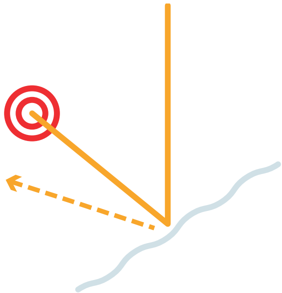
Sources of optical error

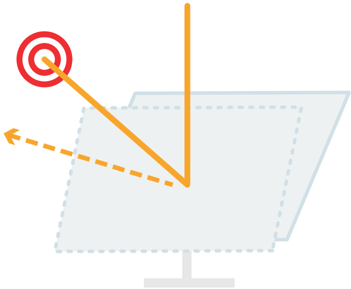
Steve Schell
CTO & Chief Engineer

steve@heliogen.com

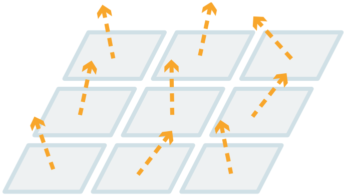
A high-performance heliostat field must address each of these error sources



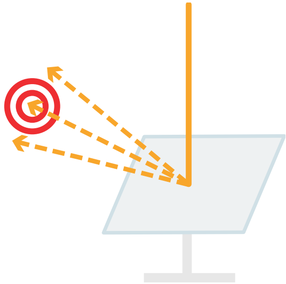
Mirror Shape Error
Deviations from ideal shape reflect rays in wrong direction, defocusing the beam



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

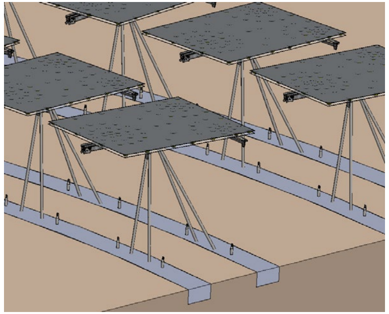
REPLACING FUELS WITH SUNLIGHT
Heliogen

Time to think outside the box

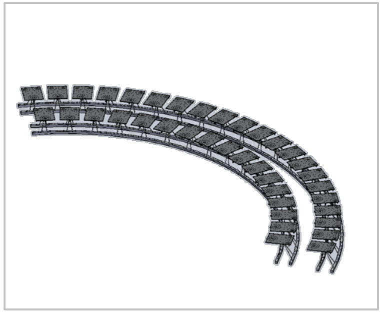
Steve Schell
CTO & Chief Engineer

steve@heliogen.com

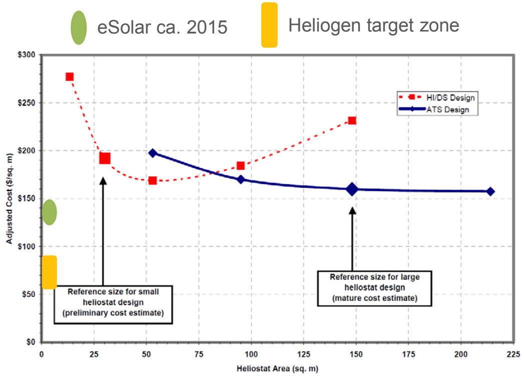
Computer vision based closed-loop tracking: System for Observing Heliostat Orientations while Tracking (SOHOT)



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



Field layout optimized for installation, cleaning, and maintenance

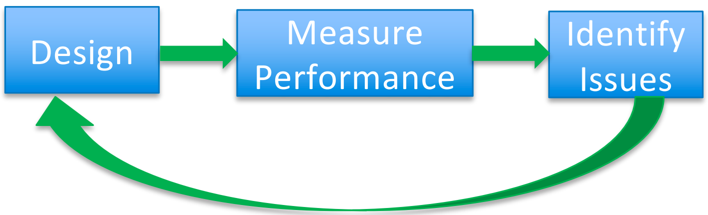


Small heliostats are more expensive?

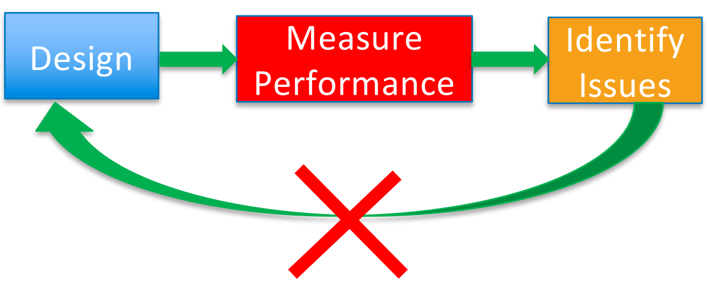
From Jones et. al. 2007 “Heliostat Cost Reduction Study”

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



Metrology and Standards

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 competitivity of heliostat or CSP technologies?

Heliostat Drives

SolarDynamics

State-of-the-Art

- Medium scale heliostats (>20m^2): slewing drive + linear actuators
- Large scale heliostats (>120m^2): 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

Contact info: Kyle Kattke - kyle.Kattke@solardynllc.com

Heliostat Field Control

SolarDynamics

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

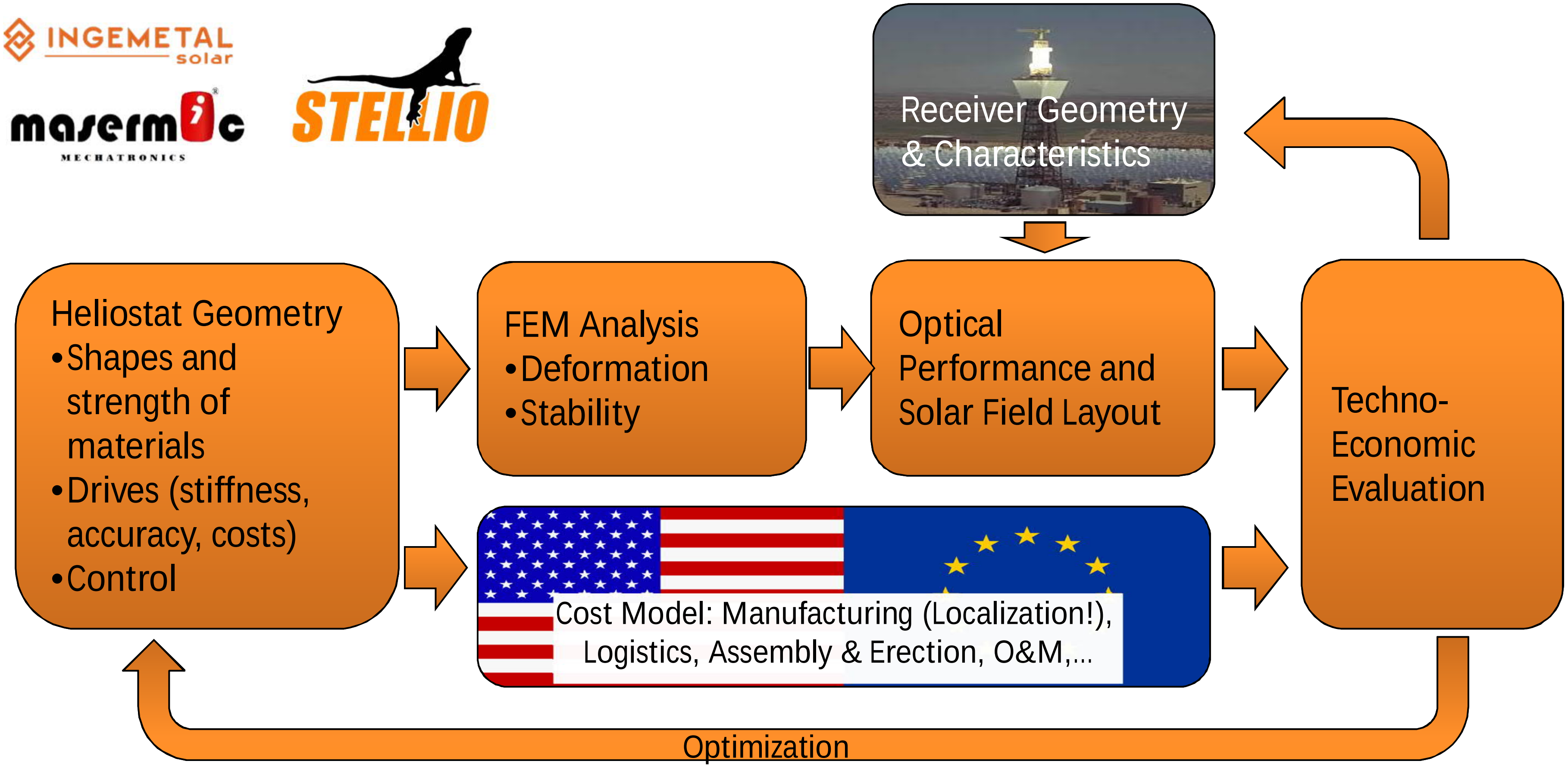
Contact info: Kyle Kattke - kyle.Kattke@solardynllc.com

schlaich
bergermann partner

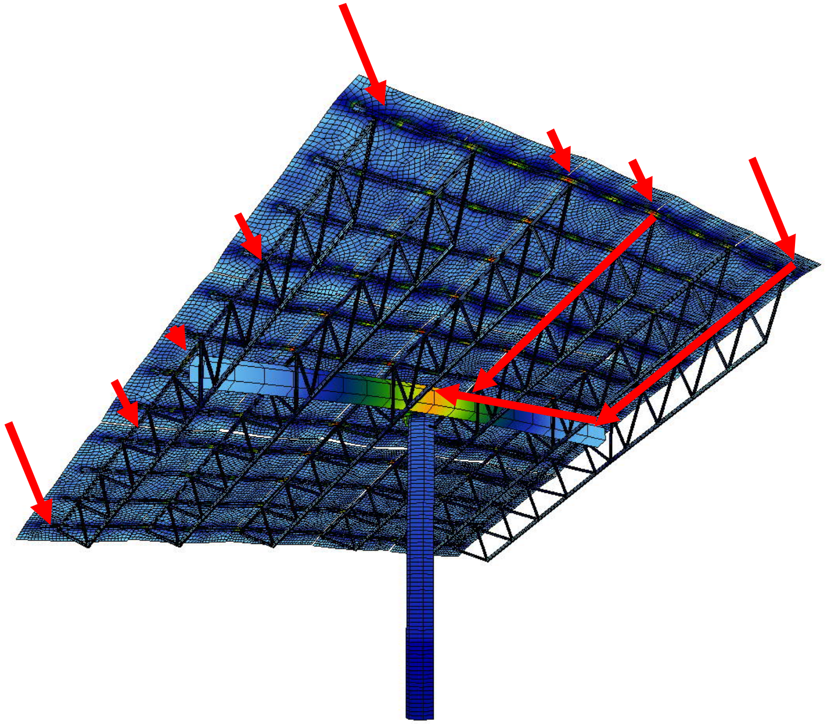
Advanced Heliostat Design / Manufacturing

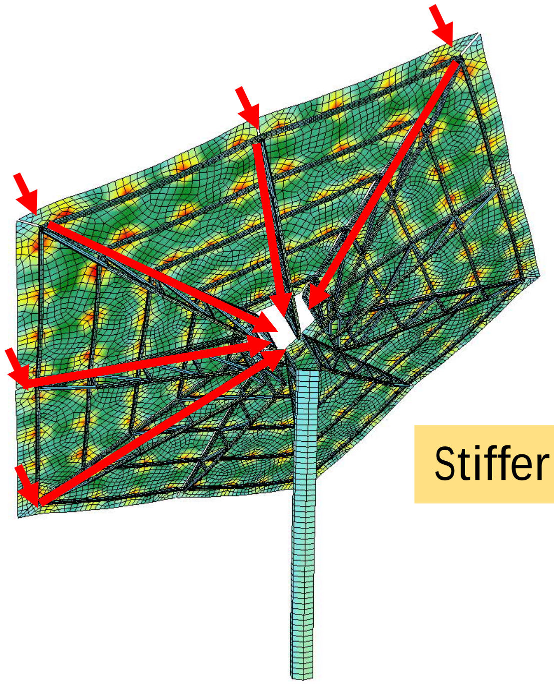
Autonomous Integrated Heliostat Field and Components Workshop

Gerhard Weinrebe
DoE, online, October 20th 2020



Advanced Heliostat Design





Stiffer Structure

Higher Structural Stiffness | Shorter Load Path | Less Deformation

ABENGOA

Power

Advanced heliostat design & manufacturing

October2020

Índex

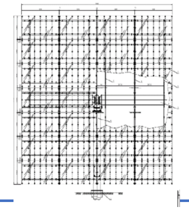
Abengoa Heliostat Evolution

<u>Solucar 120</u>

Solid tube structure / framed arms

120 m2 reflective surface

Mounted on solucar complex PS10-PS20

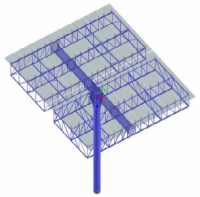


<u>ASUP 140 v1</u>

Solid tube structure / framed bolted structure

140 m2 reflective surface

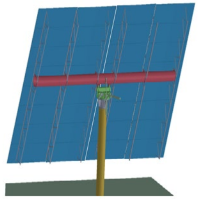
Mounted on !Khi solar plant (SA)



<u>ASUP 140 v2</u>

Solid tube structure / welded structure

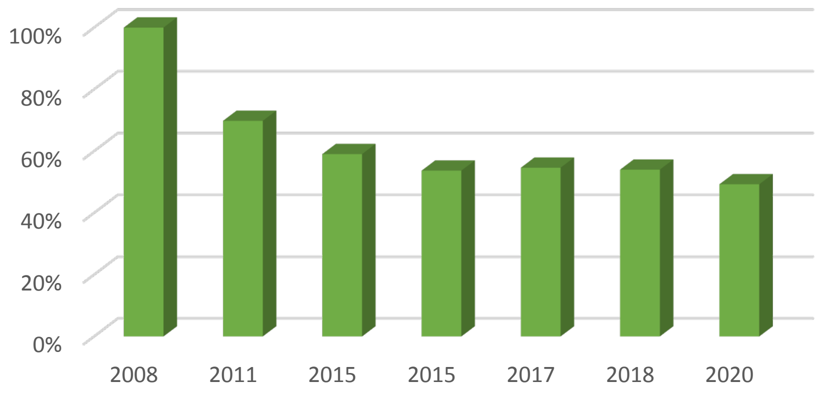
140 m2 reflective surface



Heliostat design evolution:

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

Heliostat Capex evolution in Abengoa plants & offers

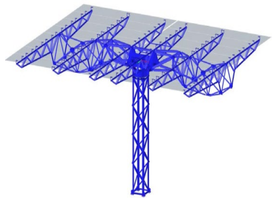


<u>ASUP 140 v3</u>

Framed structure

140 m2 reflective surface

Mounted on Atacama I solar plant (Chile)

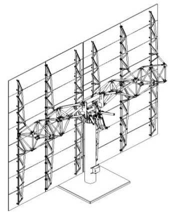


<u>ASUP 140 v5 CP</u>

Framed structure. Steel & concrete

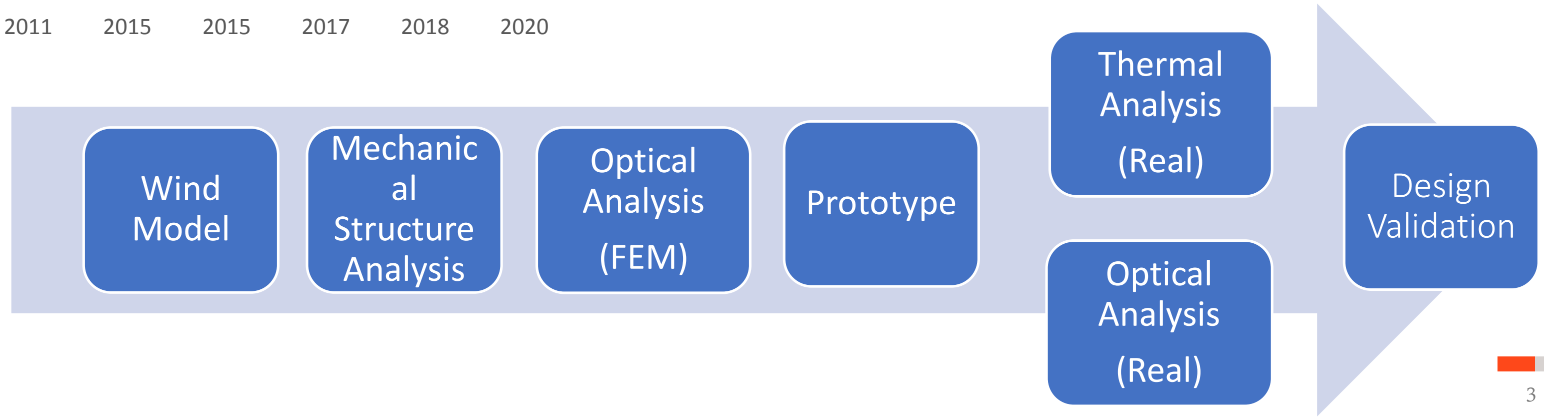
140 m2 refletive surface

Better option depending on location



Next generation:

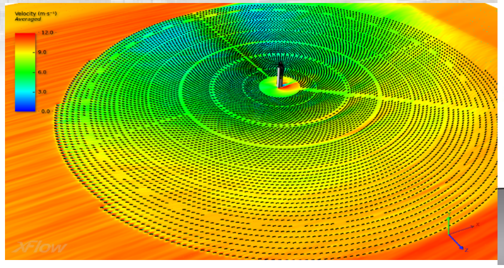
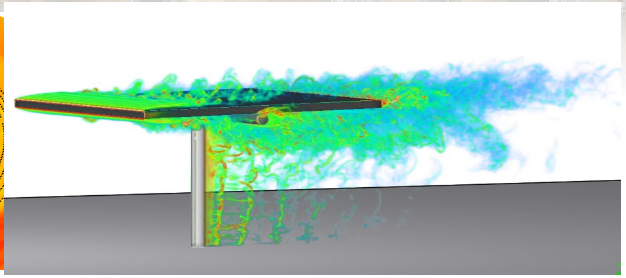
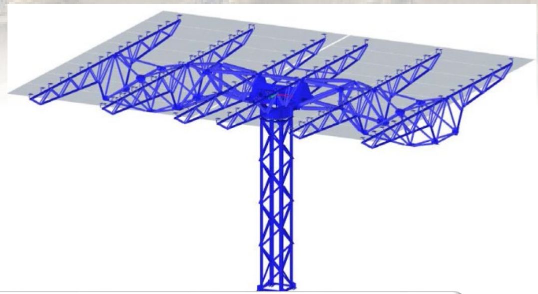
- Improving in facet design
- High precisión drives
- Improved sensor capabilties
- Autonomous heliostat
- Medium range Heliostat design



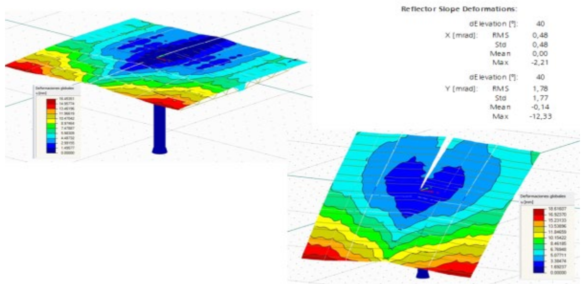
Advanced Heliostat design & manufacturing

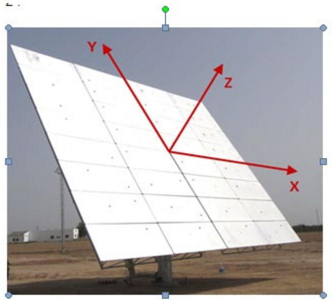
Design & calculations

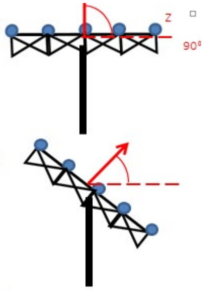
- Wind tunnel tests
- CFD calculations (X-flow +Fluent)
- Local wind velocities assesments
- FEM & structural models (static+dynamic)
- 3D mechanical models & contact models
- Workshop drawings

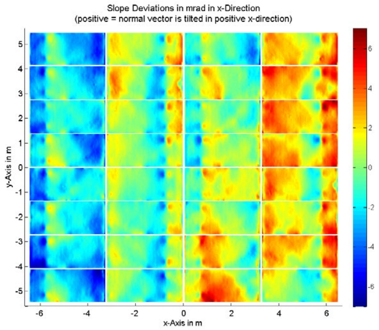




Optical Assessment





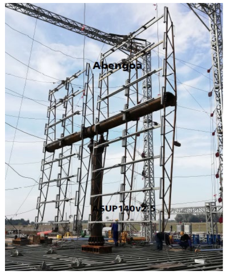


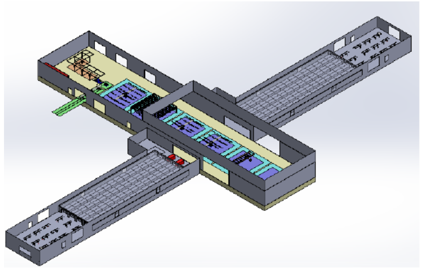


- Deviation optical shape
- Fotogrametry measurements
- Deflectometry measurements
- Tracking & aiming test
- Thermal evaluation
- Final optical validation
- Calibration alternative methods

Prototyping & Manufacturing process

- Prototypes station (solucar complex)
- Structural tests in Eucomsa platform
- Motion validation
- Lean Manufacturing process
- Manufacturing process validation
- Jigs & tools definition & validation





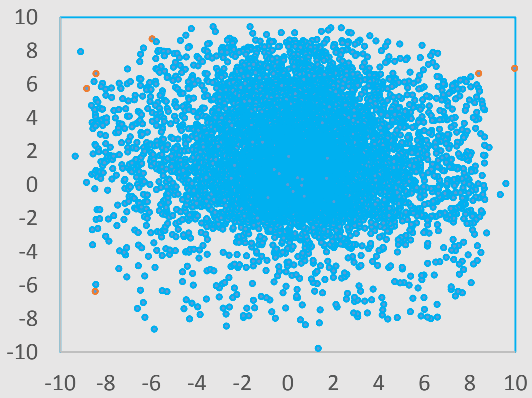
TonopahSolar

Field Deployment/ Plant Operation

TonopahSolar Field Deployment

- Assessment after Construction and Initial Installation.

Heliostat Pointing Assessment 30-DEC-2016 14:35:48 PST		
Azimuthal Error Mean	-0.4293	(mrad)
Azimuthal Error Stdv	2.5862	(mrad)
Elevation Error Mean	-1.0089	(mrad)
Elevation Error Stdv	2.3630	(mrad)
Tracking Error Mean	-1.3188	(mrad)
Tracking Error Stdv	3.4256	(mrad)
Heliostats Evaluated	6730	(number)

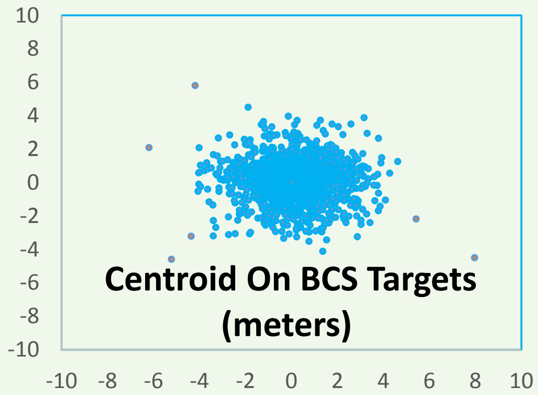


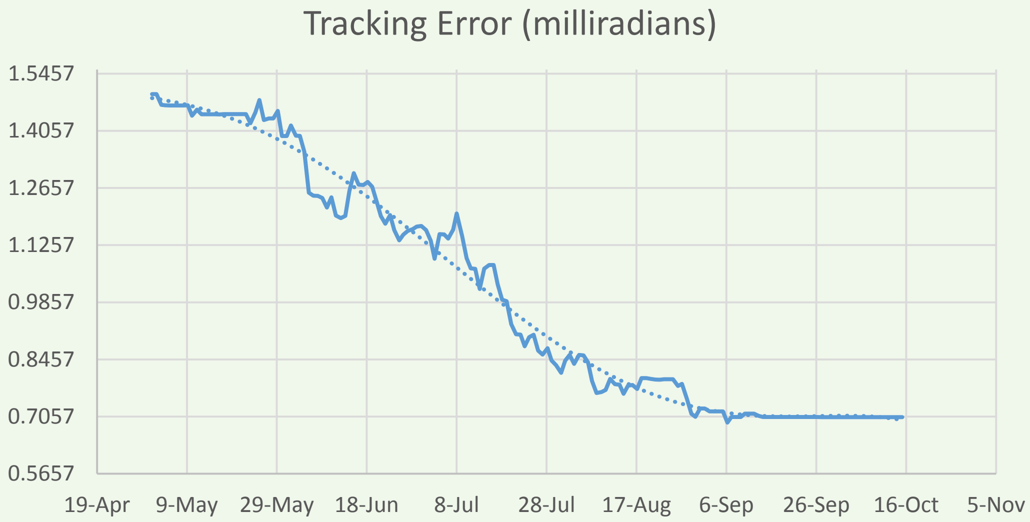
Heliostat Slope Error Assessment 31-OCT-2015		
Surface X-axis Slope Error	1.5000	(mrad)
Surface Y-axis Slope Error	2.2000	(mrad)

- We decided to concentrate on improving tracking and made many improvements to our Automated Beam Characterization System

- Present Assessment

Heliostat Pointing Assessment 13-SEP-2020 15:29:20 PDT		
Azimuthal Error Mean	-0.0136	(mrad)
Azimuthal Error Stdv	0.4901	(mrad)
Elevation Error Mean	-0.0570	(mrad)
Elevation Error Stdv	0.5092	(mrad)
Tracking Error Mean	-0.0812	(mrad)
Tracking Error Stdv	0.7045	(mrad)
Heliostats Evaluated	10214	(number)





TonopahSolar Plant Operation

- 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 MW_t 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

Iteration	TimeDate	Output (MW)	Strain (%)	Tiw (°F)	HeatShield (kW)
1	16-OCT-2020 13:09:00.000 PDT	534.3	217.4	1226.3	198
2	16-OCT-2020 13:09:00.000 PDT	533.7	157.1	1219.8	194.2
3	16-OCT-2020 13:09:00.000 PDT	533	149.1	1221.8	205.9
4	16-OCT-2020 13:09:00.000 PDT	533.1	126.1	1200	201.4
5	16-OCT-2020 13:09:00.000 PDT	531.8	122.4	1195.6	213.1
6	16-OCT-2020 13:09:00.000 PDT	531.2	119.1	1203.9	229.3
7	16-OCT-2020 13:09:00.000 PDT	530.7	112.8	1197.2	251.4
8	16-OCT-2020 13:09:00.000 PDT	529.1	109.5	1189.3	274.5
9	16-OCT-2020 13:09:00.000 PDT	530.2	103	1180.6	263.1
10	16-OCT-2020 13:09:00.000 PDT	529.1	107	1182.5	275.1
11	16-OCT-2020 13:09:00.000 PDT	528.7	104.5	1180.7	279.1
12	16-OCT-2020 13:09:00.000 PDT	528	102.9	1179.3	302.9
13	16-OCT-2020 13:09:00.000 PDT	527.8	101.2	1179	289.7
14	16-OCT-2020 13:09:00.000 PDT	527.6	99.4	1175.4	297
15	16-OCT-2020 13:09:00.000 PDT	527.7	100.4	1173.2	307.1
16	16-OCT-2020 13:09:00.000 PDT	527.4	100.4	1171.7	304.8
17	16-OCT-2020 13:09:00.000 PDT	527.4	99.5	1171.5	308.2
18	16-OCT-2020 13:09:00.000 PDT	527.2	100.4	1171	314.8
19	16-OCT-2020 13:09:00.000 PDT	526.9	99.9	1168.9	315.5
20	16-OCT-2020 13:09:00.000 PDT	527.3	98.7	1169.3	297.8

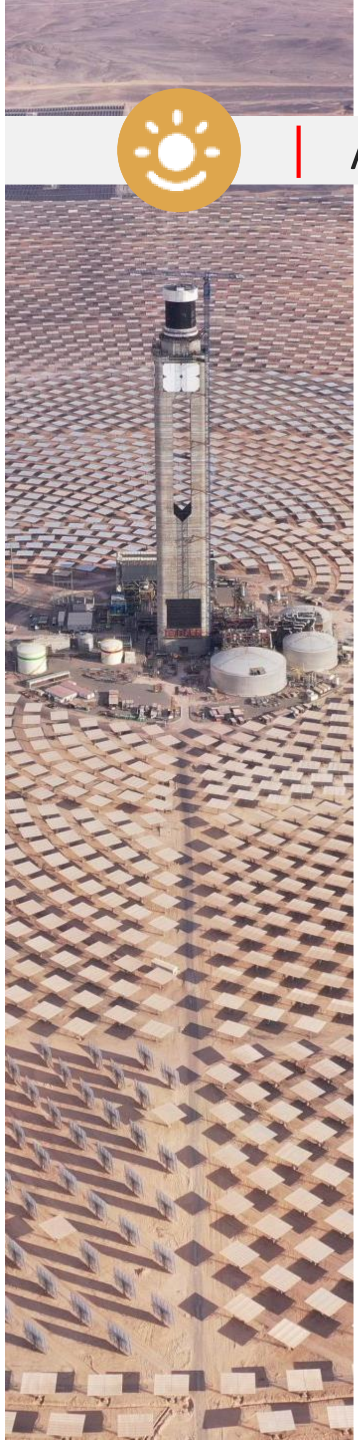
Autonomous Integrated Heliostat Field and Components:

Field deployment and Techno-economics

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

acciona

Javier López Sanz
Technical Innovation Responsible
jalopezsa1@acciona.com



acciona

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 pilling process -- dependence on geotechnical conditions

Solar Field Optimization

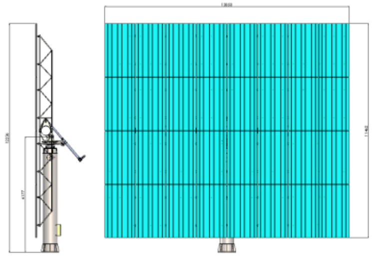
- Solar field layout optimization
- Aiming strategy optimization

Techno-economics

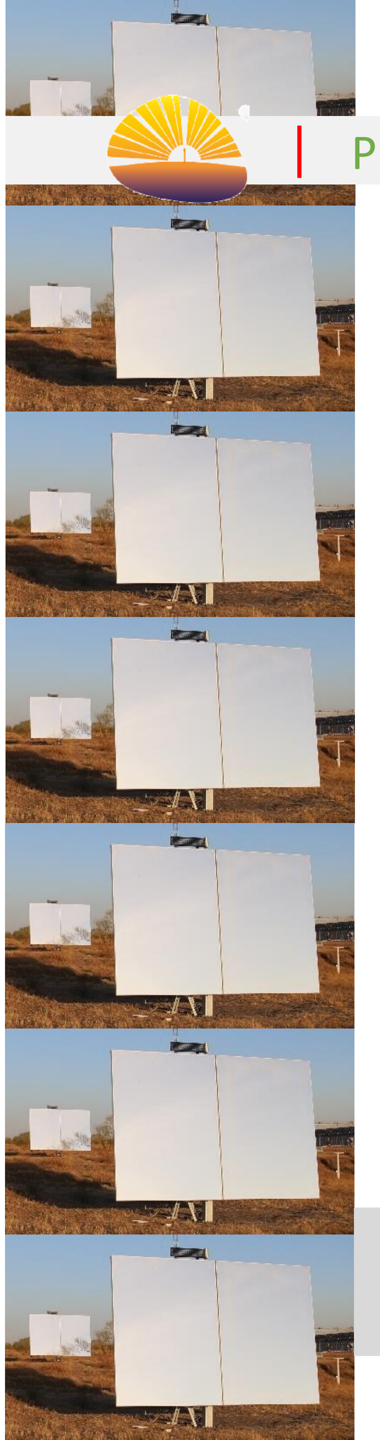
- From negotiation to serial contract: including manufacturing and logistics
- From single assembly to mass production and installation
- From theoretical operation to robustness and communication security

PHOTOn

ATH146



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



PHOTOn

tewer INGENIERÍA acciona

This project has received funding from the Eurostars-2 joint programme with co-funding from the European Union Horizon 2020 research and innovation programme

KEY CONCEPTS

- Assembled Heliostat cost = 100 €/m²
- Bi-facet heliostat of 14.4 m² -- 7,2m² per facet which 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 guaranty 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

Parameter	Units	Big Heliostat 140-160 m²	Big Heliostat 40-60 m²	ATH 146 146 m²	PHOTON Heliostat 14.4 m²
Slope error	mrad	1.8	1.4	1.6	1
Slope Error (12m/s)	Mrad	2.0	1.6	1.8	1,2
ΔSlope error with ΔT	mrad/°C	0.04-0.05	0.04-0.05	0.02	0
Tracking Error	mrad	0.8	0.3	0.6	0.3

100 MW
Reference Plant

1.099.936m²
State-of-the-art

938.880m²
PHOTOn Solar Field

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

Heliostat Best Practices

SolarDynamics

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.

CSP Best Practices Report: https://www.nrel.gov/docs/fy20osti/75763.pdf

Contact info: Hank.Price@solardynllc.com

Heliostat Best Practices

SolarDynamics

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 communcitions.

CSP Best Practices Report: https://www.nrel.gov/docs/fy20osti/75763.pdf

Contact info: Hank.Price@solardynllc.com