 5. New HelioCon Projects Planned in FY25, in Addition to the Ones Summarized in Chapters 2–13

Projects	Scope of Work
HelioCon Roadmap Study – Mid-Term Update Leads: Guangdong Zhu, Jeremy Sment	The HelioCon roadmap report revision will be focused on: • Updating the gaps and their priorities • Suggesting mitigation strategies • Expanding the scope by including its interaction with receiver technologies.
CSP Value Promotion Campaign Leads: Craig Turchi, Ken Armijo	The CSP value promotion campaign plans to: • Engage stakeholders of future commercial project deployment, such as western state utilities, industries, and relevant federal agencies • Complete a CSP value study for the United States with third-party validation • Host a CSP summit to promote CSP values.
Techno-Economic Analysis of Advanced Heliostats Leads: Alex Zolan, Parthiv Kurup	The proposed TEA will focus on establishing the baseline cost and performance of a commercially deployed heliostat design, through an industrial partnership.
Development of a Generic Heliostat Controller Compatible With Various Heliostat Hardware Lead: Matthew Muller	The project aims to identify and fully test a generic controller for on-sun tracking tests on at least two unique heliostat architectures, with a demonstrated pointing repeatability of no more than 0.5 mrad at the HelioCon performance evaluation site of NREL's Flatirons Campus.
Solar Field Performance Prediction: Case Study Lead: Alex Zolan	The proposed case study will validate HelioCon's high-fidelity solar field performance prediction model with an independent model by an industrial developer, using historical performance data at an operating plant.
Standardization of Solar Field Acceptance Testing Lead: Stephanie Meyen	HelioCon will participate the development of a solar field acceptance testing standard/guideline with other leading institutes around the world.
Validation Studies for Heliostat Composite Materials Lead: Ken Armijo	The HelioCon team plans to: • Optimize structural designs of a standardized heliostat with varying ribbed and solid materials to minimize composite material volume, weight, and costs • Fabricate miniature heliostats of modeled composite materials and test within the University of Adelaide wind tunnel • Perform rigorous validation tests over different angles of attack and wind velocities of the down-selected structures, with respect to material type, to assess mechanical stresses.

Projects	Scope of Work
Heliostat Environmental Impact Studies <u>Lead</u>: Jeremy Sment	The HelioCon team plans to: • Consult with environmental agencies on a methodology for assessing environmental impacts of heliostat fields based on similarity to PV fields • Determine subterranean temperature of artificial tortoise burrows inside and outside of heliostat fields • Determine temperature correlation between artificial tortoise burrow and ambient ground temperature measurements.

By the end of the HelioCon performance period (September 2027), HelioCon plans to make meaningful strides toward closing the gaps identified above. This includes developing new capabilities in advanced manufacturing, metrology, components and control, field deployments, and modeling, including the development of a publicly accessible TEA model to evaluate heliostat-related innovations under flexible scenarios. In addition, HelioCon will create a centralized database that compiles all available knowledge related to heliostat research, development, and deployment; training materials; and educational programs; as well as a list of licensable models, tools, and services developed and acquired under the consortium.

By the end of the performance period, HelioCon will provide a full assessment of the successes and lessons learned through the consortium as well as a summary of the remaining gaps the consortium has yet to address. HelioCon will also conduct 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 realize their technical and commercial potential in future decarbonized energy sectors, including electricity, IPH, and solar fuel production. To this end, the consortium will create a projected roadmap for future heliostat development in the United States and in the world.

References

Anderson, Cody B., Giovanni Picotti, Michael E. Cholette, Bruce Leslie, Theodore A. Steinberg, and Giampaolo Manzolini. 2023. "Heliostat-Field Soiling Predictions and Cleaning Resource Optimization for Solar Tower Plants." *Applied Energy* 352 (December):121963. https://doi.org/10.1016/j.apenergy.2023.121963.

Anderson, Cody B., Giovanni Picotti, Thomas Schmidt, Michael E. Cholette, Gregor Bern, Theodore A. Steinberg, and Giampaolo Manzolini. 2024. "The Impact of Condensation on Solar Collector Soiling: An Experimental Study." *Solar Energy Materials and Solar Cells* 275 (September):112998. https://doi.org/10.1016/j.solmat.2024.112998.

Andraka, C. 2018. "SOFAST: Sandia Optical Fringe Analysis Slope Tool for Mirror Characterization," December, 10.

Angel, Roger, Ryker Eads, Nick Didato, Matt Rademacher, Nick Emerson, and Christian Davila. 2022. "Actively Shaped Focusing Heliostat." In . Vol. 2445. Melville: American Institute of Physics. https://doi.org/10.1063/5.0086409.

Armijo, Kenneth M., Haden Harper, Zachary Bernius, Ansel Blumenthal, Luis Garcia-Maldonado, Aaron Overacker, Randy Brost, and Benjamin Bean. 2024. "HelioCon Closed Loop Controls for Heliostat Field Testing." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-03_ASME-ES2024%20HelioCon%20Closed%20Loop%20Control%20Extremum%20Seeking%20Control%20Small-Scale%20and%20Single%20Heliostat%20Testing%20v1.pdf.

Augustine, Chad, Alexander Zolan, and Kenneth Armijo. 2024. "Analysis of Gaps in Techno-Economic Analysis to Advance Heliostat Technologies for Concentrating Solar-Thermal Power." *Journal of Solar Energy Engineering* 146 (6): 061002. https://doi.org/10.1115/1.4065431.

Bakhshipour, Sahar, Matthew J. Emes, Azadeh Jafari, and Maziar Arjomandi. 2024. "Heliostat Wind Loads: Effects of the Aspect Ratio and Ground Clearance Ratio." *Solar Energy* 269 (February):112332. https://doi.org/10.1016/j.solener.2024.112332.

Egerer, Ulrike, Shashank Yellapantula, Brooke Stanislawski, Geng Xia, Scott Dana, and David Jager. 2024. "Dynamic Wind Loading on CSP Collectors: Insights From NREL's Measurements in Operational Parabolic Trough and Heliostat Fields." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-02_ASME-ES2024-presentation-egerer-share-7-11.pdf.

Emes, Matthew, Matthew Marano, and Maziar Arjomandi. 2024. "Effects of Atmospheric Boundary Layer Turbulence on Single Heliostat Wind Load Coefficients: Comparison of Field Measurements With Wind Tunnel Experiments." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-02_ASME-ES2024%20ABLRF%20Heliostat%20Wind%20Loads_Emes.pdf.

Farrell, Tucker, Kidus Guye, Rebecca Mitchell, and Guangdong Zhu. 2021. "A Non-Intrusive Optical Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Flight Path Generation/Optimization of Unmanned Aerial Systems." *Solar Energy* 225 (September):784–801, https://doi.org/10.1016/j.solener.2021.07.070. https://doi.org/10.1016/j.solener.2021.07.070.

Hamilton, William T., Michael J. Wagner, and Alexander J. Zolan. 2022. "Demonstrating Solarpilot's Python Application Programmable Interface Through Heliostat Optimal Aimpoint Strategy Use Case." *Journal of Solar Energy Engineering* 144 (030906). https://doi.org/10.1115/1.4053973.

HelioCon Website. n.d. "HelioCon Database: Power Tower Plants." Accessed September 23, 2024. https://heliocon.org/resources/plant_information_overview.html.

IEC. n.d. "IEC TC 117: Solar Thermal Electric Plants." Accessed September 23, 2024. https://www.iec.ch/dyn/www/f?p=103:23:::::FSP_ORG_ID:7851.

Kattke, Kyle, and Nathan Stegall. 2024. "Mirror Array Optimization and Prototyping." Presented at the HelioCon 2024 Annual Workshop, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/18-04_ASME-ES2024-Solar%20Dynamics-Mirror%20Array%20Optimization%20and%20Prototyping.pdf.

Kesseli, Devon. 2024. "Demonstration and Automation of Reflected Target Optical Measurement for Heliostats." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-01_ASME-ES2024_HelioCon_ReTNA_2024_v1_Kesseli.pdf.

Kesseli, Devon, Michael Wagner, Rafael Guédez, and Craig S. Turchi. 2019. "CSP-Plant Modeling Guidelines and Compliance of the System Advisor Model (SAM)." In , 170006. Casablanca, Morocco. https://doi.org/10.1063/1.5117676.

Metghalchi, Hameed. 2024. "An Educational Program on Concentrated Solar Power and Heliostats for Power Generation and Industrial Process." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/18-05_ASME-ES2024_Presentation_25-06-24_Metghalchi.pdf.

Mitchell, Rebecca A., and Guangdong Zhu. 2020a. "A Non-Intrusive Optical (NIO) Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Methodology and in-Situ Validation." *Solar Energy* 209 (October):431–45, https://doi.org/10.1016/j.solener.2020.09.004. https://doi.org/10.1016/j.solener.2020.09.004.

———. 2020b. "A Non-Intrusive Optical (NIO) Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Sensitivity Study." *Solar Energy* 207 (September):450–57, https://doi.org/10.1016/j.solener.2020.06.093. https://doi.org/10.1016/j.solener.2020.06.093.

Mitchell, Rebecca, and Tucker Farrell. 2024. "A Nonintrusive Optical (NIO) Approach to Characterize In-Situ Performance of Heliostats: Commercial Solar Field Evaluation." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 15. https://heliocon.org/HelioCon_Workshop_2024_files/18-01_ASME-ES2024_NIO%20Industry%20Integration_Mitchell.pdf.

Mitchell, Rebecca, Ye Wang, Michel Izygon, and John Pye. 2024. "Modeling Receiver Flux of Commercial Power Tower Concentrating Solar Power Plants Using Ray Tracing: Benchmark Cases for Validation and Comparison of Ray-Trace Tools." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/ASME_2024_Ray_Trace_Round_Benchmark_Presentation_v01.pdf.

Muller, Matthew. 2024. “Performance and Durability Testing of Advanced Composite Mirror Facets.” Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/18-04_ASME-ES2024_Composite_facets%207_15_24.pdf.

National Renewable Energy Laboratory. n.d. “SolTrace.” Concentrating Solar Power SolTrace. https://www.nrel.gov/csp/soltrace.html.

Sment, Jeremy, Aaron Spieles, Pete David, Matthew Bandy, Shashank Yellapantula, Kristina Ji, Brian Fournet, and Aleksandar Dimeski. 2024. “Heliostat Deployment Ecological Study and Foundation Analysis Progress.” Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-03_ASME-ES2024_HelioCon_Tortoise_and%20Staking_ASME_ES_Technical_Presentation.pdf.

Smith, Braden, and Randolph Brost. 2022. “Sandia Optical Fringe Analysis Slope Tool (SOFAST) Improvement Effort: Final Report.” SAND2022-0187, 1855054, 702684. https://doi.org/10.2172/1855054.

“SolTrace.” n.d. Accessed November 20, 2023. https://www.nrel.gov/csp/soltrace.html.

Tsiropoulou, Eirini Eleni. 2024. “HELIOCOMM: A Resilient Wireless Heliostats Communication System.” Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16. https://heliocon.org/HelioCon_Workshop_2024_files/18-03_ASME-ES2024_HELIOCOMM_UNM.pdf.

Tsiropoulou, Eirini Eleni, Aisha B. Rahman, and Md Sadman Siraj. 2024. “HELIOCOMM: A Wireless Revolution in Concentrated Solar Power Systems.” *IT Professional* 26 (3): 73–79. https://doi.org/10.1109/MITP.2024.3389502.

Tsiropoulou, Eirini, Aisha Rahman, and Md Siraj. 2024. “HELIOCOMM: Wireless Controls State-of-the-Art Report.” NREL/SR--5K00-88431, 2310347, MainId:89210. https://doi.org/10.2172/2310347.

Tsvankin, Daniel, and Matthew Muller. 2024. “Evaluation of Composite Structural Materials for Heliostat Cost Reduction.” *Journal of Solar Energy Engineering* 146 (6): 061006. https://doi.org/10.1115/1.4065433.

Wagner, Michael J., and Tim Wendelin. 2018. “SolarPILOT: A Power Tower Solar Field Layout and Characterization Tool.” *Solar Energy* 171 (September):185–96. https://doi.org/10.1016/j.solener.2018.06.063.

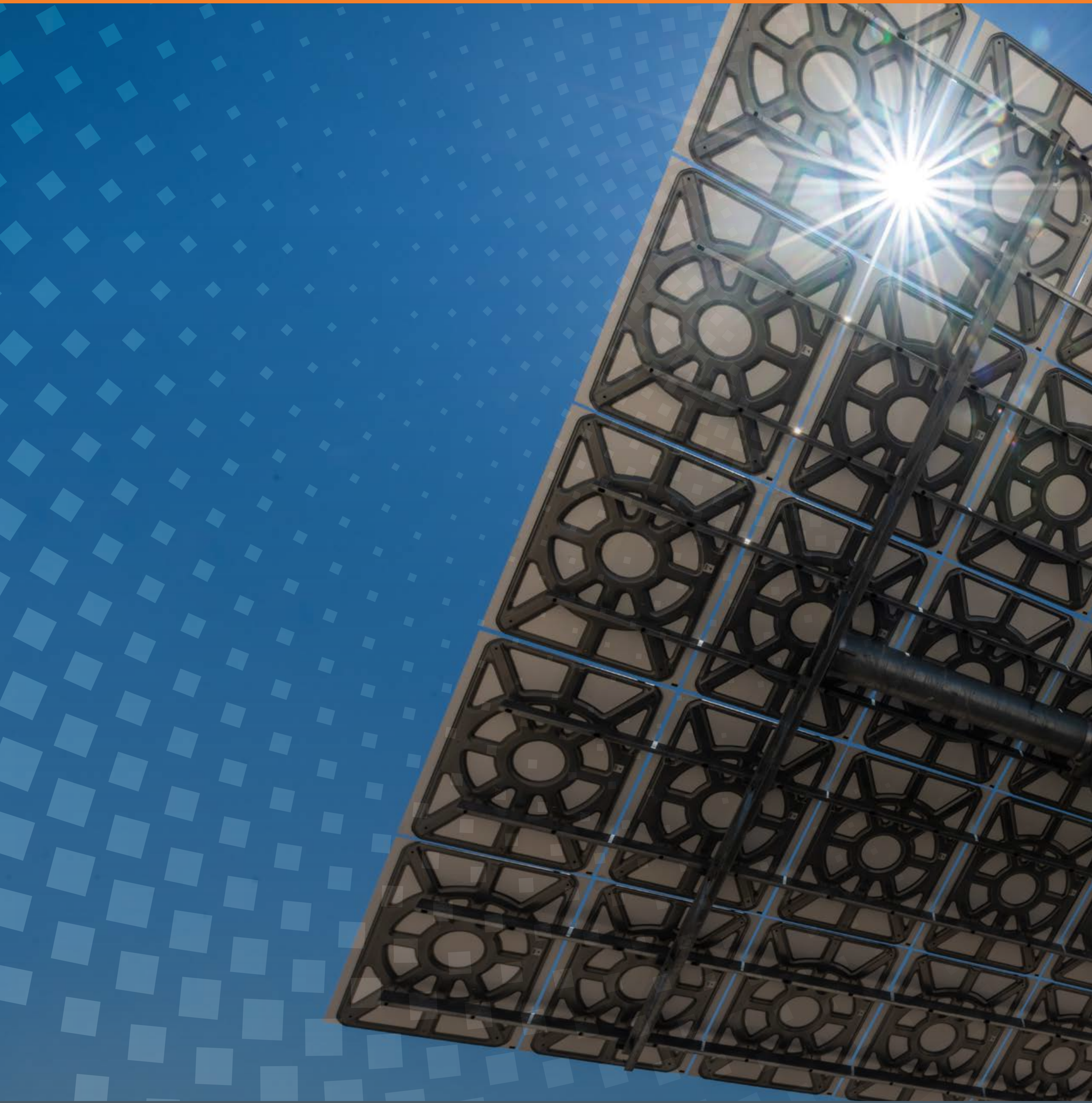
Wang, Ye, Joe Coventry, and John Pye. 2024. “Using an Equivalent Slope Error To Quantify Beam Errors of Heliostats.” Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/18-04_ASME-ES2024_Wang-compressed.pdf.

Zhu, Guangdong, Chad Augustine, Rebecca Mitchell, Matthew Muller, Parthiv Kurup, Alexander Zolan, Shashank Yellapantula, et al. 2022. “Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power.” NREL/TP-5700-83041. Golden, CO, https://www.nrel.gov/docs/fy22osti/83041.pdf: NREL. https://doi.org/10.2172/1888029.

Zolan, Alex, and Giovanni Picotti. 2024. “Forecasting Soiling-Related O&M Costs for Concentrating Solar Power Tower Plants.” Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 16.

https://heliocon.org/HelioCon_Workshop_2024_files/18-03_ASME-ES2024_Soiling_draft.pdf.

Zolan, Alex, Evan Westphal, Chad Augustine, Ken Armijo, Ye Wang, and John Pye. 2024. "Impact of Process Temperature on the Cost of Concentrating Solar Thermal Industrial Process Heat (IPH)." Presented at the ASME 2024 Energy Sustainability Conference, Anaheim, California, July 17. https://heliocon.org/HelioCon_Workshop_2024_files/18-05_ASME-ES2024_HelioCon_TEA%20draft%2007-08-2024.pdf.



NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-91036
October 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov