Towards Ubiquitous, Cost-Competitive Solar Power



Dr. Ranga Pitchumani

SunShot
U.S. Department of Energy

Presented at the ASTRI Annual Workshop | Brisbane, Australia | February 11, 2015

SunFacts

- There is more solar energy reaching the earth in one hour than the combined worldwide human consumption of energy in one year.
- Photovoltaic (PV) panels on just 0.6% of the nation's total land area could supply enough electricity to power the entire United States.
- Seven southwestern states have the technical potential and identified land area to site enough concentrating solar power (CSP) to supply more than four times the current U.S. annual demand.
- Solar energy industry has been one of the fastest growing industries in the U.S. over the last 5 years. There are now over 173,500 jobs in the solar sector, and these jobs are growing at almost 20x the rate of the U.S. economy.
  - U.S. steel industry: 86,122, U.S. automobile and light truck manufacturing industry: 142,177.
- Every 4 minutes, another American home or business goes solar.

  President Barack Obama, State of the Union Address, Jan 2014
- Every 3 weeks, we bring online as much solar power as we did in all of 2008.

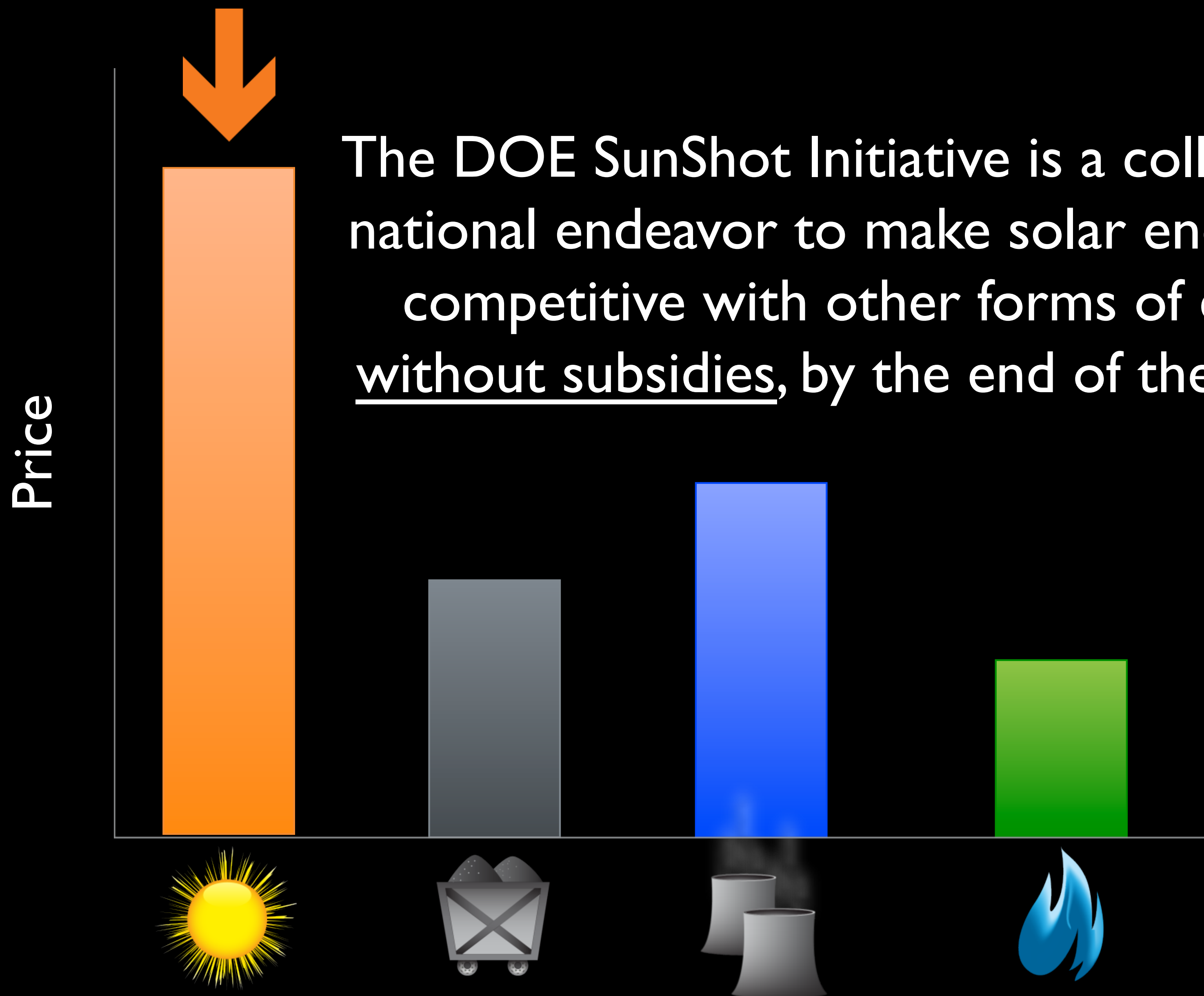
  President Barack Obama, State of the Union Address, Jan 2015

National Energy Goals

- Reduce oil imports by one-third by 2025 from 2008 levels.
- Derive 80% of America's electricity from clean energy sources by 2035.
- Reduce greenhouse gas emissions by 17% by 2020 and 83% by 2050, from 2005 baseline.

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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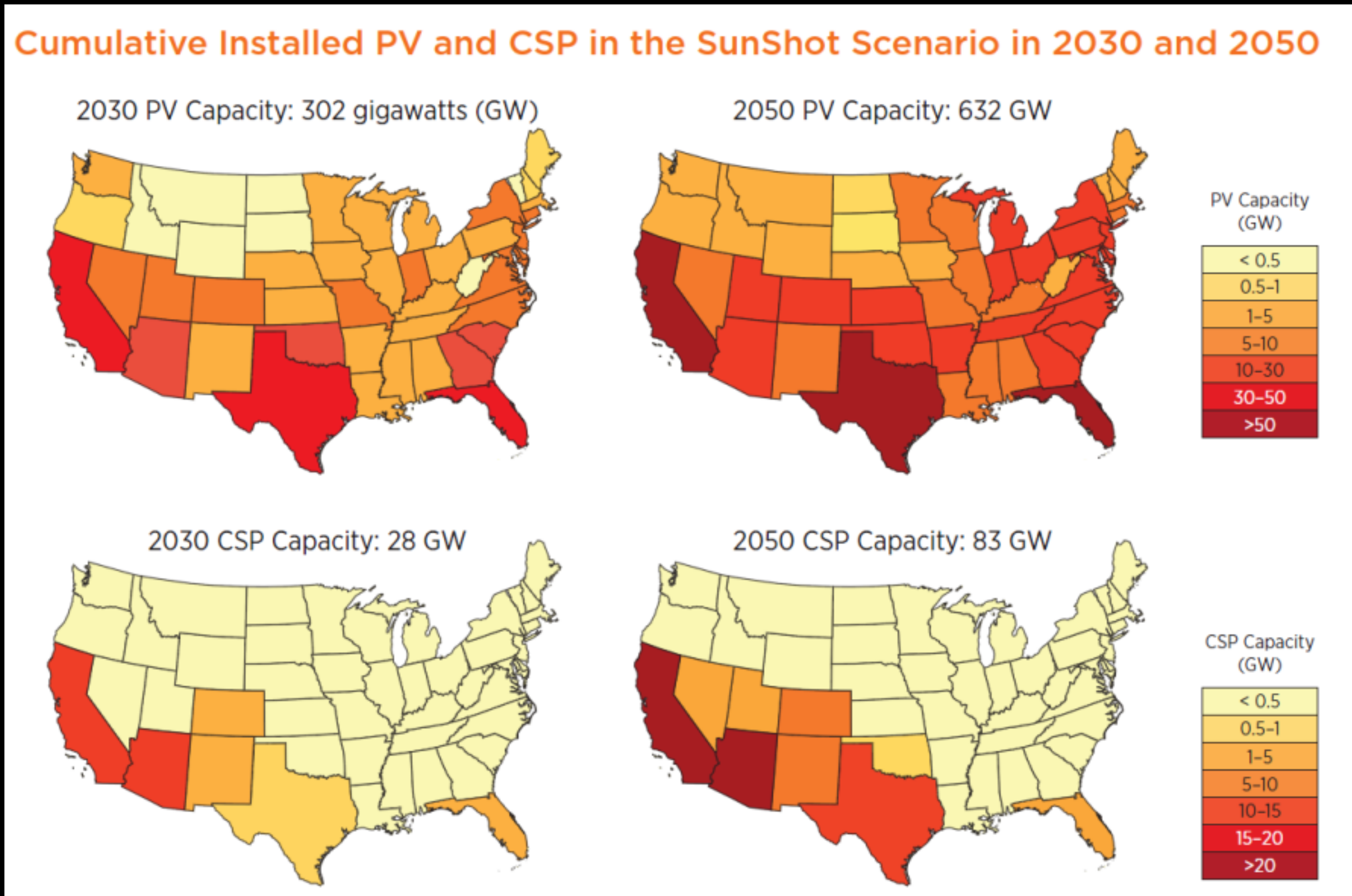
DOE SunShot Vision Study (2012)



Solar can meet **14% (300GW)** by 2030 and **27% (600 GW)** by 2050 of U.S. electricity demand

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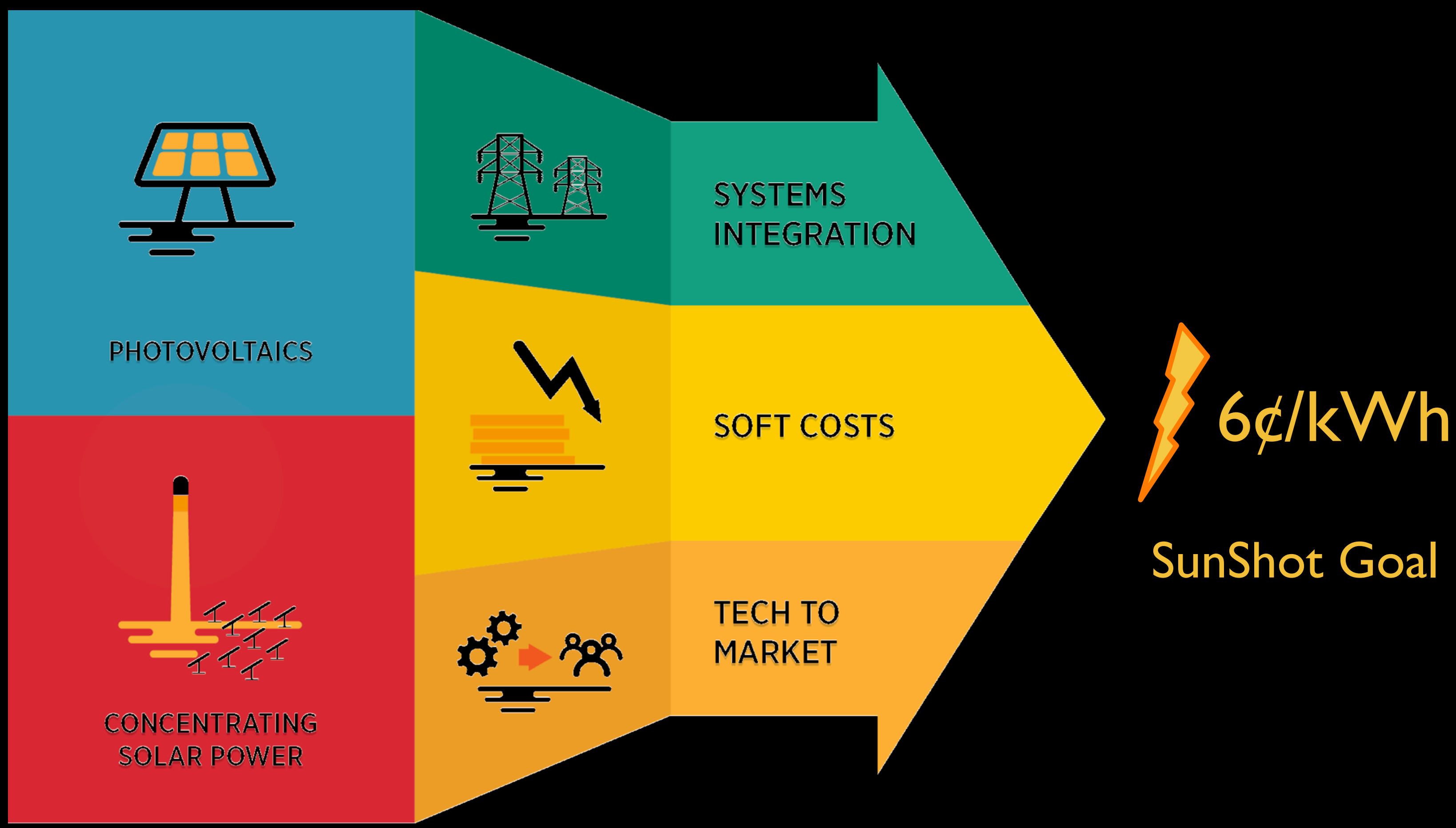
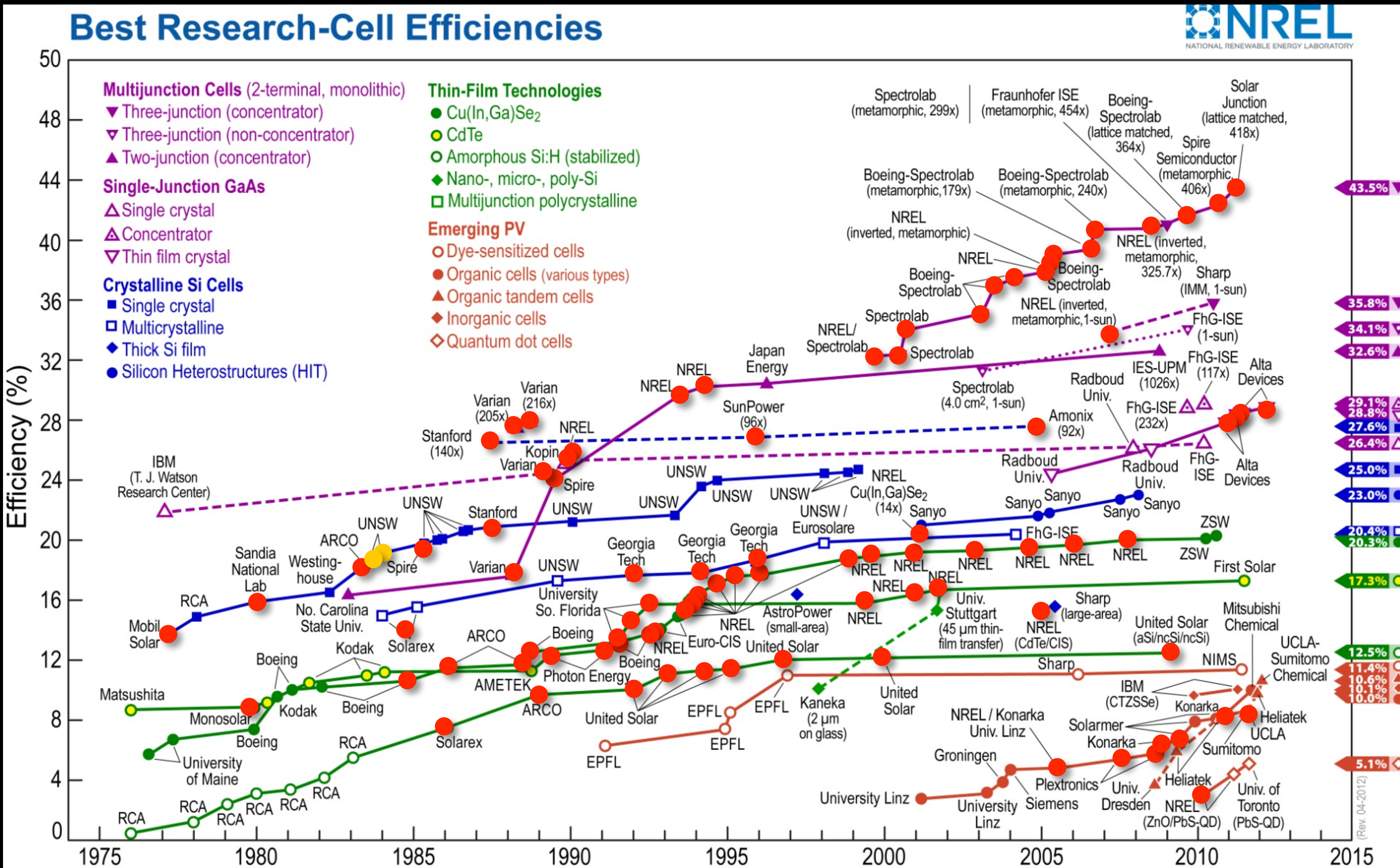
SunShot Program Structure



SunShot PV

Dr. Rebecca Jones-Albertus • Rebecca.Jones-Albertus@doe.gov



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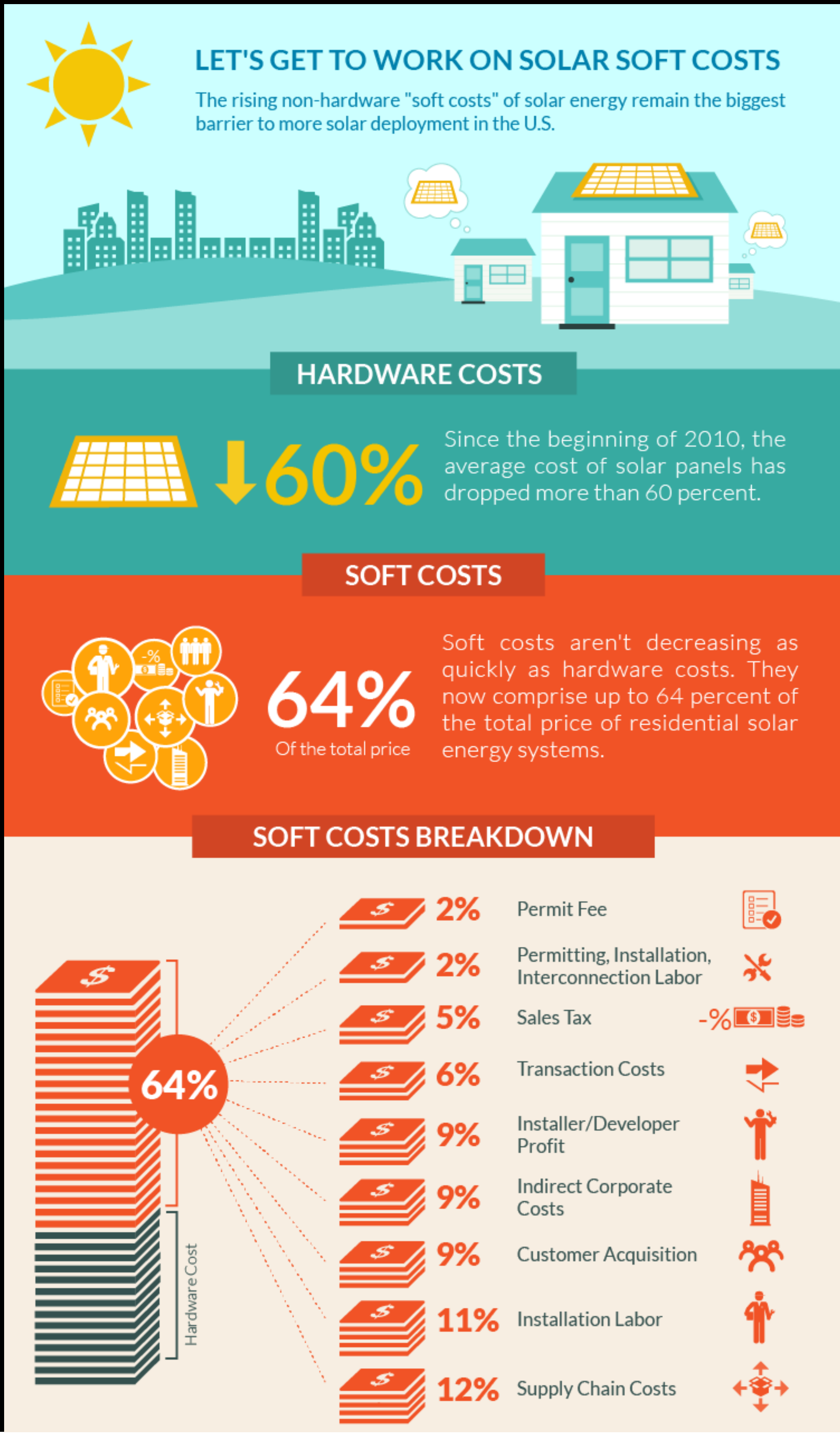
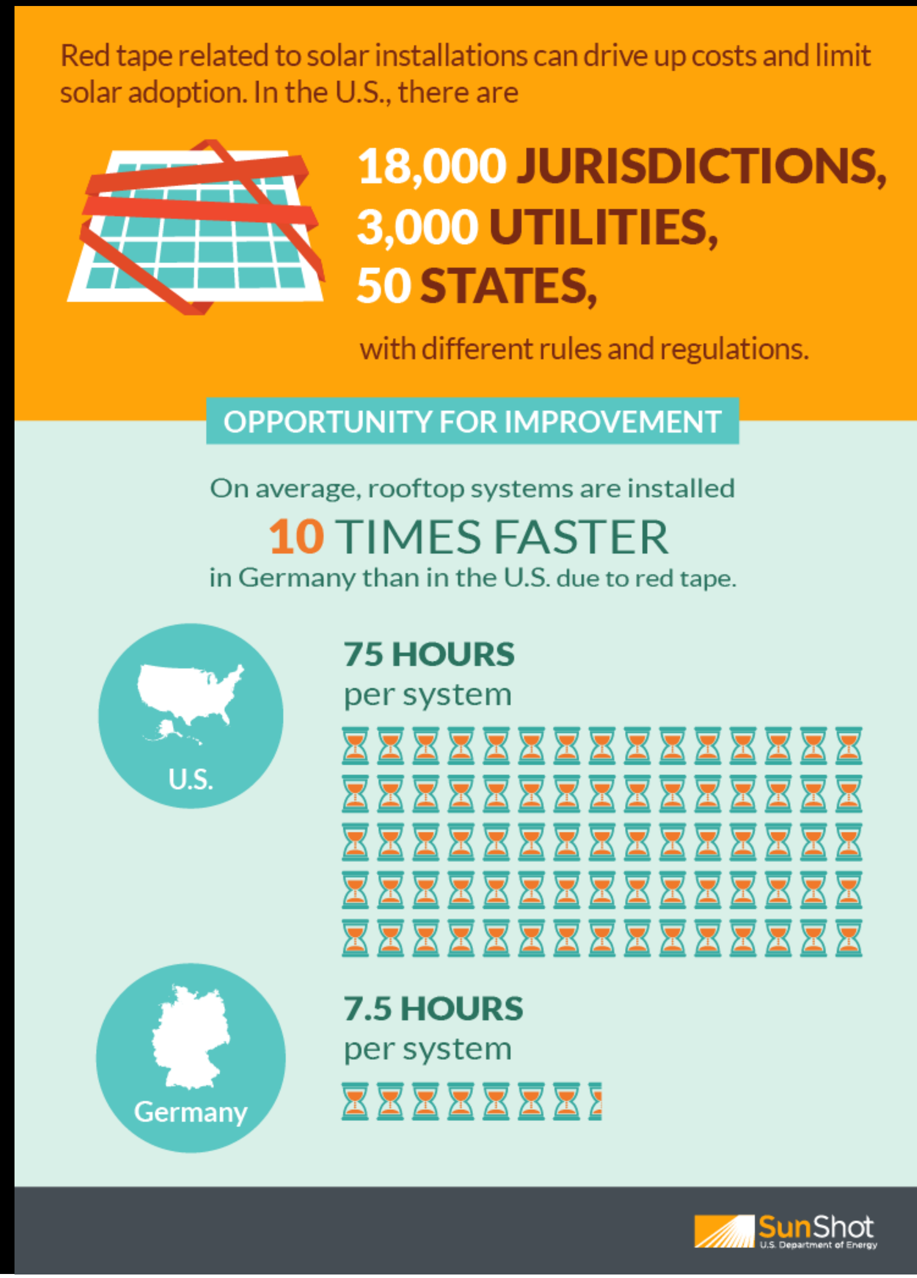
SunShot Soft Costs

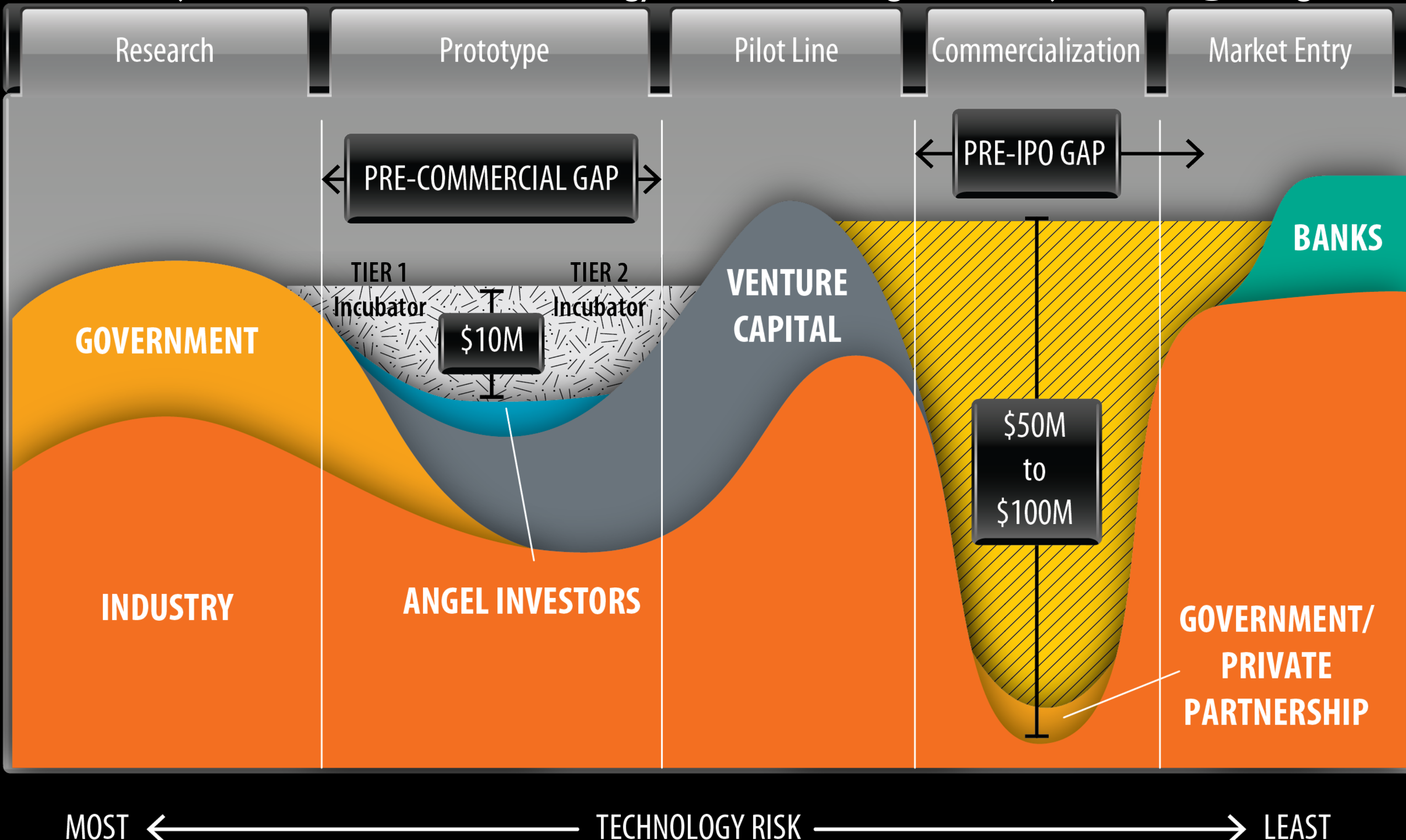
Dr. Elaine Ulrich • Elaine.Ulrich@doe.gov





Incubator: Fill Pre-Commercial Gap

Dr. Lidija Sekaric • SunShot Technology-to-Market Program • Lidija.Sekaric@doe.gov



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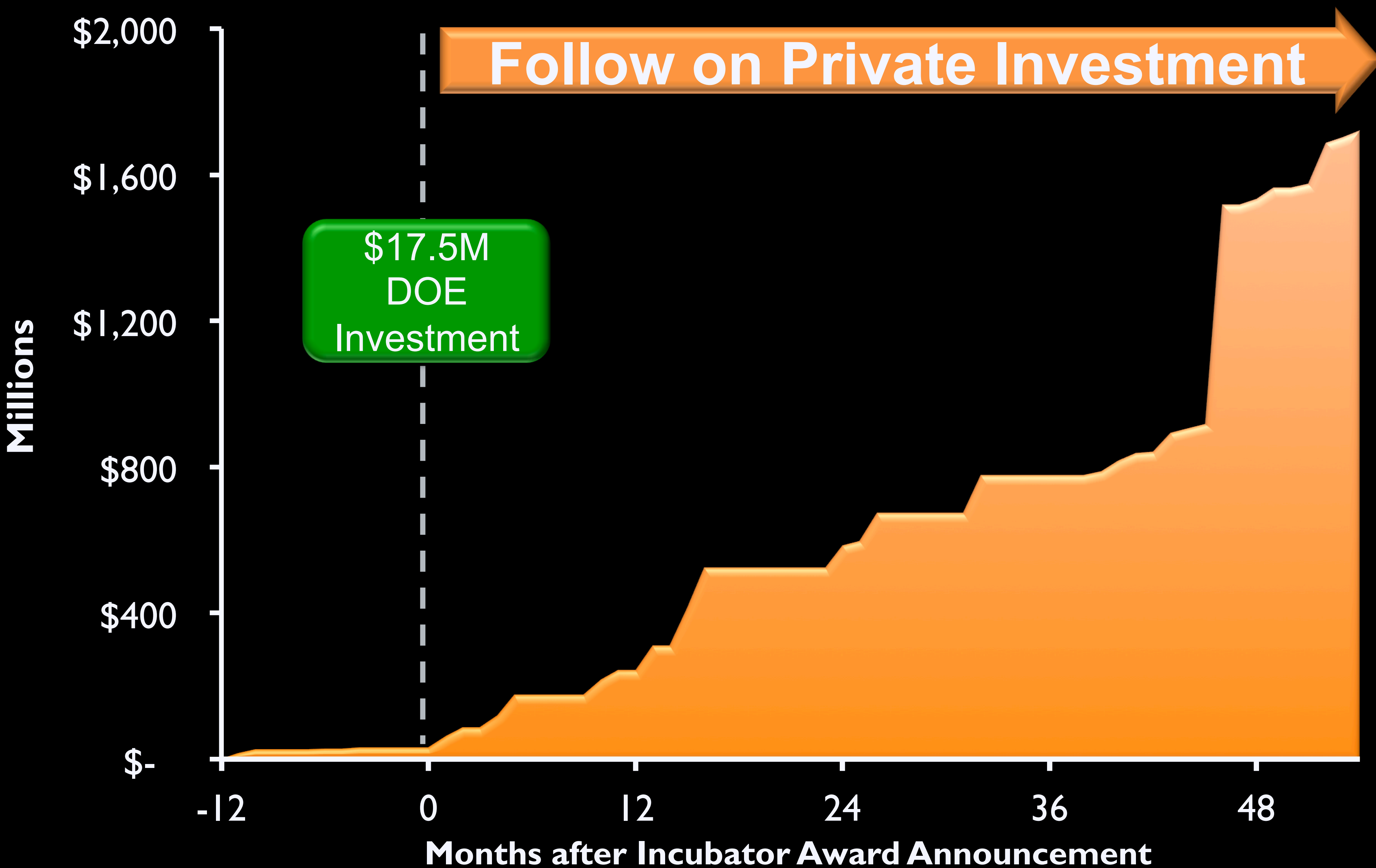
Catalyzing Private Investment

Incubator Round 1 Companies Only



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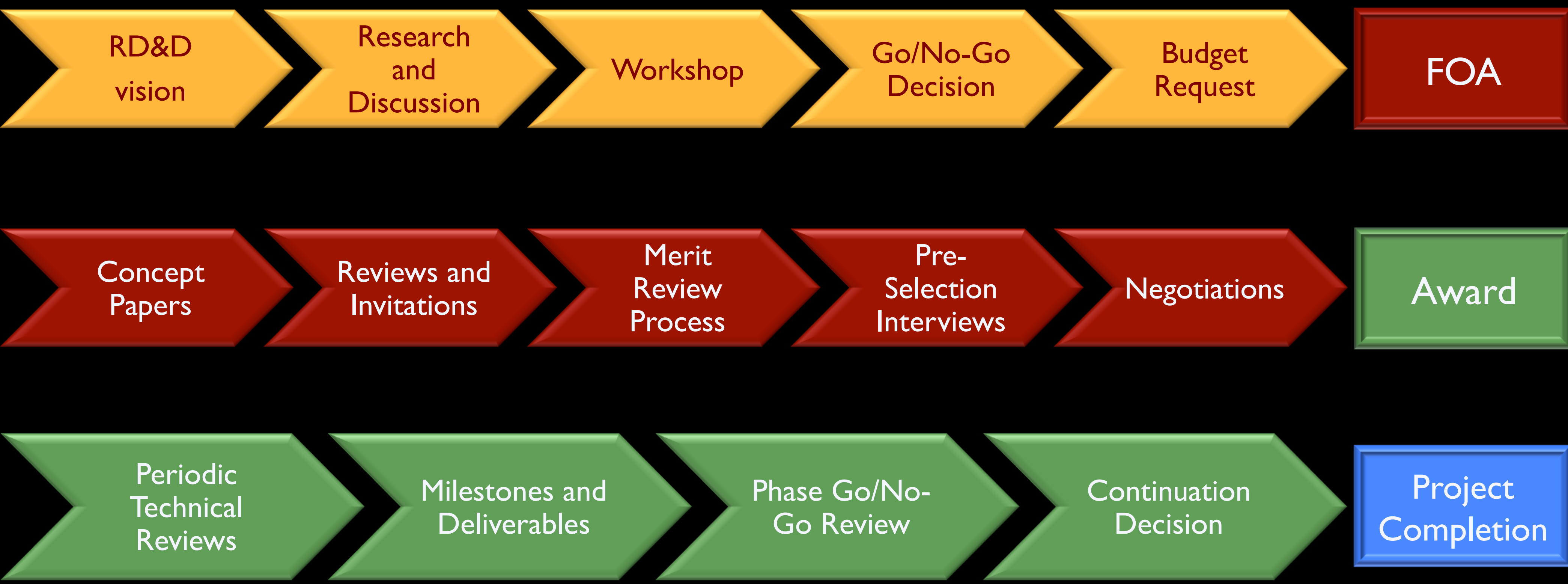
Sources: U.S. Securities and Exchange Commission public filings, Form D (2012); GE press release (2011)

Competitive Funding Process



Concentrating Solar Power

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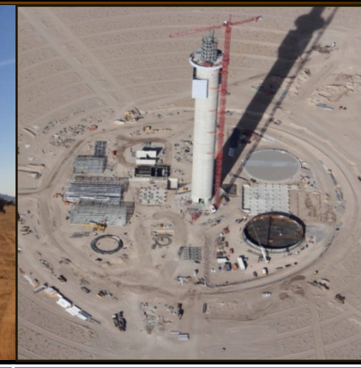
2014: The Resurgence of Big Solar!




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	February 2014	March 2014	March 2015	Late 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

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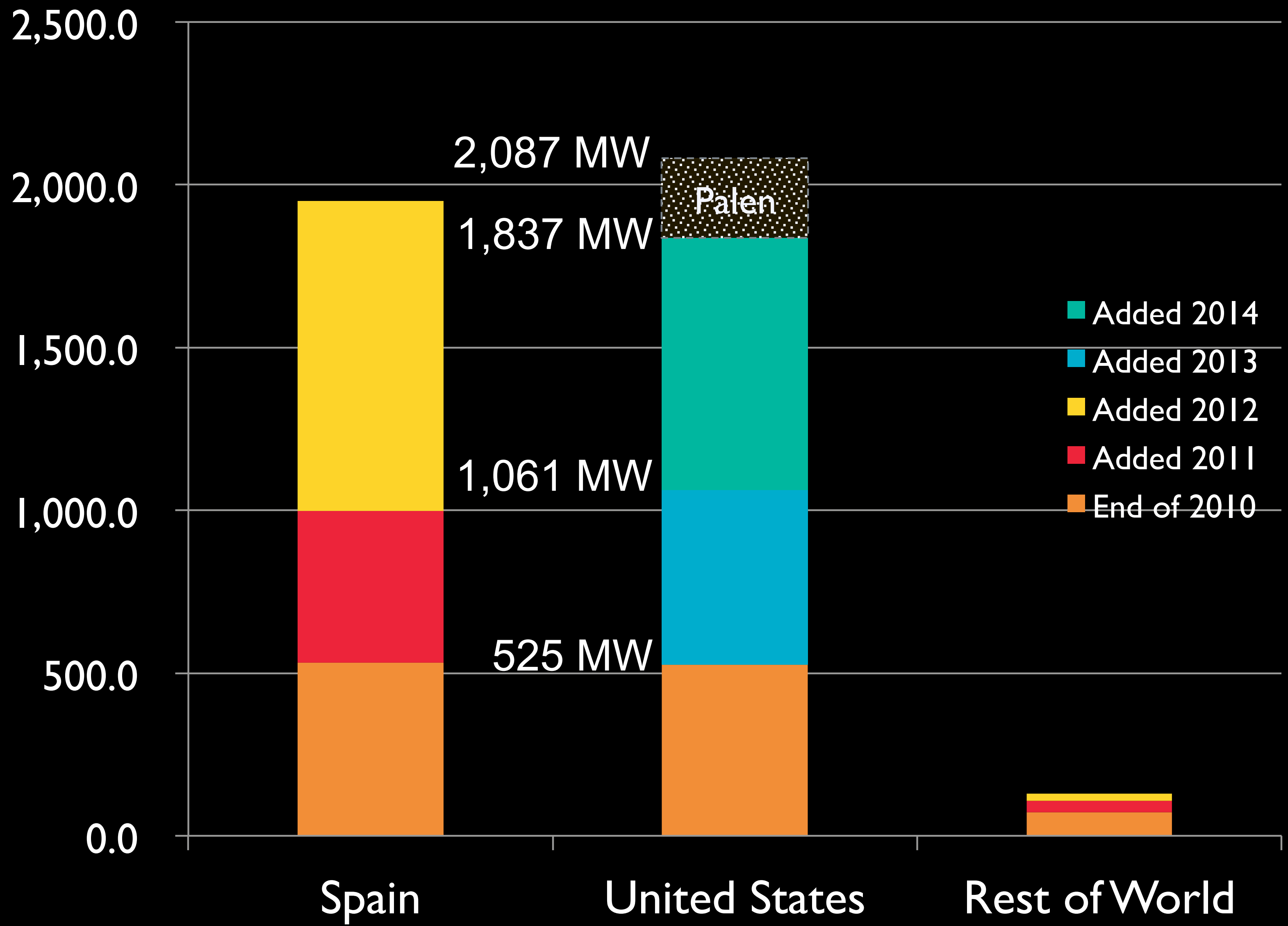
Global CSP Installations



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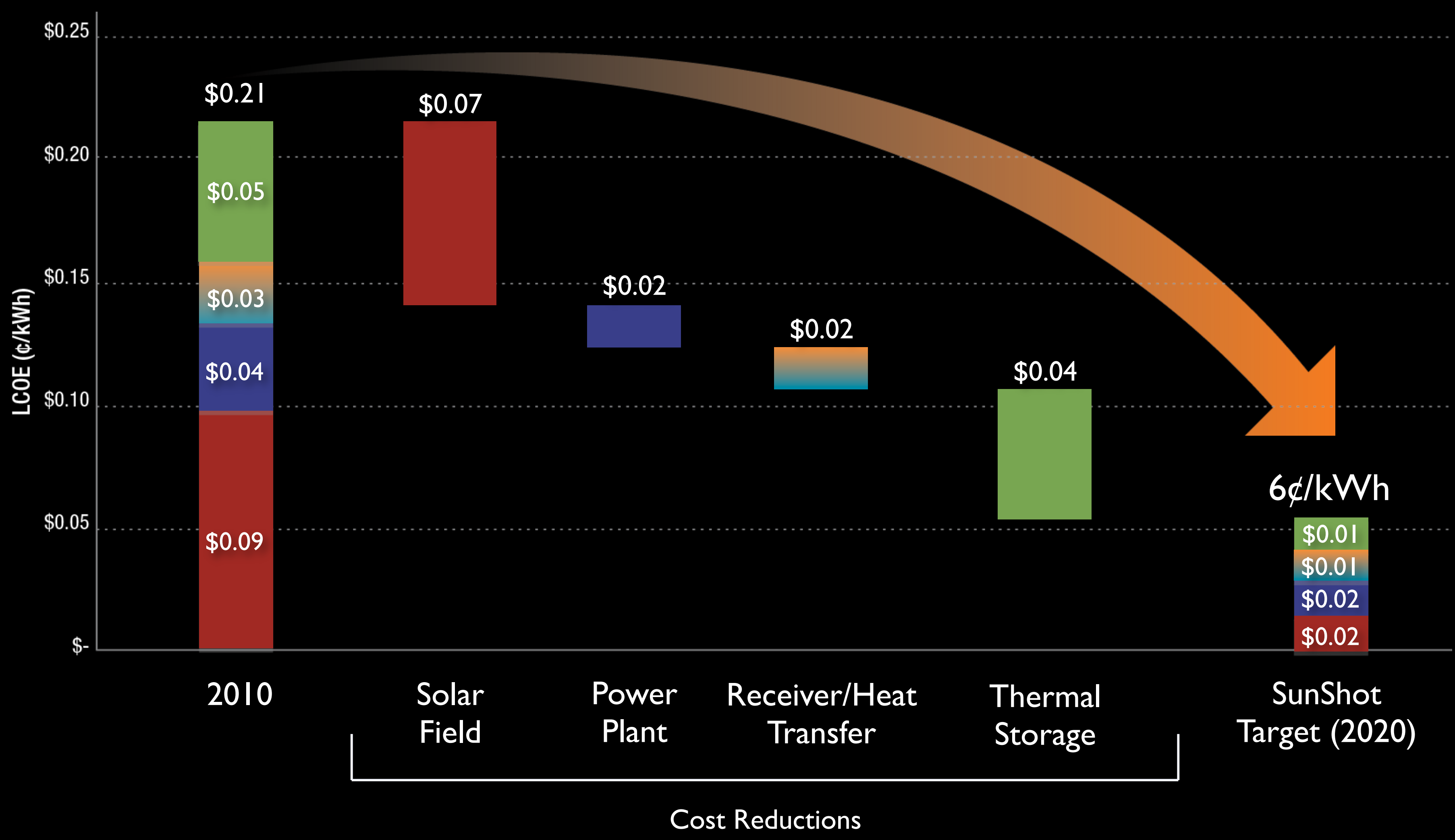
SunShot CSP Goal



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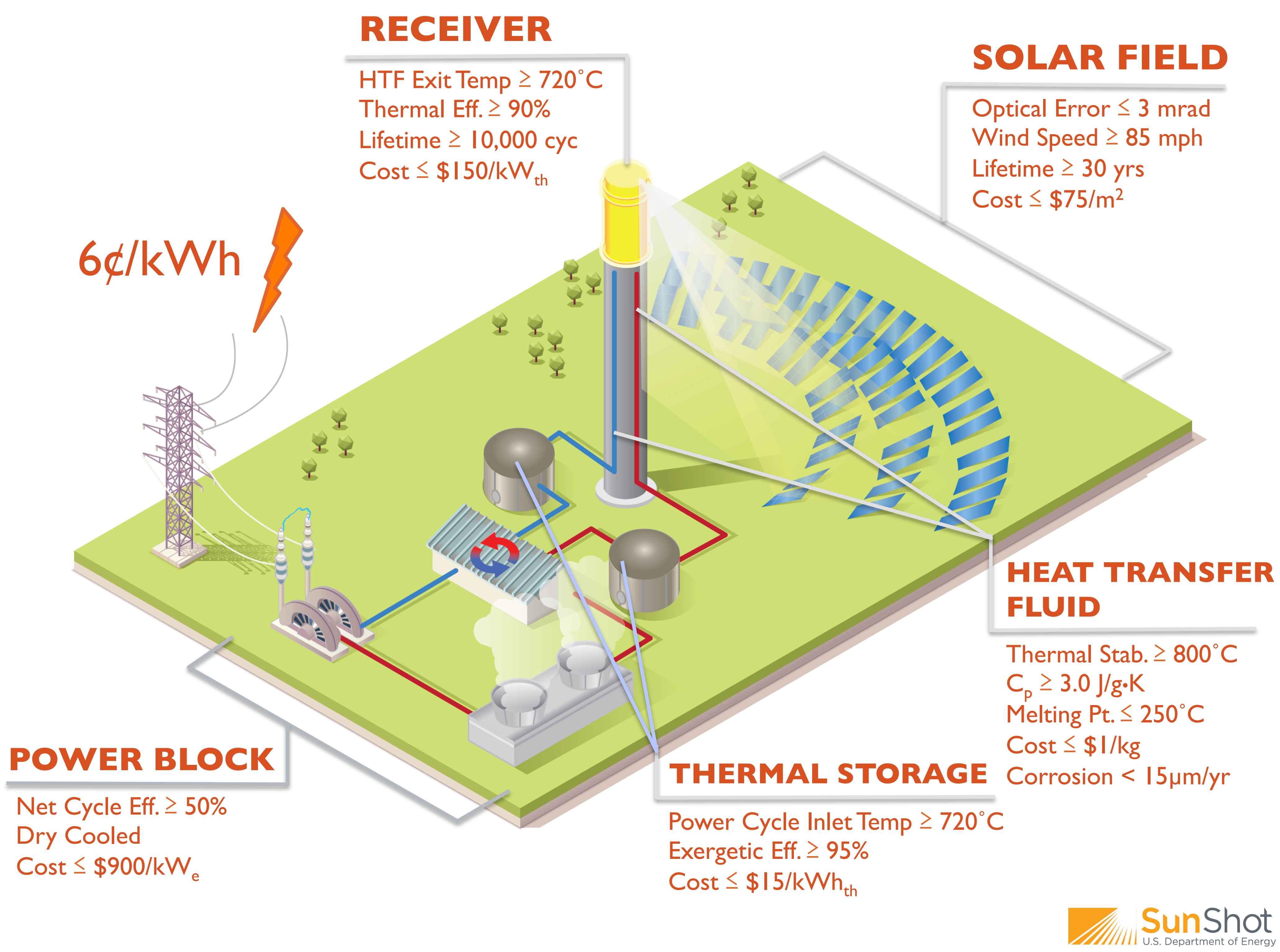
$$\eta = 1 - \frac{T_C}{T_H}$$

Increasing efficiency requires higher temperatures


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
Corrosion < 15μm/yr
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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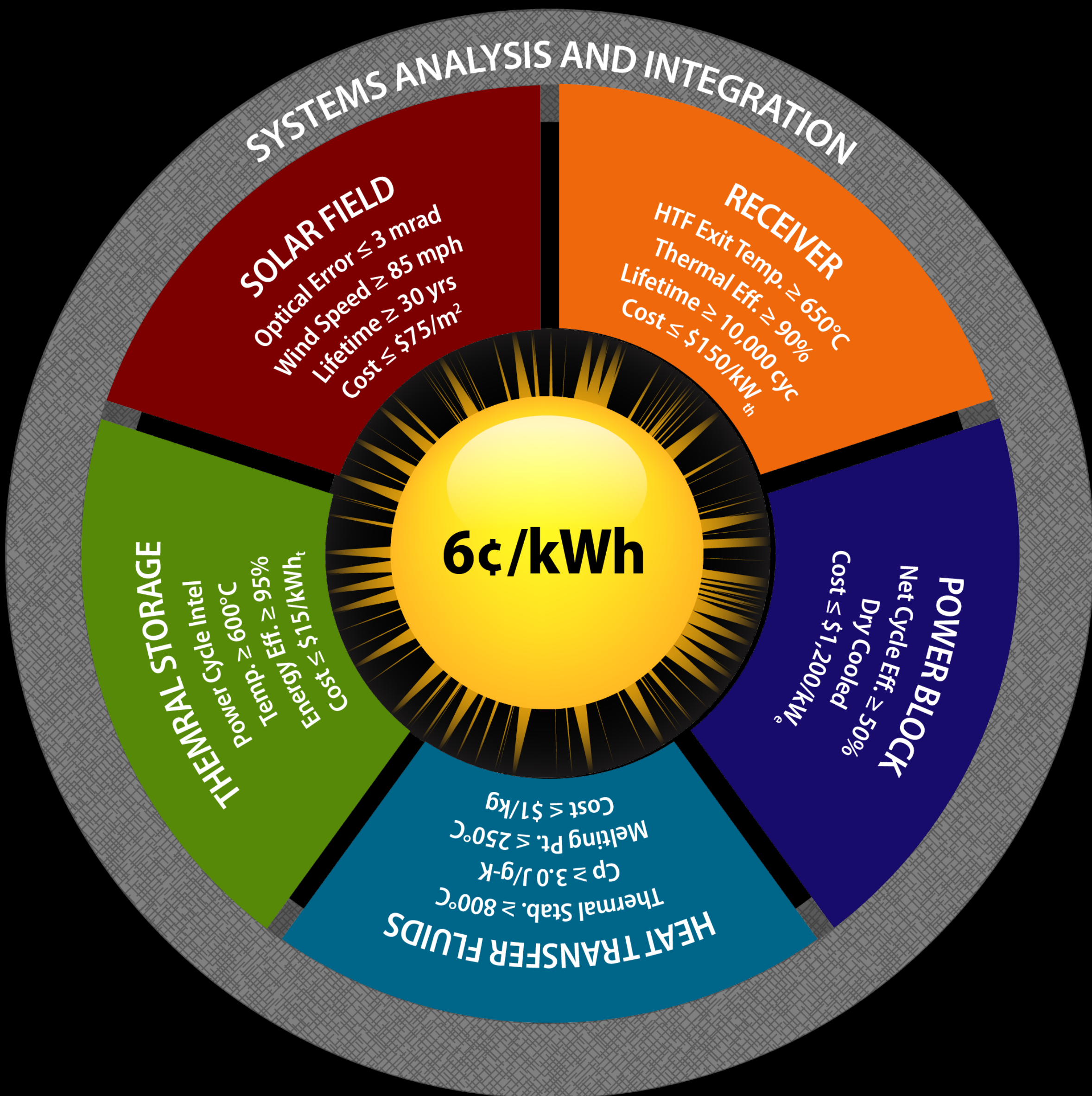
Competitive Initiatives



$30M SuNLaMP (2015)

$25M CSP: APOLLO (2014)

$25M SolarMat II (2014)

$20M CSP: ELEMENTS (2014)

$20M 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)

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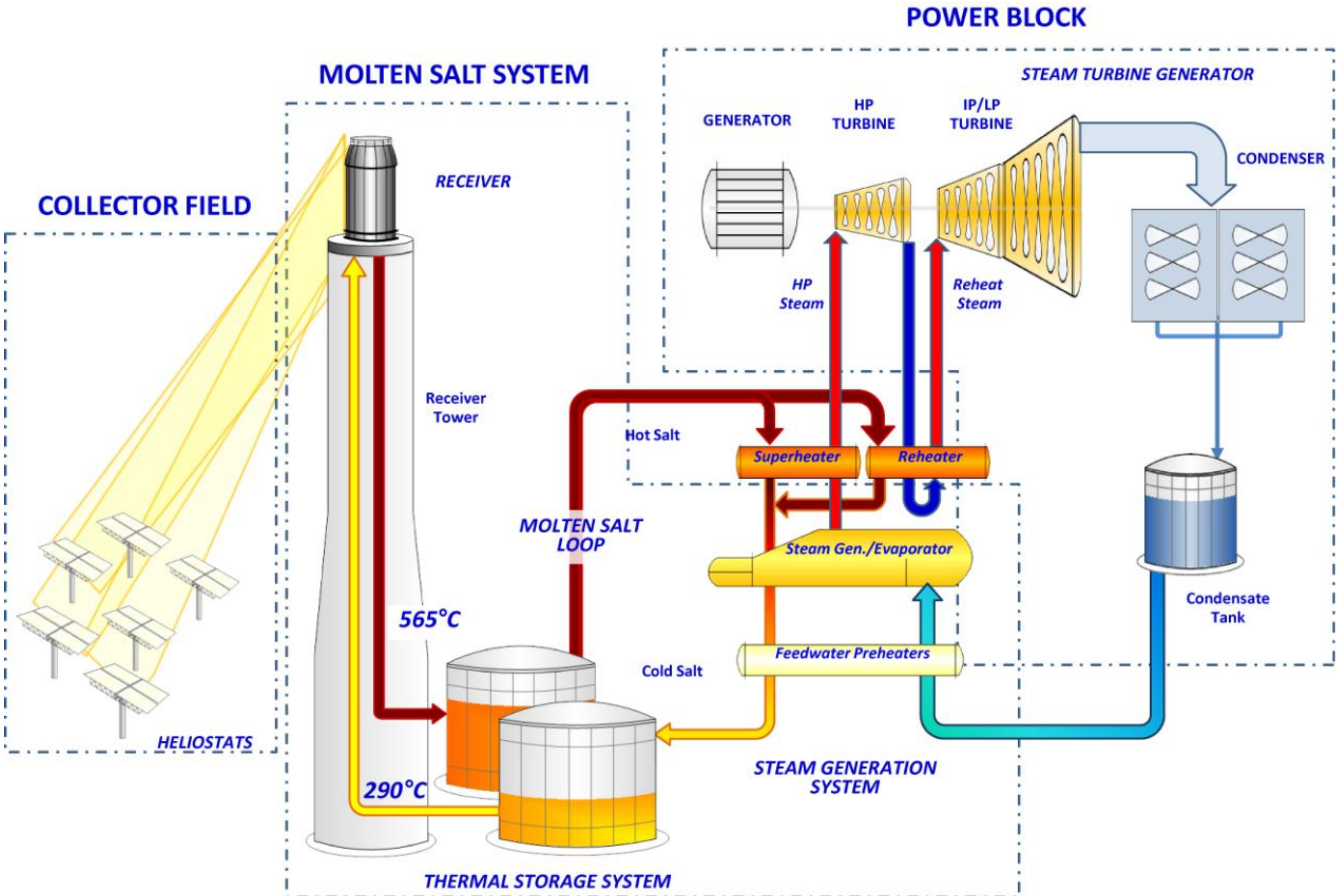

Image: SolarReserve

Collector Field
- Optical Physics
- Structural design and dynamics
- Manufacturing and Automation
- Sensors and control

Receivers
- Optical properties
- Coatings
- High temperature materials
- Chemistry
- Heat Transfer, Fluid Mechanics

TES and HTF
- Chemistry
- High temperature materials
- Materials Science
- Heat Transfer, Fluid Mechanics

Power Block
- High temperature materials
- Turbomachinery
- Chemistry
- Sensors and control

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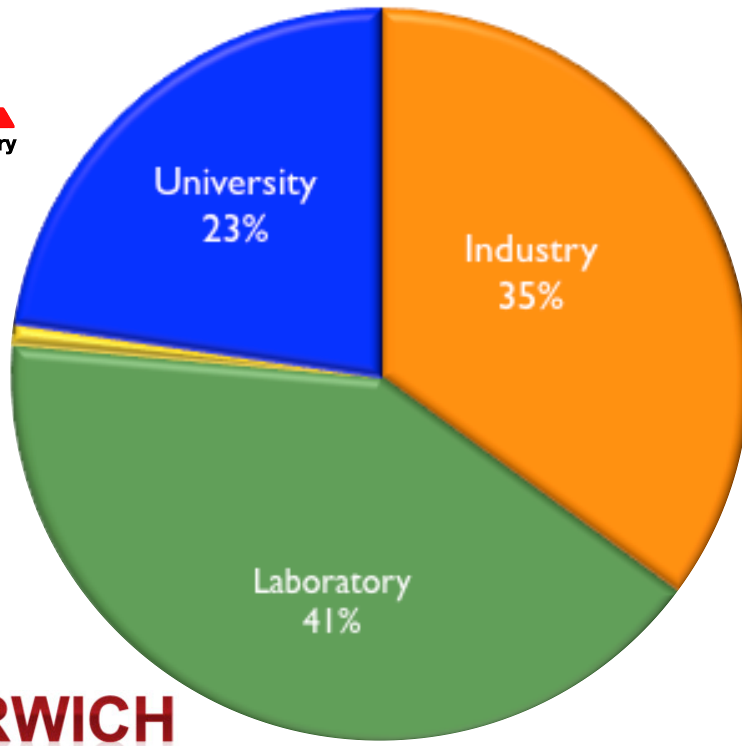


3M

BOSTON UNIVERSITY

Argonne NATIONAL LABORATORY

OSU Oregon State UNIVERSITY

SAN DIEGO STATE UNIVERSITY

Massachusetts Institute of Technology

SwRI

BrightSource

UC San Diego

THE UNIVERSITY OF ARIZONA

BraytonEnergy

SLAC STANFORD UNIVERSITY

Thermata

JPL Jet Propulsion Laboratory

PENNSTATE 1855

Pacific Northwest NATIONAL LABORATORY

SkyFuel

THE UNIVERSITY OF ARIZONA

ASU ARIZONA STATE UNIVERSITY

THE UNIVERSITY OF CALIFORNIA UCLA LET THERE BE LIGHT

SMUD

Georgia Tech

THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT

Yale UNIVERSITY

NORWICH Technologies

CU

Solaflect Energy The concentrated solar energy solution

GE

SRNL SAVANNAH RIVER NATIONAL LABORATORY

NREL

Argonne NATIONAL LABORATORY

UF UNIVERSITY of FLORIDA

SOUTHERN RESEARCH INSTITUTE

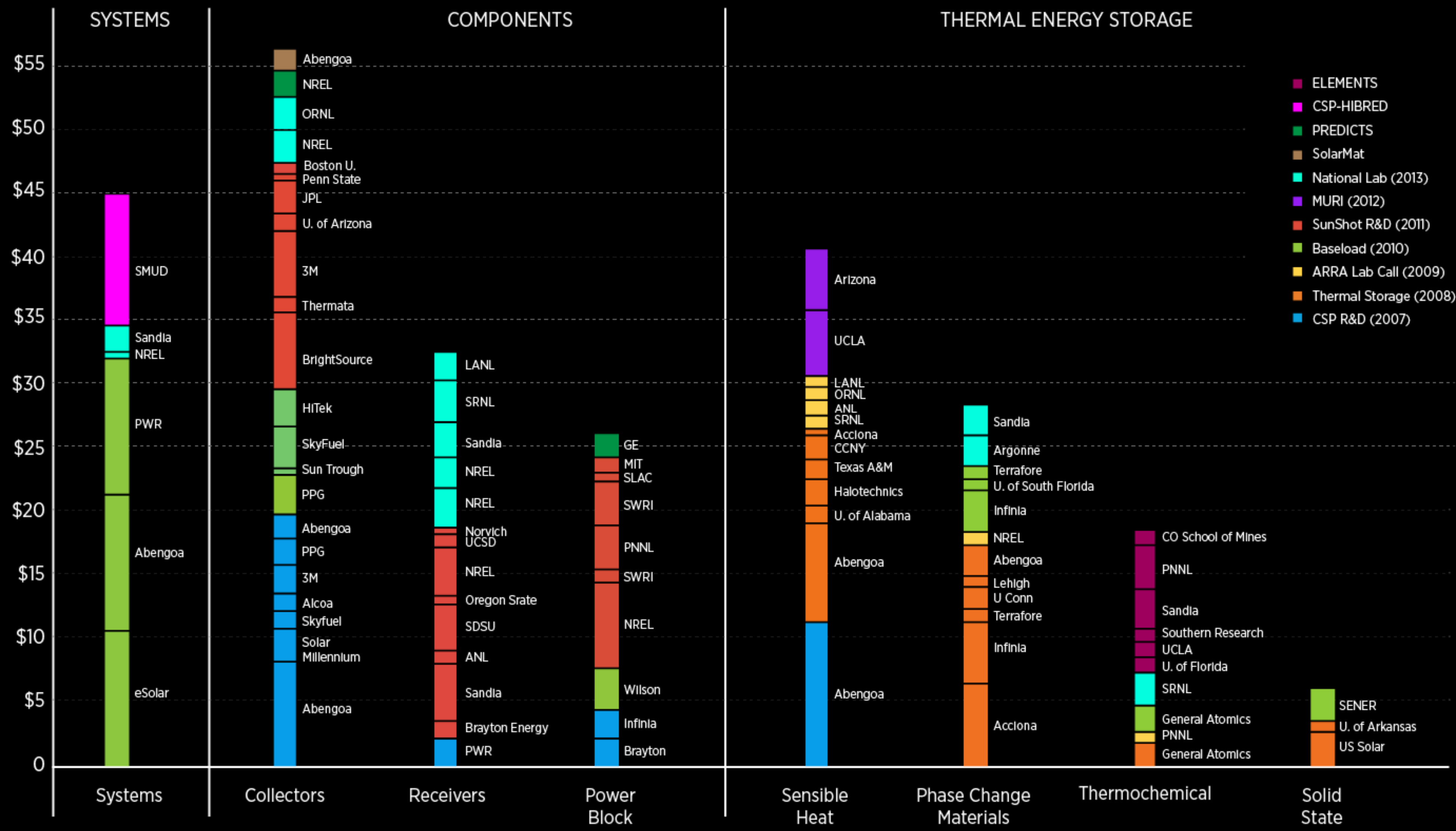
Sandia National Laboratories

OAK RIDGE National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

ABENGOA

COLORADO SCHOOL OF MINES EARTH ENERGY ENVIRONMENT



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Solar Field

Technical Objectives

- ❑ Dramatically reduce the cost of the collector field while improving or maintaining optical efficiency
  - ❑ Cost < $75/m^2 (compare to 2010 ~$250-$300/m^2)
  - ❑ Optical Error < 3 mrad
  - ❑ Sustain wind speed > 85 mph
  - ❑ Lifetime > 30 years

Approaches

- ❑ Develop high optical accuracy reflectors
- ❑ Reduce collector structure weight and material
- ❑ Develop lean and rapid manufacture, assembly and installation methods
- ❑ Highly efficient tracking and control and accurate metrology tools
- ❑ Strategies to reduce operations and maintenance (O&M) costs

Receivers

Technical Objectives

- ❑ Significantly increase operating temperatures, efficiency and lifetime
  - ❑ HTF exit temperature > 720°C
  - ❑ Thermal efficiency > 90%
  - ❑ Lifetime > 10,000 cycles
  - ❑ Cost < $150/kW$_{th}$

Approaches

- ❑ Develop novel solar selective coatings
- ❑ Develop fundamentally new receiver designs

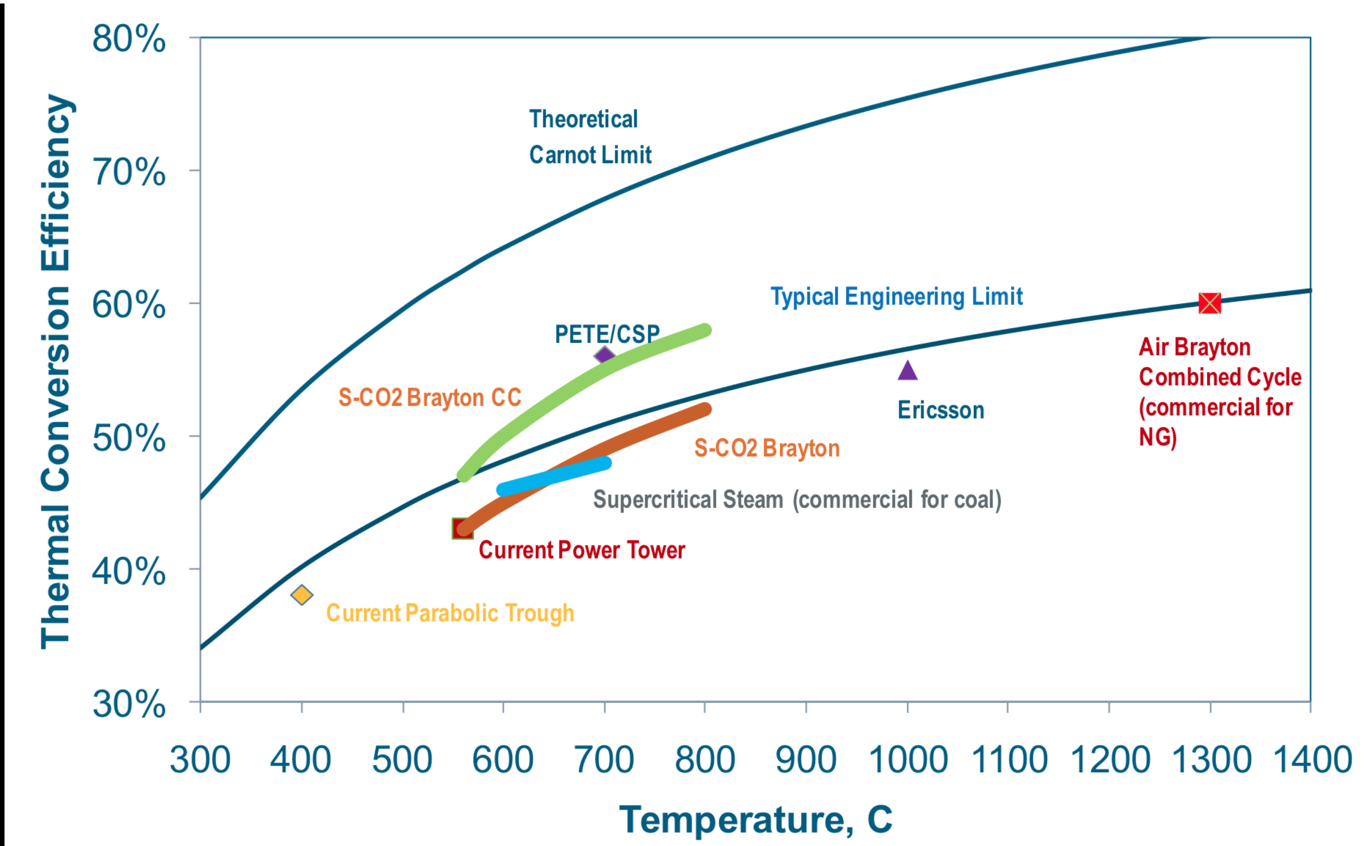
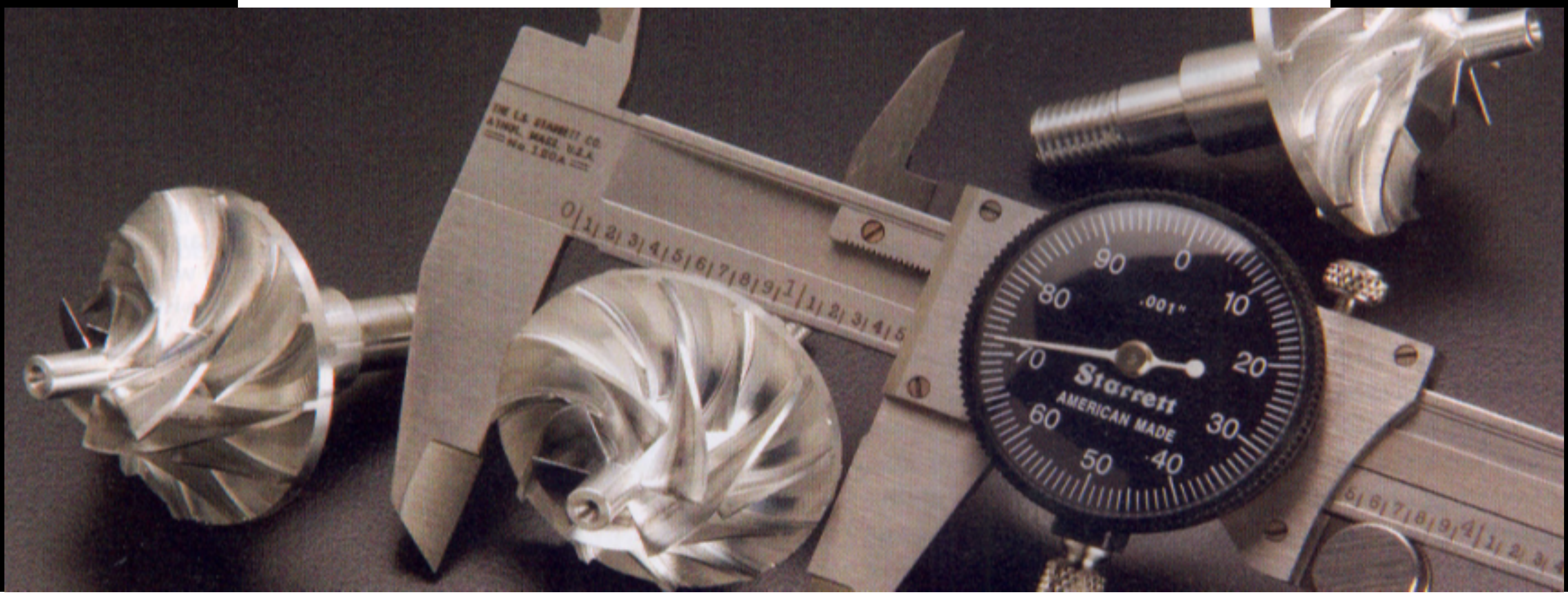
Power Conversion

Technical Objectives

- High temperature power cycles
- Net Cycle Efficiency > 50%
- Dry cooled
- Cost < $900/kW_e$

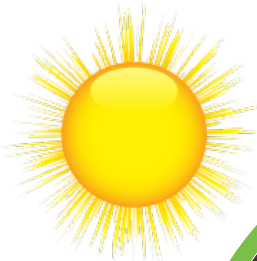
Approaches

- High temperature power cycles
- Solid state power conversion techniques
- Hybrid cycles


Thermal Conversion Efficiency
80%
70%
60%
50%
40%
30%
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Temperature, C
Theoretical
Carnot Limit
Typical Engineering Limit
PETE/CSP
S-CO2 Brayton CC
S-CO2 Brayton
Supercritical Steam (commercial for coal)
Current Power Tower
Current Parabolic Trough
Ericsson
Air Brayton
Combined Cycle
(commercial for
NG)

.001"
Starrett
AMERICAN MADE

Broad Relevance

Size = 10–250 MW_e
T = 500–1000 °C
p = 35 MPa



Size = 10–300 MW_e
T = 350–700 °C
p = 20–35 MPa

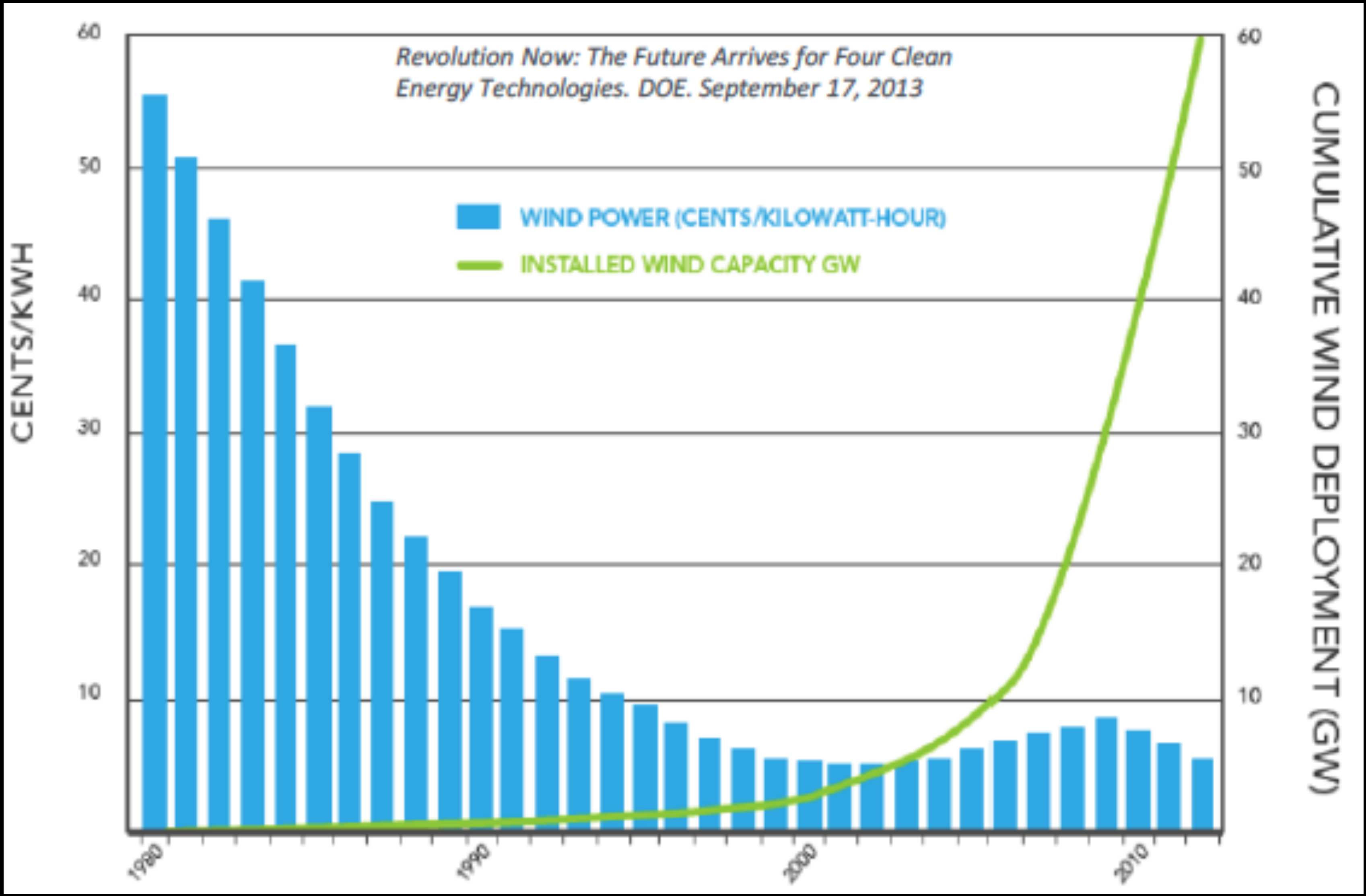
Size = 1–50 MW_e
T = 100–300 °C
p = 25 MPa

Size = 300–600 MW_e
T = 550–900; 1100–1500 °C
p = 15–35 MPa

<u>Shipboard Power and Propulsion</u>
Size = <1–100 MW_e
T = 230–1000 °C
p = 15–35 MPa

<u>Waste Heat Recovery</u>
Size = 1–10 MW_e
T = <230–650 °C
p = 15–35 MPa

Renewables are here and fast growing!



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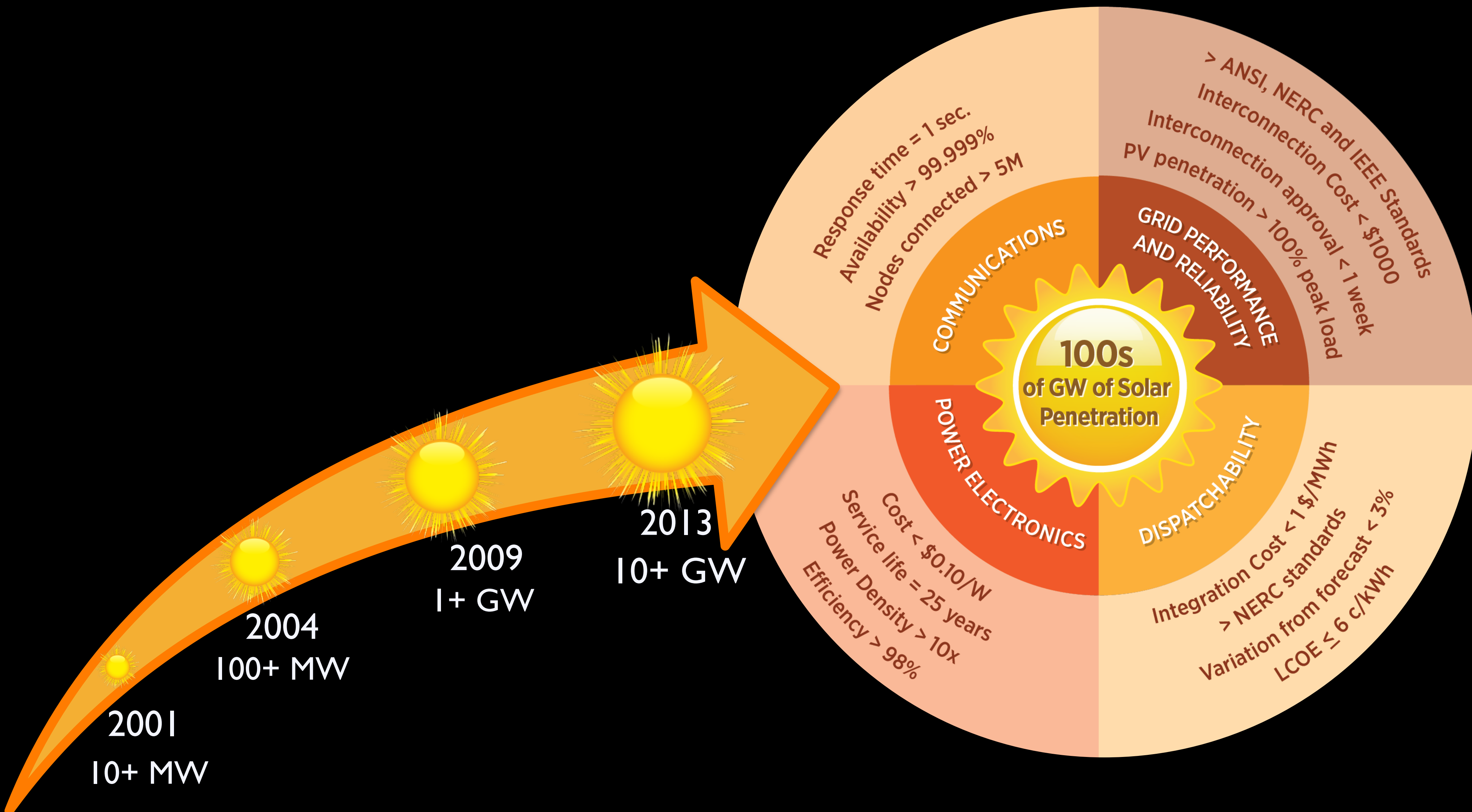
Systems Integration Challenges



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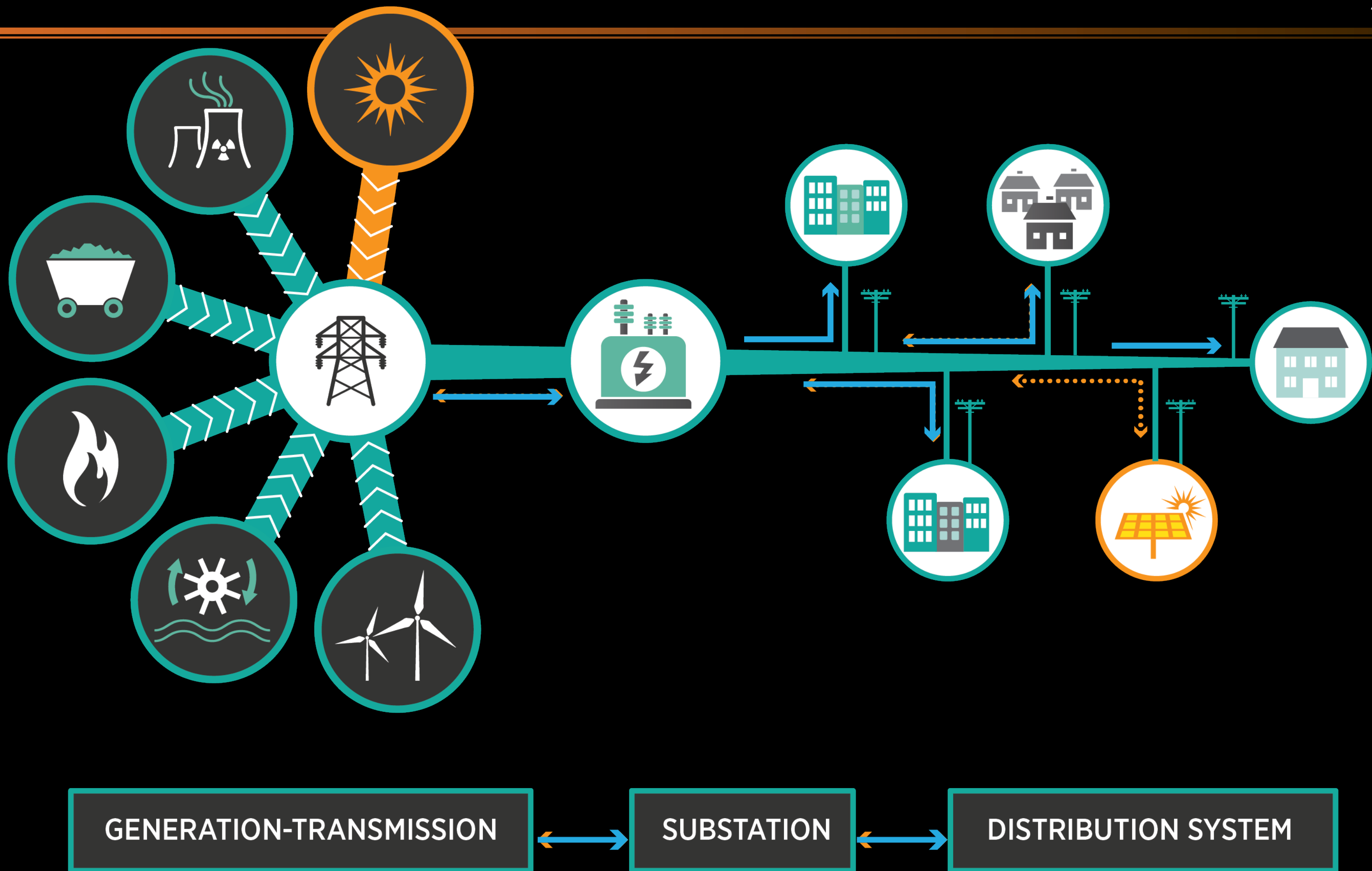
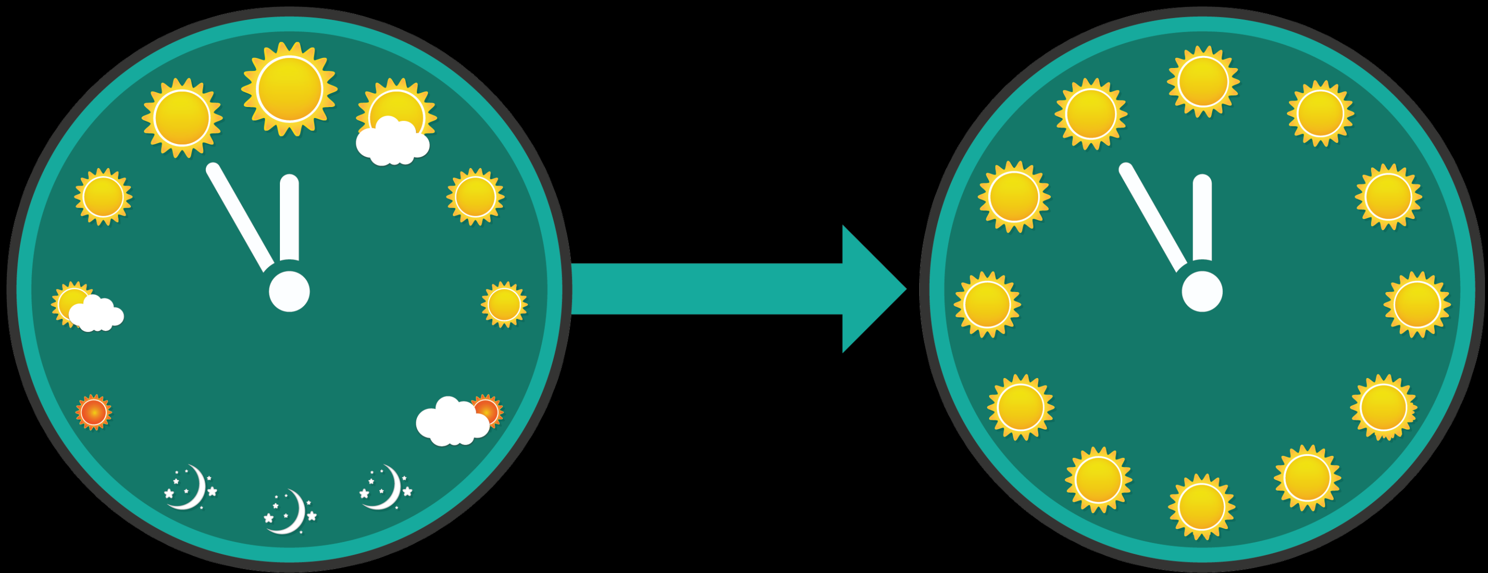
Grid Performance and Reliability



Addresses technical and regulatory challenges of integrating high penetration of solar generation at the transmission and distribution levels in a cost-effective manner, while ensuring safety and reliability of the electric grid

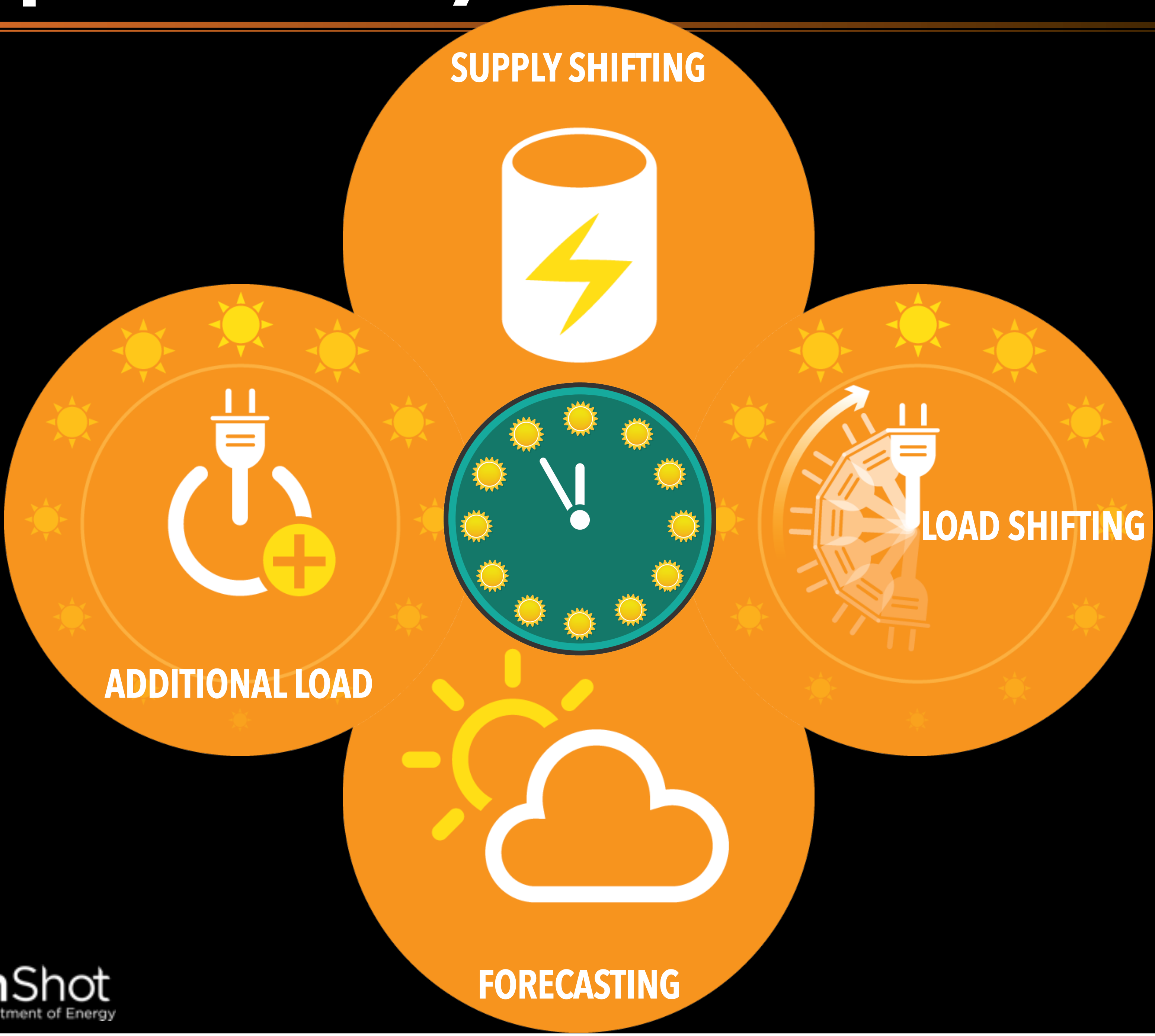
Dispatchability



INTERMITTENT SOLAR → **DISPATCHABLE SOLAR**

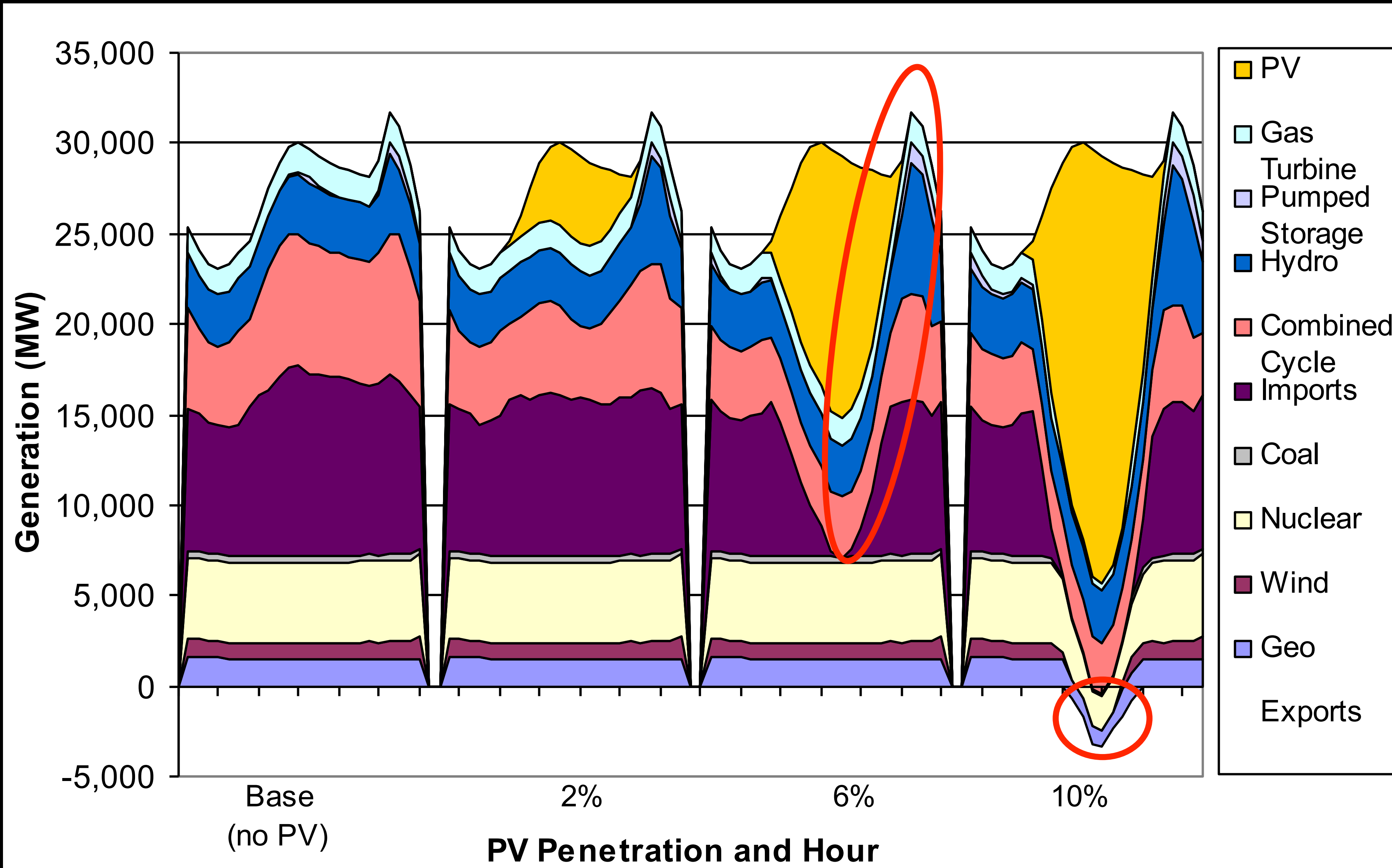
- Ensure that solar power plants based on PV and CSP technologies at utility and distributed scales are capable of being dispatched in a fashion that is comparable to or better than conventional power plants.
- Remove the costs currently associated with integrating solar PV plants into the power grid and assuring high predictability of the power output from these plants to achieve the goal of minimal curtailment and broad temporal and spatial availability of electricity generated from solar energy.

Dispatchability Solution Set



CSP with Thermal Energy Storage: A Dispatchability Option

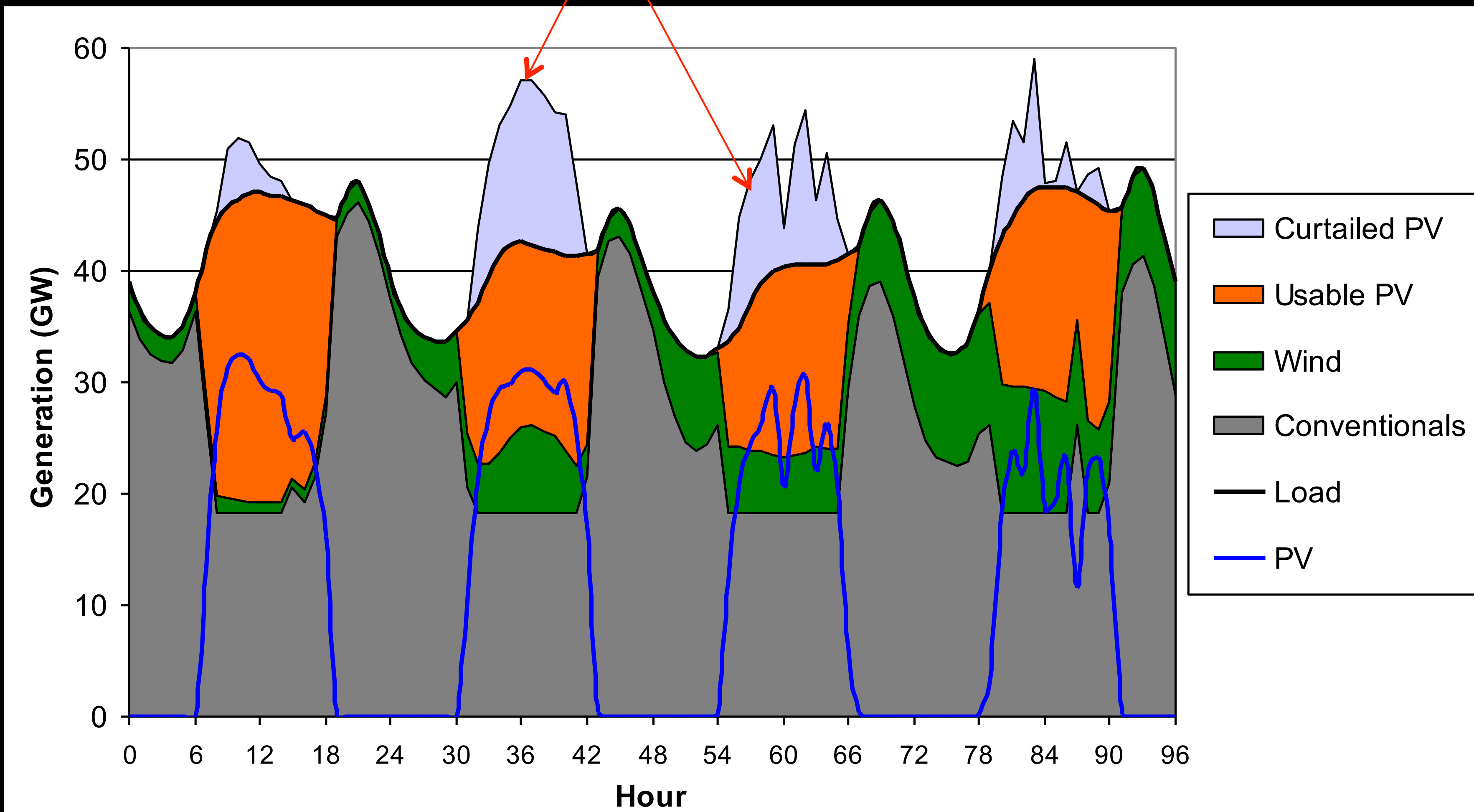
Excessive Ramp Rates and Minimum Load Constraints



Denholm, et al., (2011)

Simulated WECC system dispatch for spring day with 20% contribution from PV

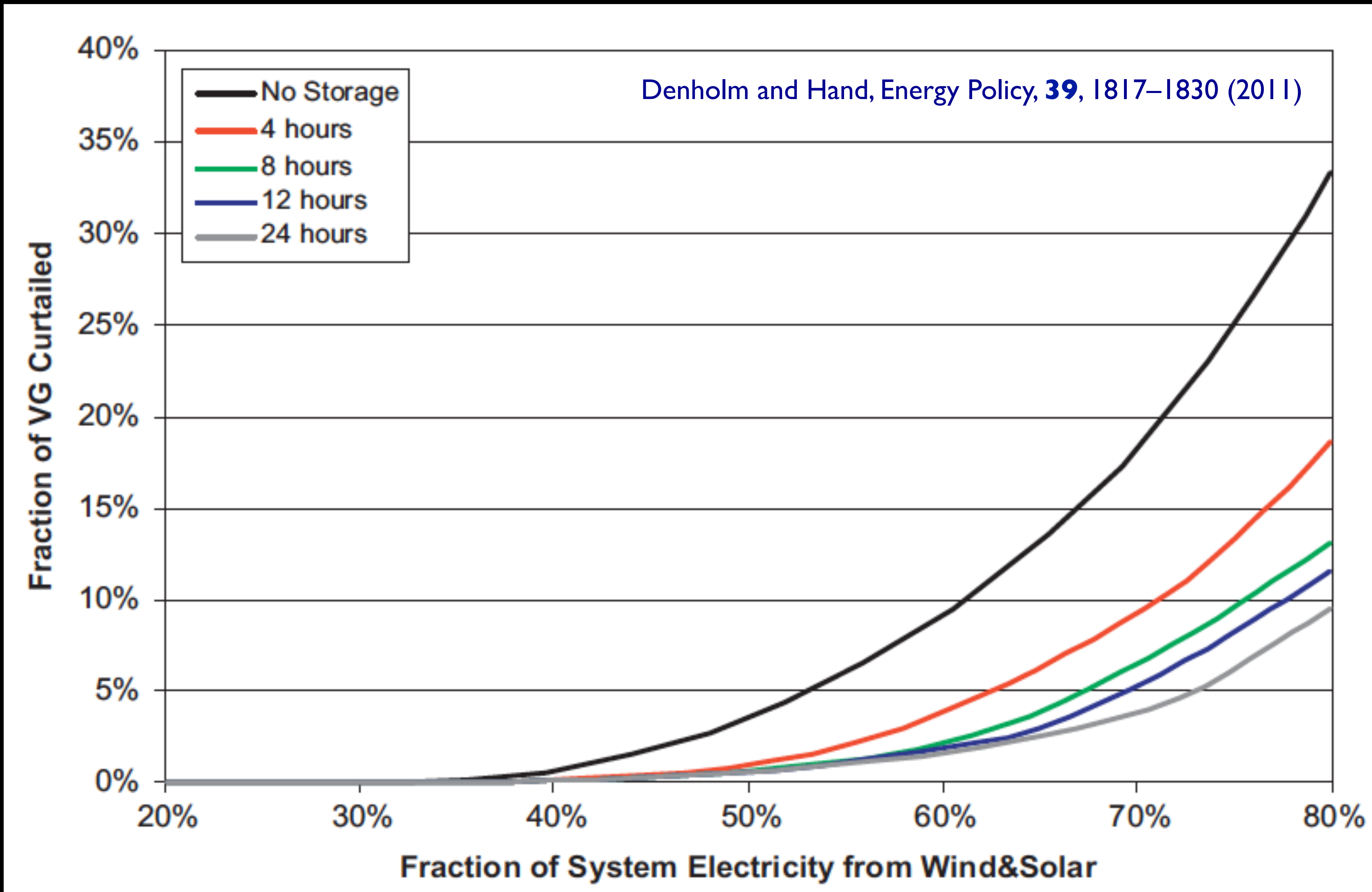
Curtailed PV based on assumed grid-flexibility



Denholm, et al., (2011)

SunShot U.S. Department of Energy

Greater grid flexibility provided by CSP with storage results in increased penetration of solar and wind



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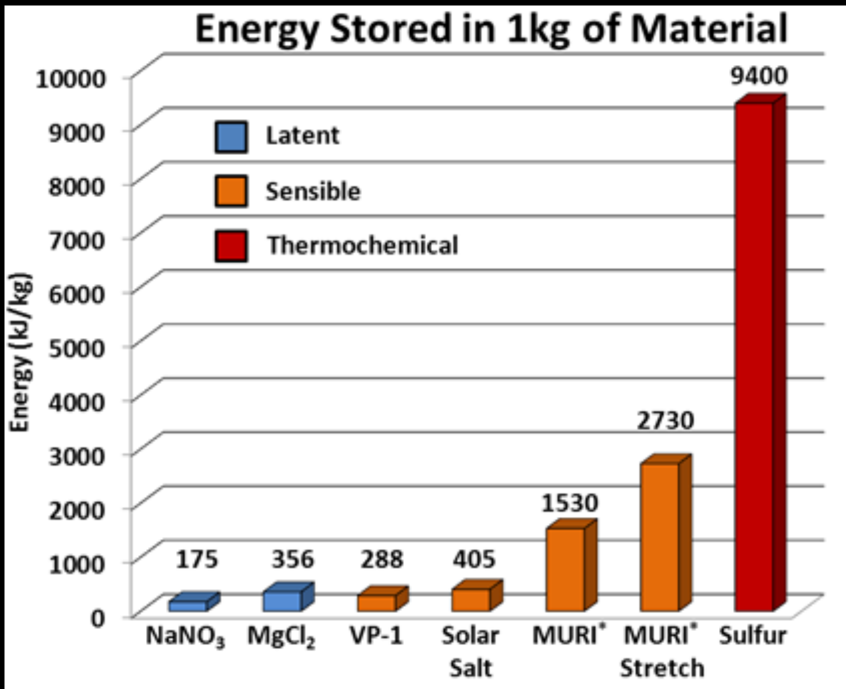
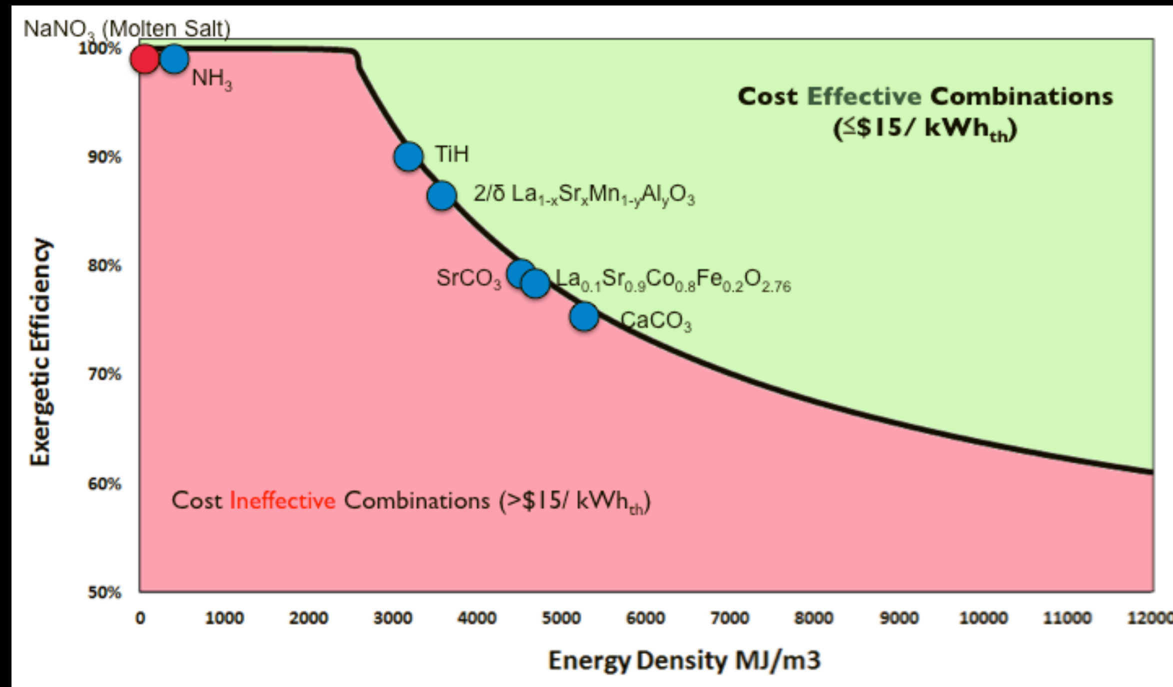
Storing Sun's Energy in Chemical Bonds:

Thermochemical Energy Storage for Concentrating Solar Power





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

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SunShot CSP in the News

ASME ENERGY FORUM

SOLAR PODCAST

PODCAST: CONCENTRATING SOLAR POWER - PART 1

PODCAST: CONCENTRATING SOLAR POWER - PART 2

PODCAST: CONCENTRATING SOLAR POWER - PART 3

SOLAR VIDEO

VIDEO: R&D ENGINEERS AND CONCENTRATING SOLAR POWER

The New York Times

New Solar Process Gets More Out of Natural Gas

April 10, 2013

CSP World

Fulfilling the Promise of Concentrating Solar Power

May 2013

Solar Industry

October 3, 2013

The DOE Contemplates The Dawn Of Global CSP

Solar Power World

Technology • Development • Installation

Concentrated Solar Power Gets A Huge Boost

October 10, 2013

IOM³ The Institute of Materials, Minerals and Mining

MW MATERIALS WORLD

Feb 1, 2014

Self-cleaning solar panels – ditching the dirt

CSP to benefit as the world's appetite for storage increases (Jun 13, 2014) social.csptoday.com/technology/csp-benefit-world's-appetite-storage-increases

DOE Says CSP Plus Thermal Storage Adds Value By Avoiding Costs (Jun 10, 2014) http://solarindustrymag.com/e107_plugins/content/content.php?content.14218

SunShot Solar CSP (Jun 9, 2014) videos.tdworld.com/video/SunShot-Solar-CSP

NREL finds up to 6-cent per kilowatt-hour extra value with concentrated solar power (Jun 9, 2014) sciencecodex.com/nrel_finds_up_to_6cent_per_kilowatthour_extra_value_with_concentrated_solar_power-135370

SunShot Awards $10 Million For Chemical-Based Thermal Storage Technologies For CSP Plants (May 30, 2014) http://www.solarindustrymag.com/e107_plugins/content/content.php?content.14188

Two innovative technologies to cut the cost of energy storage (May 30, 2014) social.csptoday.com/technology/two-innovative-technologies-cut-cost-energy-storage

DOE Awards $10 Million for Concentrating Solar Power Storage Research (May 23, 2014) www.renewableenergyworld.com/rea/news/article/2014/05/doe-awards-10-million-for-concentrating-solar-power-storage-research

SunShot CSP Professional Outreach

JULY 14–19 2013 Minneapolis, MN
ASME 2013 7th International Conference on Energy Sustainability
ASME 2013 11th Fuel Cell Science, Engineering and Technology Conference

JUNE 30–JULY 2, 2014 • BOSTON, MA
ASME 2014 8TH INTERNATIONAL CONFERENCE ON ENERGY SUSTAINABILITY
co-located with the ASME 2014 12TH FUEL CELL SCIENCE, ENGINEERING & TECHNOLOGY CONFERENCE

SunShot Symposium • Mark Lausten, Chair

- Goal: To reach a broader community than our awardee base on the SunShot goals.
- Initiated in 2012 with 3 sessions, extremely popular and well attended.
- Symposium at the 2013 conference included 5 sessions.
- Continues to grow in 2014 and 2015

SPIE Solar Energy + Technology
SPIE Optics+Photonics

San Diego Convention Center
San Diego, California, United States
17 - 21 August 2014

High and Low Concentrator Systems for Solar Energy Applications IX

Conference Chairs
Adam P. Plesniak, Amonix Inc. (United States)
Candace Pfefferkorn, SunShot Initiative, U.S. Dept. of Energy (United States)

Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 00 (2013) 000–000
ELSEVIER
Energy
Procedia
www.elsevier.com/locate/procedia

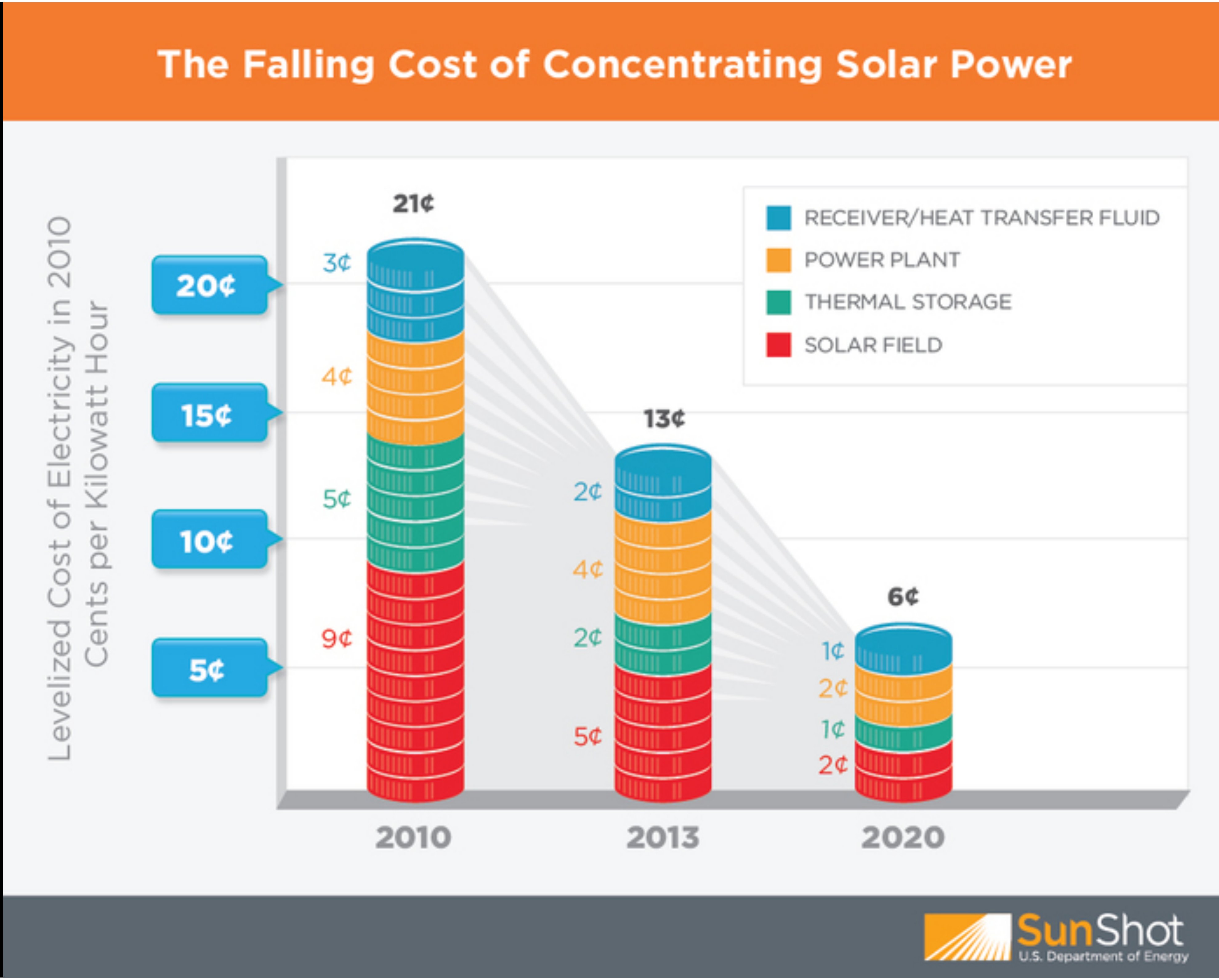
SolarPACES 2013

Proceedings of the SolarPACES 2013 International Conference

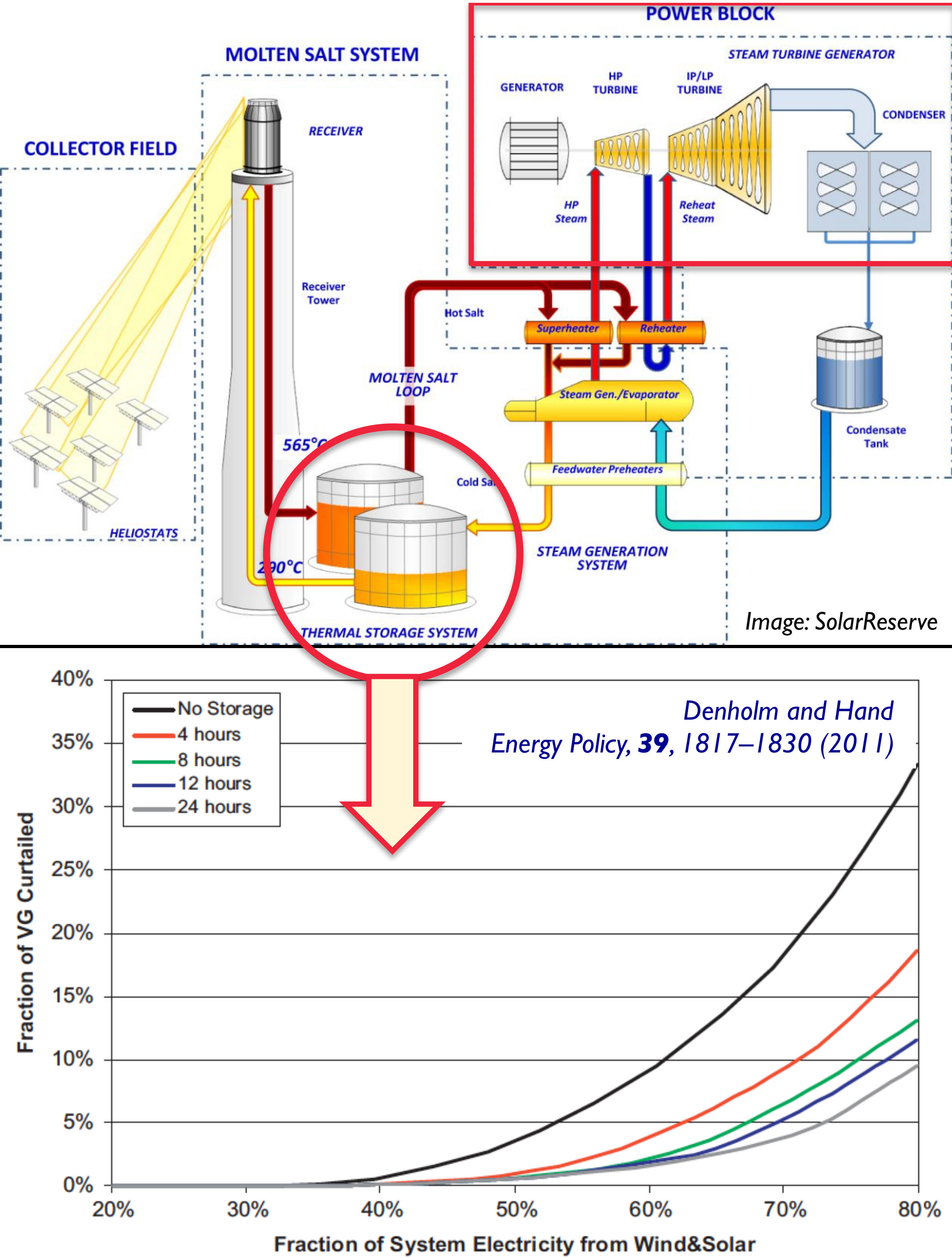
Ranga Pitchumani
Chair, SolarPACES 2013 International Conference

- Chaired and Organized by SunShot CSP Team
- 700 attendees
- 20 Plenary Speakers
- 40 Technical Sessions
- 320 Technical Paper Presentations (Oral + Poster)
- An open access edited proceedings volume of 264 peer-reviewed papers (2,532 pp.) published online in Elsevier's *Energy Procedia* *www.sciencedirect.com/science/journal/18766102/49*

Over 66% Progress towards 2020 SunShot goals



The Falling Cost of Concentrating Solar Power
Levelized Cost of Electricity in 2010 Cents per Kilowatt Hour
20¢
15¢
10¢
5¢
21¢
3¢
4¢
5¢
9¢
13¢
2¢
4¢
2¢
5¢
6¢
1¢
2¢
1¢
2¢
RECEIVER/HEAT TRANSFER FLUID
POWER PLANT
THERMAL STORAGE
SOLAR FIELD
2010
2013
2020
SunShot
U.S. Department of Energy



Thermal Energy Storage

- Inexpensive storage (2010: $27/ kWh)
- Provides for several hours of operation even when the sun is not shining
- Provides for greater incorporation of variable generators on the grid

CSP-Fossil Hybrid

- Provides for synergistic hybridization with fossil fuel power plants

CSP is a key enabling technology in the nation’s future energy generation mix

Ranga Pitchumani

Chief Scientist
ranga.pitchumani@doe.gov

www.solar.energy.gov/sunshot/csp.html
www.solar.energy.gov/sunshot/systems_integration.html
eere-exchange.energy.gov