U.S. Department of Energy

HelioCon

Heliostat Consortium for Concentrating Solar-Thermal Power

HelioCon Seminar Series: Bottom-up Analyses for Two Heliostat Collectors and an Initial Heliostat Supply Chain Analysis

Parthiv Kurup, 8th Jun. 2022

conceptional design • components • integration • mass production • heliostat field

1: Bottom-up Analyses for Two Heliostat Collectors

Heliostat Bottom-Up Cost Analysis

- Bottom-up cost estimate for the Schlaich Bergermann und Partner/sbp Stellio (Commercial) and the Solar Dynamics SunRing (Advanced) heliostats
  - Approximately 5 developers approached e.g., Brightsource, Vast Solar, and Heliogen
- Uses Design for Manufacture and Assembly (DFMA) for manufacturing analysis
- Assumes field for <u>~1.1 million m² of heliostat surface area</u>
  - <u>E.g.,</u> 80 MWe CSP power tower with 12-16 hours TES


NREL

Cost Update: Commercial and Advanced Heliostat Collectors

Parthiv Kurup, Sertaç Akar, Stephen Glynn, Chad Augustine, and Patrick Davenport

National Renewable Energy Laboratory

Technical Report
NREL/TP-7A40-80482
February 2022

https://www.nrel.gov/docs/fy22osti/80482.pdf

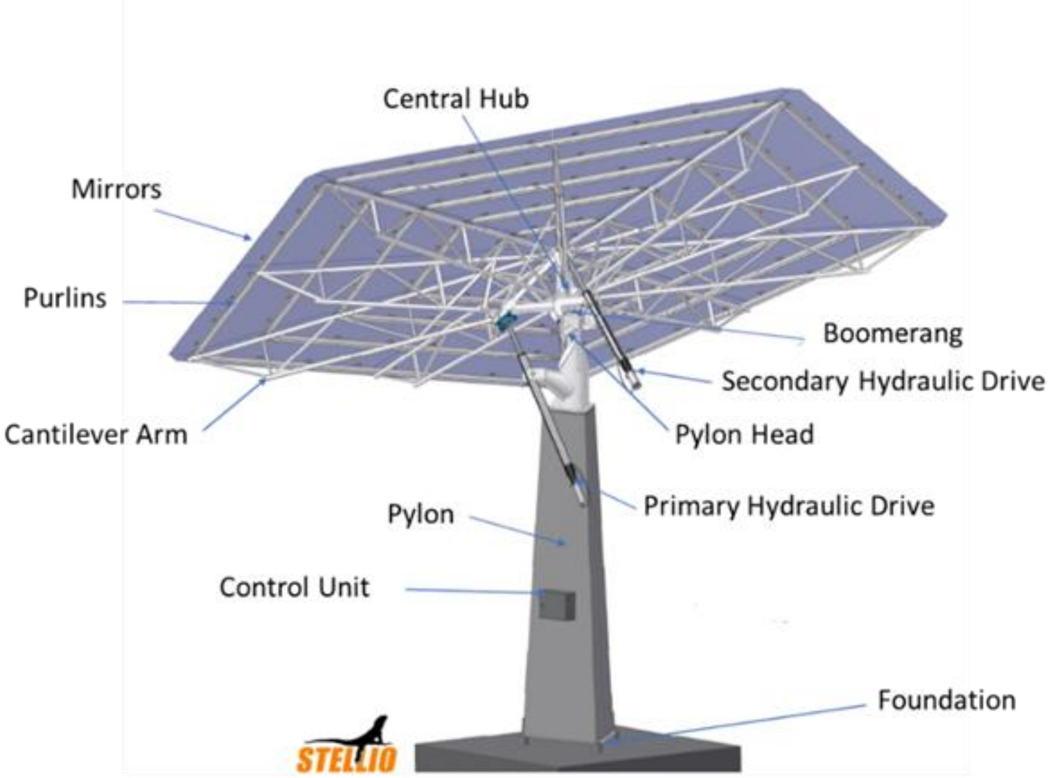
Commercial Heliostat - Stellio

- Developed in a consortium
- Deployed at the Hami Chinese plant
  - Xinjiang province near the Mongolian border
  - 50-MWe plant, 8hrs of MS storage
  - Operational since 2019
  - Stellio installed and optimized
  - 48.5m^2 heliostat instead of 47.5m^2
  - 696,751 m^2 field aperture area
  - 14,000 heliostats
  - Key implementation difference: Concrete pilings instead of foundations and steel pylons
  - Helped reduce foundations cost by 40-50%
- Being deployed at Redstone, South Africa
  - 100 MWe, 12hrs of storage
  - ACWA Power is the developer
  - Northern Cape Province

sbp Stellio Heliostat Design (Commercial)

- Novel design
  - Pentagonal, with mirror facets
  - Steel frame
  - Foundation or driven piles

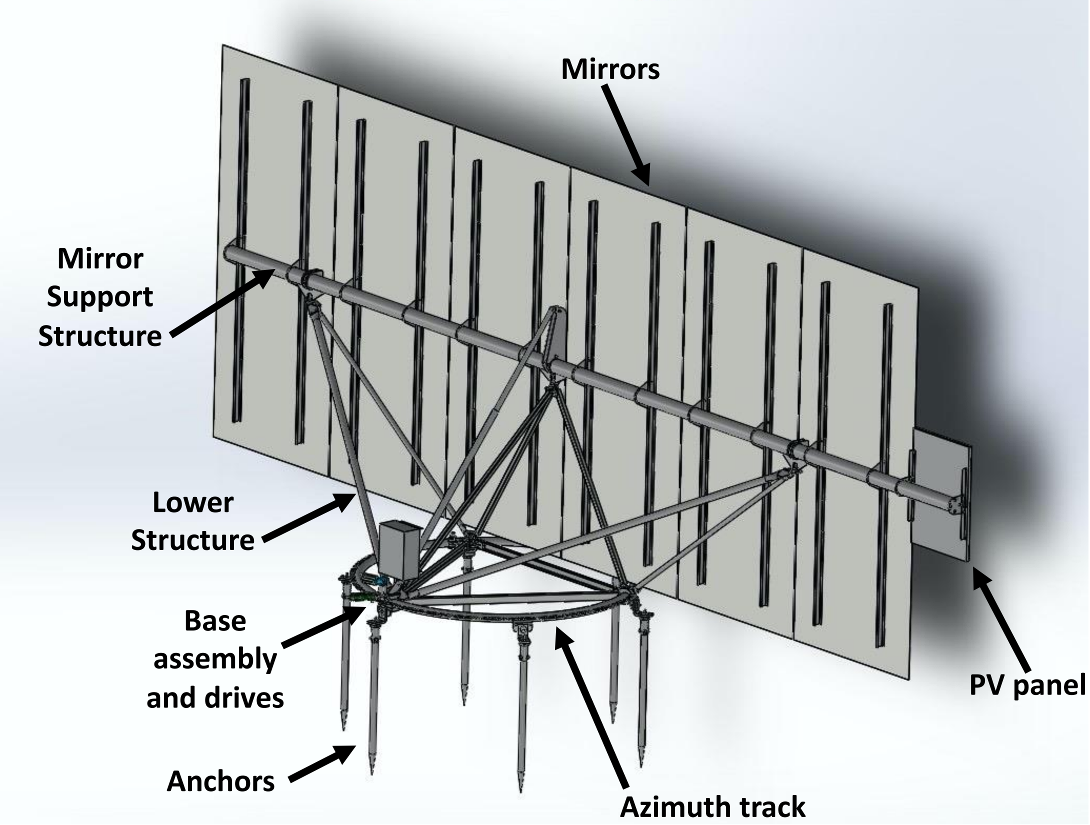
Property	Stellio
Developer	sbp (Germany)
Reflector type	4-mm glass
Individual heliostat aperture (m²)	48.5
Heliostats per field	22,239
Size of solar field (m²)	1,078,592
Design geometry	Pentagonal
Design drive type	Linear actuators
Primary frame material	Steel



Solar Dynamics SunRing Design (Advanced)

- Evolution of Abengoa's Ring of Power (ROP) design
  - Increase in aperture area, improved structure arrangement and azimuth drive
  - A simpler facet design
  - Robust foundation

Property	SunRing
Developer	Solar Dynamics (USA)
Reflector type	4-mm glass
Individual heliostat aperture (m^2)	26.964
Heliostats per field	40,000
Size of solar field (m^2)	1,078,560
Design geometry	Rectangular
Design drive type	Linear actuator, DC gearmotor
Primary frame material	Steel



Rendering of Solar Dynamics SunRing heliostat shown from behind mirrors

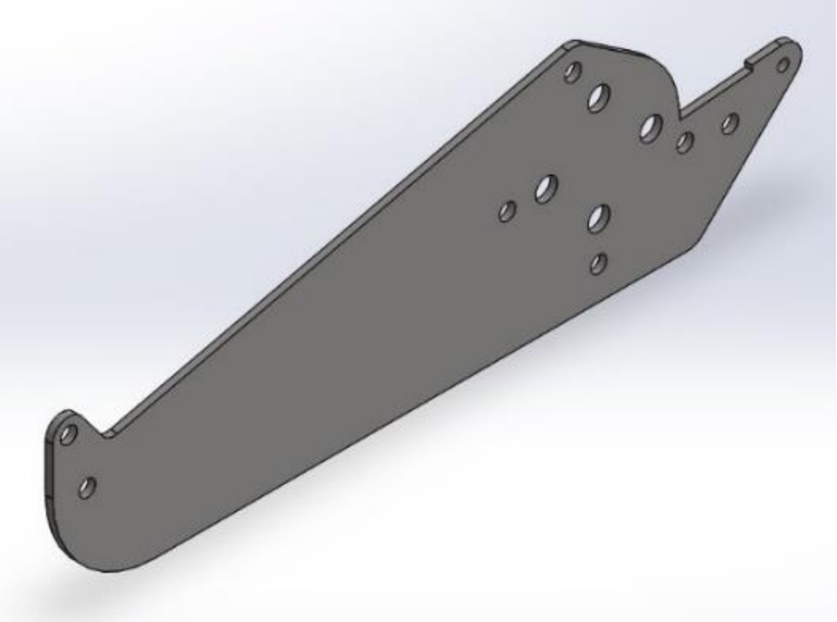
Methodology

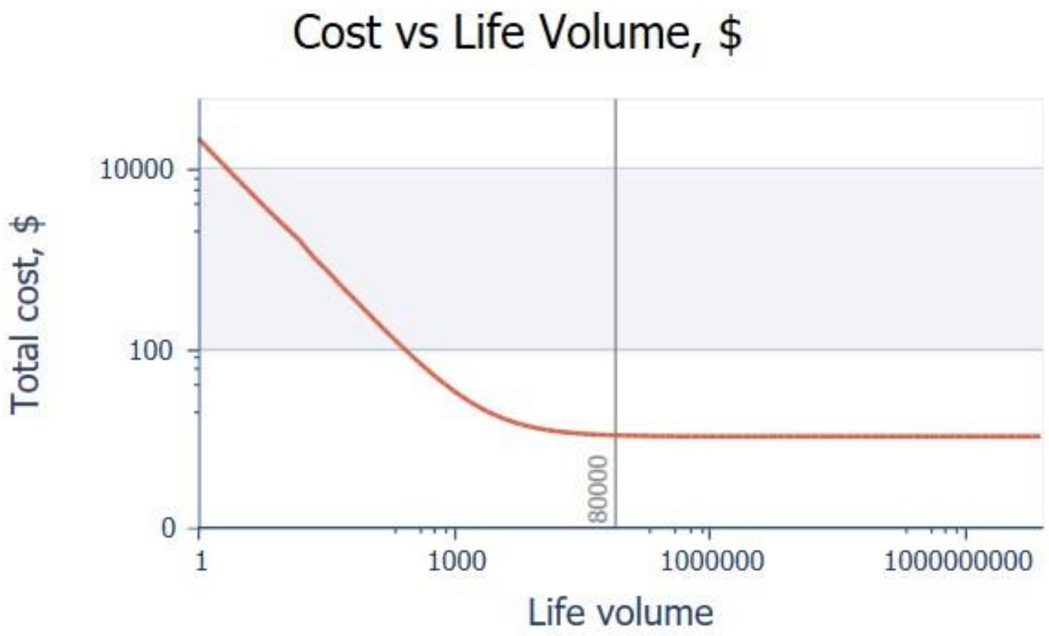
- Design for Manufacturing Analysis (DMFA)
  - Industrial software from Boothroyd Dewhurst, designed to determine manufacturing and assembly costs of components
  - DFMA has been used for other technologies e.g., small hydro, modular TES, geothermal, and advanced metal extrusion
- Design for Manufacturing (DFM):
  - Detailed databases and allows the knowledgeable user to calculate a primary manufacturing cost for each component and then assemble it within the overall product/assembly
  - Allows user to develop 'should cost'
  - Cost is based on material, process steps, machine setup time, machine and process used, and tooling investment if needed
  - Detailed CAD models used as a basis for the specific geometric considerations
  - Every component that could be directly manufactured in a commercial-scale manufacturing and fabrication shop was modeled
    - Note, the purchased parts were not modelled in DFM and DFA
  - Costs for specialist components such as receiver tubes or mirror panels were based on quotations and calculations
  - Tooling investment based on the life volume of the quantity of parts needed
- Design for Assembly (DFA):
  - Used to estimate cost of assembling (e.g., welding) the components together into sub-assemblies
  - Sub-assemblies for example include the cantilever arms

Methodology

- DFMA
  - DFM: Model the manufacturing process for each heliostat component in the Bill of Materials – BOM
  - DFA: Includes assembly costs (e.g., – welding)
  - Accounts for manufacturing volume
- 4 main areas for installed cost:
  - Manufacturing cost
  - Sub-assembly,
  - Purchased parts
  - Construction
- Cost estimates for purchased components from manufacturers and quote
- Includes on-site construction and installation costs
  - For ROP and Stellio we worked with the developers significantly

Effects of processes and volume

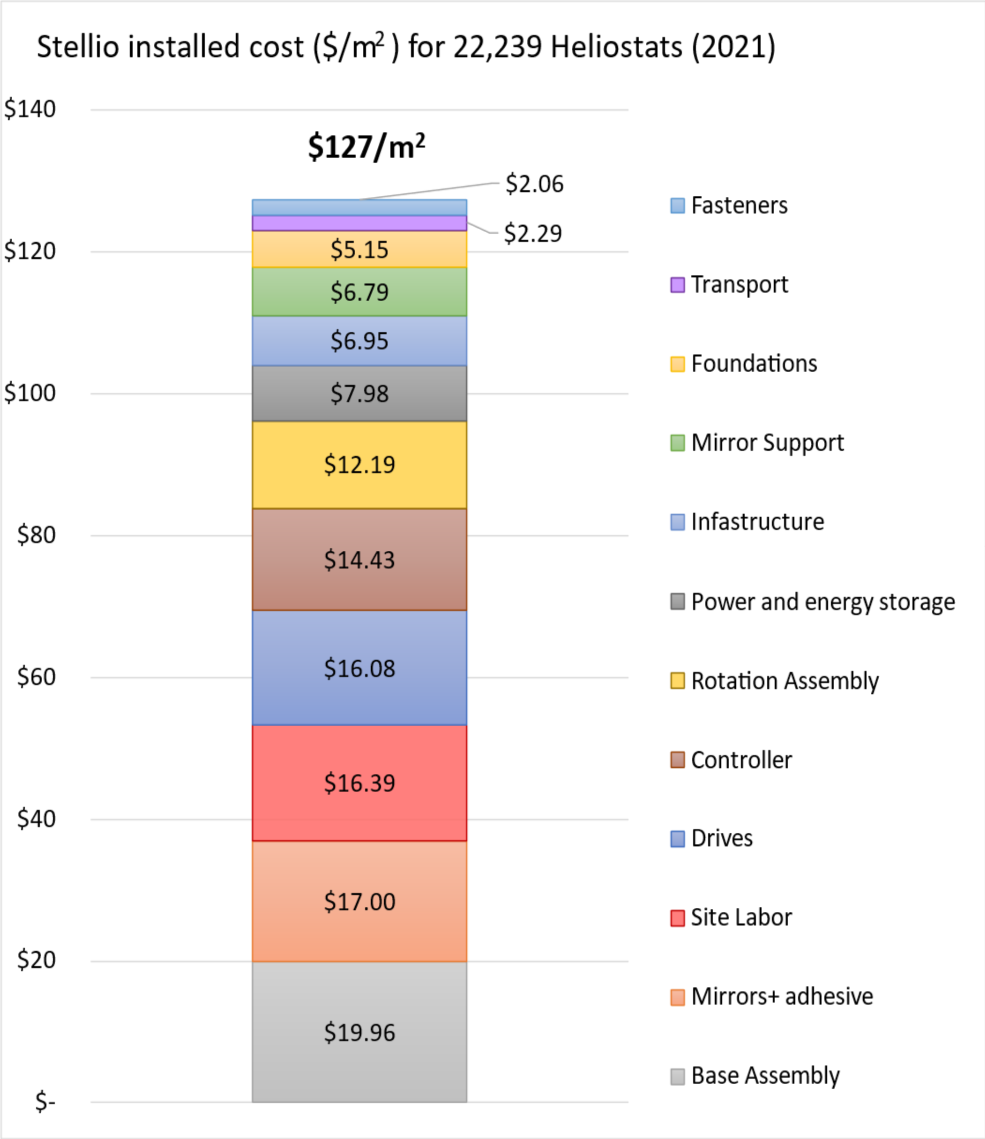


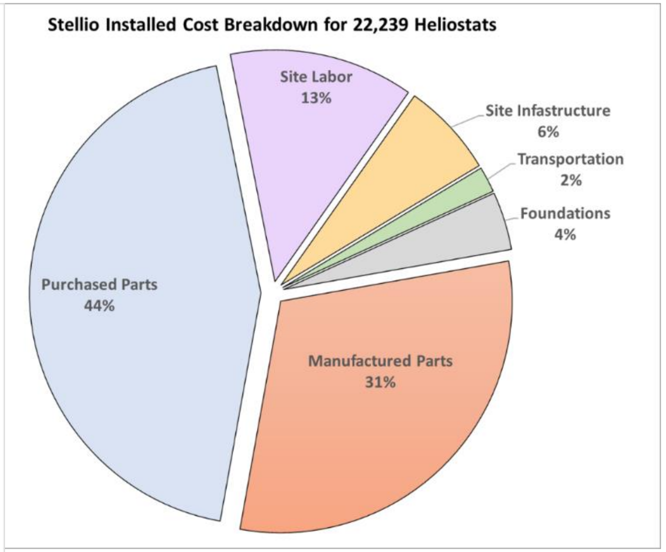


- CAD model of a Solar Dynamics SunRing actuator arm plate used as input into DFM
- Cost will be determined by process chosen e.g., stamping
- Effects of manufacturing the SunRing actuator arm plate at various production scales
  - Lowest cost for the volume associated in the heliostat field

sbp Stellio (Commercial) Results

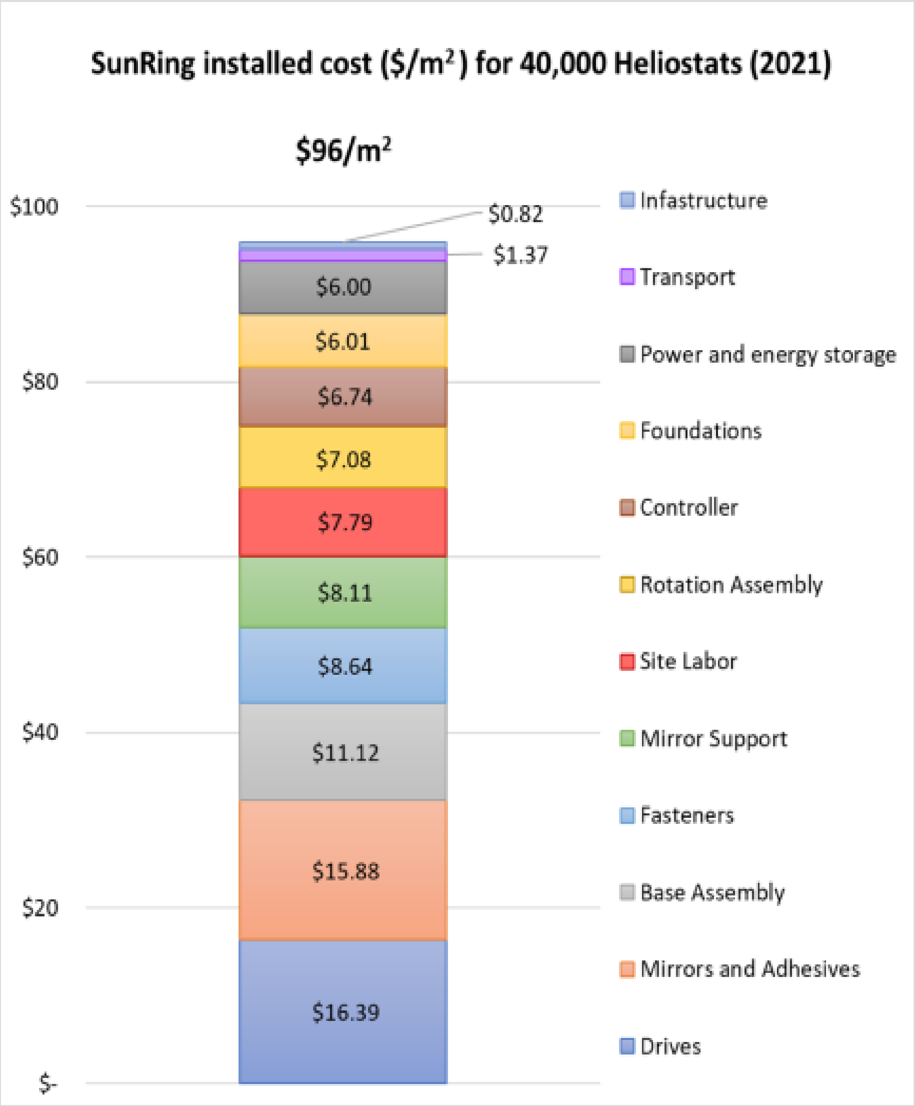
- Installed cost 127/m^2
- Field size 1,067,472 m^2
  - 22,239 heliostats
- $7.5M assembly facility
- Key cost areas
  - Base assembly (15.7%)
  - Mirrors (13.4%)
- Breakdown by category
  - 44% purchased components (e.g., rivets, mirrors, drives)
  - 31% manufactured parts (e.g., arms, frame…)

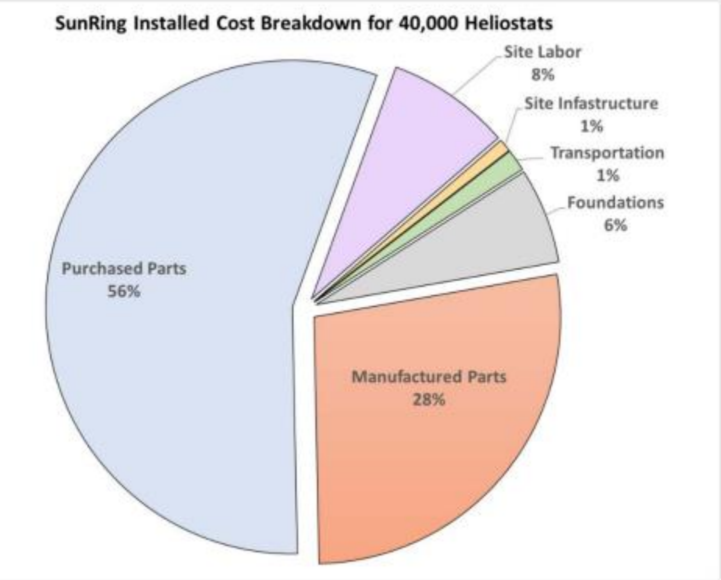




Solar Dynamics SunRing (Advanced) Results

- Installed cost ~$96/m²
- Field size 1,067,472 m²
  - 40,000 heliostats
- Purchased components are a much larger % than for the troughs
- Largest cost contributions
  - Drives (16.5%)
  - Mirrors (16%)
  - Base assembly (11%)
  - Foundations (9%)





SAM simulations highlighting impact to LCOE from heliostat cost changes

- CAPEX impacts
  - Default SAM for ~1 Mm^2: $151M
  - Commercial and Advanced ~1 Mm^2:
    - ~$137M and ~$107M **(-9% and -29%)**
- LCOE impacts
  - Location 1 (Tucson, AZ)
    - Default case SAM LCOE = ~$94/MWh
    - Commercial and Advanced cases:
      - ~$92/MWh and ~$86/MWh
      - **-3% and -9%** respectively
  - Location 2 (Daggett, CA)
    - Default case SAM LCOE = ~$92/MWh
    - Commercial and Advanced cases:
      - ~$89/MWh and ~$83/MWh

Solar field category	Default Heliostat	Commercial Heliostat cost	Advanced Heliostat cost
Individual heliostat aperture area (m^2)	144.4	48.5	27.0
Number of heliostats	7,470	22,237	39,944
SF size (m^2)	1,078,480	1,078,495	1,078,488
Solar Field installed cost ($/$m^2$)	140	127	99
Total installed heliostat field cost ($)	**$151 M**	**$137 M**	**$107 M**
Potential % decrease in overall solar field CAPEX	0%	-9.3%	-29.3%
Annual generation (GWh) at Tucson, AZ	396.844	396.844	396.844
Annual generation (GWh) at Daggett, CA	409.423	409.423	409.423
Total Installed Costs for Location 1 and 2 ($)	**$498 M**	**$481 M**	**$371 M**
Analysis period (years)	25	25	25
SAM LCOE real for Tucson, AZ (¢/kWh) – without Investment Tax Credit (ITC)	11.83	11.47	10.69
SAM LCOE real for Tucson, AZ (¢/kWh) – ITC at 26%	**9.44**	**9.16**	**8.56**
SAM LCOE real for Daggett, CA (¢¢/kWh) – without ITC	11.48	11.13	10.37
SAM LCOE real for Daggett, CA (¢/kWh) – ITC at 26%	**9.16**	**8.89**	**8.31**

Insights into the Stellio and Cost reductions

sbp Stellio

- Stellio was developed in a Consortium
  - Research (DLR), Industry (Ingemetal and Maseric), and the Developer (sbp).
  - DLR has been involved with significant performance testing.
- Learnings from the installation of the heliostats at the Hami field are being utilized in the next fields.
  - Driven piles instead of concrete foundations led to the reduction of the field installation cost by ~20%.
  - This technique is now going to be deployed at the Redstone heliostat field in South Africa.
- DLR analysis, has estimated the potential Stellio installed cost in 2025 could be $103/m^2$ in ($2016)
  - Key developments for the Stellio through 2025 include:
    - A reduction in the Site Preparation e.g., through driven piles or earth screws by nearly 50% ($11/m^2 to $5.5/m^2)[1];
    - Improved maintenance programs and closed loop control could reduce Drive cost by 25% ($45/m^2 to $33.8/m^2)[1];
    - Structure costs can be reduced by approximately 25% via reduction in material and increased automation and assembly procedures.[1]
    - With growth in the heliostat competitive market due to increased power tower deployment, there is potential for an estimated 35% cost reduction, through product standardization and improved canting procedures.[1]

Solar Dynamics SunRing Heliostat

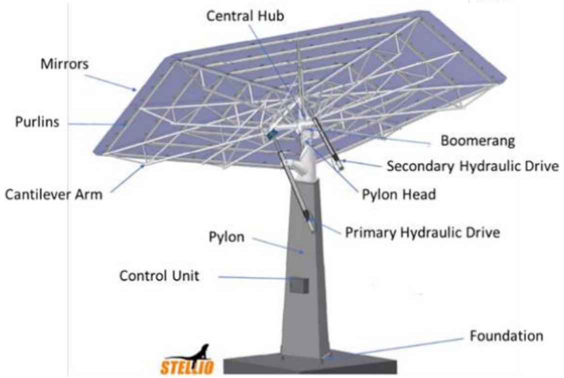
- Based on Abengoa's "Ring of Power" concept designed for simple foundation installation
- The majority of manufactured parts do not require additional machining steps allowing for stamping to be utilized for high volume manufacturing
- The SunRing was modeled with 6 helical piles for the foundation
- Large, flat mirrored aperture eases assembly tolerances
- Tracking utilizes off the shelf stepper motors and linear actuators to simplify design and reduce cost
- Detailed estimates of field assembly stations and labor calculated by an outside contractor were provided by SD to accurately estimate installation costs

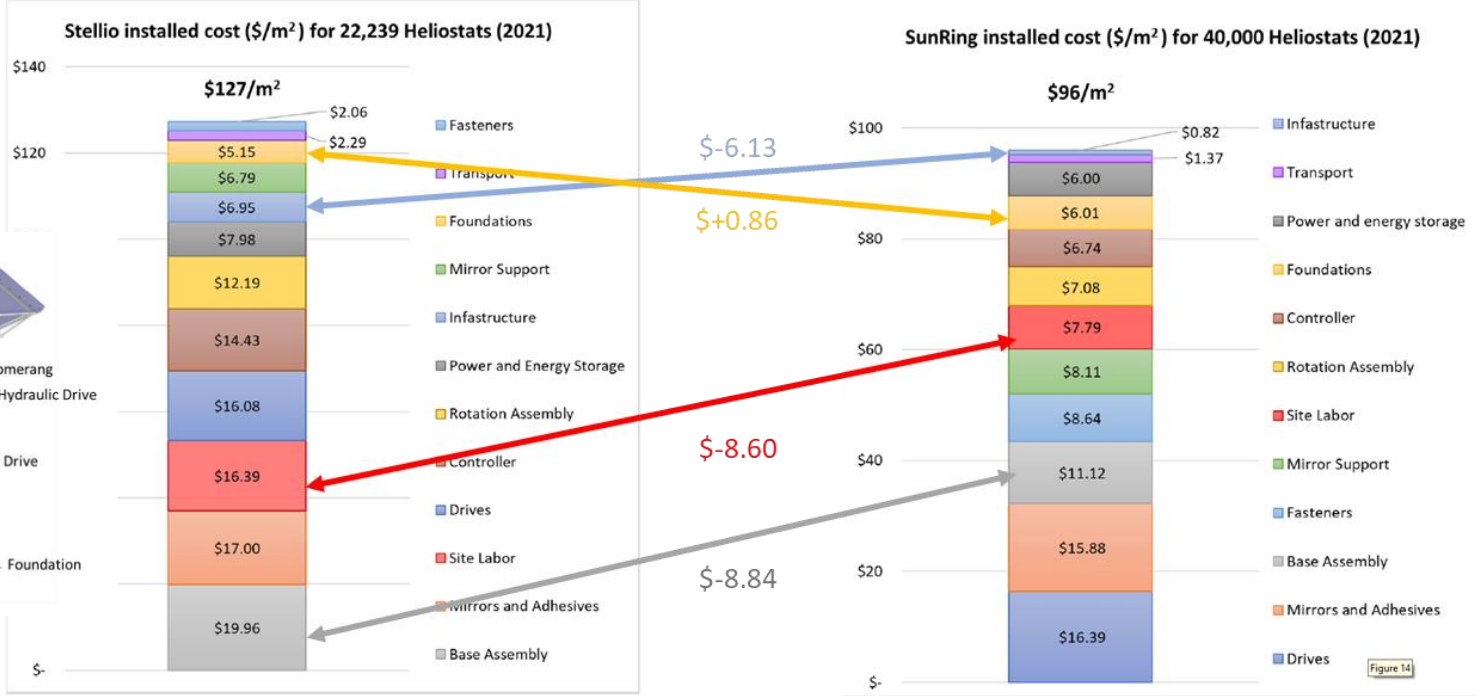
[1] LCOE Reduction Potential of Parabolic Trough and Solar Tower CSP Technology until 2025

Design-Related Cost Reductions to Deployment

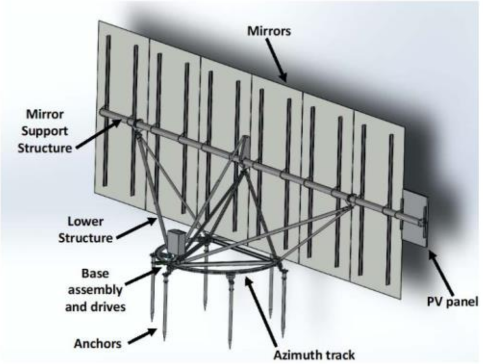
- How much is can heliostat design impact deployment costs?
- The cost analysis of the Stellio and SunRing heliostat designs found:
  - Both assume high enough levels of production (>25,000/yr) to achieve economies of scale which is more achievable for small heliostats.
  - SunRing design reveals how heliostat design can make field deployment significantly less costly (~$33/m^2)
  - LCOE studies for Roadmap have shown that heliostat costs savings must be substantial if they reduce optical performance even slightly

Deployment-related costs
$59.87/m^2





Deployment-related costs
$27.11/m^2



Kurup, P., Akar, S., Glynn, S., Augustine, C., & Davenport, P. (2022). *Cost Update: Commercial and Advanced Heliostat Collectors*. Retrieved from United States: https://www.osti.gov/biblio/1847876

Summary

- Presentations and publications
  - Parthiv Kurup, Sertaç Akar, Stephen Glynn, Chad Augustine, and Patrick Davenport. 2022. “Cost Update: Commercial and Advanced Heliostat Collectors”. NREL. https://www.nrel.gov/docs/fy22osti/80482.pdf . NREL/TP-7A40-80482
- Major results
  - Commercial heliostat estimated at $127/m^2$
  - Advanced heliostat estimated at $96/m^2$
- Uses and Impacts
  - ATB 2022 uses values such as the $127/m^2$ and confirms industry survey
  - Heliostat analysis to feed into HelioCon “Initial Heliostat Supply Chain report”
  - Shows developments in heliostat design and deployments, highlighting cost reduction to $75/m^2$
  - Could be part of future reviews and roadmaps e.g., Heliostat Cost Reduction Study (Coventry and Pye, 2014)

2: Initial Supply Chain Analysis

HelioCon Task 4: Summary Heliostat Initial Supply Chain Analysis

- Initial heliostat supply chain analysis report in review
- Summary:
  - The heliostat supply chain is primarily composed of plentiful commodity materials such as steel, aluminum, and glass
  - The lack of a near-term U.S. market is a formidable challenge to domestic CSP heliostat manufacturers.
  - CSP deployment is expected to grow in regions like China, Africa, and the Middle East over the next 3-5 years.
  - The construction of 39 GW of CSP (assuming mainly power tower) in the U.S. could have 195,000 jobs directly and indirectly associated
  - Recommendations: further detailed analysis

conceptional design • components • integration • mass production • heliostat feld

Material Content Analysis

- Material content analysis
  - Glass
    - Commercial Design: 10,786 MT
    - Advanced Design: 10,800 MT
  - Steel
    - Commercial Design: 13,343 MT
    - Advanced Design: 17,443 MT

Recent Heliostat Analysis, Material	Metric Tons (MT)	Annual U.S. Production (MT) in 2020	Percent of U.S. production (%) in 2020	Estimated Value of Sector in 2020 ($B)	Estimated Value of material in heliostat field in 2020 ($)	Sources
Glass, in Turchi et al. 2015 heliostat field	10,055	20,000,000	0.05028%	25.0	$12,568,750	(Hasanbeigi et al. 2021)
Commercial Design, Glass	10,786	20,000,000	0.05028%	25.0	$13,482,500	(Hasanbeigi et al. 2021)
Advanced Design, Glass	10,800	20,000,000	0.05028%	25.0	$13,500,000	(Hasanbeigi et al. 2021)
Steel, in Turchi et al. 2015 heliostat field	16,584	72,700,000	0.02281%	91.0	$20,758,514	(USGS 2022)
Commercial Design, Steel	13,343	72,700,000	0.01835%	91.0	$16,701,692	(USGS 2022)
Advanced Design, Steel	17,443	72,700,000	0.02399%	91.0	$21,833,741	(USGS 2022)

Jobs Impacts

- Estimated jobs (direct and indirect) for a heliostat field
  - Commercial
    - Glass: 94
    - Steel: 94
  - Advanced
    - Glass: 67
    - Steel: 88
  - Future jobs
    - 100 heliostat fields:
      - Glass: ~9,480
      - Steel: ~6,760 – 8,840

Recent Heliostat Analysis, Material	Metric Tons (MT)	Estimated Jobs in sector in 2020	Direct Jobs per field based on the MT of material produced in 2020	Indirect Jobs per field in 2020	Sources
Glass, in Turchi et al. 2015 heliostat field	10,055	87,850	44	47	(IBIS World 2021b; BLS 2021a)
Commercial Design, Glass	10,786	87,850	47	47	(IBIS World 2021b; BLS 2021a)
Advanced Design, Glass	10,800	87,850	47	47	(IBIS World 2021b; BLS 2021a)
Steel, in Turchi et al. 2015 heliostat field	16,584	72,230	16	68	(BLS 2021a; 2021b)
Commercial Design, Steel	13,343	72,230	13	54	(BLS 2021a; 2021b)
Advanced Design, Steel	17,443	72,230	17	71	(BLS 2021a; 2021b)

Material/Area	Metric Tons of Material (MT) for single field	Direct and Indirect potential Jobs for 100 heliostat fields	Direct and Indirect potential jobs for 1,000 heliostat fields
Commercial Design, Glass	10,786	9,480	94,798
Advanced Design, Glass	10,800	9,486	94,860
Commercial Design, Steel	13,343	6,761	67,609
Advanced Design, Steel	17,443	8,838	88,384

Do not cite or distribute

Solar Futures Study

Scenario	Potential GW of Solar Deployed by 2035	Emissions reductions by 2035	Potential GW of Solar PV Deployed by 2050
Reference	380	-45%	670
Decarbonization of the grid by 95% in terms of emissions by 2035 (Decarb)	760	-95%	1,050
Decarbonization with Electrification (Decarb+E)	1,000	-105%	1,570

[1]Solar Futures Study (2021)

[2]The Role of Concentrating Solar-Thermal Technologies in a Decarbonized U.S. Grid (2022)

[3]The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets

- Emissions reductions by 2035[1]
  - -45% in the reference
  - -95% in the Decarb
  - -105% in the Decarb+E
- Potential deployment of PV and Jobs for solar PV by 2035[1]
  - Potential deployment of 670-1,050 GW
  - Potential to lead to 500,000 – 1,500,000 direct and indirect solar PV jobs
- Potential CSP deployment by 2050
  - 39 GW[2]
  - If CSP can hit low-cost targets, this could be between 35 - 158 GW[3]

ATB 2022 Analysis

Overnight Cost of Capital (OCC) and CAPEX from ATB 2022 projections in 2035 and 2050

ATB 2022 Scenario	Year	Turbine Capital Cost ($/kWe)	Storage Capital Cost ($/kWe)	Field Capital Cost ($/kWe)	ATB 2022 OCC ($/kWe)	ATB 2022 CAPEX ($/kWe)
Base	2020	1,910	767	3,566	**6,242**	6,505
Moderate	2035	1,245	500	2,324	**4,069**	4,241
Advanced	2035	968	389	1,807	**3,163**	3,296
Moderate	2050	1,146	460	2,140	**3,746**	3,904
Advanced	2050	815	327	1,522	**2,761**	2,665

- 2022 ATB
  - 2020 start point
  - $6,242/kWe Overnight Capital Cost
    - Turbine: $1,910/kWe
    - Storage: $767/kWe
    - Field: $3,566/kWe
- 2035
  - Moderate: $4,069/kWe
  - Advanced: $3,163/kWe
- 2050
  - Moderate: $3,746/kWe
  - Advanced: $2,761/kWe

Challenges and Opportunities

- Challenges for heliostats:
  - Scale, complexity, cost
  - Volume precision manufacturing
  - Inconsistent demand and pipeline
  - Global supply chain disruptions
  - Uncertain U.S. and global growth prospects
- Opportunities:
  - Global near-term and long-term growth potential
  - U.S. innovation and funding landscape
  - CSP heliostat knowledge and experience
  - Use in other markets
  - Jobs and domestic content

Summary

- Publication
  - Parthiv Kurup, Sertaç Akar, Chad Augustine, David Feldman, and Mark Mehos. 2022. “Initial Heliostat Supply Chain Analysis”. NREL. In review, to be published
- Major results
  - The heliostat supply chain is primarily composed of plentiful commodity materials
  - Few large suppliers of key components like glass and mirrors
  - In the U.S. domestic supply for steel and commodities exists
  - Jobs impacts e.g., ~10k jobs in the Steel and Glass industries if 100 heliostat fields can be deployed
- Uses and Impacts
  - Future further detailed analysis
  - Different heliostat designs and suppliers can be identified
  - Feeds into HelioCon Advanced Manufacturing and Roadmap efforts

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

Thank you.

Parthiv.Kurup@nrel.gov

More From HelioCon

- Past seminar presentations now available on the NREL YouTube learning channel: https://www.youtube.com/playlist?list=PLmIn8Hncs7bGAK-hIf4qxuAbHUHK-xgZK
- Slides available here: https://drive.google.com/drive/folders/1162LN82ImgurpCODnJDLKsERCWo-698R?usp=sharing
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov

Next Seminar June 29th!

HelioCon Seminar Series: Soiling Losses for Concentrating Solar Power – Prediction, Assessment, and Mitigation

Speaker: Dr. Michael Cholette, QUT

When: 3-4pm MDT Wednesday June 29th

Zoom:https://nrel.zoomgov.com/j/1616379989?pwd=Q2xXN3o3UnMxbTdaUGpIRy95bFhGQT09