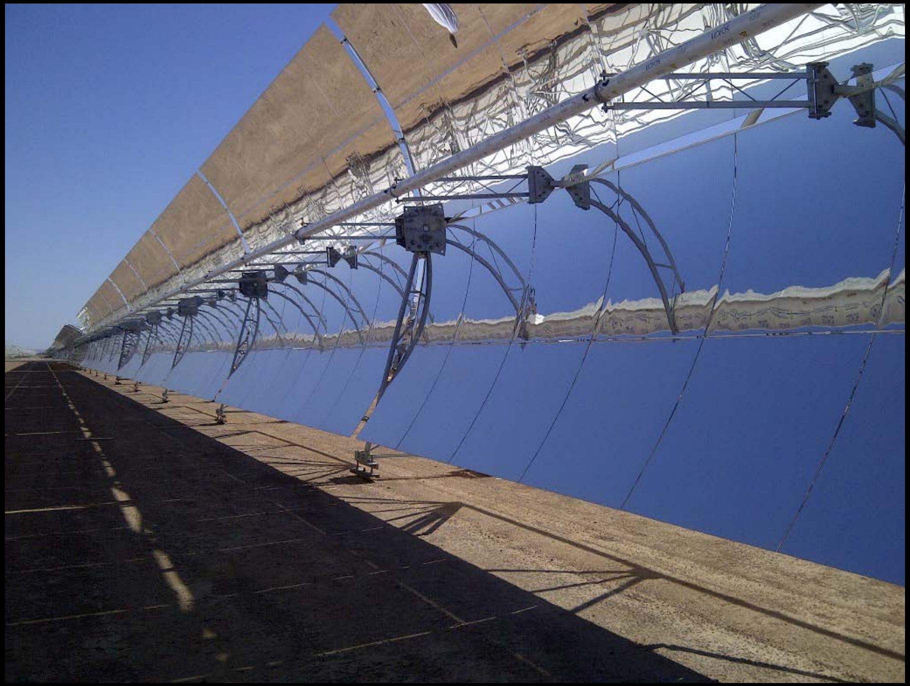
Concentrating Solar Power

Supercritical CO_2 Power Cycles Symposium; March 2016

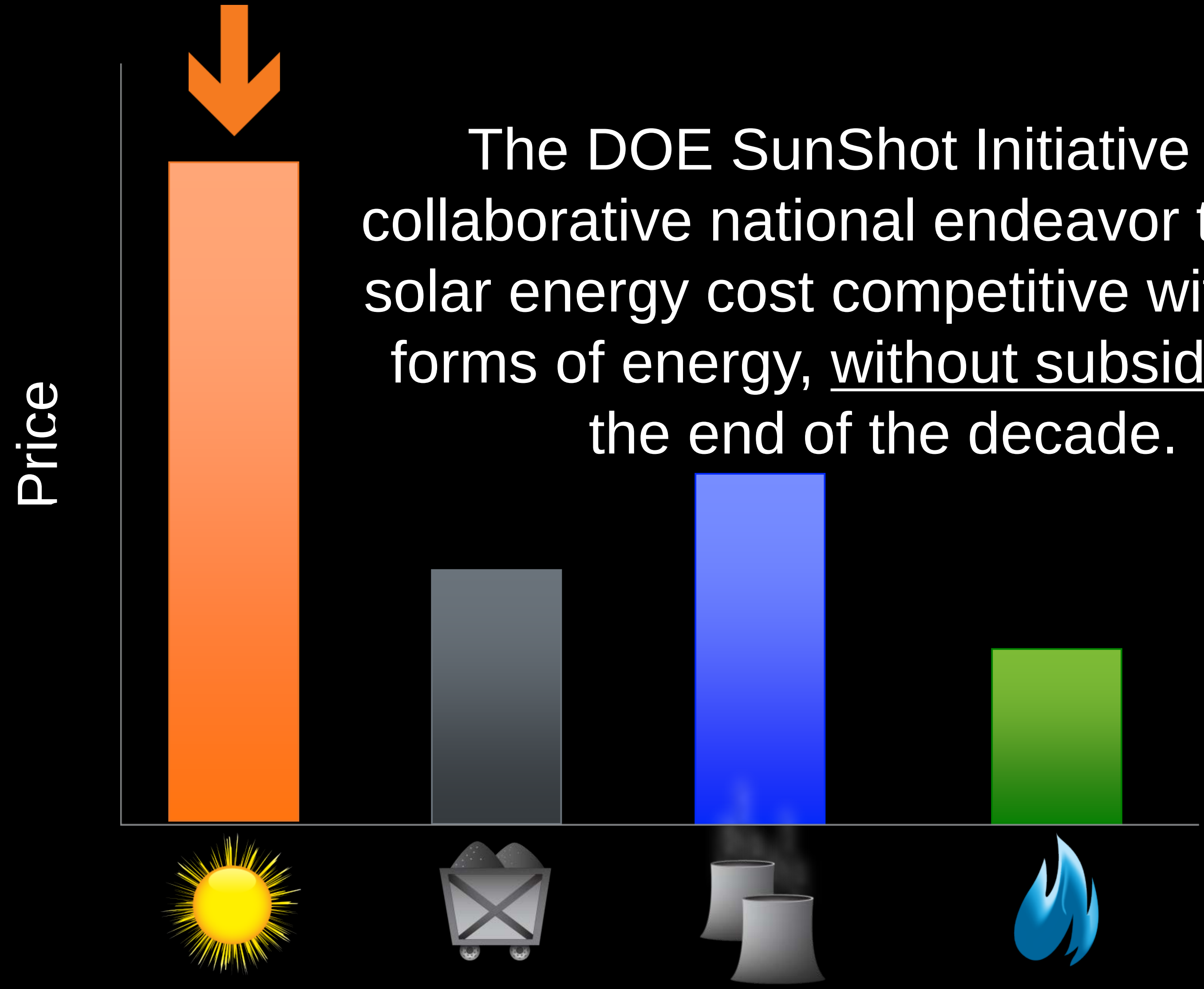
Matthew Bauer

SunShot
U.S. Department of Energy

Aerial View of Solana (AZ, 280 MW) and Ivanpah (CA, 392 MW) Generating Stations,



SunShot Initiative



The DOE SunShot Initiative is a collaborative national endeavor to make solar energy cost competitive with other forms of energy, without subsidies, by the end of the decade.

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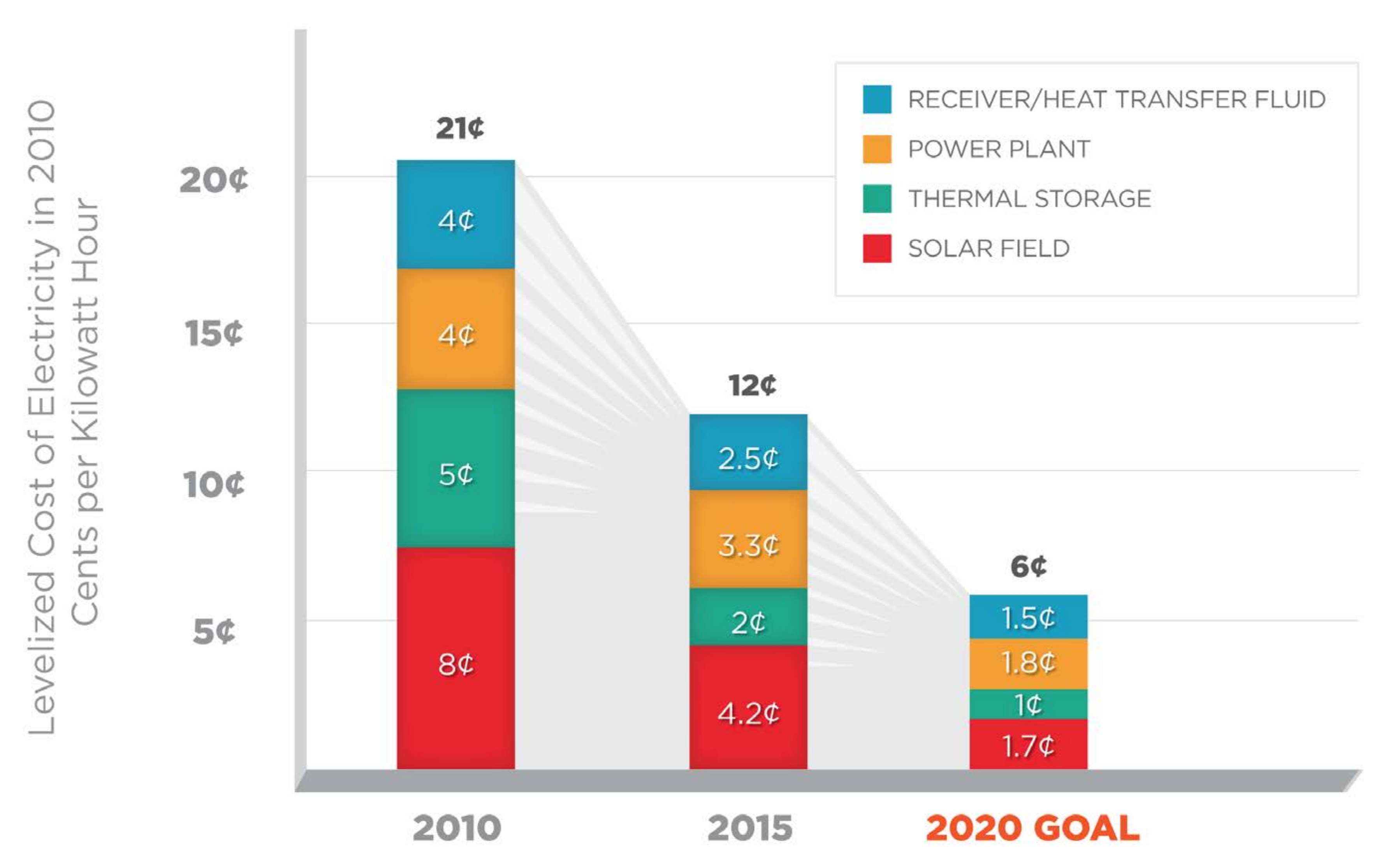
The Falling Cost of CSP



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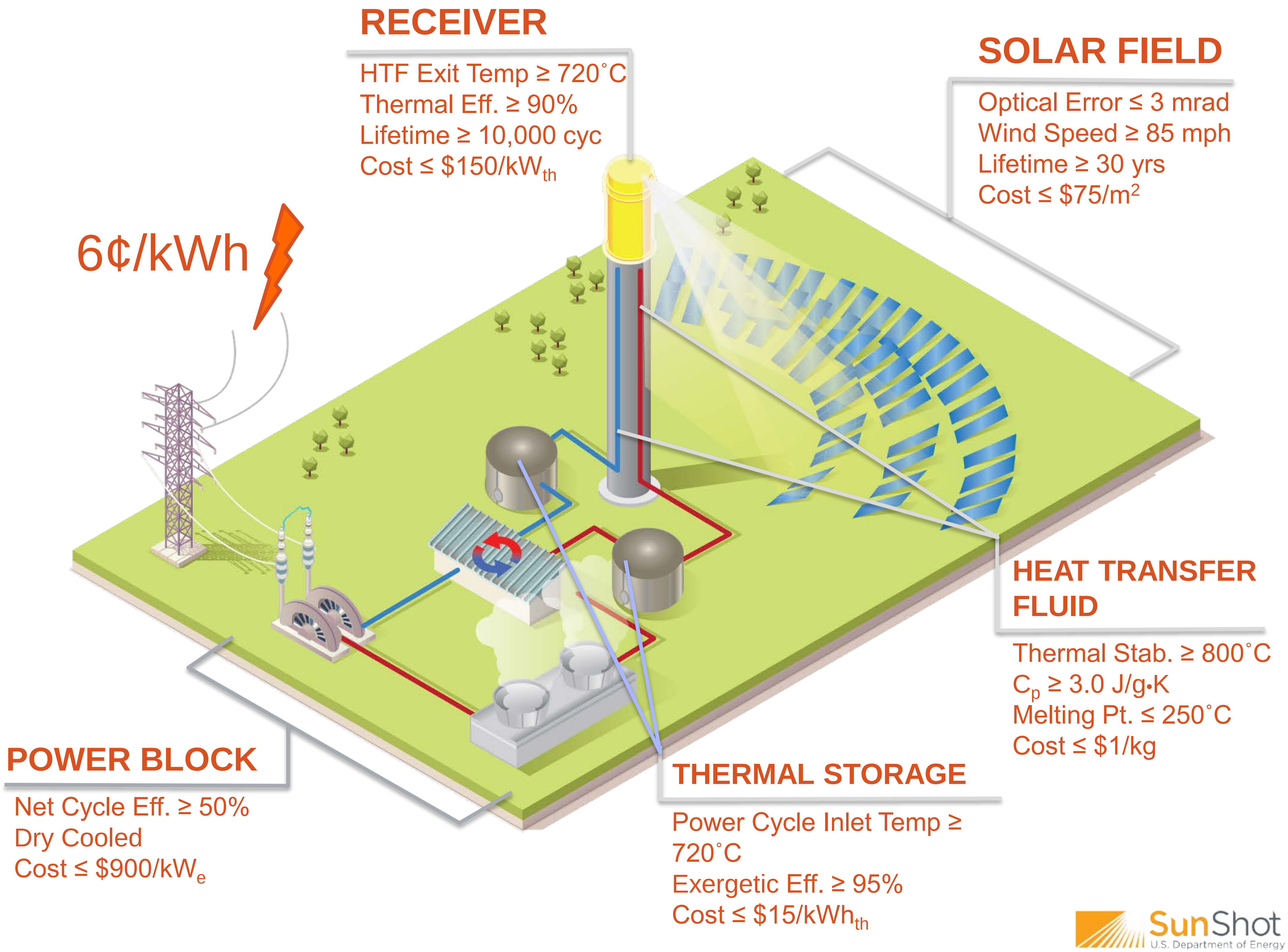

RECEIVER
HTF Exit Temp ≥ 720˚C
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cyc
Cost ≤ $150/kW$_{th}$
SOLAR FIELD
Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
Cost ≤ $75/m^{2}
6¢/kWh
HEAT TRANSFER FLUID
Thermal Stab. ≥ 800˚C
C_p ≥ 3.0 J/g•K
Melting Pt. ≤ 250˚C
Cost ≤ $1/kg
POWER BLOCK
Net Cycle Eff. ≥ 50%
Dry Cooled
Cost ≤ $900/kW$_{e}$
THERMAL STORAGE
Power Cycle Inlet Temp ≥ 720˚C
Exergetic Eff. ≥ 95%
Cost ≤ $15/kWh$_{th}$
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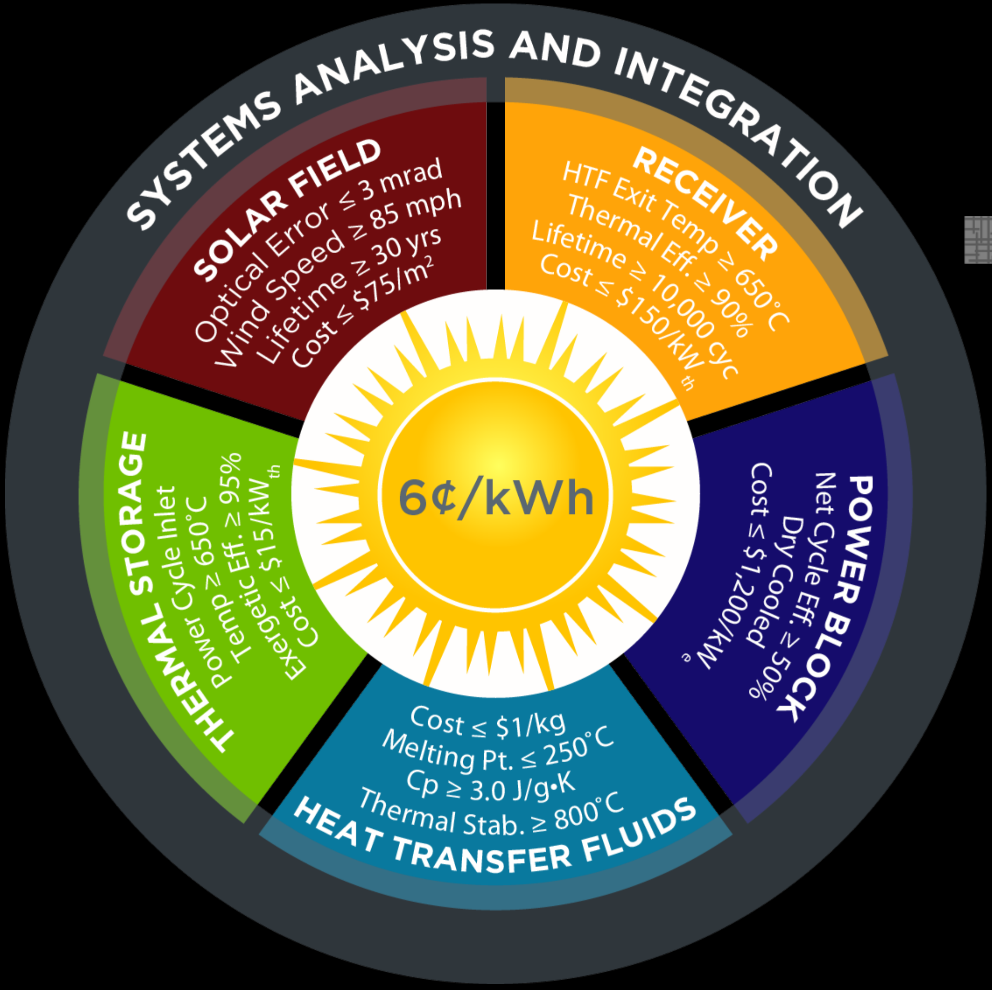
Competitive Initiatives

- $15M COLLECTS (2016)
- $29M CSP SuNLaMP (2015)
- $33M CSP: APOLLO (2015)
- $25M SolarMat II (2014)
- $20M CSP: ELEMENTS (2014)
- $10M CSP-HIBRED (2013)
- $ 8M PREDICTS (2013)
- $15M SolarMat (2013)
- $10M SunShot MURI (2012)



- $30M National Lab R&D (2012)
- $ 5M BRIDGE (2012)
- $56M SunShot CSP R&D (2012)
- $ – M Incubator/SBIR (Recurring)
- $53M CSP Baseload (2010)
- $29M ARRA (2009)
- $27M Thermal Storage (2008)
- $25M CSP R&D (2007)

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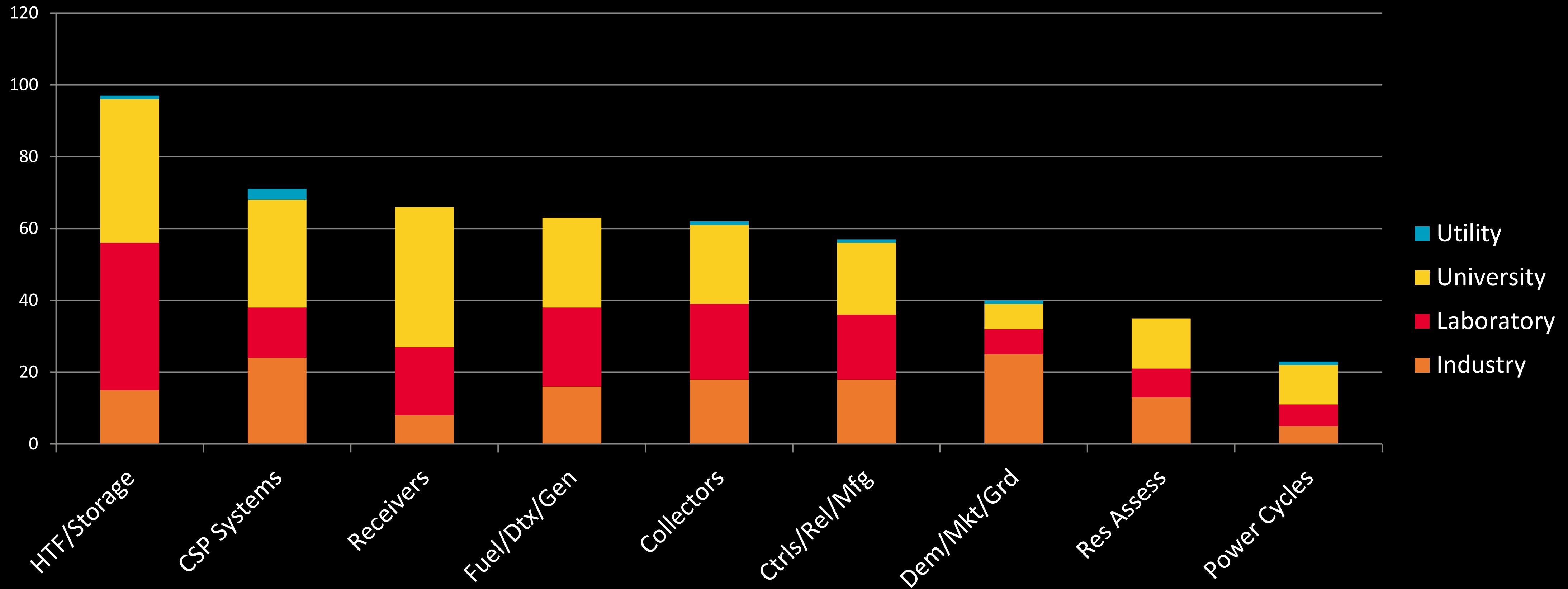
CSP Apollo Awards

Awardee	Topic	Award Amount
Abengoa Solar LLC	Collectors	$1,221,015
Boston University	Collectors	$1,150,000
Oregon State University	Receivers	$2,000,000
SolarReserve, LLC	Receivers	$2,357,159
Abengoa Solar LLC	Receivers	$2,697,434
Dartmouth College	Receivers	$656,831
Argonne National Laboratory	TES/HTF	$1,050,000
Southern Research Institute	TES/HTF	$2,000,000
Brayton Energy	TES/HTF	$2,600,000
Southwest Research Institute	Power Cycles	$5,350,000
GE Global Research	Power Cycles	$3,800,000
Purdue University	Power Cycles	$3,845,079
Ceramatec, Inc	Power Cycles	$2,348,776
University of Wisconsin	Power Cycles	$1,899,257
Total		**$32,975,551**

CSP SunLamp Awards

Awardee	Topic	Award Amount
Oak Ridge National Laboratory	Collectors	$2,800,000
Argonne National Laboratory	Collectors	$3,624,366
Oak Ridge National Laboratory	Receivers/Power Cycles	$2,175,000
Sandia National Laboratory	Receivers	$882,416
Los Alamos National Laboratory	Receivers	$3,450,000
Los Alamos National Laboratory	TES/HTF	$3,000,000
National Renewable Energy Laboratory	TES/HTF	$1,000,000
Sandia National Laboratory	Power Cycles	4,586,966
National Renewable Energy Laboratory	Power Cycle	$3,000,000
National Renewable Energy Laboratory	Systems Analysis	$2,249,897
Sandia National Laboratory	Facilities	$2,250,000
Total		**$29,018,645**

SolarPACES 2013- Papers by Topic



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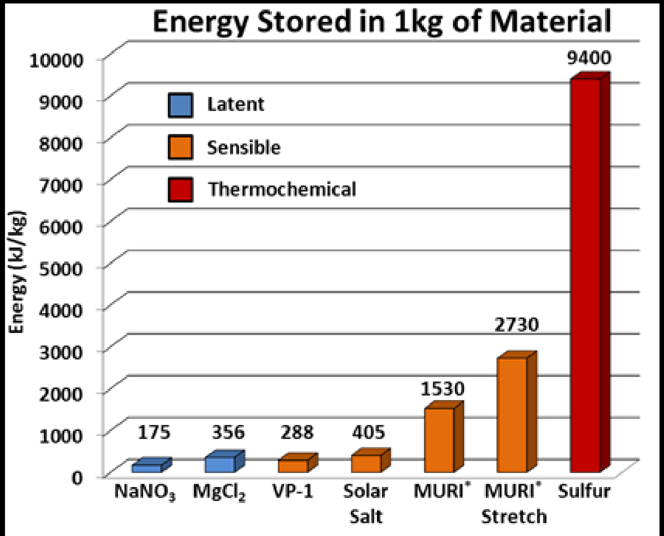
SunShot sc-CO_2 Cycle Portfolio Highlights

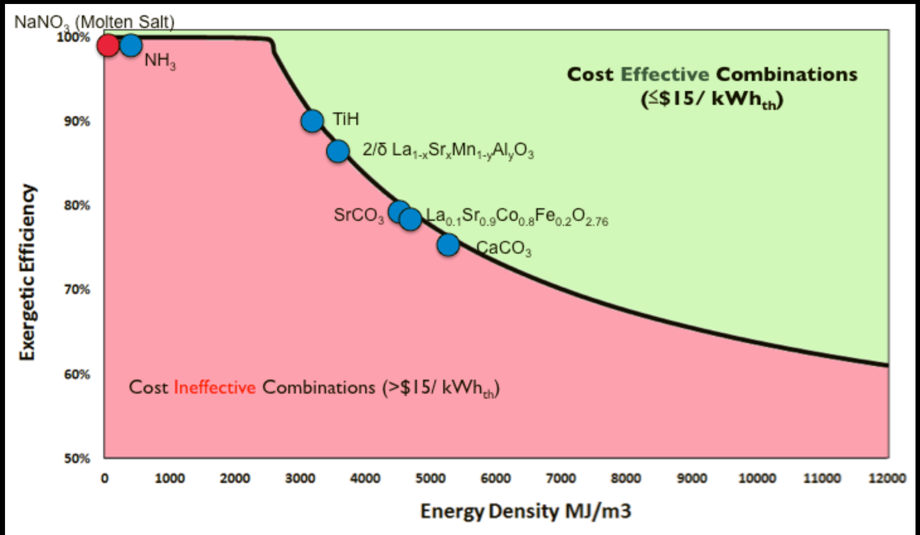
Primary Heater (HTF to CO_2 heat exchanger)				
2015 SunLamp	2015 Apollo	2012 National Lab R&D	2012 SunShot, 2015 Apollo	2012 SunShot, 2015 Apollo
Sandia National Laboratorie; Australian National University	Purdue University; The University of Wisconsin Madison; Georgia Institute of Technology	NREL National Renewable Energy Laboratory	Brayton Energy LLC; SRNL Savannah River National Laboratory	OSU Oregon State University
Particle to CO_2	Salt to CO_2	Direct CO_2 Receiver	CO_2 Rec. +TCES	Direct CO_2 Receiver

Turbomachinery			
2012 SunShot	2013 Predicts	2015 Apollo	2015 Apollo
SwRI; GE; TharEnergy	GE; SwRI	SwRI; Samsung Techwin	GE; SwRI
Turboexpander	Bearings / Seals	Compander	Compression
Heat Exchangers	**Corrosion**		**Technoeconomics**
2015 Apollo	2015 SunLamp	Various Awards	2015 SunLamp
The University of Wisconsin Madison	Oak Ridge National Laboratory	The University of Wisconsin Madison	NREL National Renewable Energy Laboratory
Regenerator			Sys. Advisory Model

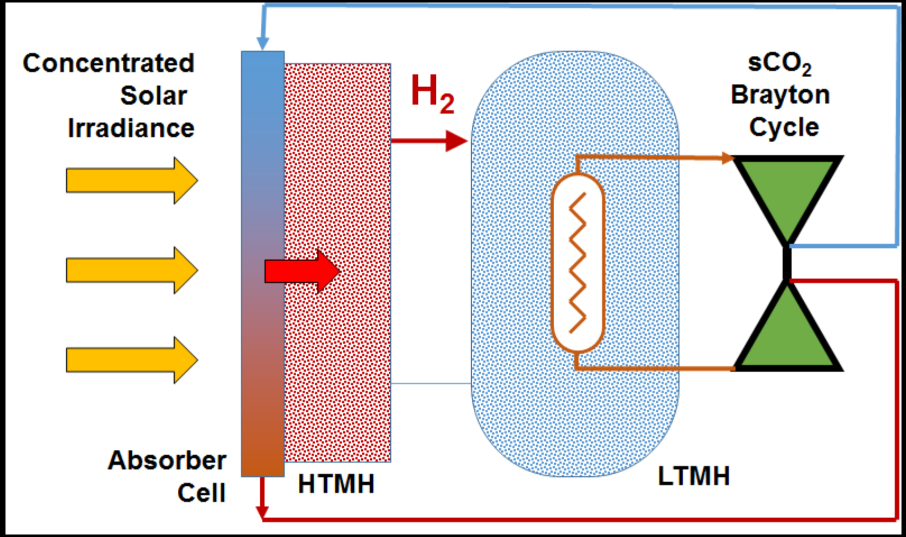
Storing Sun's Energy in Chemical Bonds:

Thermochemical Energy Storage for CSP





Coupling chemical storage with sCO_2



Chemical Energy Density >> Sensible, Latent Energy Densities

1. Can we engineer CSP integrated energy storage based on chemical reactions to capture and release energy on demand

2. Can we do so in a cost-effective manner with high efficiency to meet the SunShot goals

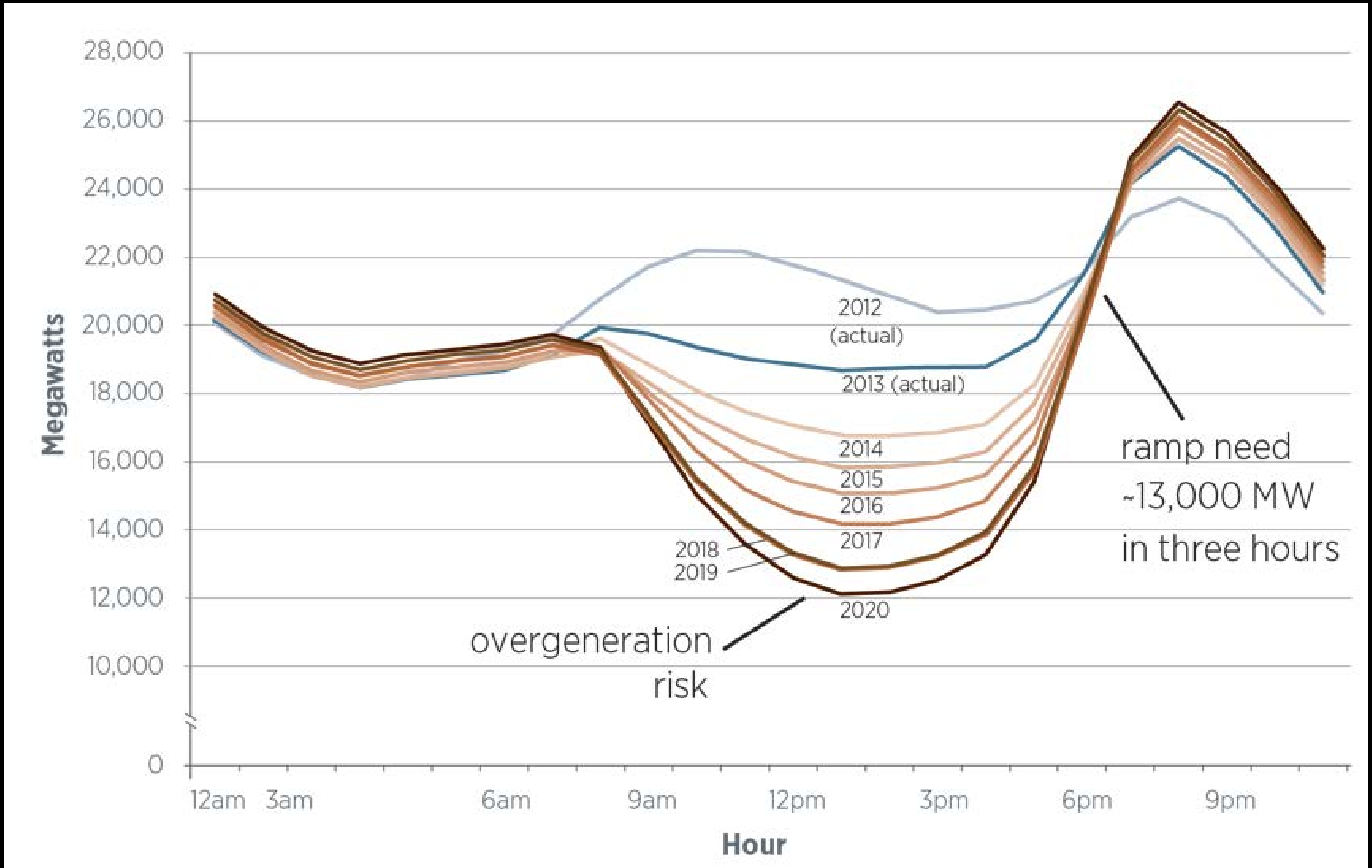
"Direct" sCO_2 + TCES

1. Photon to sCO_2 Heat Exchanger

2. sCO_2 to Storage Thermal Exchange "Charging"

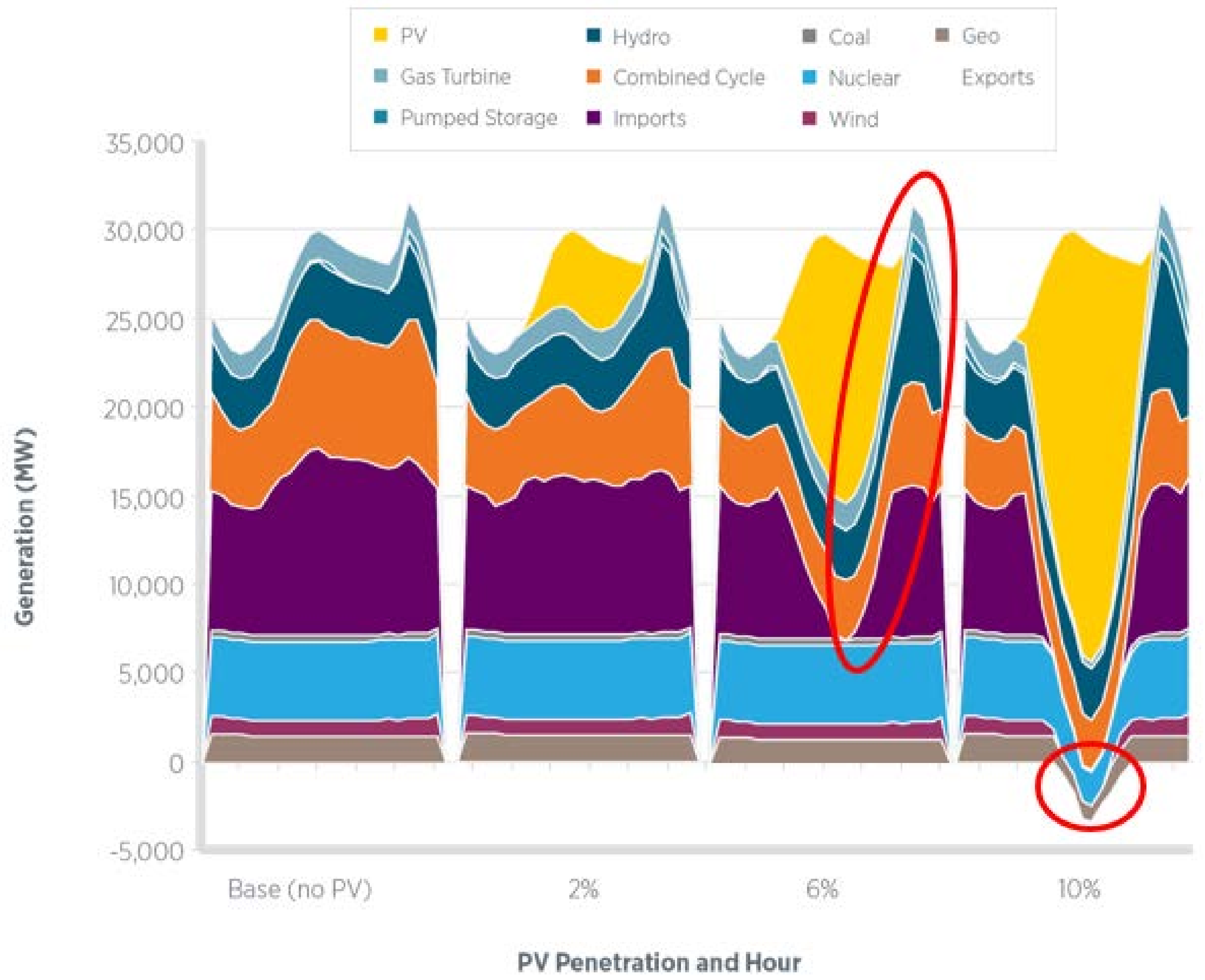
3. Storage to sCO_2 Exchange "Discharging"

Near term opportunities: should CSP only be baseload?



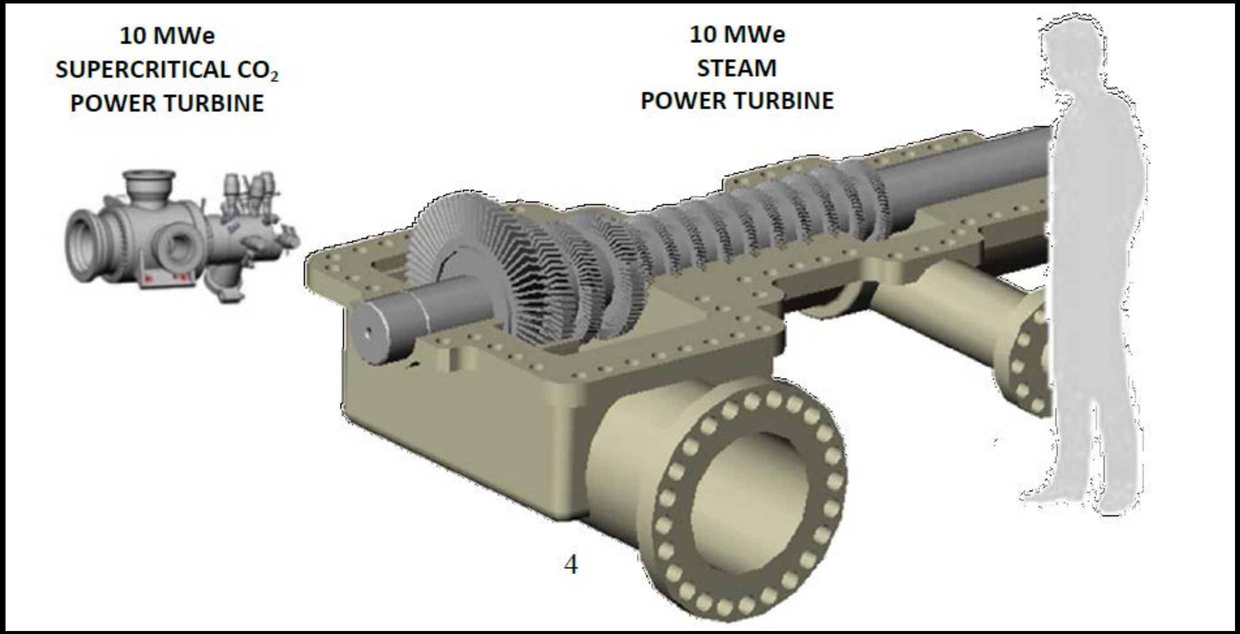
http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Excessive Ramp Rates and Minimum Load Constraints



Denholm, et al., (2011)

Modular CSP: 10-50 MW scale



- Collector field and power cycle are key bottlenecks to modular "On site" CSP construction
  - Modular trough collectors process has been successfully demonstrated through SolarMat FOA

Michael Persichilli, Alex Kacludis, Edward Zdankiewicz, and Held, Timothy; Supercritical CO2 Power Cycle Developments and Commercialization: Why sCO2 can Displace Steam; Power-Gen India & Central Asia 2012

Recently Completed U.S. Power Plants

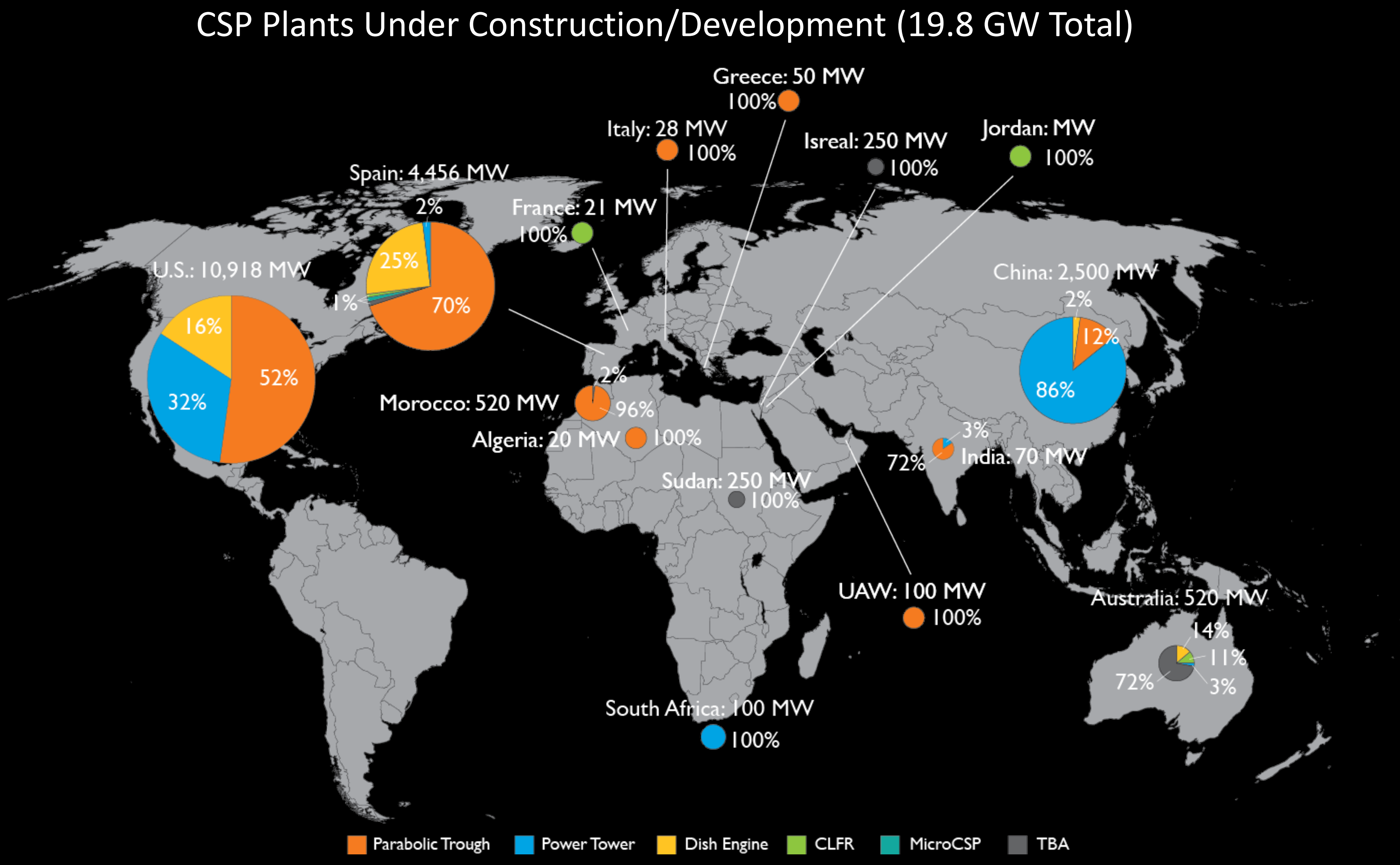




Project	Solana	Ivanpah	Genesis	Crescent Dunes	Mojave
Utility	APS	SCE + PG&E	PG&E	NVE	PG&E
State	Arizona	California	California	Nevada	California
Size	280 MW	392 MW	250 MW	110 MW	280 MW
Technology	Trough/Storage	Tower	Trough	Tower/Storage	Trough
COD	October 2013	January 2014	March 2014	November 2015	December 2014
DOE Loan	$1.45 B	$1.63 B	$0.85 B	$.74 B	$1.2 B
Company	Abengoa	BrightSource	NextEra	SolarReserve	Abengoa

Total New CSP in US: 1,312 MW

Global CSP Development Pipeline (2011)



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Source: "Concentrating Solar Power 2011: Technology, Costs and Markets," GTM Research • greentech.com

Technology development to support high temperature power cycles

Collector Field

- Cost < $75/m^2$
- Concentration ratio > 50
- Operable in 35 mph winds
- Optical error < 3.0 mrad
- 30 year lifetime

	Receiver	Material & Transport	Thermal Storage	HTF to $sc\text{-}CO_2$ Heat Exchanger
	Cost < $150/kW$_{th}$ *Thermal Eff. > 90%* *Exit Temp > 720˚C* *10,000 cycle lifetime*	*Cost < $1/kg* *Operable range from 250˚C to 800˚C*	*Cost < $15/kWh$_{th}$* *99% energetic efficiency* *95% exergetic efficiency*	
Direct sc-CO2	• High pressure fatigue challenges • Absorptivity control and thermal loss management	• Minimize pressure drop • Corrosion risk retirement	• Indirect storage required • Cost includes fluid to storage thermal exchange	• Not applicable
Liquid	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Potentially chloride salt, ideal material not determined • Corrosion concerns dominate	• Direct or indirect storage may be superior	• Challenging to simultaneously handle corrosive attack and high pressure working fluid
Falling Particle	• Most challenging to achieve high thermal efficiency	• Suitable materials readily exist	• Particles likely double as efficient sensible thermal storage	• Possibly greatest challenge • Cost and efficiency concerns dominate

Super Critical CO2 Brayton Cycle

- Net thermal to electric efficiency > 50%
- Power cycle system cost < $900/kW$_e$
- Dry cooled heat sink at 40˚C ambient
- Turbine inlent temperature near 720˚C

Subsystems must be redesigned to be compatible with operation above 720°C.

Third Generation CSP

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