Fields of twisting heliostats for electricity, direct air capture and making syngas and cement

Roger Angel
University of Arizona

- Funded by two 18 month awards:
  - DOE SIPS now at end of 5th of 6 quarters
  - Heliocon award, now ½ way through

Contributors

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- at the University of Arizona:
  - Professors Roger Angel (PI), Peiwen Li, Daewook Kim
  - Matt Rademacher, Nick Didato, Justin Hyatt, Heejoo Choi, Hyukmo Kang
  - Students: Andrew Vagher, Yiyang Huang
  - Jennifer Pierson, Business
- at Sandia National Lab:
  - Randolf Brost and Braden Smith

Funded by:
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
ENERGY TECHNOLOGIES OFFICE

Background

The University of Arizona manufactures the world's largest telescope mirrors and has built on this experience to make concave mirrors for sunlight concentration as shown above, each one 10 m^2 in area and producing a solar focus intense enough to melt a 15 mm diameter hole in 6 mm thick steel (inset) in 10 seconds, at 1,400 °C.

The team yesterday – basking sunlight focused by twisting heliostat

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Yiyang Huang, grad student   Andrew Vagher, grad student
- Matt Rademacher, engineer   Nick Didato, engineer

Goals of the DOE/NREL projects

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Make the first full-scale (8 m^2) heliostat with precision twisting reflector.
- Test at U Arizona
- Take to Sandia NSTTF to compare with non-twisting heliostats
- Demonstrate accurate closed loop tracking using a central camera in each heliostat
- Compare field designs with and without twisting capability

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Present state of heliostats in renewable energy

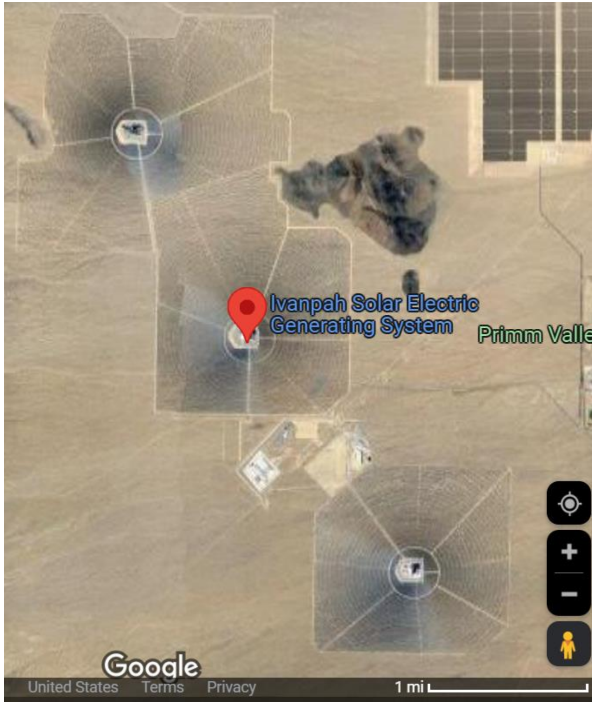
- Basically, all central receiver CSP in utility scale, Ivanpah-like plants,
- Not a big contributor to solar electricity –
- 1% - 2% fraction compared to PV
- Not commercially competitive

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Ivanpah - the problem: energy yield ½ PV, per km^2

- Largest utility scale in the world, the only one in USA, **no storage**, system with 3 towers and receivers
- DNI 2700 $kWh/m^2/year$
- 170,000 14 m^2 heliostats spread over 12 km^2
- Published: 750,000 MWh/yr, = 62,500 $MWh/km^2/yr$
- https://en.wikipedia.org/wiki/Ivanpah_Solar_Power_Facility

- The problem - compare with PV
- PV yields twice as much, 125,500 $MWh/km^2/yr$ from same site (GHI of 6 $kWh/m^2/day$)
- Bolinger, M. and G. Bolinger. 2022. *Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density*



Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

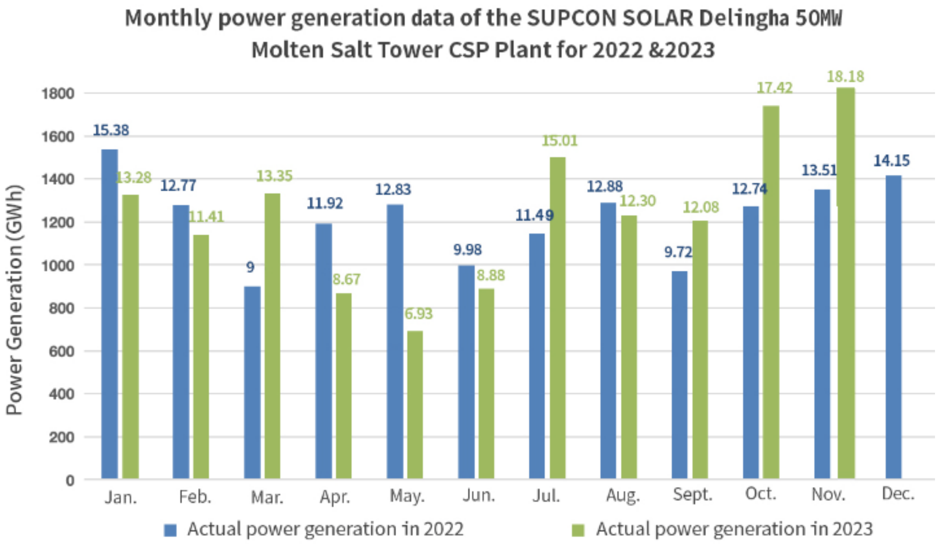
Delingha new molten salt with storage

- One of China's CSP pilot projects, somewhat better

Yield 64% of PV per km^2, with storage

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- 50MW capacity, 7-hour molten salt storage and 27,135 20 m^2 heliostats,
- Ground area 2.25 km^2
- 12 GWh/mo = 64,000 MWh/km^2/year
- 750 m radius, 15 m diameter tower

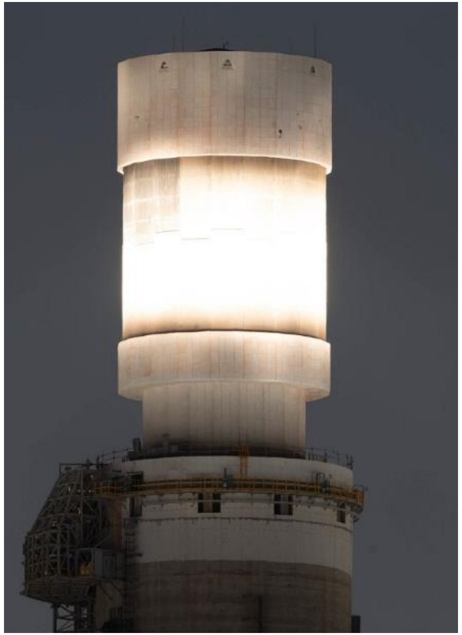


- Compare with PV - 100,000 MWh/y/km^2 at this site

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

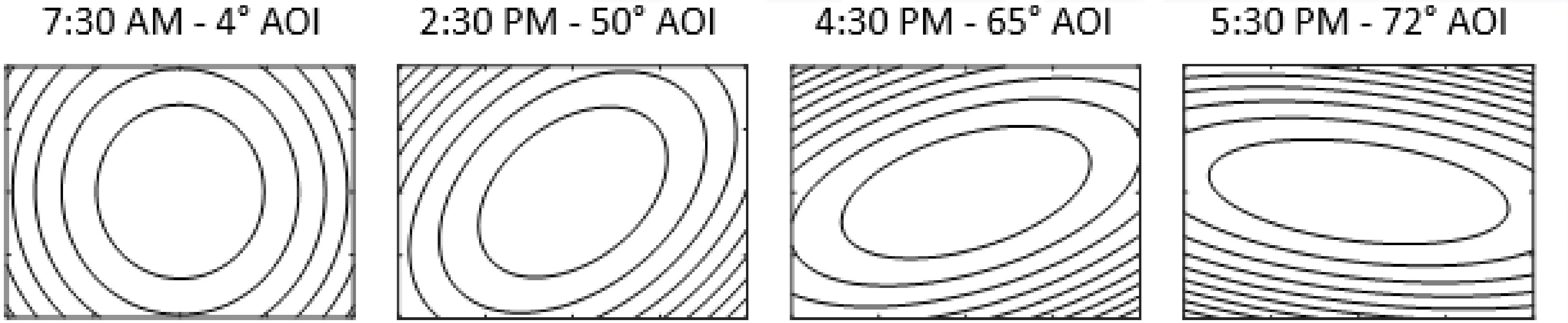
How can CSP central receiver be more competitive?

- Increase temperature from standard 565°C of molten salt
  - Increases Carnot efficiency
- Can get to ≥ 800C with same cylindrical central receiver , if sunlight better focused for higher concentration.
- Fundamental limit to concentration is set by optics – each heliostat needs to form a sharp image of the solar disc on the receiver.



Optical limit

- To get the highest concentration, each heliostat in the field must focus the sunlight to a disc image
- Mirror shape must change from early morning to late afternoon, depending on angle of incidence (AOI)

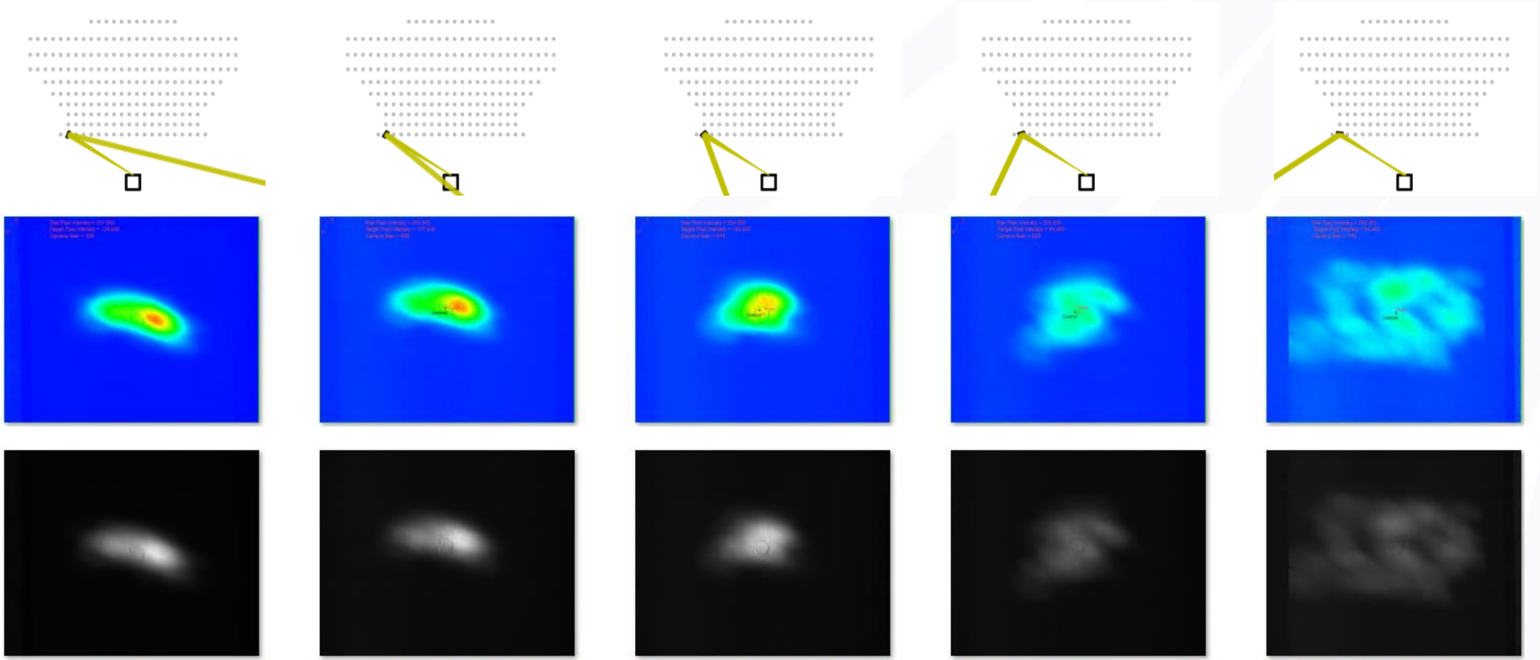


- Calculated for representative alt – az heliostat due W of receiver at 20° elevation, equinox, 33° lat.
- Elliptical contours, angle rotates through the day

If shape not changes, focus degrades with changing angle of incidence

Funded by:
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
Y TECHNOLOGIES OFFICE

Images collected February 10, 2023.



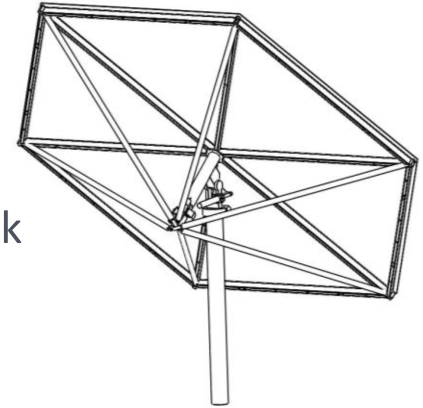
Early | Solar Noon | Late

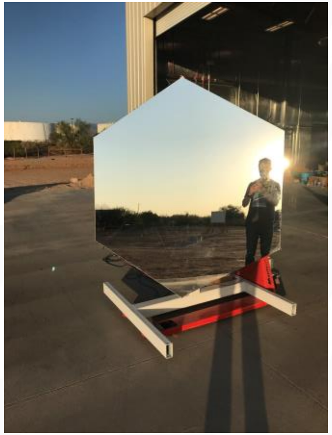
From Brost, et al., "Variation in Reflected Beam Shape and Pointing Accuracy Over Time and Heliostat Field Position," SolarPACES 2023.

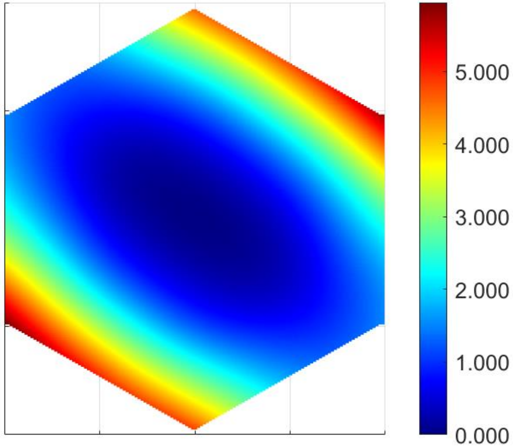
Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

2020 field test with hexagonal twisting heliostat

- One-piece mirror,
  - 3 mm thick glass
  - Area 1.58 m^2
- Alt-az mount
- 3 computer-controlled actuators to set shape





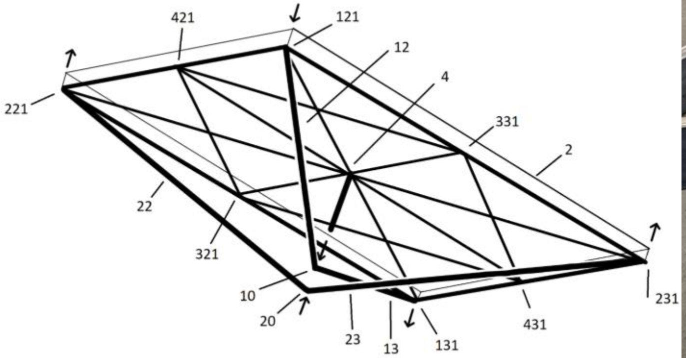


Solar disc image obtained at 2:30 pm, screen 40 m to the East, 62° AOI

New concept for automatic twisting, target axis mount

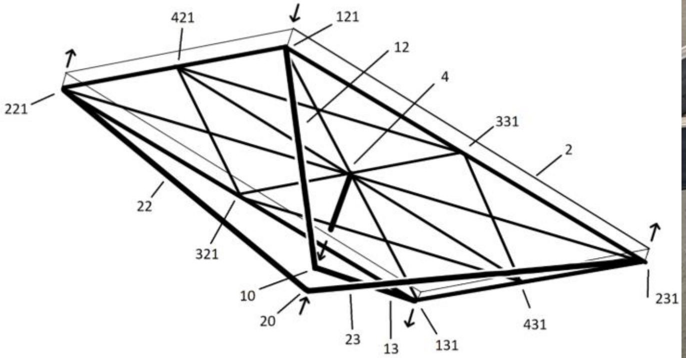
Reflector support frame welded from 1” x 4” steel tube I

Made in the U Arizona central Machining and Welding shop



Reflector support frame welded from 1” x 4” steel tube I

Made in the U Arizona central Machining and Welding shop



Funded by:
U.S. DEPARTMENT OF ENERGY

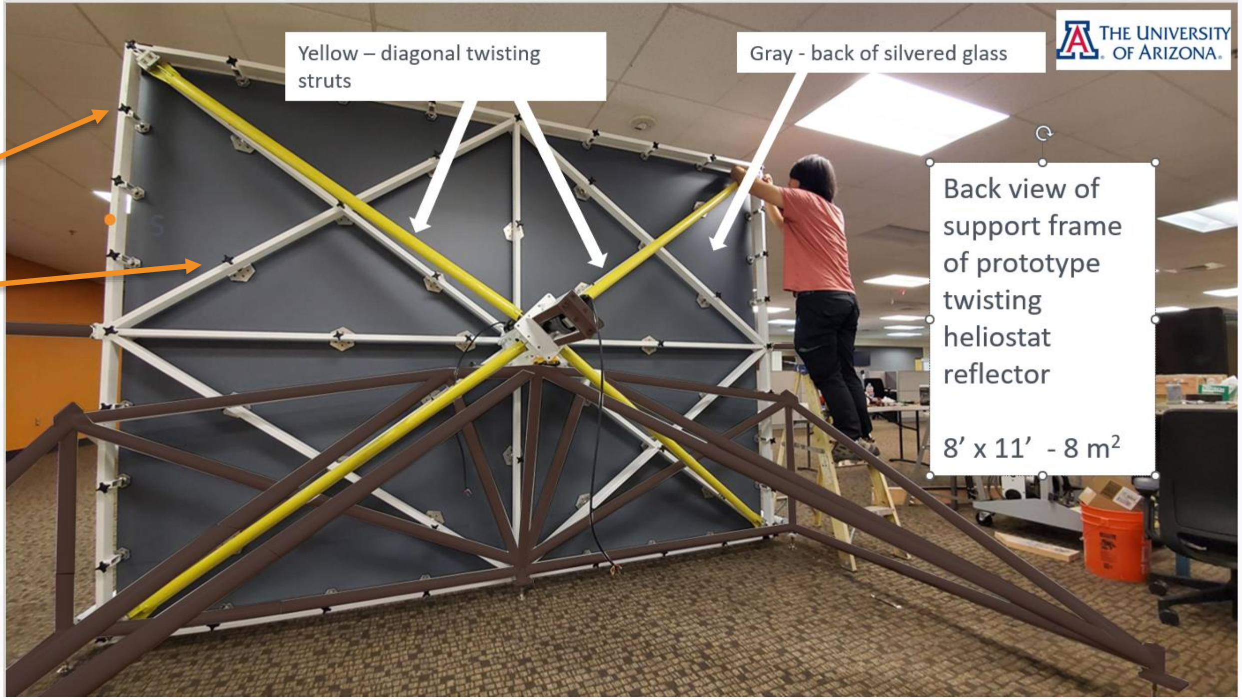
Back view shows frame with twisting struts attached

Frame in white and central back strut in white
Twisting struts in yellow

58 knobs initial setting before glass attached to heights calculated to give AOI 60° shape for untwisted white frame

Frame twisting action of yellow back struts calibrated here using temporary linear actuators to induce axial stroke

Reflector supported off floor from center strut, via brown structure



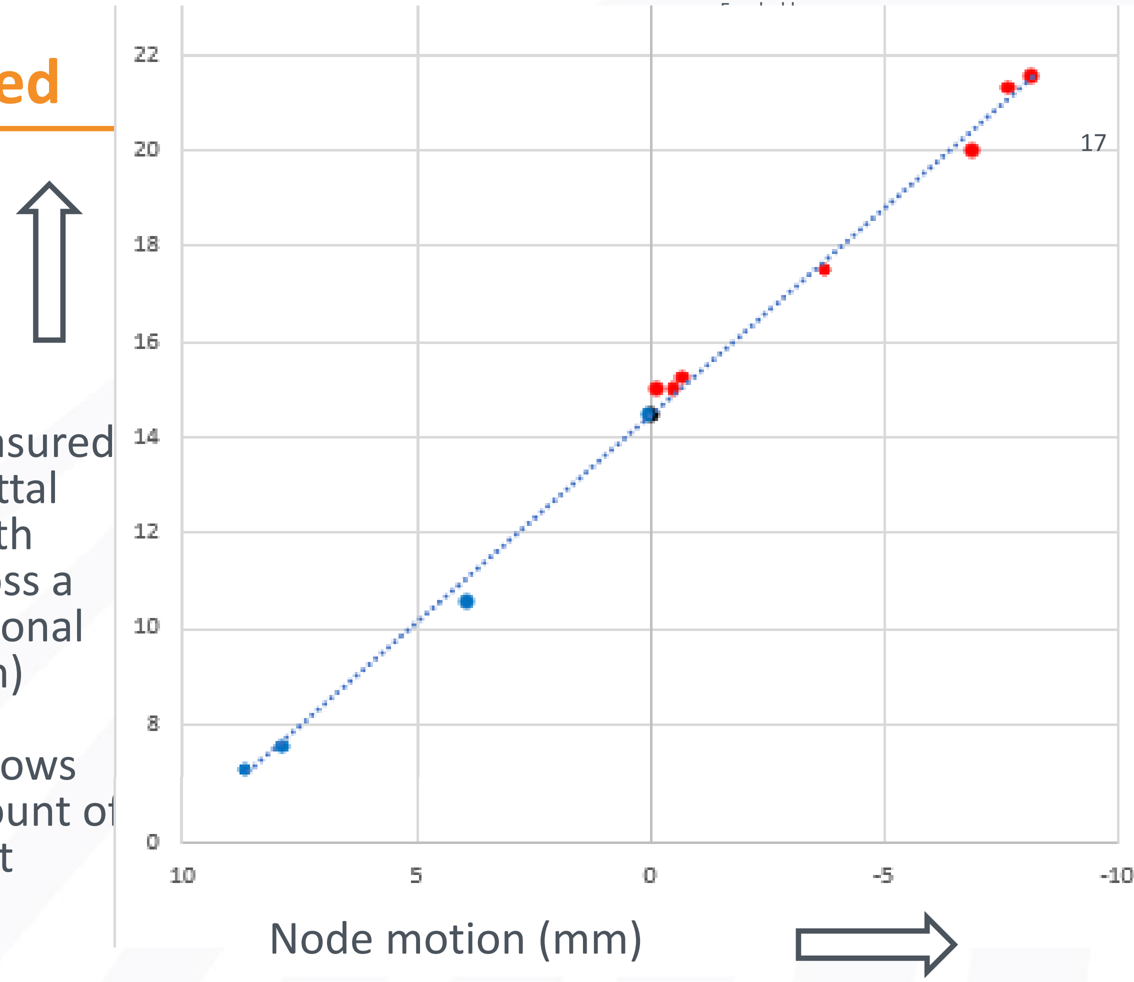
Reflector twisting calibrated as a function of node motion

- Calibration made with linear actuators moving the central nodes axially
- Yellow diagonals cause the twisting
- Very little hysteresis

- Further shape adjustment and calibration details given as part of Task 2 (metrology)

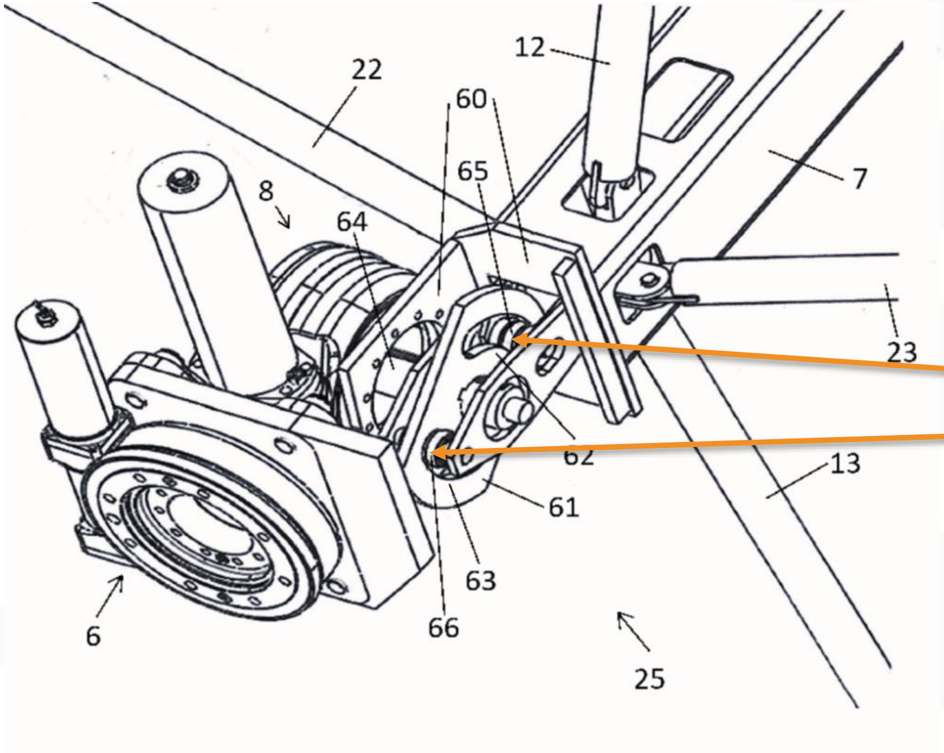
Measured sagittal depth across a diagonal (mm)

- shows amount of twist



Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

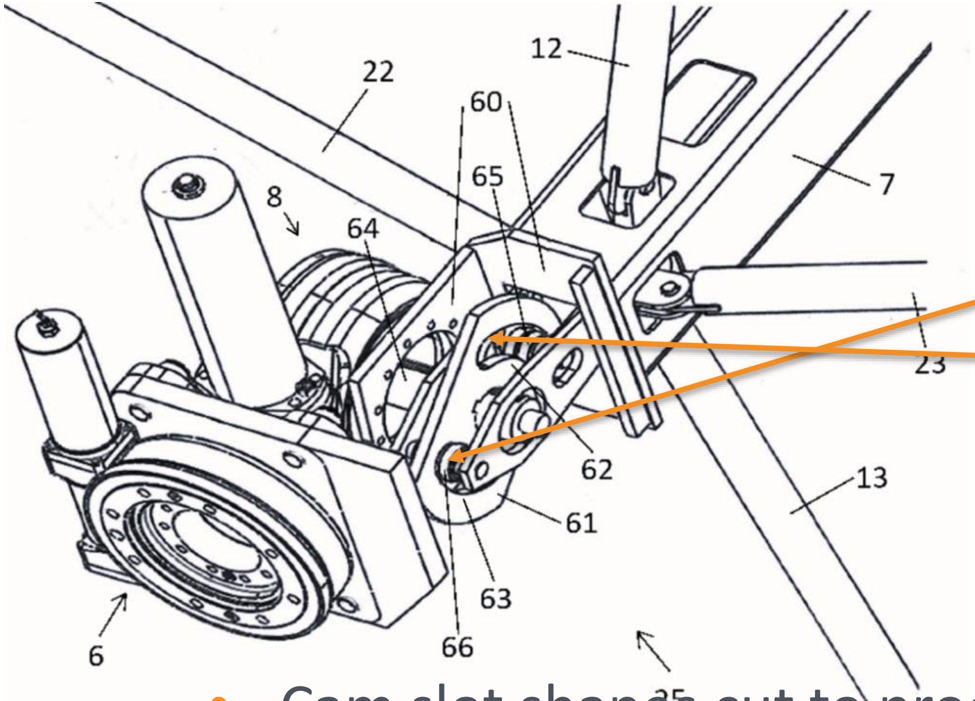
In Q4, add target axis mount with cam twisting

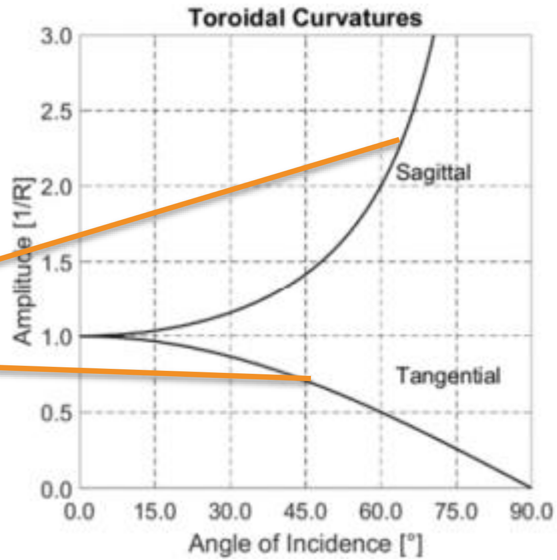


- The cam slot shapes will be cut using the twist calibration data

Cam mechanism made to drive twisting by the cross axis slew bearing

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE





- Cam slot shapes cut to produce desired curvature changes

Mechanism with attached to cross-axis drive

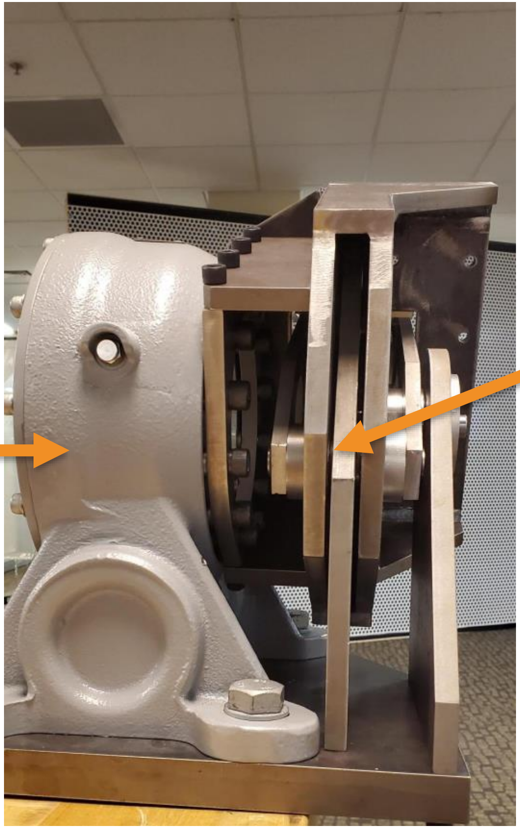
Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Cam slots cut in steel plate
- Clevises driven up and down as cross axis drive rotates

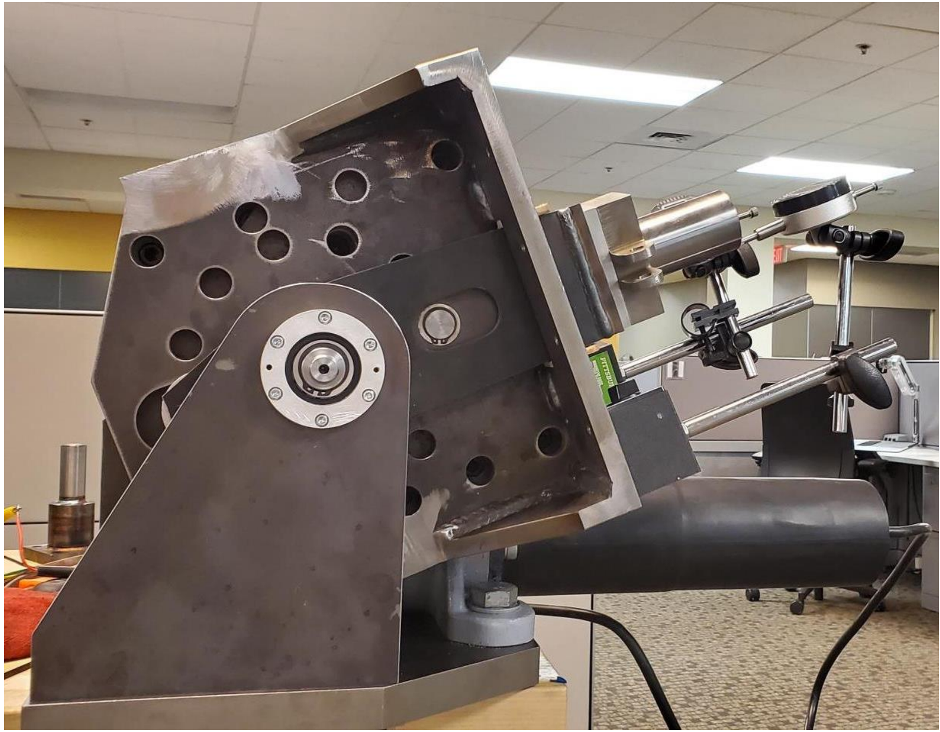
Mechanism details

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Cross axis drive turned to 70° angle of incidece



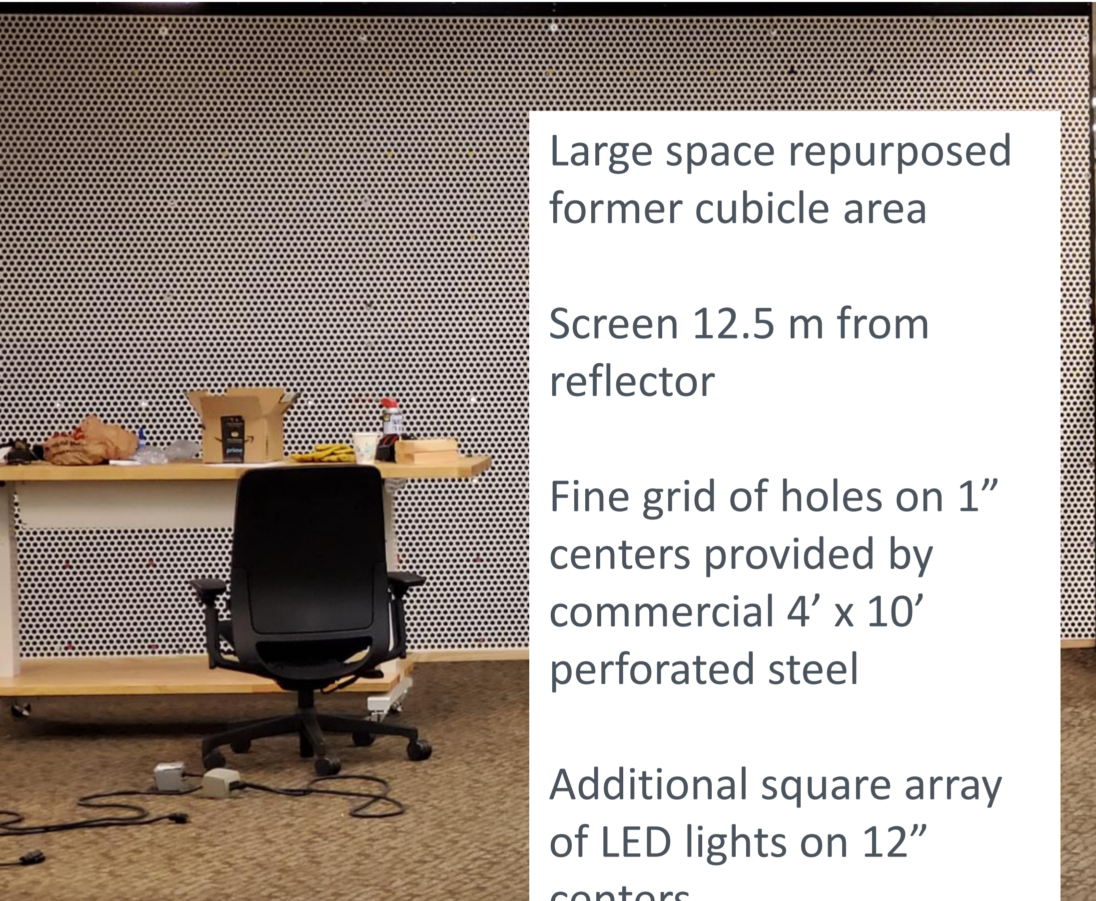
Cam fixed to base plate that attaches to target axis drive



View down cross axis, showing dial indicators to measure clevis motion

Indoor metrology and shape setting

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

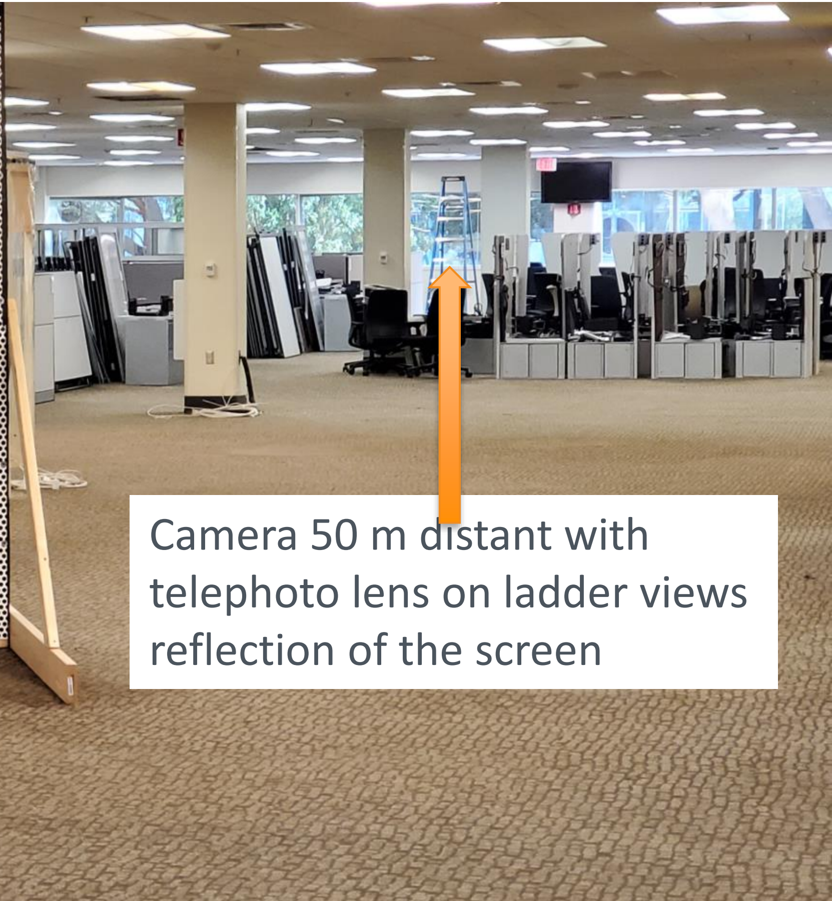


Large space repurposed former cubicle area

Screen 12.5 m from reflector

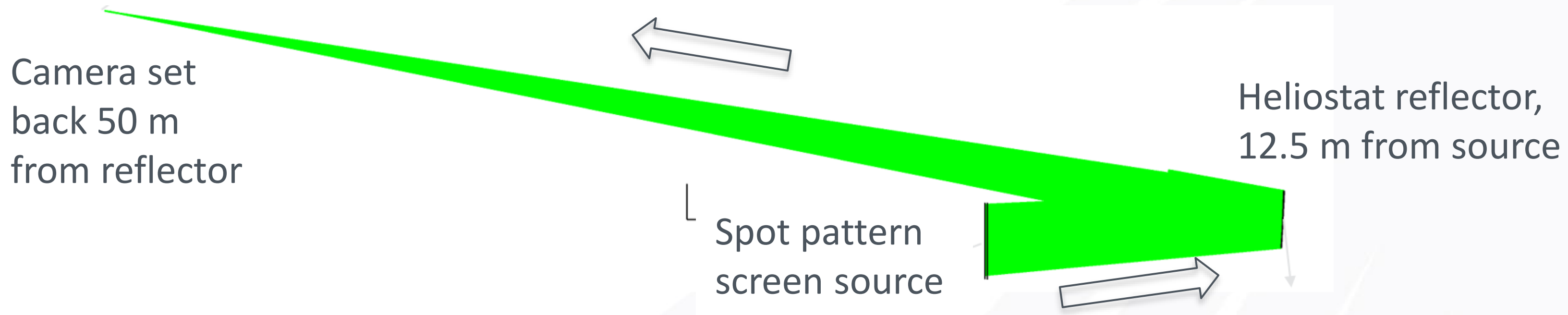
Fine grid of holes on 1” centers provided by commercial 4’ x 10’ perforated steel

Additional square array of LED lights on 12” centers



Camera 50 m distant with telephoto lens on ladder views reflection of the screen

High resolution metrology method

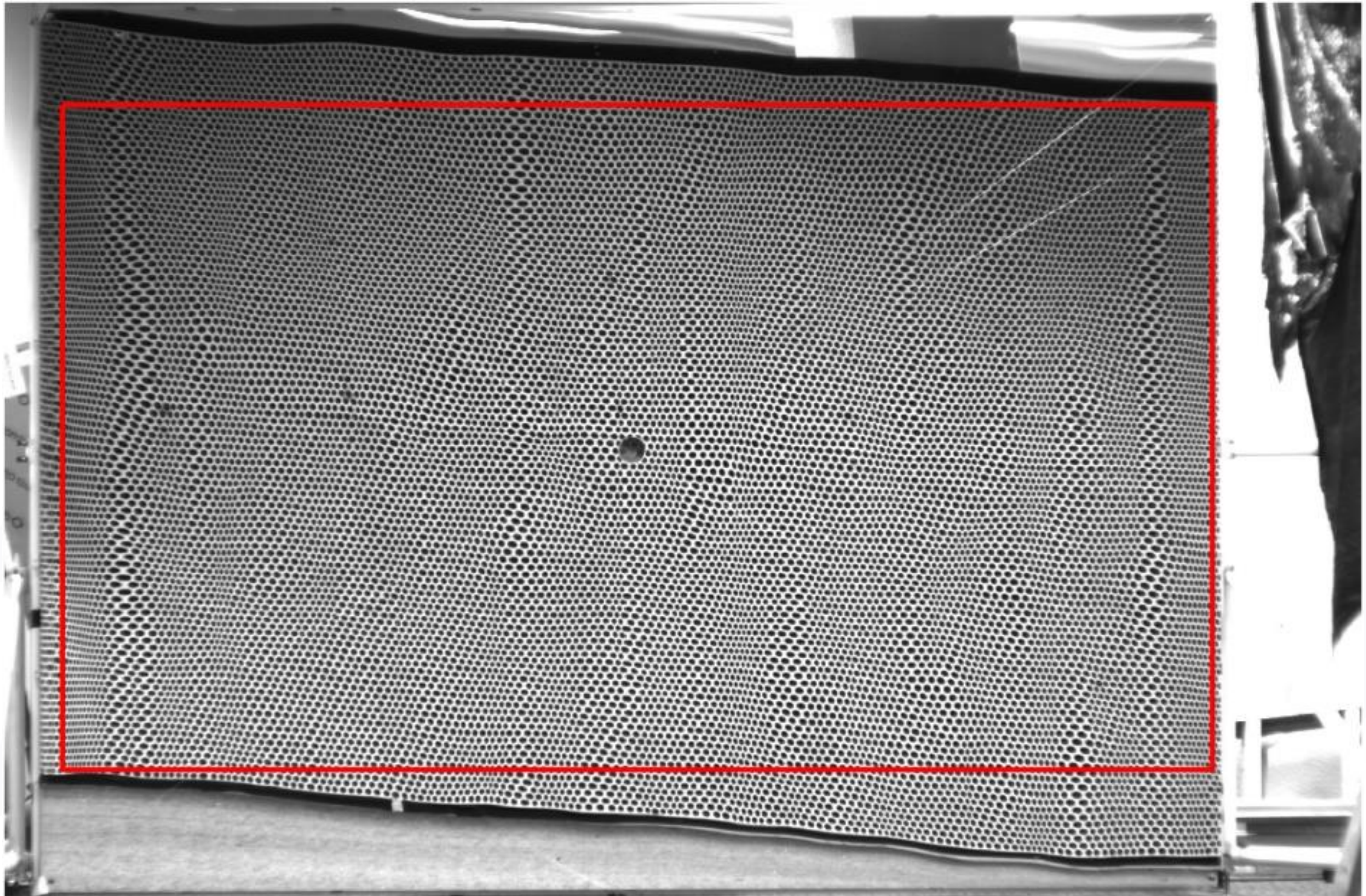


- Slope errors become apparent as distortion of spot pattern
- Development started in Q3
  - Demonstrated potential for high measurement accuracy , 0.1 mrad,
- Applicable to heliostats in field, given suitable placement of weatherproof spot screen

Screen viewed by camera, reflected by heliostat mirror

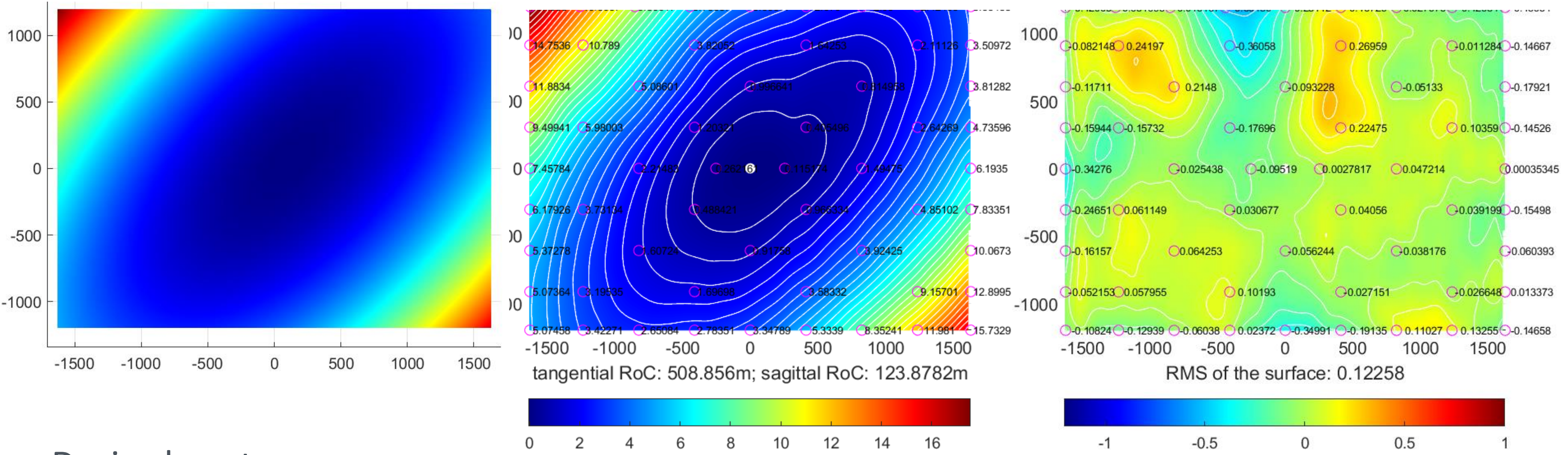
Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Twisting causes rectangular grid to spear as a parallelogram
- Local slope errors show up as distortion of spot pattern



Final metrology results for the reflector set for 60° AOI

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE



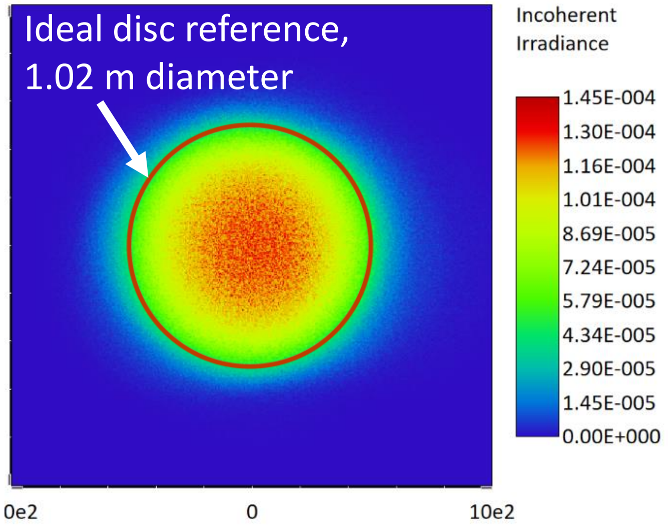
Desired contour map
(used for Zemax reference

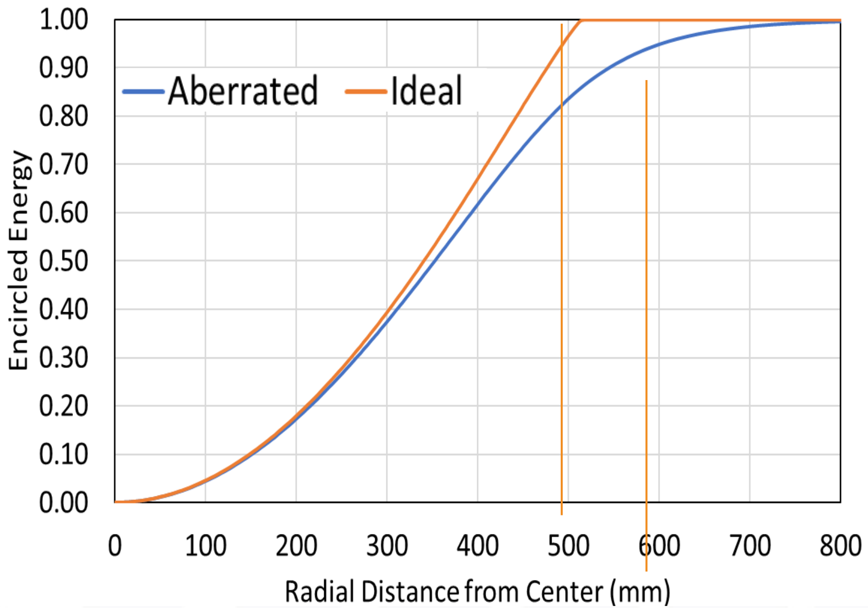
Measured contour map
17 mm P-V

Difference contour map
0.12 mm rms error -

Disc image from surface map by ray tracing

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE





- Solar disc image calculated for 113 m focal distance
- Same for all angles of incidence

- Encircled energy
  - 86% in ideal 1.02 m dia.
  - 95% in 1.2 m diameter

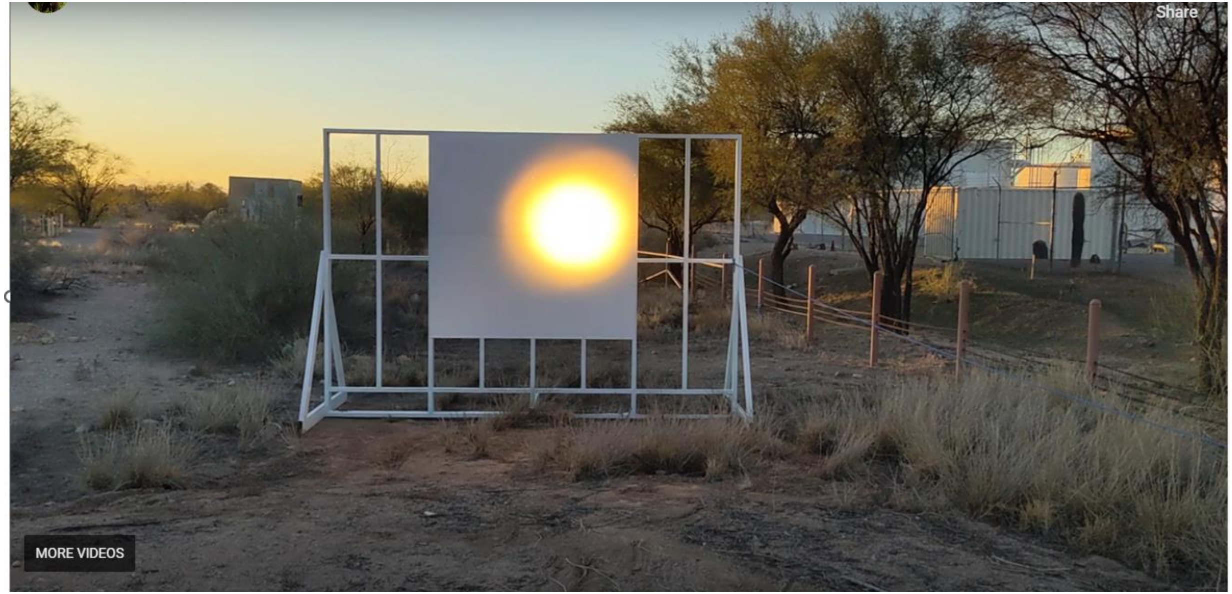
Completed heliostat at U AZ Tucson test site

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

Here's what we saw

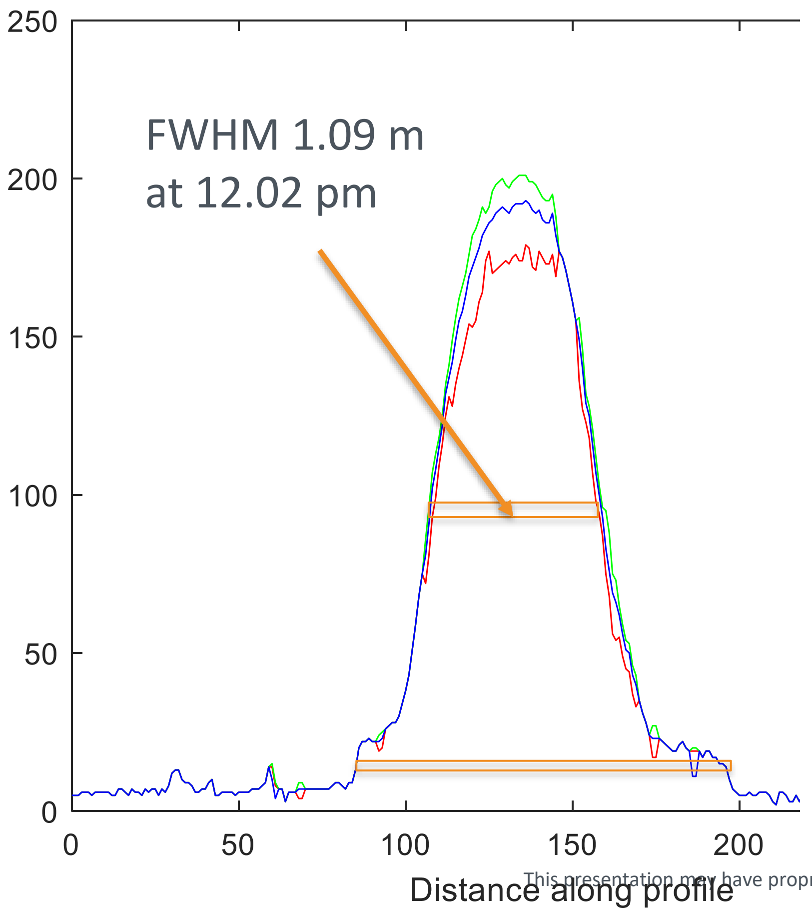
Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

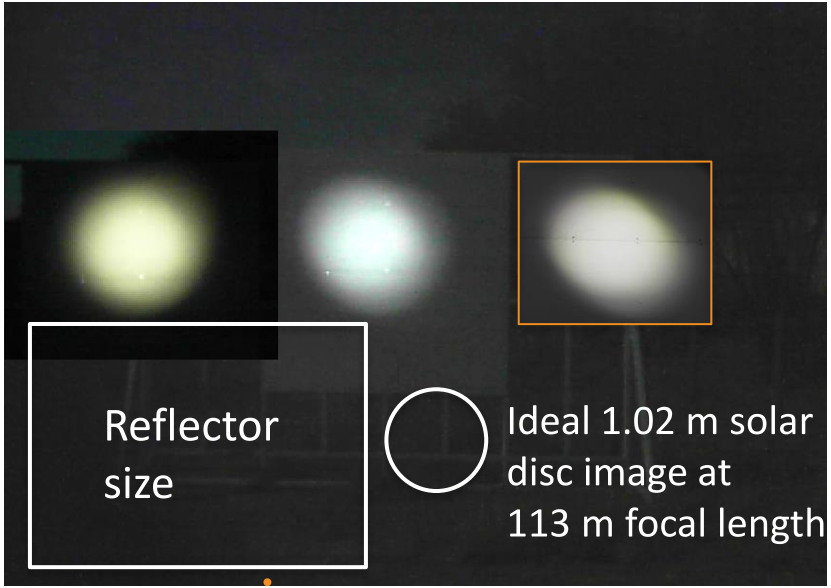
- Disc image of the sun!
- Screen 2.44 m square at 113 m
- Evening, sun at nearly normal incidence
- Image saturated



Images of solar disc formed over full day

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

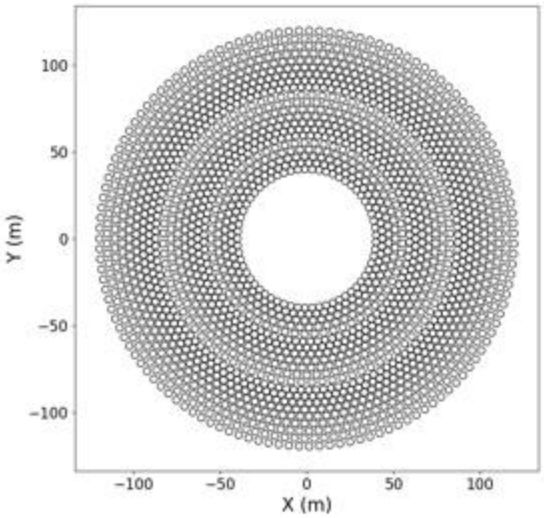


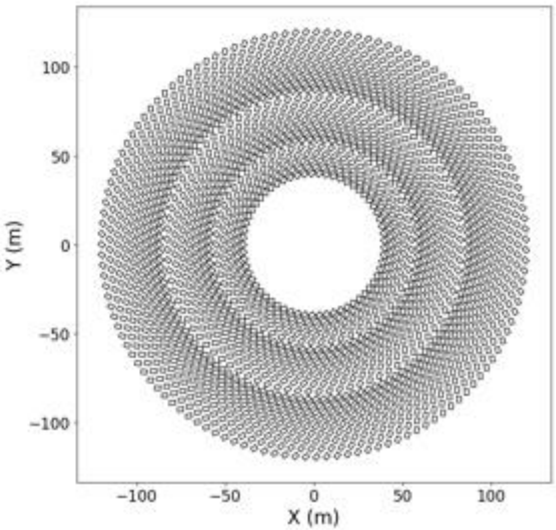


- **5:07 PM**
- solar az: 241
- solar el: 6
- AOI: 14.8

- **12:02 PM**
- solar az: 171
- solar el: 36
- AOI: 48.6

- **9:05 AM**
- solar az: 130
- solar el: 17
- AOI: 68.6


100
50
0
−50
−100
Y (m)
−100
−50
0
50
100
X (m)


100
50
0
−50
−100
Y (m)
−100
−50
0
50
100
X (m)

Design for s-CO2 10 Mwe turbine

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

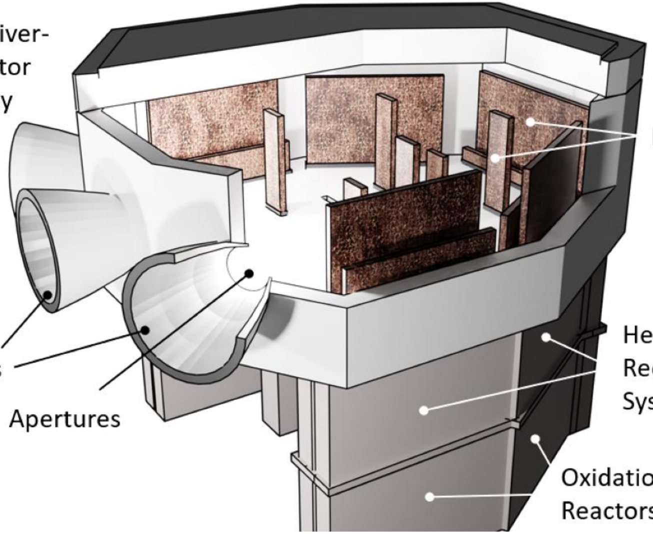
- 2064 x 32 m^2 heliostats
- Each heliostat made using 4 facets of present8 m^2

size on twisting steel support

Getting to 1500C for syngas, cement

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Twisting heliostats with round disc images are ideal
- 100 – 200 images, each 10x concentration give 1000-2000 conc. at entrance
- Compound parabolic concentrators give further 10x concentration
- Model at 8 am on equinox gives 3,500 kW/m^2
- Black body loss minimized
- Productive throughout the year



Brendelberger ceria reactor

Basics of direct air capture, DAC

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- Burning fossil fuel has added > 1 trillion tons of CO_2 to the atmosphere
- Even when we stop burning it, this will take centuries to dissipate, and in the meantime keep the world hot
- Tens of meters of sea level rise could easily occur
- Hence the need for DAC
- To reduce the trillion tons in 50 years takes 20 billion tons per year, worldwide removal
- 1 billion tons/year a modest start for the USA

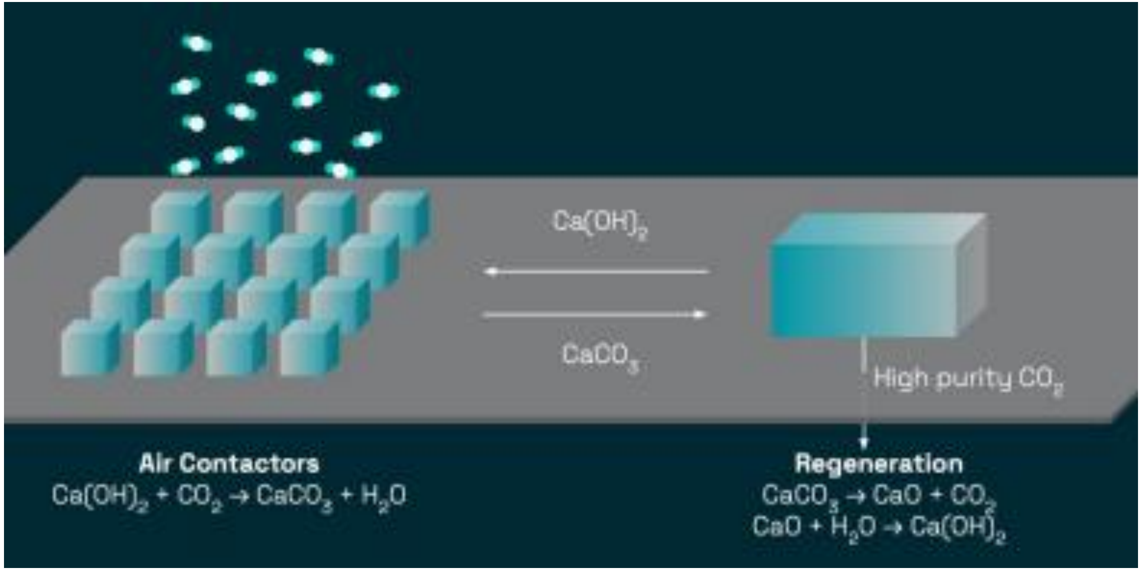
Renewable energy for 1 billion tons/year?

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

- For a variety of methods, need 7.5 GJ /ton (equal to 2,500 kWh)
- Using electricity, with 80% efficiency, would take 3 trillion kWh/billion tons CO2
- PV generates 0.1 billion kWh/km^2 , so need 30,000 km2 of PV panels, 20 times present US land in utility scale generation
- And this is for just 2% of what we would need per year for 50 years!
- We have a serious problem, can heliostats help?

Carbon capture using limestone - Heirloom

Funded by:
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE



- Decomposition of $CaCO_3$ requires roughly 4 GJ per metric ton of CO_2
- Reaction occurs at 900°C. 1000 ton/year facility started in California
- Uses renewable electricity to heat and recycle the limestone

Solar Energy directly for calcination?

Funded by: U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY SOLAR ENERGY TECHNOLOGIES OFFICE

- Anton Meir et al, ASME 2005
- Multitube Rotary Kiln for the Industrial Solar Production of Lime
- Increase solar efficiency and reduce land area by factor 3