Supercritical Carbon Dioxide Power Cycle: Next Generation Power

Rocky Mountain AIChE
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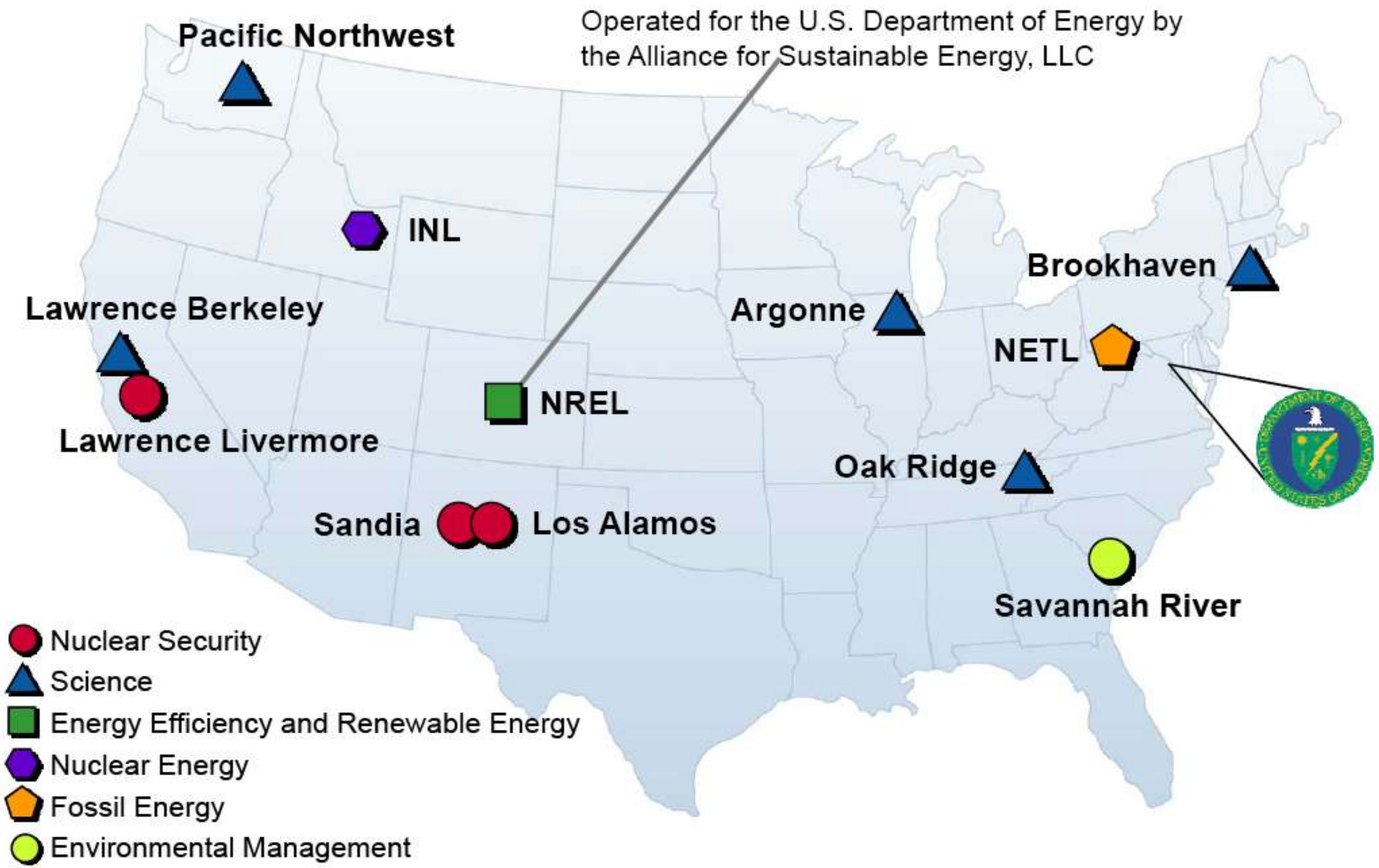
Craig Turchi, PhD
CSP Program, NREL
craig.turchi@nrel.gov

US National Laboratories



NREL's Areas of Research

Efficient Energy Use

- Vehicle Technologies
- Building Technologies
- Industrial Technologies

Renewable Resources

- Wind and water
- Solar
- Biomass
- Geothermal

Energy Delivery and Storage

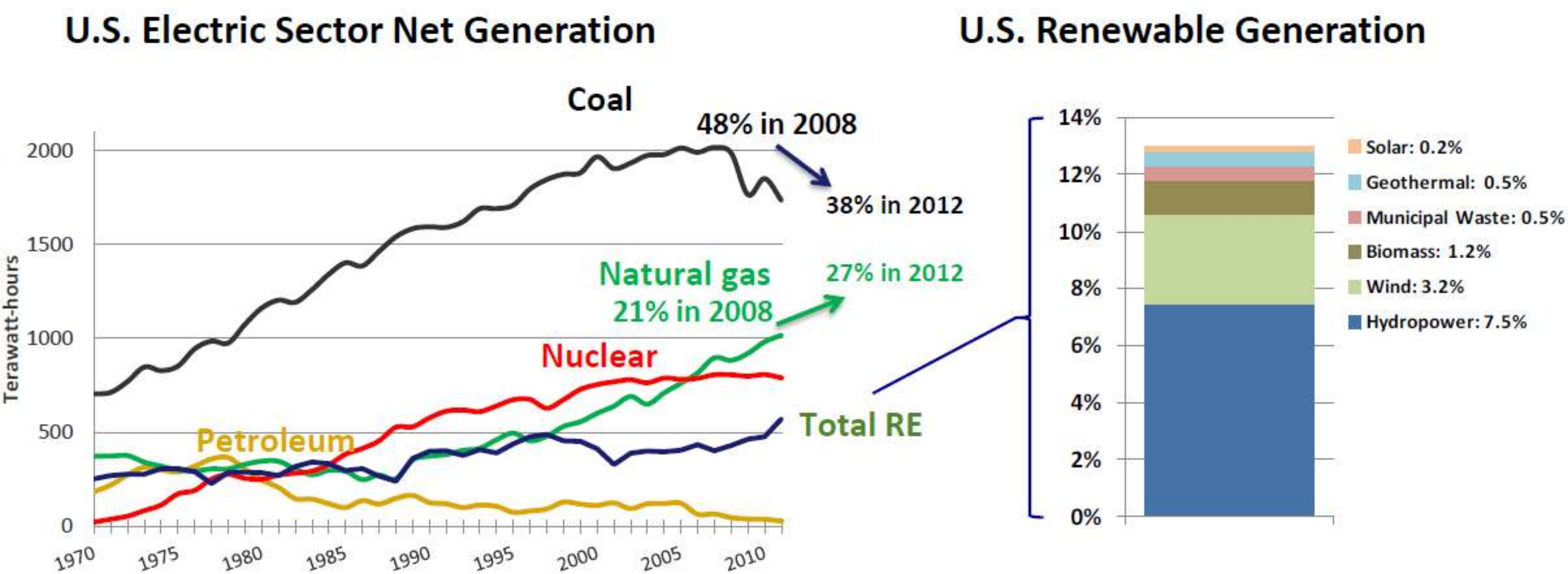
- Electricity Transmission and Distribution
- Alternative Fuels
- Hydrogen Delivery and Storage

2100 employees (full-time and contract)
2012 budget $405 million

Presentation Outline

- US and World Energy Resources
- Introduction to Concentrating Solar Power (CSP)
- Supercritical CO_2 Power Cycle
  - General attributes
  - Applications

US Electricity Sources



Energy Information Agency, Annual Energy Outlook, 2012

Solar is Growing

Thursday, March 14, 2013 2:26 PM MT Extra

Study: Solar industry saw record year in 2012, with 3,313 MW of solar PV installed

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By Michael Copley

Tools

Declining costs for solar panels and installed solar-power systems have helped the U.S. solar industry leapfrog from its spot as one of the most expensive power sources to one of the cheapest. Solar is also the fastest-growing energy source in the U.S. and a leading source of new electricity that increasingly is capable of competing with conventional

Saudi Arabia Plans $109 Billion Boost for Solar Power

By Wael Mahdi - Nov 22, 2012 9:53 AM MT

3 COMMENTS QUEUE

Saudi Arabia plans to produce electricity from its first nuclear plant by 2020 and begin operating a solar farm by 2015, said an official at the agency developing the country's renewable energy program.

The country will start work on its first solar-power facility early next year, which may take as much as 24 months to complete, Khalid al-Suliman, vice president at the King Abdullah City for Atomic and Renewable Energy, told the state-owned Saudi Press Agency.

Al-Suliman said the project will get underway once the government approves his agency's plan for renewable energy. He told the press agency yesterday that he expects to receive official approval early next year.

Saudi Arabia, which is tapping renewable energy as a way to free more crude oil for export, is planning for $109 billion in investment to create a solar industry that generates a third of the nation's electricity by 2032.

China to Boost Solar Power Goal 67% as Smog Envelops Beijing

By Bloomberg News - Jan 30, 2013 4:39 AM MT

5 COMMENTS QUEUE

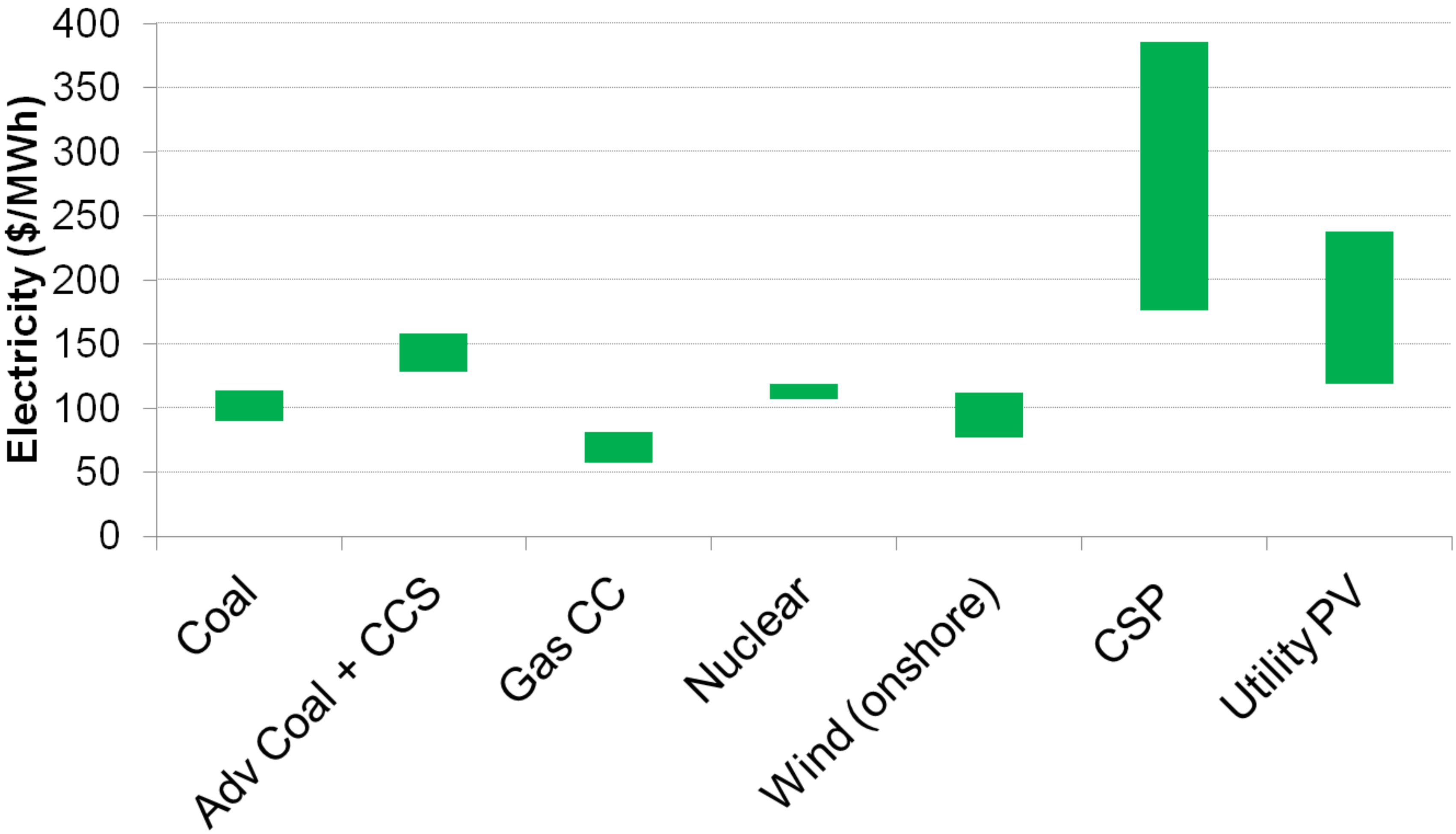
China plans to increase its goal for solar-power installations in 2015 by 67 percent to reduce reliance on fossil fuels blamed for greenhouse gases and as smog in Beijing reached record hazardous levels this month.

The world's biggest emitter of carbon-dioxide plans to raise the solar target to 35 gigawatts by 2015 from 21 gigawatts set last year, boosting demand for manufactures that suffer from slowing sales in Europe, Shi Dinghuan, the counselor of China's State Council and the president of Chinese Renewable Energy Society, said today by phone.

"We've got more pressure to save energy and reduce emissions as smog worsens due to pollution," he said. China will use renewable energy to cut coal consumption and support the domestic industry amid U.S. and Europe anti-dumping charges against Chinese solar products, Shi said.

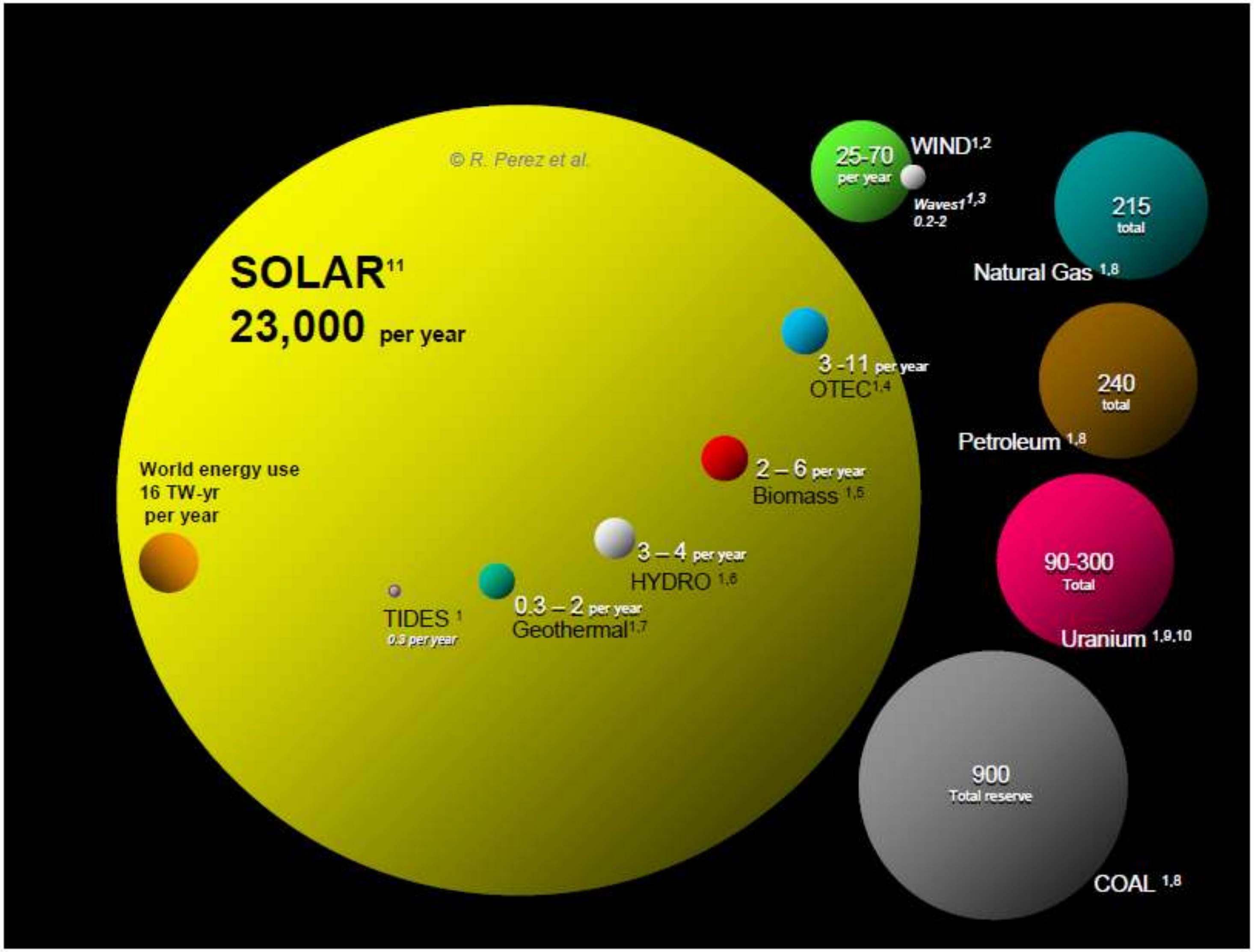
Sources: Bloomberg.com, SNL Energy

But, Solar is still Expensive



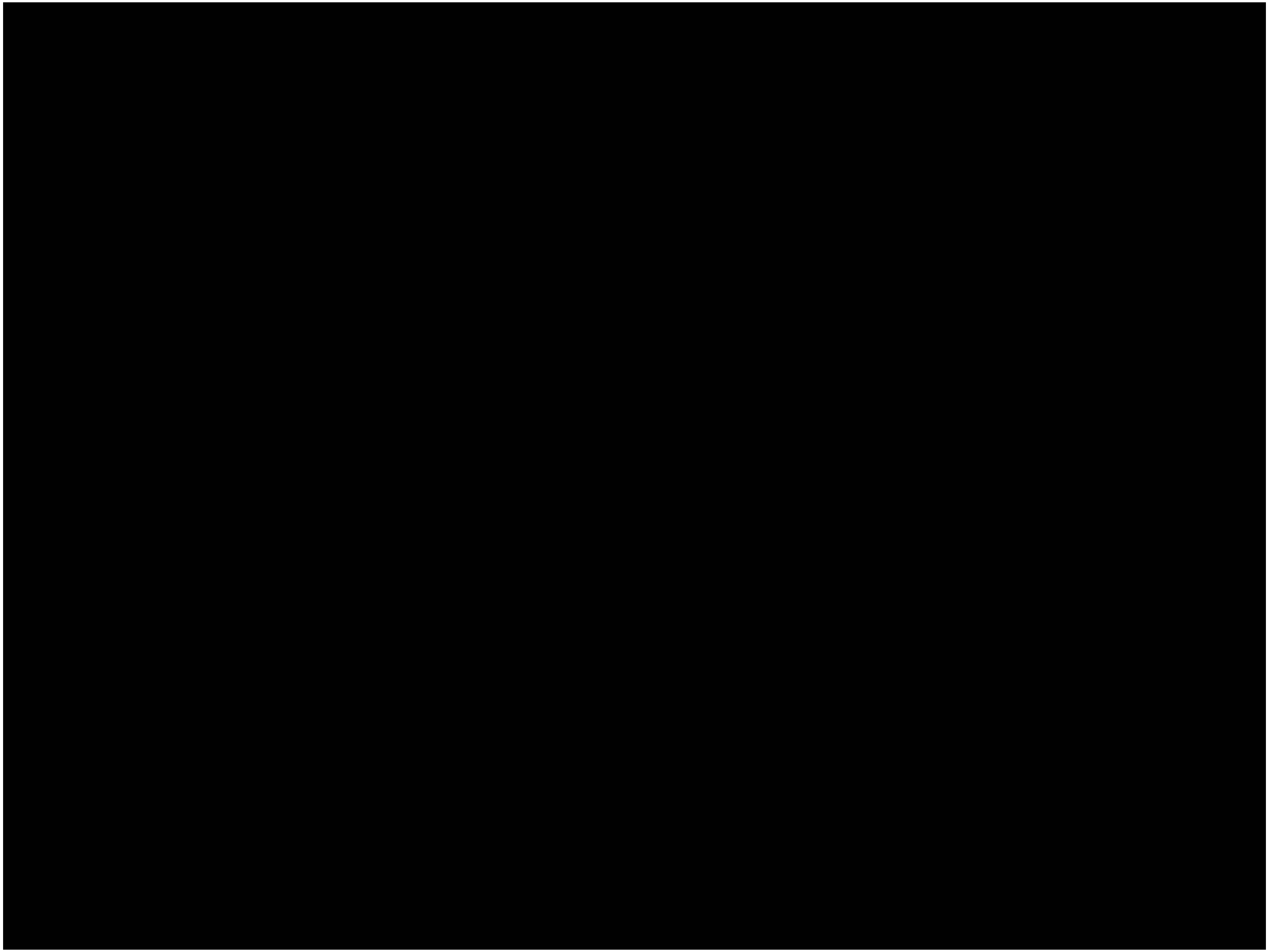
Levelized cost of electricity in nominal 2010 dollars. Wind and solar include no incentives. Energy Information Administration, Annual Energy Outlook 2012. June 2012, DOE/EIA-0383.

Energy Potential: Solar is the Gorilla in the Room



Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables. Values in Terawatt-years. (Perez & Perez, 2009.)

Power Towers Video



Torresol Energy 20 MW Gemasolar Seville, Spain

Power Towers under Construction: BrightSource 392 MW Ivanpah, California

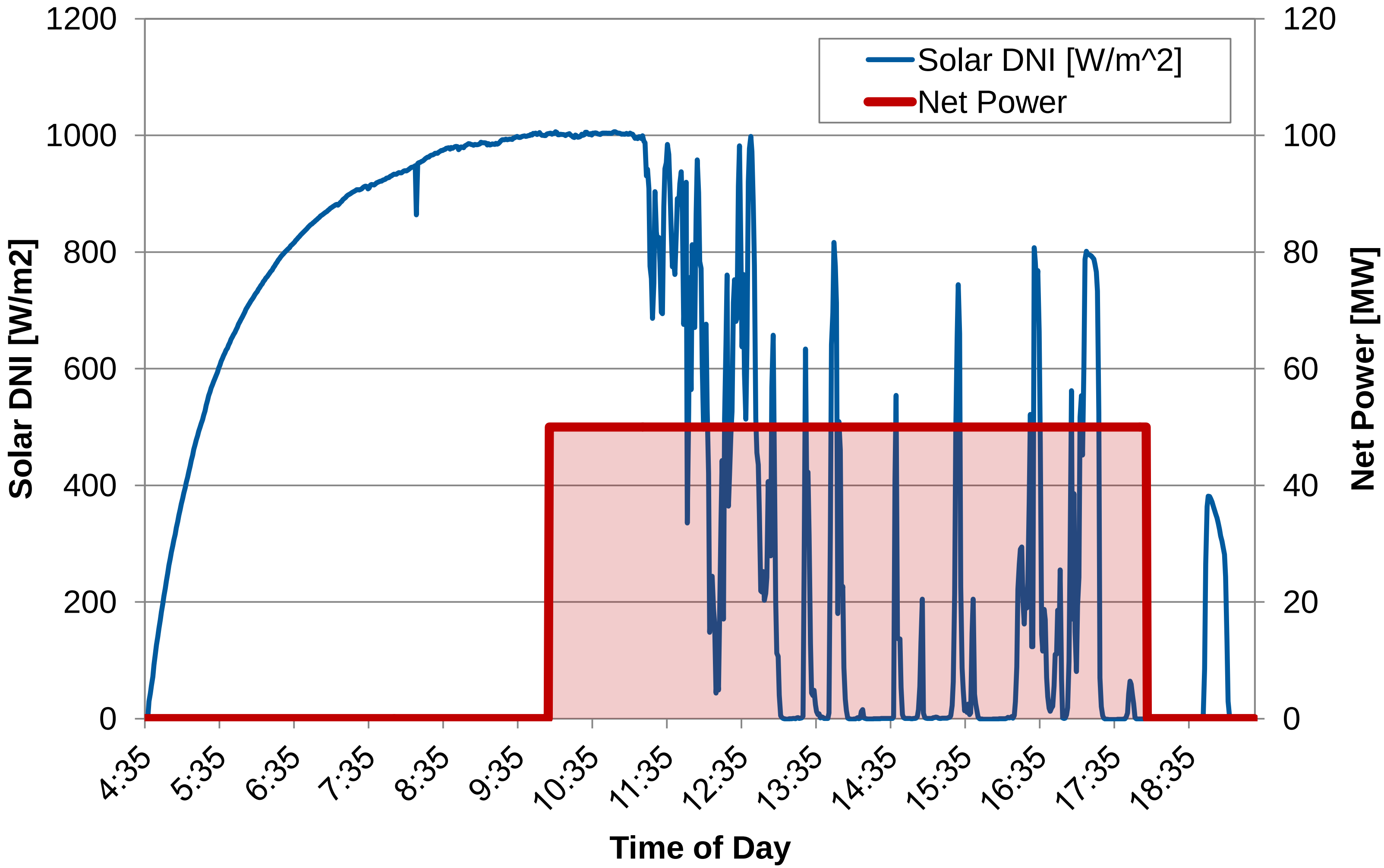
Power Towers under Construction: SolarReserve 110 MWe Crescent Dunes, Nevada

Fast Facts:

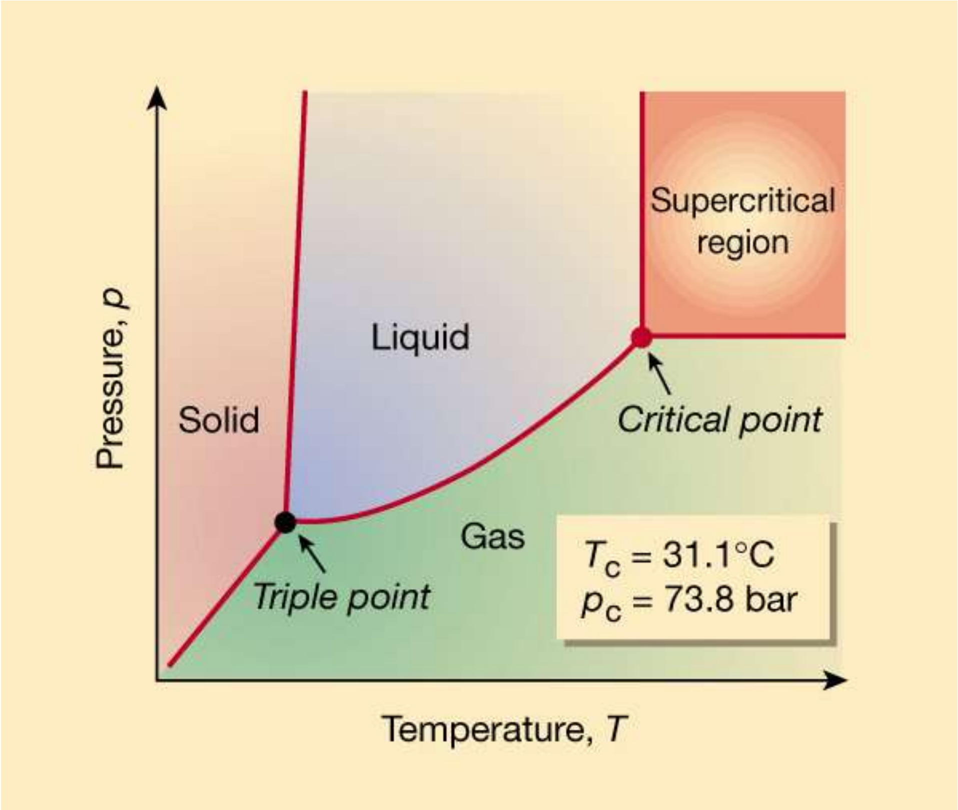
- 10 hours of thermal energy storage
- 195-m tall tower
- 600 construction jobs; 45 permanent jobs
- 1600-acre site
- Hybrid cooling

Looking down at the storage tank foundations

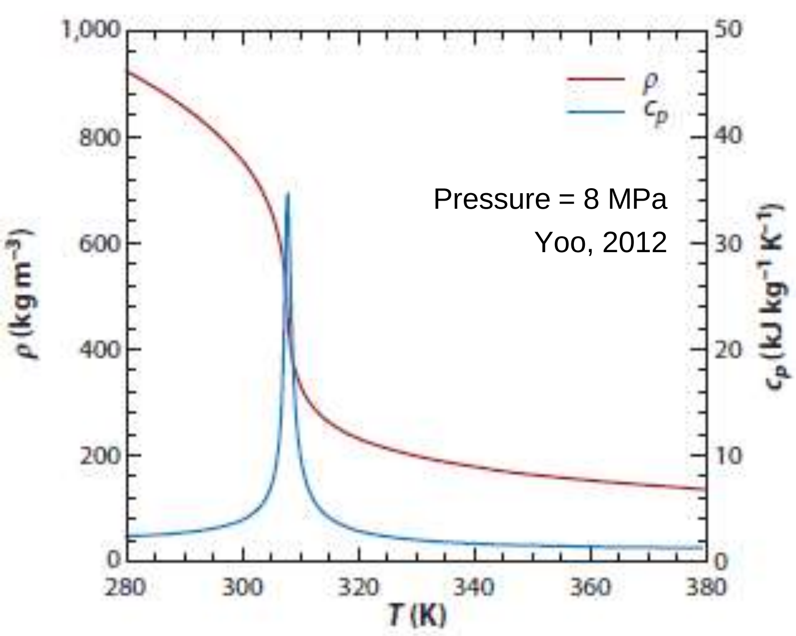
Value of CSP with Thermal Energy Storage



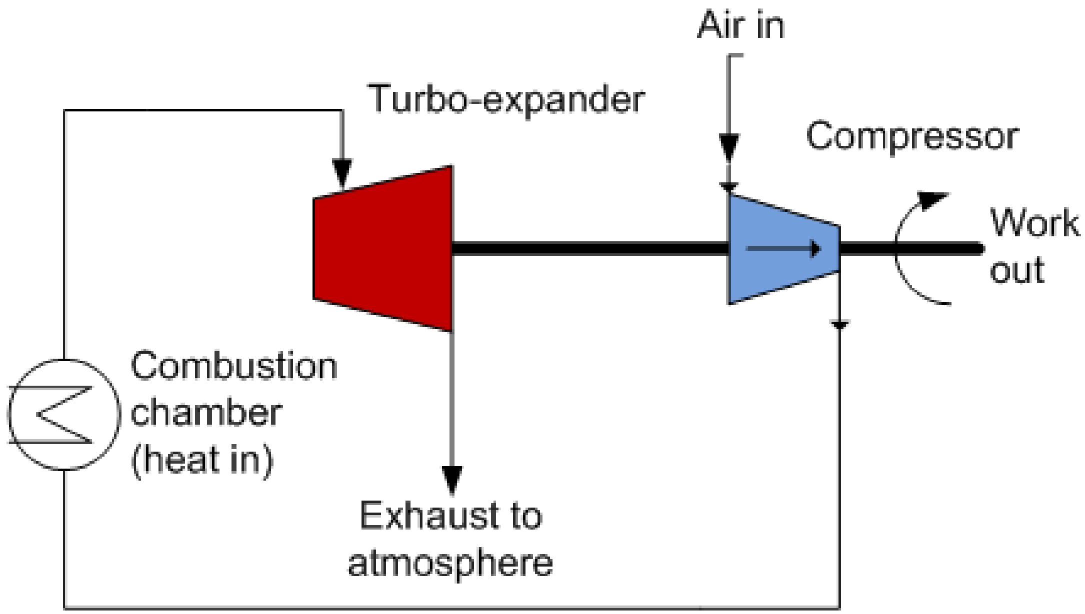
Supercritical CO_2 Brayton Cycle



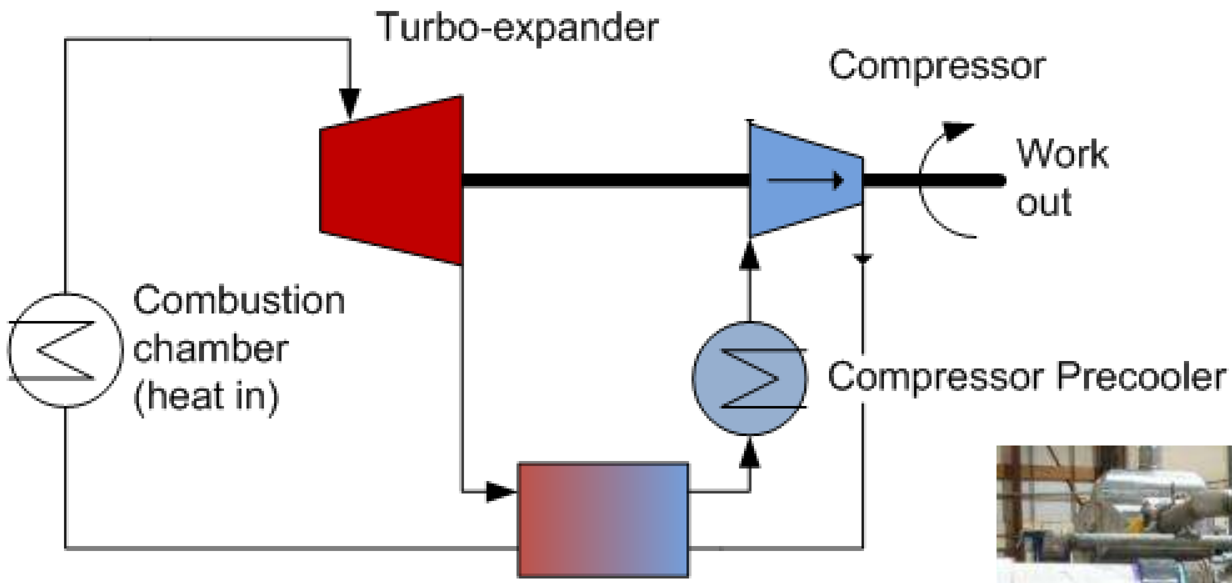
Density and Heat Capacity

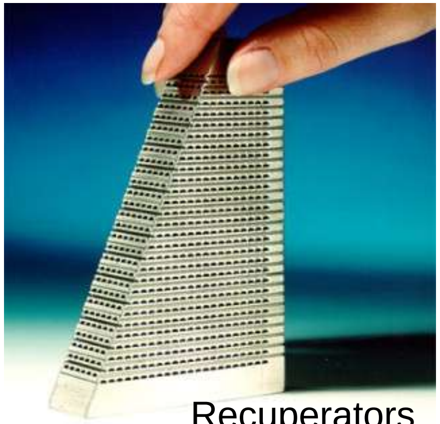


Open Brayton Power Cycle



Closed Brayton Power Cycle





Recuperators

Brief History of the Closed Brayton Cycle (CBC)

1939 First commercial CBC at Escher Wyss in Zurich (2 MW, air)

1949 Air CBC efficiency greater than contemporary steam cycles

1956-1977 Ravensburg air CBC accumulates 120,000 hrs operation at average 91% availability

1967 Feher catalogs candidate supercritical fluids for use in CBC

1968 Angelino proposes s-CO_2 power cycles including the "recompression" cycle

2006 Dostal rekindles interest in s-CO_2 CBC by examining its use for Gen IV nuclear power plants

2009 Sandia National Labs builds 250 kW recompression cycle at Barber-Nichols in Arvada, CO

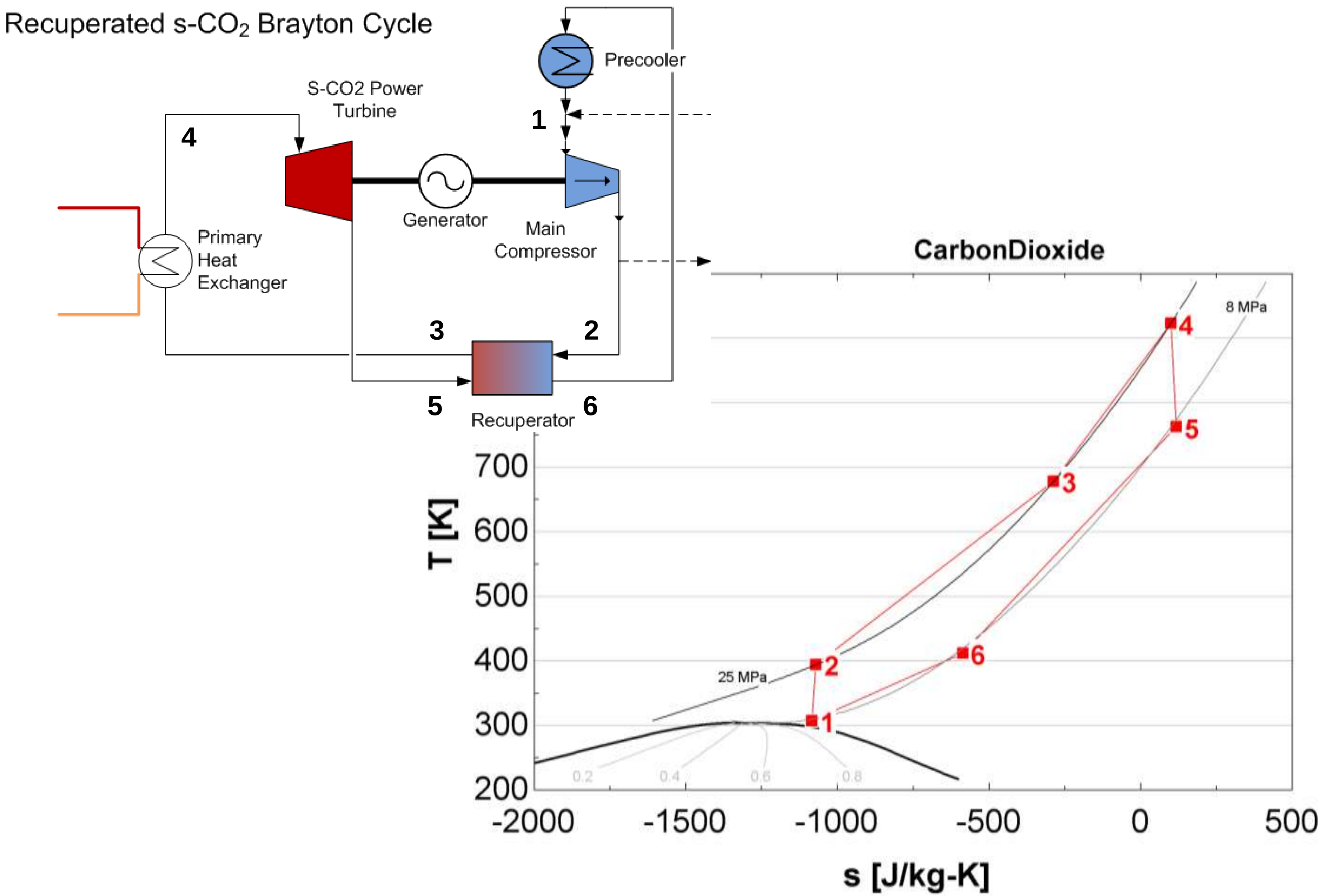
2012 Echogen Power Systems designs 7 MW s-CO_2 system for waste heat recovery

2012 SunShot funds testing of ~10 MW high-temp s-CO_2 turbine

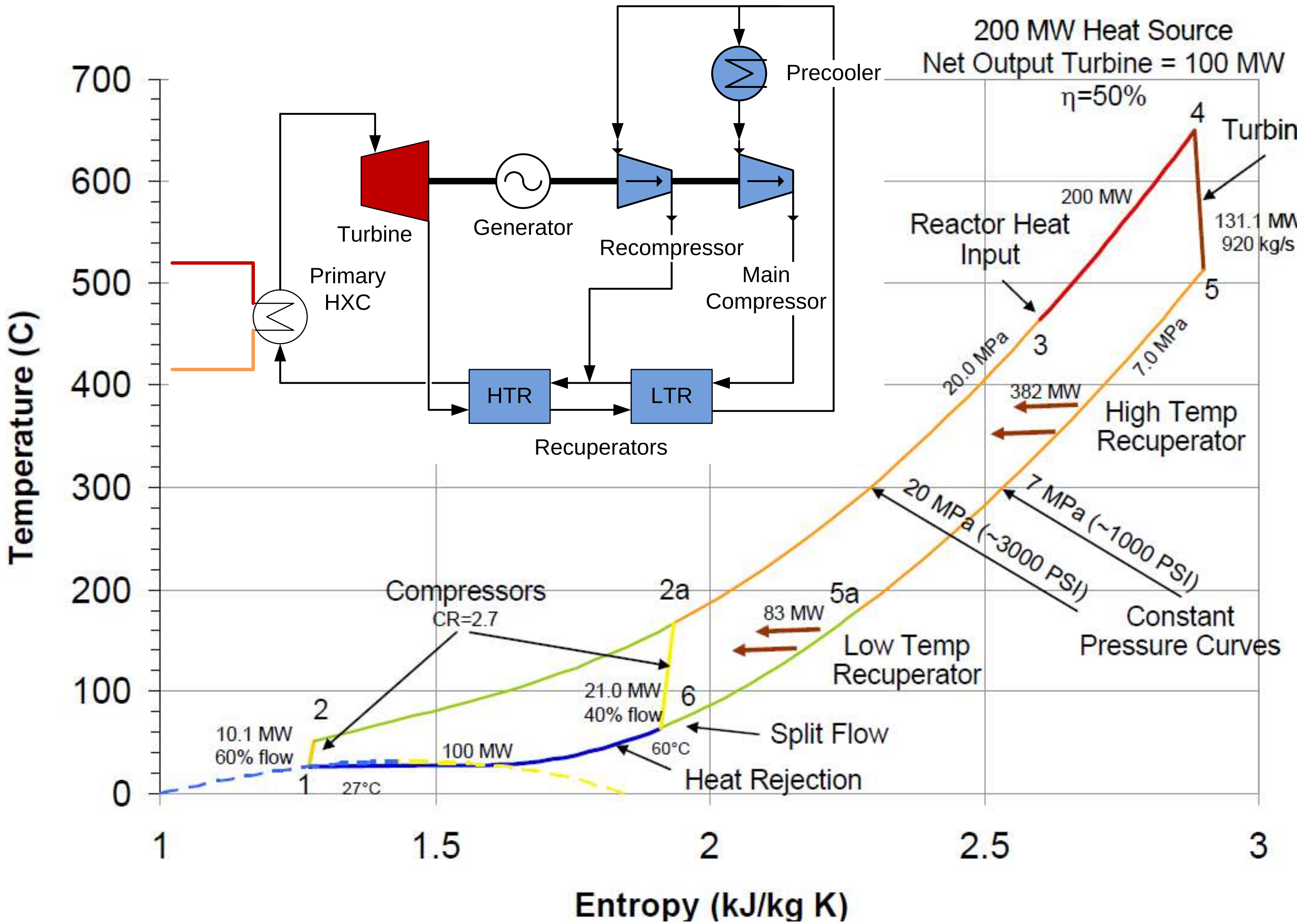
Attractive features of s-CO_2 Brayton Cycle

- Simpler cycle design than steam Rankine
- Higher efficiency than steam Rankine
- High density working fluid yields compact turbomachinery
- Optimum turbine size 10 to 300 MWe
- Low-cost, low toxicity, low corrosivity fluid
- Thermally stable fluid at temperatures of interest to CSP (550C to 750C)
- Single phase reduces operational complexity

"Simple" s-CO_2 Brayton Cycle



S-CO_2 Recompression Brayton Cycle

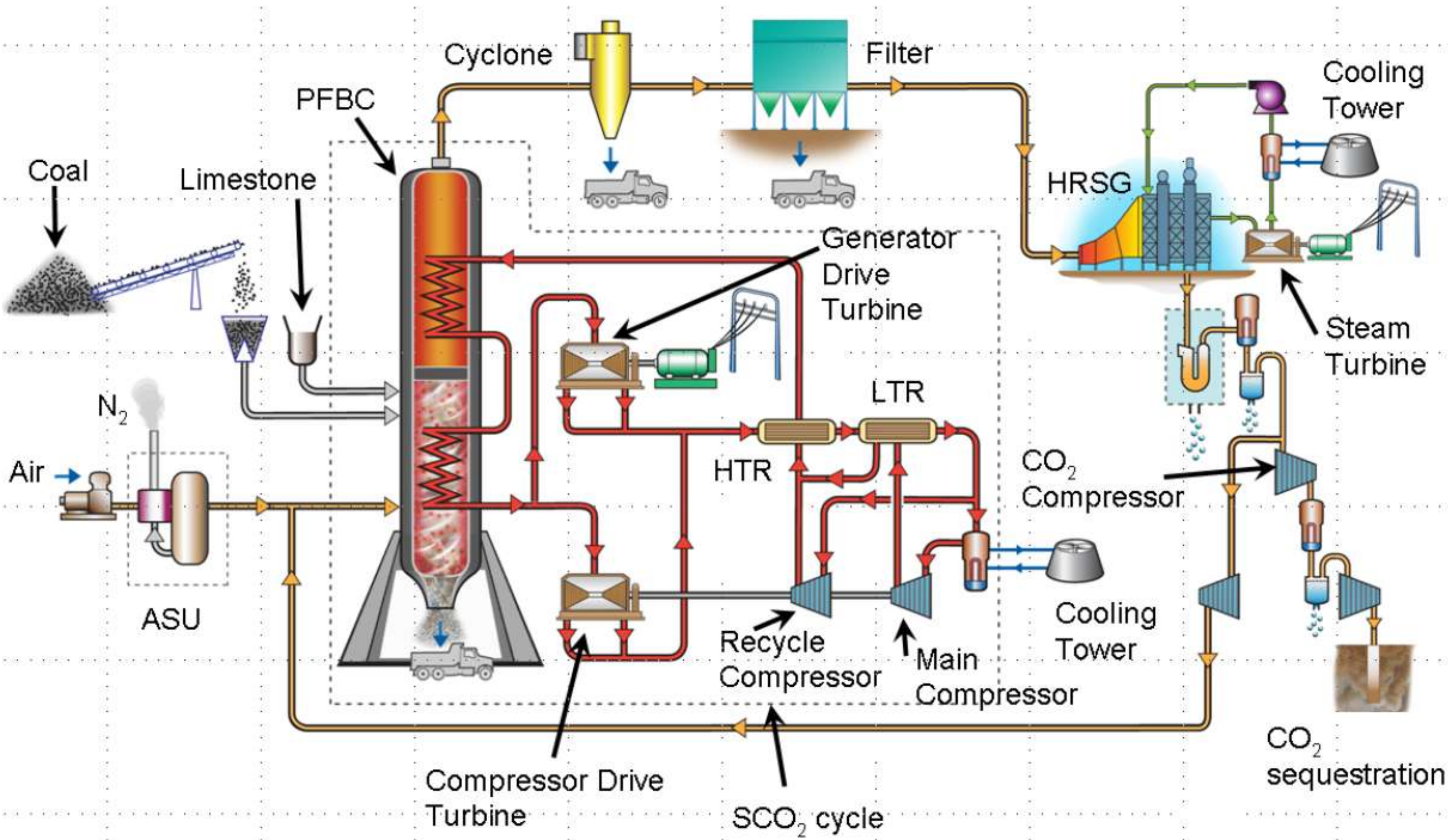


Parma, et al., "Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept," SAND2011-2525, May 2011.

S-CO_2 Brayton has Potential in Multiple Markets

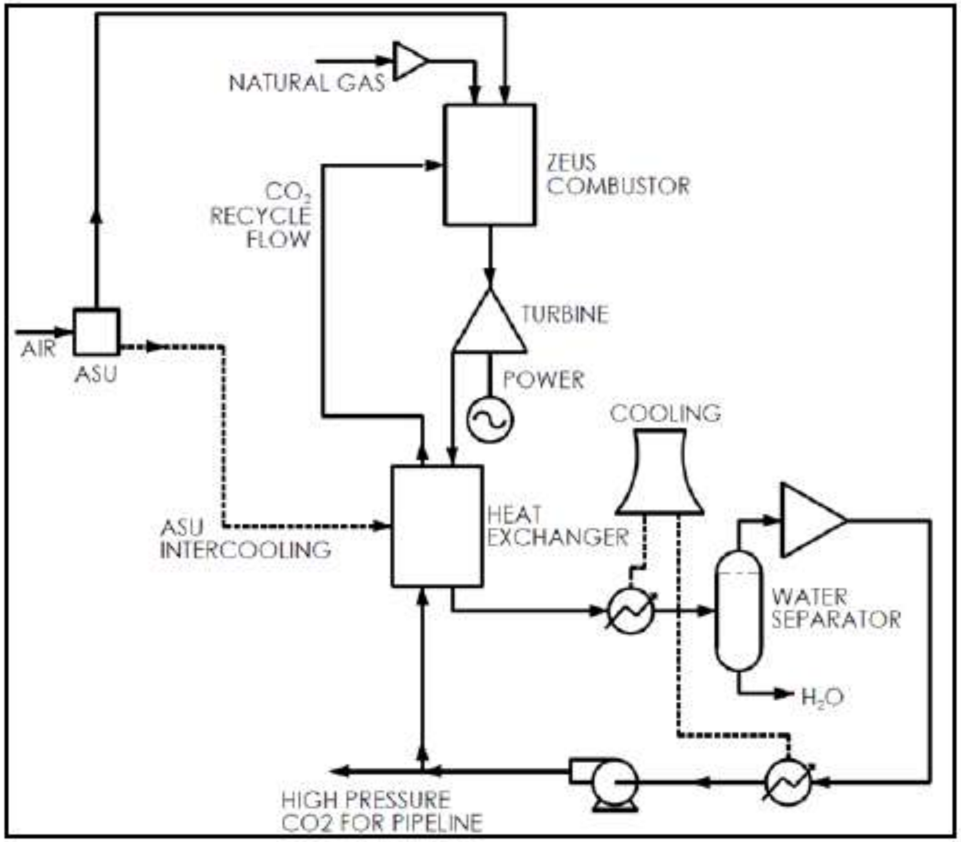
Power Sector	Why?	Who?
Nuclear	Good match to Gen IV sodium fast reactor designs	Sandia, Argonne, INEL
Fossil	Next generation coal plants with oxy-fuel combustion and CO2 capture	NETL, Pratt & Whitney Rocketdyne (PWR)
Marine Power	Compact and fast responding turbomachinery	Knolls and Bettis Atomic Power Labs
Waste Heat Recovery	Simple cycle design with high efficiency	Echogen, Dresser-Rand
Solar	Allows for higher conversion efficiency in high-temperature power towers	NREL, PWR
Grid Electricity Storage	Reversible cycle: heat pump / power turbine	ABB

Oxy-Fuel Combustion and CCS Application



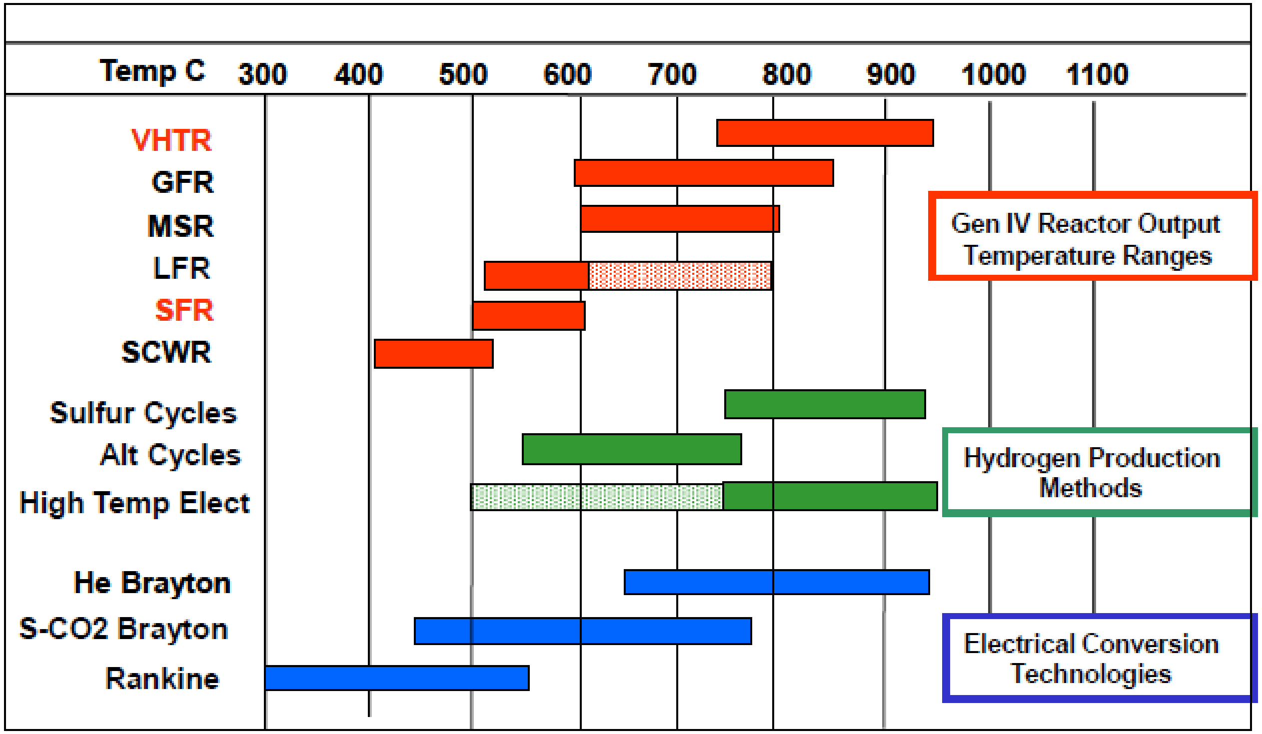
S-CO2 Turbomachinery Technology Development for Power Plant Applications, Pratt & Whitney Rocketdyne, RD11-159

Oxy-Fuel Direct Combustion Application



Nuclear Power Applications

- Under investigation by Generation IV nuclear power researchers in US, Europe and Asia
- Applicable to multiple Gen IV reactor concepts



Picard, Supercritical CO2 Power Cycle Symposium, 2009.

US Department of Energy SunShot Initiative

"The SunShot Initiative will spur American innovations to reduce life costs of solar energy and re-establish U.S. global leadership in this growing industry."

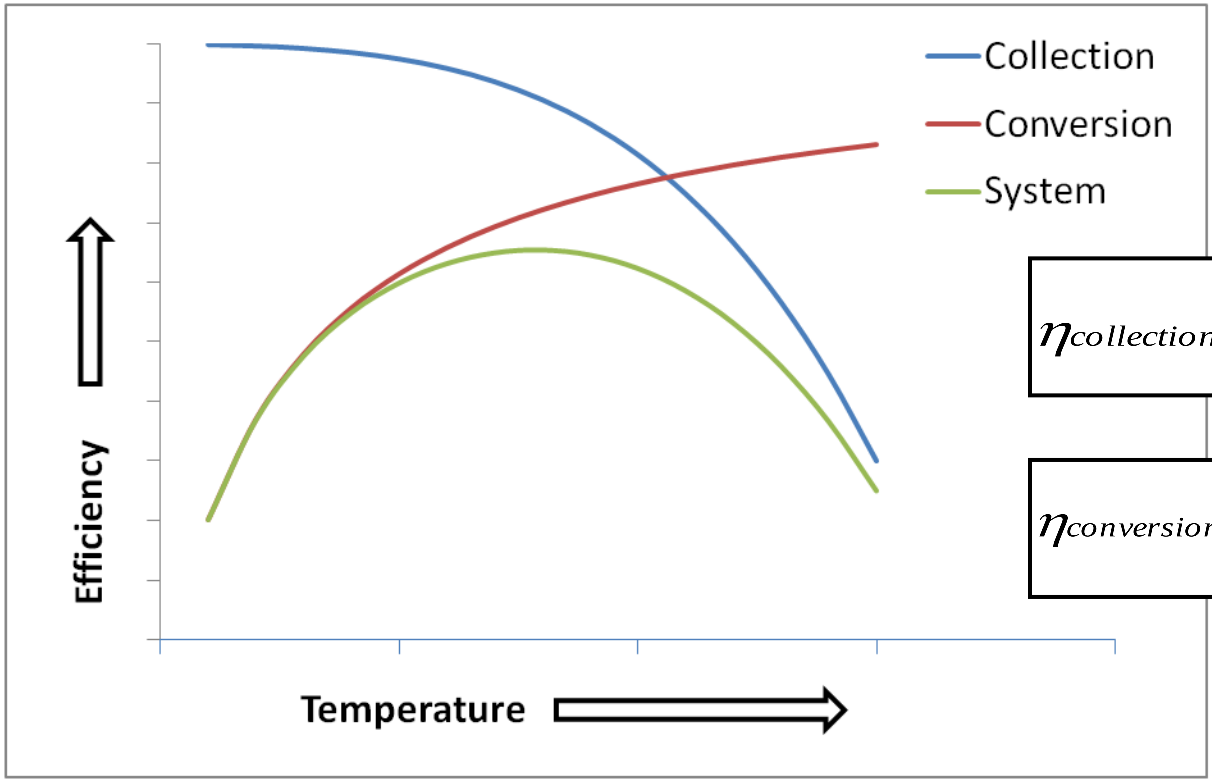
U.S. Energy Secretary Steven Chu

February 2011

- DOE's **SunShot** Initiative aims to make solar electricity cost-competitive with conventional forms of energy before 2020.
- Reducing the costs of utility, commercial and residential installations by approximately 75% could enable widespread deployment of solar energy.
- Coordination among the DOE Solar Program, Office of Science, and ARPA-E.

SunShot
U.S. Department of Energy

CSP System Efficiency

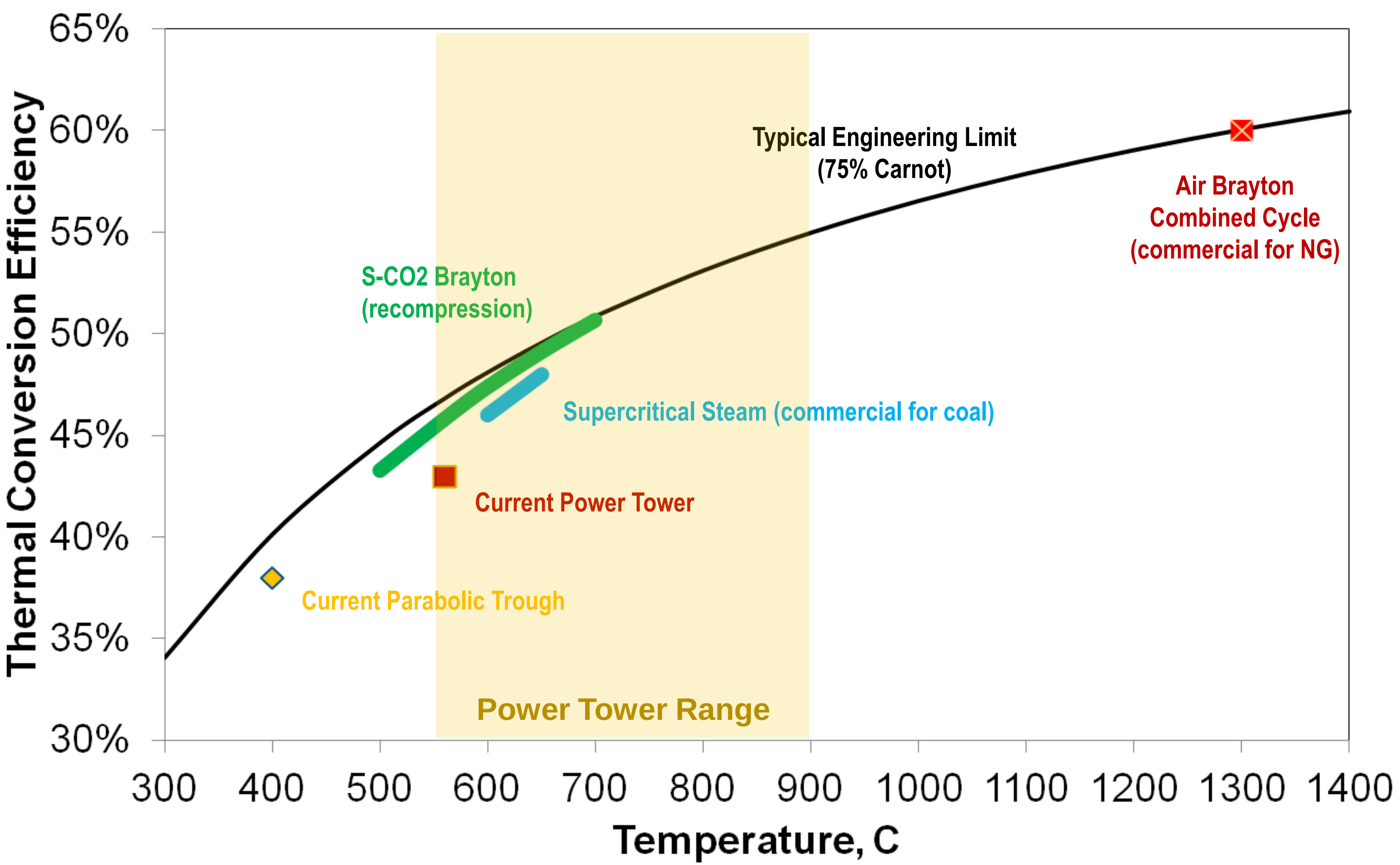


$$\eta_{collection} \approx \frac{IC\alpha - \varepsilon\sigma T^4}{IC}$$

$$\eta_{conversion} \approx (1 - \frac{T_C}{T_H}) * 0.75$$

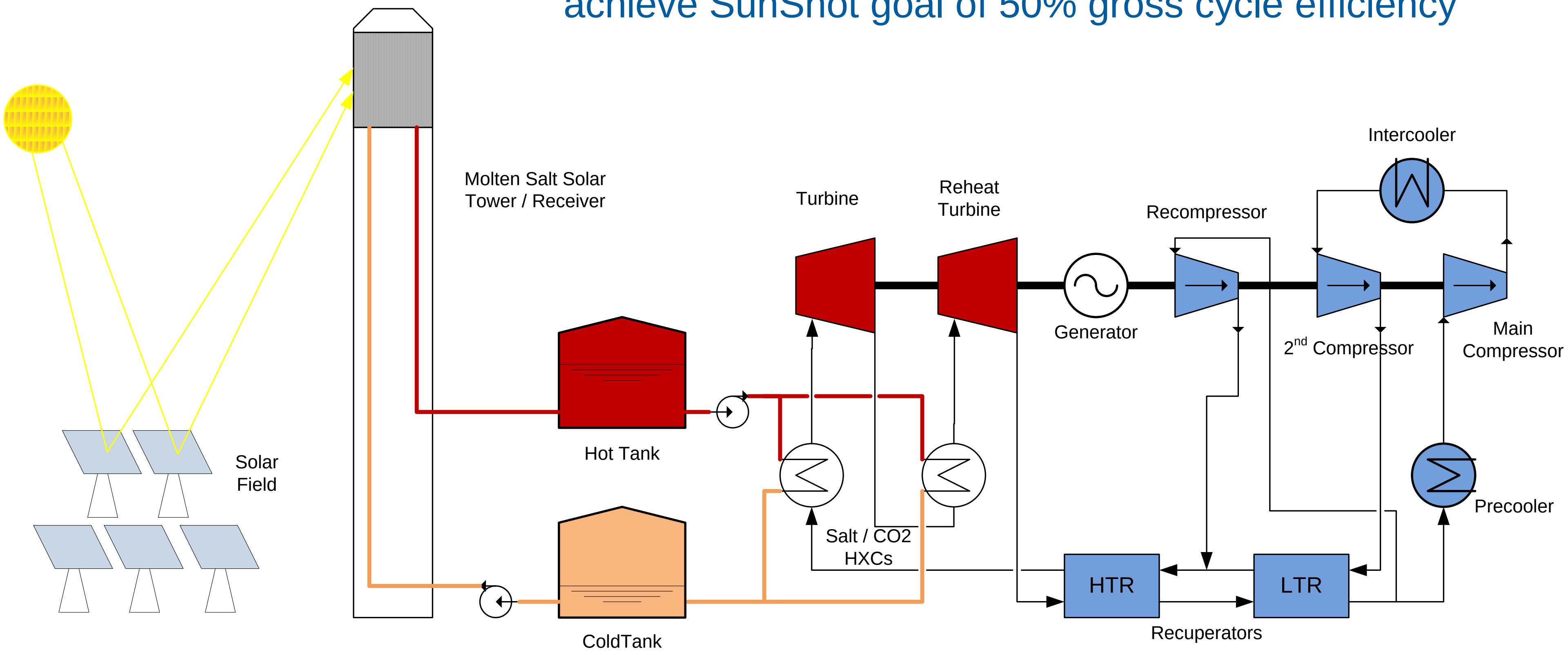
Maximizing efficiency requires maintaining good collection efficiency while moving to higher conversion temperatures.

Power Cycle Options for CSP



Solar Thermal Power Application

Dry-cooled, recompression cycle with reheat coupled to high-temp molten salt power tower to achieve SunShot goal of 50% gross cycle efficiency



Demonstrating s-CO_2: Pilot Test Catch-22

- An optimized 20 kW prototype s-CO_2 turbine is ¼" diameter and spins at 1,500,000 rpm
- A manufacturable s-CO_2 prototype turbine of 6" diameter spinning at 20,000 rpm produces 10 MW and requires a ~$20M support facility

S. Wright, *Mechanical Engineering*, Jan 2012

10 MW $s\text{-}CO_2$ Turbine Test

Echogen's EPS100 process skid

Objectives:

1. Design, fabricate and validate a $s\text{-}CO_2$ Brayton cycle that is capable of operation at up to 700C and dry cooling conditions
2. Validate and map power turbine and compressor performance
3. Simulate advanced CSP/$s\text{-}CO_2$ system performance and estimate LCOE to meet SunShot goals

NREL NATIONAL RENEWABLE ENERGY LABORATORY

ECHOGEN power systems

Sandia National Laboratories

Barber Nichols

THE UNIVERSITY of WISCONSIN MADISON

ABENGOA SOLAR

EPRI ELECTRIC POWER RESEARCH INSTITUTE

s-CO_2 Brayton Cycle Research Needs

- Corrosion and materials compatibility data at high T, P
- Long-term testing of recuperators
- Design and validation of primary heat exchangers; understanding of s-CO_2 / HTF interactions
- Validation of power turbine bearings, seals, stop-valves
- Cycle models of transient operation, start/stop, off-design operation
- Demonstration of cycle operations and equipment durability

Thank you!

For more information:

http://www.nrel.gov/csp/

http://maps.nrel.gov/

http://solareis.anl.gov/

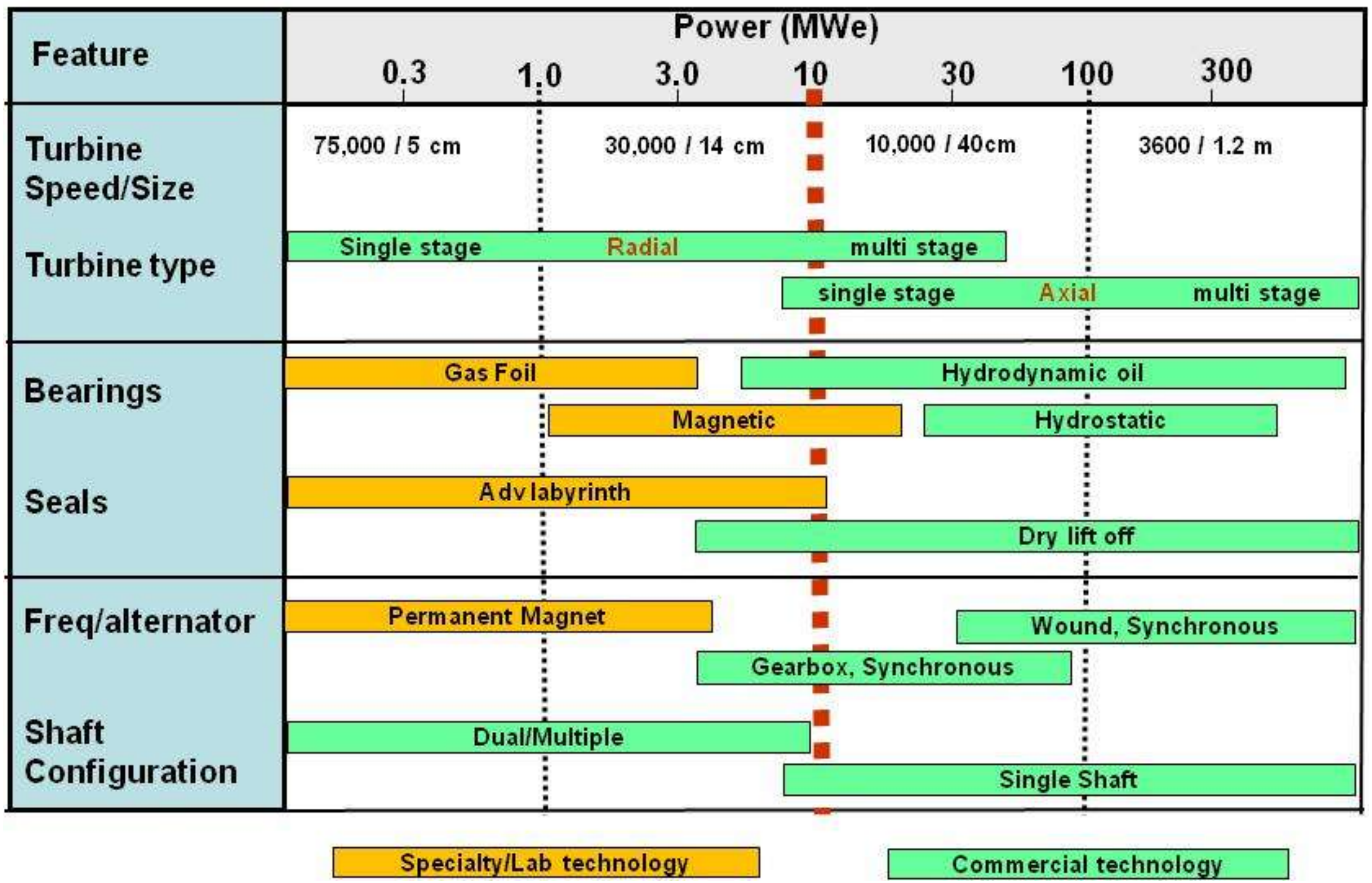
NREL's trough module test facility

Craig Turchi
Concentrating Solar Power Program
303-384-7565
craig.turchi@nrel.gov

Support slides

Why 10 MWe Scale?

- 10 MW is the minimum size that allows use of commercial design technologies



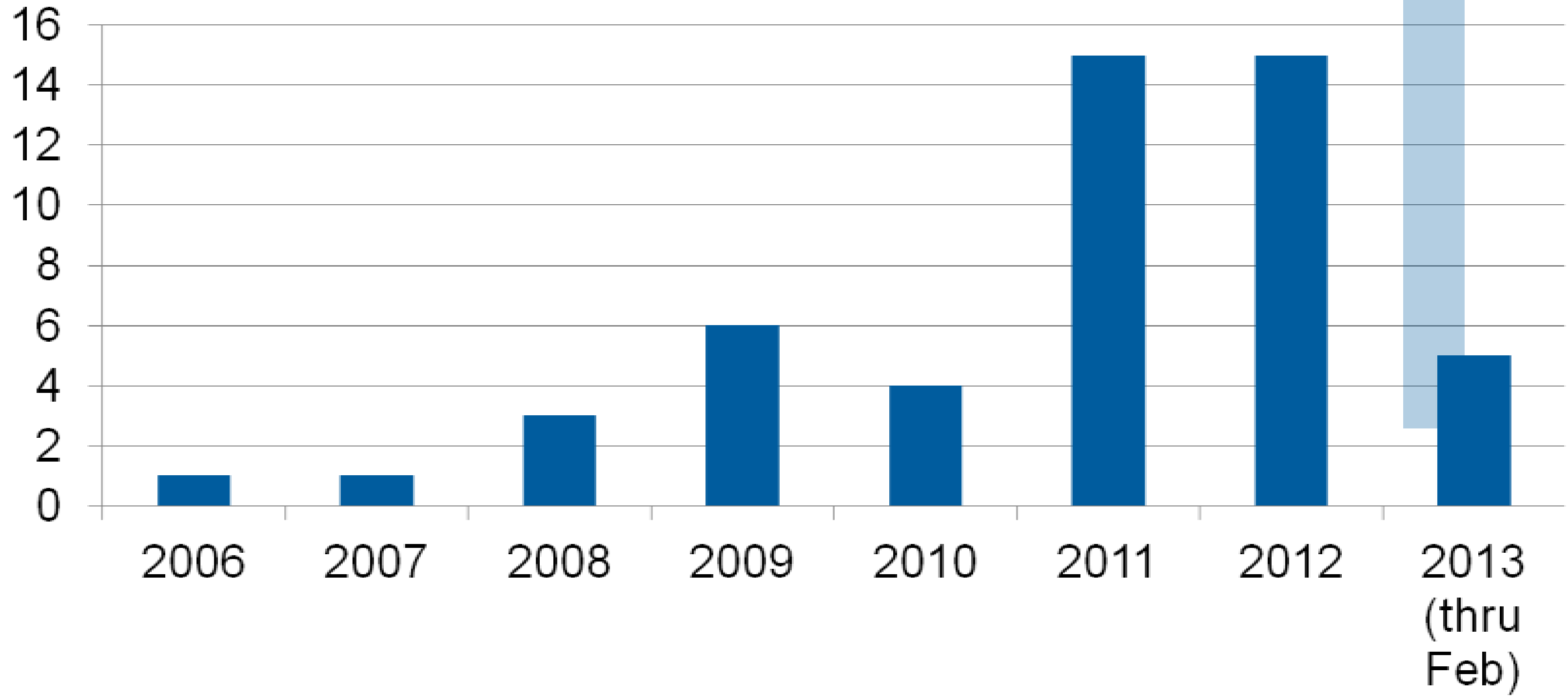
CSP Plant Characteristics

---- Deployed ---- Future Opportunities (Towers)

CSP Design and primary Heat Transfer Fluid	2010 Oil Trough	2013 Salt Tower	Supercrit. Steam	Air Brayton Cycle	S-CO_2 Brayton Cycle
Performance Data:					
Turbine MW_e (Range)	50-125	20-110	400+	0.3-200	10-150
Receiver T/P (°C/bar)	391/100	565/140	610/250	1300/30	700/250
Power Cycle Gross Effic.	0.38	0.42	0.47	0.40	0.50
Thermal Storage Options	Oil, Salt	Molten salt	Molten salt	Ceramic blocks	Molten salt
Cost:					
LCOE (cents/kWh, no ITC)	19	15	11	<10?	<10?

LCOE = levelized cost of electricity
ITC = investment tax credit

Journal Publications on s-CO_2 Brayton Cycle



Solar Potential in the Southwest

Solar Potential in Southwest US:

6,900 GW (6x current US generation capacity)

16 million GWh (4x current US annual electricity consumption)

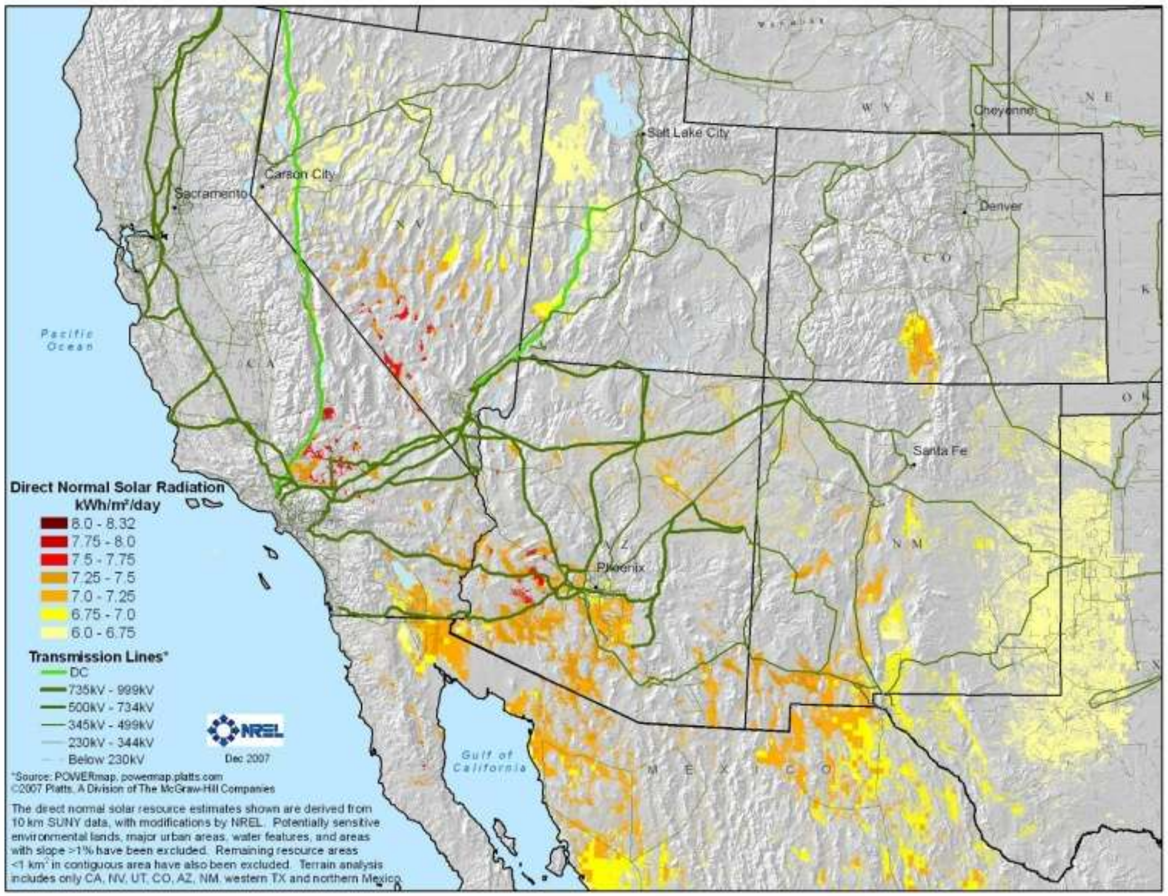
Assumptions:

DNI Solar Resource ≥ 6.75 kWh/m2/day

Plant footprint = 5 acres/MW

Annual capacity factor = 27%

Map represents land that has no primary use today, excludes land with slope > 1% and excludes known environmentally or culturally sensitive lands.



Thermal Inertia

Comparison of power output from large CSP and PV plants located within 50 km of each other.

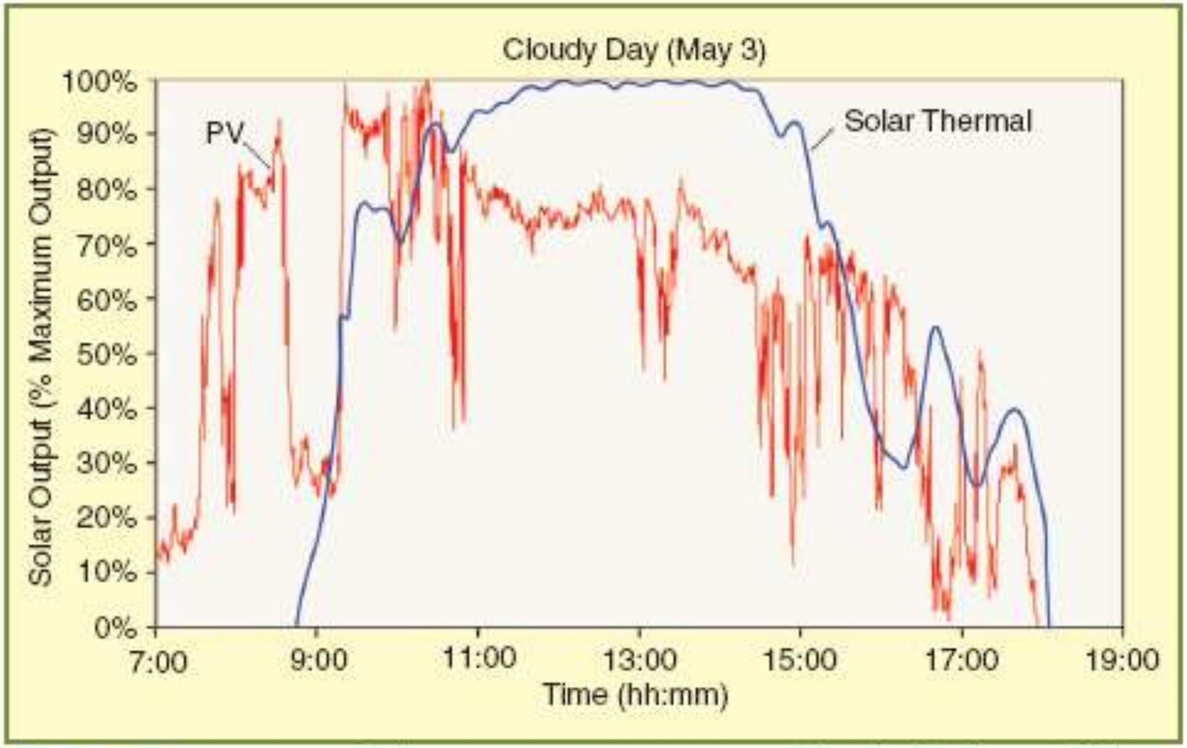
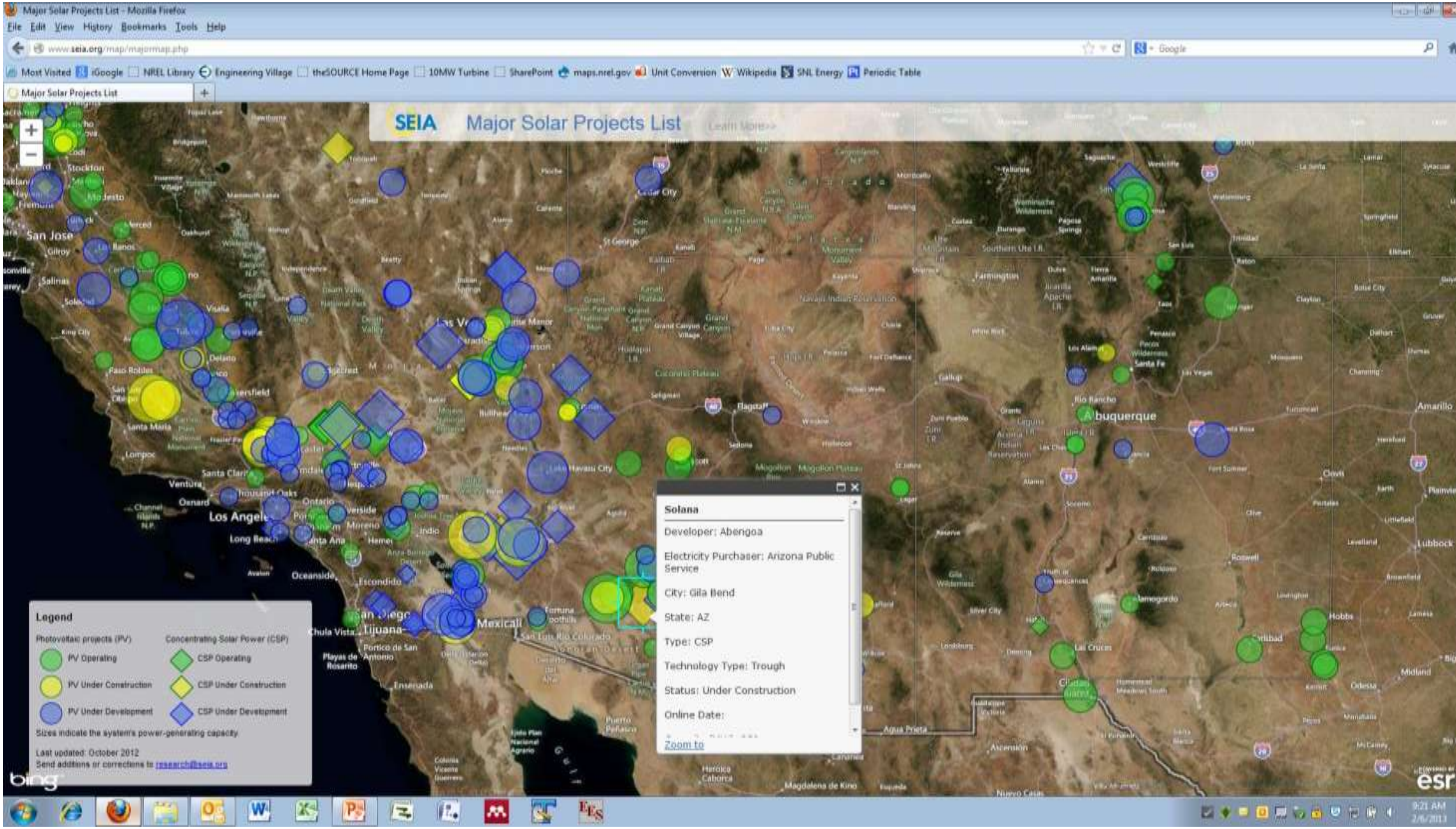


figure 10. Comparison of short-term variations in PV (red) and solar thermal (blue)

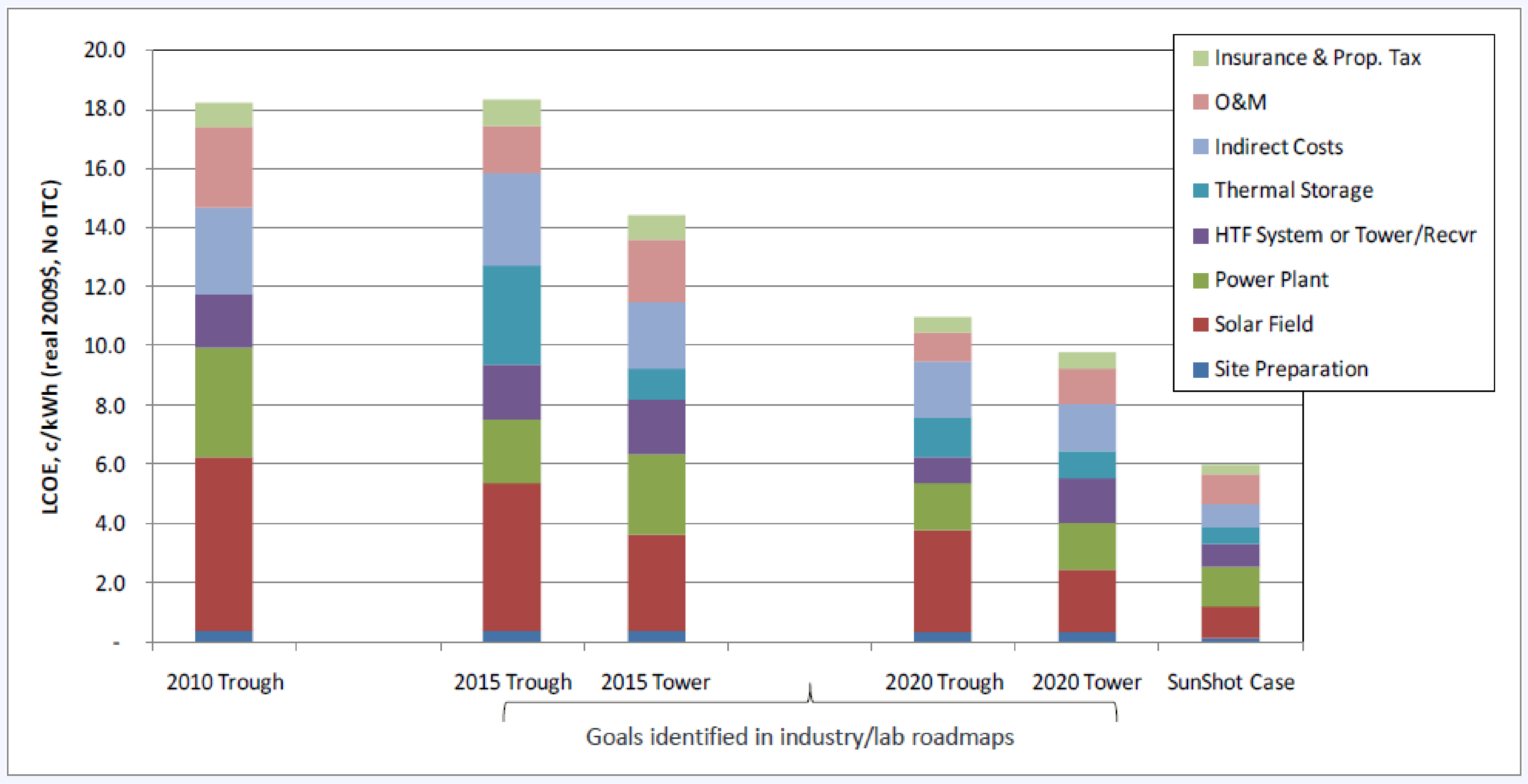
Mehos, et al., IEEE Power & Energy Magazine, May/June 2009.

Projects List from SEIA

http://www.seia.org/map/majormap.php

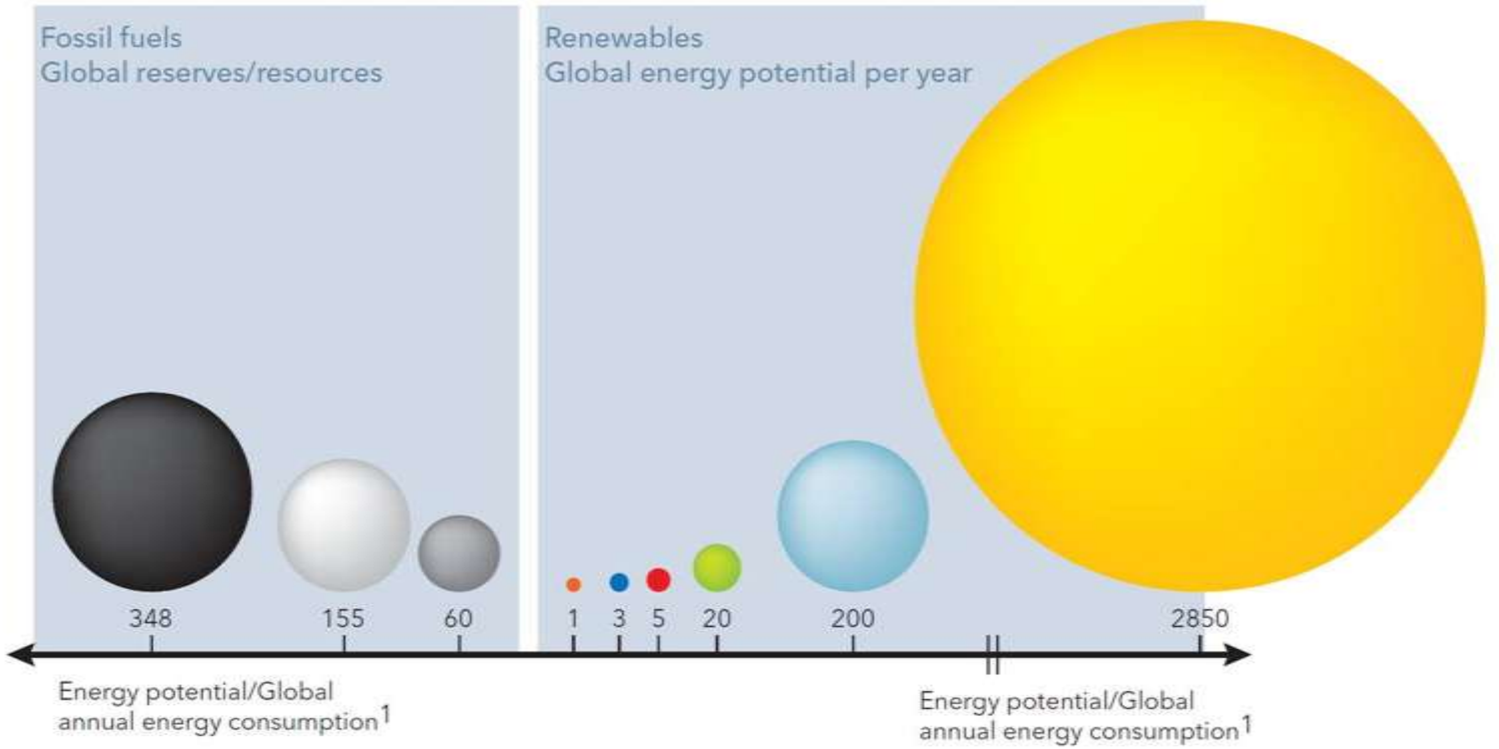


Unsubsidized CSP Trough and Tower Costs



Assumed location is Daggett, CA

Solar Energy Potential



	Energy potential Reserves/Resources[2]	Thereof conventionally utilizable[2]
Coal	~ 135.000 EJ	
Natural gas	~ 60.400 EJ	~ 12.000 EJ
Crude oil	~ 23.000 EJ	~ 9.800 EJ

Global energy demand 2006: ~ 470 EJ

	Energy potential (amount of energy p. a.)[2]	technologically utilizable (state of the art)[2]
Solar radiation	~ 1.111.500 EJ	~ 1.482 EJ
Wind energy	~ 78.000 EJ	~ 195 EJ
Biomass	~ 7.800 EJ	~ 156 EJ
Geothermal	~ 1.950 EJ	~ 390 EJ
Hydro/tide power	~ 1.170 EJ	~ 78 EJ

University of Twente, Netherlands, http://www.utwente.nl/mesaplus/nme/Introduction/