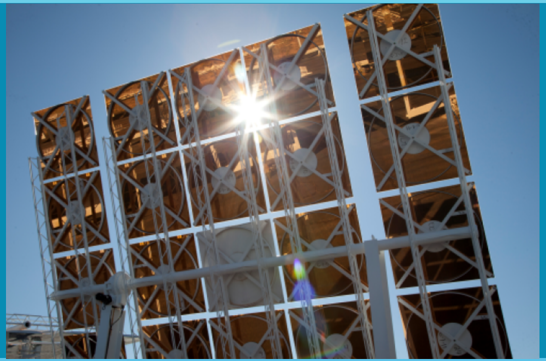
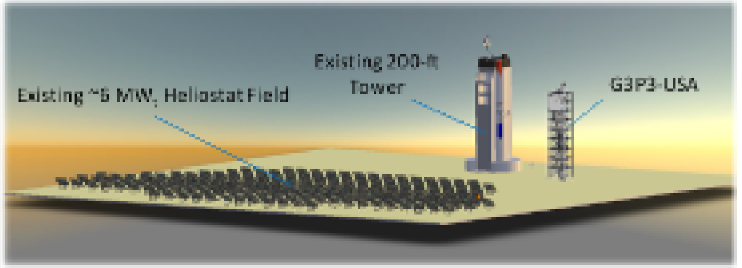
SAND2021-13741PE

Sandia National Laboratories



Concentrating Solar Thermal Technologies

Deep Decarbonization of our Primary Energy Sectors



PRESENTED BY

Clifford K. Ho, Ph.D.

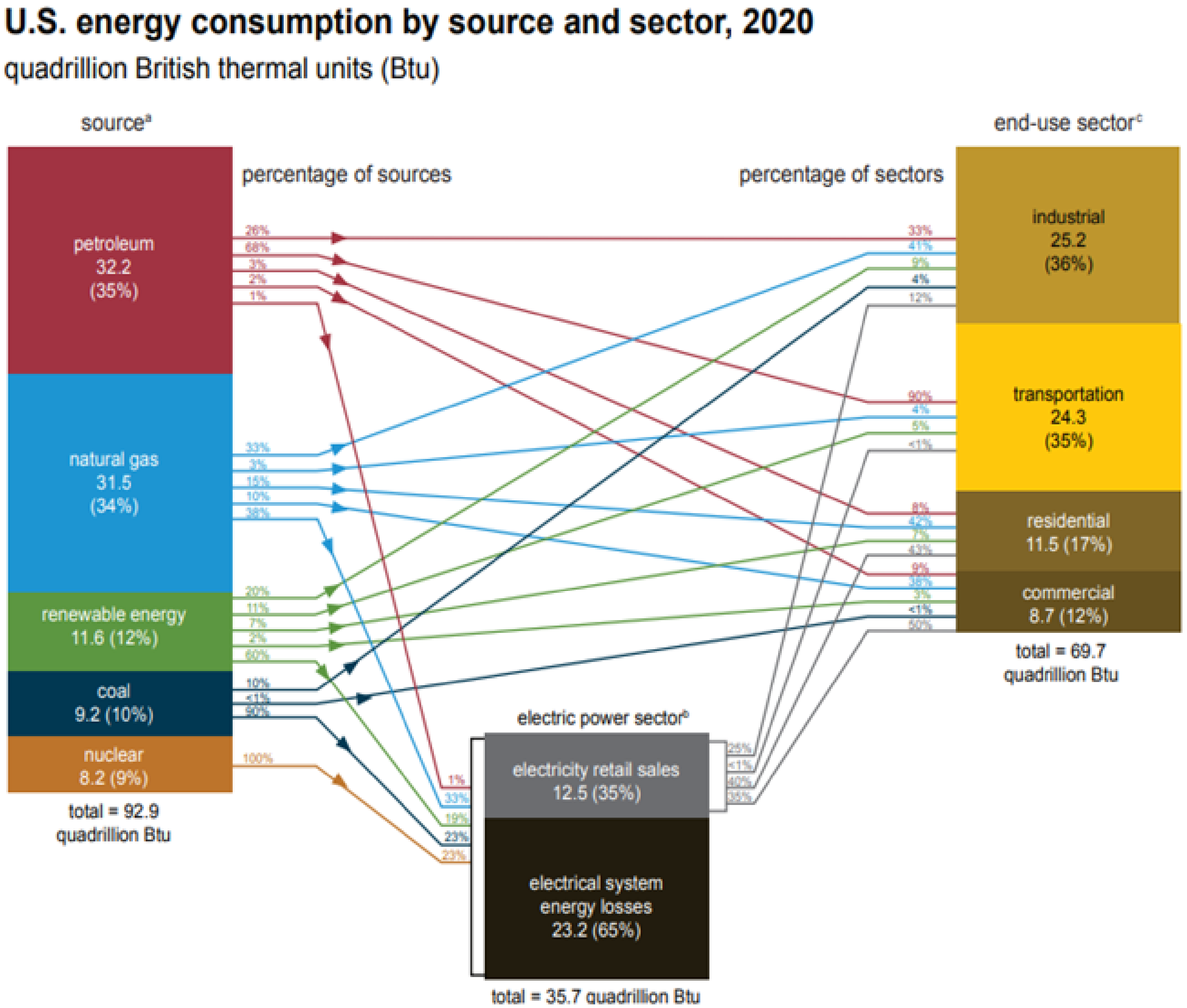
Sandia National Laboratories, Albuquerque, NM, ckho@sandia.gov

SAND2021-XXXX

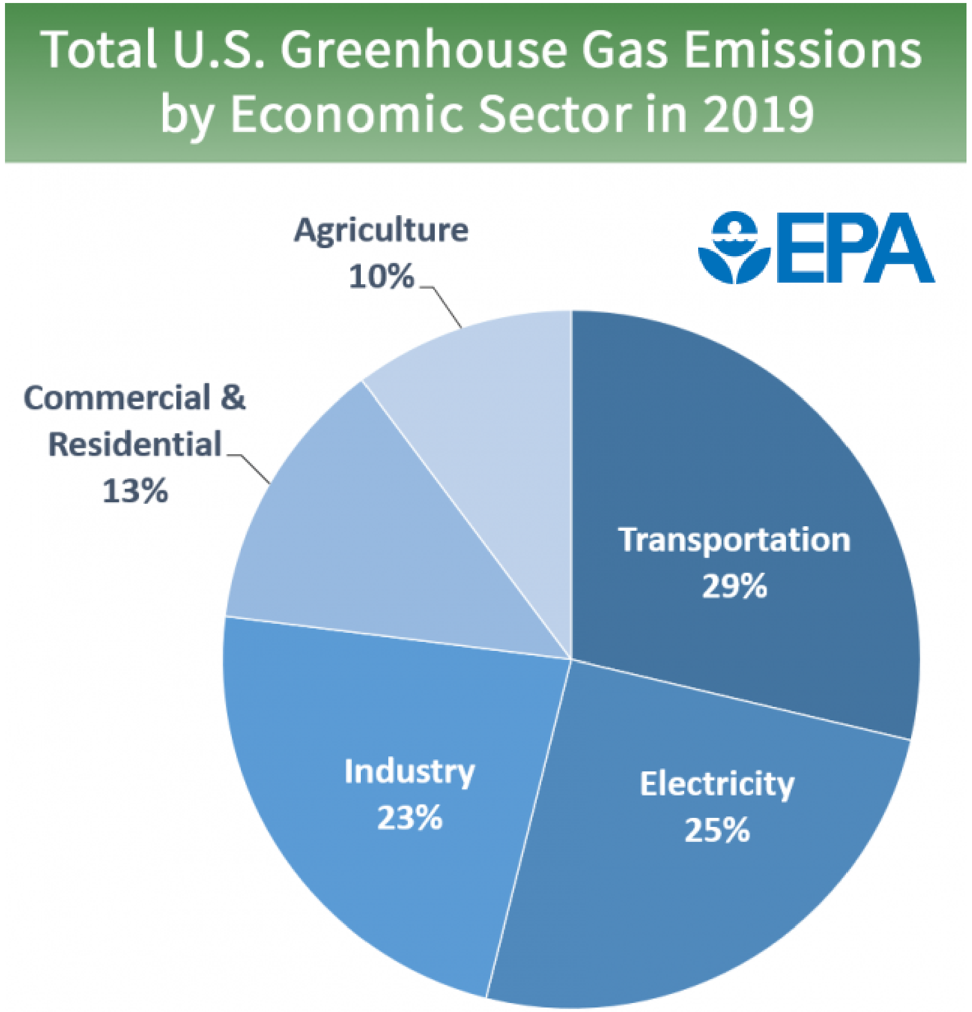
Overview

- Decarbonization of **Electricity Generation** 
- Decarbonization of **Industrial Process Heat** 
- Decarbonization of **Transportation Fuels** 

Energy Consumption in the U.S. and GHG Emissions



https://www.eia.gov/energyexplained/us-energy-facts/

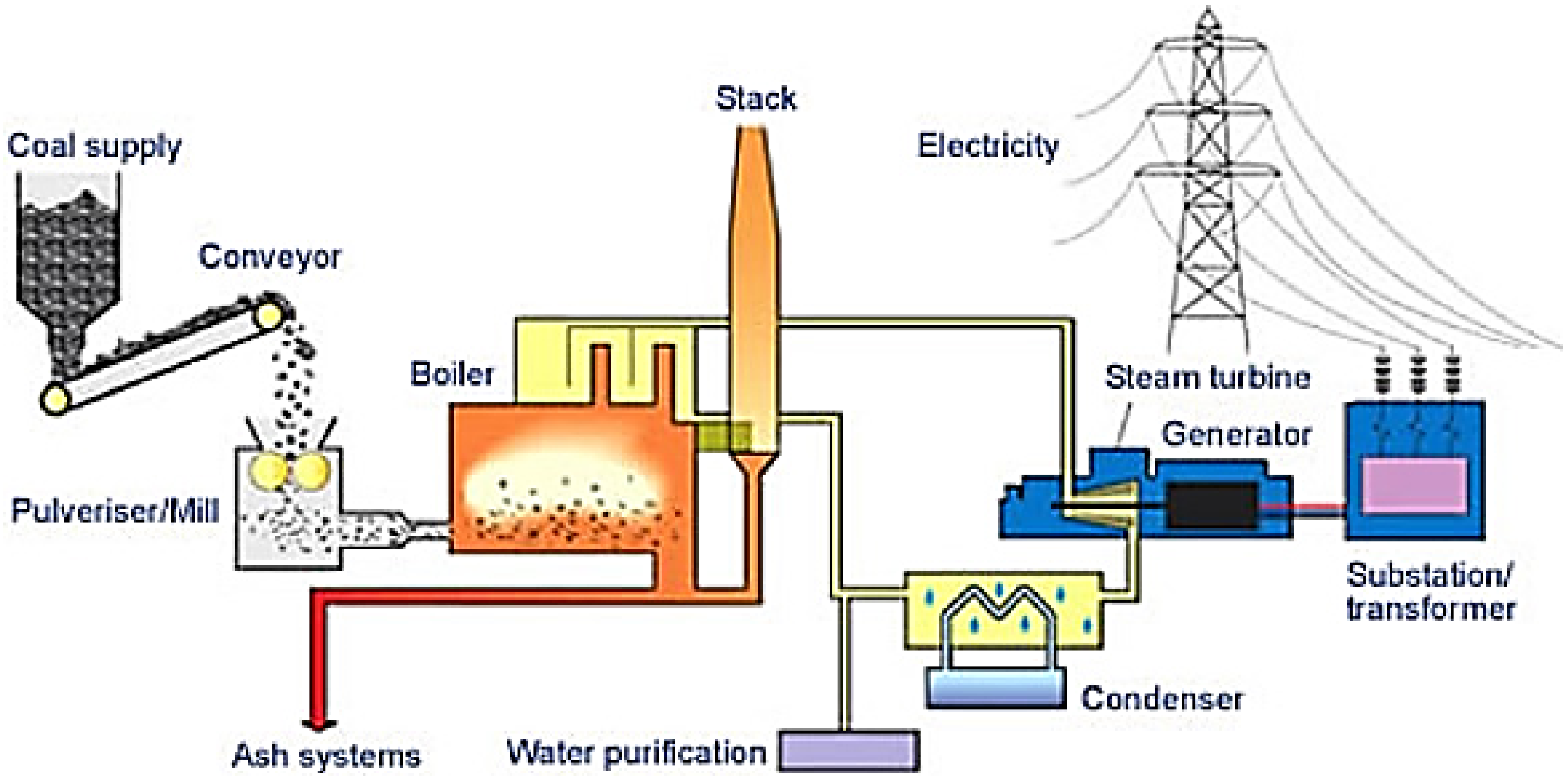


Total U.S. Emissions in 2019 = 6.6 billion metric tons of CO_2 equivalent.

https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

What is Concentrating Solar Power (CSP)?

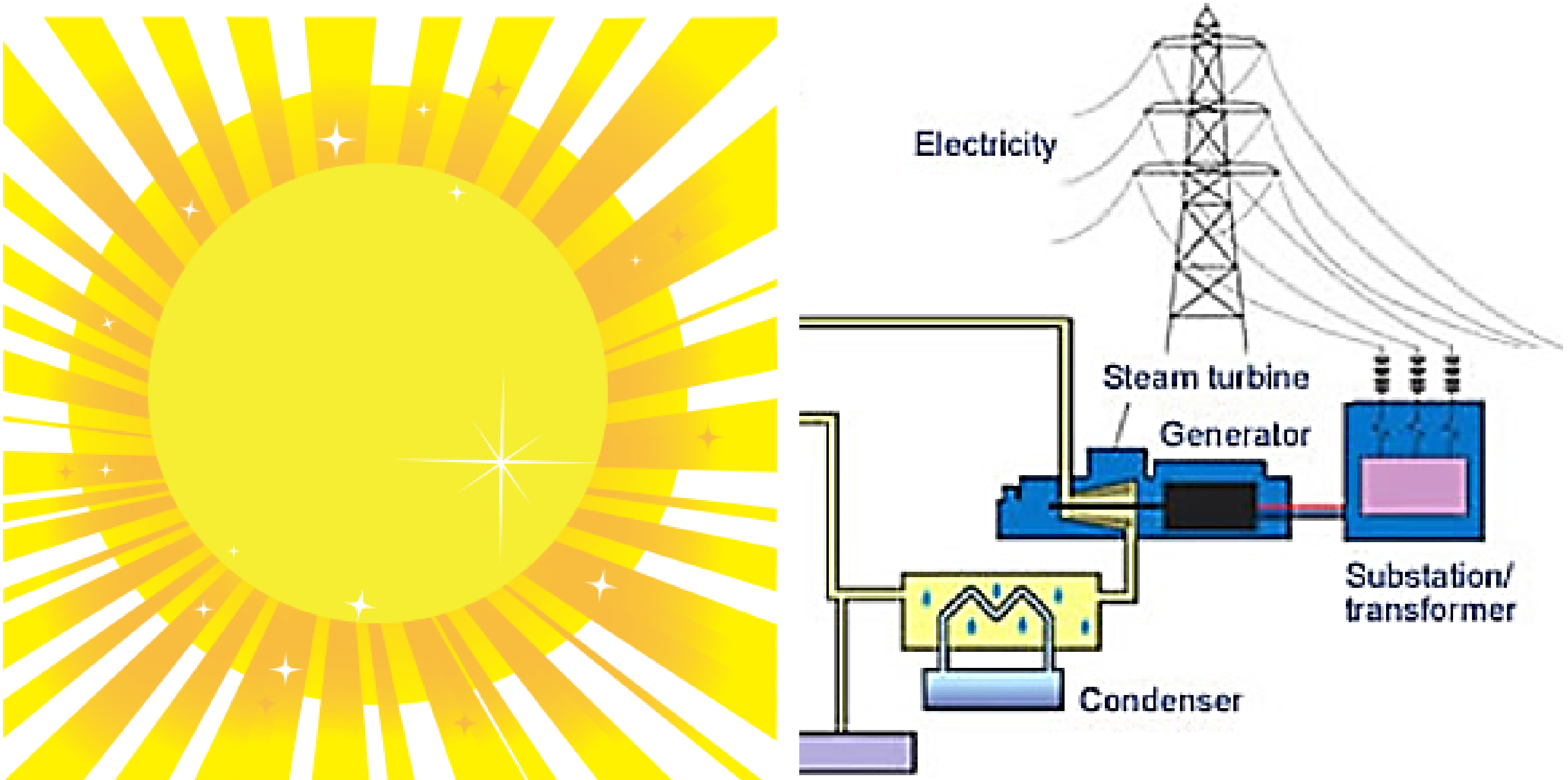
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle



Coal-Fired Power Plant

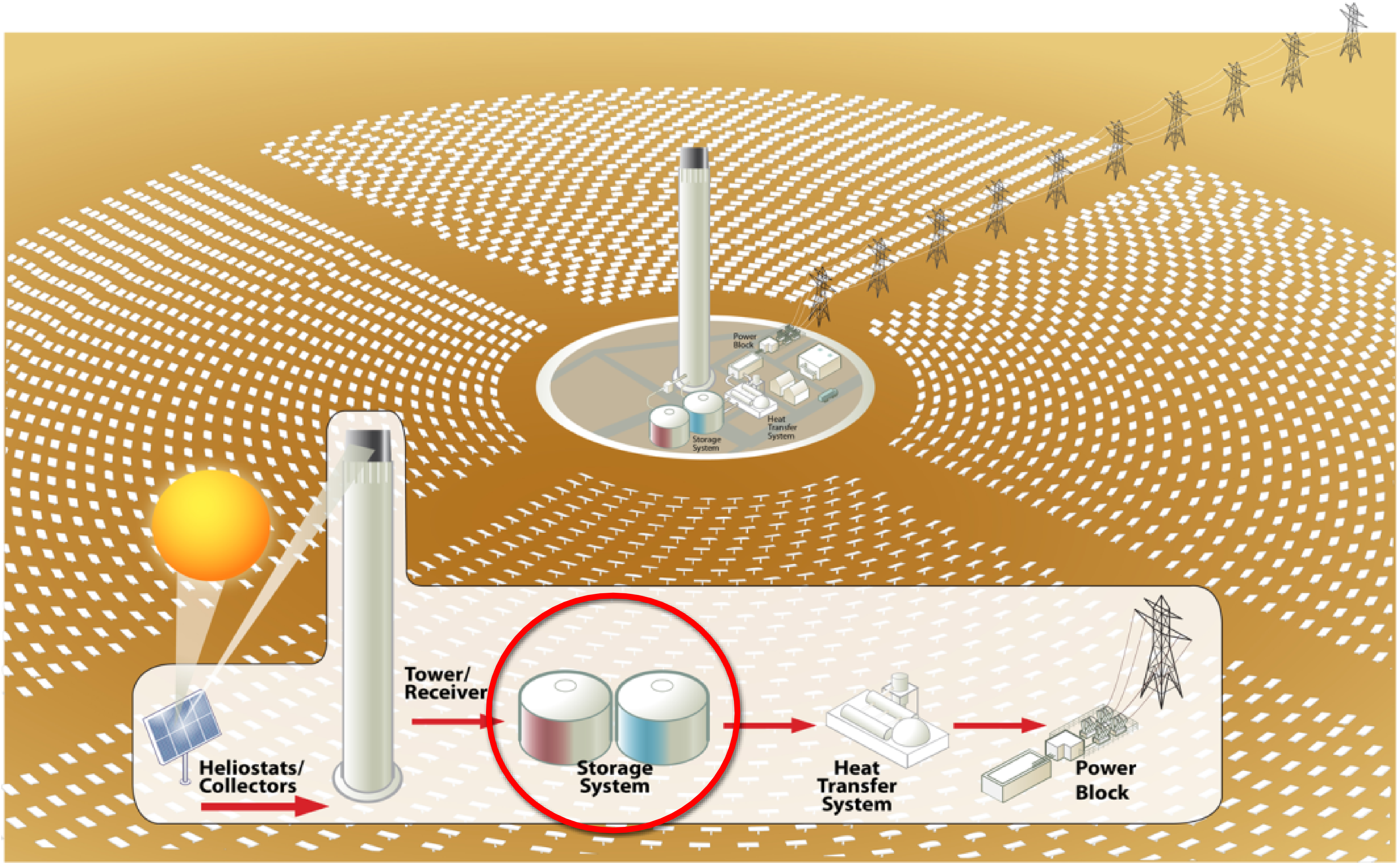
What is Concentrating Solar Power (CSP)?

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



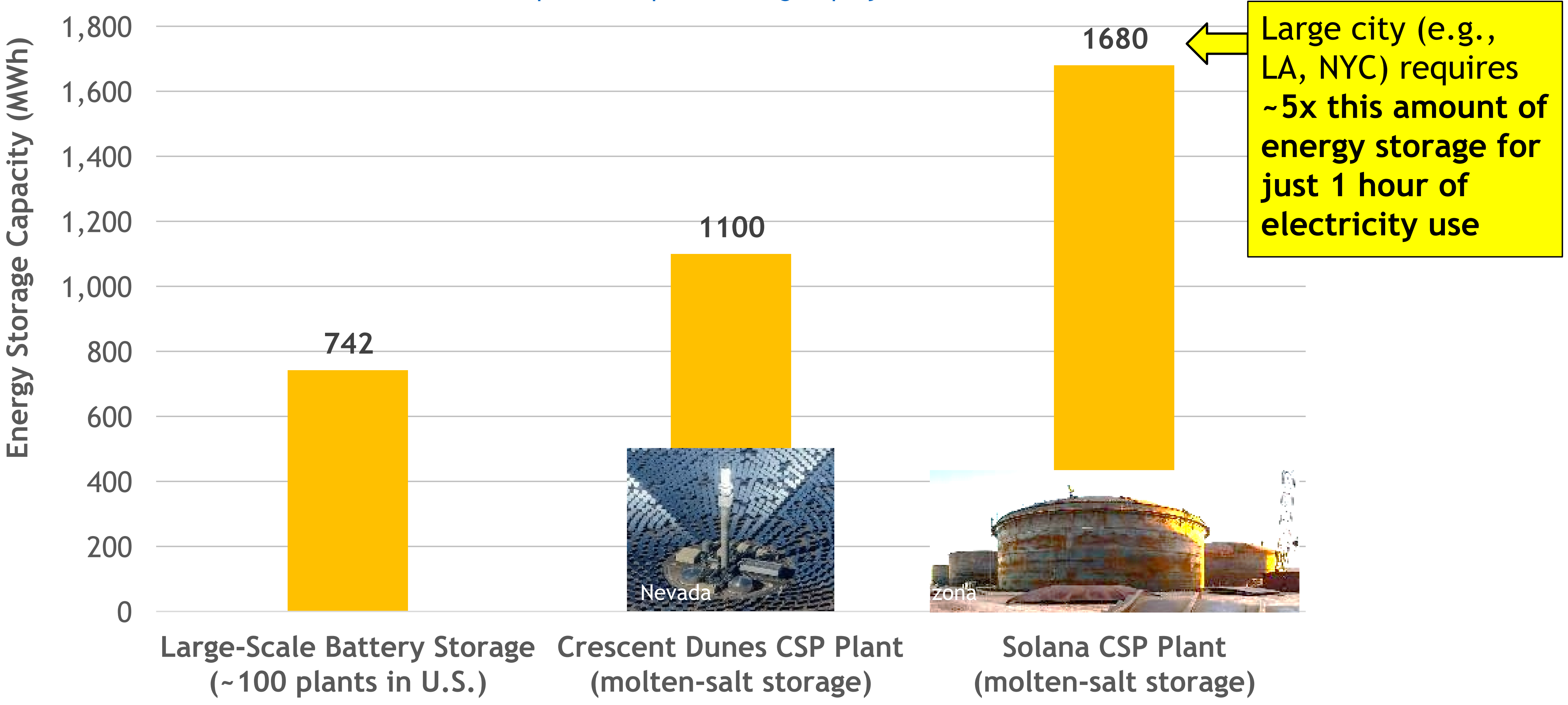
Concentrating Solar Power

Concentrating Solar Power (CSP)



Growing Need for Large-Scale Energy Storage

Battery data from U.S. Energy Information Administration (**June 5, 2018**)
CSP data from https://solarpaces.nrel.gov/projects



Timeline of CSP Development

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

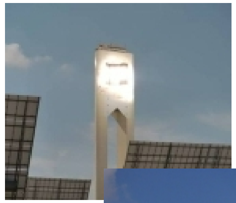
Stirling Energy Systems
1.5 MW_e, AZ, 2010

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

Timeline of CSP Development

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

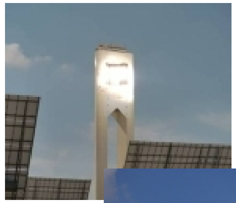
Stirling Energy Systems
1.5 MW_e, AZ, 2010

Ivanpah,
steam, 377
MW_e, CA,
2014

All commercial CSP plants around the world use designs and/or concepts developed or tested at Sandia's NSTTF

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

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



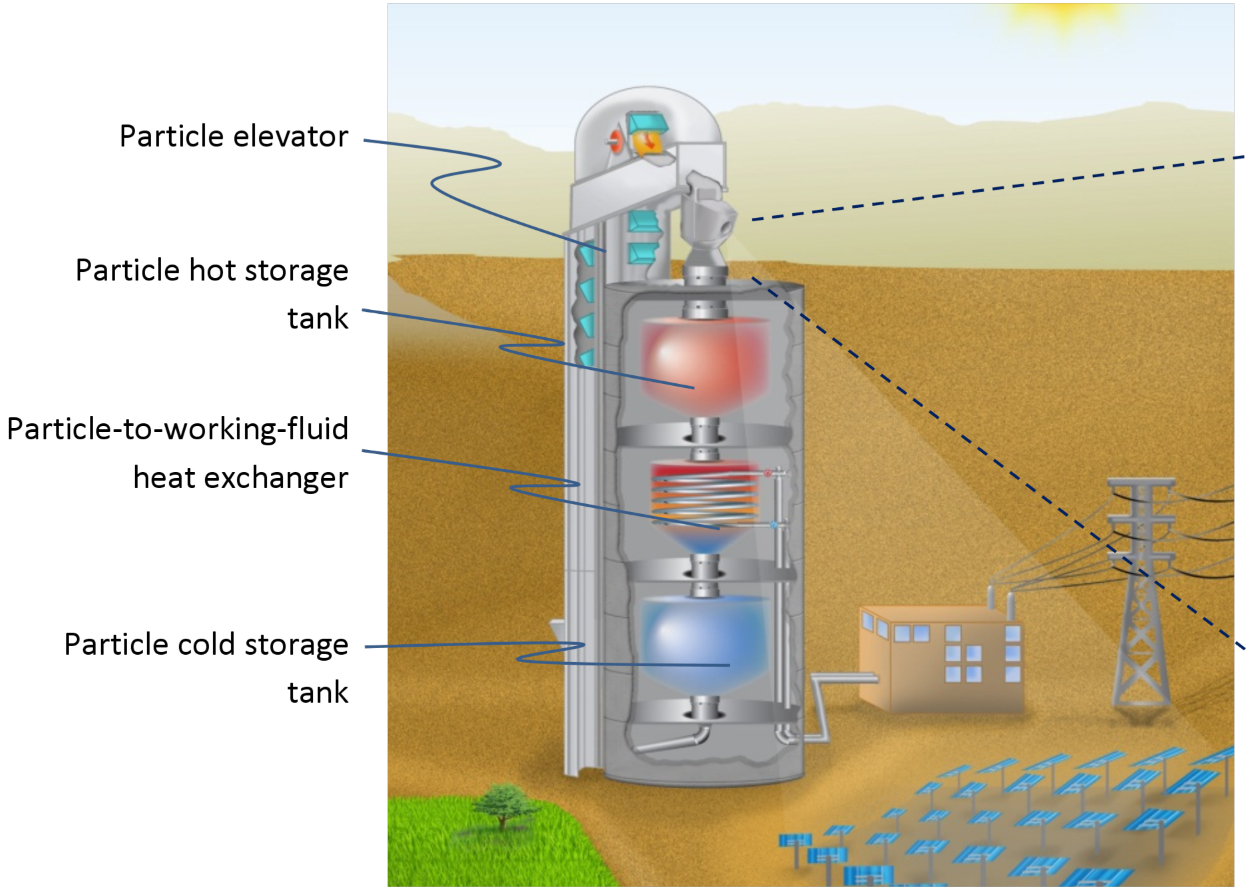
PS10/20,
steam, Spain,
2007-2009

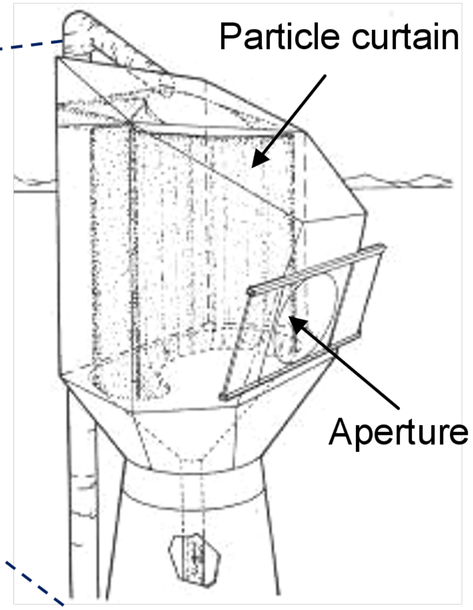
Gemasolar, molten salt, 19
MW_e, Spain, 2011

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

Particle-Based Concentrating Solar Power

High-Temperature Particle-Based CSP





Falling particle receiver

Particle-Based Concentrating Solar Power

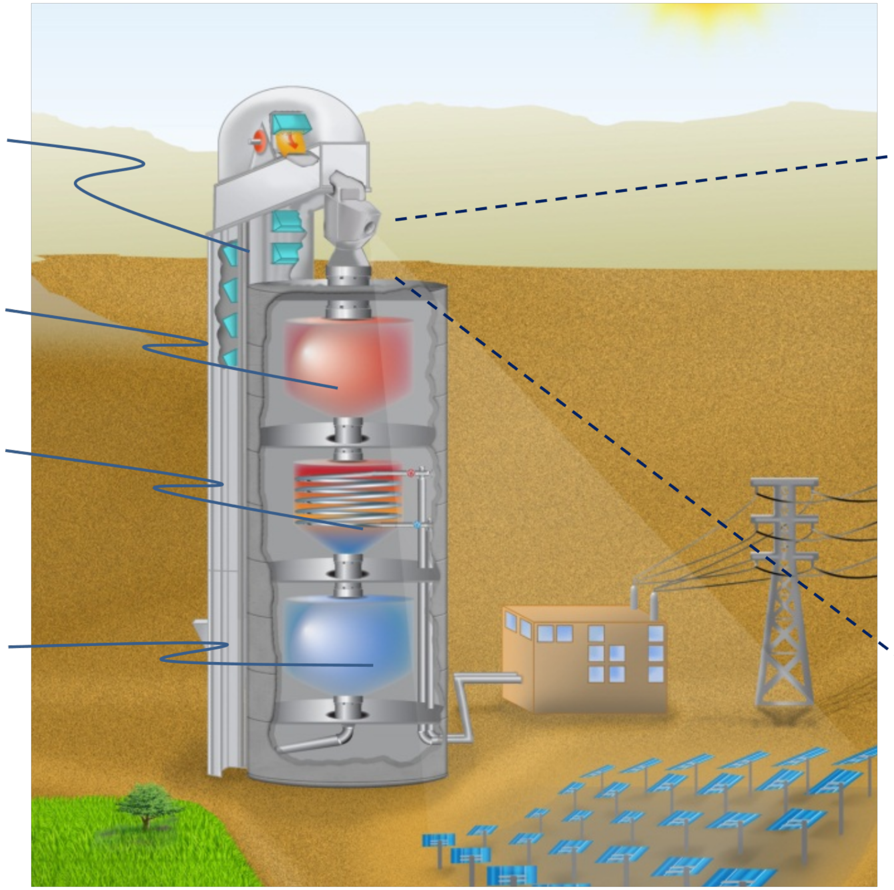
High-Temperature Particle-Based CSP

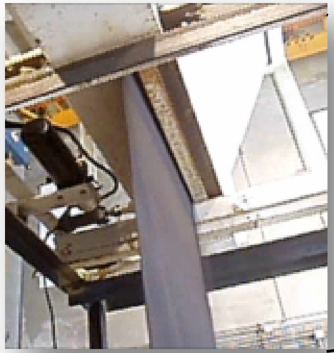
Particle elevator

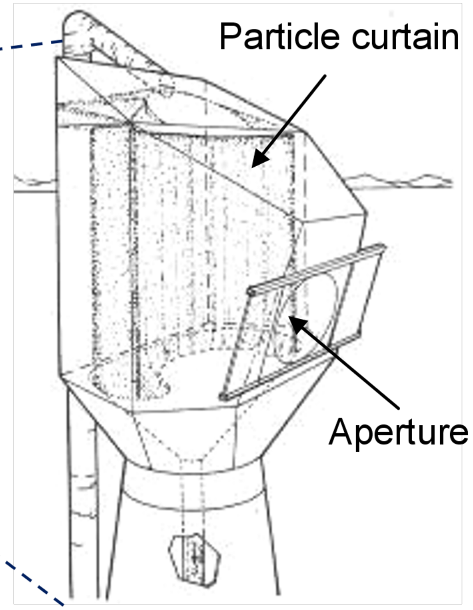
Particle hot storage tank

Particle-to-working-fluid heat exchanger

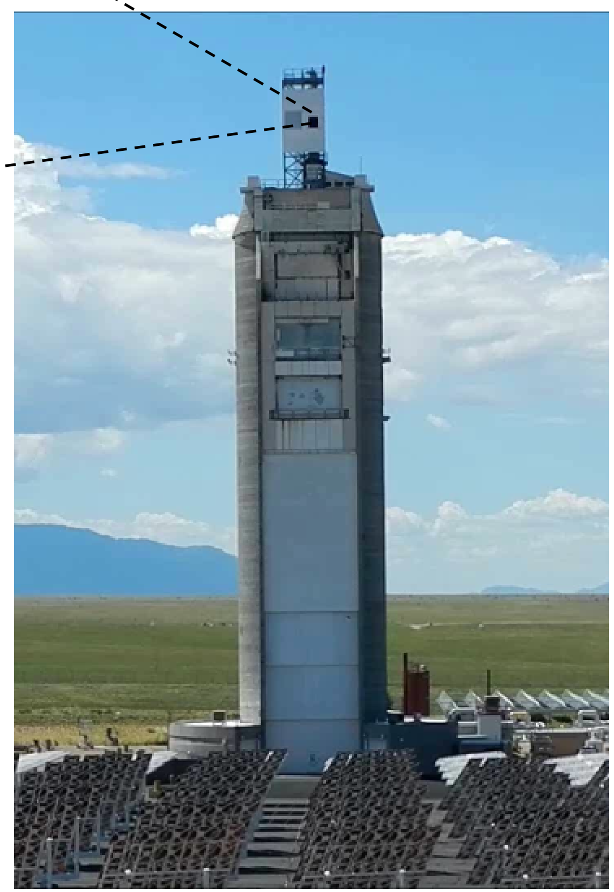
Particle cold storage tank







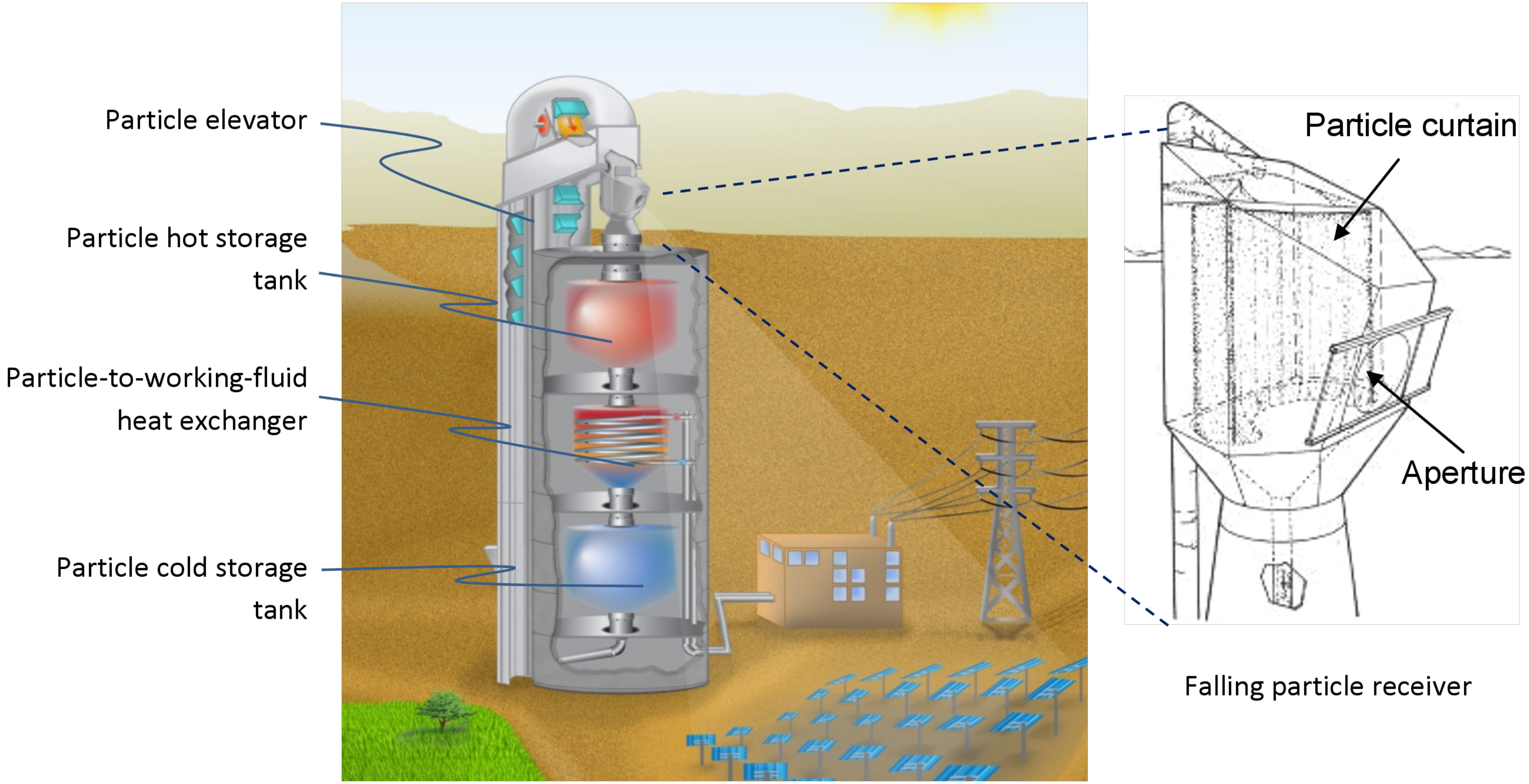
Falling particle receiver



National Solar Thermal Test Facility
Sandia National Laboratories

Particle-Based Concentrating Solar Power

High-Temperature Particle-Based CSP



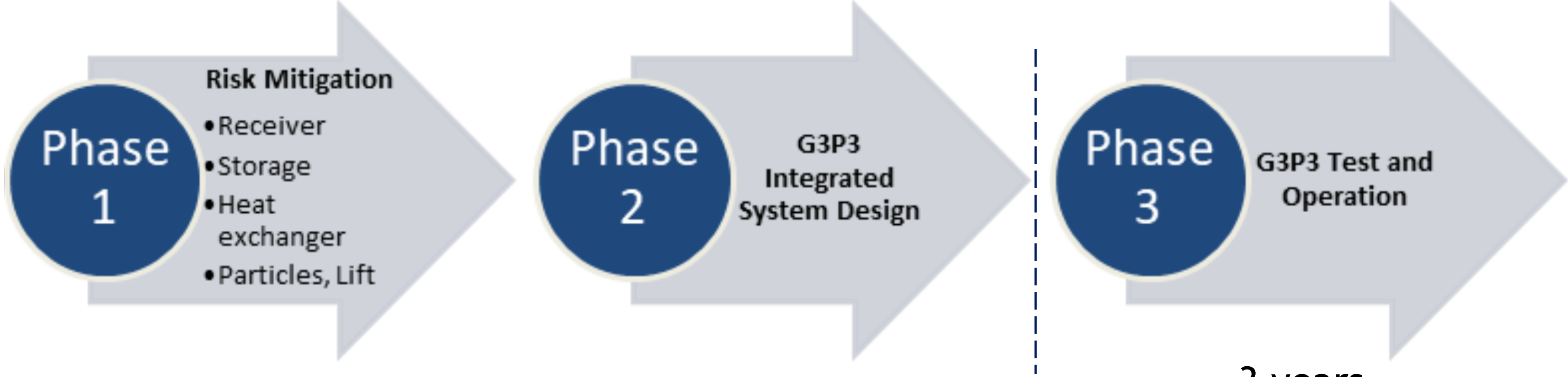
Falling particle receiver

- Higher temperatures (>1000 ˚C) than molten nitrate salts
- Direct heating of particles vs. indirect heating of tubes
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles

DOE Generation 3 CSP Program (FY19 – FY24)

Achieve higher temperatures, higher power-cycle efficiencies, and lower LCOE

Brayton Energy	NREL	Sandia
Gas Phase Pathway	Liquid Phase Pathway	Solid Phase Pathway



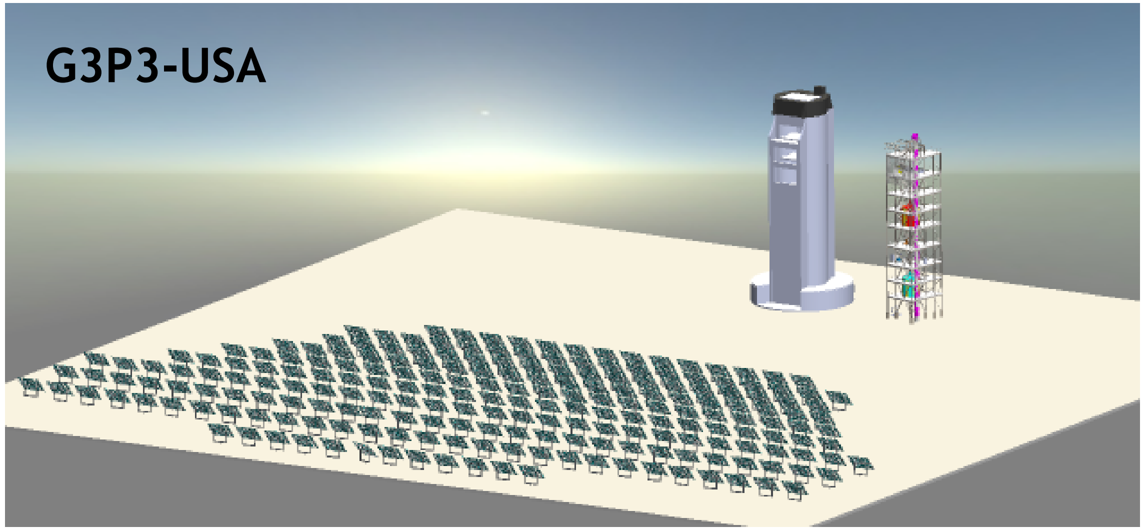
18 months
FY19 – FY20

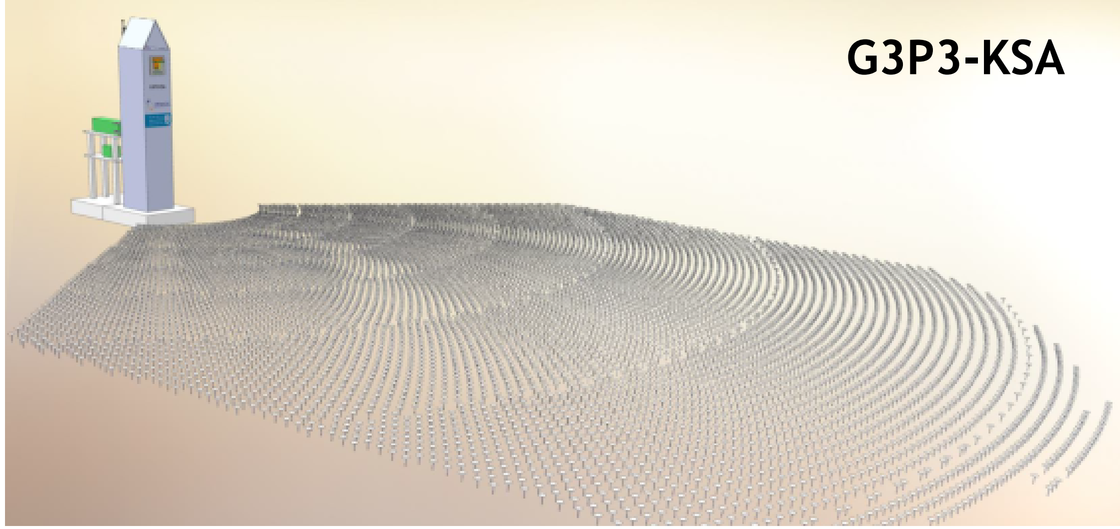
6 months
FY20

DOE
Downselection
(March 2021)

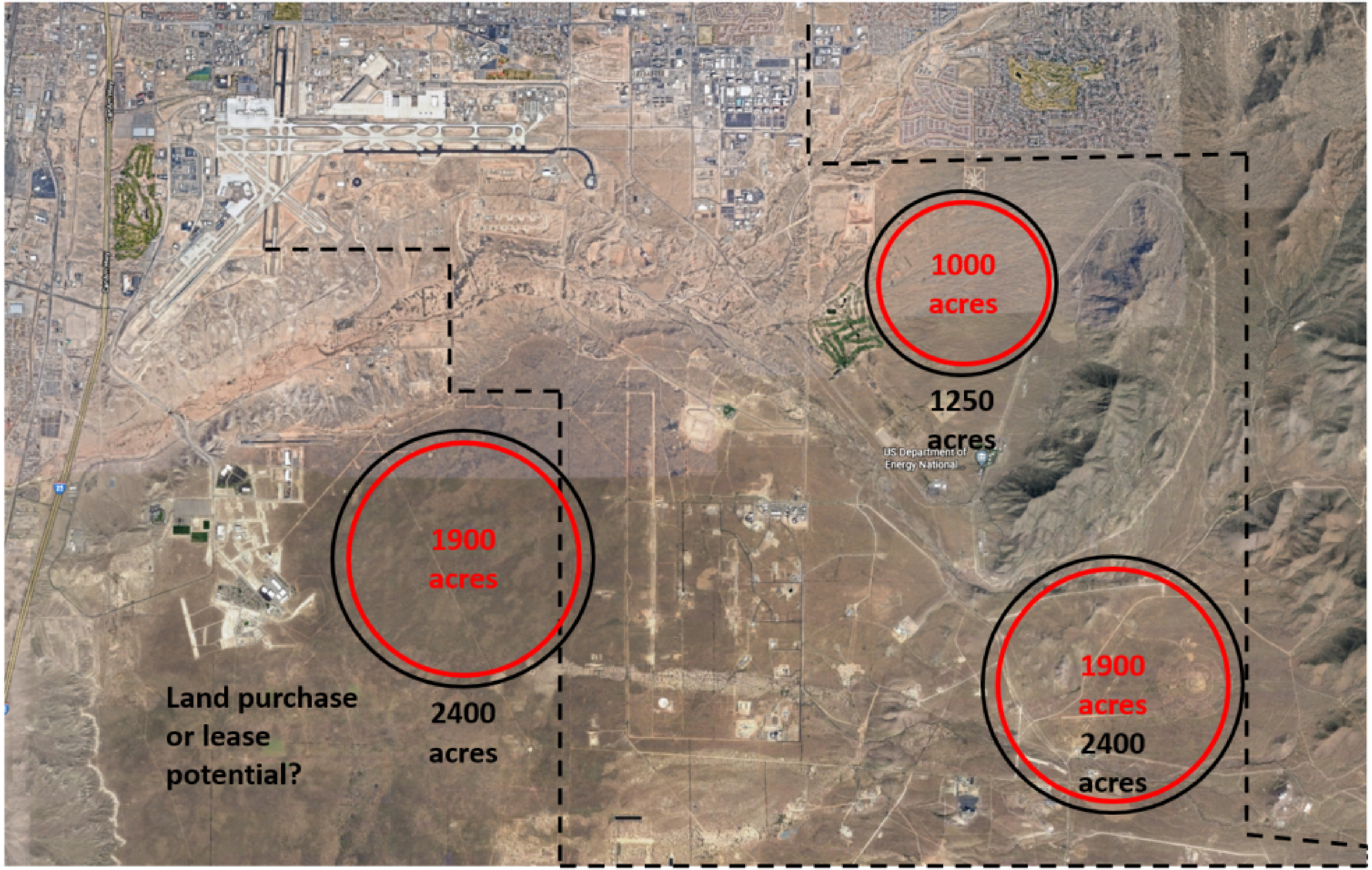
3 years
FY21 – FY23

G3P3-USA and G3P3-KSA



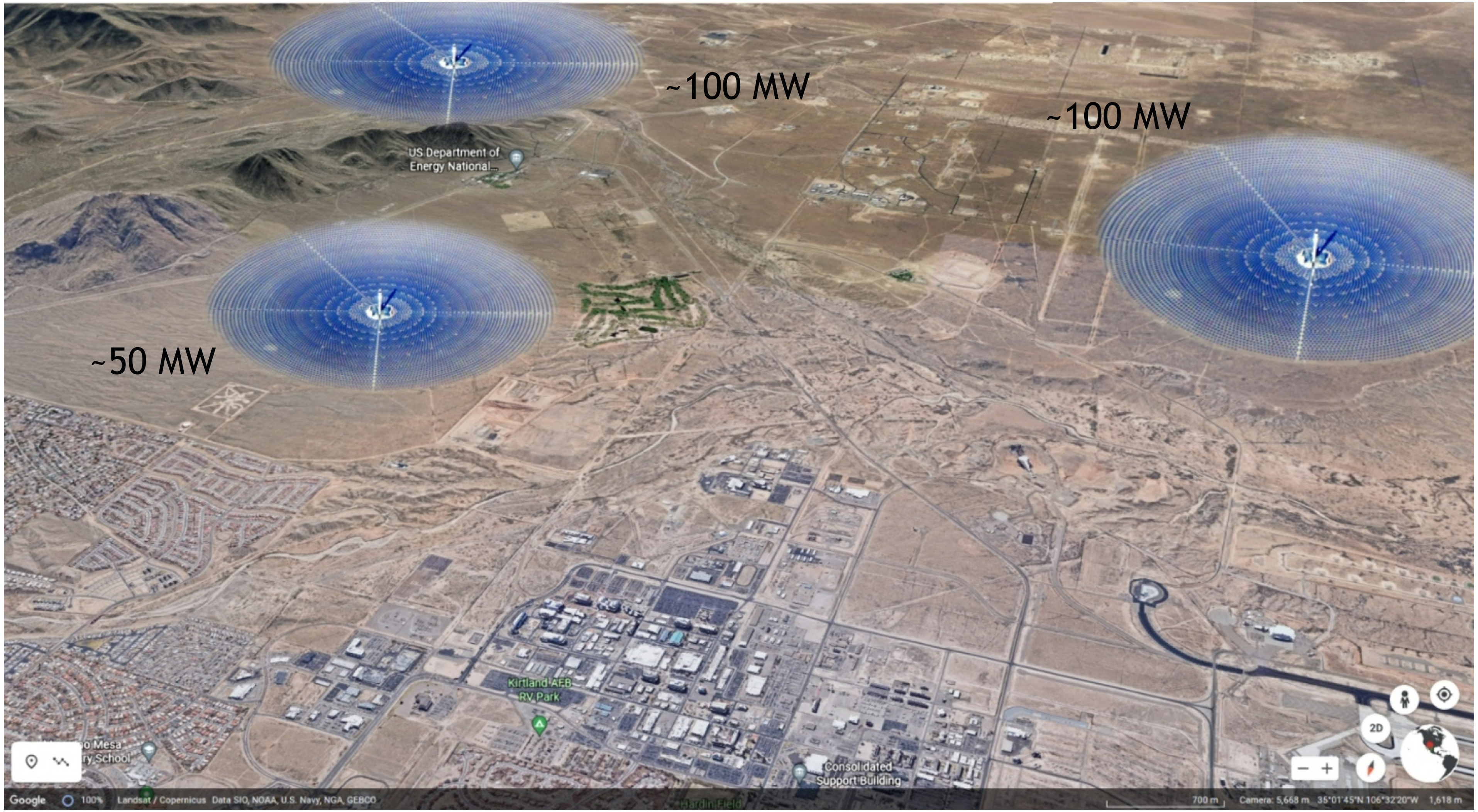


CSP for Sandia and Kirtland Air Force Base?



Potential ~1000 acre site (50 MW) looking east

Looking southeast – three potential sites



CSP Study for Sandia NM and KAFB

SANDIA REPORT
SAND2021-12294
Printed October 2021

Sandia National Laboratories

100% Carbon-Free Electricity for Sandia NM and KAFB Using Concentrating Solar Power (CSP)

Clifford K. Ho, H. Evan Bush, Daniel Villa, Nicole Rinaldi, Nathan R. Schroeder, and Jeremy Sment

Overview

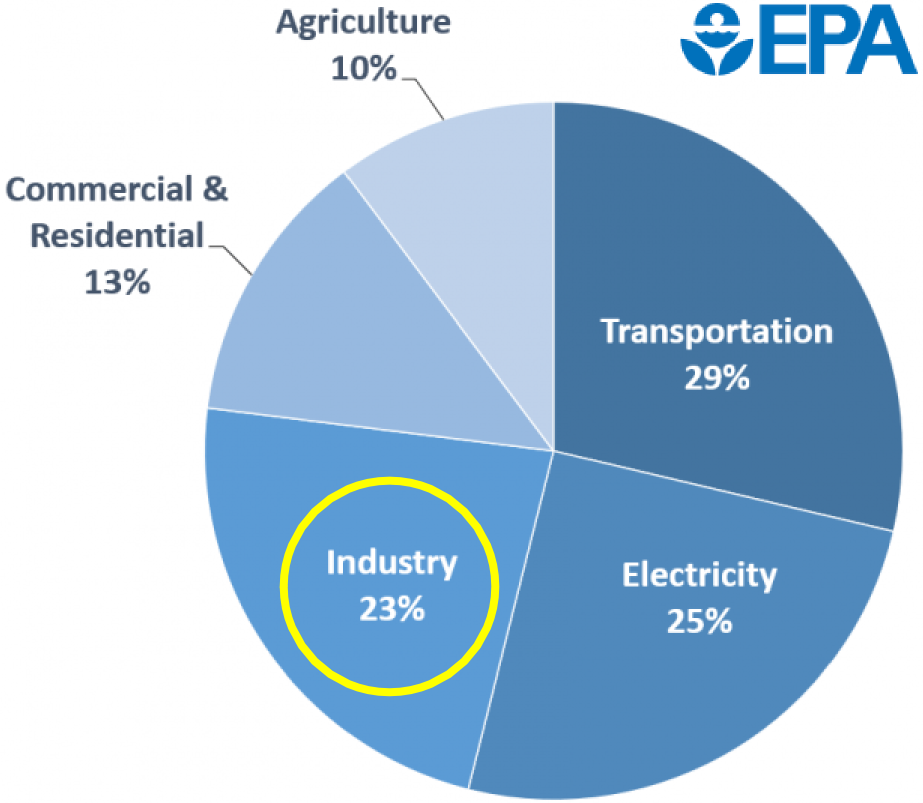
- Decarbonization of **Electricity Generation**

- Decarbonization of **Industrial Process Heat**

- Decarbonization of **Transportation Fuels**

Problem Statement

Total U.S. Greenhouse Gas Emissions by Economic Sector in 2019



Total U.S. Emissions in 2019 = 6.6 billion metric tons of CO_2 equivalent.

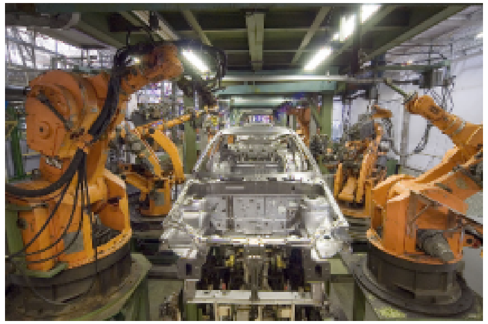
https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Nearly a quarter of all greenhouse gas emissions in the U.S. are from Industrial Processes and Manufacturing

Cement and steel production

Food processing and drying

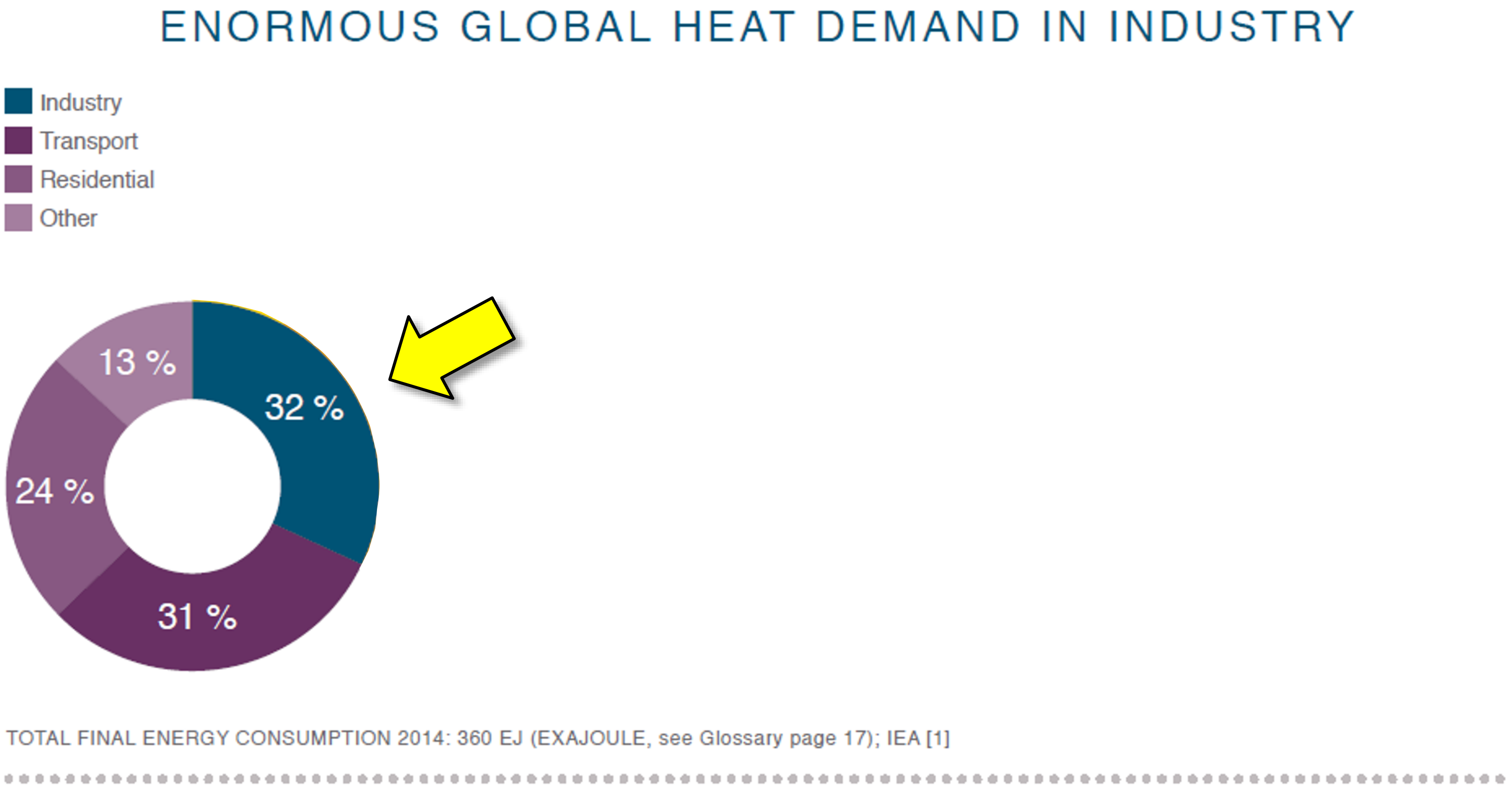
Chemicals (e.g., NH_3)



Electrification/automation

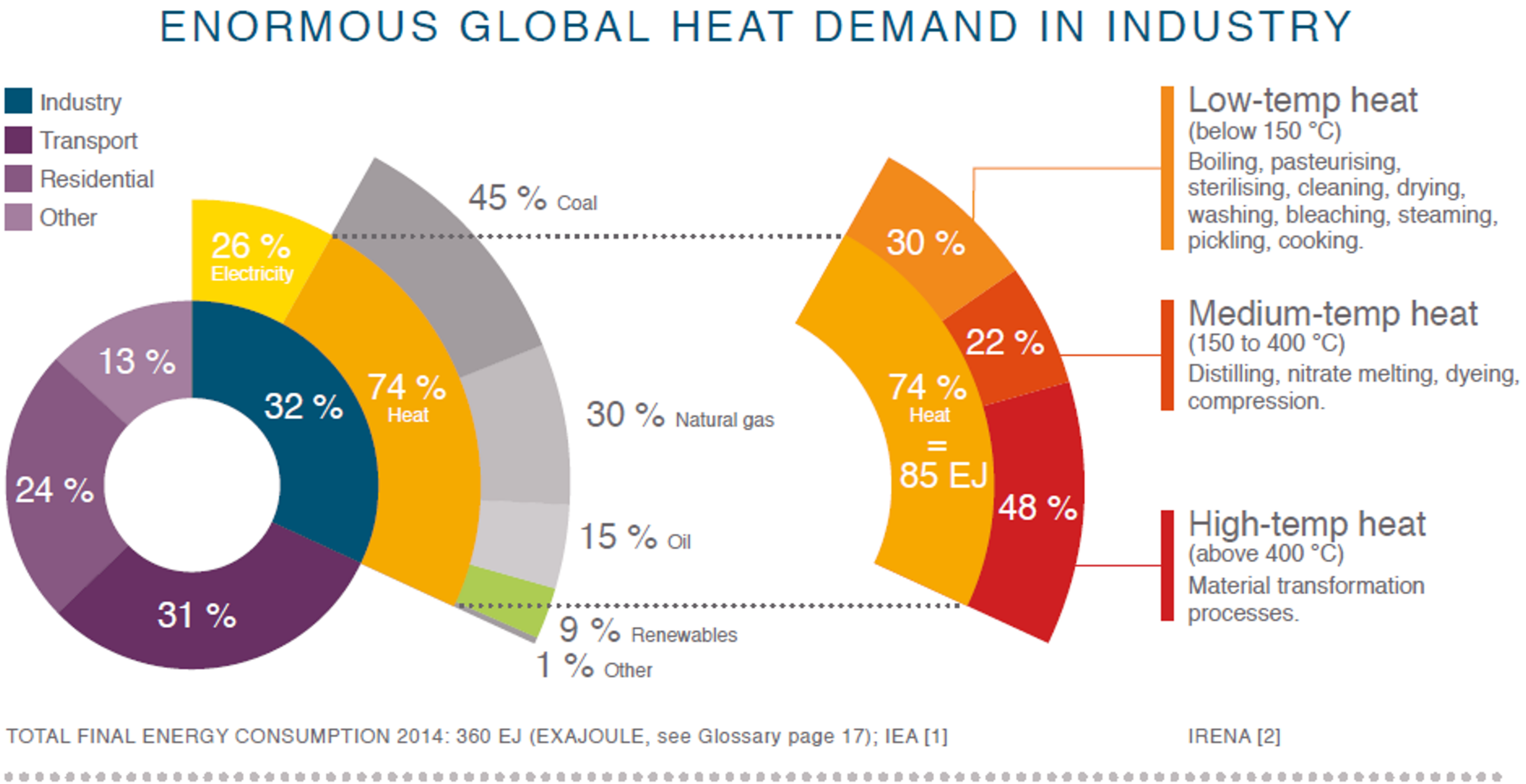
Petroleum refining

Untapped Potential for Industrial Heat



Source: Solar Heat for Industry (2017), www.solar-payback.com
[4] European Solar Thermal Industry Federation (ESTIF), Solar Heat for Industrial Process Heat – a Factsheet, www.estif.org

Untapped Potential for Industrial Heat



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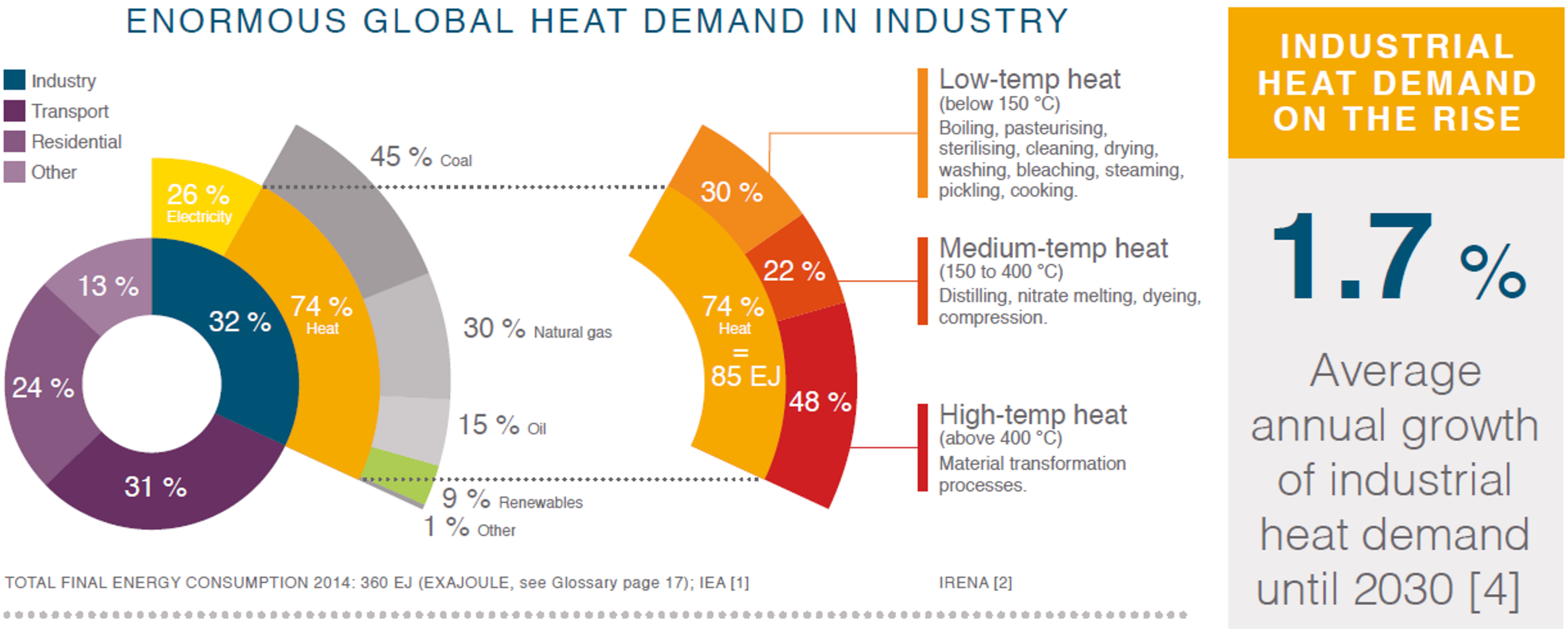
Untapped Potential for Industrial Heat



Source: Solar Heat for Industry (2017), www.solar-payback.com

[4] European Solar Thermal Industry Federation (ESTIF), Solar Heat for Industrial Process Heat – a Factsheet, www.estif.org

Food Processing – Pasta Drying Example

The following is an example of a Barilla pasta plant in Foggia, Italy, that plans to use solar thermal heat for pasta drying.

Solar Thermal Input (particle-based receiver, DLR)

Fresh extruded pasta (moist) → Heat → Dry pasta ready for packaging

~8e6 kWh_t/year

7000 tonnes/year

Key takeaway: A single Barilla pasta plant can avoid 1,500 tons of CO_2 per year using solar thermal for drying. Assuming a carbon price of $40/ton, this would save the plant $60,000/year.

HelioHeat HiFlex Project for Barilla pasta drying plant

(rendering from HelioHeat; presented by H. Al-Ansary at 2021 SolarPACES plenary)

Overview

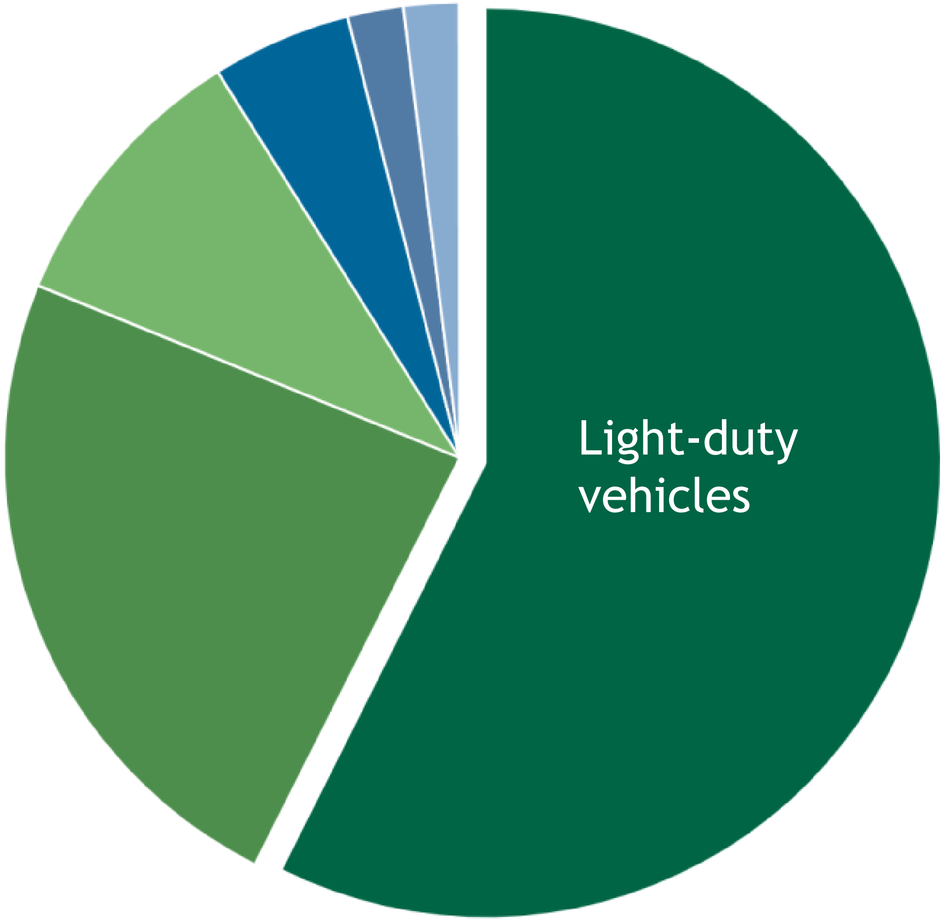
- Decarbonization of **Electricity Generation**

- Decarbonization of **Industrial Process Heat**

- Decarbonization of **Transportation Fuels**

GHG Emissions from Heavy Duty Transportation

2019 U.S. Transportation Sector GHG Emissions by Source



~40% of our transportation sector will be difficult to electrify (aircraft, ships, rail, heavy-duty trucks)

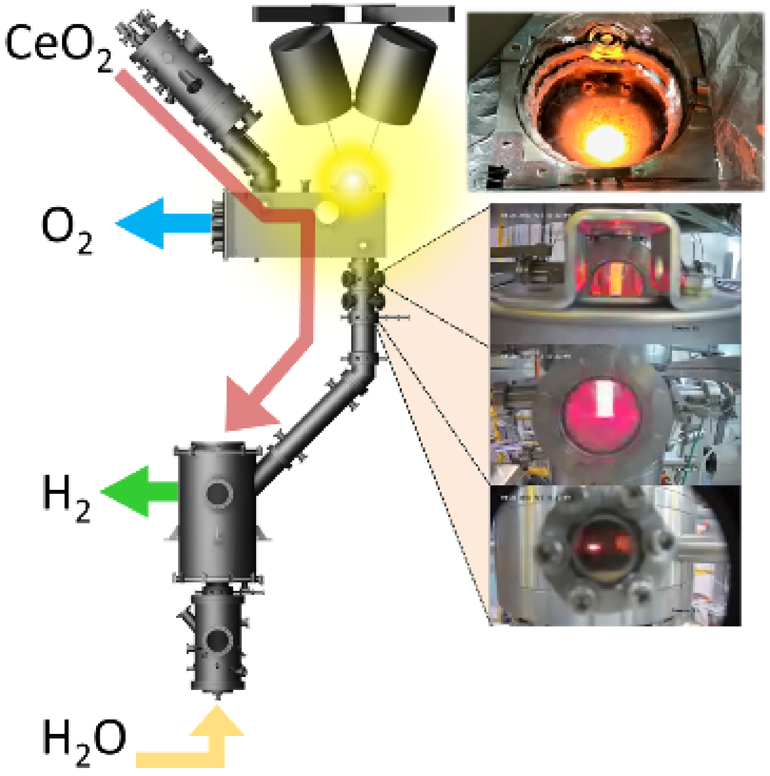
- Light–Duty Vehicles – 58%
- Medium– and Heavy–Duty Trucks – 24%
- Aircraft – 10%
- Other – 5%
- Rail – 2%
- Ships and Boats – 2%

https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

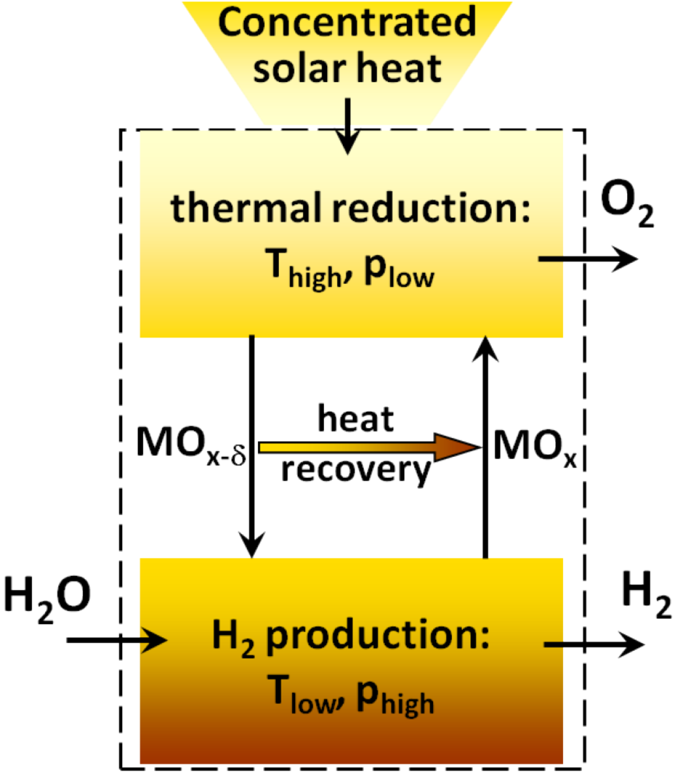
Hydrogen Production

Solar Thermo-Chemical Hydrogen Production (STCH)

- Replace steam-methane reforming with solar thermochemical hydrogen production
- Solar heat can thermochemically induce water-splitting in some materials



Adapted from McDaniel, Zimmerman, et al.

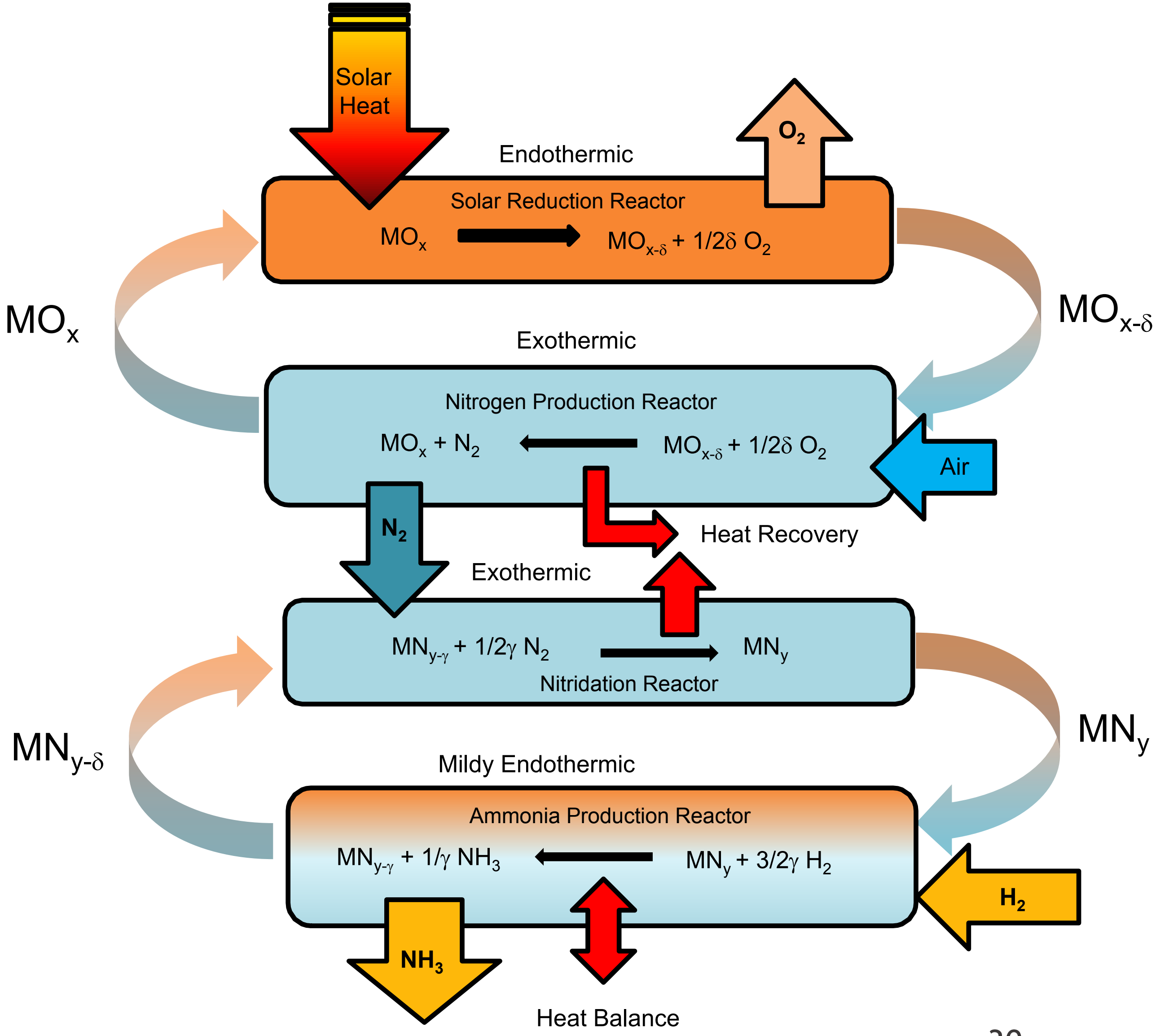


Two-step metal oxide cycle

STCH reactor at NSTTF

Ammonia Production

Solar Thermal Ammonia Production (STAP) A. Ambrosini, SNL

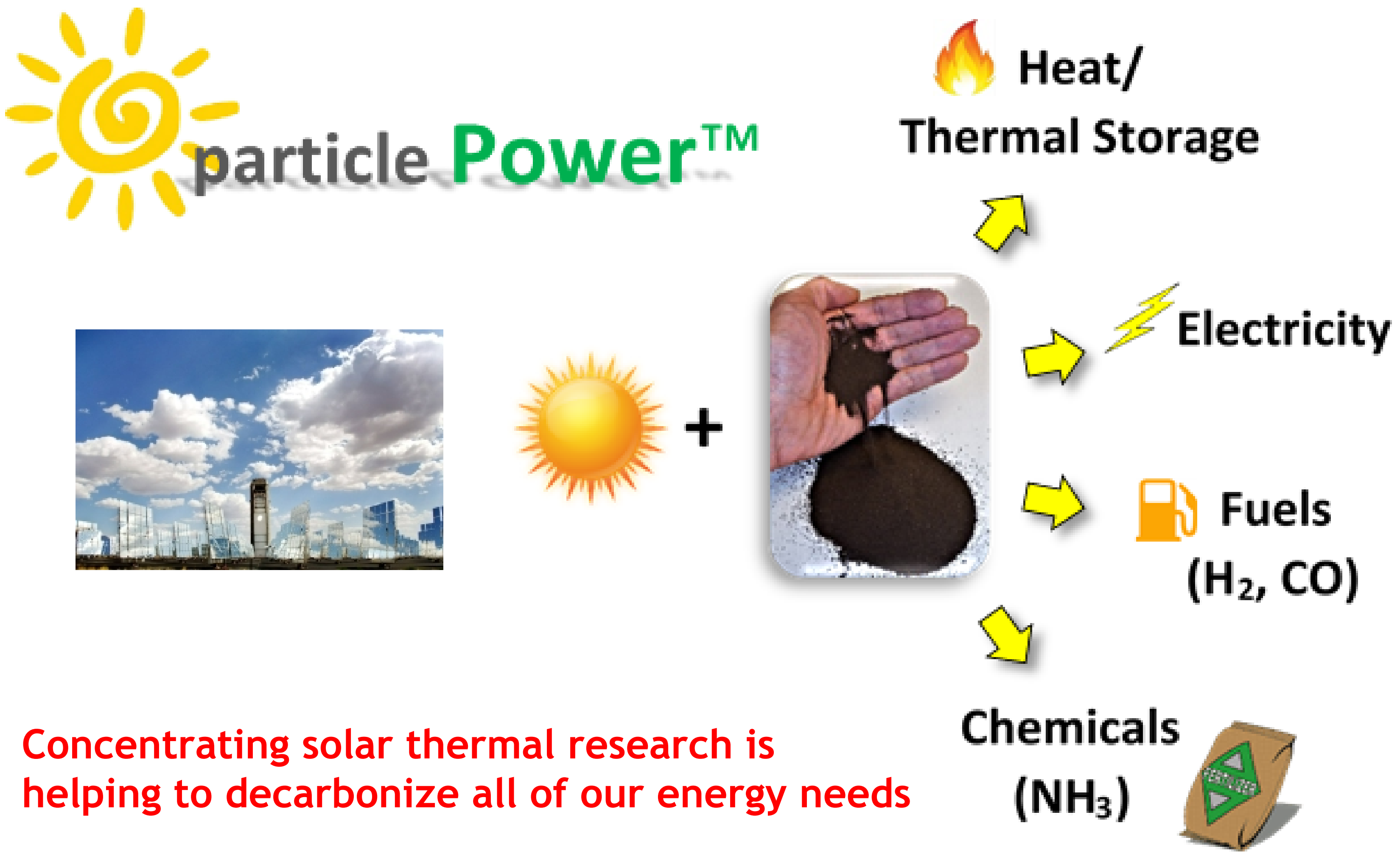


Solar thermochemical technology to produce nitrogen (N_2) from air for the subsequent production of ammonia (NH_3)

- Inputs are sunlight, air, and hydrogen; the output is ammonia
- Significantly lower pressures than Haber -Bosch
- Greatly decreases or eliminates carbon footprint

Summary

Concentrating Solar Thermal Technology



Concentrating solar thermal research is helping to decarbonize all of our energy needs

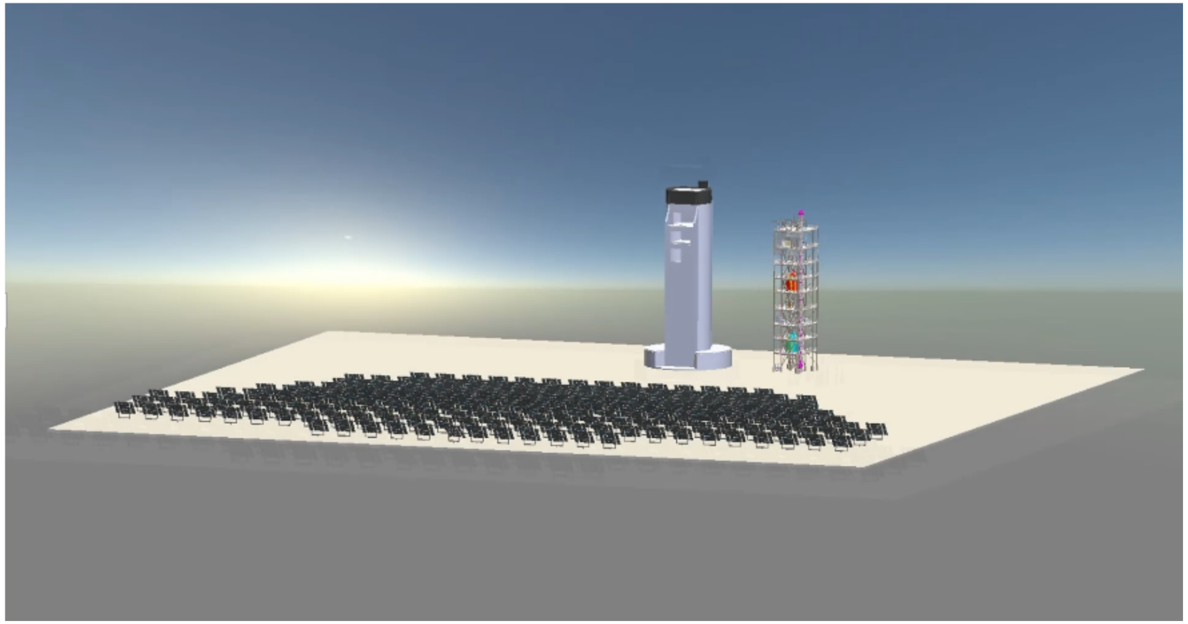
Backup Slides

U.S. Investment in CSP R&D

DOE investing in CSP technologies pioneered by Sandia

- DOE Gen 3 CSP (~$80M)
  - Develop next generation high-temperature solar-thermal power generation (FY19 – FY23)
  - **Sandia received $35M for particle-based system** (~16 domestic & international partners)
- DOE TESTBED/Heliogen
  - $39M DOE, $30M cost share FY20 – FY24
  - Solarized supercritical CO_2 power cycle with thermal storage; solar fuels
  - **Sandia is a key partner**
- DOE Annual Lab and FOA calls
  - ~$30M - $60M per year in CSP and solar thermal R&D

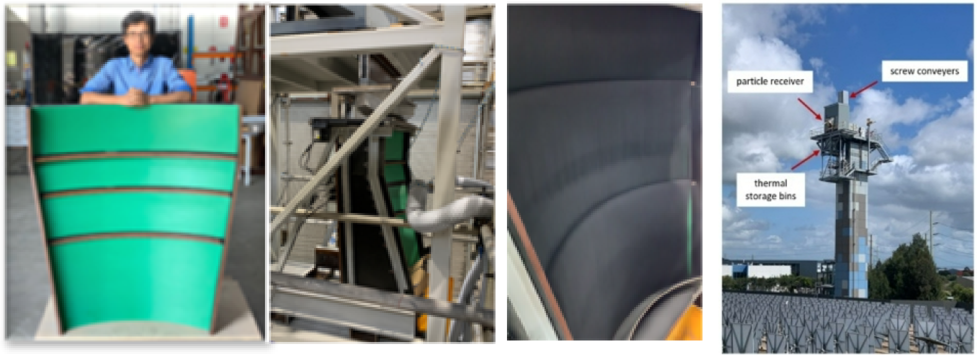
Sandia Gen 3 Particle Pilot Plant



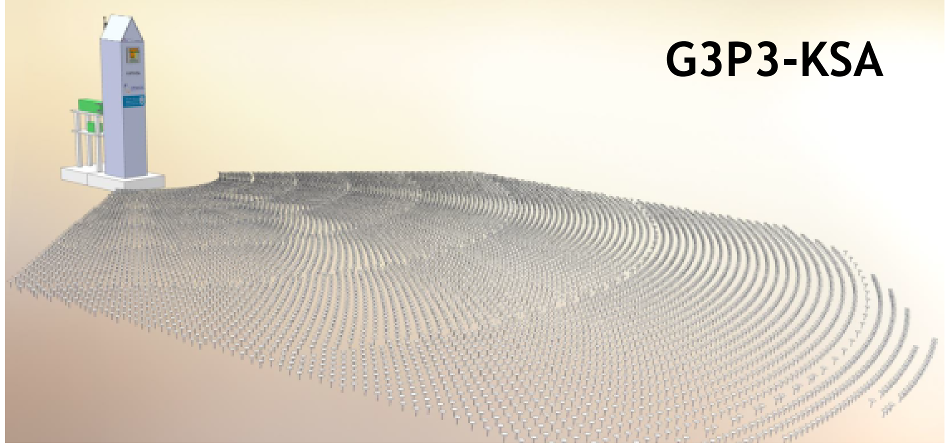
Breakthrough Energy Ventures

Global Investments and Sandia Partnerships

CSIRO



- International CSP Partners
  - Australian Solar Thermal Research Institute (ASTRI)
    - CSIRO, Australian National University, U. Adelaide
  - Saudi Electricity Company / King Saud U.
  - DLR – German Aerospace Center
    - **Process heat** (HiFlex – **Barilla**, **drying of pasta using heated particles**, Foggia, Southern Italy)



Millions being invested globally in Sandia & CSP

Barilla

DLR and Sandia received a $1.5M DOE Technology Commercialization Fund award

Cement Manufacturing: 36% of CO_2 emissions due to construction is from cement production, with 55% from high energy demands during processing with the use of fossil fuels.

Jessica Rimsza (8915)

Solar Thermal Input

$CaCO_3(s)$ + Heat → $CaO(s)$ + $CO_2(g)$

Pre-Heating 1866 kJ/kg $CaCO_3$
25°C -> 800°C

Calcination 5499 kJ/kg $CaCO_3$
1300-1400°C

Cooling 1663 kJ/Kg $CaCO_3$
1400°C -> 100°C

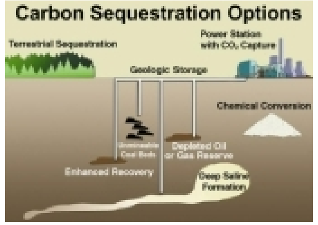
Heat Recovery

Solar Thermal Input

Pre/Heating for: Grinding, Mixing, Transport

Further Processing for Cement Production

CO_2 Sequestration and Capture



$CaCO_3(s)$ + Energy

Heat Recovery

Cp=68 k J/C kg $CaCO_3$

Raw Material Preparation
534 kJ/kg $CaCO_3$

Solar Thermal Input

Replacing coal with renewable energy in the US could reduce CO_2 emission by ~81 million tonnes per year and capture of the remaining CO_2 would generate \$810 million dollars in tax revenue via a carbon tax.

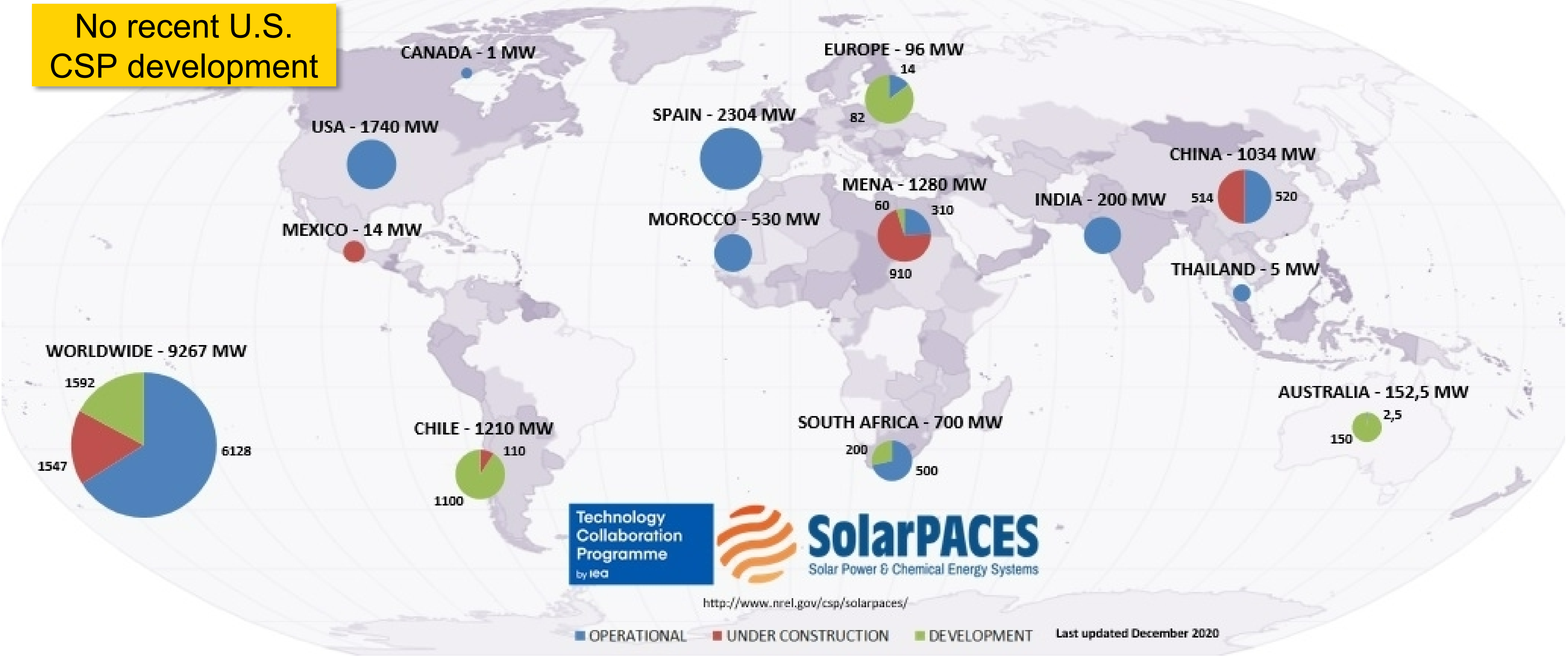
Cement produced (tonnes) = 90 million tonnes, Energy to concert $CaCO_3$ into cement clinker = 3186 kJ/kg, CO_2 produced during cement production (kg/kg of cement clinker produced) = 900, Carbon tax (\$/ton of CO_2 captured) = 20

Ref: Liu, Z. et al. (2015) *J. Energy Inst.*, *88*(1) Huntzinger and Eatmon (2009) *J. Clean. Prod.*, *17*(7) Yao et al. (2020) *Energies* 13(5257)

GLOBAL CONCENTRATING SOLAR POWER PLANTS

All commercial CSP plants around the world use technology developed or tested at Sandia

No recent U.S. CSP development

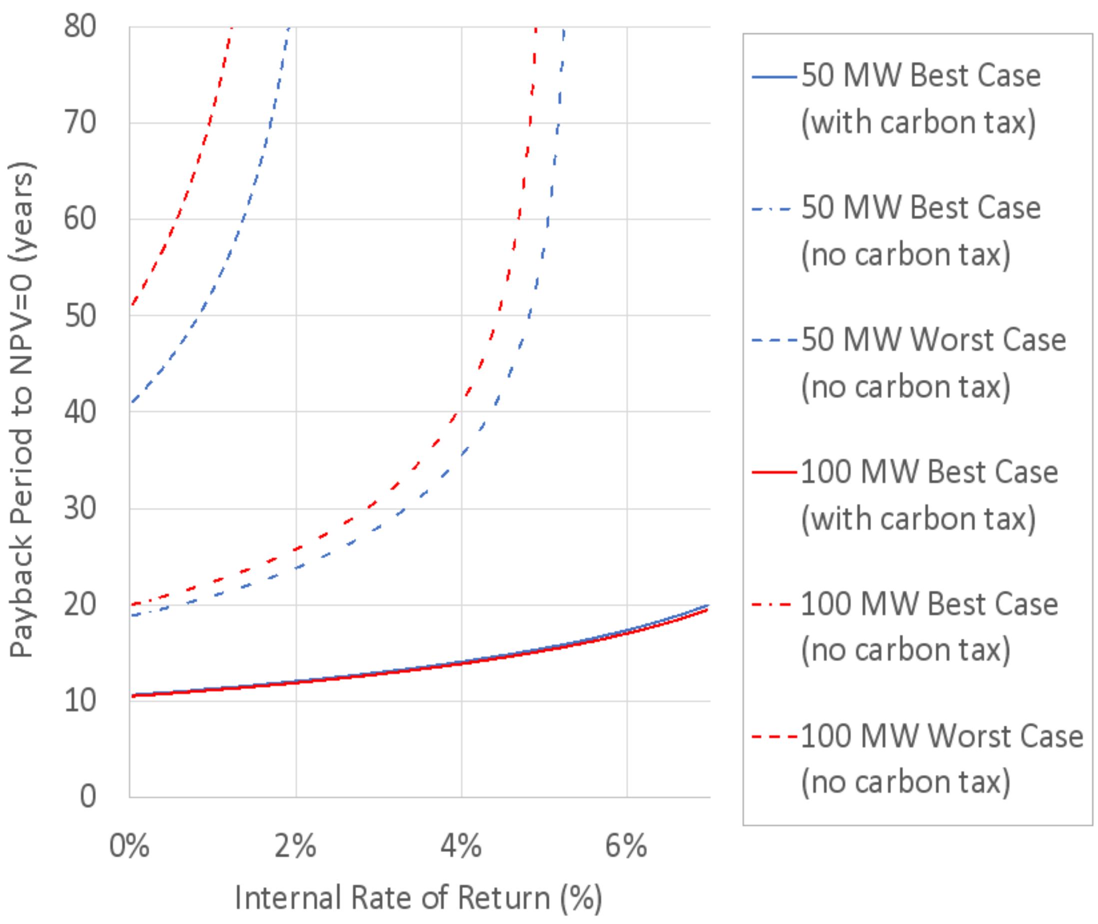


Summary of CSP Study for Sandia NM and KAFB

Parameter/ Finding	Option		Notes
	Sandia NM	Sandia NM + KAFB	
Annual energy required	~300 - 400 GWh	~400 - 600 GWh	Based on actual and projected energy consumption for Sandia NM and KAFB from 2019 – 2040 (Section 2)
Peak load	~30 – 40 MW	~50 – 70 MW	Peak loads are greater in the summer and less in the winter.
CSP plant capacity	50 MW	100 MW	Nameplate capacity exceeds average power requirement of ~30 MW (Sandia) and ~50 MW (Sandia + KAFB) to simultaneously charge storage
Thermal storage capacity	15 hours (750 MWh)	15 hours (1.5 GWh)	Occasional periods with multiple days of cloudiness may yield energy deficits (Section 3.1)
Estimated annual electricity produced	~200 – 300 GWh	~400 – 700 GWh	Predicted using probabilistic model in System Advisor Model (SAM) (Section 3.2)
Land and siting requirements	~1000 acres	~2000 acres	Calculated in SAM (Table 1). See Section 3.3.2 for 3D renderings of potential siting locations.
Overnight construction cost	~$300M - $400M	~$500M - $800M	Calculated in SAM (Section 3.2)
Annual electricity cost avoided	~$14M	~$24M	Based on actual cost for electricity consumed by Sandia NM in 2019; total cost of electricity consumed by Sandia NM + KAFB calculated from ratio of annual electricity consumed
Potential annual carbon costs avoided	~$7M - $11M	~$13M - $22M	Based on existing bills proposed by the 117th congress ranging from $15 - $59 per ton of carbon emitted; price escalation not included. See Table ES- 2 for more details.
Annual O&M	~$2M - $4M	~$4M - $8M	From SAM and JEDI models.
Payback Period	14 - ∞ years	14 - ∞ years	Assumes 4% real interest rate and avoided annual costs of carbon emissions. See Table ES- 2 for more details.
Jobs Created	~1,000 (construction) 60 (operation)	~2,000 (construction) ~100 (operation)	From JEDI
CO_{-2} Offsets	~200,000 tons/yr	~300,000 – 400,000 tons/yr	Based on carbon intensity of ~0.6 tons CO_2/MWh for fossil-fuel-based electricity

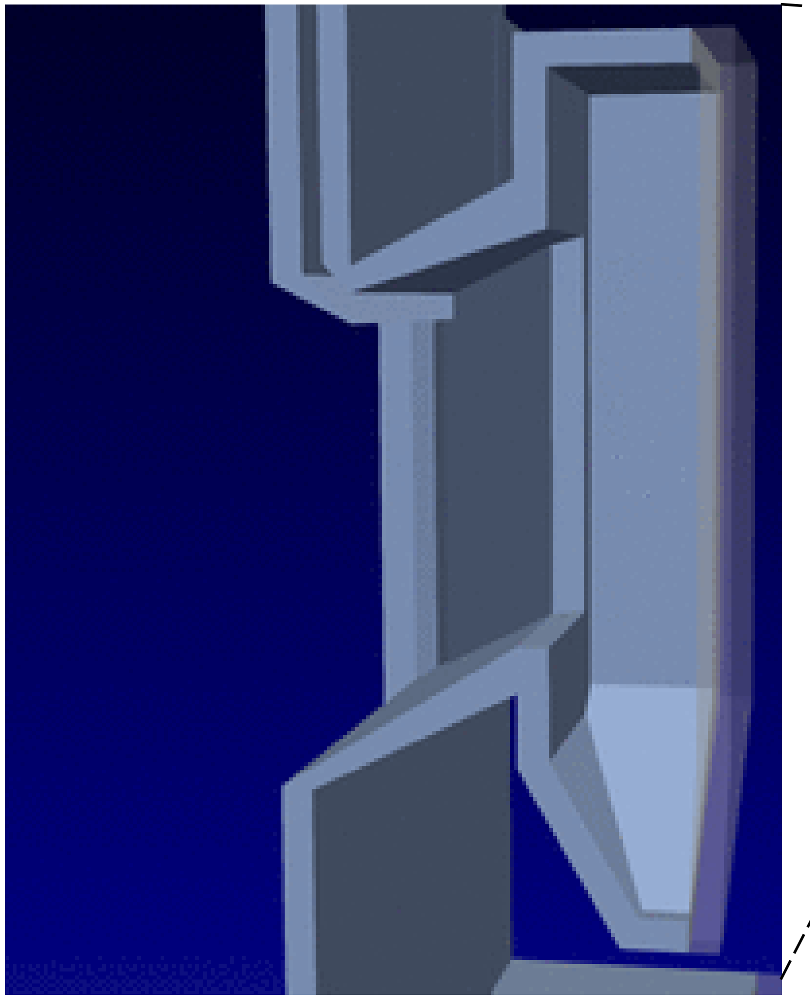
Payback Period Analysis

Parameter	50 MW			100 MW		
	Best Case (with carbon tax)	Best Case (no carbon tax)	Worst Case (no carbon tax)	Best Case (with carbon tax)	Best Case (no carbon tax)	Worst Case (no carbon tax)
Overnight Construction Cost ($M)	263	263	416	479	479	833
O&M Costs ($M/yr)	0	0	3.8	0	0	7.6
Avoided Energy Costs ($M/yr)	14	14	14	24	24	24
Avoided Carbon Tax ($M/yr)	10.8 (182,400 tons/year avoided at $59/ton)	0	0	21.7 (376,800 tons/yea r avoided at $59/ton)	0	0
Payback period at 4% IRR (yr)	14.1	35	∞	13.9	41	∞

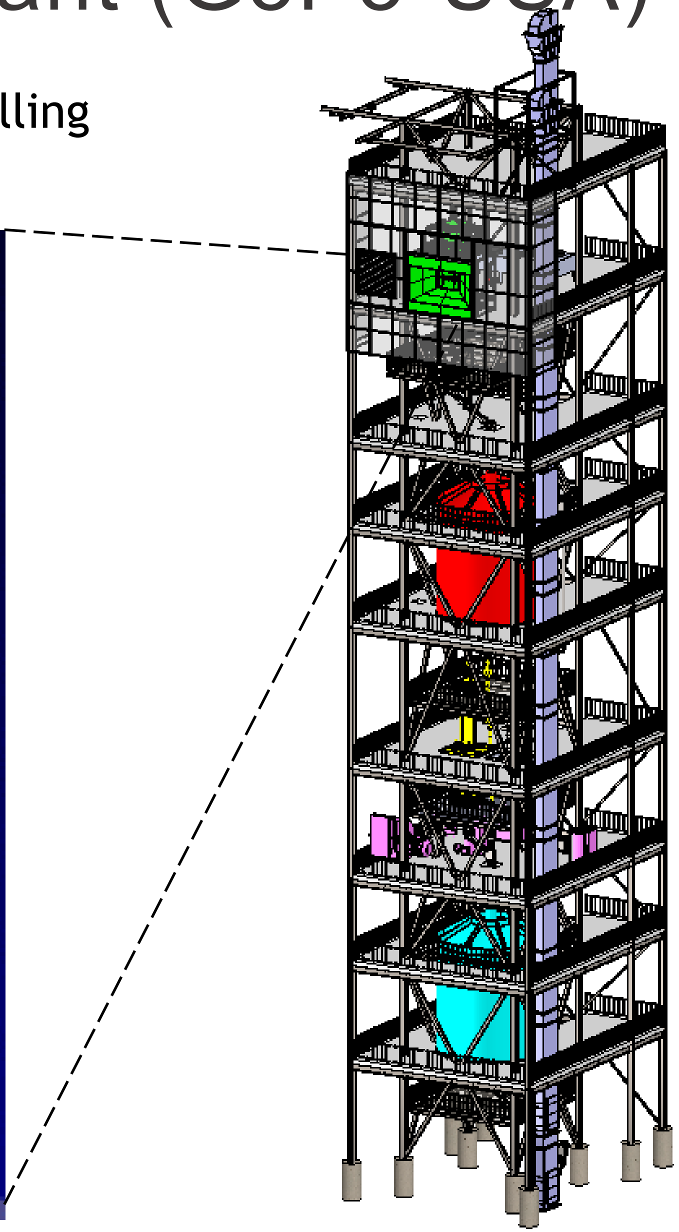


Gen3 Particle Pilot Plant (G3P3-USA)

Next-Generation High-Temperature Falling Particle Receiver



HPC Modeling from 1500, B. Mills



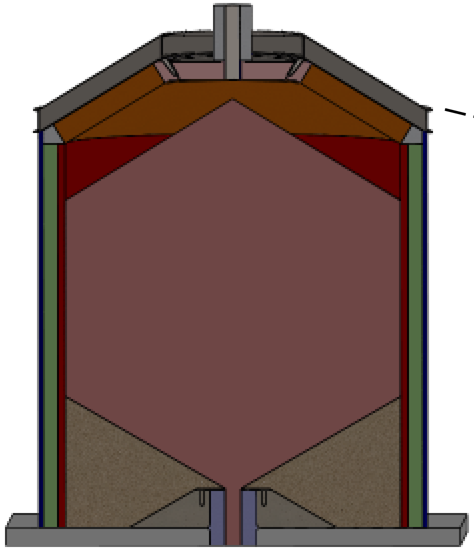
K. Albrecht, SNL

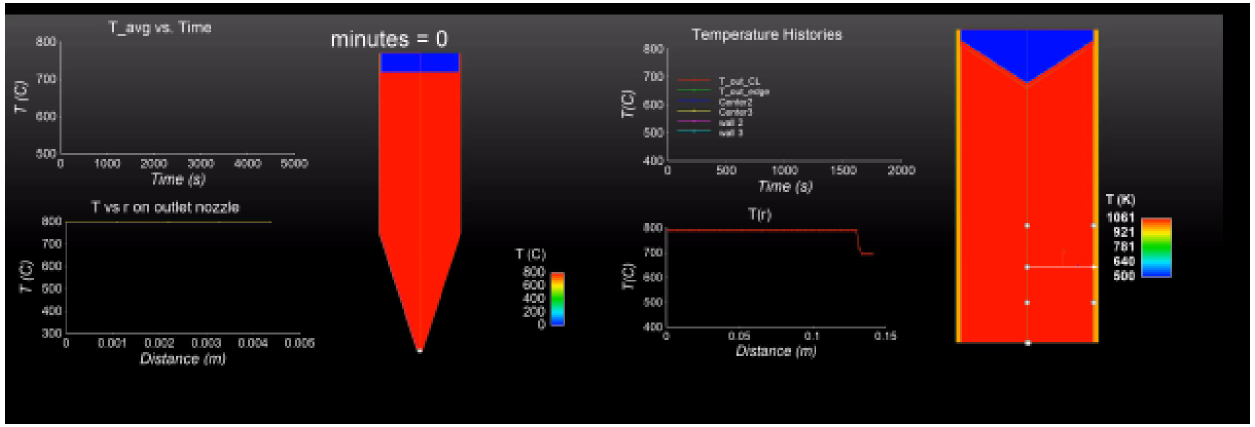
Gen 3 Particle Pilot Plant

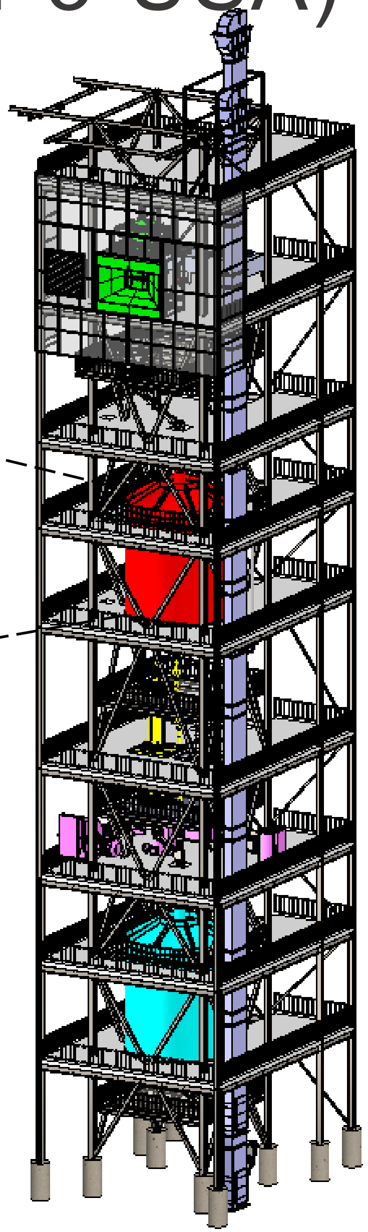
- ~1 – 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 – 400 micron ceramic particles (CARBO HSP 40/70)

Gen3 Particle Pilot Plant (G3P3-USA)

High-Temperature Particle Storage Bin
(Allied Mineral Products, Matrix PDM, Sandia)







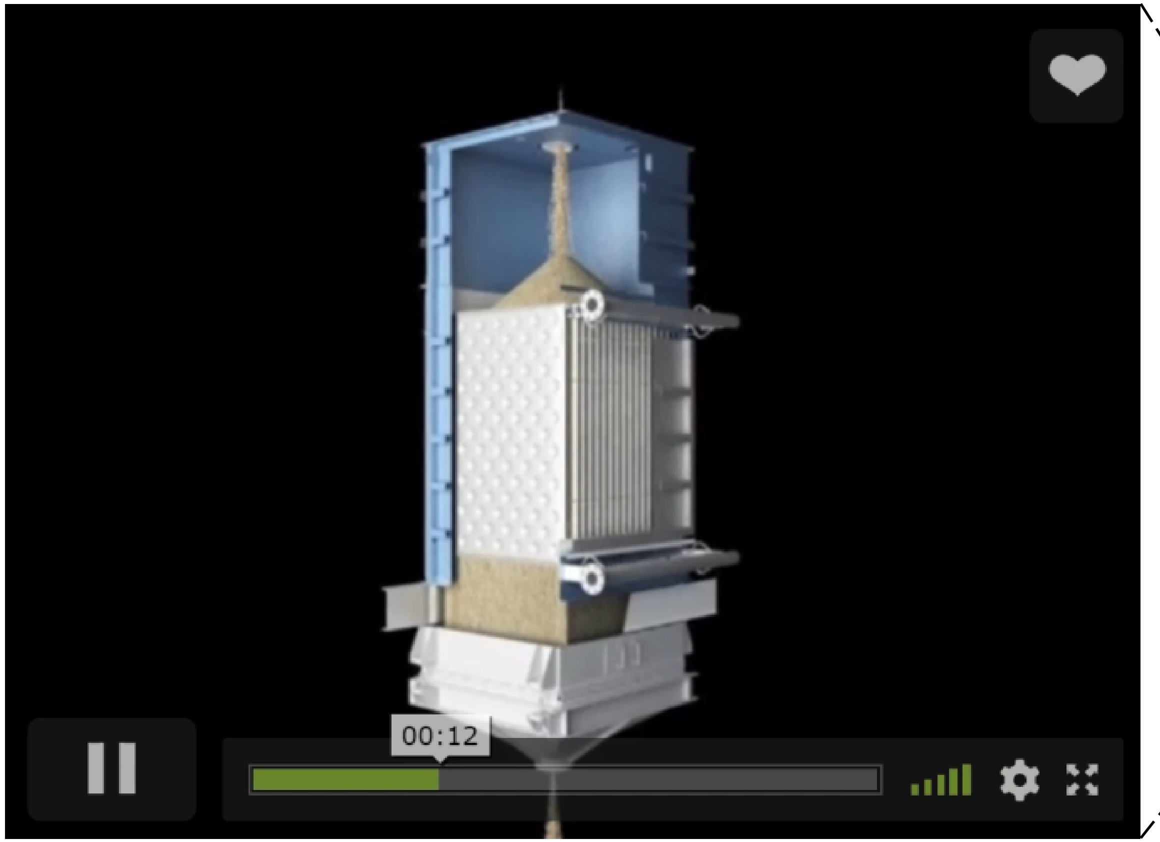
Gen 3 Particle Pilot Plant

- ~1 – 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 – 400 micron ceramic particles (CARBO HSP 40/70)

K. Albrecht, SNL

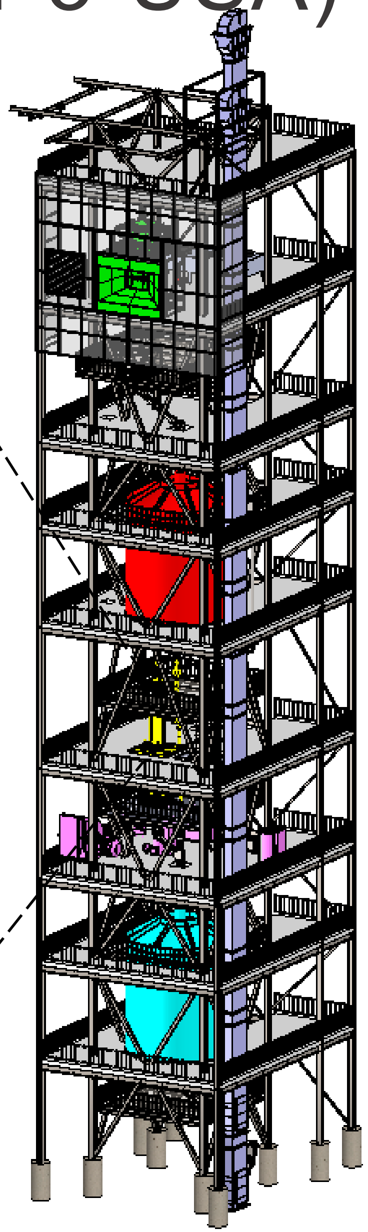
Gen3 Particle Pilot Plant (G3P3-USA)

High-Temperature Particle-to-sCO_2 Heat Exchanger
(VPE, Solex, Sandia)



https://www.solexthermal.com/our-technology/cooling/

Some collaboration with 1800 (materials)



K. Albrecht, SNL

Gen 3 Particle Pilot Plant

- ~1 – 2 MW_t receiver
- 6 MWh_t storage
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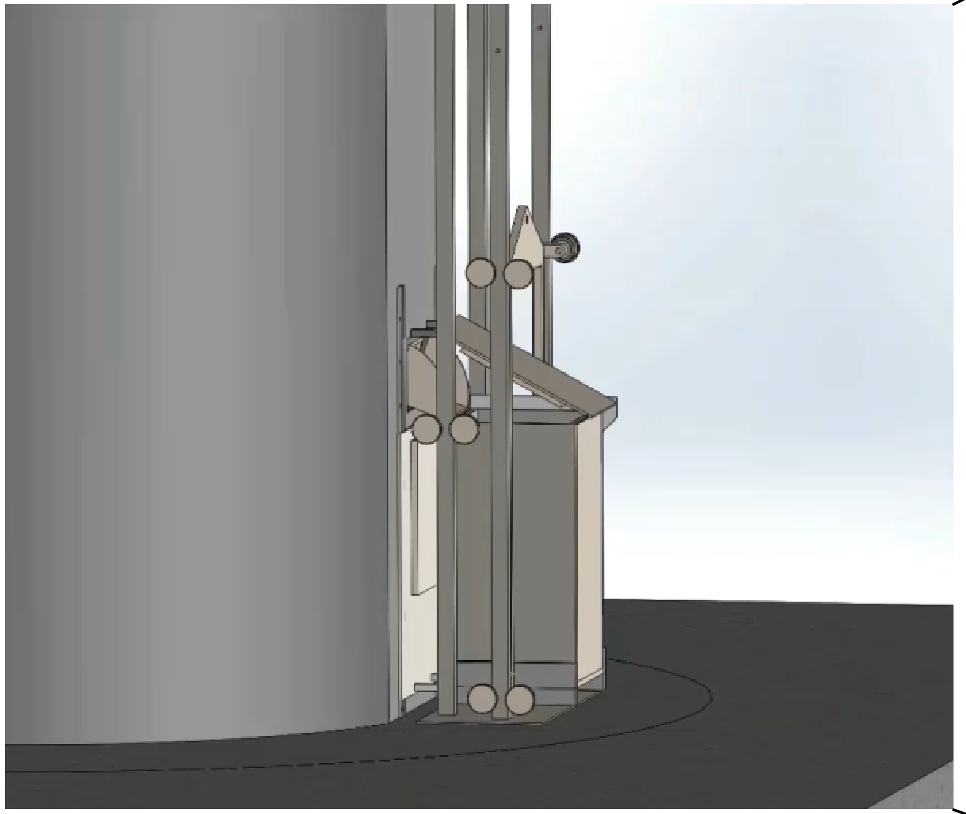
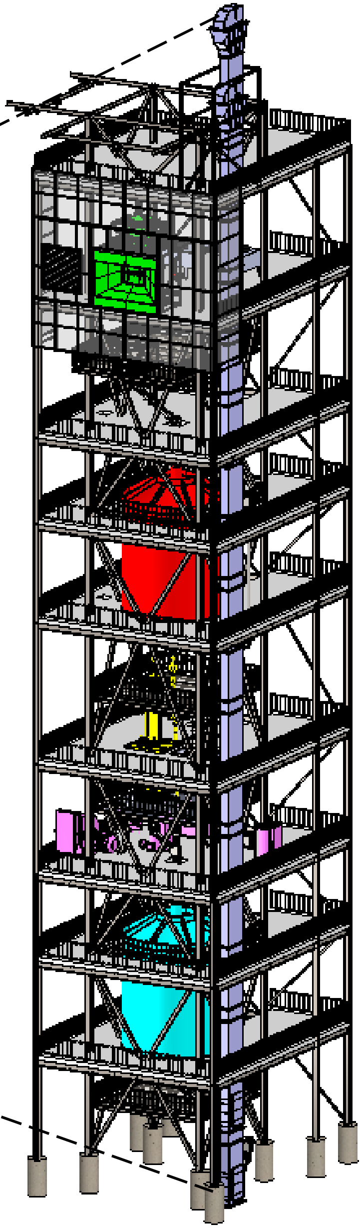
Particle Lift and Conveyance

High-Temperature Particle Lift and Conveyance
(SNL, Georgia Tech, MHE, KSU, Magaldi)



K. Repole and S. Jeter, Georgia Tech

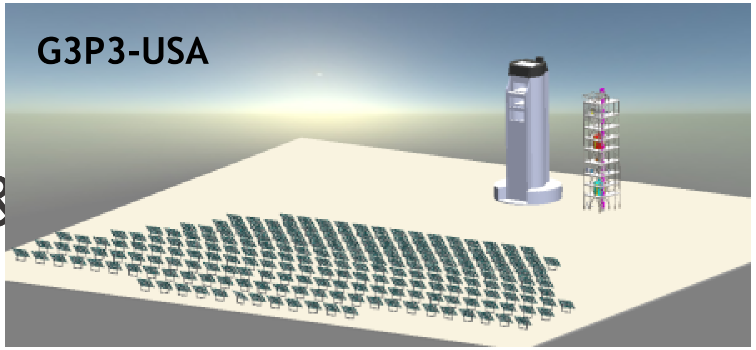


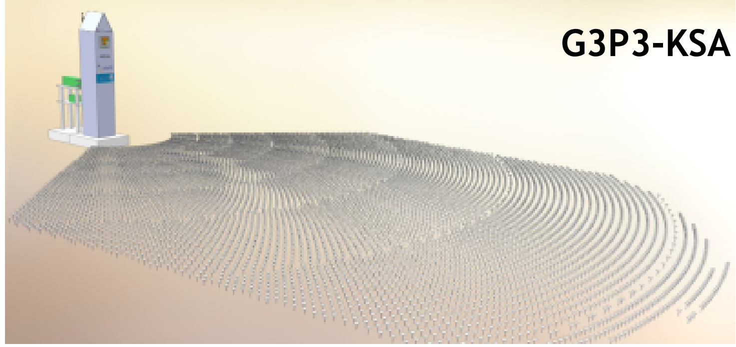
K. Albrecht, SNL

Key Remaining Gaps

- Demonstration of high-temperature, large-capacity particle lift and conveyance with low heat and particle loss
- Heat loss and reliability of chain-driven bucket elevators
- Loading and unloading processes for skips
- Commercial scale-up

Summary





- G3P3-USA and G3P3-KSA being developed
- Key components evaluated in G3P3 Phases 1 &
  - Receiver
  - Particle-to-sCO2 heat exchanger
  - Storage
- Key risks of G3P3
  - Particle and heat loss from open-aperture receiver
  - Heat loss from storage and bucket elevator
  - Low particle-side heat-transfer coefficients in heat exchanger
  - High cost of diffusion-bonded heat exchanger
- Contingencies
  - Fluidized-bed heat exchanger (Babcock & Wilcox, SandTES TU Wien)
  - Skip hoist for particle lift
  - Tower-integrated particle storage bins

Opportunity Space

1. Carbon-free feedstock & chemical processes

$CaCO_3 \rightarrow CaO + CO_2$

$Fe_2O_3(s) + 3\ CO(g) \rightarrow 2\ Fe(s) + 3\ CO_2(g)$

4. Recycling and repurposing

2. Fossil-free heat and electricity sources

3. Novel sequestration methods

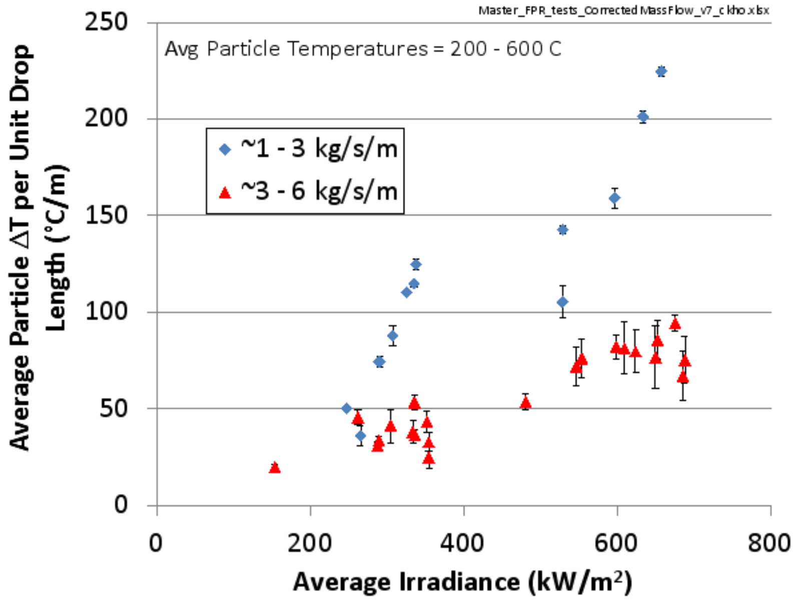
Decrease CO_2 emissions across entire product life cycle from feedstock, to processing, to sequestration, and finally to recycling of materials to feedstock

Particle Pathway Team

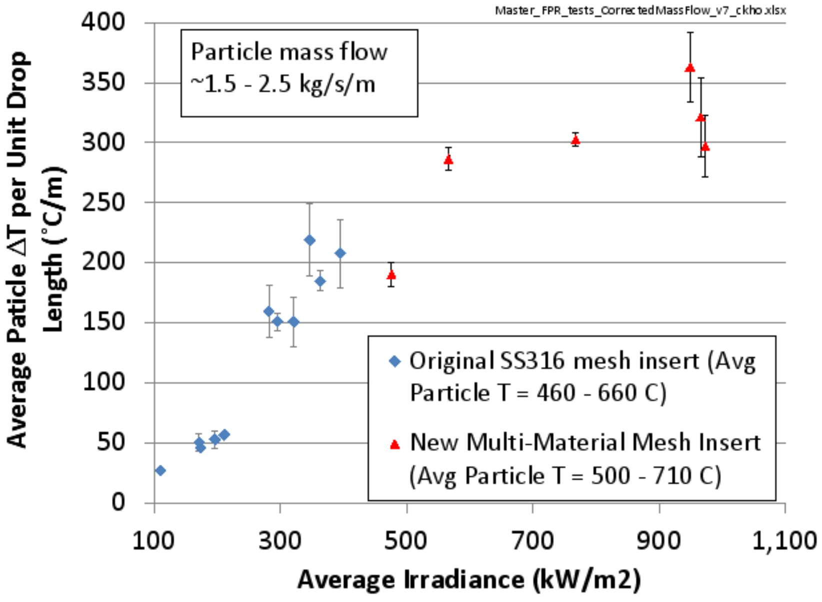
Role	Team Members	
PI / Management	• Sandia National Labs (PI, PMP, financial, facilities)	
R&D / Engineering	• Sandia National Laboratories • Georgia Institute of Technology • King Saud University • German Aerospace Center	• CSIRO • U. Adelaide • Australian National University • CNRS-PROMES
Integrators / EPC	• EPRI • Bridgers & Paxton / Bohannan Huston	
CSP Developers	• SolarDynamics	
Component Developers / Industry	• Carbo Ceramics • Solex Thermal Science • Vacuum Process Engineering • FLSmidth	• Materials Handling Equipment • Allied Mineral Products • Matrix PDM
Utility	• Saudi Electric Company	

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

Acknowledgments

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

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  - DOE Project Managers: Matthew Bauer, Shane Powers, Vijay Rajgopal, Levi Irwin, Andru Prescod, Mark Lausten, Avi Shultz