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

Technical Gap Analysis of Heliostat Components & Controls

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Components & Controls (C&C) Definition/Scope

Scope Definitions:

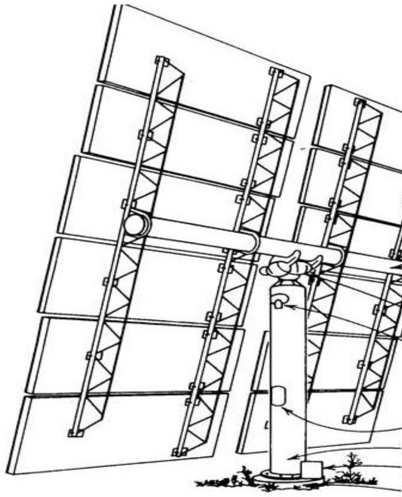
- **High Accuracy:** Pointing accuracy with errors <mrad tolerance & accuracy over varying temperatures. Required calibration procedures may be replaced by precision/repeatability requirements.
- **Optimized Pointing:** Robust mechanical rigidity against variable wind loads, with minimized backlash
  - Large heliostat size under wind load creates minimum requirements for stiffness and strength.
- **Environmental Reliability:** These include ubiquitous blowing sand, high temperature, large daily temperature changes, and occasional moisture.
- **Optimized Service Life:** Components must maintain high accuracy & reliability for 30 yrs.
  - If heliostat adjusts its position every 10 s while tracking, this amounts to over 47 million incremental motions. This far exceeds the service life of other low-cost mechanical systems with less-stringent performance requirements.
- **Low cost:** Achieve DOE SunShot cost target, components must be of rel. low cost (e.g. drive must meet the above requirements at a cost of $17/m^2, a reduction from the current state of the art by almost a factor of two).

Objectives:

- **Determine Priority** of C&C's for HelioCon to Support CSP Bankability.
- **Considered Areas of R&D**
  - **Components**
    - Testing protocols and sites for drives and controls launched
    - Cataloging actuator/drive types versus heliostat size
    - Identifying optimum drives for varying load conditions
    - Quantifying cost reductions for optimum heliostat sizes/loads
    - Develop approaches and test beds for characterizing components/subsystems, & new tools for C&C characterization
    - Develop & benchmark existing measurement tools.
  - **Controls**
    - State-of-the-art control techniques and gaps
    - Characterization for controls and communication performance & reliability limitations that impact costs.
    - Wireless Control
    - Wiring and controls reliability, flexibility and Power/Communication signal degradation identification
  - **Publish** standard operating procedures, guidelines and publications.

Task 6 C&C Team:

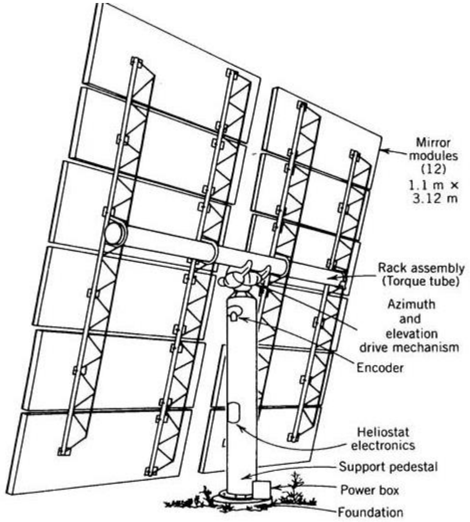
- Sandia: Ken and Rebecca
- NREL: Matt Muller
- ASTRI: Mike Collins (CSIRO), Matt Emes & Maziar Arjomandi (Univ. Adelaide)



Components State of the Art

Mirrors

- Conventional design for reflective area metallic structural support, an adhesive layer, a protective copper layer, a layer of reflective silver, and a top protective layer of thick glass.
- Standard 3-5° canting employed for individual concentrated focusing
- Reliability challenges exist with temperature, corrosion, soiling and abrasion (hail).
- Wind loading or cyclical heat can facilitate flexing and warpage over time.
- 3-4 mm thick, though interest for 1 mm to reduce costs



Torque Tubes

- Torque tubes provide an axis for control of elevation angle.
- Reliability can be compromised in the presence of high weight loads or wind speeds
- Optimization studies in wind found small heliostats in low wind speed require small diameter torque tubes with thick walls.
- As wind speed increase required diameter increases and wall thickness can stay constant or decrease slightly.
- Torque tubes can also be used to create ganged heliostat systems where facet rows share a single torque tube.

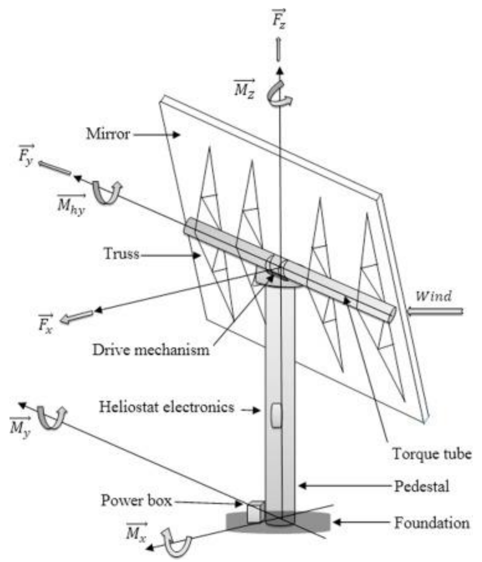
Components State of the Art

Pedestals

- Conventional pedestals are cylindrical tubes for control of the azimuth angle.
- Pedestals can face reliability challenges from non-uniform pressure distributions that occur in turbulent atmospheres.
- Reliability can be improved by counteracting maximum bending moments at base of pedestal with properly designed anchor foundations.
  - Some installations add further depth to allow plants to grow at base for reducing erosion
- Optimization studies show reliability can also be increased with larger pedestal diameter, though the gain is small. Increasing wall thickness has a larger impact on reliability.

Truss System

- Truss systems can vary greatly, but typical design use vertical truss systems centered about horizontal torque tube.
- At least four vertical truss systems typically used to support heliostat facets.
- Truss systems are typically mirrored about horizontal torque tube.
- Reliability in wind can be improved by increasing cross-sectional area of truss components



Components State of the Art

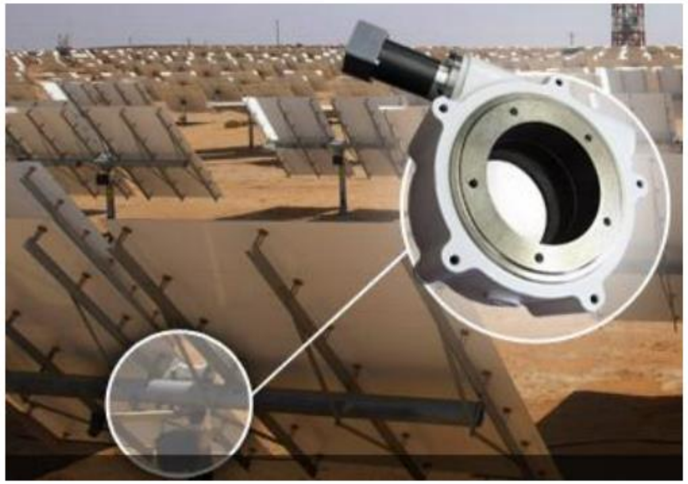
Drives

- Heliostats (>20m^2): Slewing Drive + Linear Actuators
  - Rotary electromagnetic motors
- Heliostats (>120m^2): hydraulic drives
  - Drives contain seals, gaskets and hydraulic fluid, which can have fouling issues that impact performance.
- CFD studies show pedestal mounted drive systems may be at risk from damage in high turbulence conditions.
  - Turbulence can introduce high bending moments at pedestal base and hinge supports.
- Alternate drive systems (e.g. slope or cables) may be cheaper than pedestal mounted drives.
  - Rim drives with cables may also cheaper solutions.
- Optimization studies have found that linear slope drives can provide lower tracking error & costs than slew drives
  - Linear slope drives often have lowest LCOE.

Components State of the Art

Drives Continued

- Azimuth drives using worm/slew gear systems for power transmission are one of the most expensive components in a serial heliostat.
- Jackscrew actuated by a DC-motor is commonly seen in small sized heliostats, as well as for elevation drives on larger heliostats.
  - Jackscrew is often much more feasible than worm gears, due to its lower cost and robustness.
  - Jackscrew consists of an ACME-thread screw, actuated by an integrated DC-motor. Piston lengths of jackscrews designed for solar applications and commonly available are about 500-1200 mm



Azimuth drive with worm-gear – a typical standard solution.
Source: (Conedrive, 2013)

Left: Jackscrew for solar applications, stainless steel, sold for 235 €
Source: (SatControl, 2013)
Right: Serial heliostat actuated by two jack-screws
Source: (SatControl, 2013)

Heliostat Controls

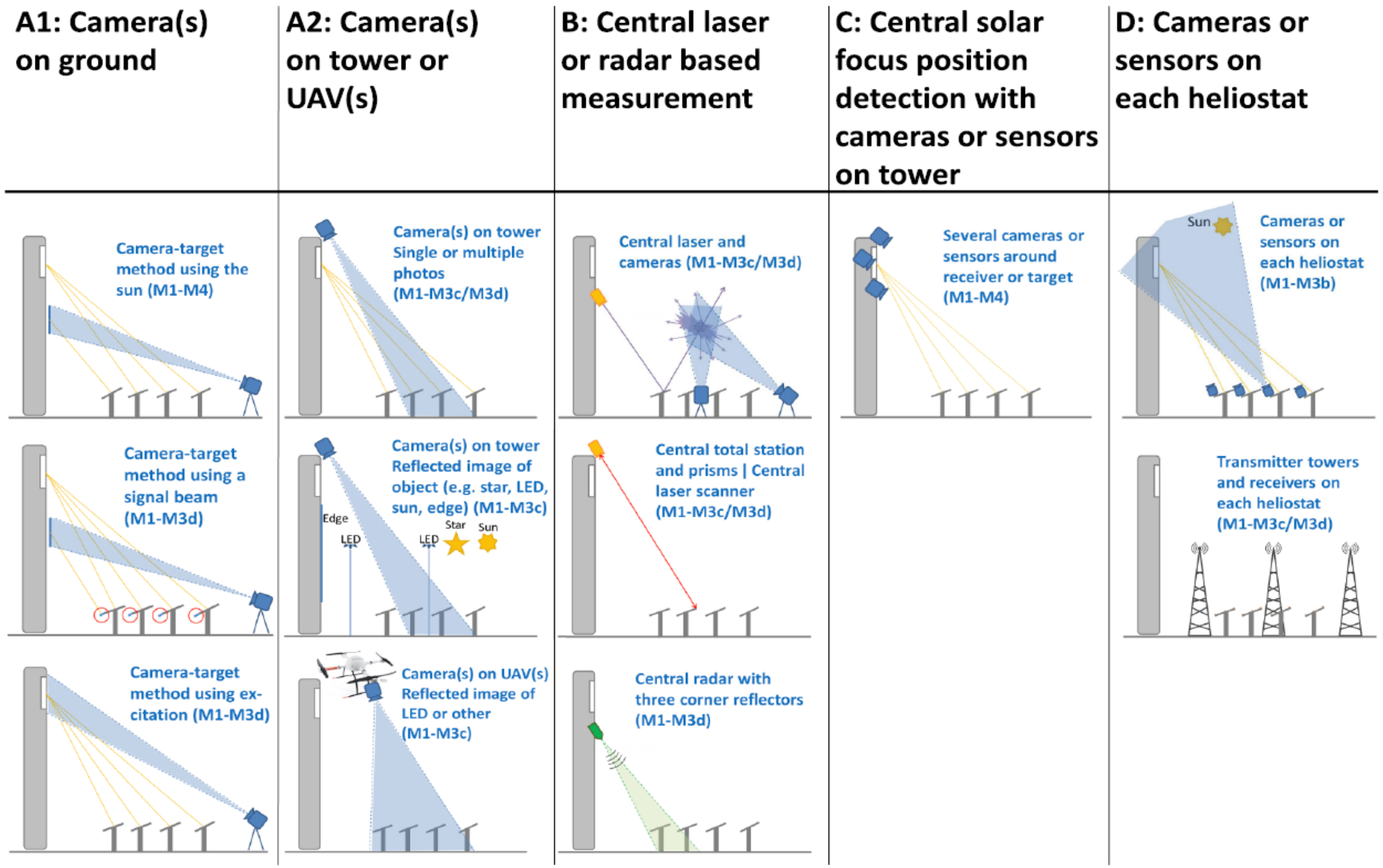
- The operational modes:
  - **Wake-up mode:** Heliostat moves from a stow position to a sun-tracking position
  - **Maintenance mode:** Heliostat is available for manual operation and mechanical and electronic maintenance
  - **Stow mode:** Heliostat is in a storm-protection position
  - **Tracking mode:** Heliostat tracks the sun
  - **Calibration mode:** Heliostat error vector is able to be auto calibrated.

- Movement by two-axis motorized system, controlled by computer.
  - Computer is given latitude/longitude of heliostat's position and time/date. Using astronomical theory, controller calculates sun direction (e.g. its compass bearing and angle of elevation).
  - Given direction of receiver, computer calculates direction of required angle-bisector, & sends control signals to motors.
  - Sequence of operations is repeated frequently & with high resolution to keep the mirror properly oriented.
  - Traditionally, primary rotational axis is vertical and secondary is horizontal.

- Drives or linear actuators facilitate movement and contain seals, gaskets and hydraulic fluid.
  - Drives & Encoders/Computer include gaskets and seals to keep moisture out but has wear and humidity intrusion over time.

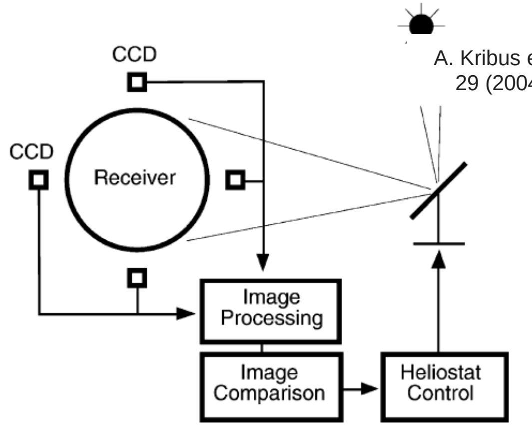
Closed Loop Controls

- Open-loop central computer control utilizes little information concerning heliostat's azimuth/elevation within an algorithm for tracking.
- Closed-loop control allows operator to know exact location & diagnostics for each individual heliostat vs. entire array.

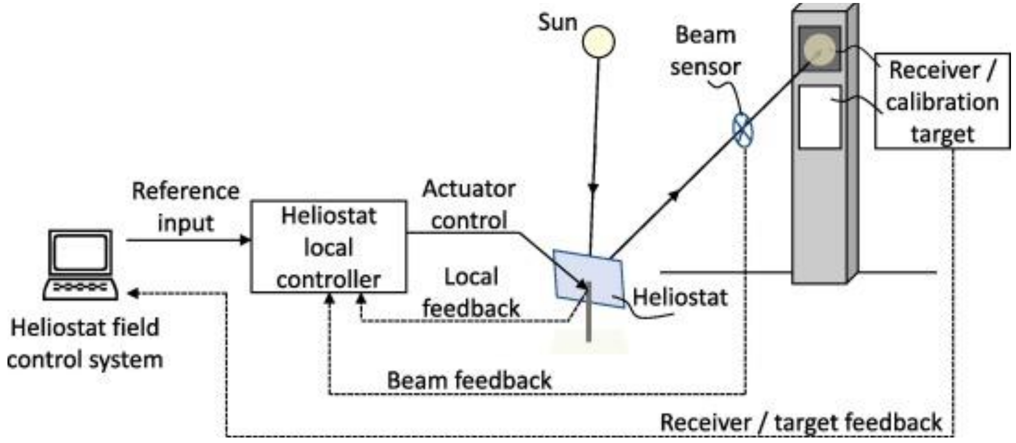


J. C. Sattler *et al.*, "Review of heliostat calibration and tracking control methods," *Sol. Energy*, vol. 207, pp. 110–132, Sep. 2020

A. Kribus et al., Energy 29 (2004) 905-913



The heliostat control loop is closed by acquisition of four images around the receiver aperture, and generating a control signal by image processing.



Pearson, J. and Chen, B., An Assessment of Heliostat Control System Methods, *SERI/SP-253-2390, DE86004416*

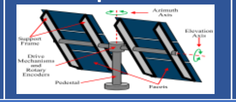
C&C Stakeholder Engagement & Surveys

- C&C survey analysis that identifies those with highest opportunities for development & cost reduction.
  - Coordination with Task 8 TEA for financial gaps
- Further meetings with leading CSP and C&C developers and key POCs pertaining to standards needed for confident project development in U.S.
- Screening the design and evaluation standards with baseline criteria
  - Critical standards for RD community to communicate
- For all critical C&C components and testbeds
  - Identify the lead for a given expertise and testbeds
    - Scope of work (SOW) estimate
    - Assemble working group and assign thrust leads
    - Submit a work timeline
- Coordination with other other tasks as necessary.
- **<u>Interest in more participants!</u>**

C&C Survey Highlights

Topic Area	Field standard	Research Focus	Gaps
Drives	• Azimuth worm drive • Horizontal axis linear actuation • Hydraulic actuation for large heliostats	• Rim drives for azimuth tracking • Alternate actuation (e.g. cable, ballast)	• Pragmatic wind load specification • Drive type variety
Mirrors/facets	• Second surface glass mirror • Adhesive-and-turnbuckle mounts to structure	• Sandwich panels • Glass-free reflectors • Anti-soiling coatings	• Reliable, high-performance coatings • Low-cost, high-reflectivity mirrors • Environment-tailored reflector technology • Heliostat-specific durability standard
Structures	• Pedestal-type with pylon and torque tube • Triangulated facet backing • Steel construction	• Composite structure • Non-pedestal geometry • Ganged micro-heliostats	• Low- or no-steel structures • Pragmatic definition of location-specific wind loads
Communication	• Wired: fiber-optic • Wireless: radio control with field repeaters	• Low-power wide-area networks (LPWAN) • Network security	• Flexible communications infrastructure • Standardized requirements and testing
Power	• Wired: buried copper • Wireless: heliostat-mounted PV	• DNI measurement via PV • Long-term reliability	• Cabling reduction • Energy storage system longevity
Closed-loop control	• Open-loop sun tracking • Closed-loop pointing calibration • Closed-loop field control	• Low-downtime calibration methods • Field beam characterization	• Broad field acceptance • Consistent <1mrad total error
System integration	• Vendor- and EPC-specified qualification testing	• IEC CSP standards • Robust beam quality and tracking error quantification	• Heliostat-specific design qualification standard • Global performance standards • O&M and design cost coupling • Definition of acceptable and accepted degradation and aging

Roadmap Study – Initial List of Gaps:

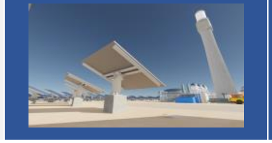
Heliostat Development Cycle	Conceptual Design:	Heliostats Components:	An Integrated Heliostat:	Mass Production of Heliostats:	A Heliostat Field:
					

No.	Gaps	a	b	c	d	e
	Heliostat-Centric Structure					
C1	Composites or other advanced structures (e.g., torque tubes, pedestals, foundation) are necessary for hitting cost targets • Material selection for rigidity, wind load, and weight reduction	X	X	X	X	
	Drives Performance					
C2	Alternatives are needed to drive design being driven by worse case wind loads as this is a significant boundary to cost reduction	X	X	X		
C3	Alternate drives for cost reduction have not been fully explored	X		X	X	X
	Performance and reliability of coatings and materials for heliostat mirrors					
C4	Coatings for mirrors are needed to improve performance and reliability	X	X	X	X	X
C5	Lower cost mirror materials are needed with comparable performance	X				
C6	Mirror quality should be adaptable to environmental conditions but there is no standards or guidance on how to do this	X	X			X
	Controls					
C7	Flexible communication and controls interconnections are needed			X		X
C8	Growing Wireless systems approaches could introduce significant technical issues, standardized requirements and testing capabilities need to be created	X	X	X	X	X
C9	Closed loop must be more broadly applied to achieve: • Automated calibration and reduce commissioning time • Cost Reduction • Reduce drive requirements • Improve performance to achieve field error less than 1mrad	X	X	X	X	X
	Standards					
C10	Need design qualification standards for heliostats to build confidence in C&C's and subcomponents	X	X	X		
C11	Need performance standards for heliostats			X		X
C12	Need for CSP-Centric durability standards for the glass and mirror		X			
	Safety, Resiliency & Security					
C13	Heliostats are automatic mechanisms which can exert dangerous forces and create fire hazards			X		X
C14	Safety is especially important for wireless systems. Redundancies within the controls will be critical especially for SCRAM operations			X		X
C15	Concerns over Cybersecurity attacks on a heliostat field could create a variety of high consequence events					X
	Cross cutting C&C					
C16	Design and O&M are not well coupled (especially problematic with drives/mirrors)	X	X	X	X	X
C17	Reliability/degradation/ aging is not well defined yet this can impact pointing accuracies and system performance over time (especially problematic with drives/mirrors)	X	X	X	X	X

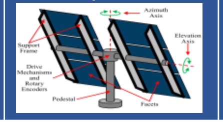
C&C Gaps Down-Selection

Heliostat Development Cycle

Conceptual Design:



Heliostats Components:



An Integrated Heliostat:

Mass Production of Heliostats:

A Heliostat Field:

Heliostat Development Cycle	Conceptual Design	Components	Integrated Heliostat	Deployed Field
Tier 1 (Most important)	C5: Lower cost mirror designs are needed with comparable performance to existing glass mirrors.	C1: Composites or other advanced structures (e.g., torque tubes, pedestals, foundation) are necessary for hitting cost targets.	C8: Wireless systems approaches must be broadly introduced to capitalize on lower plant cost while wireless risks and technical issues must be avoided. Standardized requirements & testing capabilities are needed.	C9: Closed loop control must be more broadly applied to achieve higher flux performance and auto alignment/calibration processes. C10: Need design qualification standards for heliostats to enable bankable C&C’s, heliostat long term performance, and shorten design improvement cycles.
Tier 2	C2: Alternatives are needed to impact design being driven by worse case wind loads as this is a significant boundary to cost reduction.	C4: Coatings for mirrors needed to improve performance & reliability. C3: Alternate drives for cost reduction have not been fully explored. C16: Design and O&M are not well coupled (especially problematic with drives/mirrors).		C6: Mirror quality should be adaptable to environmental conditions but there are no standards for this. C11: Need performance standards for heliostats. C12: Need for CSP-Centric durability standards for the glass and mirror. C17: Reliability/degradation/ not well defined yet. can impact pointing accuracies and system performance over time.
Tier 3 (least important)			C7: Flexible wired communication & controls interconnections needed. C14: Safety is especially important for wireless systems. Redundancies	C13: Heliostats are automatic mechanisms which can exert dangerous forces and create fire hazards. C15: Concerns over Cybersecurity attacks

C&C Gaps Impacts – Tier 1 Gaps (Priorities)

Gaps	If Not Addressed	Impact
C1: Composites or other advanced structures (e.g., torque tubes, pedestals, foundation) are necessary for hitting cost targets.	Steel structures will remain at \$20-30/m^2 and with each project being at risk due to fluctuations in steel market prices, for example a 200% increase in 2021.	Structural materials will be reduced by 50% to \$10/m^2 and LCOH reduction by 3.0%
C5: Lower cost mirror designs are needed with comparable performance to existing glass mirrors.	Continued high heliostat costs since mirror and mirror supports costs comprise ~\$24/m^2 burden on a CSP plant.	Mirror facet costs will be reduced by 50% to ~\$12/m^2 to enable plant developers to get closer to \$50/m^2 goal. LCOH reduction by 3.6%.
C8: Wireless systems approaches must be broadly introduced to capitalize on lower plant cost while wireless risks and technical issues must be avoided. Standardized requirements & testing capabilities are needed.	Uncertainty with signal transmission and quality within the heliostat technology space can lead to operational and contingency issues that reduce availability by up to 5% absolute. If wireless systems are not installed 85% wire reduction will not be achieved.	Reliable wireless control will reduce heliostat field costs and commissioning time. This could allow provide a 5% absolute improvement in field availability. LCOH reduction by 4.2%
C9: Closed loop control must be more broadly applied to achieve higher flux performance and auto alignment/calibration processes.	Plant installation times will remain excessively long compared to PV and other renewable projects and fewer projects will be achieved. Drive costs reduction of 10% will not be achieved. Field performance will not improve by 10%. O&M costs will not achieve a 25% reductions. Availability will not achieve a 5% reduction.	Closed loop controls reduce installation time and cost, enhance performance, and increased uptime. calibration time. Overall, this could provide a 25% reduction in OM cost, 5% improvement in availability, 10% reduction in drive cost (\$2.8/m2), improvement in field performance as ran in SAM per a degradation of total error from 4.3 to 6 mrad over 20 years. The sum of the cross reaching benefits of closed loop control & LCOH reduction by 11.1%
C10: Need design qualification standards for heliostats to enable bankable C&C's, heliostat long term performance, and shorten design improvement cycles.	Advanced heliostat designs will not be rapidly accepted by project developers. Cost reduction in heliostats will be slow and per the current trends \$75/m^2 will be achieved rather than \$50/m^2.	Heliostat-centric standards would provide better guidance on how to compare tradeoffs between alternate components, structures, and size of heliostat within a system wide performance perspective. Standards are also a must have for the industry to continue to install projects and grow. Accepted standards will reduce heliostat cost by approximately \$50/m^2, & enable LCOH reduction by 15%.

Heliostat Advanced Components & Closed Loop Controls Test Bed

- Objective: Advanced Comms and Controls R&D to capitalize on lower plant cost while improving perf. and reliability for addressing wireless risks and technical issues.
- Deliverable: Upgraded heliostat field controls test bed system, with flexible power and communication (e.g. signal attenuation) capabilities, which meet commercial functional requirements (e.g. BrightSource, Heliogen and Solar Dynamics systems).
  - In Collaboration with Wind evaluation (M. Emes {ASTR} & S. Yellapantula {NREL}) & Metrology evaluation (G. Zhu {NREL} & R. Brost {Sandia})
- Milestone(s):
  - FY23: Review of existing closed-loop control and wireless control architectures, interference issues, flexibility issues, cyber security challenges. Interview stakeholders on needs and priorities that use wireless technologies and closed loop controls. Develop designs for at least 1 operational test bed.
  - FY24: Completion of at least one flexible components and closed loop controls heliostat test bed. Will include convolved optical and mechanical error characterization. Identify heliostat cyber security/safety challenges with respect to communication protocols.
  - FY25: Validation of the test bed (See PMP Metrics for Details).
  - FY26: Open a Components & Closed-Loop Controls system testbed for industry/collaborators technical validations/evaluations
- **Need for Collaborators & RFP Applicants!**

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Thank you.

Back-Up Slides

C&C Survey Questions

- What are the top reasons for heliostat downtime in the operational phase of CSP plants?
- What are the most expensive repairs (including labor hours) for heliostat operation & maintenance?
- What are the most unreliable components for heliostats (including controller components)?
- What are the most significant challenges in maintaining heliostat performance, including desired targeting alignment?
- Have you had significant issues with soiling and cleaning of heliostat mirrors? If so, please describe the issues and the cleaning methods used.
- Do you see a direct need for codes or standards to improving commissioning or operations of CSP plants?
  - If yes, what specific areas require codes or standards?
- Is heliostat resiliency and security a concern?
- Please describe any other problems or concerns with heliostats that were not covered in previous responses.
- With respect to the cost, reliability, and operability of heliostat components (and their control systems), what are the most important areas of development?