NREL
Transforming ENERGY

# NREL CSP Facilities and Capabilities Overview

Mark Mehos

HelioCon Seminar Series

January 12, 2022

# Discussion

- Brief NREL/Solar Overview
- NREL CSP Facilities and Capabilities
- Related Research (past and present)
- Related Literature (for reference)

# Discussion

- Brief NREL/Solar Overview
- NREL CSP Facilities and Capabilities
- Related Research (past and present)
- Related Literature (for reference)

# NREL at-a-Glance

2,926

## Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

## World-Class

facilities, renowned technology experts

More than

900

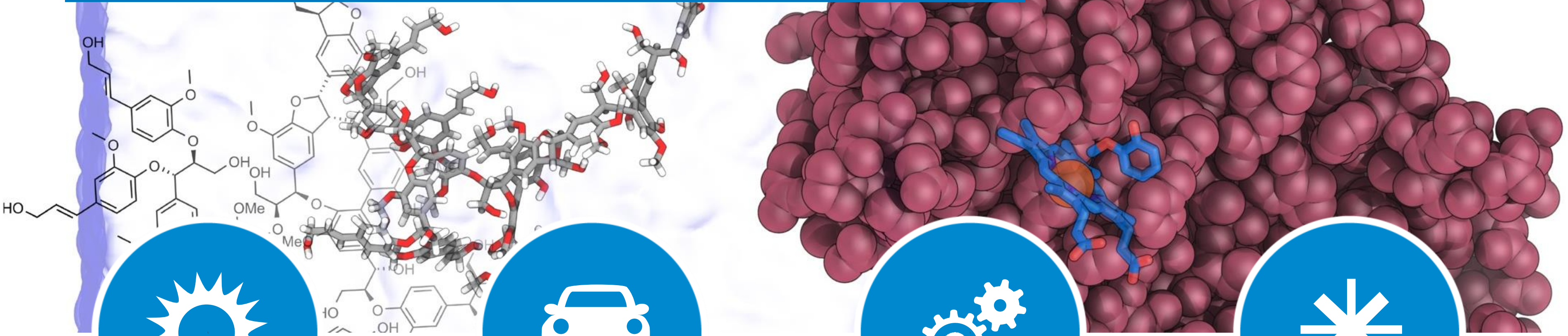
## Partnerships

with industry, academia, and government

## Campus

operates as a living laboratory

# NREL Science Drives Innovation




## Renewable Power

- Solar
- Wind
- Water
- Geothermal

## Sustainable Transportation

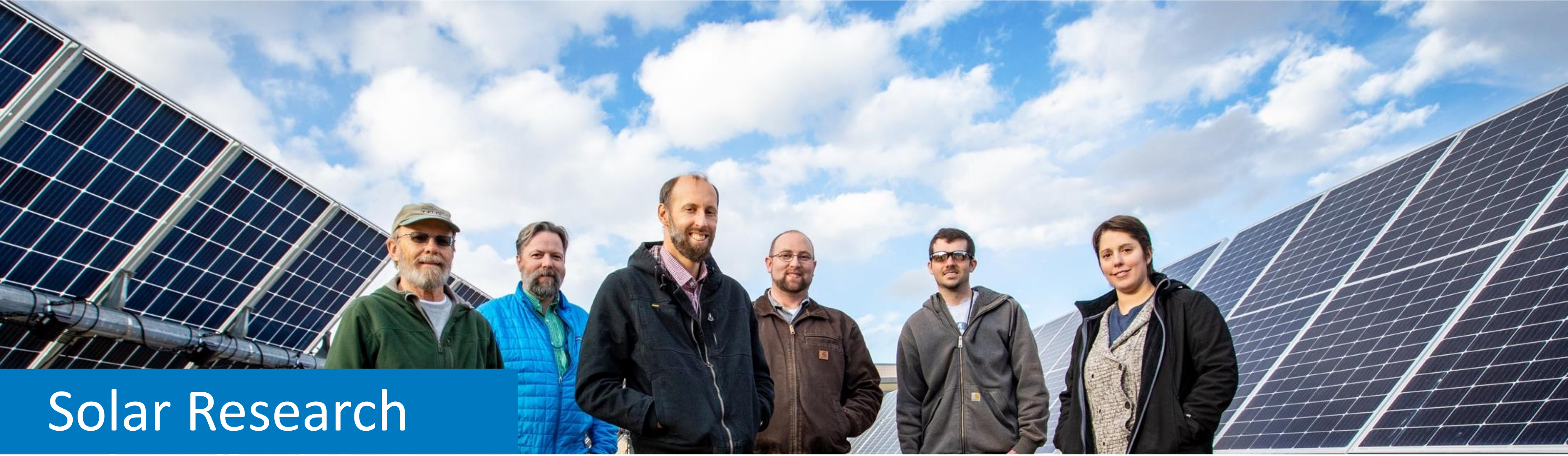
- Bioenergy
- Vehicle Technologies
- Hydrogen

## Energy Efficiency

- Buildings
- Advanced Manufacturing
- Government Energy Management

## Energy Systems Integration

- Grid Integration
- Hybrid Systems
- Security and Resilience



# Solar Research

Areas of research include concentrating solar power, photovoltaics, grid integration, and market analysis.

Together, these areas will enable reliable, low-cost solar energy at scale—on the grid and beyond the grid.

## Research Challenges

- Integrate large amounts of solar energy into the power grid while maintaining security and reliability, and enhancing resilience
- Improve the efficiency, lifetimes, and manufacturability of photovoltaic materials
- Develop technologies for a third generation of concentrating solar power plants to further reduce costs and improve thermal storage capabilities
- Capture surplus solar energy to provide heat and produce fuels and clean water
- Create flexible, highly efficient solar cells that can make low-cost power available without wires anywhere the sun shines
- Make solar an even better investment through work on bankability, reliability, and recyclability

# Solar Research

Areas of research include **concentrating solar power**, photovoltaics, grid integration, and market analysis.

Together, these areas will enable reliable, low-cost solar energy at scale—on the grid and beyond the grid.

## Research Challenges

- Integrate large amounts of solar energy into the power grid while maintaining security and reliability, and enhancing resilience
- Improve the efficiency, lifetimes, and manufacturability of photovoltaic materials
- **Develop technologies for a third generation of concentrating solar power plants to further reduce costs and improve thermal storage capabilities**
- Capture surplus solar energy to provide heat and produce fuels and clean water
- Create flexible, highly efficient solar cells that can make low-cost power available without wires anywhere the sun shines
- Make solar an even better investment through work on bankability, reliability, and recyclability

# Solar Research

Areas of research include **concentrating solar power**, photovoltaics, grid integration, and market analysis.

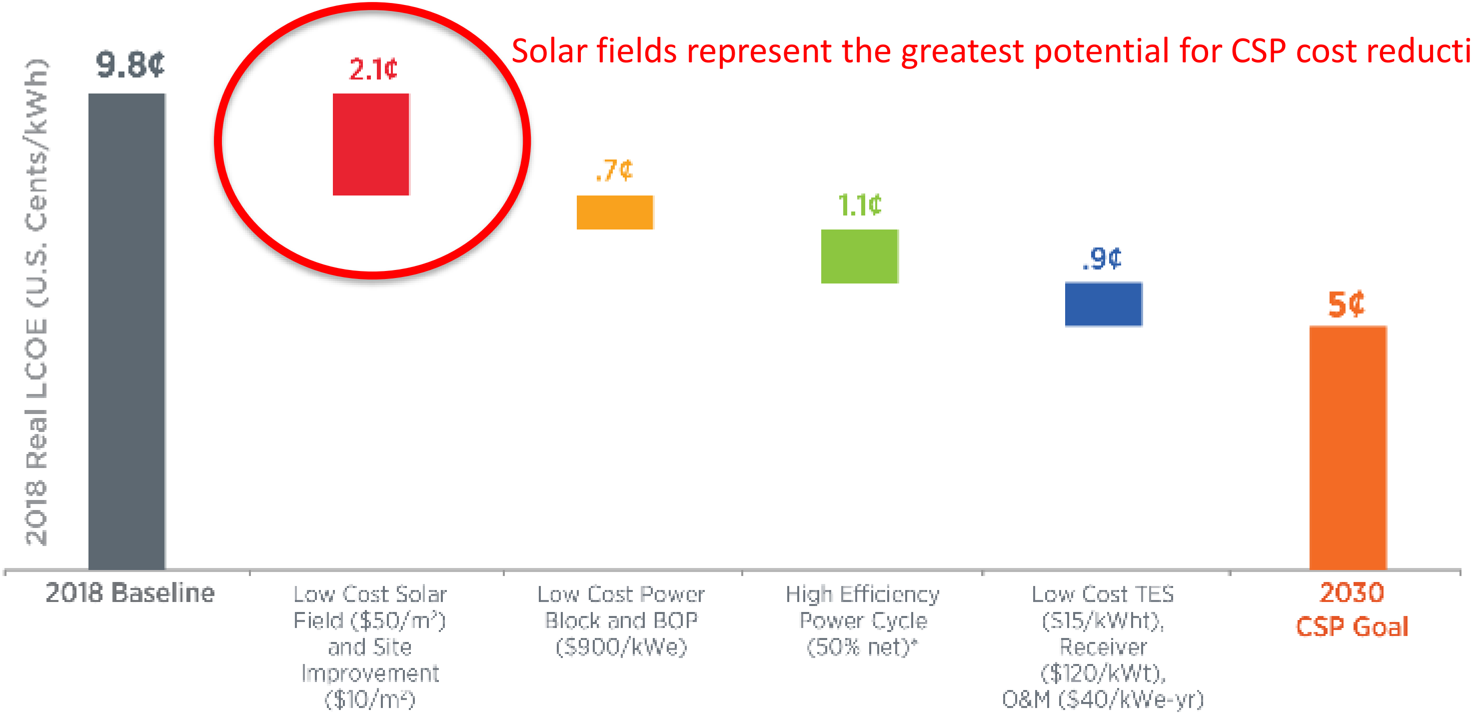
Together, these areas will enable reliable, low-cost solar energy at scale—on the grid and beyond the grid.

## Research Challenges

- **Integrate large amounts of solar energy into the power grid while maintaining security and reliability, and enhancing resilience**
- Improve the efficiency, lifetimes, and manufacturability of photovoltaic materials
- **Develop technologies for a third generation of concentrating solar power plants to further reduce costs and improve thermal storage capabilities**
- **Capture surplus solar energy to provide heat and produce fuels and clean water**
- Create flexible, highly efficient solar cells that can make low-cost power available without wires anywhere the sun shines
- **Make solar an even better investment through work on bankability, reliability, and recyclability**

# A Pathway to 5 Cents per KWh for Baseload CSP from Materials to Grid

Solar fields represent the greatest potential for CSP cost reduction




*Assumes a gross to net conversion factor of 0.9

# Discussion

- Brief NREL/Solar Overview
- NREL CSP Facilities and Capabilities
- Related research (past and present)
- Related literature (for reference)

# Thermal Systems Research at NREL


## Current Research

### CSP/CST

- Next Generation Concentrating Solar Power (CSP) systems
- Concentrating Solar Thermal (CST) for industrial process heat

### Solar and Hybrid Systems Optimization

- CSP-TES/PV-Batt hybrid systems optimization and operation
- Optimized design and dispatch of hybrid utility-scale generation

### Thermal Energy Storage

- Pumped thermal energy storage, Electric thermal energy storage
- “Low” temperature molten salt storage systems
- High-temperature particle storage systems

### Solar Thermal Fuels

- Solar thermochemical hydrogen (STCH)
- High-temperature electrolysis

Materials Science → Engineering Design and Analysis → Lab & Field Characterization → Systems Integration → Grid Optimization

# Our NREL CSP Team (or most of them)

# Dedicated CSP R&D and Support Facilities at NREL

## South Table Mountain and Field Test Laboratory

High Flux Solar Furnace


Ultra-Accelerated Weathering System

Advanced Optical Materials Laboratories

# Advanced Optical Material Laboratories (AOM) - Weatherability

**Ci5000** Weatherometer
Xenon arc lamp exposure chamber-2 Suns, 60°C, 60 %RH

## Advanced Optical Material Laboratory (AOM)

- The advanced optical materials laboratories (three labs located at NREL's FTLB) support developing and testing optical materials used in renewable energy and energy efficiency systems (e.g. CSP, PV & Electrochromic window development).
- Reliability exposure chambers and equipment simulate a variety of conditions, including sunlight, various temperature and humidity levels, rain, freeze/thaw, hail, and salt spray.

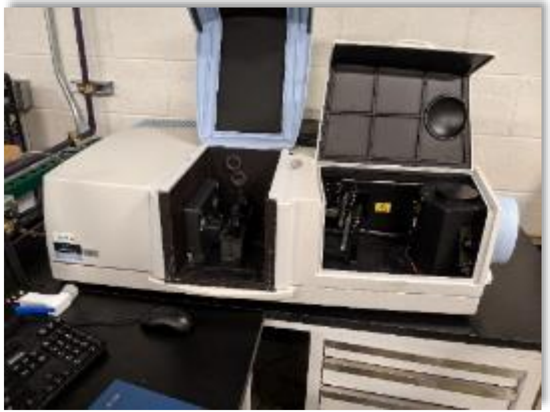
**Solar Simulator** -Abet Technologies Model 11048-1 3 kW multi-sun UV solar simulator, customer reconfigurable to a full spectrum 2 suns 300x300 mm field simulator.

**XR260** Weatherometer integrates the recent developments in environmental chamber and xenon solar simulation technology. The XR260 is capable of testing modules up to 1.9 meters by 1.4 meters.

## Accelerated Weathering Systems:

- Ci5000s
- UAWS
- Tenney
- BlueM
- XR260
- Scrub Testers

# Advanced Optical Material Laboratories (AOM) - Characterization



**LAMBDA 1050** – A UV/Vis system designed for analysis of coatings, high performance glass, solar, and advanced materials and components.

**<u>Advanced Optical Material Laboratory (AOM)</u>**

- The laboratory tools and instruments that allow measurement of optical properties (reflectance, absorptance, transmittance) and performance measure a wide range of feature sizes (from nanometers to meters) and sample sizes (from millimeters to tens of meters) traceable to the National Institute of Standards and Technology.

## Optical Characterization Tools:

- Lambda 1050
- Specular Reflectometers (D&S)
- Portable Reflectometers (SOC)
- FTIR + SOC 100 HDR

# AOM Laboratory Instrument Inventory

| Equipment Name | Manufacturer and Model # | Equipment Function | Equipment capabilities |
|---|---|---|---|
| Blue M Large | Thermal Product Solutions | Oven | Dark<br>85°C and 85%RH<br>65°C and 65%RH<br>65°C and 85%RH |
| Blue M Small | Thermal Product Solutions | Enviromental Chamber | |
| Ci5000 (5 units) | Atlas | Enviromental Chamber | 10%-95% Relative Humidity in light cycles<br>Light output up to 2 suns<br>See filter options to choose spectrum options |
| L1050 | Perkin Elmer | Spectrophotometer | |
| D&S (2 units) | Devices & Services | Specular Reflectometer | 7mr, 15mr, 25mr at 660nm |
| XR260 | Atlas | Enviromental Chamber | 4 Xe Lamps producing 1 sun output<br>4 ft. x 6 ft. Test Plane<br>0%-90% Relative Humidity<br>-10°C to 110°C with light exposure<br>-40°C to 110°C Dark |
| ET100 | Surface Optics Corporation | Portable Emissometer | Emmitance |
| FTIR | Thermo Fisher | FTIR | |
| SOC 410-Solar | Surface Optics Corporation | Portable Spectrophotometer | Hemispherical reflectance at 7 wavelength bands |
| Small Solar Simulator | ORIEL Corporation | Enviromental Chamber | Xe lamp filtered from 300-500nm<br>NREL built chambers can add low and high temperature and low and high relative humidity exposure |

# AOM Laboratory Instrument Inventory

| Equipment Name | Manufacturer and Model # | Equipment Function | Equipment capabilities |
|---|---|---|---|
| Medium Solar Simulator | ABET Technologies | Enviromental Chamber | Xe lamp filtered from 300-500nm<br>NREL built chambers can add low and high temperature and low and high relative humidity exposure |
| Sun 2000 (Large Solar Simulator) | ABET Technologies | Enviromental Chamber | Xe lamp filtered from 300-500nm<br>NREL built chambers can add low and high temperature and low and high relative humidity exposure |
| Goniometer | ramé-hart | Contact Angle Goniometer | |
| Salt Spray | Atlas | Enviromental Chamber | |
| Vacuum Oven | Georgia Oven Company | Oven | Temperature <650°C<br>Vacuum >1 x $10^{-4}$ mtorr |
| Tenney | Thermal Product Solutions | Enviromental Chamber | 20%-98% relative humidity (at sea level and 24°C)<br>-73°C - +200°C, ±0.3°C |
| Ovens (Multiple) | Various | Oven | The Optical Materials lab has 5 dedicated ovens/furnaces |
| Emmaqua | Atlas | Accelerated Outdoor Weathering | |
| Ultra Accelerated Weather System (UAWS) | NREL | Accelerated Outdoor Weathering | Cooled samples are exposed to natural sunlight concentrated 100 times below 500 nm |
| Scrub Abrasion | BYK | Abrasion Testing | Brush scrub system using brushes of various materials<br>Tests can be run with or without dust |
| Tabor Abrader | Taber Industries | Abrasion Testing | Abrasion wheels in multiple materials of varying abrasive qualities available |

# South Table Mountain Site

# Ultra-Accelerated Weathering System (UAWS)

## Ultra-Accelerated Weathering System (UAWS)

- Specimens can be exposed under ultra-high irradiance with ultra-high fidelity to natural sunlight spectral power distribution (SPD) and without the specimens melting or burning (thermal oxidation).
- The equipment is unique in its ability to concentrate the UV. NREL has one of only three existing UAWS in the world.

Current/Potential Customers: CSP developers, solar field providers, mirror providers. Previously was used for UV coating development, mirrors, thin films, and several outside specialized paint manufacturers.

R&D 100

# High Flux Solar Furnace (HFSF)

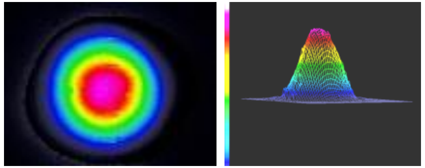
NREL's HFSF

- Research for components used in concentrating solar power systems such as receivers, collectors, and reflector materials
- Design-point or high-flux conditions for on-sun functional component performance, material testing of high-temperature materials, solar thermochemical hydrogen production, perovskites, and solar-selective coatings.

Current/Potential Customers: The HFSF is a National Laboratory User Facility and is available to assist with research for Universities, Businesses, National Laboratories, Department of Energy, Department of Defense, solar companies (US & Abroad), space agencies, CSP (component, small scale/prototype receivers), hydrogen production, durability research (materials, components), biomass production & CPV.

# NREL's HFSF is a 10 kW optical furnace for testing of high temperature processes or applications requiring high heating rates or solar concentration.

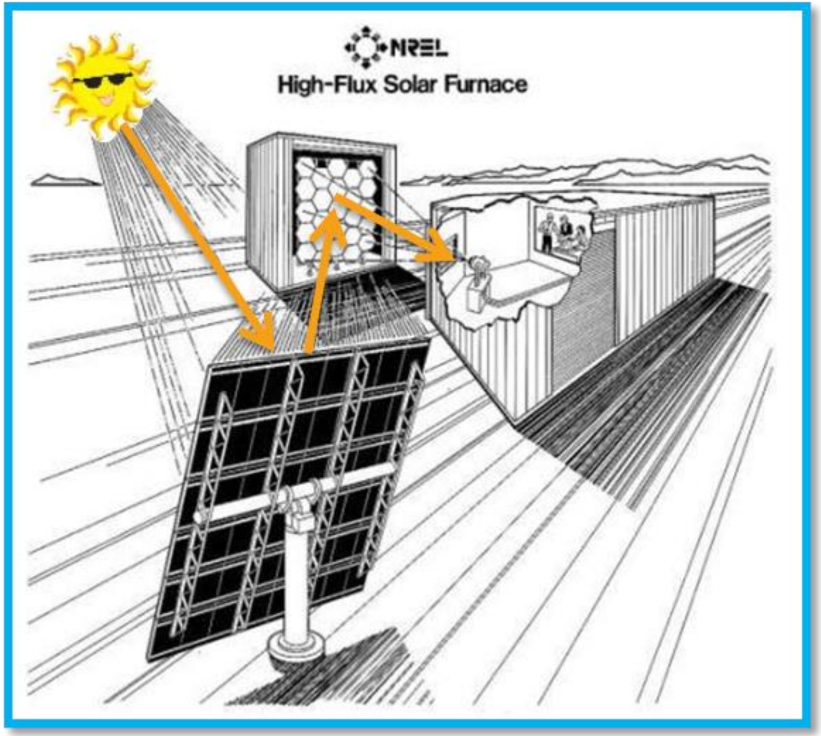
The HFSF can produce peak solar flux of 250 $W/cm^2$ or 2500 suns with primary concentrator and higher fluxes with secondary concentrators.



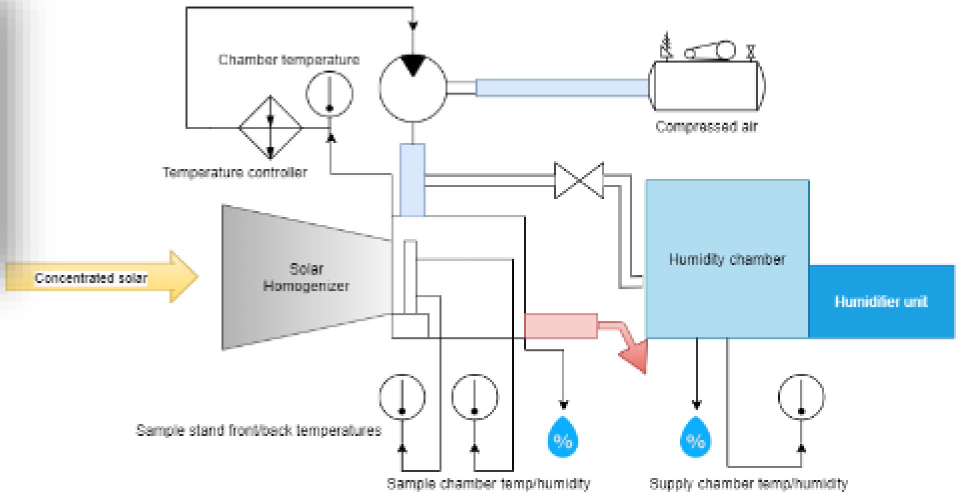
Flux Distribution at focal point.

Key components:

- Heliostat
  - 31.8 $m^2$
- Primary Concentrator
  - 25 hexagonal facets
  - 100 x concentration/facet
- Laboratory – research area
  - Programmable XYZ table
  - Extensive data acquisition
  - Reconfigurable for variety of research
  - Adjustable flux levels

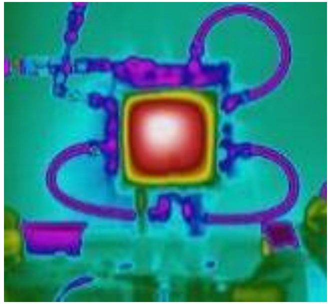


# New Absorber Accelerated Aging Test Apparatus with Multiple Stress Factors




## Coating parameters

- ✓ Optical Absorptivity
- ✓ Optical Emissivity
- ✓ Oxidation rate
- ✓ Corrosion rate
- ✓ Coating Adhesion
- ✓ Cracking density
- ✓ Coating thickness



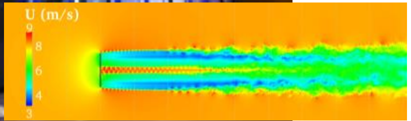
# Dedicated CSP R&D and Support Facilities at NREL

## Energy Systems Integration Facility

Collector Characterization Laboratory

TES Components and Materials

High Performance Super Computer (HPC)



# Optical Characterization Laboratory

## Optical Characterization Lab (OCL)

Sandia SOFAST
NREL NIO-a

- OCL's capabilities allows solar mirror developers and solar power plant developers, operators, and other stakeholders to ensure qualities of solar collectors in the laboratory and in-situ conditions.

Current/Potential Customers: Mirror developers, CSP solar collector developers, CSP power plant owners, CSP service providers in solar field performance assessment.

Large Area Environmental Test Chamber

# Anticipated New CSP R&D and Support Facilities

## NREL Flatirons Campus

NIO Heliostat Characterization

To be developed under HelioCon:

- Indoor opto-mechanical Load Testing
- Optical characterization of in-situ heliostats
- Wind-load testing of in-situ heliostats

Existing wind turbine static and dynamic blade test facility

Wind load testing of in-situ PV panels

# Discussion

- Brief NREL/Solar Overview
- NREL CSP Facilities and Capabilities
- Related research (past and present)
- Related literature (for reference)

# Sampling of Relevant Past and Current Research Projects

- Accelerated reflector aging using Xenon-Arc Lamp Exposure (XALE)
- Distant Observer (DO)
- Non-Intrusive Optical Technology (NIO)
- Heliostat Aimpoint and Layout Optimization Software (HALOS)
- Wind-loading on CSP collectors
- CSP Best Practices
- Leveraging PV Research at NREL

# XALE | *Accelerated reflector aging using Xenon-Arc Lamp Exposure*

Contact Guangdong.Zhu@nrel.gov

**Objective:**

Develop a test and measurement guideline for accelerated reflector aging tests using a xenon arc lamp equipped weatherometer. Use the results to calculate degradation rates for various accelerated environmental conditions.

Step 1:
*Initial Characterization*
Take reflectance data on unexposed samples

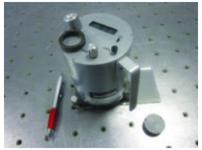
Step 2:
*Exposure*
Place samples in arc-lamp weatherometer for specified time, temperature, humidity, and irradiance parameters

Step 3:
*Final characterization*
Repeat measurements from step 1 for comparison

Step 4:
*Analysis*
Compute degradation over time for associated weathering conditions

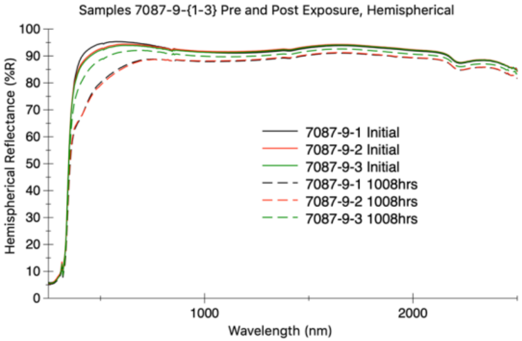
Surface Optics Corporation
*410-Solar*
Rapid hemispherical and specular reflectance data – used for assessing surface uniformity and field measurements

PerkinElmer
*Lamda 1050 Spectrophotometer*
Bench-mounted, high-fidelity hemispherical reflectance measurements at 5 nm resolution over the entire solar spectrum



Devices and Services
*15R-RGB Spectral Reflectometer*
Portable reflectometer for measuring mirror specularity – a critical component to optical performance monitoring

ATLAS
*Ci-5000 Weatherometer*
Xenon-arc lamp equipped weatherometer with controls for humidity, temperature, and solar irradiance.




Example of sample reflectance degradation for 1008 hrs of exposure. Metric used is hemispherical reflectance measured with L1050 (above)

Plot sourced from RPPR – Q2, FY21 for XALE

# XALE | *Accelerated reflector aging using Xenon-Arc Lamp Exposure*

Contact Guangdong.Zhu@nrel.gov

**Objective:**
Develop a test and measurement guideline for accelerated reflector aging tests using a xenon arc lamp equipped weatherometer. Use the results to calculate degradation rates for various accelerated environmental conditions.

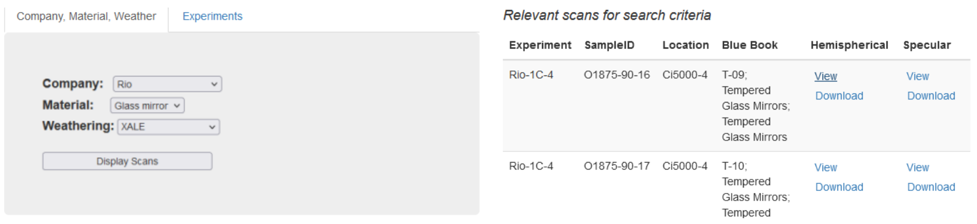
Step 1:
*Initial Characterization*
Take reflectance data on unexposed samples

Step 2:
*Exposure*
Place samples in arc-lamp weatherometer for specified time, temperature, humidity, and irradiance parameters

Step 3:
*Final characterization*
Repeat measurements from step 1 for comparison

Step 4:
*Analysis*
Compute degradation over time for associated weathering conditions

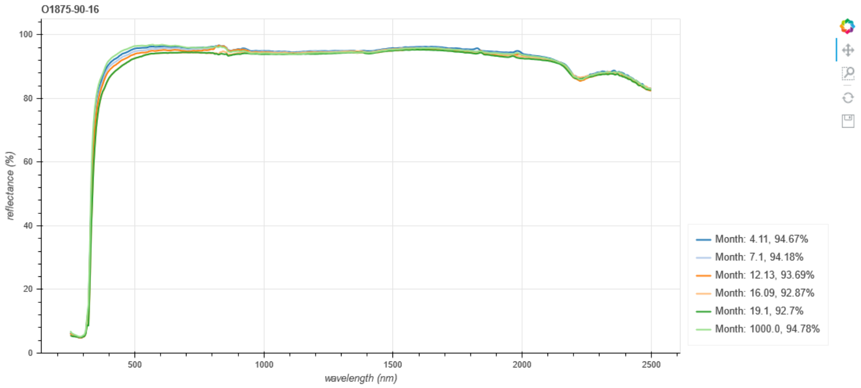
http://ec2-54-245-31-104.us-west-2.compute.amazonaws.com:8080/


Company, Material, Weather | Experiments

Company: Rio
Material: Glass mirror
Weathering: XALE
Display Scans

*Relevant scans for search criteria*

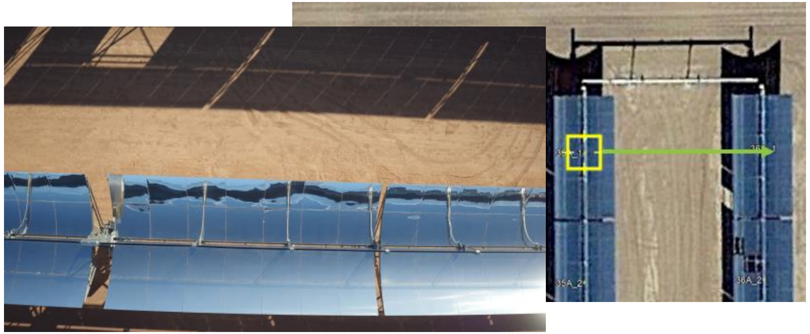
| Experiment | SampleID | Location | Blue Book | Hemispherical | Specular |
|---|---|---|---|---|---|
| Rio-1C-4 | O1875-90-16 | Ci5000-4 | T-09; Tempered Glass Mirrors; Tempered Glass Mirrors | View Download | View Download |
| Rio-1C-4 | O1875-90-17 | Ci5000-4 | T-10; Tempered Glass Mirrors; Tempered | View Download | View Download |



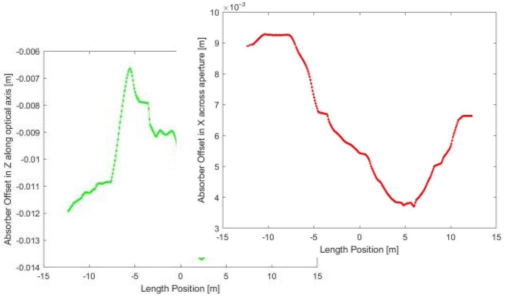
# Distant Observer

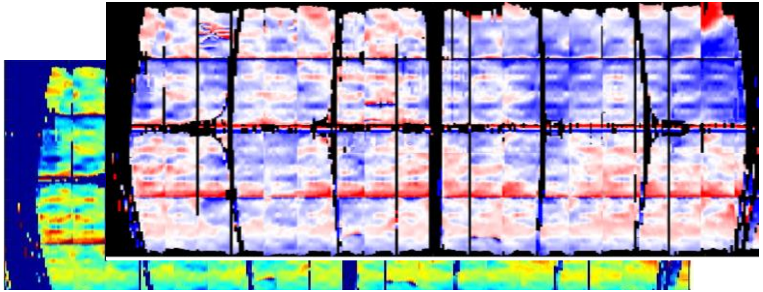
- Distant Observer is an optical measurement tool initially conceived and developed at NREL (2012)
- The tool uses a series of images (or video) of a receiver reflection panning across a parabolic trough collector to measure mirror slope and offset of the absorber tube.
- Recently, this software has been adapted for UAS data collection and faster processing with machine learning and computer vision techniques.

Contact Devon.Kesseli@nrel.gov

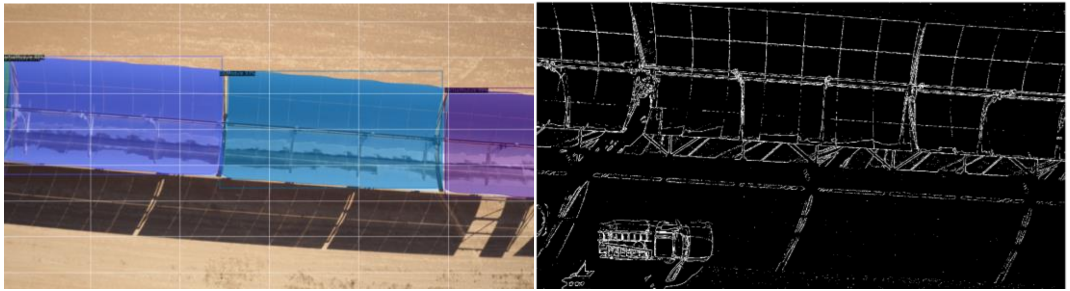


DO Inputs: video collected by UAS.



DO Results: absorber tube offset (above) and surface slope error (below)



DO Developments: deep learning and computer vision analysis automation.

# The Non-Intrusive Optical (NIO) Technology

- NIO allows for the efficient optical assessment of a commercial-scale CSP solar field
- Heliostats are scanned in seconds using Unmanned Aircraft Systems (UAS) imaging
- The method produces detailed optical characterization data over the full mirror surface for every heliostat (slope, canting, and tracking error)

Contact Rebecca.Mitchell@nrel.gov

## UAS Data Collection

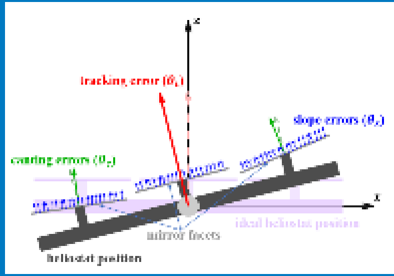
UAS allows for image scanning of each heliostat in seconds

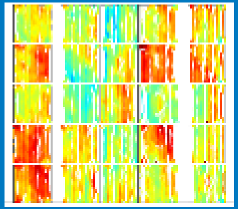
## Image Processing

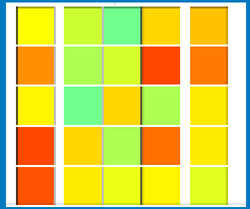
Images are post-processed to detect heliostat features and reflected tower edge

## Optical Characterization

Distortions in the tower reflection are quantified to derive slope, tracking, and canting errors.



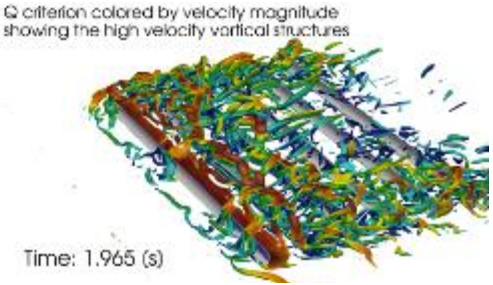





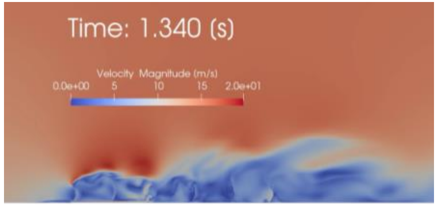
# Wind-loading on CSP collectors

Wind-loading is one of the primary drivers of structural design costs of CSP collector structures. 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. Therefore, this current project aims to:

- Accurately **characterize wind conditions** and flow structures in an **operational parabolic trough** power plant
- Characterize the **loads on parabolic troughs** and correlate to the wind conditions
- Develop a **computationally inexpensive simulation model** for **deep array** CSP collector configurations
- Plan a **measurement campaign for heliostats** in an operational power tower power plant


Snapshot of the simulated CFD flow-field of the complex flow conditions between the rows for 6-row parabolic-trough setup.

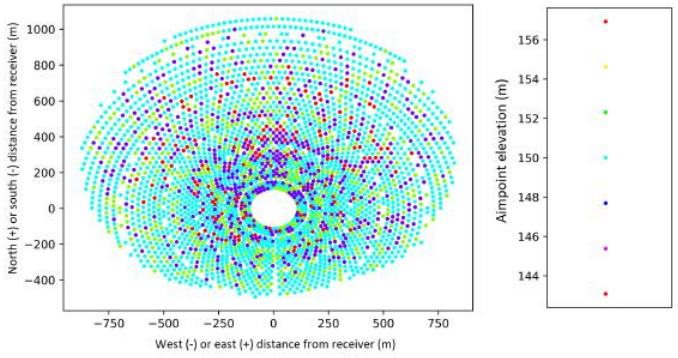



Contact Shashank.Yellapantula@nrel.gov

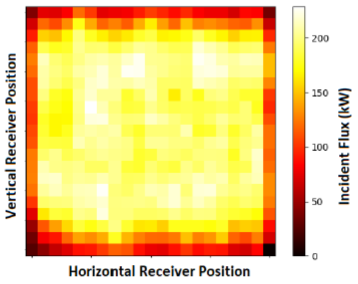
# Heliostat Aimpoint and Layout Optimization Software (HALOS)

Open-Source code available at https://github.com/NREL/HALOS

- Interfaces with NREL's SolarPILOT to obtain high-fidelity flux maps
  - Accepts flux maps from other packages in flat-file format
- Obtains optimized aiming strategies for large-scale systems using integer programming methods
  - Adheres to flux and gradient limits on receiver surface
- Includes heuristic for layout improvement according to field utilization




Example aiming strategy for heliostat field (left) and elevation of each aimpoint (right)




Example flux map on receiver surface

Contact Alexander.Zolan@nrel.gov

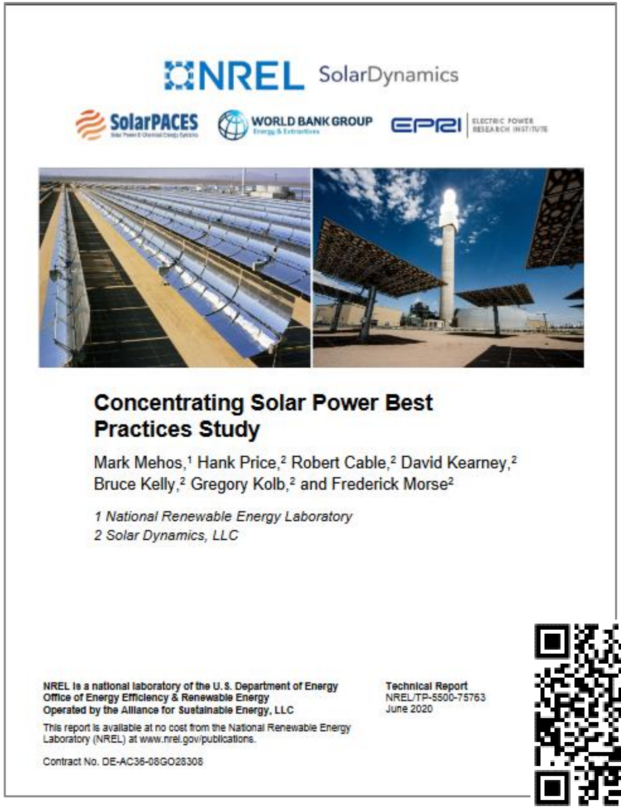
# CSP Best Practices Studies

Full report can be downloaded at
https://www.nrel.gov/docs/fy20osti/75763.pdf

- Includes recommendations involving the design, installation, and maintenance of CSP solar fields

Executive Summary:

*“Not all collector or heliostat technology is the same. Although few participants considered collector or heliostat technology to be a significant issue, collector/heliostat technology can make or break a project, and many providers have learned much over the last 10 years.”*


NREL SolarDynamics
SolarPACES WORLD BANK GROUP EPRI

Concentrating Solar Power Best Practices Study

Mark Mehos,[1] Hank Price,[2] Robert Cable,[2] David Kearney,[2] Bruce Kelly,[2] Gregory Kolb,[2] and Frederick Morse[2]

1 National Renewable Energy Laboratory
2 Solar Dynamics, LLC

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-5500-75763
June 2020

Contact Mark.Mehos@nrel.gov

# Leveraging PV Research at NREL

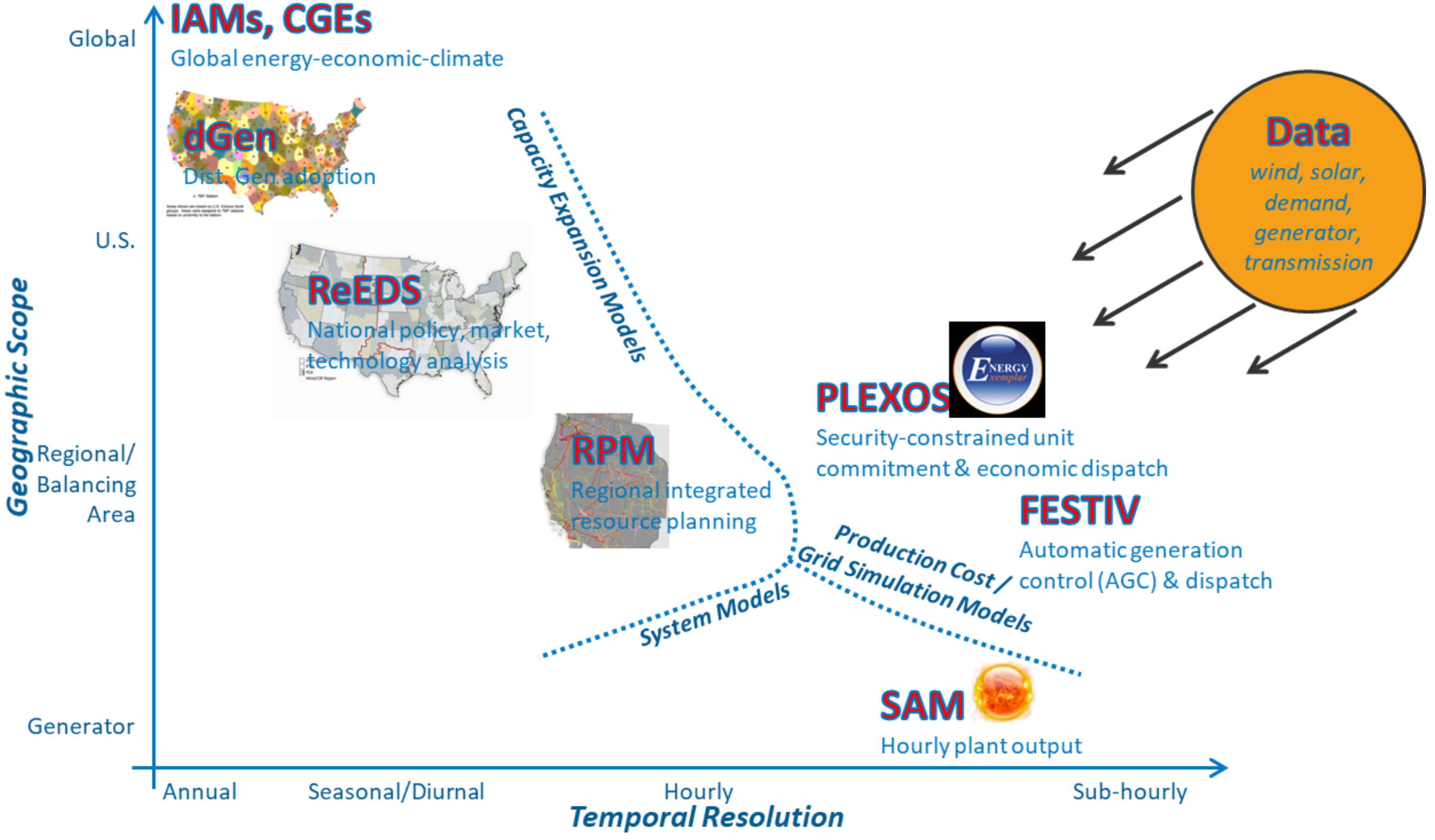
## Past and current SETO/PV-funded research with potential applications to CSP/HelioCon

- Lead on IEC work to publish design qualification standard for solar trackers (IEC 62817)
- Work with test labs to develop necessary equipment and test criteria for testing of solar trackers
- Development of algorithms to analyze solar tracker performance
- Development of algorithms to extract soiling loss metrics from performance data
- Development of soiling models based on particulate and other environmental data
- Development of soiling measurement equipment
- PVfleets project offers potential database of multiyear high frequency wind data at various US locations

# Technoeconomic Analysis Tools

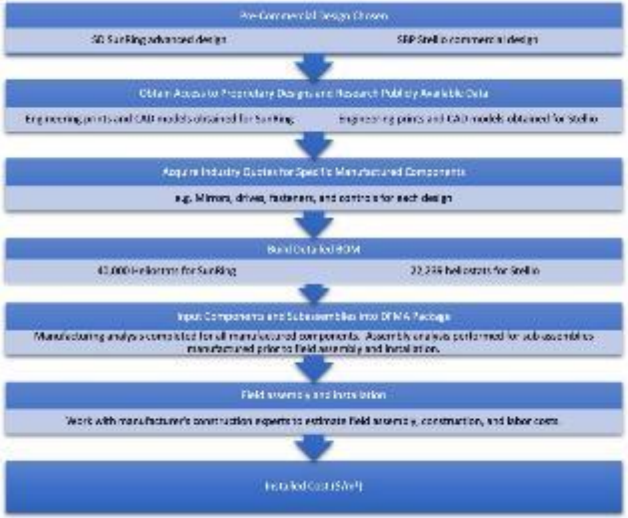
NREL's suite of techno-economic analysis tools can be used to assess the national impact of heliostat cost reductions

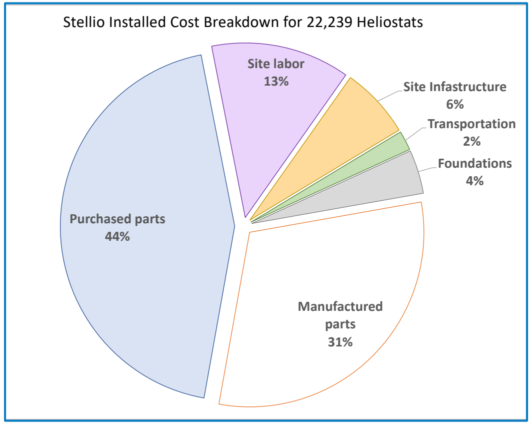
Contact

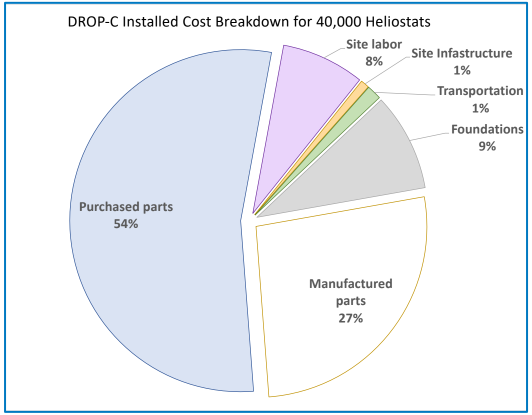


# Bottom-up Heliostat Costing

- Detailed bottom-up manufacturing analysis for commercial and advanced parabolic trough designs using Design for Manufacturing Analysis (DMFA) software
- Detailed bottom-up manufacturing analysis for commercial and advanced heliostat designs using Design for Manufacturing Analysis (DMFA) software (forthcoming)

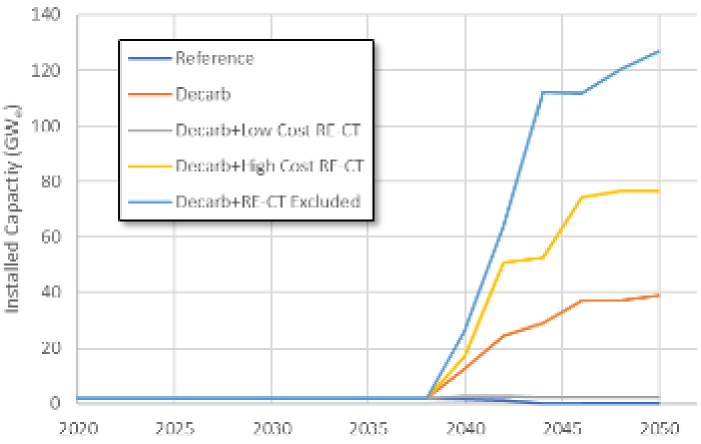


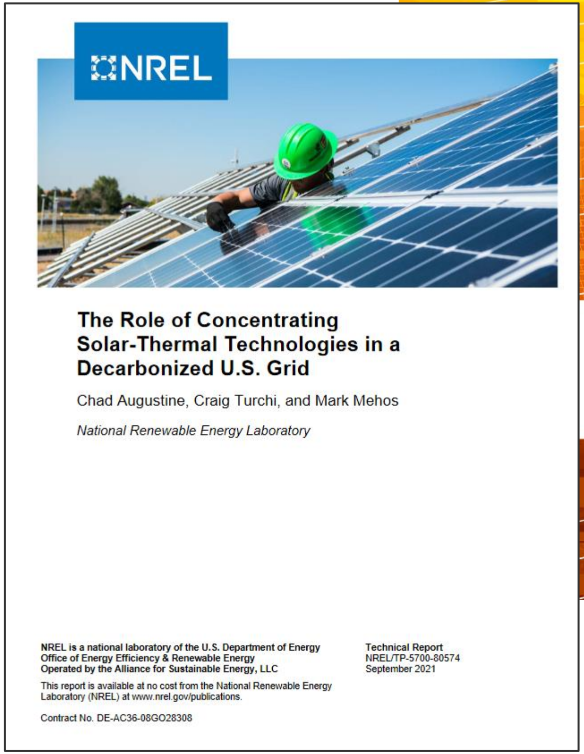




Contact Parthiv.Kurup@nrel.gov

# Potential CSP Deployment in the US if DOE CSP and PV 2030 Cost Targets are Achieved



NREL

**The Role of Concentrating Solar-Thermal Technologies in a Decarbonized U.S. Grid**

Chad Augustine, Craig Turchi, and Mark Mehos

*National Renewable Energy Laboratory*

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-5700-80574
September 2021


Contact Chad.Augustine@nrel.gov

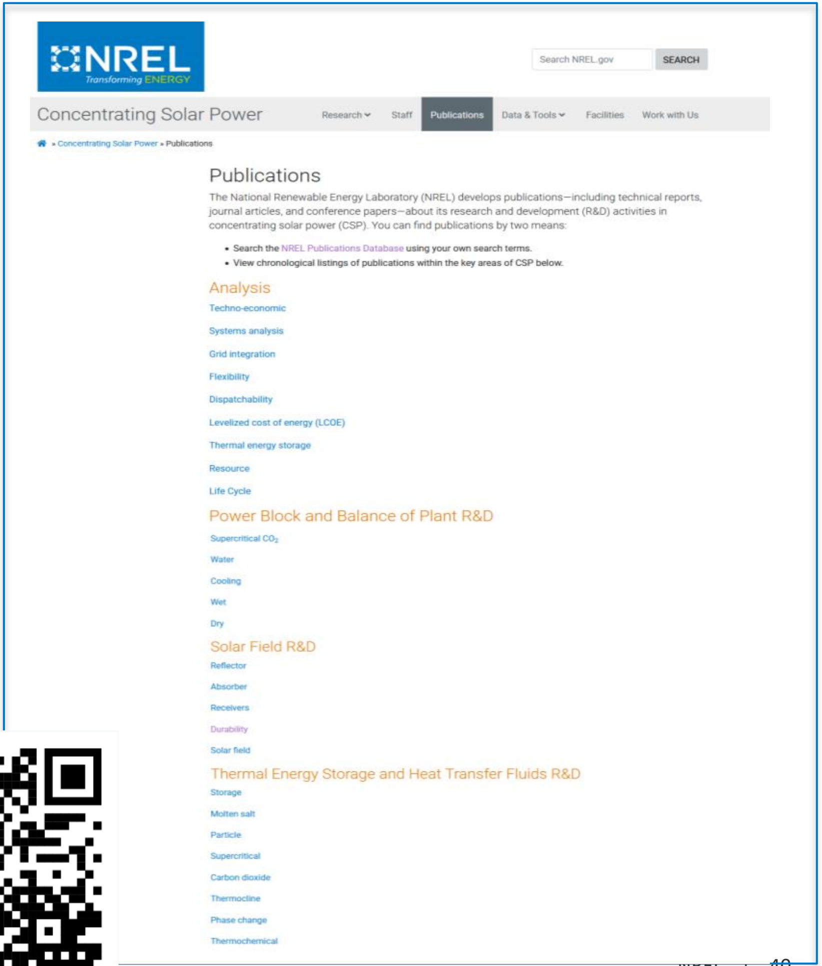
# Discussion

- Brief NREL/Solar Overview
- NREL CSP Facilities and Capabilities
- Related research (past and present)
- Related literature (for reference)

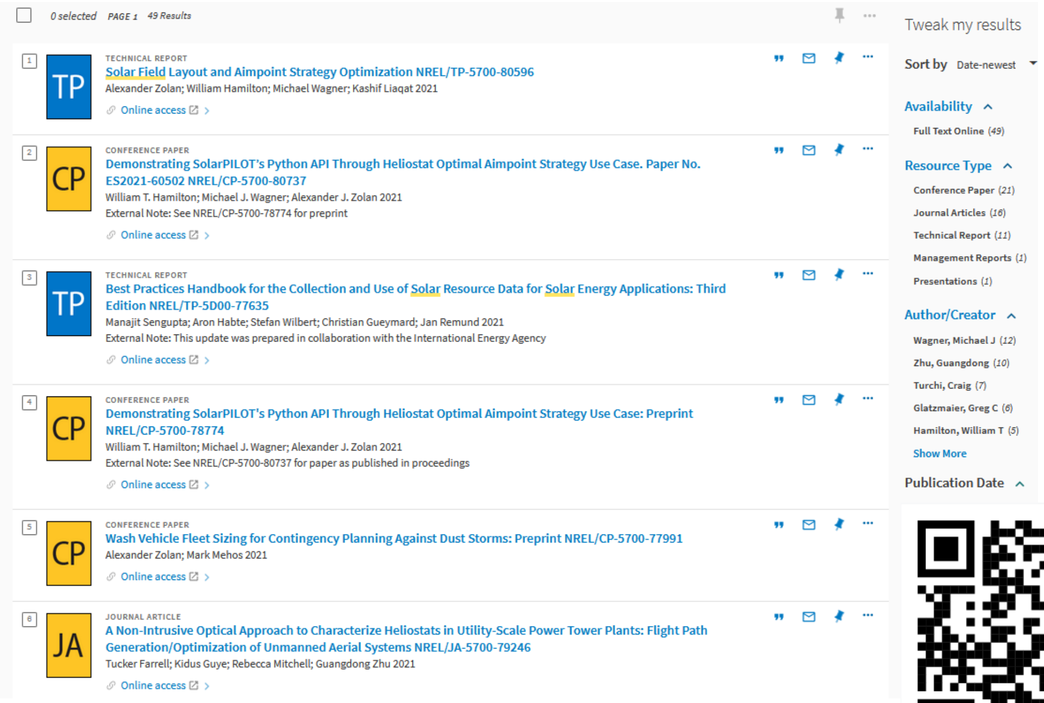
# Find more CSP-Related publications at CSP-Related Publications at https://www.nrel.gov/csp/publications

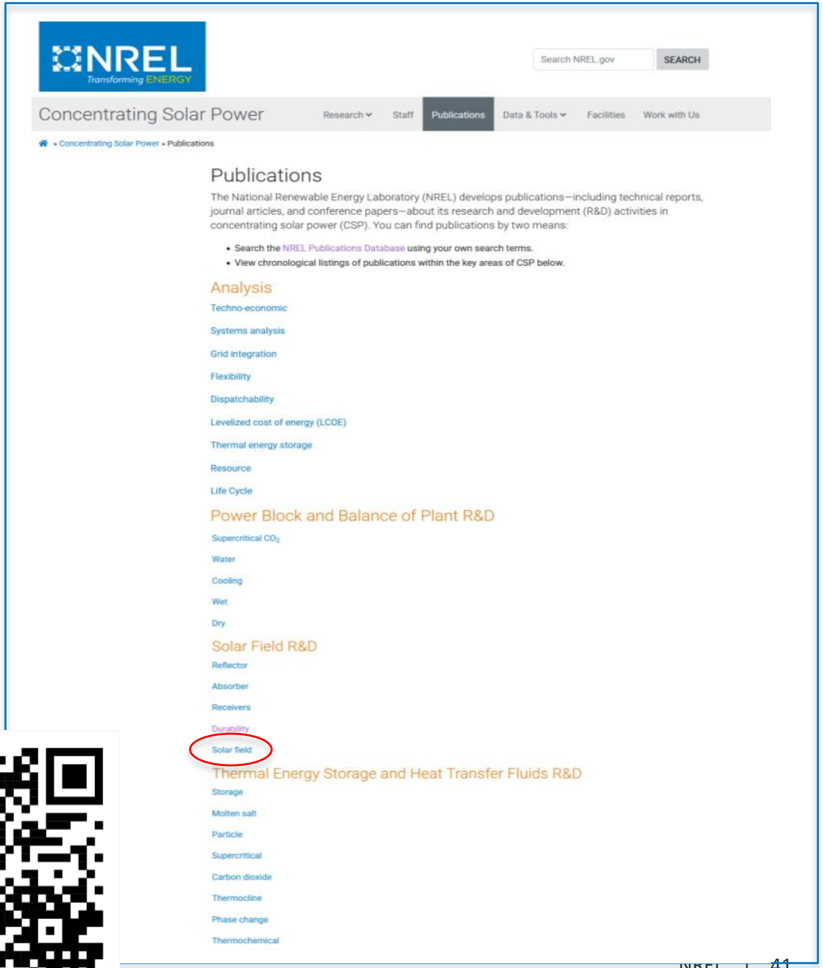
## Search categories include:

- Analysis
- Power Block and Balance of Plant
- Solar Field R&D
- Thermal Energy Storage and Heat Transfer Fluids



# Example: Solar Field R&D -> Solar Field



# NIO References


- Mitchell, Rebecca A., and Guangdong Zhu. "A Non-Intrusive Optical (NIO) Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Methodology and in-Situ Validation." Solar Energy, vol. 209, Oct. 2020, pp. 431–45. ScienceDirect, https://doi.org/10.1016/j.solener.2020.09.004.
- Farrell, Tucker, et al. "A Non-Intrusive Optical Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Flight Path Generation/Optimization of Unmanned Aerial Systems." Solar Energy, vol. 225, Sept. 2021, pp. 784–801. DOI.org (Crossref), https://doi.org/10.1016/j.solener.2021.07.070.
- Mitchell, Rebecca A., and Guangdong Zhu. "A Non-Intrusive Optical (NIO) Approach to Characterize Heliostats in Utility-Scale Power Tower Plants: Sensitivity Study." Solar Energy, vol. 207, NREL/JA-5500-75833, Elsevier, July 2020. www.osti.gov, https://doi.org/10.1016/j.solener.2020.06.093.
- Zhu, Guangdong, et al. "On Characterization and Measurement of Average Solar Field Mirror Reflectance in Utility-Scale Concentrating Solar Power Plants." Solar Energy, vol. 99, Jan. 2014, pp. 185–202. ScienceDirect, https://doi.org/10.1016/j.solener.2013.11.009.

# Durability of Optical Materials References


- T. Farrell, F. Burkholder, G. Zhu; "Measurement and Reporting Guidelines for Solar Mirror Aging Test by Using Xenon Arc Lamp Exposure (XALE) Chamber." NREL Technical Report (under internal review)
- Y. Cao, F. Burkholder, D. Celvi, C. Schreiber, G. Zhu; "Analysis on NREL's Solar Mirror Material Database (SMMD)." Journal Paper (under internal review)
- G. P. Butel; B. M. Coughenour; H. A. Macleod; C. E. Kennedy; J. R. P. Angel, "Reflectance Optimization of Second-Surface Silvered Glass Mirrors for Concentrating Solar Power and Concentrating Photovoltaics Application." Article No. 021808 NREL/JA-5500-58912 2012 Journal of Photonics for Energy 2, 1, (2012), 13 pp.
- C. E. Kennedy; K. Terwilliger, "Optical Durability of Candidate Solar Reflectors." Journal of Solar Energy Engineering 127, 2, (May 2005), pp. 262-269
- Matthew H. Gray; Robert Tirawat; Katelyn A. Kessinger; Paul F. Ndione High Temperature Performance of High-Efficiency, Multi-Layer Solar Selective Coatings for Tower Applications." 2015 Energy Procedia 69, (May-15), pp. 398-404

# TEA and Modeling References

- Should include relevant SAM references, AIMPOINT, Solar Futures Studies?, Manufacturing cost study report?, etc.


- Kesseli, Devon, et al. "CSP-plant modeling guidelines and compliance of the system advisor model (SAM)." *AIP Conference Proceedings*. Vol. 2126. No. 1. AIP Publishing LLC, 2019.
- Zolan, Alexander, et al. *Solar Field Layout and Aimpoint Strategy Optimization*. No. NREL/TP-5700-80596. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2021.
- Wagner, Michael J., et al. "Optimized dispatch in a first-principles concentrating solar power production model." Applied Energy 203 (2017): 959-971.
- Hamilton, William T., et al. "Dispatch optimization of concentrating solar power with utility-scale photovoltaics." Optimization and Engineering 21.1 (2020): 335-369.

# NREL Front Surface Soiling Capabilities

- Industry engagement
  - Lead PV Quality Assurance Task Force (PV-QAT) – 12: Soiling –Sensors, Cleaning, Abrasion, and Modeling
  - PV Fleet analysis – Includes automated evaluation of utility and commercial installation soiling rates
  - NREL USA Soiling map, https://www.nrel.gov/pv/soiling.html
  - Organize International PV Soiling Workshop, https://web.cvent.com/event/c9eef921-ef59-4596-91a0-a9f89ed5a1a1/summary
- Cleaning Standards and Best Practices
  - IEC 62446-2: PV Systems-Requirements for Testing, Documentation and Maintenance; includes section on best practices for cleaning
    - Best Practices in Photovoltaic System Operations and Maintenance, 2nd Edition
    - NREL/Sandia/Sunspec Alliance PV O&M Working Group
  - Developing new publication for best practices related to soiling
  - IEC-622788-7-3 PV Abrasion Standard to qualify coatings associated with soil cleaning
    - "The Abrasion of Photovoltaic Glass: A Comparison of the Effects of Natural and Artificial Aging," DOI: 10.1109/JPHOTOV.2019.2947029
  - Artificial soiling and cleaning standard being developed with Arizona State University
- Soiling Studies
  - "A comprehensive review of the impact of dust on the use of solar energy," http://dx.doi.org/10.1016/j.rser.2012.12.065
  - Completing 5 year study on induced damage from cleaning in high soiling environments
    - Soiling and cleaning: Initial observations from 5-year PV glass coating durability study," doi.org/10.1016/j.solmat.2018.05.039
  - Studied different soiling and bonding mechanisms, developed models, and standards
    - E.g., "Addressing Soiling," https://www.nrel.gov/docs/fy20osti/72853.pdf
- Anti-soiling coatings; work with different partners on different approaches, e.g.:
  - "Self-Cleaning Hybrid Hydrophobic-Hydrophilic Surfaces;" doi.org/10.1109/ JPHOTOV.2019.2955559
  - "Talus Anti-Soiling Shield" for PV and Heliostats, More Sun, https://www.youtube.com/watch?v=94fSmw2QHqs
  - "Electrodynamic Shield," Superclean Glass, www.cebip.org/news/superclean-glass-advances-to-american-made-solar-prize-finals

# Special Thanks to DOE/SETO

Some of the facilities and capabilities described in this presentation are funded through a separate DOE lab-call award: **“SETO National Lab Core Capabilities - NREL CSP Optical Facilities.”** We will soon be soliciting feedback regarding which optical facilities (existing or future) best serve the needs of the research and industry communities.

# Thank you


Mark Mehos

mark.mehos@nrel.gov

www.nrel.gov/csp



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


NREL

Transforming ENERGY

# More From the HelioCon Seminar Series

- Slides and presentation recording coming soon
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov
- Access Dr. Margaret Gordon's seminar on Sandia's CSP capabilities here: https://nrel.zoomgov.com/rec/share/p7gau8-dni6VBRBSbUvtpodXCRt1yE5roTKgalBP3BsWChlpg-Q8rO4FGuM7u431.4k8-DD0OvUSN5j9K

Next Seminar February 3rd!

**HelioCon Seminar Series: Technoeconomic Analysis of Heliostat Technologies**
Speaker: Dr. Chad Augustine, NREL
When: 3-4pm Thursday February 3rd
Zoom:https://nrel.zoomgov.com/j/1605655978?pwd=elJOR28yZGZGRWNHa09OSGphU28zUT09