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ENG 505 ENERGY SURETY AND SYSTEMS

Concentrating Solar Thermal Power Systems

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SANDIA REVIEW & APPROVAL NUMBER

Exceptional service in the national interest

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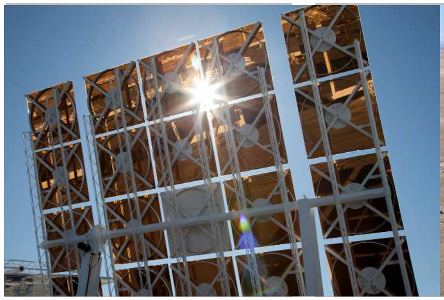

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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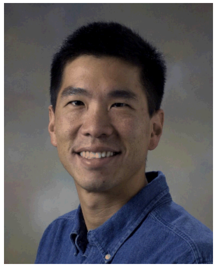
Cliff Ho - Bio



- Ph.D. in Mechanical Engineering from U. California at Berkeley, 1993
- Employee at Sandia since 1993
  - Yucca Mountain Project, microchemical sensors, water surety, solar energy
- Currently work in the concentrating solar technologies group at the solar tower (since 2008)

Outline of Presentation

- **Complex Systems: Definition and Approaches**
- **Concentrating Solar Thermal Power Systems**
  - Introduction and Technology Description
  - Commercial Applications
  - Market and Economics
  - Research Needs / Systems Analysis Example
- **Summary and Review**

Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous elements
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

Recall: Approaches to Complex Systems

- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Complex Adaptive Systems Engineering
- Sandia Software Tools
- Sandia Disciplines

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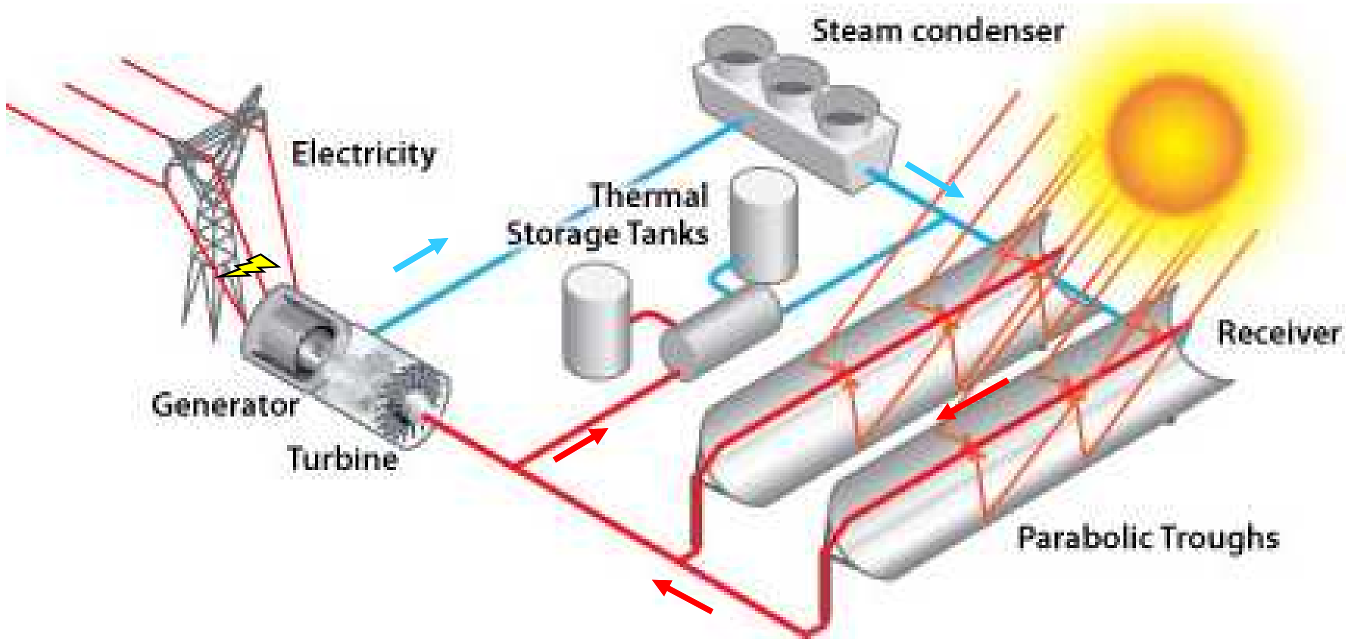
What is CSP?

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to generate steam, which turns a turbine and generator to produce electricity

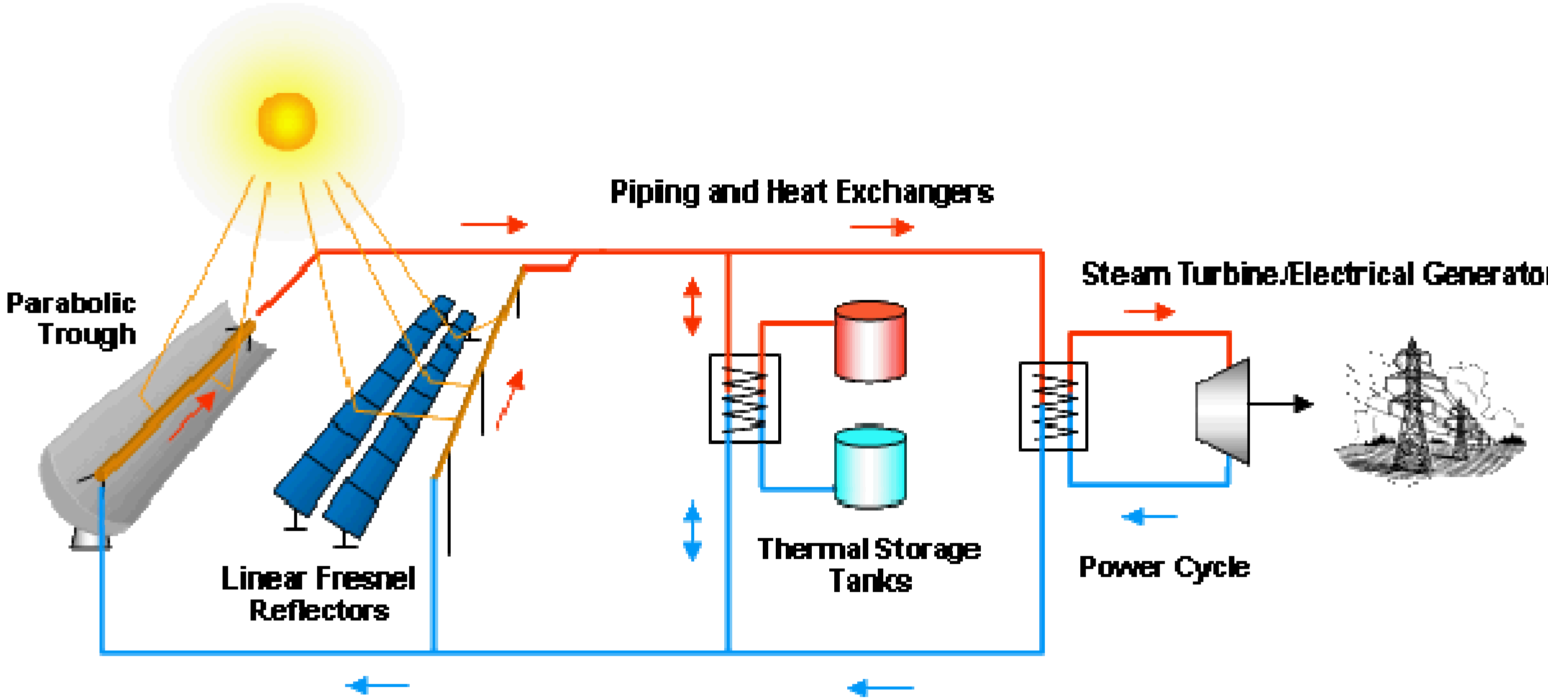


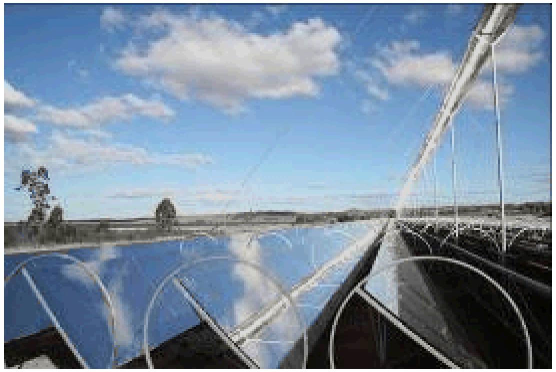
From the U.S. DOE Solar Energy Technologies Program Web Site:
http://www.eere.energy.gov/basics/renewable_energy/linear_concentrator.html

CSP Technologies

- Line Focus
  - Parabolic Troughs
  - Linear Fresnel
- Central Receivers “Power Towers”
- Dish Engines

Line Focus Systems

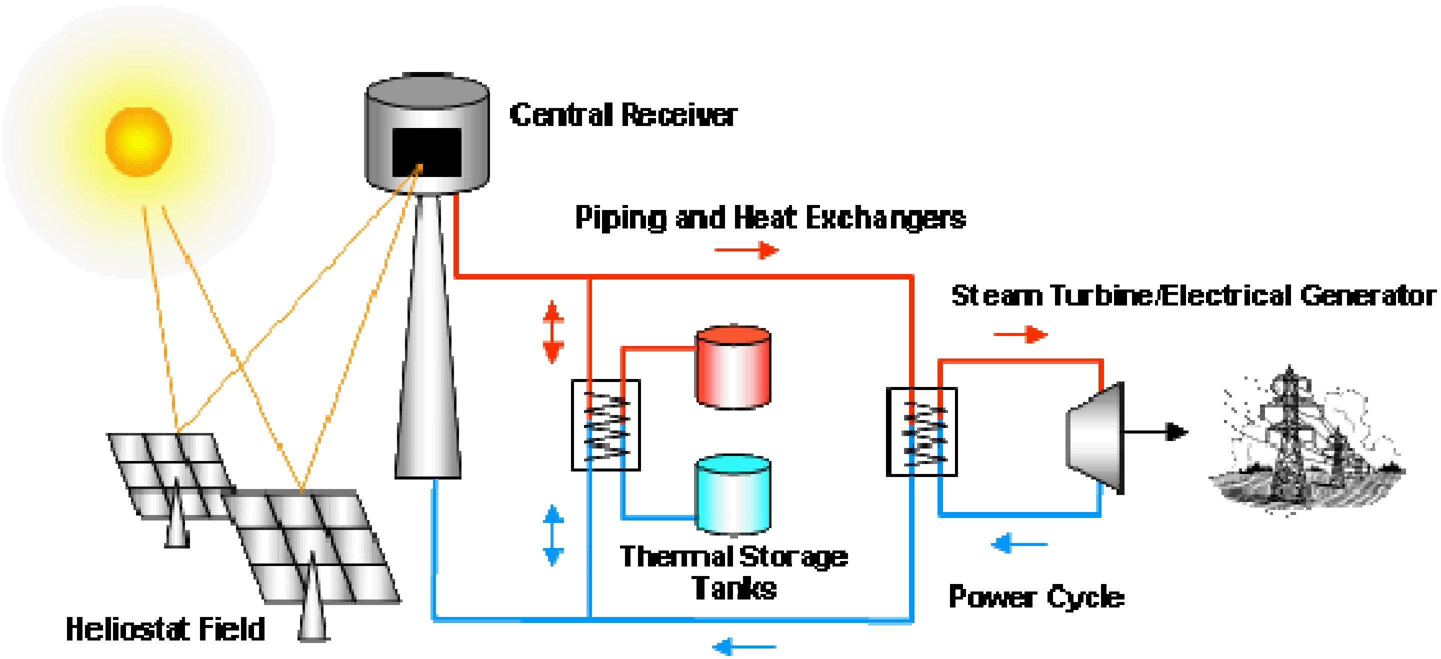




Parabolic trough (left) and linear Fresnel (right) collector systems (photos from http://en.wikipedia.org/wiki/Solar_thermal_energy)

Central Receivers

"Power Towers"



Central Receivers

"Power Towers"

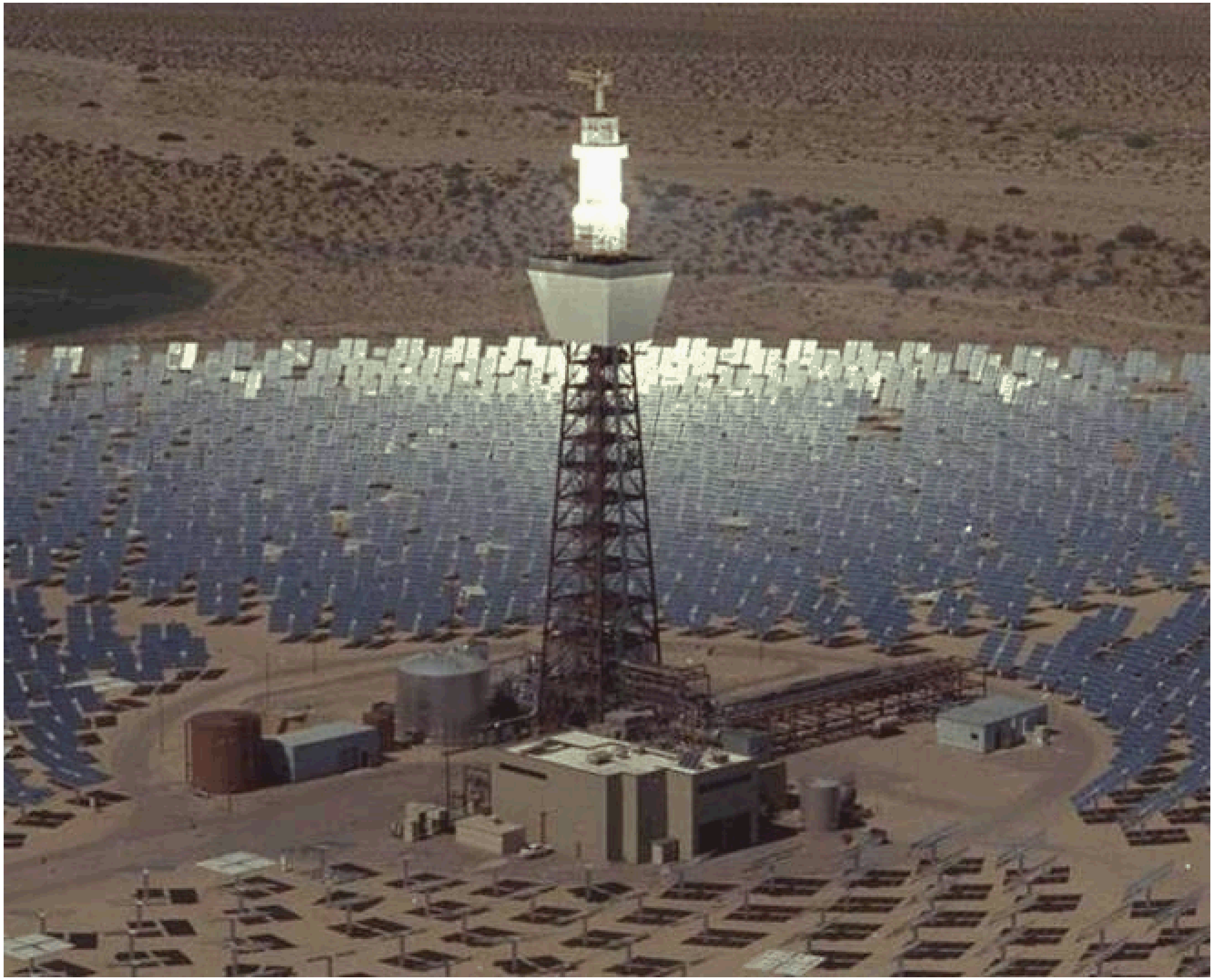


Photo of Solar Two power tower plant in operation in Daggett, CA (photo from Sandia National Laboratories, photo 2897)

Dish/Engine Systems

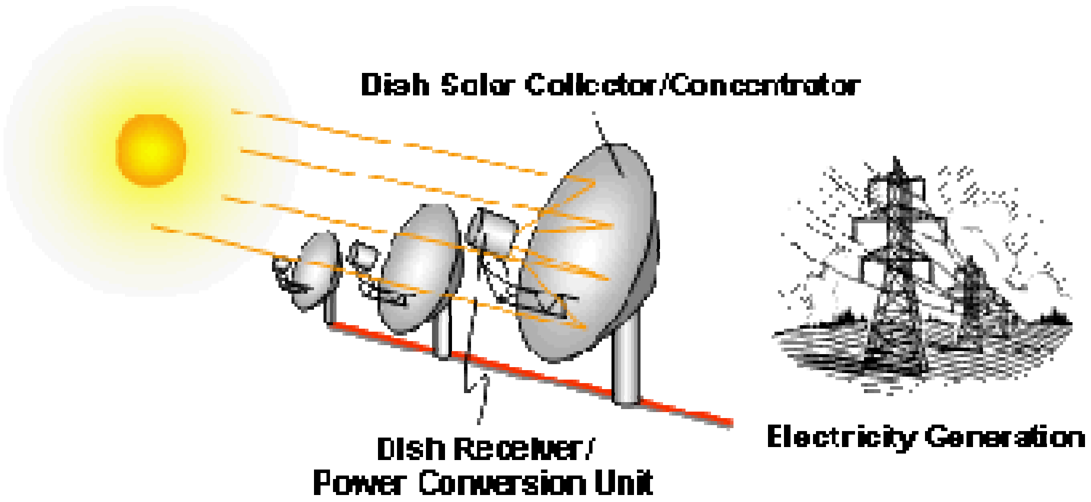


Illustration and photo of dish/engine system
(photo from http://en.wikipedia.org/wiki/Solar_thermal_energy)

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CSP Plants in the U.S.

http://en.wikipedia.org/wiki/SEGS

- Solar Electric Generating System (SEGS) Plant
  - 9 parabolic trough plants in Mojave Desert, CA (started in 1980’s)
  - 354 MW installed capacity
- Nevada Solar One
  - Near Las Vegas, NV
  - 64 MW installed capacity
  - Commissioned ~2009

eSolar Power Tower

5 MW in Lancaster, CA (started in 2009)
24,000 heliostats, two modules

Stirling Energy Systems Dish/Engine Plant

1.5 MW, 60 dishes near Phoenix, AZ (started in 2010; filed for bankruptcy in 2011)

CSP in Spain

Nearly 500 MW of CSP power plants are in operation or have been constructed

- Many more CSP plants are planned

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). Commissioned in May 2011.

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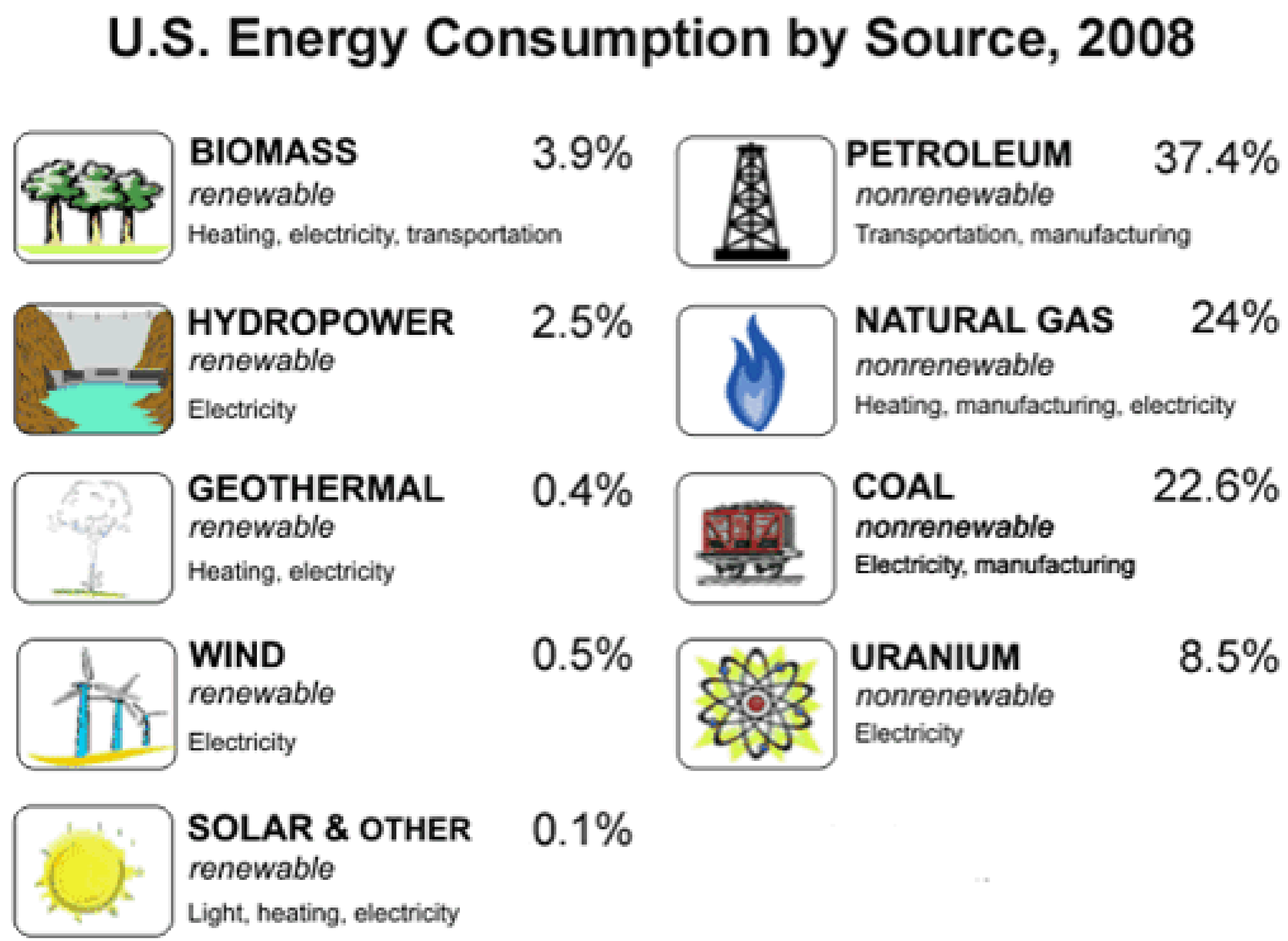
Energy Consumption



Source: Energy Information Administration, Annual Energy Review (2008)

What is LCOE?

- Levelized Cost of Electricity (Energy)

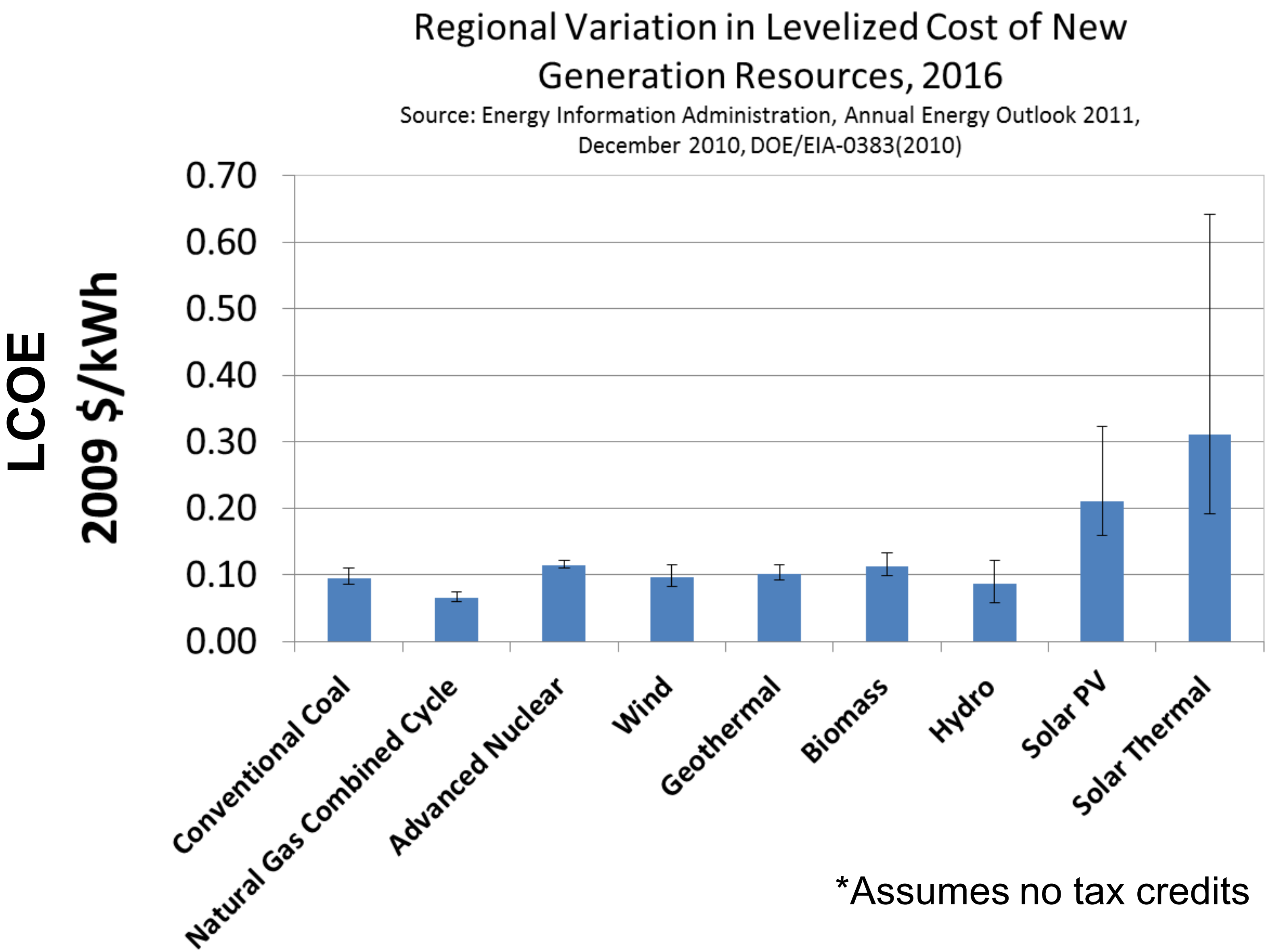
$$LCOE = \frac{Annualized\ Cost\ of\ Power\ Plant\ (\$)}{Annual\ Net\ Energy\ Production\ (kWh)}$$

where:

Power [Watt] = [Joules / second]

Energy [Joule] = [Watt] * [second] = [kW] * [hour] * (1000 W/kW) * (3600 sec/hour)

Electricity Costs (LCOE)*



*Assumes no tax credits

DOE SunShot Goal

- **Reduce LCOE of solar-generated electricity to $0.06/kWh by 2020 with no tax credits**
  - Reduce cost of installed solar energy systems by 75%
  - Enable solar-generated power to account for 15–18% of America's electricity generation by 2030

SunShot
U.S. Department of Energy

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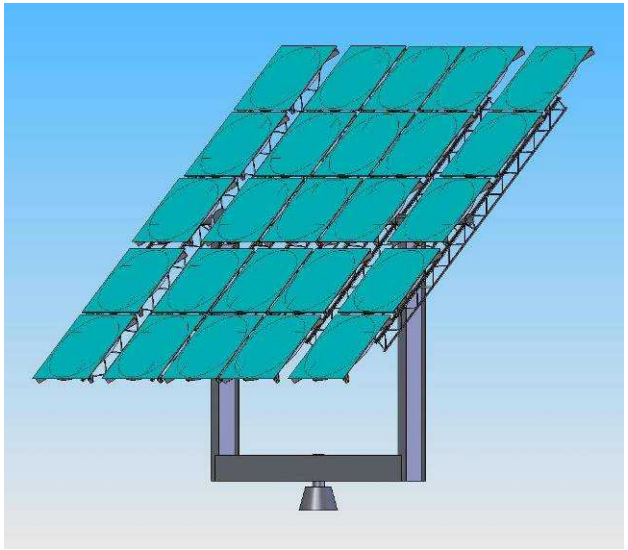
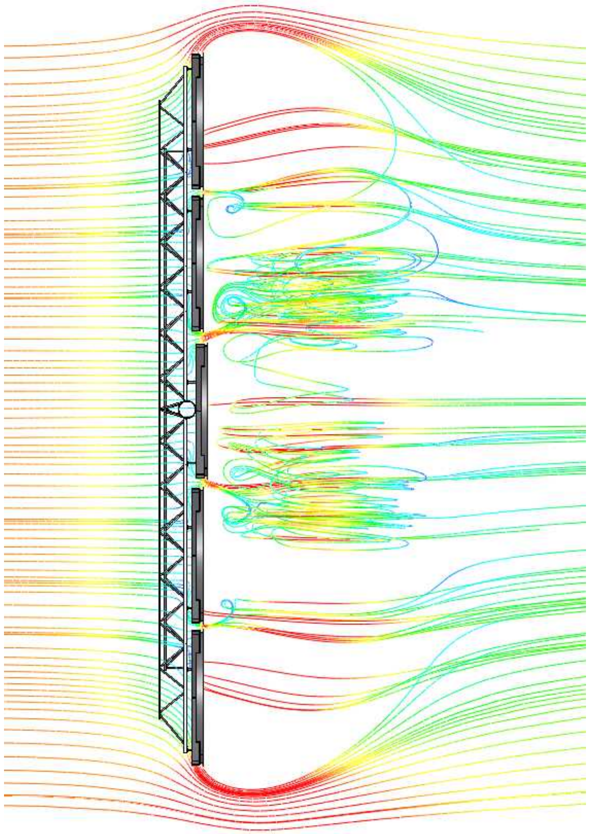
Research Needs

- Collectors (Mirrors) and Optical Performance
- High-Temperature Receivers
- Advanced Power Cycles
- Thermal Energy Storage
- Tools
- Novel Systems

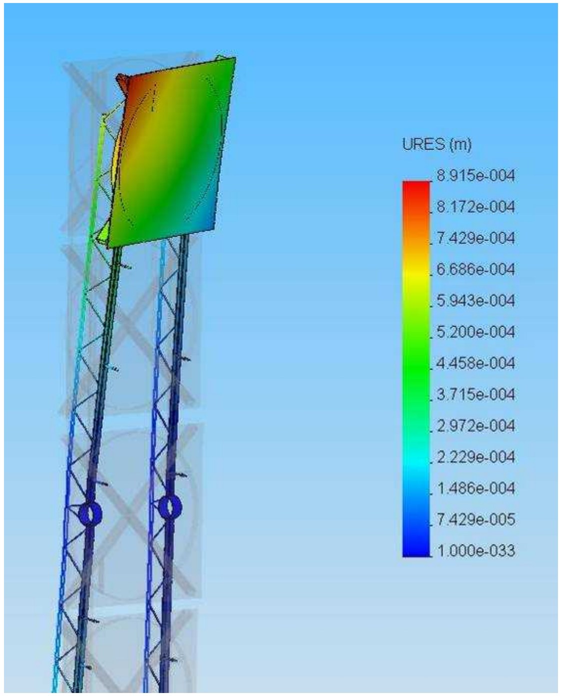
Collectors and Optical Performance



3D Solidworks model of heliostat at Sandia



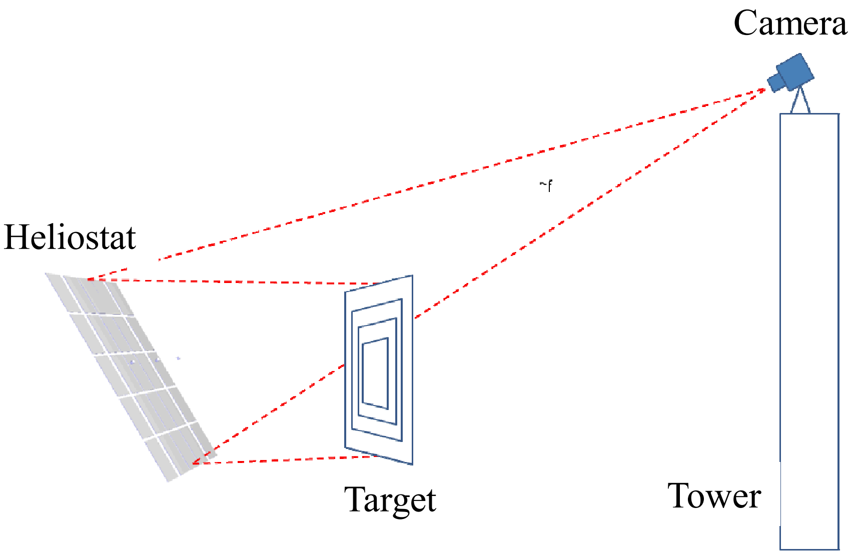
CFD simulations of flow over heliostat



FEA analysis of loads on facet

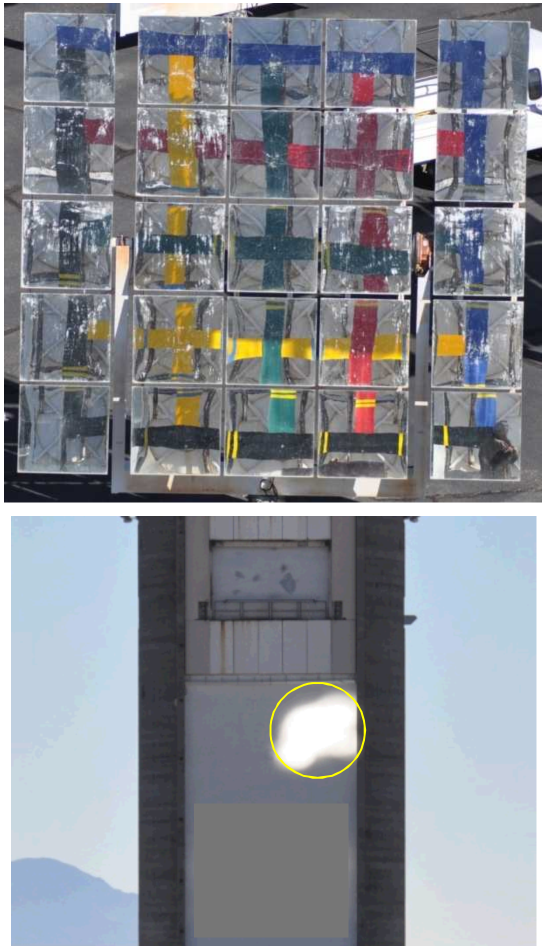
Optical Alignment

(Yellowhair, Sproul, Chavez)



Results

Before alignment



After alignment

Anti-Soiling Coatings

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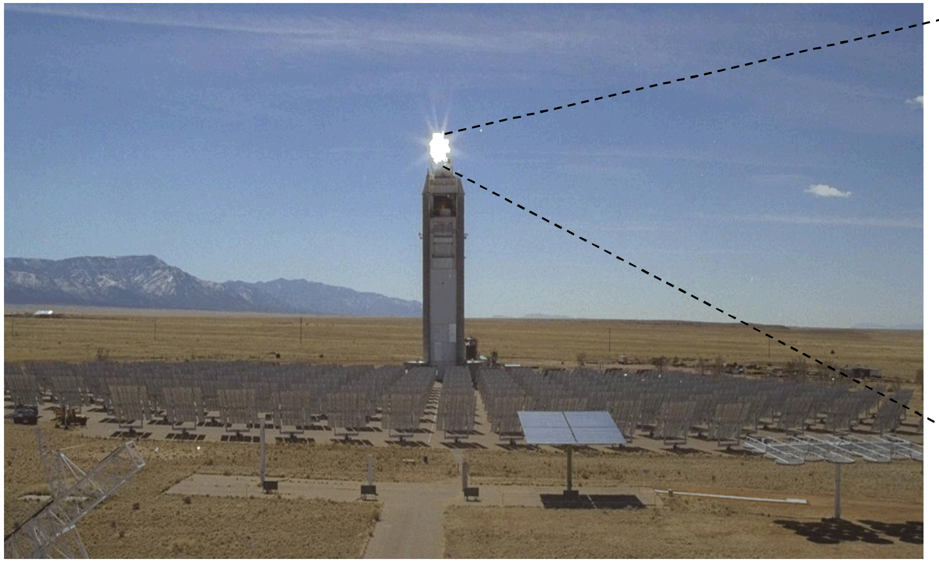
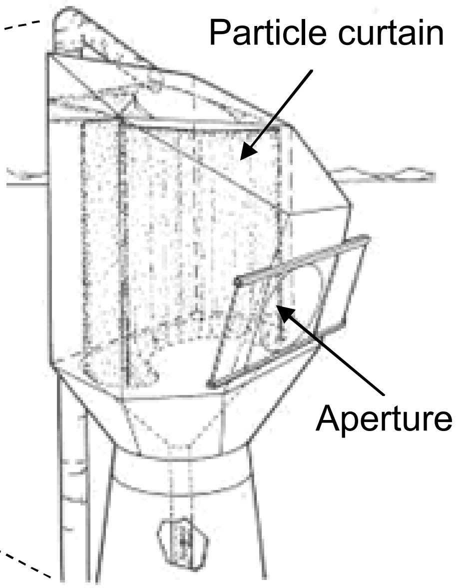
- Need anti-soiling coatings for mirrors to reduce need for washing and maintain high reflectivity

High-Temperature Receivers



National Solar Thermal Test Facility, Sandia National Laboratories, Albuquerque, NM



Solid particle receiver

- Ceramic sand-like particles fall through an open cavity
- Direct irradiation and heat absorption by particles

Thermal Energy Storage

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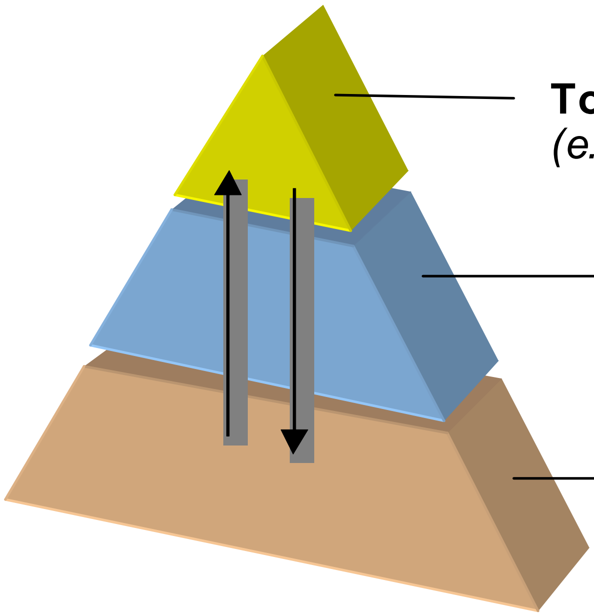
- Sensible (single-phase) storage
  - Low temperature melting-point molten salts
    - Reduce heating needs at night to prevent freezing
  - Stability of heat transfer fluids at higher temperatures
  - Solid storage (particles, graphite, concrete, ceramics)
- Phase-change materials
  - Use latent heat to store energy
- Thermochemical storage
  - Converting solar energy into chemical bonds (e.g., sulfur thermochemical cycle)

Systems Analysis Example for CSP

CSP Systems Analysis



Total system models – performance and cost
(e.g., SAM, SOLERGY)

Component and process models
(e.g., collector/reflector optics, receiver performance, thermal storage processes, power output)

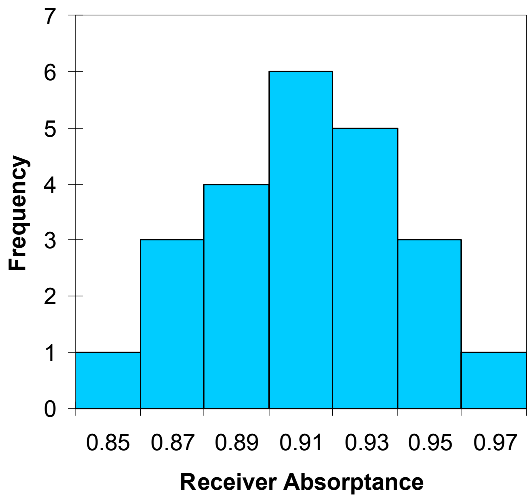
Input parameters and distributions
(e.g., geometry, reflectivity, solar radiation, temperature, flow rates, efficiencies, costs)

Need to honor uncertainties in component and process models to improve reliability of total-system models

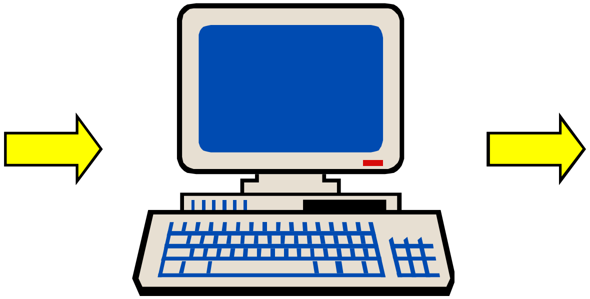
Why Use Probabilistic Modeling?

- Performance and cost models have typically used deterministic models
  - No quantification of uncertainty and confidence
  - Sensitivity (one-off) analyses provide limited insight
- Probabilistic modeling
  - Quantification of uncertainties and likelihood of achieving cost and performance metrics
  - Identification and ranking of the most important parameters and processes

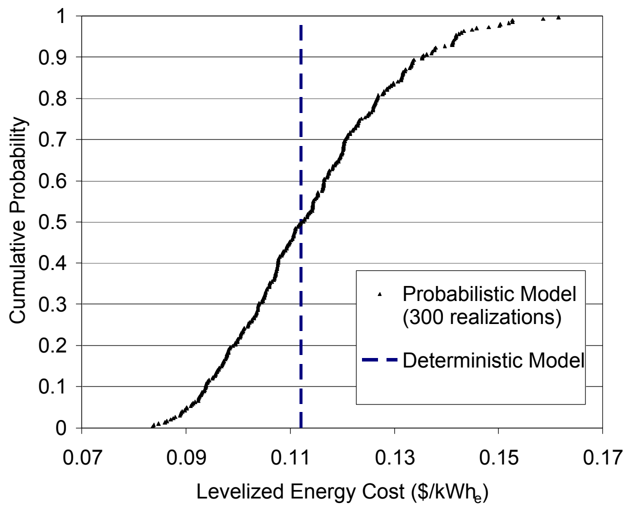
Probabilistic Modeling Approach



Stochastic Inputs
(Latin Hypercube Sampling)



Multiple Computer Simulations
(e.g., SOLERGY, SAM)



Distribution of Results
(Multiple Simulations)

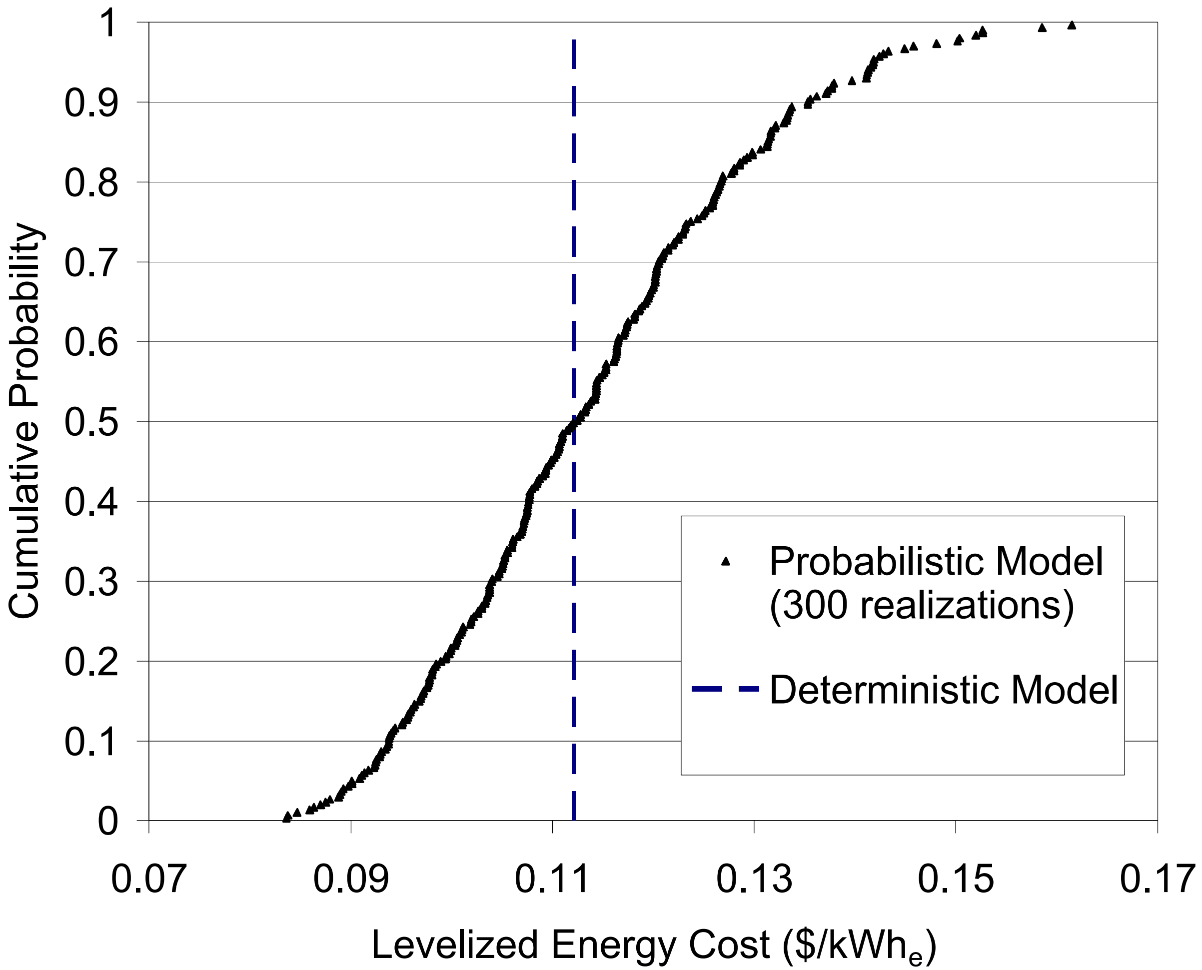
Simple Example

(Levelized Cost of Electricity in $/kWh)

$$\text{LCOE} = \frac{\text{Annualized Capital Costs} + \text{Annual O\&M Costs}}{(\text{Annual Energy Generated})(\text{Availability})}$$

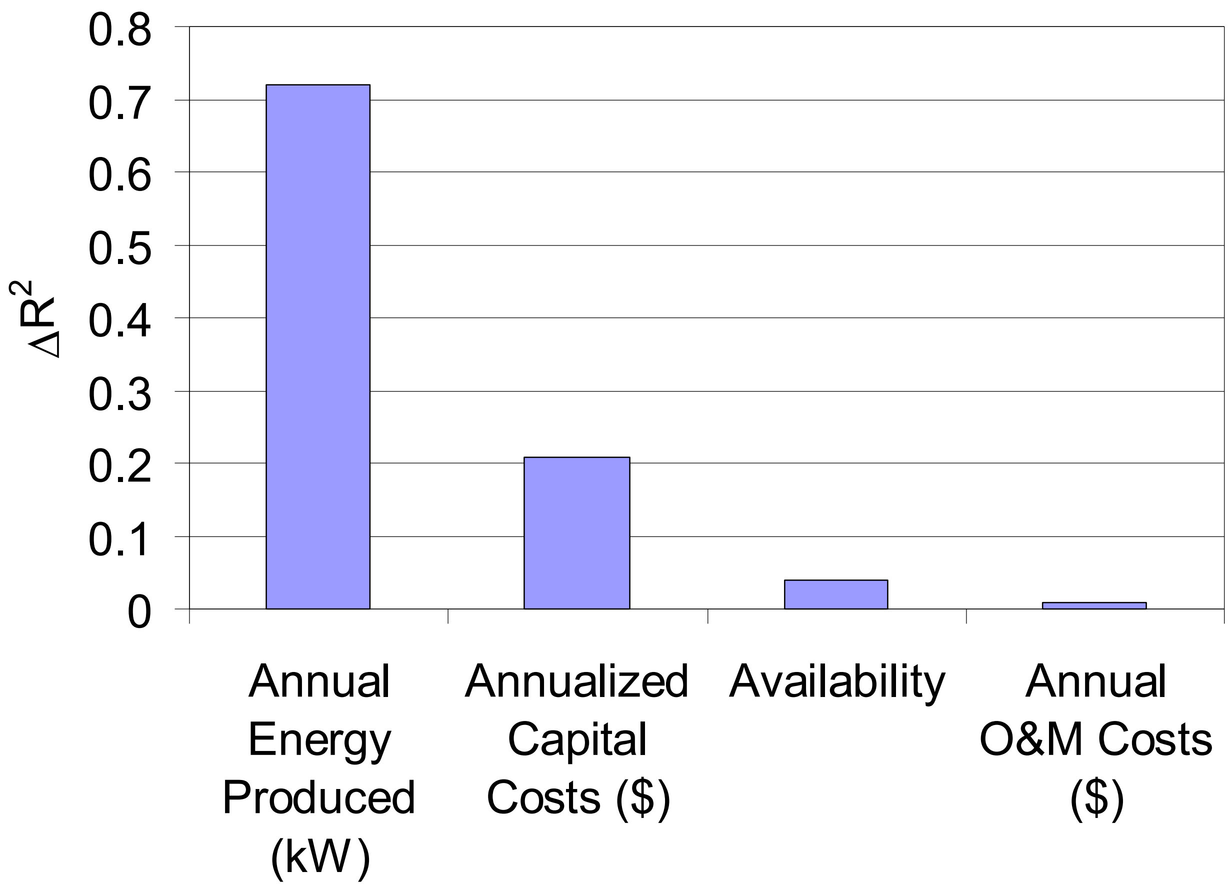
Parameter	**Distribution (30 year life)**
Capital Costs ($M)	Uniform 28.4 – 37.3
O&M Costs ($M)	Uniform 3.6 – 5.4
Annual Energy (kWh)	Uniform 2.96E+08 – 4.44E+08
Availability	Uniform 0.85 – 0.95

Benefit #1:
Quantified Uncertainty



Provides estimate of confidence in model results

Benefit #2:
Quantified Sensitivity Analysis



Ranking of most important parameters

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Summary

- Concentrating Solar Power (CSP) provides utility-scale electricity
  - Uses mirrors to concentrate solar flux onto receiver
  - Hot working fluid converts heat to mechanical energy via heat engine (e.g., steam turbine, Stirling engine), which spins a generator for electricity
  - Extra heat can be used for thermal storage to generate electricity during night or cloudy periods

Summary

- Market and Economics of CSP
  - Currently, only ~0.1% of U.S. energy consumption is from solar energy
    - ~80% from PV, ~20% from CSP
  - Current cost of CSP is significantly higher than fossil-fuel power plants
  - DOE SunShot goal is to reduce LCOE to $0.06/kWh by 2020
    - LCOE (levelized cost of energy) = annualized cost / annual energy production

Summary

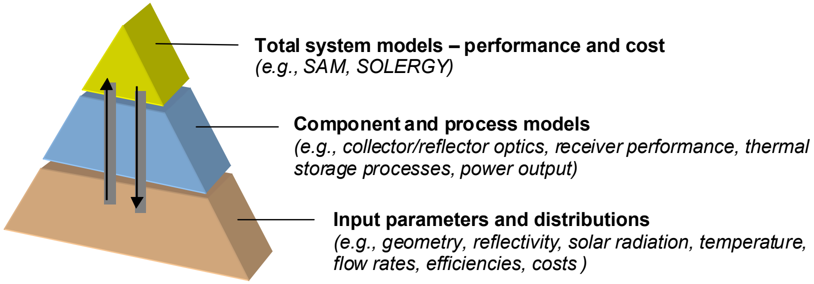
- Some Research Needs for CSP
  - Collectors (Mirrors) and Optical Performance
  - High-Temperature Receivers
  - Advanced Power Cycles
  - Thermal Energy Storage
  - Tools
  - Novel Systems

Review of Complex Systems Elements

- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Complex Adaptive Systems Engineering
- Sandia Software Tools
- Sandia Disciplines

Mathematics

- This approach considers mathematics techniques and tools that contribute to defining complex systems
  - Modeling considers multiple levels and scales



  - Stochastic (probabilistic) modeling approach
    - Latin Hypercube Sampling of random variables to account for uncertainty
    - Multiple realizations
    - Uncertainty and sensitivity analyses
      - Determine likelihood of achieving cost and performance metrics
      - Identify and rank most important parameters and processes

Sandia Tools

Sandia has contributed to the development of a large number of tools used in CSP R&D:

- **Systems Analysis**
  - SOLERGY, DELSOL, LHS, SAM
- **Flux Analysis**
  - HELIOS, CIRCE, MIRVAL, DELSOL, PHLUX
- **Mirror Characterization/Alignment**
  - SOFAST, TOPCAT, SOFAST, AIMFAST, H-FACET
- **Reliability**
  - ProOpta

Sandia Expertise and Disciplines

- Research and development for concentrating solar thermal power systems requires diverse expertise and disciplines:
  - Expertise
    - Energy systems
    - Optics
    - Thermodynamics
    - Heat transfer
    - Dynamics
    - Electronics
    - Materials
  - Disciplines
    - Engineering (mechanical, chemical, electrical, optical)
    - Materials Science
    - Chemistry
  - Resources:
    - National Solar Thermal Test Facility
    - High performance computing
    - Materials laboratories

Concentrating Solar Thermal Power Systems

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