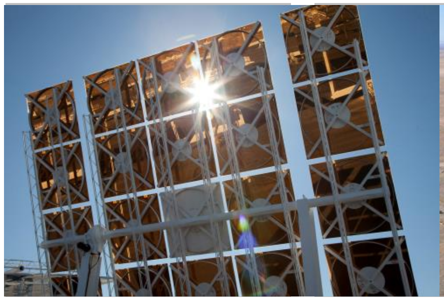
State of the Art of Solar Tower Technology

Exceptional service in the national interest

Sandia National Laboratories

Clifford K. Ho
Sandia National Laboratories
Concentrating Solar Technologies Dept.
Albuquerque, New Mexico, USA
ckho@sandia.gov, (505) 844-2384

SAND2016-9390



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

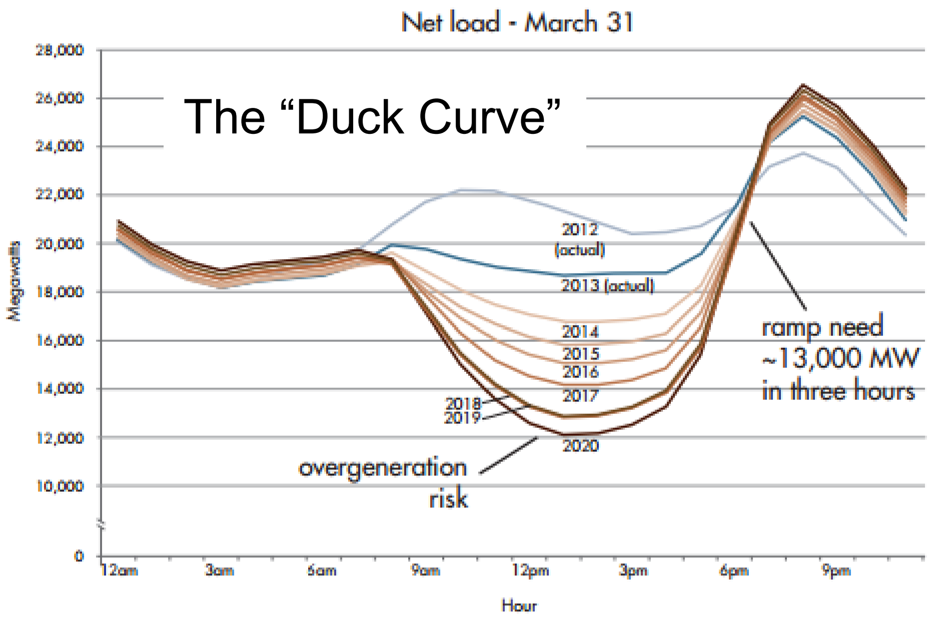
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

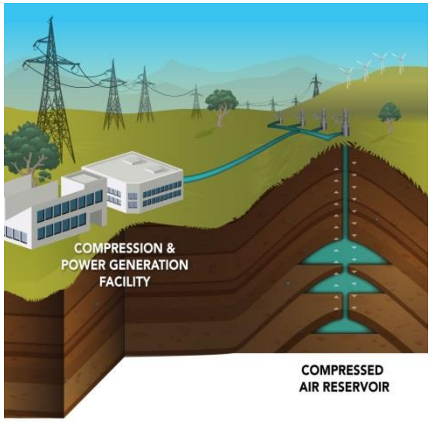
- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Commercial Solar Tower Plants
- Challenges and Research Needs
- Summary

Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand, even at high penetration
- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $0.20/kWh_e - $1.00/kWh_e
  - Compressed air and pumped hydro – geography and/or resource limited



Source: California Independent System Operator



Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage

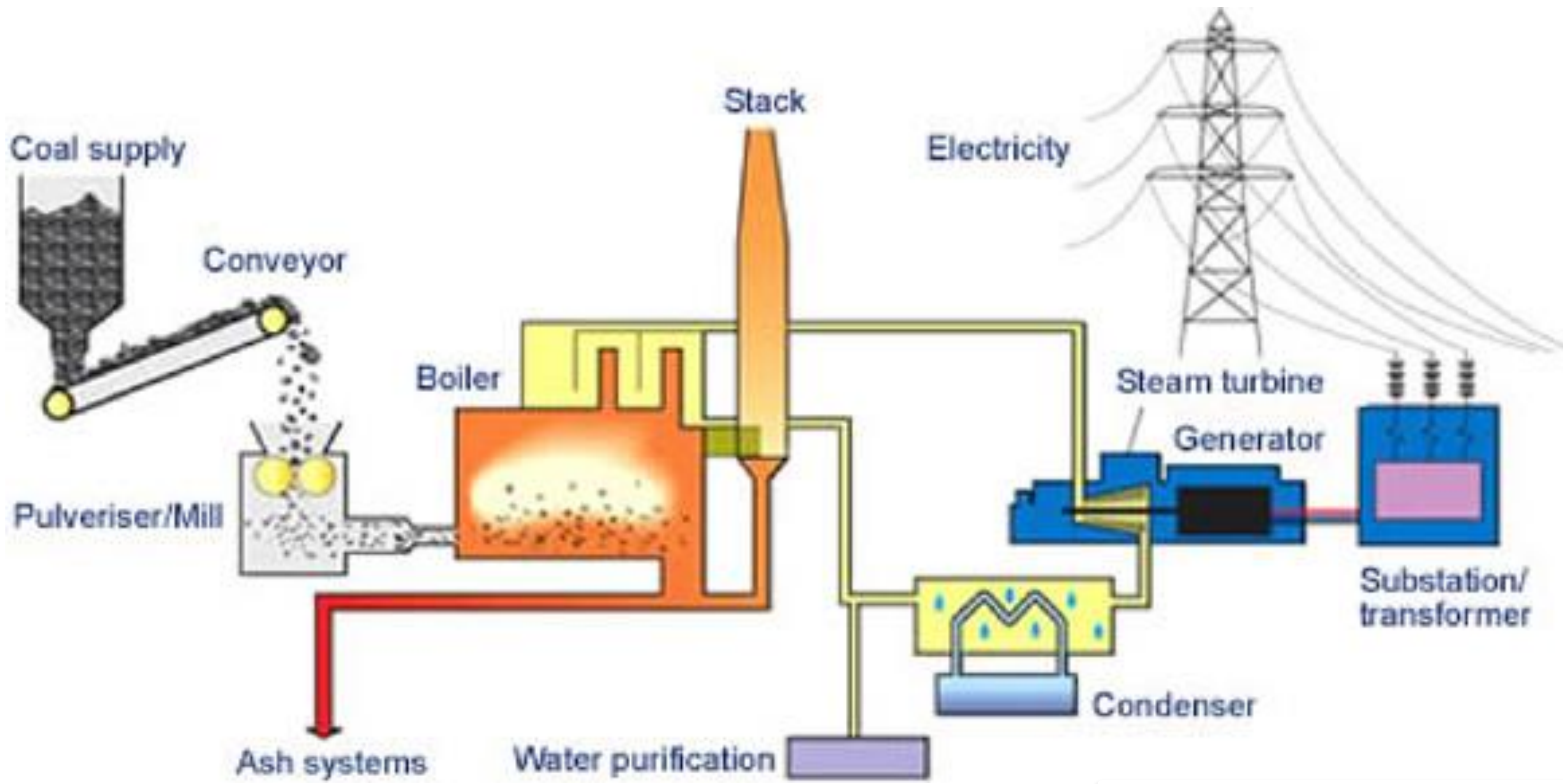
→ Concentrating solar power (CSP) with thermal energy storage

Outline

- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Commercial Solar Tower Plants
- Challenges and Research Needs
- Summary

What is Concentrating Solar Power (CSP)?

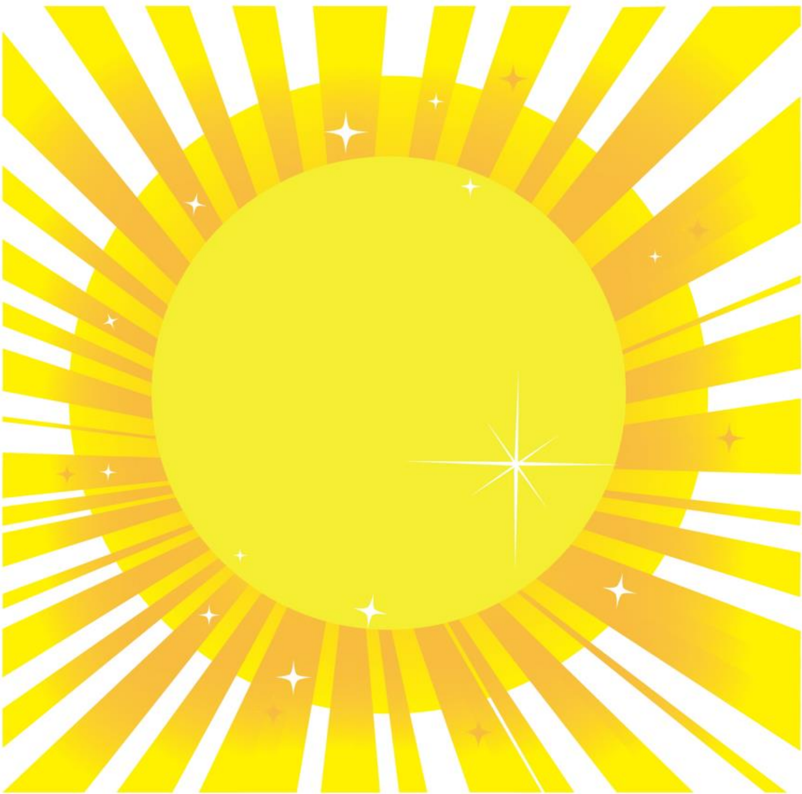
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

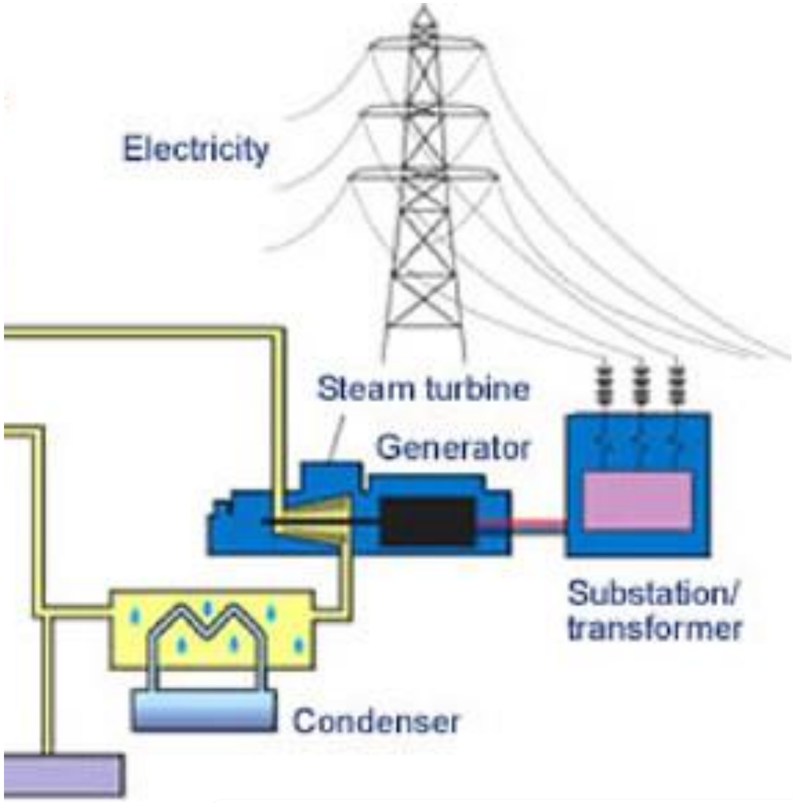


Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle

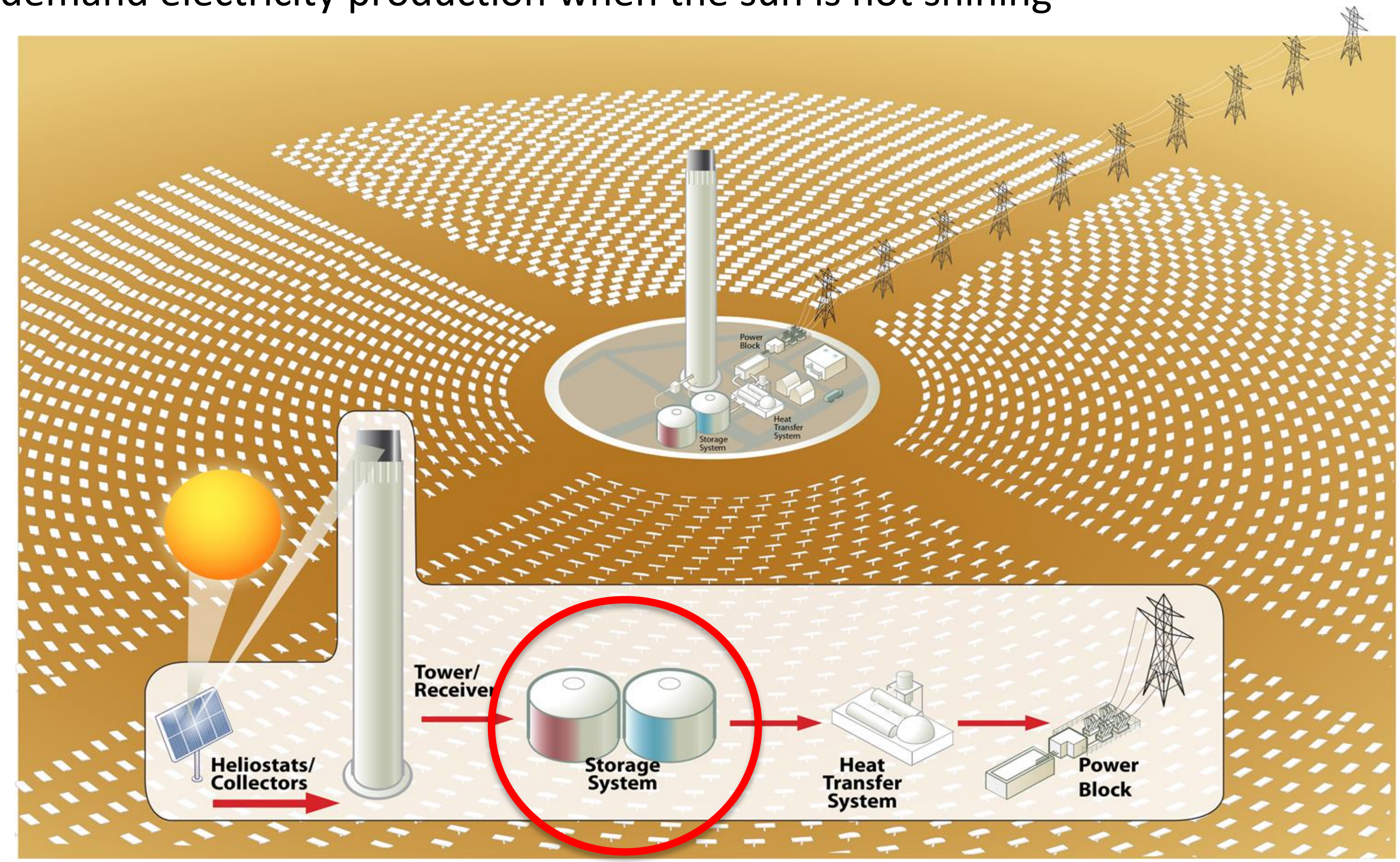




Concentrating Solar Power

CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



Timeline of CSP Development

Sandia National Laboratories

Solar One and Solar Two
10 MW_e
Daggett, CA
1980's – 1990's

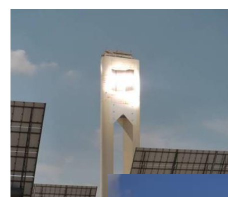
Stirling Energy Systems
1.5 MW_e, AZ, 2010

Ivanpah, steam, 377 MW_e, CA, 2014

1970's → 1980's – 1990's → 2000's → SunShot 2011 -

National Solar Thermal Test Facility
6 MW_t, Albuquerque, NM, Est. 1976

SEGS, 1980's
9 trough plants
354 Mw_e, CA



PS10/20, steam, Spain, 2007-2009

Gemasolar, molten salt, 19 MW_e, Spain, 2011

Crescent Dunes, molten salt, 110 MW_e, NV, 2015

Outline

- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Commercial Solar Tower Plants
- Challenges and Research Needs
- Summary

Direct Steam Solar Towers

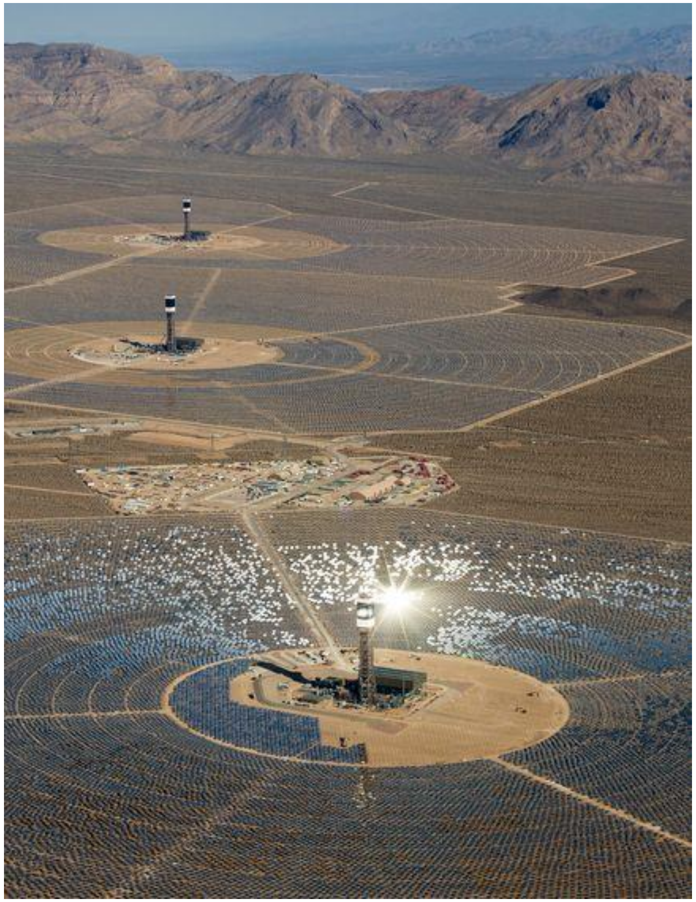
PS10 and PS20 (Seville, Spain)

- First commercial power tower plants in the world (2007, 2009)
- 11 MW and 20 MW
- Saturated steam
  - 250 C, 45 bar steam, wet cooling

Ivanpah Solar Power Tower

California (near Las Vegas, NV)

http://news.nationalgeographic.com



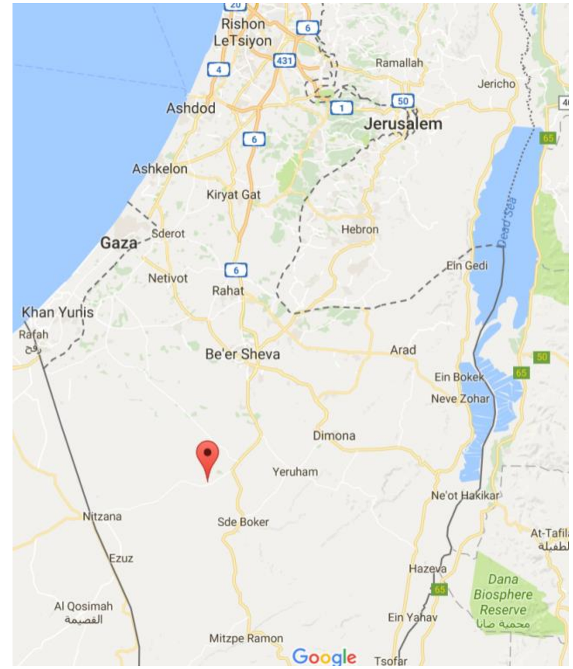
Three towers, 392 MWe, superheated-steam at 540 C, 160 bar, air-cooled (2014)

Ashalim Solar Power Station

(Under Construction 2015 - 2017)

Sandia National Laboratories

- 121 MWe Solar Tower
  - 2% of Israel’s electricity needs
  - 110,000 households
- Superheated steam
  - ~600 C
- Wi-Fi controlled heliostats



Receiver and heliostat field under construction

Photo credit: Jack Guez/AFP (May 2016)

Molten Salt Solar Tower

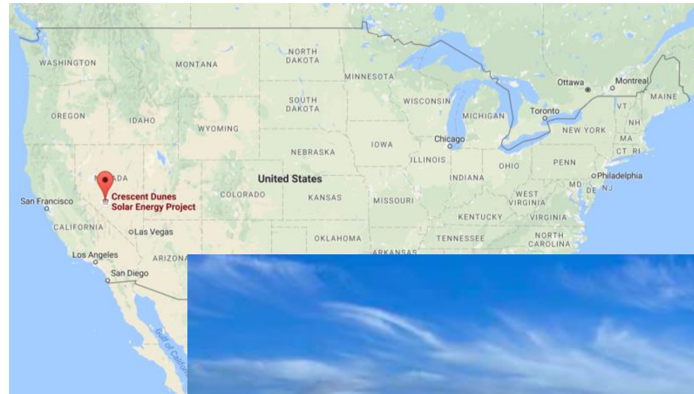
Gemasolar

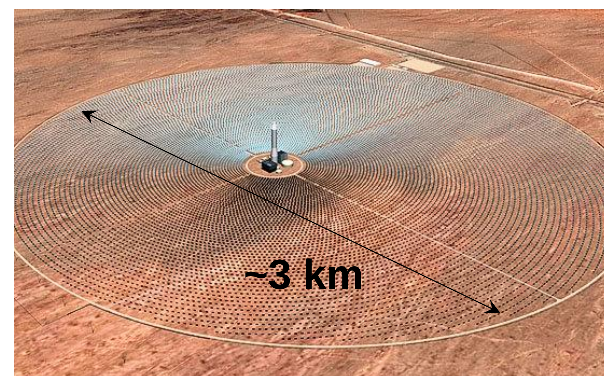
(near Seville, Spain)

- 1st commercial power tower (19 MW) in the world with "24/7 dispatchable energy production" (15 hours of thermal storage using molten salt), wet cooling. Commissioned in May 2011.

Crescent Dunes

Tonopah, Nevada



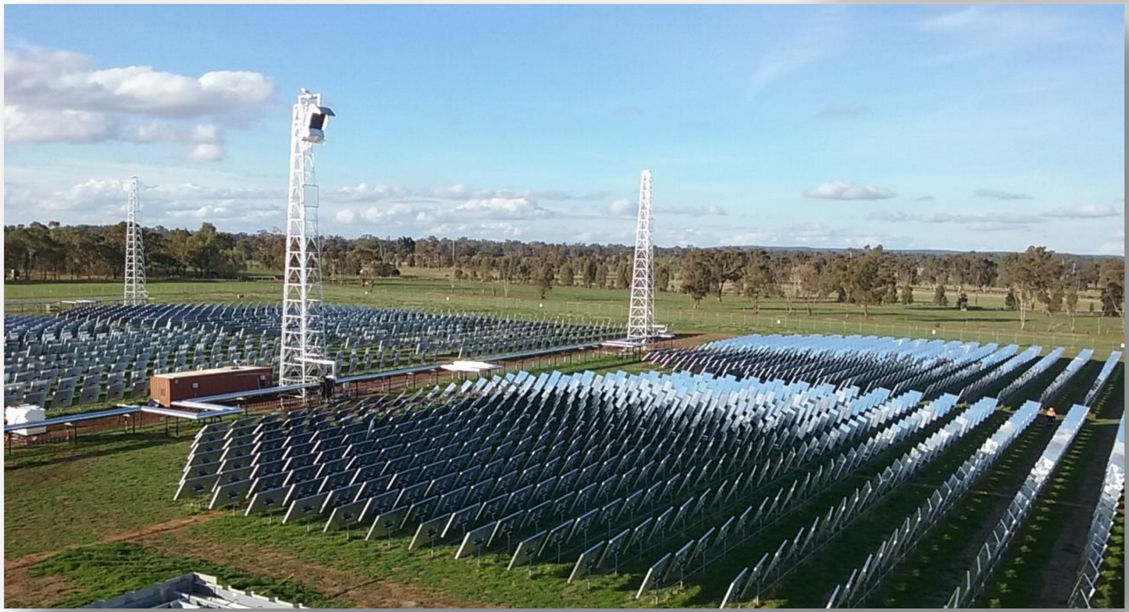


110 MWe, 570 C molten-salt, 10 hours of storage, hybrid air-cooled condenser (2015)

Liquid Sodium Solar Tower

Jemalong Solar Station - Australia

- Expected start in 2016
- 1.1 MW_e
- Liquid sodium
  - 560 C
  - 3 hour storage
  - Dry cooling



5 modular solar fields with 30 m towers

Outline

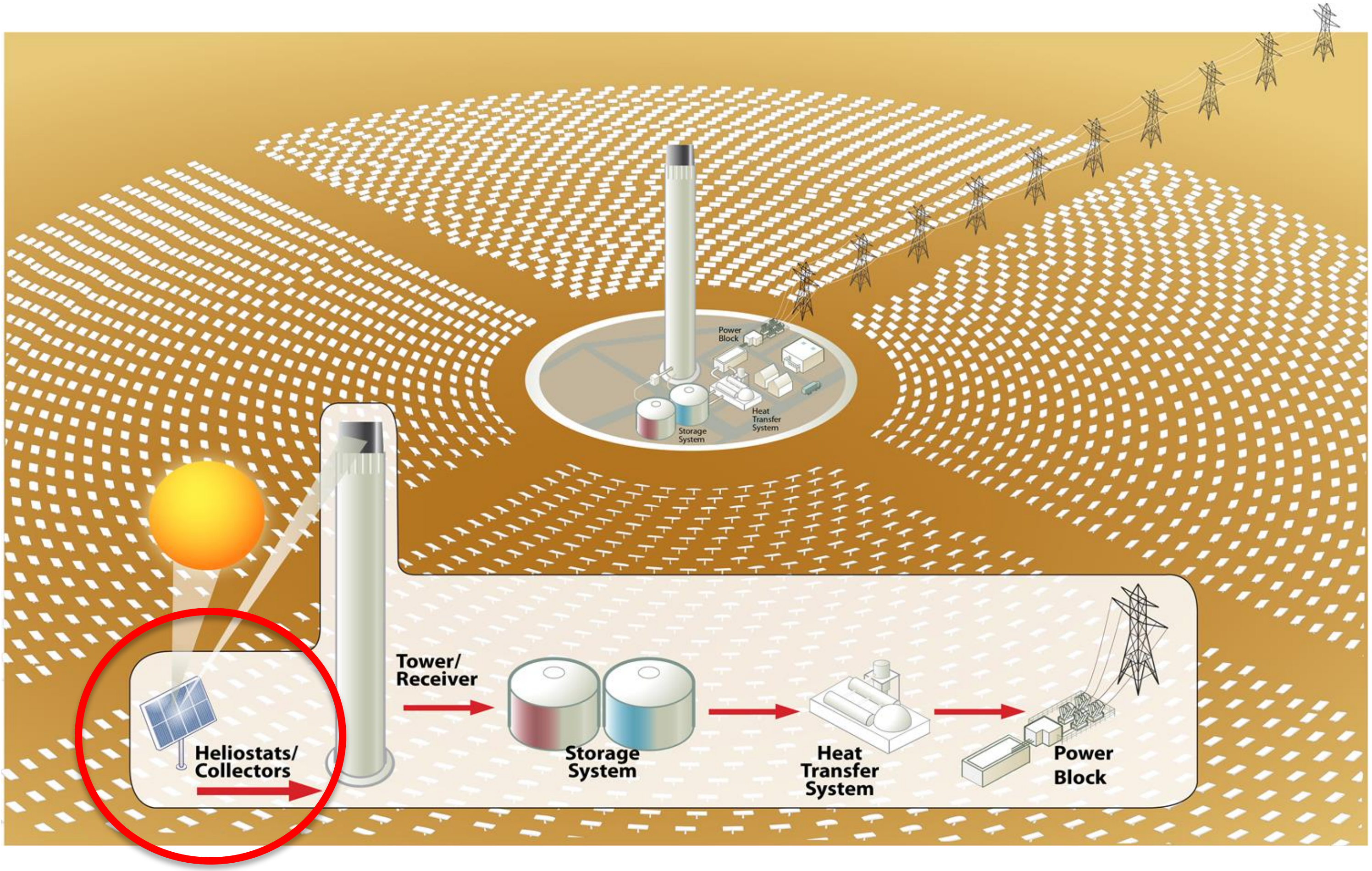
Sandia National Laboratories

- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Commercial Solar Tower Plants
- Challenges and Research Needs
- Summary

Challenges and Research Needs

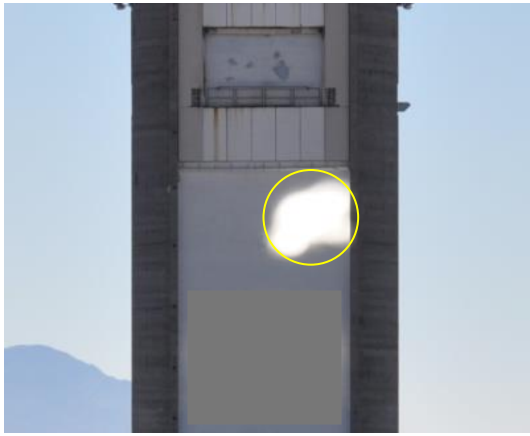
- Heliostat Alignment and Optical Performance
- High-Temperature Receivers
- Thermal Energy Storage

Heliostats and Optical Performance



Optical Accuracy – Alignment & Tracking

- Mirrors need to be properly aligned and focused
- Need accurate tracking



Before

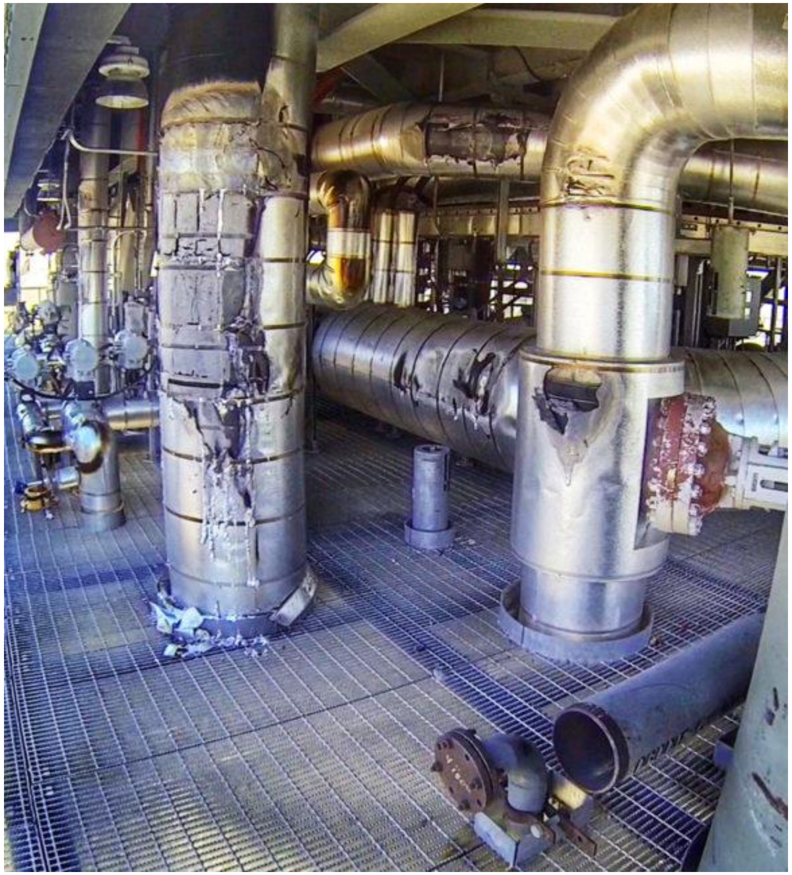
After

What happens if heliostats are misaligned or not tracking properly?

- Reduced energy production
- Overheating / fire hazard

In May 2016, mirrors that were not tracking properly caused a small fire in the Unit 3 tower at Ivanaph, igniting wiring and insulation around pipes

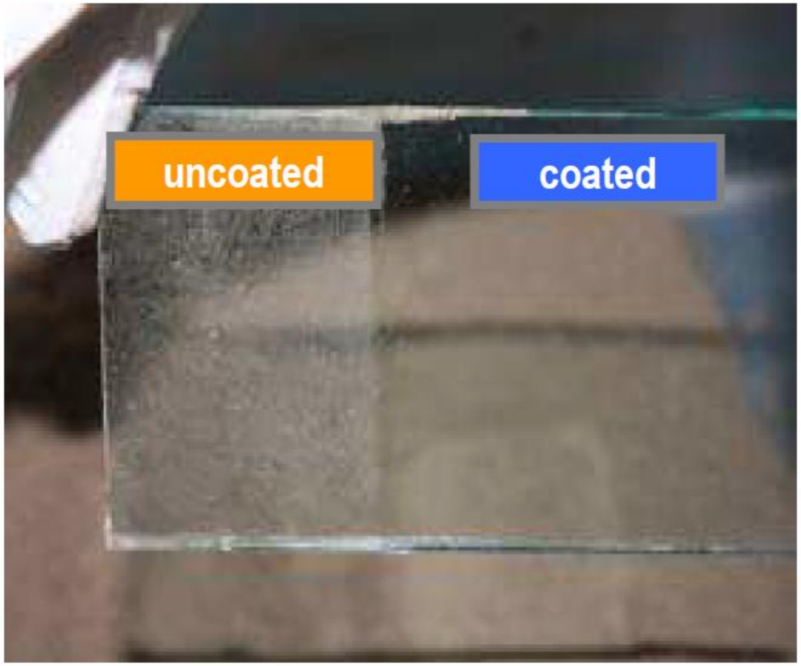
San Bernardino County Fire Department/A)



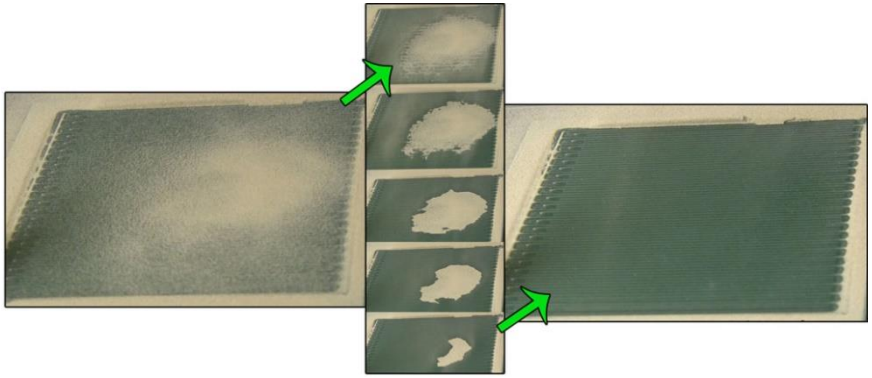
Mirrors need to be kept clean

- Need anti-soiling coatings or devices for mirrors to reduce need for washing and maintain high reflectivity

Anti-Soiling Coatings and Devices



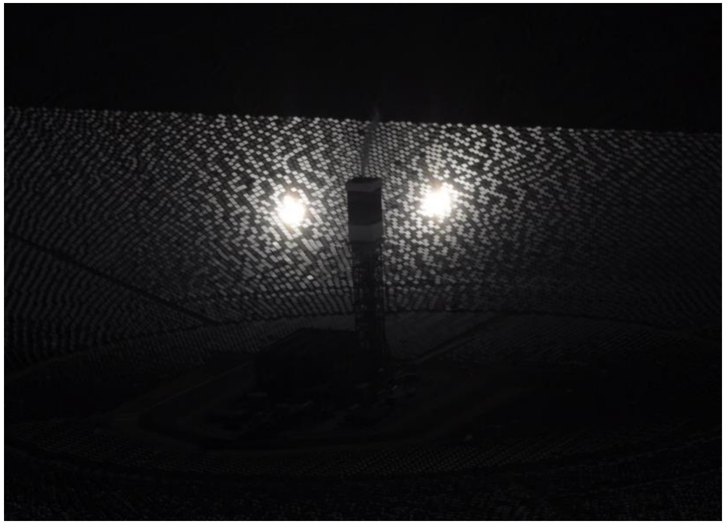
3M Anti-Soiling Coating
(nanoparticle based liquid pH ~3)



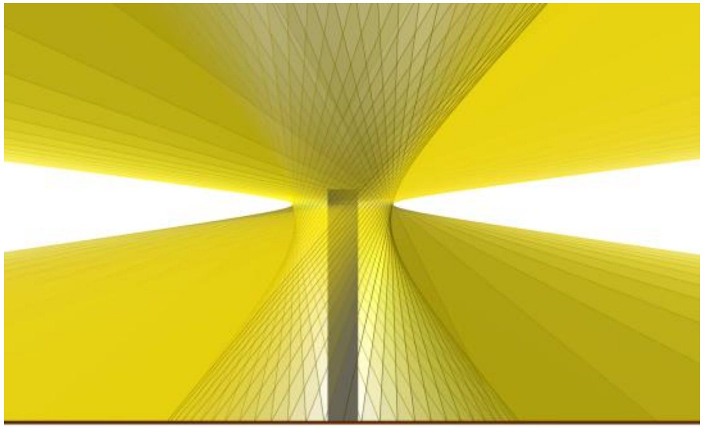
M. Mazumdar (Boston University)
Electrodynamic screens charge particles and lift them off the surface

Need to Prevent Glare

Looking Northeast at Ivanpah Unit 1, 9:10 AM PDT (~3 miles away from glare)



Ryan Goerl, NRG

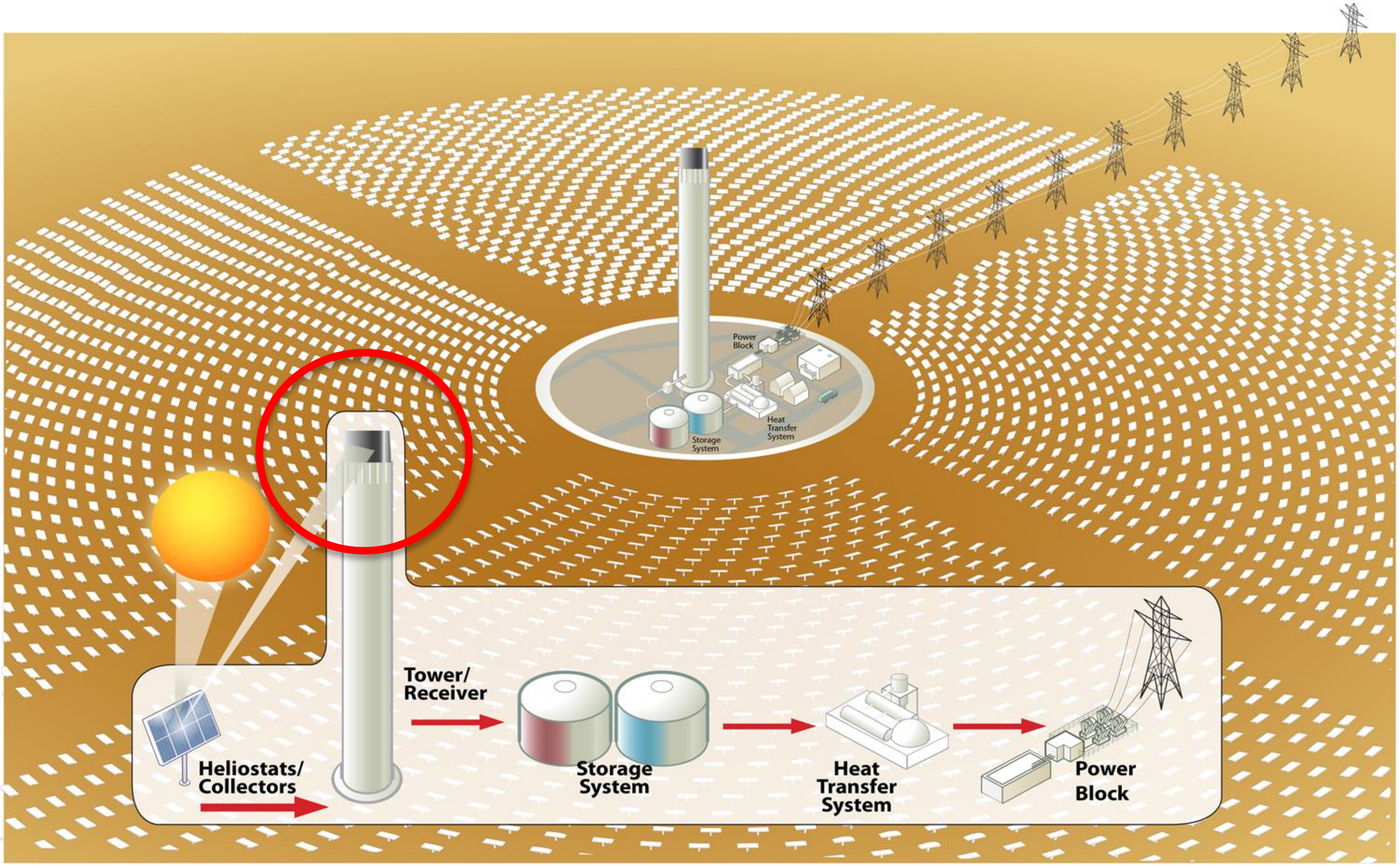


Reduce Avian Mortality and Hazards

- Recent reports of birds being singed and killed by solar flux at CSP plants have drawn a significant amount of attention and negative publicity
- Need alternative heliostat standby aiming strategies that mitigate avian flux hazards and glare

MacGillivray Warbler with "Grade 3" solar flux injury found at Ivanpah CSP Plant (Kagan et al., 2014)

Receivers



Power Block
Heat Transfer System
Storage System
Tower/ Receiver
Heliostats/ Collectors
Storage System
Heat Transfer System
Power Block

High-Temperature Receivers

Sandia National Laboratories

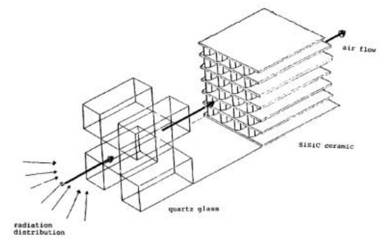
- Maximize solar absorptance and minimize heat loss (selective absorber coatings, geometry, concentration ratio)
- Need materials that operate at high temperature (>700 °C) and are durable in air

Cavity receiver

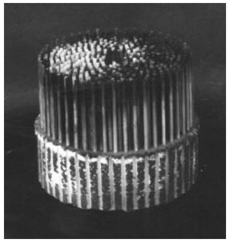
External tubular receiver

Types of Receivers & Challenges

- Gas-Based Central Receivers
  - Low heat transfer coefficient, low efficiency, heat exchange, flow instabilities, storage
- Liquid-Based Central Receivers
  - Decomposition of molten nitrate salts > 600 C, corrosivity of chloride salts, freezing of salts, material durability
- Solid-Particle Central Receivers
  - Particle/fluid heat exchange, high convective loss, particle attrition, particle conveyance and control



Pitz-Paal et al. (1991)


“Porcupine”
(Karni et al., 1998;
Kribus, 1999, 2001)


Solar Two
Molten Salt
Receiver
(Pacheco,
2002)

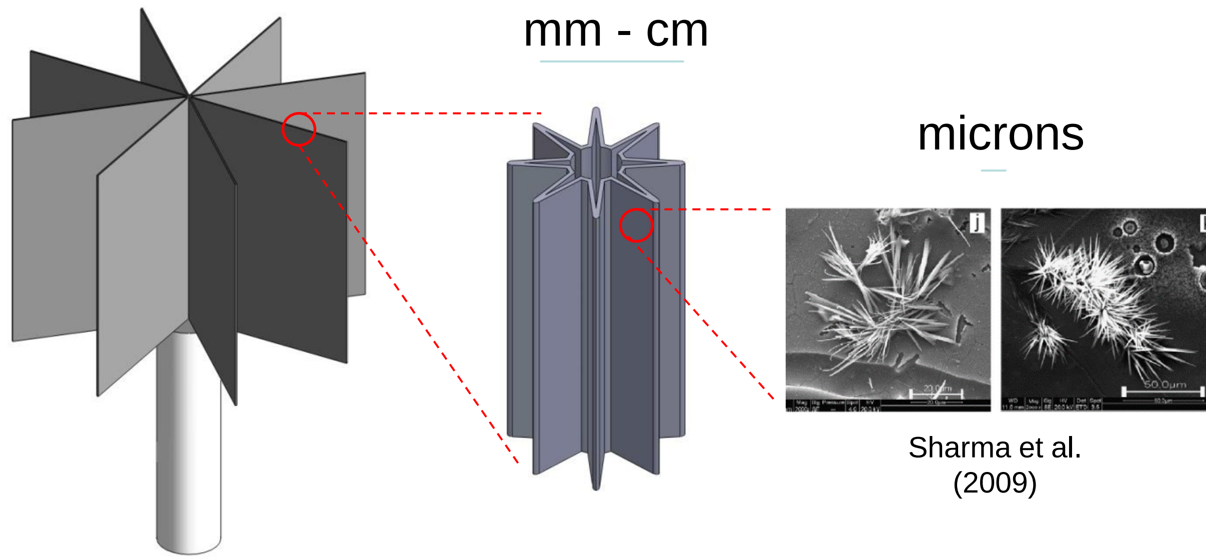
Fractal-Like Receiver Designs

- Develop fractal-like designs and structures across multiple scales to increase solar absorptance while minimizing heat loss

~10 m

Conventional cylindrical solar receiver

meters



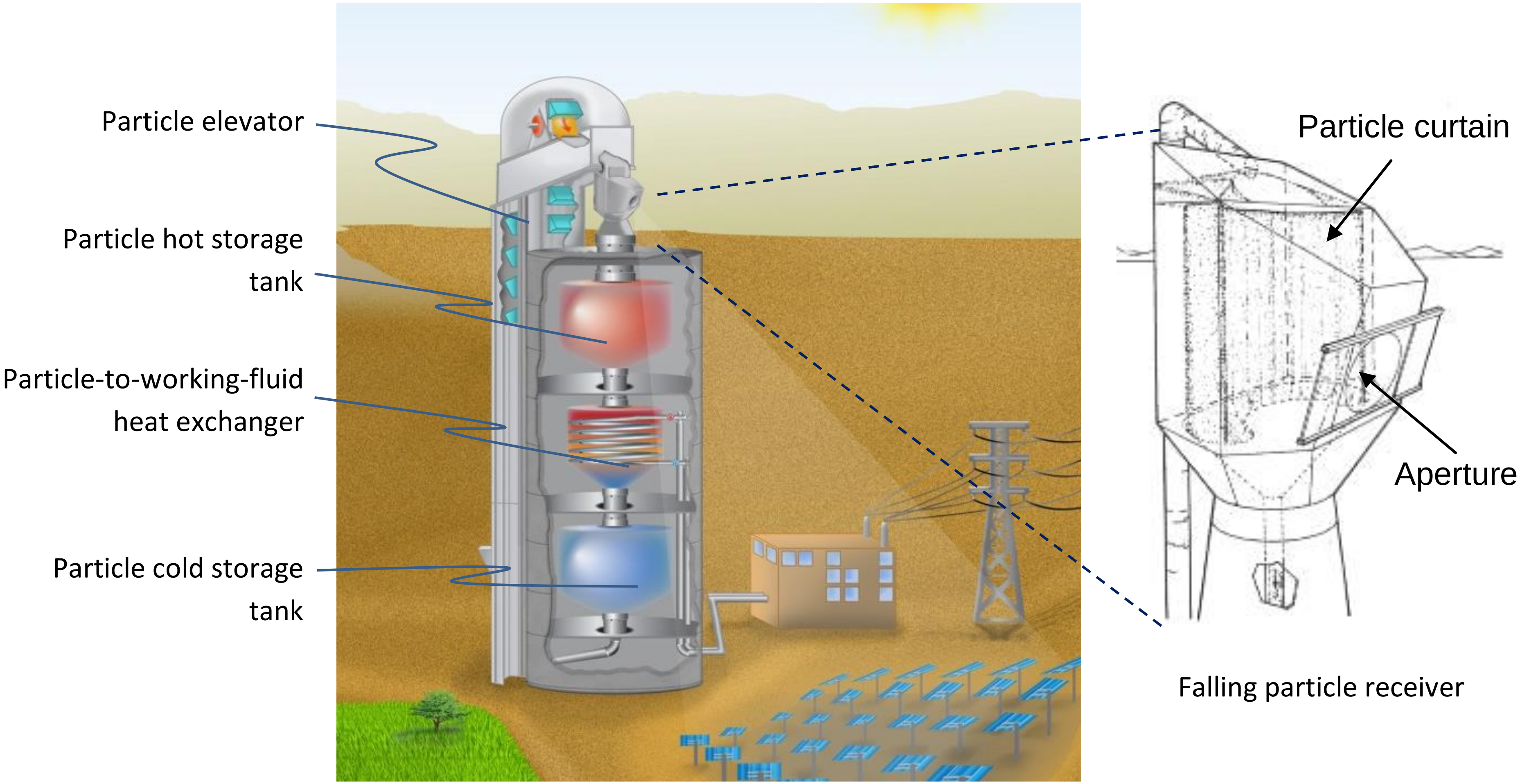
Sharma et al. (2009)

New fractal-like designs with light-trapping and low-emittance properties at multiple scales

Patents Pending

High Temperature Falling Particle Receiver (DOE SunShot Award FY13 – FY16)

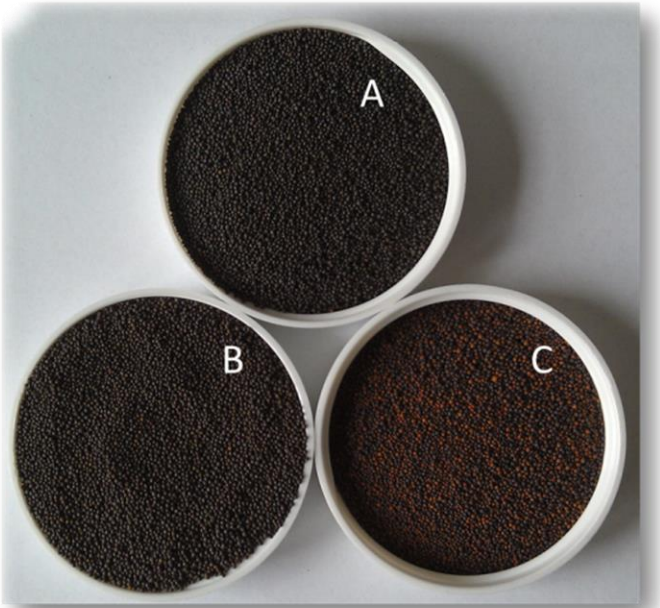
Sandia National Laboratories



Participants: Sandia, Georgia Tech, Bucknell U., King Saud Univ., DLR

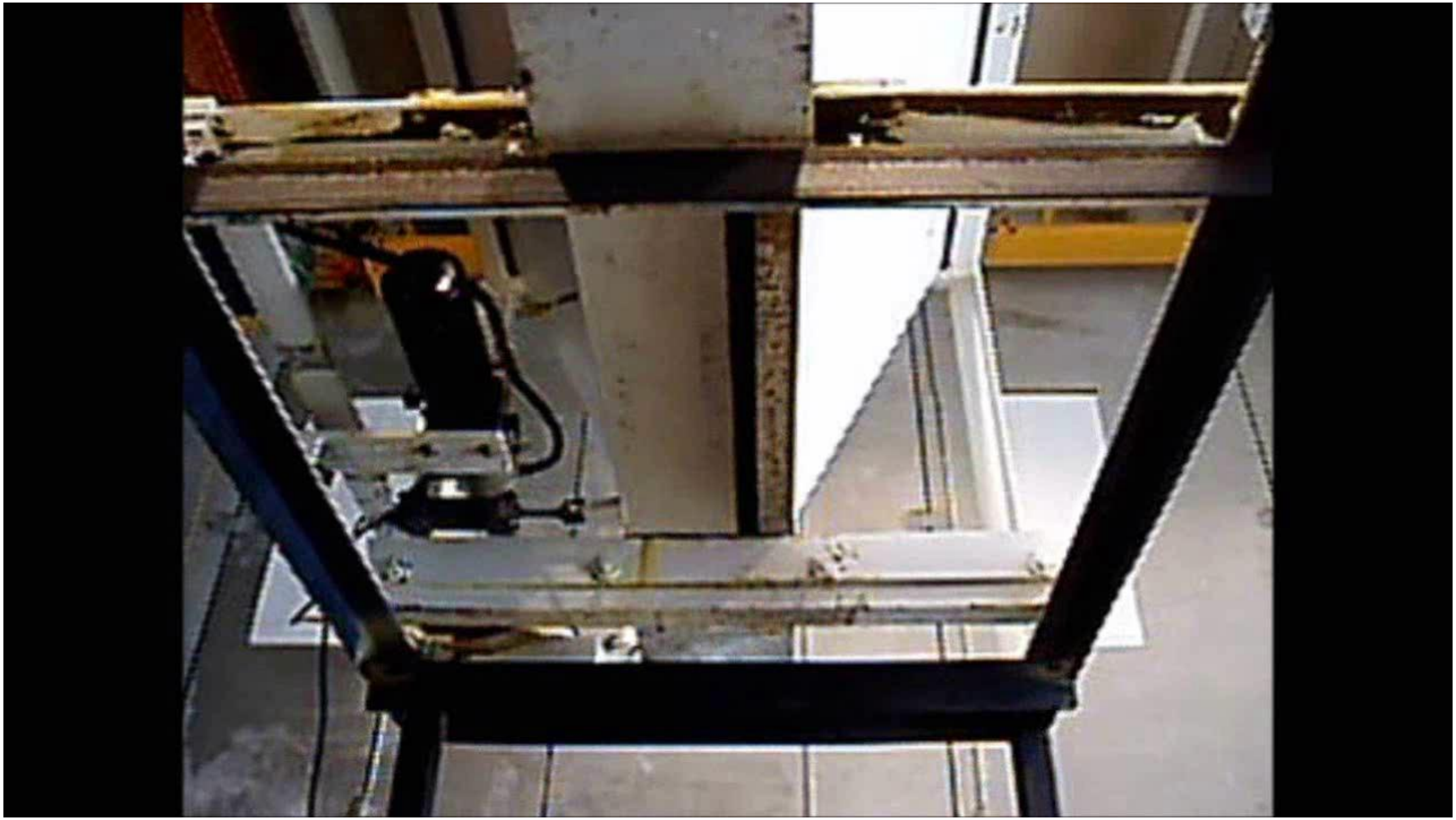
Advantages of Particle Receivers

- Direct heating of particles
  - Higher temperatures than conventional molten salts
    - Enable more efficient power cycles (e.g., sCO2 at ~700 C)
  - Higher solar fluxes for increased receiver efficiency
- Direct storage of hot particles
  - Reduced costs

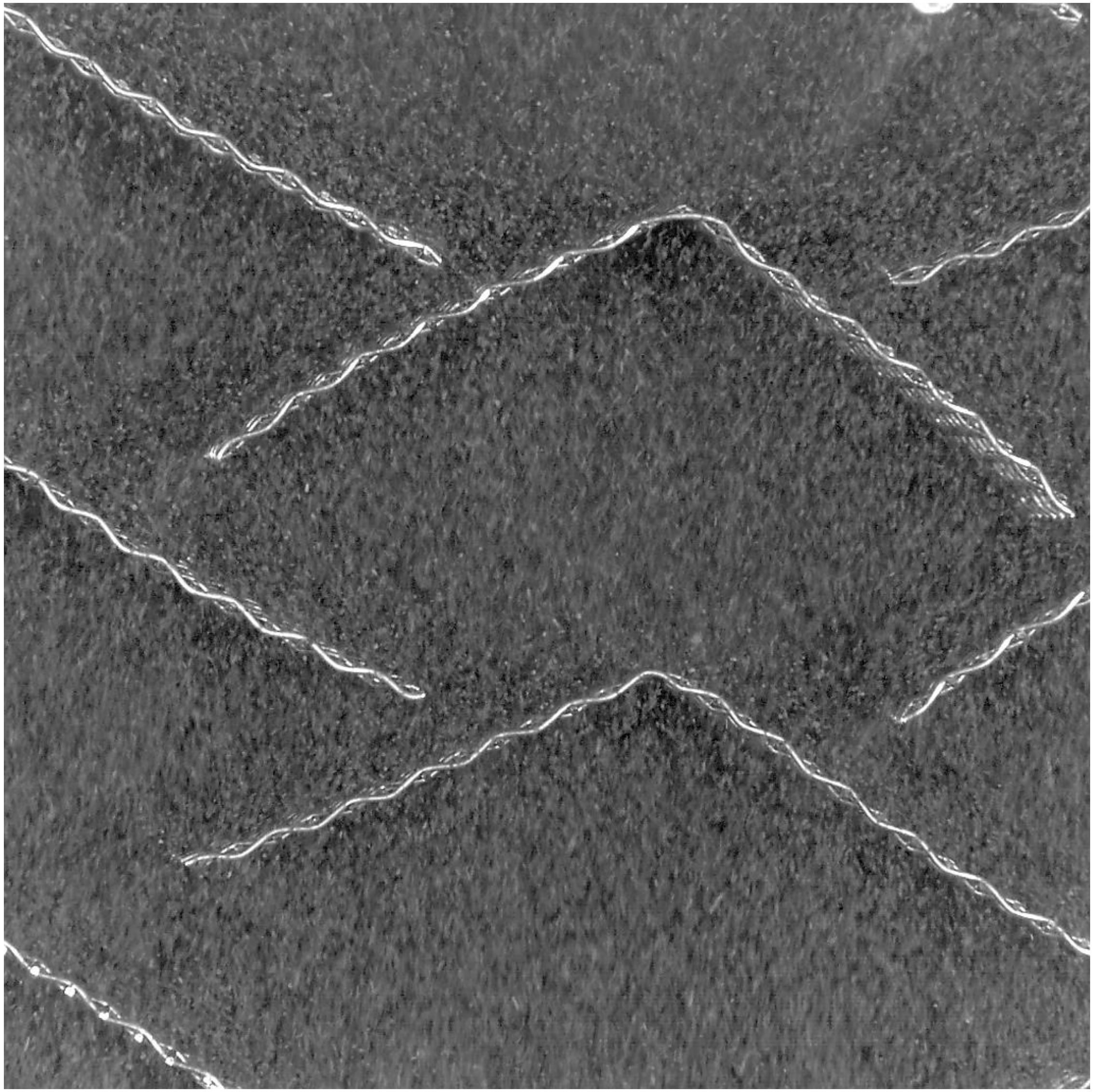


CARBO ceramic particles (“proppants”)

Particle Receiver Designs – Free Falling



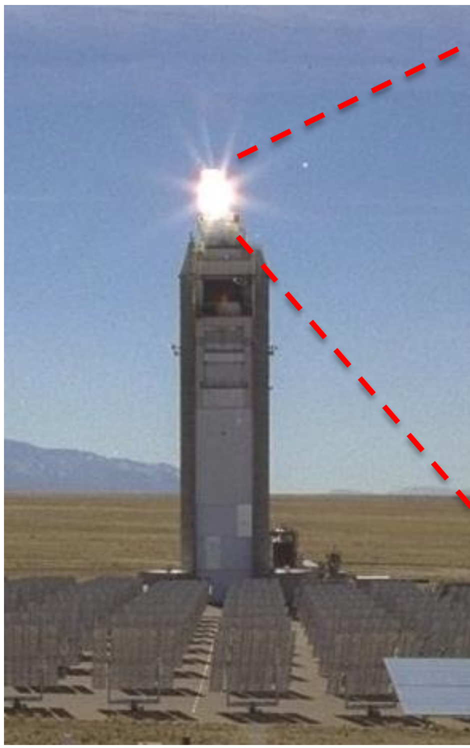
Particle Flow over Chevron Meshes

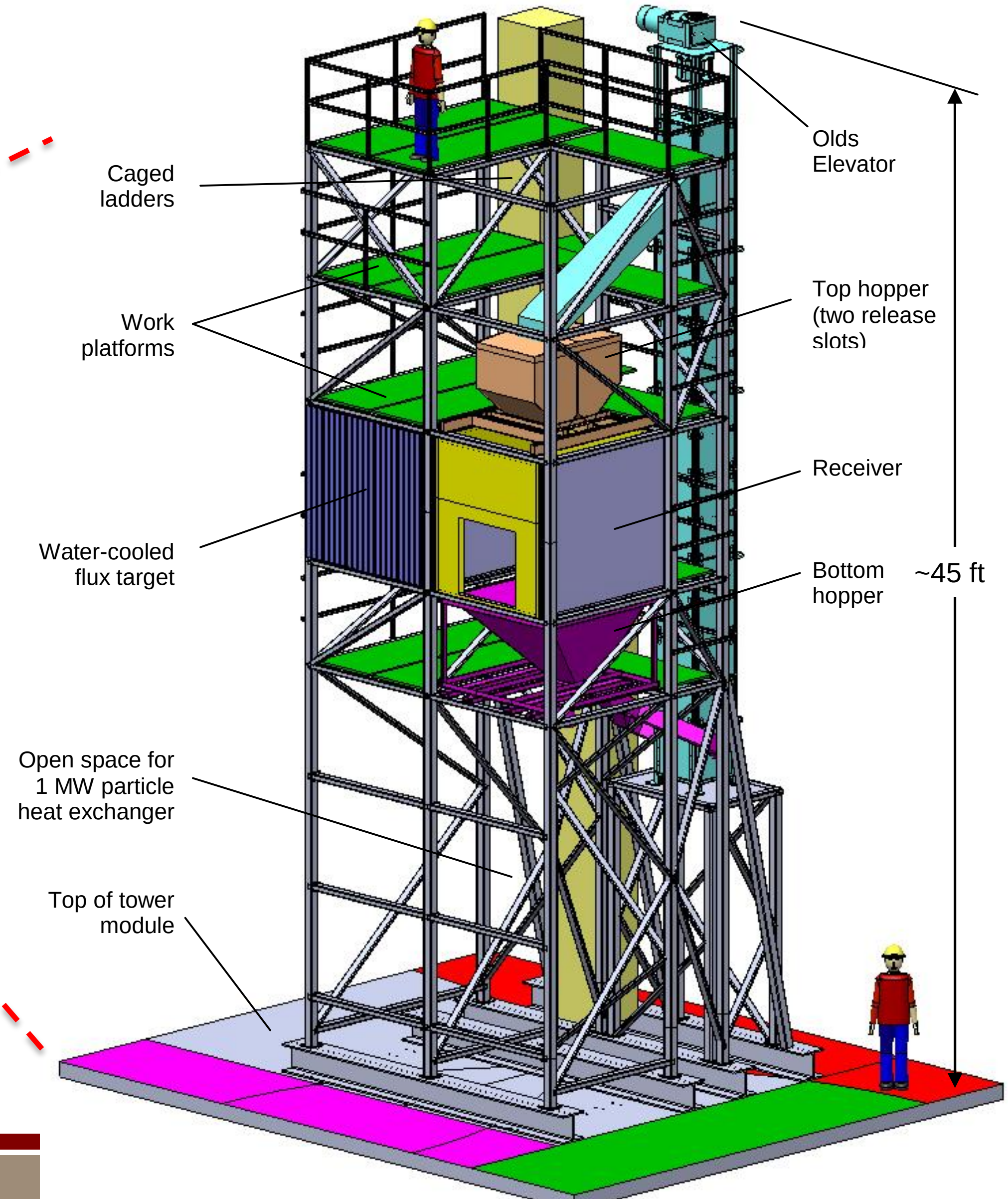


Pros: particle velocity reduced for increased residence time, heating, and flow control

Cons: Mesh structures exposed to concentrated sunlight (~1000 suns)

Prototype System Design

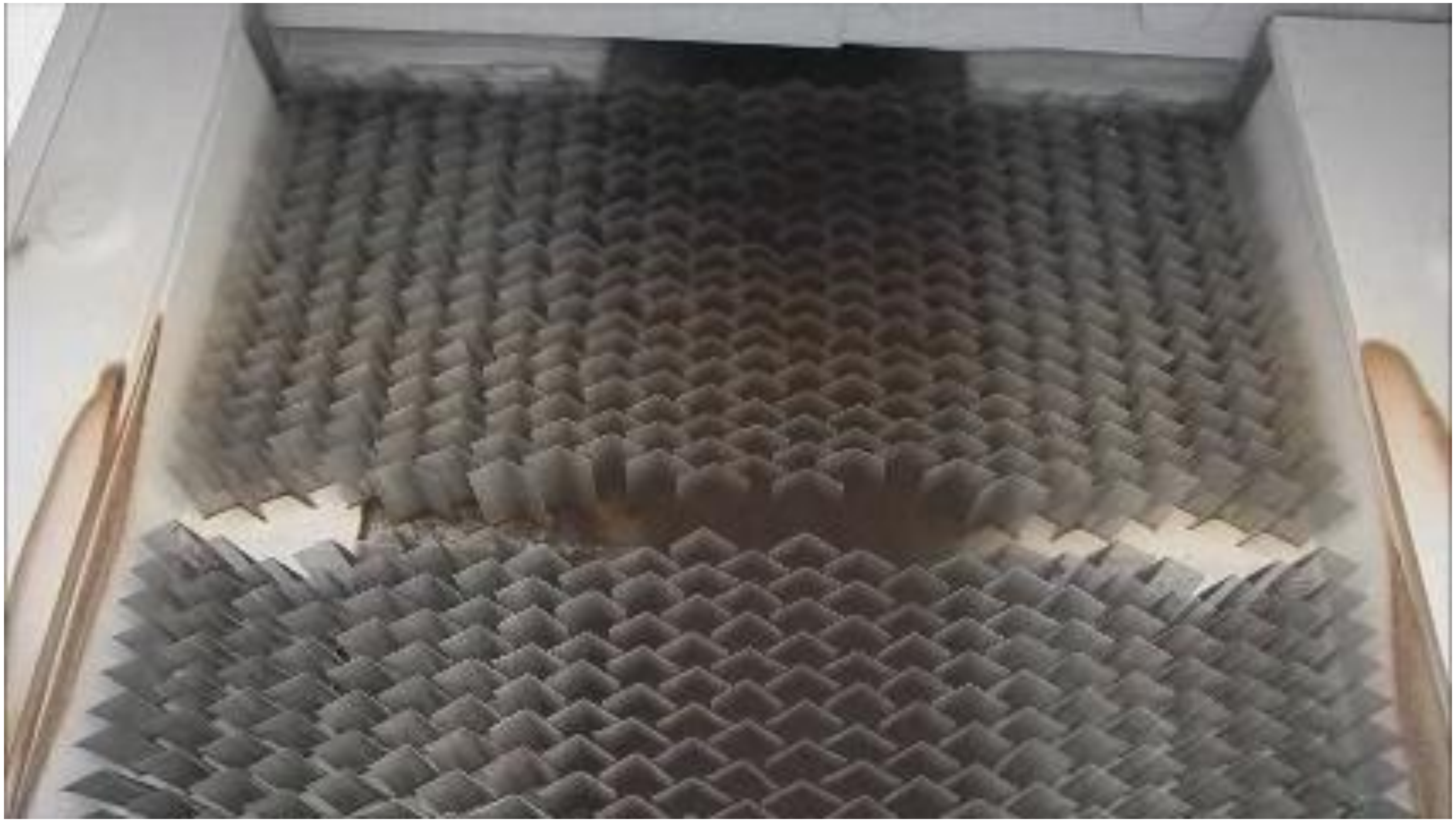




On-Sun Tower Testing

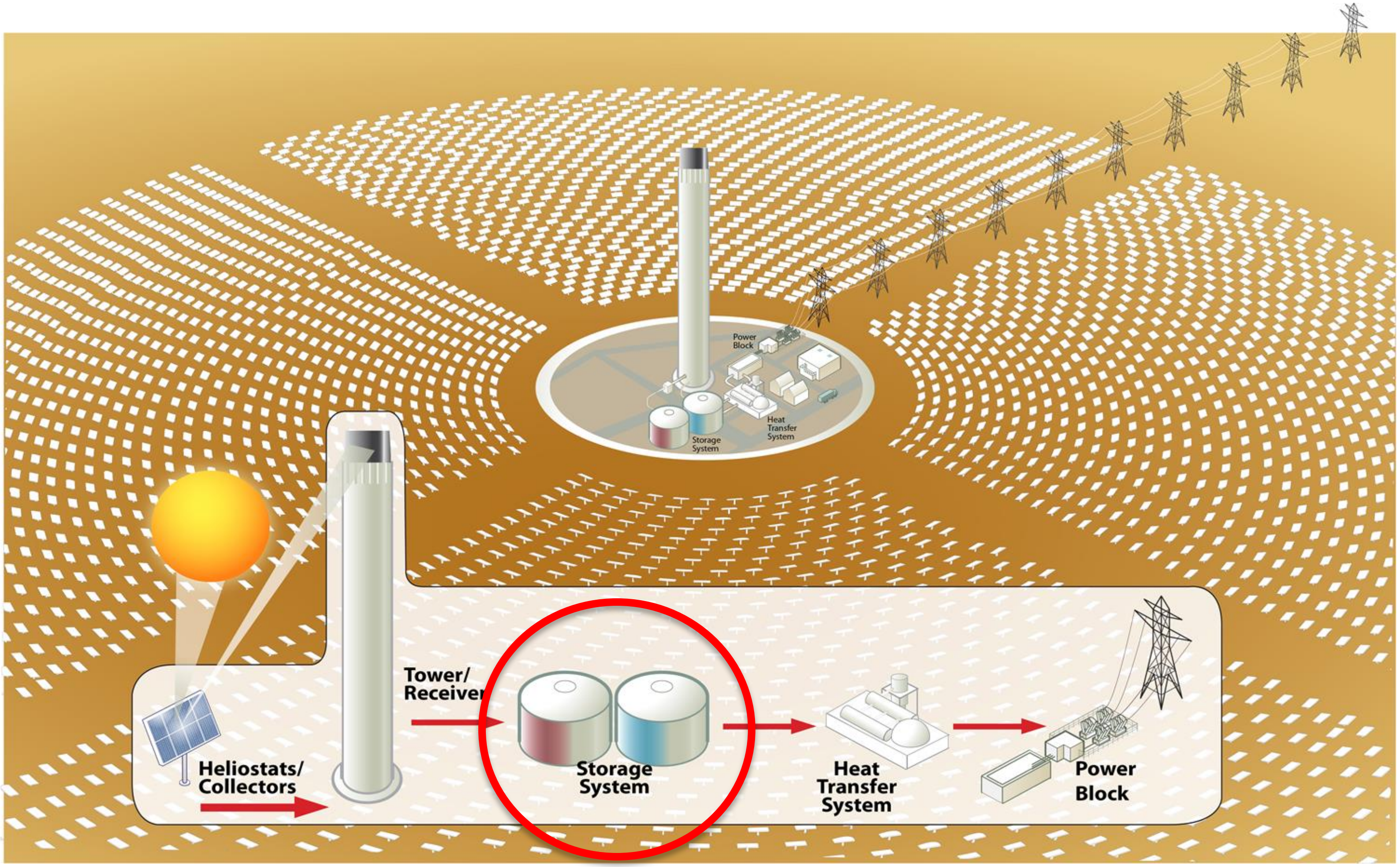
Over 600 suns peak flux on receiver
(July 20, 2015)

On-Sun Tower Testing



Particle Flow Through Mesh Structures
(June 25, 2015)

Energy Storage



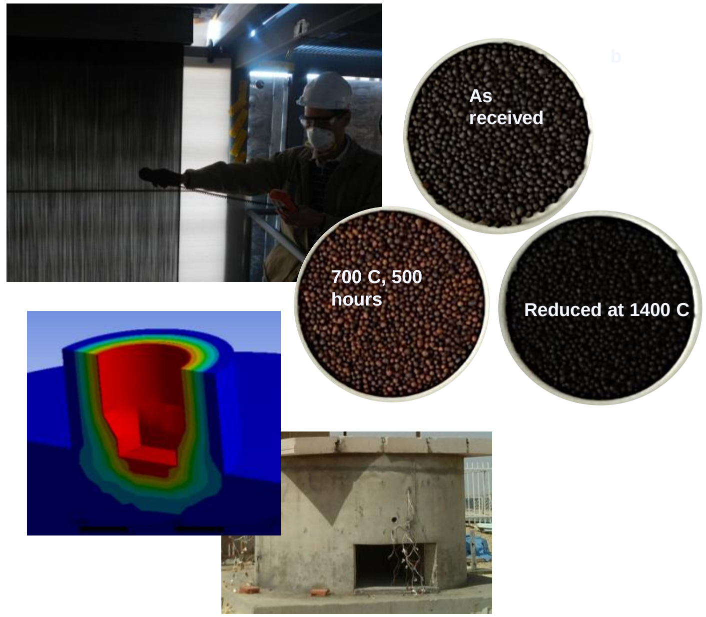
Types of Thermal Energy Storage

- Sensible (single-phase) storage
  - Use temperature difference to store heat
  - Molten salts (nitrates, carbonates, chlorides)
  - Solids storage (ceramic, graphite, concrete)
- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)
- Thermochemical storage
  - Converting solar energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)

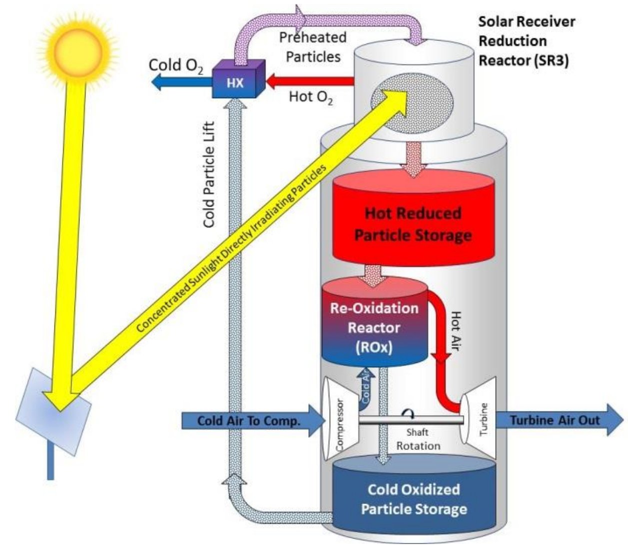
Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Research in Thermal Energy Storage

Corrosion studies in molten salt up to 700 C in “salt pots”

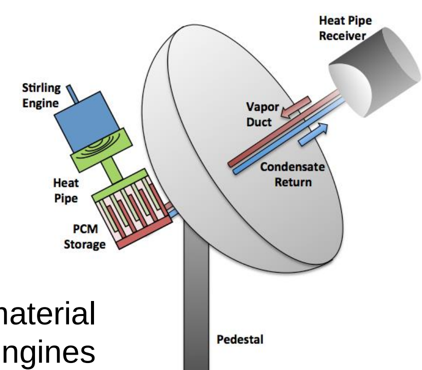


Ceramic particle storage and heating with falling particle receiver



Thermochemical particle storage with reduction/oxidation of perovskites

Component testing with molten-salt test loop



Latent phase-change material storage in dish engines

Outline

- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Commercial Solar Tower Plants
- Challenges and Research Needs
- Summary

Summary

- Concentrating Solar Power (CSP) provides utility-scale electricity and energy storage
  - Uses mirrors to concentrate solar flux onto receiver
  - Hot working fluid converts heat to mechanical energy to spin a turbine/generator for electricity
  - Extra heat can be used for thermal storage to generate electricity during night or cloudy periods

Summary

- State of the Art Commercial Solar Towers
  - Direct Steam
  - Molten Salt
  - Liquid Sodium

Summary

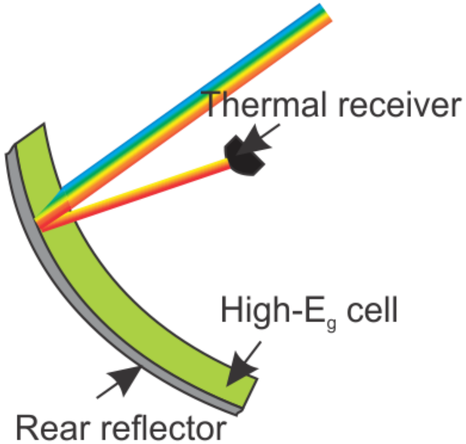
- Market and Economics of CSP
  - Currently, only ~1% of U.S. electricity is from solar energy
    - >90% from PV, <10% from CSP
  - Current cost of CSP is significantly higher than fossil-fuel power plants and other renewables (PV, wind)
    - Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage
      - ~$0.12/kWh vs. $0.30/kWh - $1.00/kWh
  - DOE SunShot goal is to reduce LCOE to $0.06/kWh by 2020

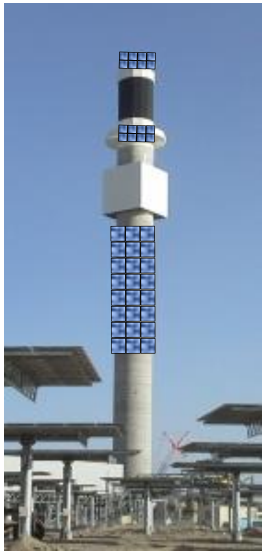
Summary

- Research is needed to improve efficiency and reduce costs
  - Mirror Alignment, Tracking, and Optical Performance
  - High-Temperature Receivers / Materials
  - Storage Technologies
  - Efficient power cycles
    - (e.g., Solarized Supercritical CO_2 Brayton Cycle)

Future Directions

- Molten Salt Solar Towers
  - South Africa – Redstone 100 MW + 12 hour storage (SolarReserve)
  - Chile, South America - ~1 GW of Solar Towers + 13 hours storage (SolarReserve)
  - China – 10 GW of CSP mandated; 9 Molten Salt Plants (~500 MW) announced
- Hybrid CSP + PV
  - Spectrum splitting
  - Co-location / recovery of spillage
- Next generation high-temperature power cycles and processes
  - Solarized supercritical CO_2 Brayton cycle
  - Solar fuels





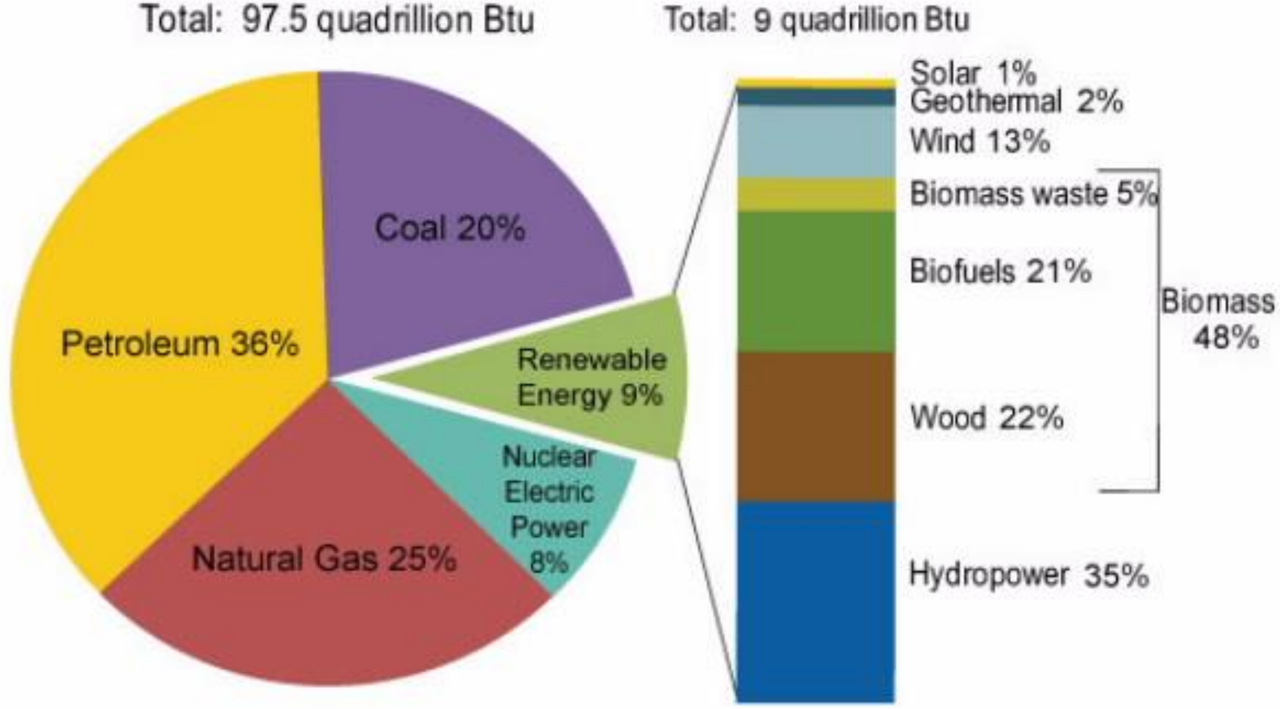
Arizona State University – Professor Zachary Holman

Questions?

Cliff Ho, (505) 844-2384, ckho@sandia.gov

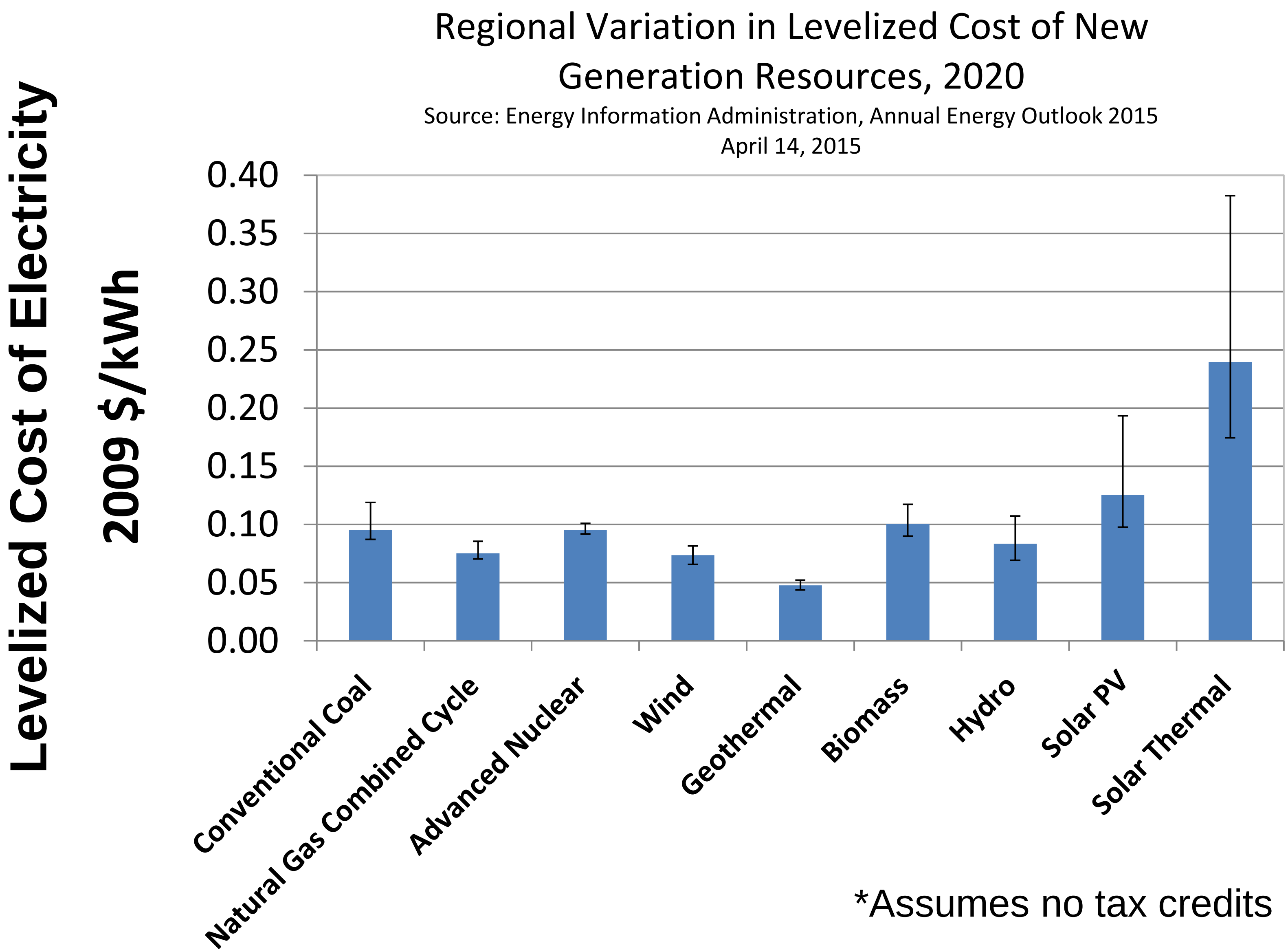
Backup Slides

U.S. Energy Consumption by Energy Source, 2011



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 10.1 (March 2012), preliminary 2011 data.

Electricity Costs (LCOE)*



*Assumes no tax credits

DOE SunShot Goal

- **Reduce LCOE of solar-generated electricity to $0.06/kWh by 2020 with no tax credits**
  - Reduce cost of installed solar energy systems by 75%
  - Enable solar-generated power to account for 15–18% of America’s electricity generation by 2030

Comparison of Energy Storage Options

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost[1] ($/MWh$_e$)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency[2]	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life[3]	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/ environmental impacts	N/A	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	N/A	N/A
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

Thermal Energy Storage Goals

- Capable of achieving high temperatures (> 700 C)
- High energy and exergetic efficiency (>95%)
- Large energy density (MJ/m^3)
- Low cost (<\$15/kWh_t; <\$0.06/kWh_e for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid (h > 100 W/m^2-K)

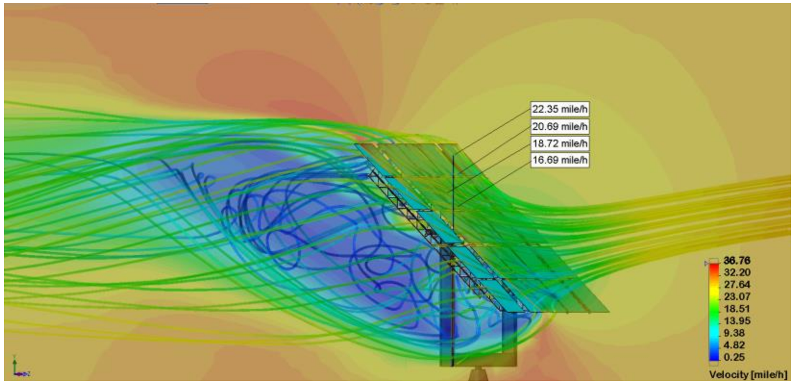
Sandia National Laboratories

TABLE 1 | The Physical Properties of Selected Thermal Energy Storage Media. Sensible Energy Storage Media, Both Liquid and Solid, Are Assumed to Have a Storage Temperature Differential of 350°C with Respect to the Calculation of Volumetric and Gravimetric Storage Density

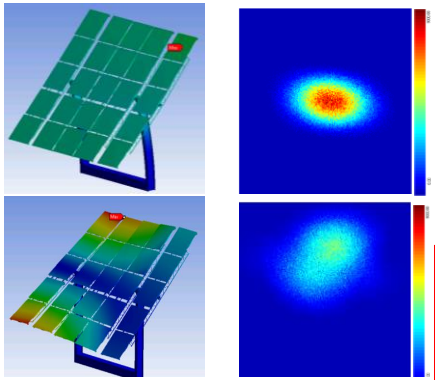
Storage Medium	Specific Heat (kJ/kg-K)	Latent or Reaction Heat (kJ/kg)	Density (kg/m^3)	Temperature Range (°C) Cold	Temperature Range (°C) Hot	Gravimetric Storage Density (kJ/kg)	Volumetry Storage Density (MJ/m^3)	References
Sensible Energy Storage—Solids								
Concrete	0.9	–	2200	200	400	315	693	23
Sintered bauxite particles	1.1	–	2000	400	1000	385	770	24
NaCl	0.9	–	2160	200	500	315	680	23
Cast iron	0.6	–	7200	200	400	210	1512	25
Cast steel	0.6	–	7800	200	700	210	1638	23
Silica fire bricks	1	–	1820	200	700	350	637	23
Magnesia fire bricks	1.2	–	3000	200	1200	420	1260	25
Graphite	1.9	–	1700	500	850	665	1131	26
Aluminum oxide	1.3	–	4000	200	700	455	1820	27
Slag	0.84	–	2700	200	700	294	794	28
Sensible Energy Storage—Liquids								
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	1.6	–	1815	300	600	560	1016	17
Therminol VP-1®	2.5	–	750	300	400	875	656	29
Silicone oil	2.1	–	900	300	400	735	662	23
Carbonate salts	1.8	–	2100	450	850	630	1323	23
Caloria HT-43®	2.8	–	690	150	316	980	676	25
Sodium liquid metal	1.3	–	960	316	700	455	437	25
Na-0.79K metal eutectic	1.1	–	900	300	700	385	347	30
Hydroxide salts (ex. NaOH)	2.1	–	1700	350	1100	735	1250	27
Latent Energy Storage								
Aluminum	1.2	397	2380	–	660	397	945	28
Aluminum alloys (ex. Al-0.13Si)	1.5	515	2250	–	579	515	1159	31, 32
Copper alloys (ex. Cu-0.29Si)	–	196	7090	–	803	196	1390	32
Carbonate salts (ex. Li_2CO_3)	–	607	2200	–	726	607	1335	32
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	1.5	100	1950	–	222	100	195	28
Bromide salts (ex. KBr)	0.53	215	2400	–	730	215	516	33
Chloride salts (ex. NaCl)	1.1	481	2170	–	801	481	1044	33
Flouride salts (ex. LiF)	2.4	1044	2200	–	842	1044	2297	33
Lithium hydride	8.04	2582	790	–	683	2582	2040	31
Hydroxide salts (ex. NaOH)	1.47	160	2070	–	320	160	331	31
Thermochemical Energy Storage								
$SO_3(g) \leftrightarrow SO_2(s) + 1/2O_2(g)$	–	1225	–	–	650	1225	–	28, 30, 34
$CaCO_3(s) \leftrightarrow CO_2(g) + CaO(s)$	–	1757	–	–	527	1757	–	28, 34
$CH_4(g) + CO_2(g) \leftrightarrow 2CO(g) + 2H_2(g)$	–	4100	–	–	538	4100	–	35
$CH_4(g) + H_2O(g) \leftrightarrow 3H_2(g) + CO(g)$	–	6064	–	–	538	6064	–	35
$Ca(OH)_2(s) \leftrightarrow CaO(s) + H_2O(g)$	–	1351	–	–	521	1351	–	28, 30, 34
$NH_3(g) \leftrightarrow 1/2N_2(g) + 3/2H_2(g)$	–	3900	–	–	195	3900	–	36

Siegel (2012)

Wind Impacts – Optics and Fatigue

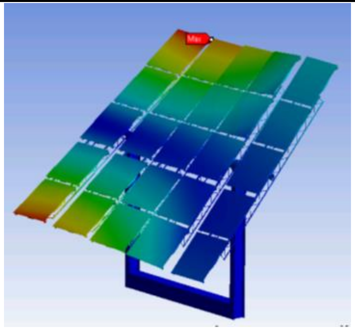
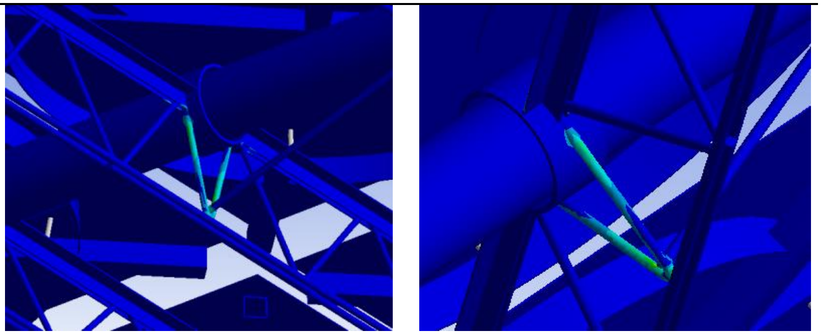


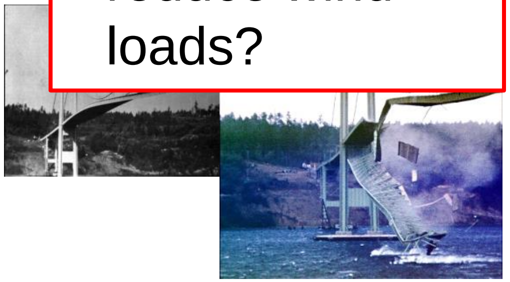
J. Sment, J. Christian, J. Yuan



Optics impacted by "sway" or out-of-plane bending

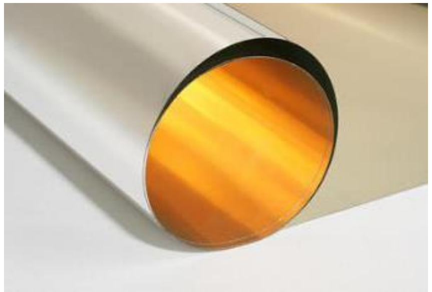
- Need dampeners or anti-vibration devices
- "Winglets" to reduce wind loads?

Mode shape	Fatigue Affected Areas
 Mode 2	 Truss Cross Members at Torque Tube

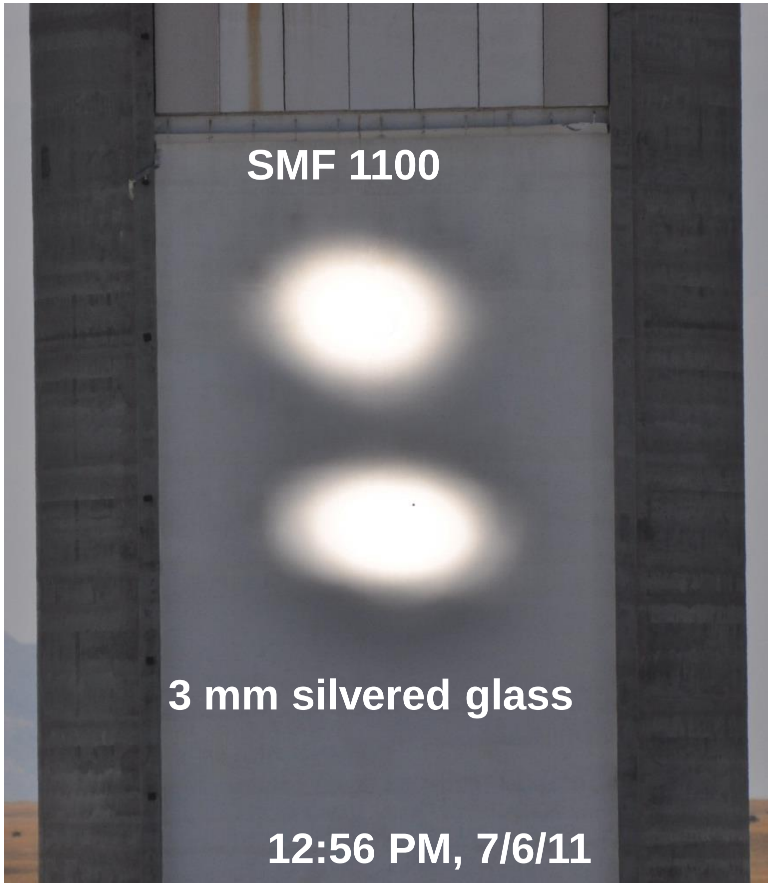


Tacoma Narrows Bridge collapsing under 40 mph winds (1940)

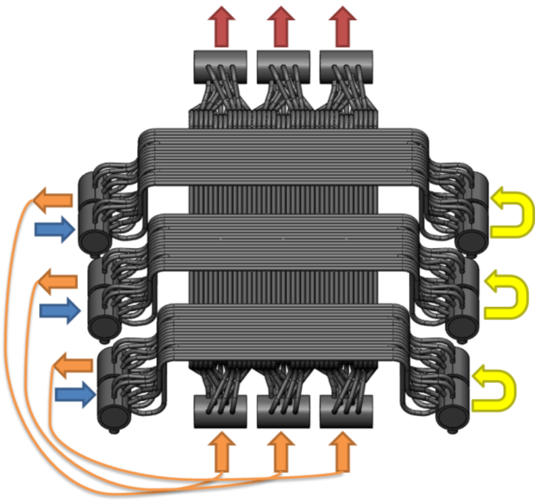
Advanced Reflective Materials

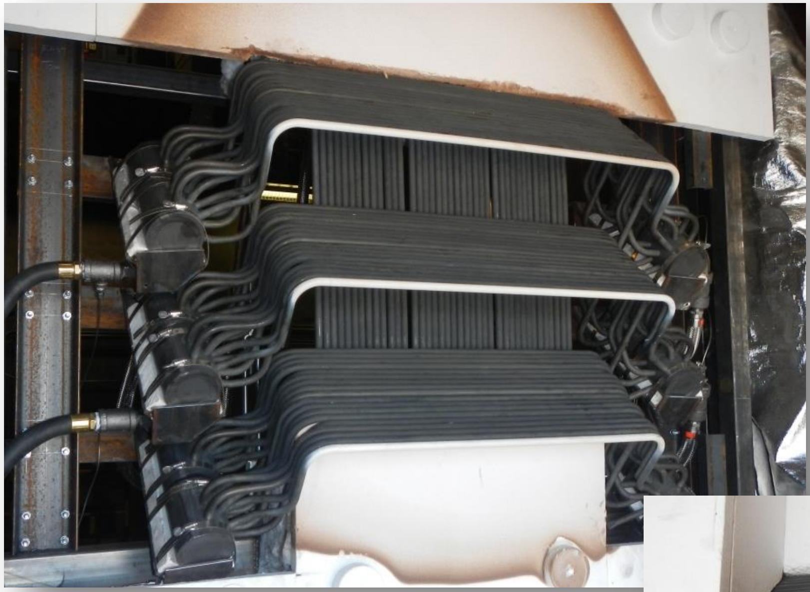


Heliostat with 3M™ Solar Mirror Film 1100



On-Sun Bladed Receiver Testing





Bladed receiver exhibited ~5% increase in thermal efficiency over flat receiver