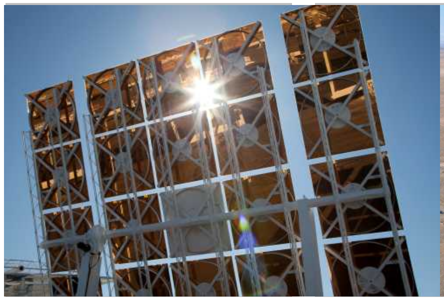
SAND2017-13125C

State of the Art in Concentrating Solar Tower Technology



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SAND2017-XXXX

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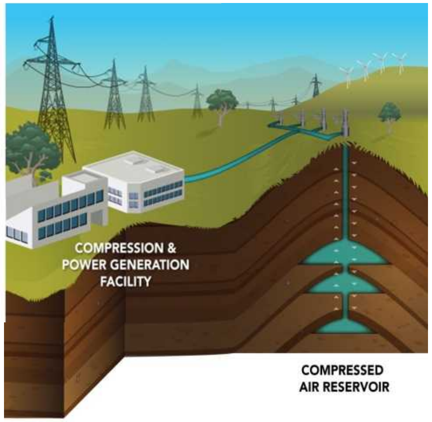
Outline

- **Introduction to CSP**
- **State-of-the-Art CSP Tower Technology**
- **Emerging Technologies**
- **Summary**

Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand in evenings
- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $\$0.20/\text{kWh}_e$ - $\$1.00/\text{kWh}_e$
  - Compressed air and pumped hydro – geography and/or resource limited



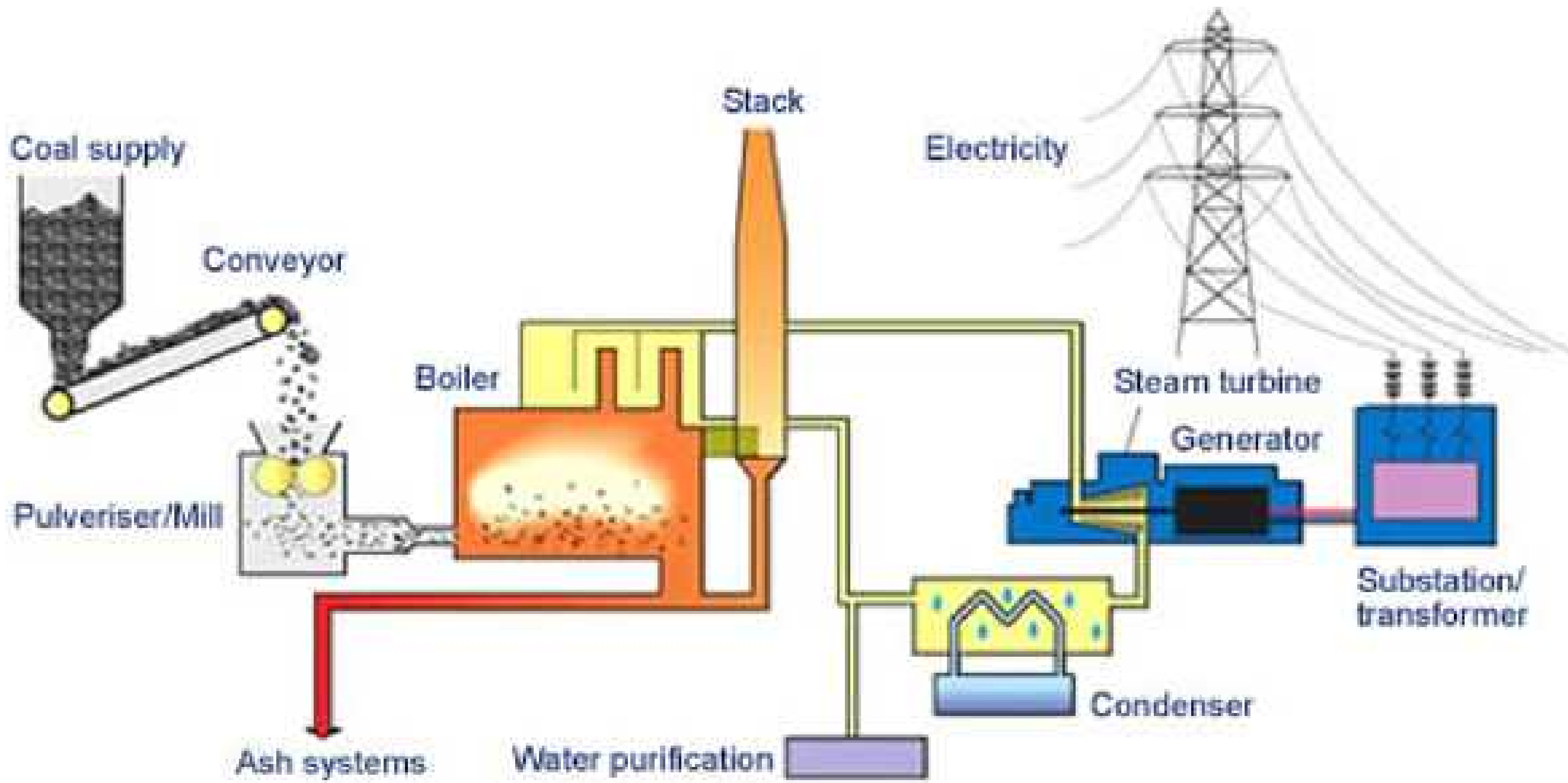
Need

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

→ Concentrating solar power (CSP) with thermal energy storage

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

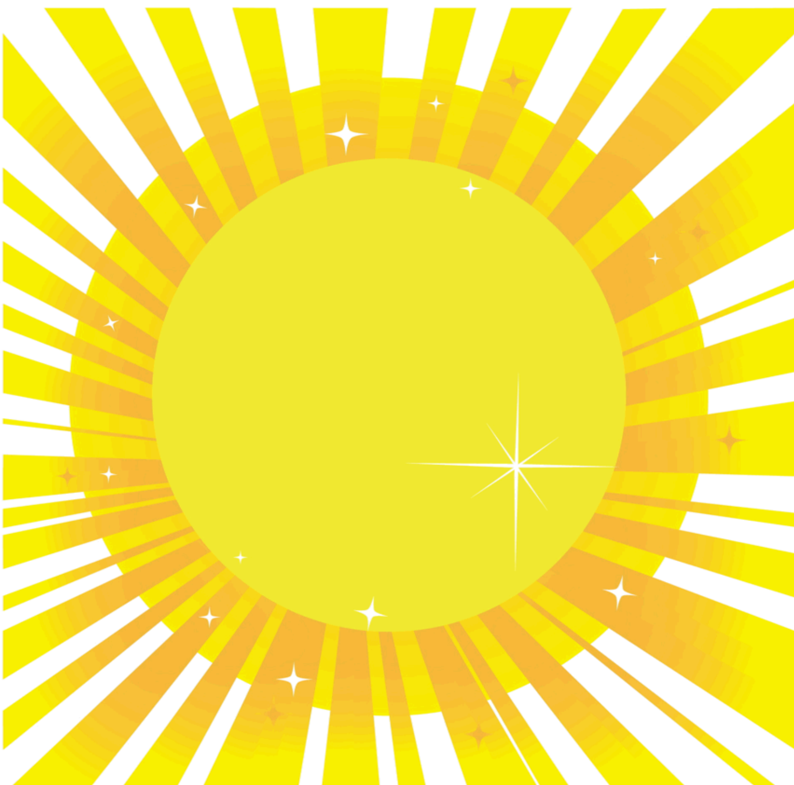


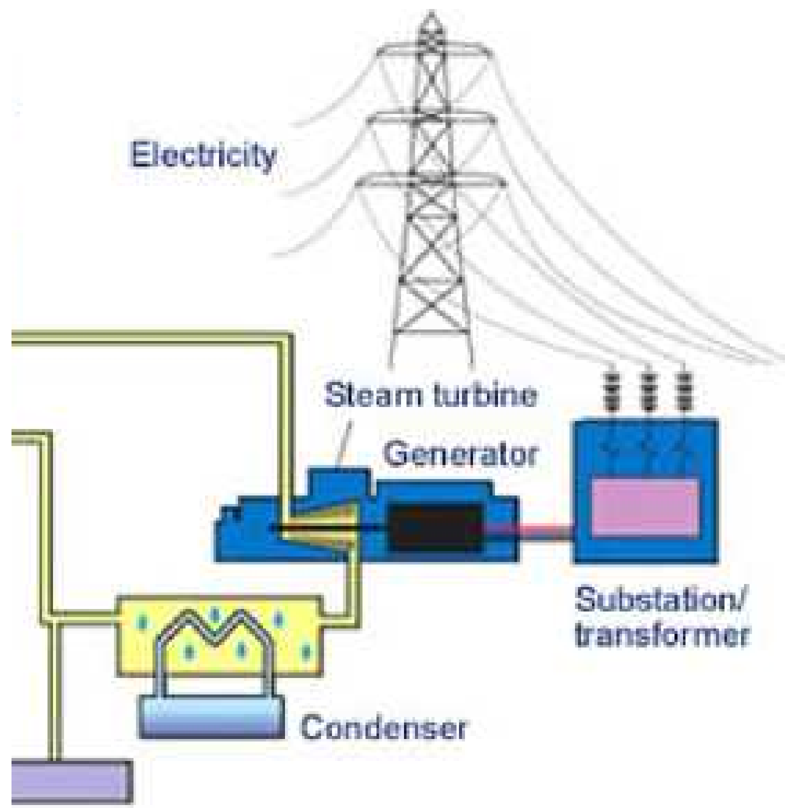
Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

Sandia National Laboratories

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

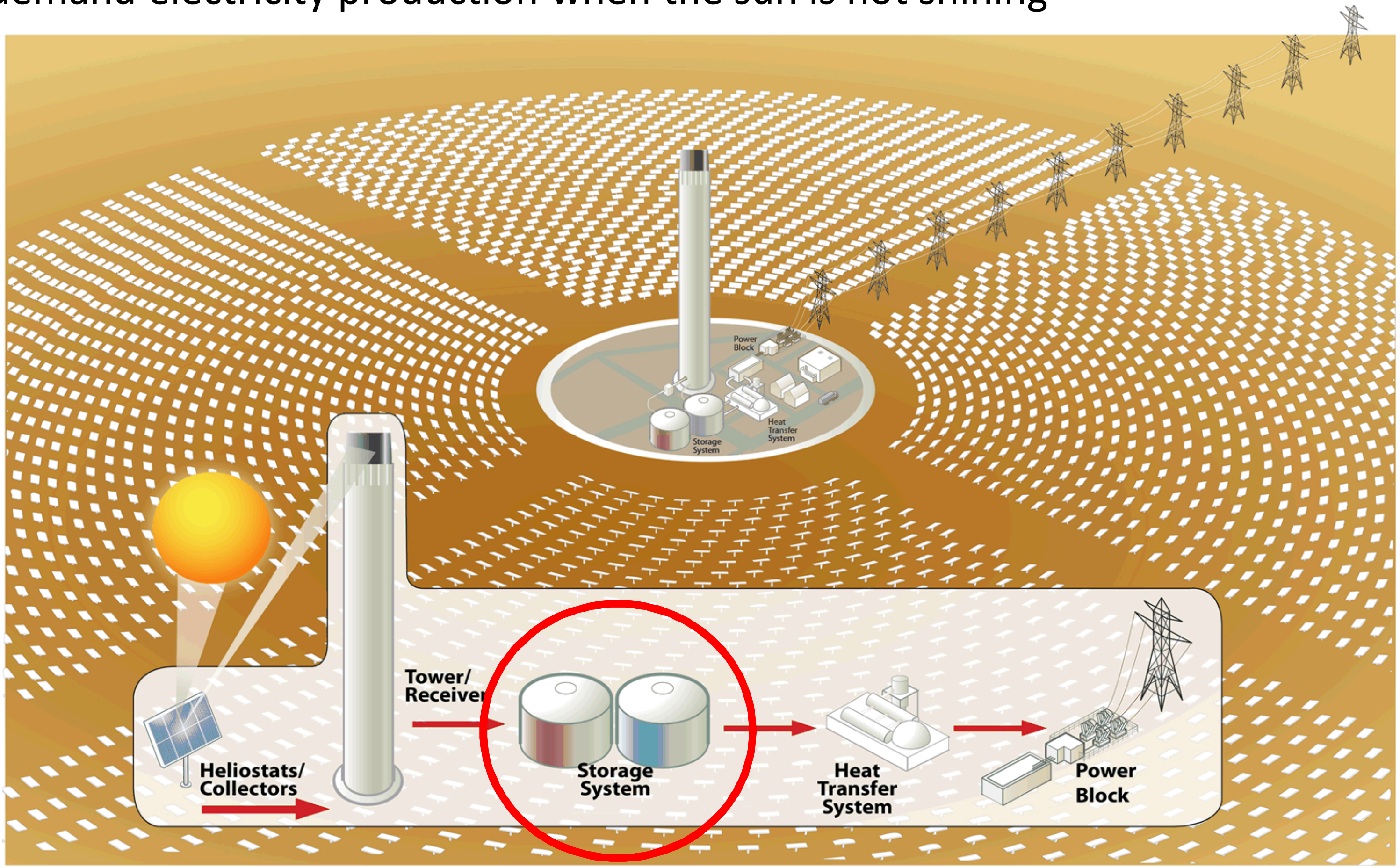




Concentrating Solar Power

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

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

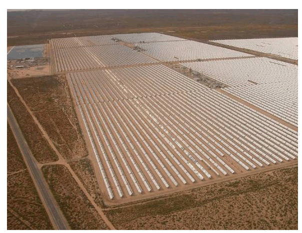
1970's

1980's – 1990's

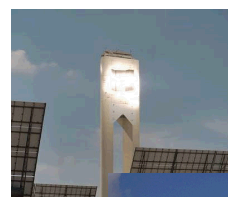
2000's

SunShot 2011 -

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

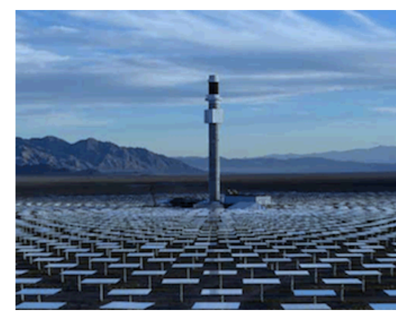


SEGS, 1980's
9 trough plants
354 MW_e, CA



PS10/20, steam, Spain, 2007-2009

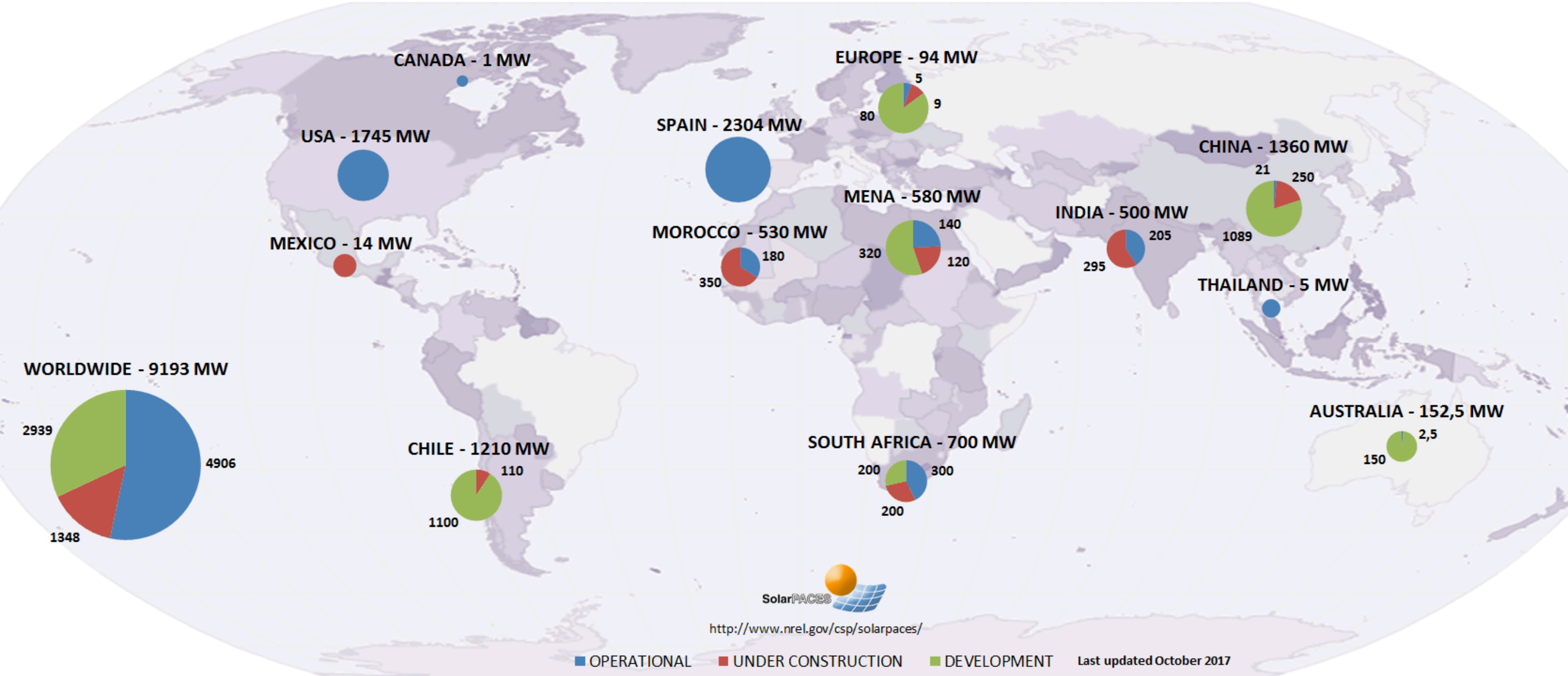
Gemasolar, molten salt, 19 MW_e, Spain, 2011



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

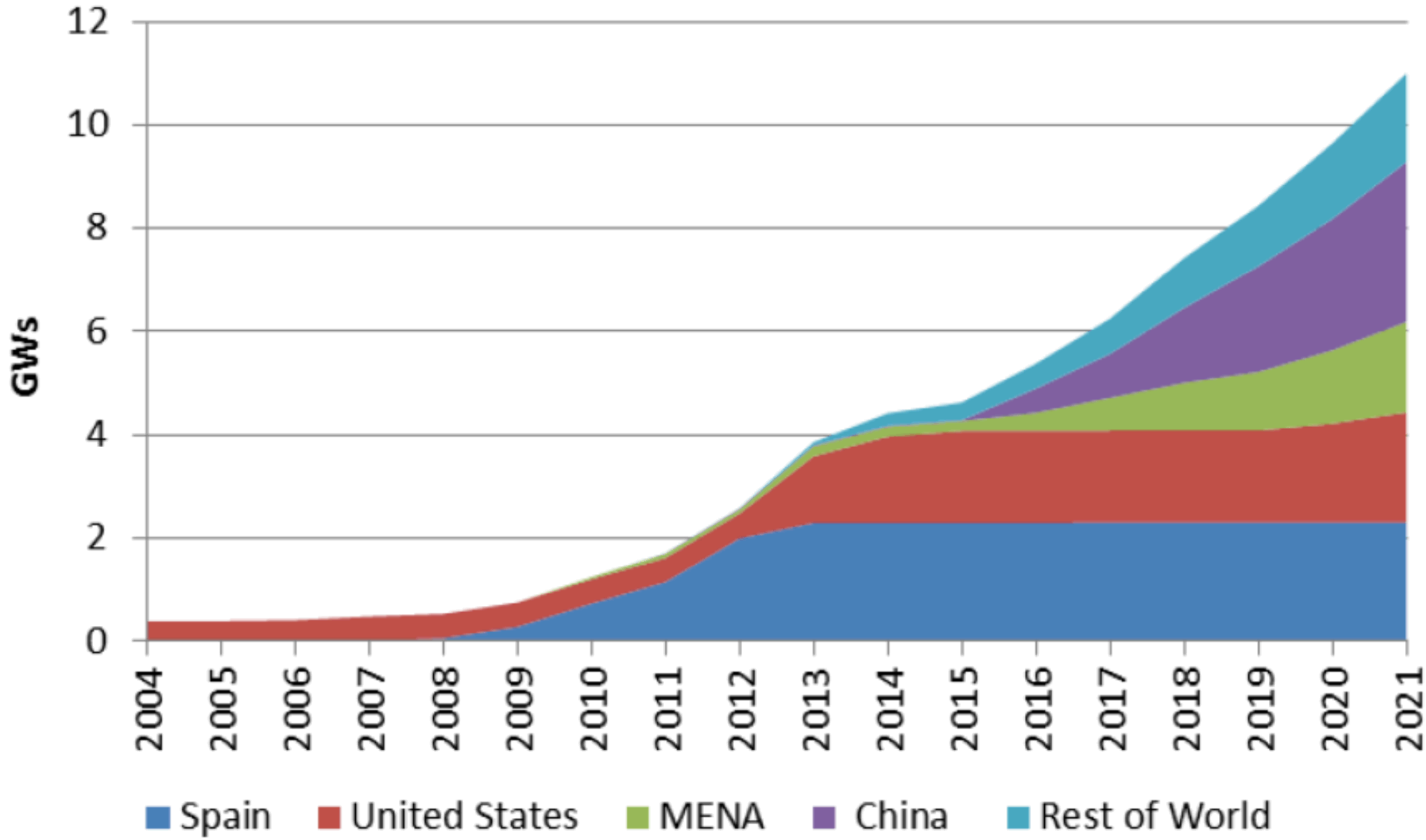
CSP Projects Around the World

Through October 2017



http://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

Actual and Projected Growth of CSP



https://www.nrel.gov/docs/fy17osti/67464.pdf

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Direct Steam Solar Towers

PS10 and PS20 (Seville, Spain)

Sandia National Laboratories

- 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)

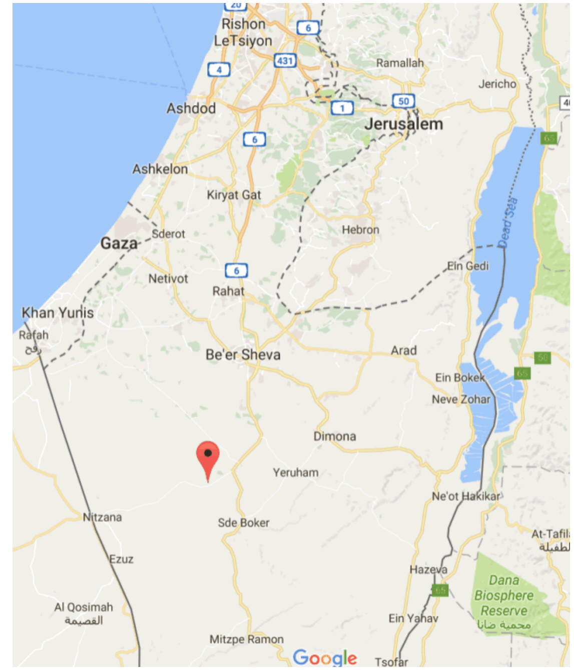
http://news.nationalgeographic.com

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

Ashalim Solar Power Station

(Under Construction 2015 - 2017)

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



Receiver and heliostat field under construction

Photo credit: Jack Guez/AFP (May 2016)

Molten Salt Solar Tower

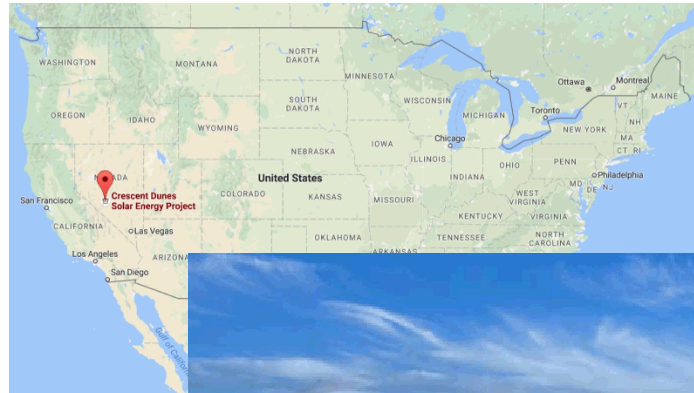
Gemasolar

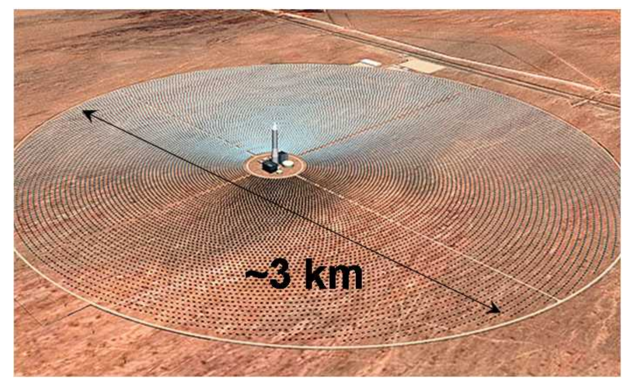
(near Seville, Spain)

- 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

- Commissioned January 2017
- 1.1 MW_e
- Liquid sodium
  - 560 C
  - 3 hour storage
  - Dry cooling

5 modular solar fields with 30 m towers

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Light Trapping Receivers

Fractal-Like Receiver Designs

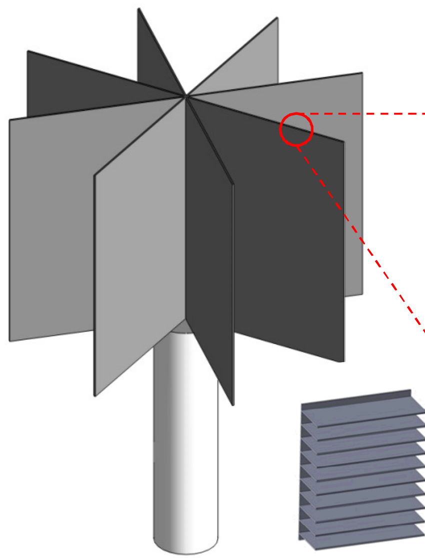
Sandia National Laboratories

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

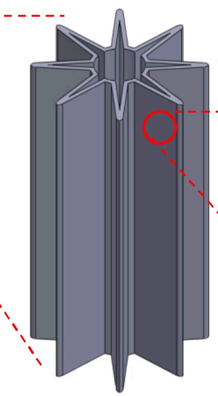
~10 m

Conventional cylindrical solar receiver

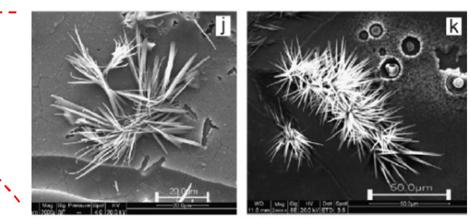
Macro Scale
meters



Meso Scale
mm - cm



Micro Scale
microns



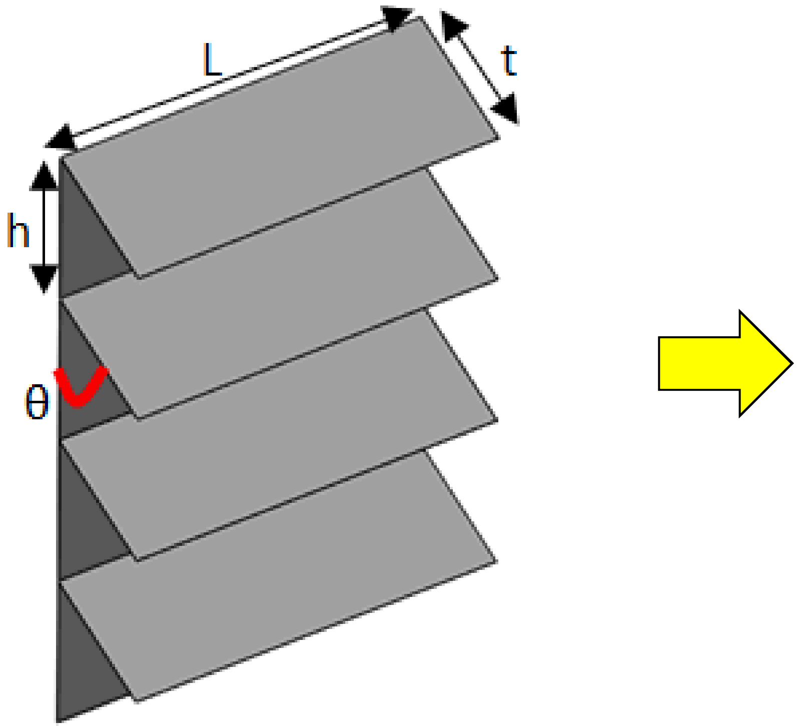
Sharma et al. (2009)

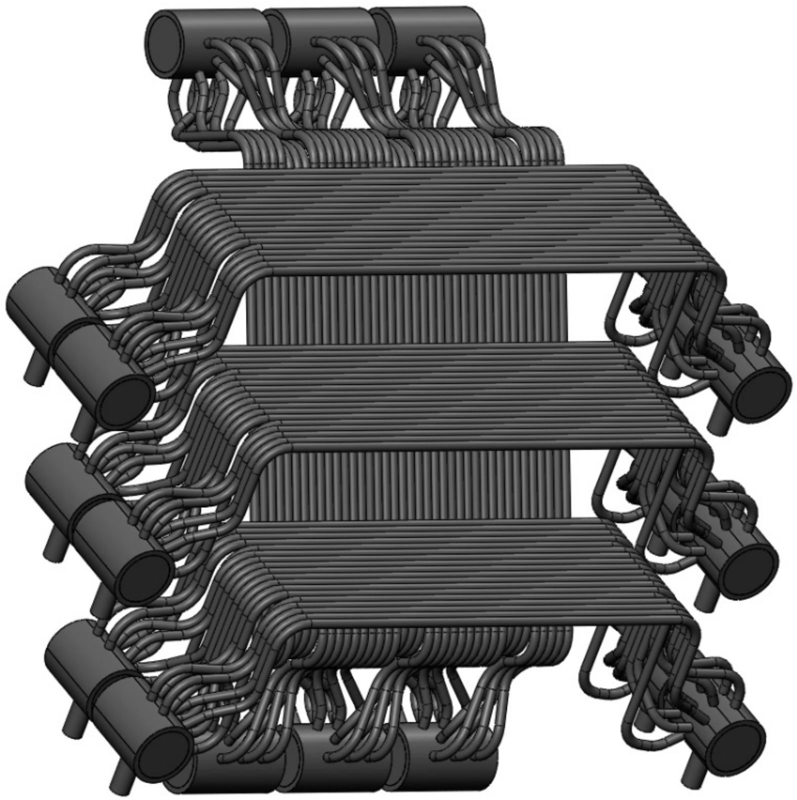
New fractal-like designs with light-trapping and low-emittance properties at multiple scales

Patents Pending

Bladed Receivers (ANU and Sandia)

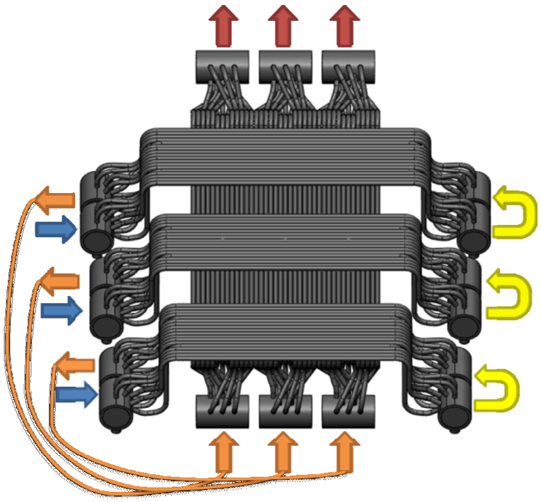
- CFD simulations revealed that horizontal bladed receiver yielded highest efficiencies





Bladed receiver configuration after parametric study
(Ortega et al., 2017)

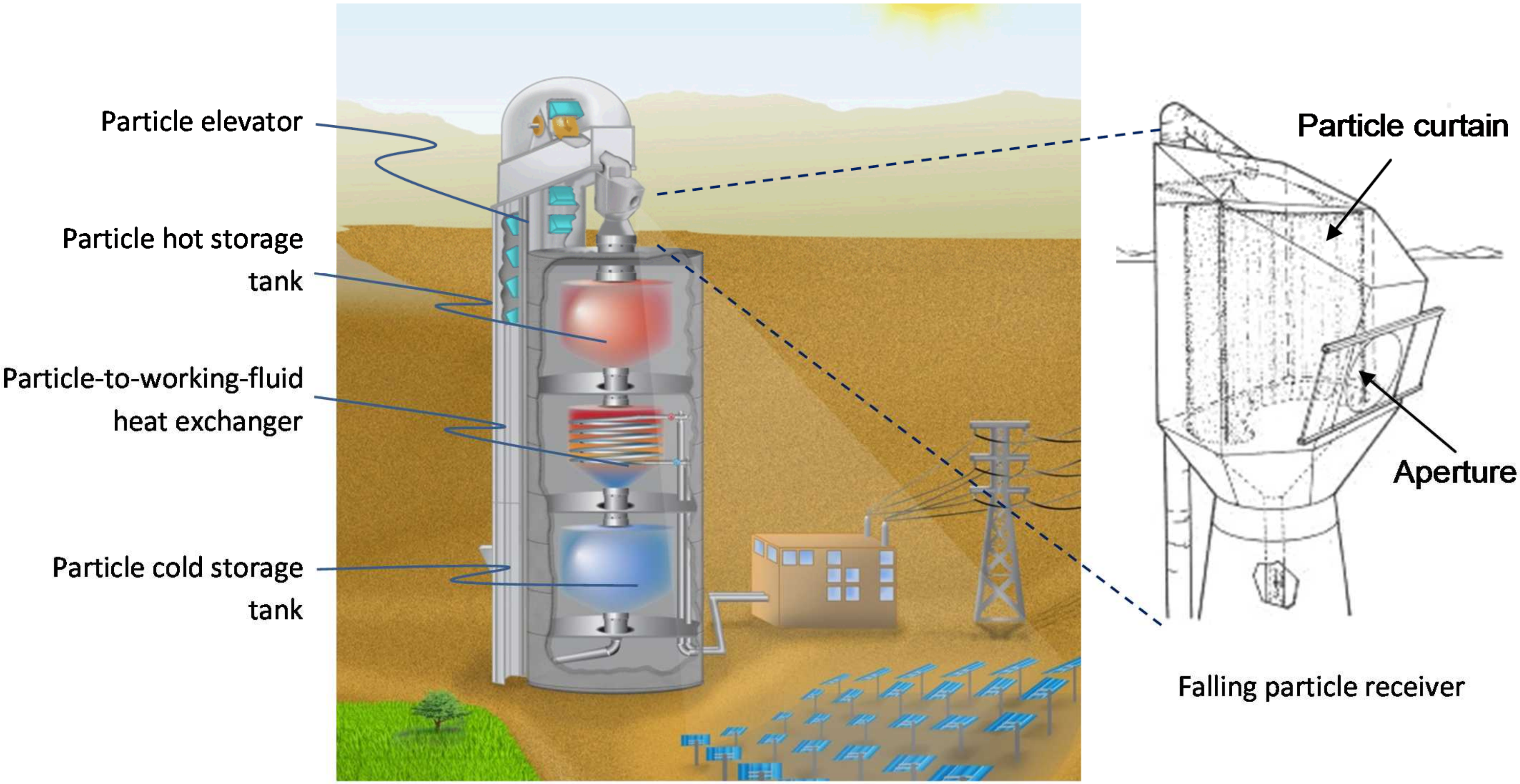
On-Sun Bladed Receiver Testing



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

Direct Absorption of Concentrated Sunlight

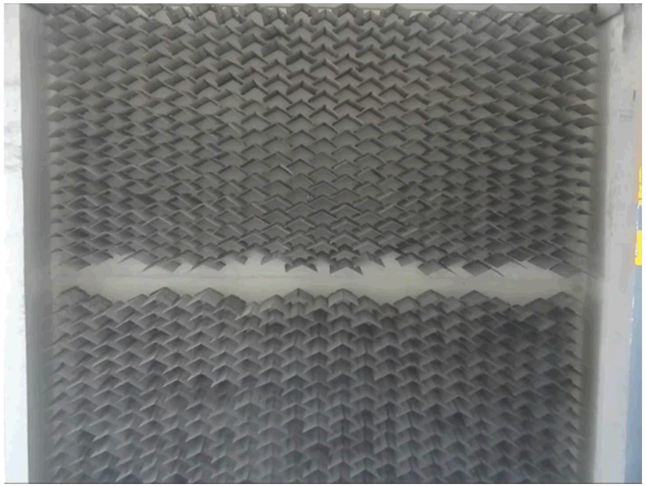
High Temperature Falling Particle Receiver (DOE SunShot Award FY13 – FY16)



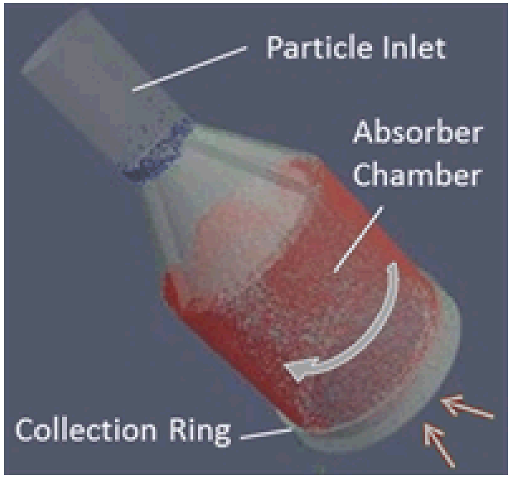
Participants: Sandia, Georgia Tech, Bucknell U., King Saud Univ., DLR

Alternative Particle Receiver Designs

Free-Falling (SNL)



Obstructed Flow
(GT, KSU)

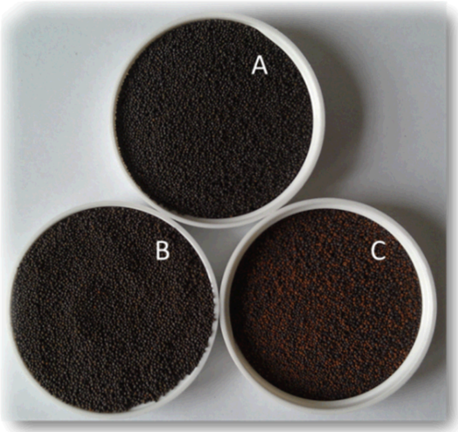


Centrifugal (DLR)

Fluidized Bed

Advantages of particle Power™

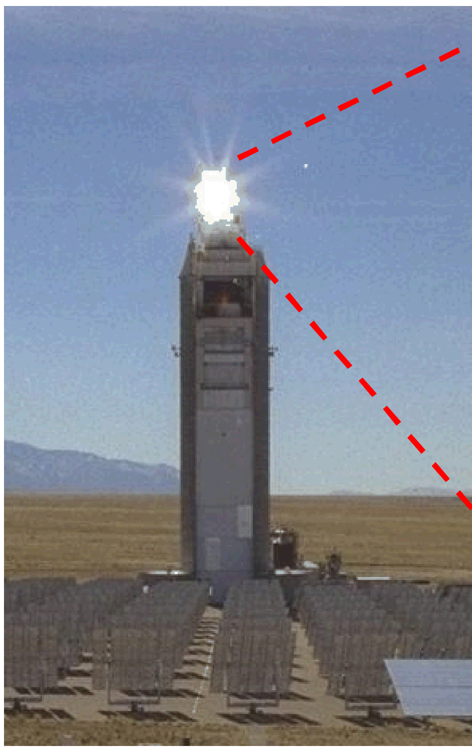
- Higher temperatures than molten salts (>1000 ˚C)
  - Enables more efficient power cycles
- Direct heating of particles vs. indirect heating of tubes
  - Higher solar fluxes for increased receiver efficiency
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles
  - Reduced costs without extra heat exchangers and separate storage media



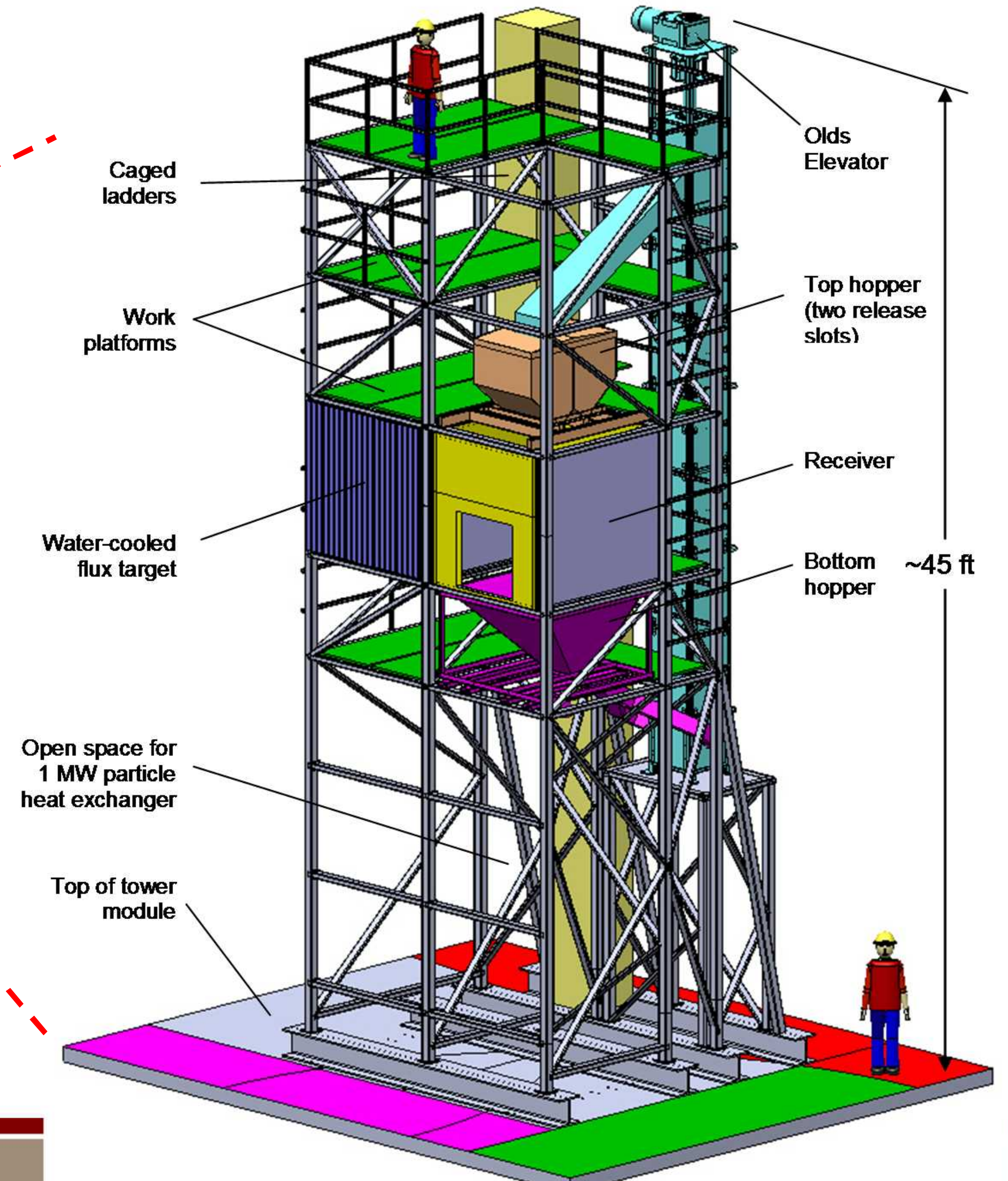
N. Siegel, Bucknell U.

CARBO ceramic particles (“proppants”)

Prototype System Design



National Solar Thermal Test Facility
Sandia National Laboratories



On-Sun Tower Testing

National Solar Thermal Test Facility
Sandia National Laboratories

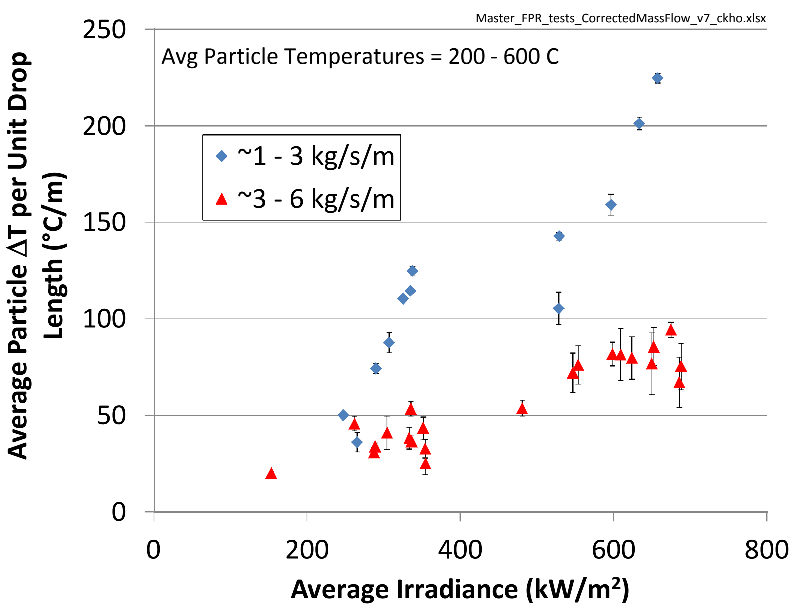
Over 600 suns peak flux on receiver
(July 20, 2015)

On-Sun Tower Testing

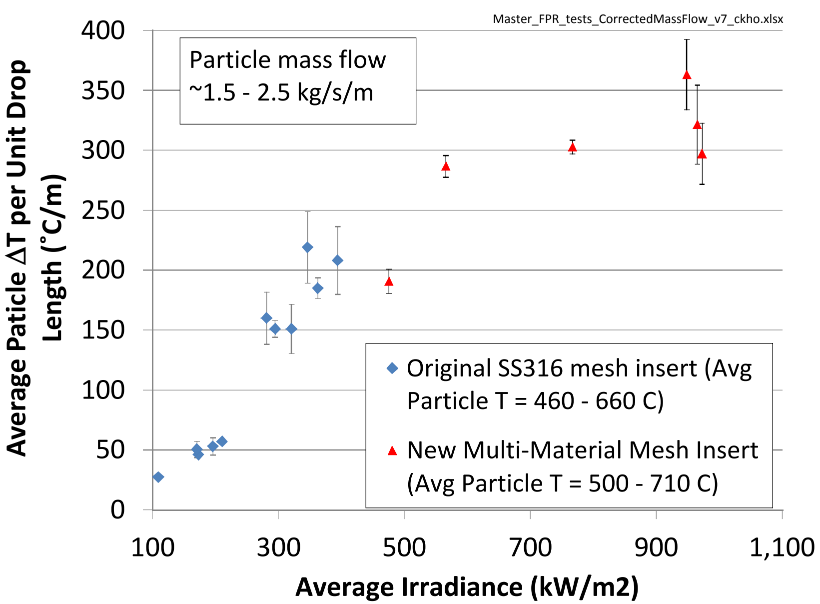
Particle Flow Through Mesh Structures
(June 25, 2015)

Direct Particle Heating Results

- Achieved average particle outlet temperatures > 800 ˚C
  - Peak particle outlet temperatures > 900 ˚C
- Particle heating up to ~200 – 300 ˚C/(m of drop); 1 – 3 kg/s
- Thermal efficiency up to ~70% to 80%



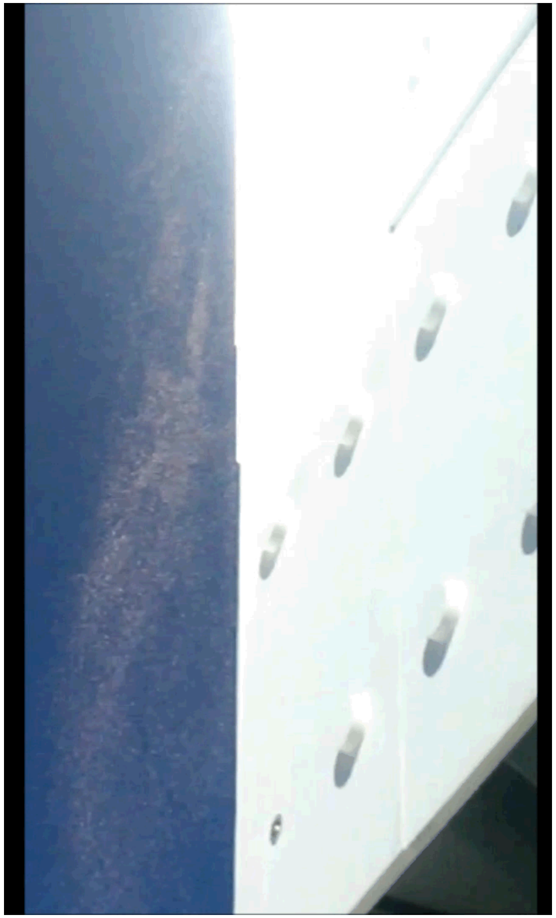
Free-Fall



Obstructed-Flow

Particle and Heat Loss

- Need to reduce particle and heat losses from receiver aperture
- Need particle imaging method to characterize losses



Particle loss from aperture during on-sun test

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Summary

- Renewables require energy storage for increased penetration
- Concentrating solar power provides utility-scale electricity AND energy storage for dispatchability when it is most needed
  - Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage
- State-of-the-Art CSP Towers
  - Direct Steam
  - Molten Salt
  - Liquid Sodium
- Emerging Technologies
  - Light Trapping Receivers
  - Particle Receivers

Acknowledgments

Sandia National Laboratories

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arpa·e

Sandia National Laboratories

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Georgia Tech

Bucknell UNIVERSITY

SolAero TECHNOLOGIES

Australian National University

CSIRO

جامعة الملك سعود King Saud University

DLR

Questions?

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Backup Slides

What happens if heliostats are misaligned or not tracking properly?

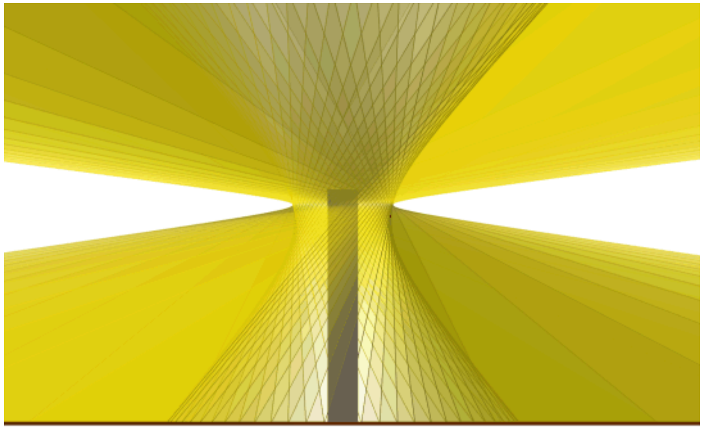
- Reduced energy production
- Overheating / fire hazard

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

San Bernardino County Fire Department)

Need to Prevent Glare

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



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)