Autonomous Integrated Heliostat Field and Components

Introduction and Overview

Avi Shultz, Ph.D.
CSP Program Manager
Solar Energy Technologies Office Mission

Our mission is to accelerate the development and application of technology to advance low-cost, reliable solar energy in the U.S.

To achieve this mission, solar energy must:

- Be **affordable** and **accessible** for all Americans
- Support **reliability**, **resilience**, and **security**
- Create a sustainable industry that supports jobs, manufacturing, and the **circular economy** in a wide range of applications
Potential CSP Deployment in the US if DOE CSP and PV 2030 Cost Targets are Achieved

2018 Real LCOE (U.S. Cents/kWh)

2018 Baseline: 9.8¢
Low Cost Solar Field ($50/m²) and Site Improvement ($10/m²): 2.1¢
Low Cost Power Block and BOP ($900/kWe): .7¢
High Efficiency Power Cycle (50% net): 1.1¢
Low Cost TES ($15/kWh), Receiver ($120/kWe), 0&8 (40/kWe-yr): .9¢
2030 CSP Goal: 5¢

Murphy, et al. 2019, NREL/TP-6A20-71912

*Assumes a gross to net conversion factor of 0.9
CSP with Storage is Solar Energy On-Demand

Oil-Based Troughs with steam rankine cycle (~400 °C)

Molten Salt Towers with steam rankine cycle (~565 °C)

‘Gen 3 CSP’: Novel Heat Transfer Media with advanced power cycle (>700 °C) @ 5¢/kWh
Solar Thermal Industrial Process Heat

Priority Areas:

• Reduce the levelized cost of heat, with thermal energy storage, in temperature ranges of high priority to industrial processes
• Improve the thermal efficiency of solar-thermal-coupled processes
• Develop long-duration, thermochemical storage of solar energy (i.e. solar fuels and chemical commodities)
CSP Technical Targets

Competitive Programs

- **$43M** FY 2020 SETO FOA (2020)
- **$30M** FY 2019 SETO FOA (2019)
- **$22M** FY 2018 SETO FOA (2019)
- **$21M** Solar Desalination (2018)
- **$22M** FY19-21 National Lab Call (2018)
- **$70M** Gen3 CSP Systems (2018)
- **$15M** Gen3 CSP Lab Support (2018)
- **$9M** COLLECTS (2016)
- **$32M** CSP: APOLLO (2015)
- **$29M** CSP SuNLaMP (2015)
- **$1.4M** SolarMat II (2014)
- **$10M** CSP: ELEMENTS (2014)
- **$1.1M** SunShot Incubator (Recurring)
- **$4M** PREDICTS (2013)
- **$2M** SolarMat (2013)
- **$10M** CSP-HIBRED (2013)
- **$27M** National Lab R&D (2012)
- **$10M** SunShot MURI (2012)
- **$56M** CSP SunShot R&D (2012)
- **$0.5M** BRIDGE (2012)
- **$62M** CSP Baseload (2010)
CSP Funding Portfolio

For full research portfolio, visit: energy.gov/eere/solar/concentrating-solar-power
Autonomous, Integrated Heliostat Field & Components – October 20th, 2020
Next Generation Receivers – October 29th, 2020
Unlocking Solar Thermochemical Potential – date tbd
Pumped Thermal Energy Storage Innovations – date tbd
CSP Performance and Reliability Innovations – date tbd

*Timing for some sessions currently being finalized – full details and registration links will be posted here: https://bit.ly/CSP-workshops
Autonomous Integrated Heliostat Field and Components

Workshop Objectives and Agenda

Andru Prescod, Ph.D.
Technical Advisor
Why the focus on Heliostats?
Solar field cost reductions will help the industry achieve 5 Cents per kWh for Baseload CSP in 2030

*Assumes a gross to net conversion factor of 0.9
To help achieve the 2030 cost reduction goal, a suite of strategies and solutions have to be pursued.

**Potential Solutions**

- Improving the supply chain
  - Difficult to impact at both R&D and Pilot scales
- Standardization of materials, tools and components
- Cheaper manufacturing methods and materials
- Autonomous controls and wireless communication
- Optimizing optical performance
Technology agnostic portfolio including next-generation troughs and heliostats

**Drop-C Heliostat**

Low cost heliostat with innovative supporting structure to withstand high wind loads. Coupled to a wireless mesh network and capability for rapid calibration and low pointing errors. Validated to be compatible with surround-type receivers.

**ATLAS Parabolic Trough**

Long continuous array to reduce rotary interconnects. Variable drive spacing to reduce moment accumulation. Lighter, simpler frame design enabled by “low-torque” design condition. Novel large-format mirror design enables frame simplification. Non-trenched alternative systems for drive power and tracking control.

**Simplified Melting and Rotation-joint Technology (SMART) for Molten Salt Troughs**

Improving the cost and reliability of molten salt HTFs at temperatures up to 565°C in parabolic trough solar fields, to accelerate the transition to commercial project development through increased bankability. Critical technical challenges such as the freeze-recovery subsystem, the rotation-expansion piping joints, and the need to re-optimize the solar field design based on recent hardware and market evolution are addressed.
...and novel collector designs, targeting industrial process heating

**Green Parabolic Trough Collector**

Two design elements to achieve very low cost. 1) the use of a special grade of wood as the structural material, and the geometric arrangement of the structural members in a material-efficient typology.

**Low Cost Linear Fresnel Collector**

Linear Fresnel CSP collector system, that focuses mirrors using plastic extrusion structures deployed on a sealed waterbed foundation. The architecture uses light-weight, recyclable, 30-year outdoor plastics instead of traditional CSP systems’ expensive concrete and steel support structures to focus mirrors on a receiver to produce thermal energy.

**Internal Compound Parabolic Concentrator with low-cost heat pipe and vacuum tube with integrated optics**

Flexible (non-tracking) installation, low O&M cost. Provides low-cost, dispatchable heat @ 120 C.
Collector Metrology

**UFACET/NIO for Heliostats**
UAV measurements of slope and canting errors in heliostats. Two approaches, using 1) a target heliostat and 2) the tower to determine errors.

**Direct Observer for Parabolic Troughs (NREL)**
Measures slope and receiver alignment errors in Parabolic troughs.

**Lidar Inspection Tool**
Uses 3D scanning Light Detecting And Ranging (LiDAR) sensors in the automatic/autonomous assessment of the optical errors in large scale CSP heliostat fields. Demonstrated ability to acquire highly accurate point cloud measurements across several Sandia NSTTF heliostats.
And more opportunities exist as we look towards 2030

- Higher system-level efficiencies can be achieved with increased Average Concentration Ratios and Receiver Temperatures
- Additional opportunities include Reduced Collector Field Deployment time, Novel Reflectors and Low cost, accurate drives

Influence of Concentration Ratio and Temperature: Combined Power Cycle and Receiver Efficiency

- Higher system-level efficiencies can be achieved with increased Average Concentration Ratios and Receiver Temperatures
- Additional opportunities include Reduced Collector Field Deployment time, Novel Reflectors and Low cost, accurate drives
Workshop Goals

- Allow interested researchers to engage with SETO and global heliostat experts in an informal panel format to share insights and lessons learned in the most recent heliostat advances and what challenges remain.
  - All statements made by panelists and participants are personal reflections, based on their experiences in the industry.

- Update CSP stakeholders on a subset of DOE’s portfolio of projects and general strategy to achieve the SunShot 2030 goals.

- At the end of this workshop we will spend a few minutes on closing statements. Please direct any additional questions to andru.prescod@ee.doe.gov.
## Workshop Agenda and Meeting Format

**Tuesday, October 20, 2020**

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There will be two 75 minute panels. Each panel will have unique participants and a moderator.

Questions will be solicited from the audience using the Q/A feature in WebEx at the bottom right corner of your screen.

Please type your question there and they will be asked in the order received.
Panelists

Panel #1

Steve Schell  Alberto Fernandez  Kyle Kattke

Panel #2

Hank Price  Javier Lopez

Guangdong Zhu  Gerhard Weinrebe  Yaniv Binyamin  Mark Ayres
## Panel #1

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Will center the discussion around 3 major themes

- **Theme #1: Heliostat Manufacturing and Measurements**
- **Theme #2: Heliostat System Performance**
- **Theme #3: Heliostat R&D Structure and Teaming**
Theme #1: Heliostat Manufacturing and Measurements

- What innovations in automated manufacturing and installation are feasible in the near future to reduce the installed cost of heliostats?

- What efforts are needed, if any, to develop relevant codes and standards for heliostat manufacturing, installation, and performance?

- What innovations are possible to reduce the structural costs of heliostats?

- What advances are necessary for the CSP industry to converge on standard optimized heliostat designs, size, form factors, assembly techniques, and/or sub-component supply chains? What research is necessary to enable that standardization and resolve existing supply chain gaps?
Theme #2: Heliostat System Performance

- What can be done to develop more efficient, automated cleaning methods for heliostats?

- What efforts are necessary, if any, to improve performance models (e.g., higher fidelity, sub-hourly models) and Typical Meteorological Year (TMY) estimates that consider the full range of Direct Normal Incidence (DNI) over a time interval, or other transient environmental conditions?

- The impact of wind loads varies from site to site, on account of different terrains and field layouts and heliostat design. What is the potential impact (on performance and installed cost) of better understanding how wind loading varies based on local conditions throughout the field?

- What is the minimum scale required of a heliostat field in a test campaign to successfully de-risk innovations in closed-loop control and wireless communication? Please specify in terms of number of heliostats, facet area, land area, testing time, or any other relevant metric that should be considered. Additionally, what other research efforts are required to de-risk innovations in closed-loop control, autonomous controls, and wireless communication?
Theme #3: Heliostat R&D Structure and Teaming

- What are the advantages and disadvantages of SETO support for heliostat R&D to take place through conventional single-organization/PI, limited-scope research projects versus a dedicated US-based center of excellence?

- What innovations have been developed in adjacent research communities (e.g., robotics and controls) that should be incorporated into heliostat research initiatives?

- What key research infrastructure, in terms of research equipment, personnel, and testing capability, is necessary to be developed for the US to be a global leader in the acceleration and development of next-generation heliostat technology?
Will center the discussion around 3 major themes

- **Theme #1: Heliostat Techno-economic Analysis**
- **Theme #2: Field Deployment/Plant Operation**
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Theme #1: Heliostat Techno-economic Analysis

- What can be done to help foster information sharing and key learnings throughout the industry to help reduce costs and increase collector performance?

- What specific testing campaigns are needed to validate extrapolations from experimental heliostat designs and components to accurate estimates of commercial installed costs?

- What advances are necessary for the CSP industry to converge on standard optimized heliostat designs, size, form factors, assembly techniques, and/or sub-component supply chains? What research is necessary to enable that standardization and resolve existing supply chain gaps?
Theme #2: Field Deployment/Plant Operation

- What innovations in field installation and commissioning of heliostat fields can be developed to reduce plant construction schedules?

- What, if any, research is needed to develop either solutions or guidelines for pile driving, foundation pouring, or other civil engineering processes for different geographical field conditions (e.g., soil types, etc.)?

- High concentration ratios require high pointing accuracy. What efforts are needed to reduce canting and tracking errors in heliostats to achieve less than 1% spillage and/or optimize integrated control of the solar field and receiver sub-systems to maintain an optimum flux profile?
Theme #3: Heliostat R&D Structure and Teaming

- What are the advantages and disadvantages of SETO support for heliostat R&D to take place through conventional single-organization/PI, limited-scope research projects versus a dedicated US-based center of excellence?

- What innovations have been developed in adjacent research communities (e.g., robotics and controls) that should be incorporated into heliostat research initiatives?

- What key research infrastructure, in terms of research equipment, personnel, and testing capability, is necessary to be developed for the US to be a global leader in the acceleration and development of next-generation heliostat technology?
## Closing Statements

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Thank you for attending!

- Please direct any questions to [andru.prescod@ee.doe.gov](mailto:andru.prescod@ee.doe.gov)
- And remember to register for the other upcoming CSP workshops in the series
- Next Generation Receivers Workshop is scheduled for October 29th 2020.
Sources of optical error

A high-performance heliostat field must address each of these error sources

- **Mirror Shape Error**: Deviations from ideal shape reflect rays in wrong direction, defocusing the beam.
- **Tracking Error**: Imperfect tracking places beam in incorrect position at the receiver.
- **Canting Error**: Misalignment between mirror facets enlarges and defocuses the beam.
- **Off-Axis Aberrations**: “Ideal” shape of mirror depends on sun position; at other orientations the beam is distorted.

Steve Schell
CTO & Chief Engineer
steve@heliogen.com
Time to think outside the box

Computer vision based closed-loop tracking: System for Observing Heliostat Orientations while Tracking (SOHOT)

Design for high-volume (auto, consumer electronics) manufacturing processes

Field layout optimized for installation, cleaning, and maintenance

Small heliostats are more expensive?

From Jones et. al. 2007 “Heliostat Cost Reduction Study”
Metrology and Standards

- A Typical product development cycle

- Metrology and standards are largely missing for heliostats in CSP
  - Over 10,000 heliostats in a field
  - Optical precision ~ 2 mrad
    - An additional 2 mrad may result into 20% energy reduction
What Are We Missing?
- Resource characterization
  - Solar irradiation
  - Weather conditions (operational/survival)
- Definition of optical errors
  - Specular reflectance (soiling characterization)
  - Slope error (Distribution, RMS, one-dimensional, two-dimensional...)
  - Tracking error
  - Pointing error
  - Canting error
- Measurement of optical errors
- Durability
  - Material
  - Structural
- Then, how to best
  - Assess performance
  - Operate a solar field
  - Design new products

How Do We Fill this Gap?
- First all, do we all (most of us) agree its importance?
- Whose responsibility?
  - Research institutes?
  - Industry?
  - Professional society?
- Who should lead the effort?
- What approach?
  - Research
  - Guideline development
  - Review
  - Standards (National and international)
- Where is the support?
- Priority?
- How to apply them to the existing industry?
- How to use them to increase future competitiveness of heliostat or CSP technologies?
Heliostat Drives

State-of-the-Art

- Medium scale heliostats (>20m²): slewing drive + linear actuators
- Large scale heliostats (>120m²): hydraulic drives

Challenges

- Dynamic load governed by highest tracking wind speed
  - Leads to low utilization because majority of drive lifetime sees low, nominal wind speeds/loads
  - Defining a lifetime load profile/histogram is challenging. Function of site wind speed and direction and heliostat location in field
- Qualifying performance/reliability over 30-year lifetime
  - Heliostat performance is highly sensitive to drive wear overtime
  - Accelerated lifetime testing needed which subjects the drive to the wear mechanisms present in real environment
  - Heliostat performance over time in existing fields is not public knowledge

Opportunities

- Closed-loop control will enable less stiff and less precise drives
- Gearboxes are sized by fatigue life, and it is common to use a constant design load. A better approach is to use the heliostat’s histogram of drive loads to size components.
- Develop standards for heliostat drive testing
Heliostat Field Control

State-of-the-Art

- Local heliostat control: custom integrated controllers and PLC based controllers
- Field communication: wireless and wired communication
  - Largest network: Brightsource Ashalim Plot B - 50,600 wireless heliostats

Challenges

- Achieving low cost heliostat field control is primarily a challenge for small scale heliostats
- Requires using custom integrated controller
  - High up-front engineering cost, typically specific to heliostat design
- Wireless field communication needed to keep costs low
  - Commercial deployments are typically first-of-a-kind in terms of network scale
  - Wireless performance is a function of environment which necessitates a solar field with intended heliostat for testing
  - Must guard against wireless signal jamming and interception by potential attacks

Opportunities

- Mixing wired and wireless communication solutions in the field
- Existing solar fields could be used to test wireless field communication
Advanced Heliostat Design / Manufacturing
Autonomous Integrated Heliostat Field and Components Workshop

Gerhard Weinrebe
DoE, online, October 20th 2020
Advanced Heliostat Design

Heliostat Geometry
- Shapes and strength of materials
- Drives (stiffness, accuracy, costs)
- Control

FEM Analysis
- Deformation
- Stability

Optical Performance and Solar Field Layout

Techno-Economic Evaluation

Cost Model: Manufacturing (Localization!), Logistics, Assembly & Erection, O&M,...

Optimization
Clever Structure & Clever Controls

Higher Structural Stiffness | Shorter Load Path | Less Deformation

Stiffer Structure
Advanced heliostat design & manufacturing

ABENGOA

Power

October 2020
Índice

1 - Abengoa Heliostats Evolution
2 - Advanced Heliostat design & manufacturing
Abengoa Heliostat Evolution

Heliostat design evolution:

- Solucar 120 in PS10-20
- ASUP140 V1 in Khi solar one
- ASUP140 V3 in atacama
- ASUP140 V5
- ASUP140 V2.6

Next generation:

- Improving in facet design
- High precisión drives
- Improved sensor capabilities
- Autonomous heliostat
- Medium range Heliostat design

Heliostat Capex evolution in Abengoa plants & offers
Advanced Heliostat design & manufacturing

Design & calculations
- Wind tunnel tests
- CFD calculations (X-flow +Fluent)
- Local wind velocities assessments
- FEM & structural models (static+dynamic)
- 3D mechanical models & contact models
- Workshop drawings

Optical Assessment
- Deviation optical shape
- Fotogrametry measurements
- Deflectometry measurements
- Tracking & aiming test
- Thermal evaluation
- Final optical validation
- Calibration alternative methods

Prototyping & Manufacturing process
- Prototypes station (solar complex)
- Structural tests in Eucomsa platform
- Motion validation
- Lean Manufacturing process
- Manufacturing process validation
- Jigs & tools definition & validation
Tonopah Solar
Field Deployment/ Plant Operation
Assessment after Construction and Initial Installation.

- We decided to concentrate on improving tracking and made many improvements to our Automated Beam Characterization System.
An Integrated Heliostat Field / Receiver Thermo-fluid Model, **FLUXCALC**, is run every 30 seconds in **Real-Time Mode** to integrate a Heliostat Field Ray Trace Flux calculation with the Receiver IR, Backwall Thermocouple and Flow Measurements.

**FLUXCALC** also runs in a **Dispatch Mode** every 2 minutes to determine Heliostat Aimpoints that maximize MWt output while respecting Receiver Tube Strain, Tube Innerwall Temperature and Heat-Shield Flux Limits.

**FLUXCALC** uses a Conjugate Gradient algorithm to find the Heliostat Aimpoint Dispatch. The following chart shows the convergence of the Heliostat Aimpoint Solution with the constraints:

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<th>Iteration</th>
<th>Time/Date</th>
<th>Output (MW)</th>
<th>Strain (%)</th>
<th>Tiw (°F)</th>
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Autonomous Integrated Heliostat Field and Components: Field deployment and Techno-economics

SETO CSP R&D Virtual Workshop Series
20/10/2020

Javier López Sanz
Technical Innovation Responsible
jalopezsa1@acciona.com
BATTERY LIMITS AND LESSONS LEARNED

Correlations
- Autonomous heliostats → Medium-Small heliostats due to autonomy limitations
- Small heliostat → Higher number of foundations
  + Higher number of foundations + Autonomous Control System → Global minor civil works costs
  + Small heliostats → Higher optical quality → minimize slope error → minimize the solar field size under isoproduction
  + Small heliostats → minimize tracking error under wind loads → minimize the solar field size under isoproduction
  + High optical quality + specific aiming strategy → Spillage losses reduction
  + Smaller optimized solar field size → Minor total reflective surface + Higher optical quality

HIGHER OPTICAL EFFICIENCY OF THE SOLAR FIELD.....BUT....WHAT ABOUT THE COSTS AND ROBUSTNESS OF THE SOLUTION?

From manufacturing to installation
- From detailed design to prototype manufacturing
- From prototype to certification
- From certification to industrial serial process
- From industrial serial process to supply chain management
- From supply chain to solar field assembly
- From foundations to piling process -- dependence on geotechnical conditions

Solar Field Optimization
- Solar field layout optimization
- Aiming strategy optimization

Techno-economics
- From negotiation to serial contract: including manufacturing and logistics
- From single assembly to mass production and installation
- From theoretical operation to robustness and communication security

PHOTOOn

ATH146
KEY CONCEPTS
- Assembled Heliostat cost = 100 €/m²
- Bi-facet heliostat of 14.4 m² → 7.2 m² per facet which is the largest facet of the world with spherical curvature
- Glass to Glass Sandwich panel facet design
- Auto-calibration System: one facet with solar sensor, being the facet master
- PV module external to the facet for autonomous purposes
- Minor civil works due to pilling process standardized in the PV-2V technology
- Accurate calibration among pilling due to Smart Dynamic Tracking Algorithm and Auto-calibration System

BENEFITS BEYOND STATE-OF-THE-ART
- Optimized cost in mass production due to design, logistics and assembly cost balancing
- Glass-to-glass sandwich panel facet → reduce canting operations and guarantee slope error of facets by manufacturing
- Glass to Glass Sandwich panel facet → reduce slope error by temperature dependence during operation
- Auto-calibration System + Dynamic Tracking algorithm → Minor tracking error and quick calibration of solar field
- Optimized aiming strategy to reduce cosine factor losses → Heliostat reallocation and asymmetrical lay-outs
- Optimized Solar Field → Minor total reflective surface → Minor maintenance and cleaning cost (10% OPEX REDUCTION)
- Civil works cost due to Pilling process → 25% SOLAR FIELD CAPEX reduction in the worst geotechnical conditions
- EPC cost reduction correlated to financial, contingency and margin costs → 15% OTHER COSTS REDUCTION

HIGHER OPTICAL EFFICIENCY OF THE SOLAR FIELD + MINOR CAPEX & OPEX = 15% LCOE REDUCTION

OPTICAL QUALITY COMPARISON

<table>
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<tr>
<th>Parameter</th>
<th>Units</th>
<th>Big Heliostat 140-160 m²</th>
<th>Big Heliostat 40-60 m²</th>
<th>ATH 146 146 m²</th>
<th>PHOTOn Heliostat 14.4 m²</th>
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<td>1.6</td>
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100 MW Reference Plant
1.099.936 m² State-of-the-art
938.880 m² PHOTOOn Solar Field

Javier López Sanz - Technical Innovation Responsible jalopezsa1@acciona.com
Heliostat Best Practices

Heliostat Qualification
• Need for design standards (optics, structural, testing, control)
• The optical, assembly, and installation characteristics of a prototype heliostat must be fully verified prior to commercial acceptance.
• The number of prototypes must be large enough to demonstrate an acceptable fabrication process and repeatable optical characteristics. The number of prototypes will depend on the type, size, complexity of the heliostat, and previous experience with similar designs.

Heliostat Optics
• The optical efficiency of a heliostat field can be more difficult to maintain than originally expected.
  • Consider loss of optical accuracy as heliostats are moved from the fabrication shop to be installed in the field.
  • Once a heliostat is installed, recanting the mirror modules is a difficult task.
• Consider defocusing of mirror optics due to differences in the coefficients of thermal expansion for the glass mirror and the metal/composite structure supporting the glass mirror.
• Some level of beam blocking is an expected part of an optimized heliostat-field layout and typically reduces receiver energy collection by a few percent. Heating of the back of the mirror modules is inevitable due to blocking effects. Evidence now suggests that this few percent could be doubled due to the combined blocking/defocus effect.
• Aimpoint Verification: every few weeks the aiming accuracy of each heliostat should be checked.

Heliostat Availability
• Electrical system: grounding, harmonics, low voltage levels, lightening protection
• Position encoders: for proper operation, the head clearance must be checked and adjusted periodically, and the optical devices must be kept clean.
• Drives: lifetime and reliability is critical.
• Communications: reliability of communication.
Heliostat Best Practices

Heliostat Control Software

- Integration between the receiver system and heliostat field is essential. Often proprietary software is used.
  - Need validated heliostat control software.
  - Need to consider obsolescent of hardware and software. Consider technical support during O&M.

Heliostat Cleaning

- Heliostats need to be able to be rapidly cleaned. This should be considered and tested on prototypes.
  - Cleaning equipment needs to consider uneven surface and impact of wet soil conditions.
- Develop an optimum washing strategy, a detailed knowledge of the field reflectivity is required.
  - Heliostats closest to the tower should be given the highest priority due to smaller beam size and reduced spillage.
  - Consider frost and dew. To minimize frost accumulation, a vertical stow can be used during winter nights when wind conditions do not require horizontal stow.
  - Need to have a plan to address rapid soiling events (reflectivity drops 10-40%).

General CSP Best Practices

- Need for improved knowledge of technology by developers/owners, EPCs, O&M contractors
- Improved project owner technical specification/EPC contracts
- Improved modeling (finer time increments, improved solar resource assessment)
- Avian safety: manage high flux zones.
- Commissioning of heliostat field: safety of construction crews, power and communications.

Contact info: Hank.Price@solardynllc.com