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CSP Training: Agenda and Module 1: Basic Theory

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Sponsored by College of the Desert

BrightSource Ivanpah, CA

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Introduction: James (Jim) Pacheco

- Principal Member of Technical Staff at Sandia National Labs (SNL)
- Engineer by training (MSME, BSME)
- Combined 18 years experience conduct RD&D of CSP technology
  - 15 years from Sandia National Laboratories
  - 3 years at eSolar (VP Molten Salt Systems & Thermal System Group)
- Developed trough and power tower technologies
  - SNL's Concentrating Solar Power Program manager
  - PI on eSolar's DOE CSP Baseload award to develop modular molten salt power towers
  - VP Thermal Systems Group responsible for development, engineering, design and performance characterization of eSolar's receivers and thermal storage systems
  - SNL's project lead for the Solar Two project responsible for tests and evaluations
  - SNL's Project lead for Power Tower Technology in DOE's Concentrating Solar Power Program
  - SNL's Team Leader of Near-Term Thermal Storage for Parabolic Troughs

Day 1 Agenda

- Introduction
- 1. Basic Theory of Operation Overview
  - What is Concentrating Solar Power?
  - Types of Concentrating Solar Power Plants
    - Parabolic Trough, Fresnel, Dish, Power Towers
    - Power Towers
      - Molten Salt
      - Volumetric Air
      - Direct Steam
- 2. Fuel
  - Irradiance and Insolation
  - TMY and Prediction
  - Measurement of solar irradiance
    - Global horizontal
    - Diffuse
    - Direct Normal

Day 1 Agenda

- 3. Modeling CSP plants
  - Waterfall efficiency
    - Conversion Efficiencies and soiling effects
- 4. Basic construction and Design
  - Systems Overview and Design tradeoffs
    - Solar field size
    - Tower height and construction
    - Receiver design
      - Flux profiles
      - Materials
    - Solar multiple
    - Storage
    - Dry vs wet cooling
    - Hybridization methods

Day 2 Agenda

- 5. Startup and Shutdown
  - Receiver startup and ramp rates
    - Building pressure and temperature
    - Superheat
    - Reheat
  - Piping warmup
  - Turbine warmup and ramp rates
    - Admissible steam conditions
- 6. Major System Operations
  - Boiler Operations
  - Turbine Operations
  - Generator Operations
  - ACC Operations
- 7. Plant Operation influences on the grid

Day 2 Agenda

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- 8. Response to Weather Changes
  - Cloud transients
  - Winter Operation
- 9. Water Chemistry
  - Treatment
  - Blowdown
- 10. Plant Performance Measurements
  - Receiver Power output
  - Receiver Efficiency
  - Daily Performance
  - Annual Performance
- 11. Safety Concerns
  - Glint/Glare

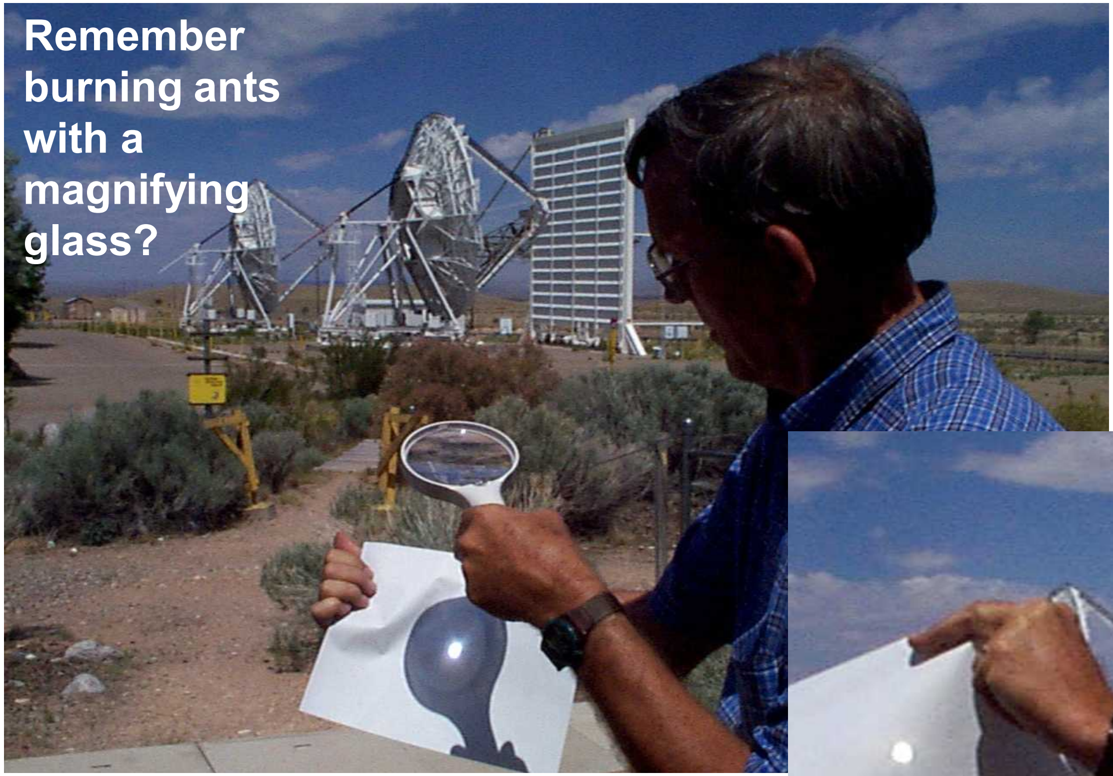
1. BASIC THEORY OF OPERATION OVERVIEW

Basic Theory of Operation Overview

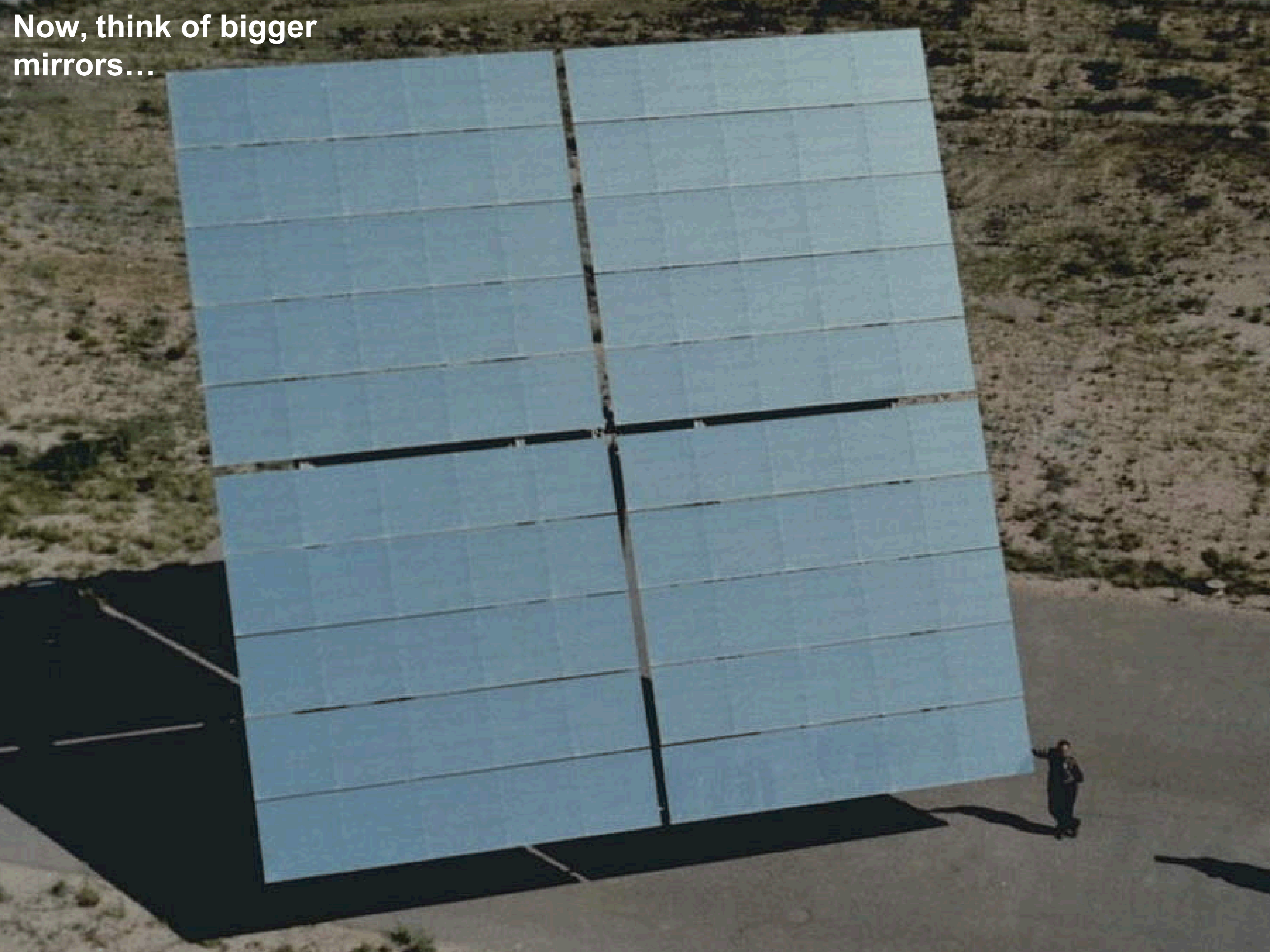
- Types of Concentrating Solar Power Plants
  - What is Concentrating Solar Power?
  - Parabolic Trough, Fresnel, Dish, Power Towers
  - Power Towers
    - Molten Salt
    - Volumetric Air
    - Direct Steam

Concentrating Solar Power is not…

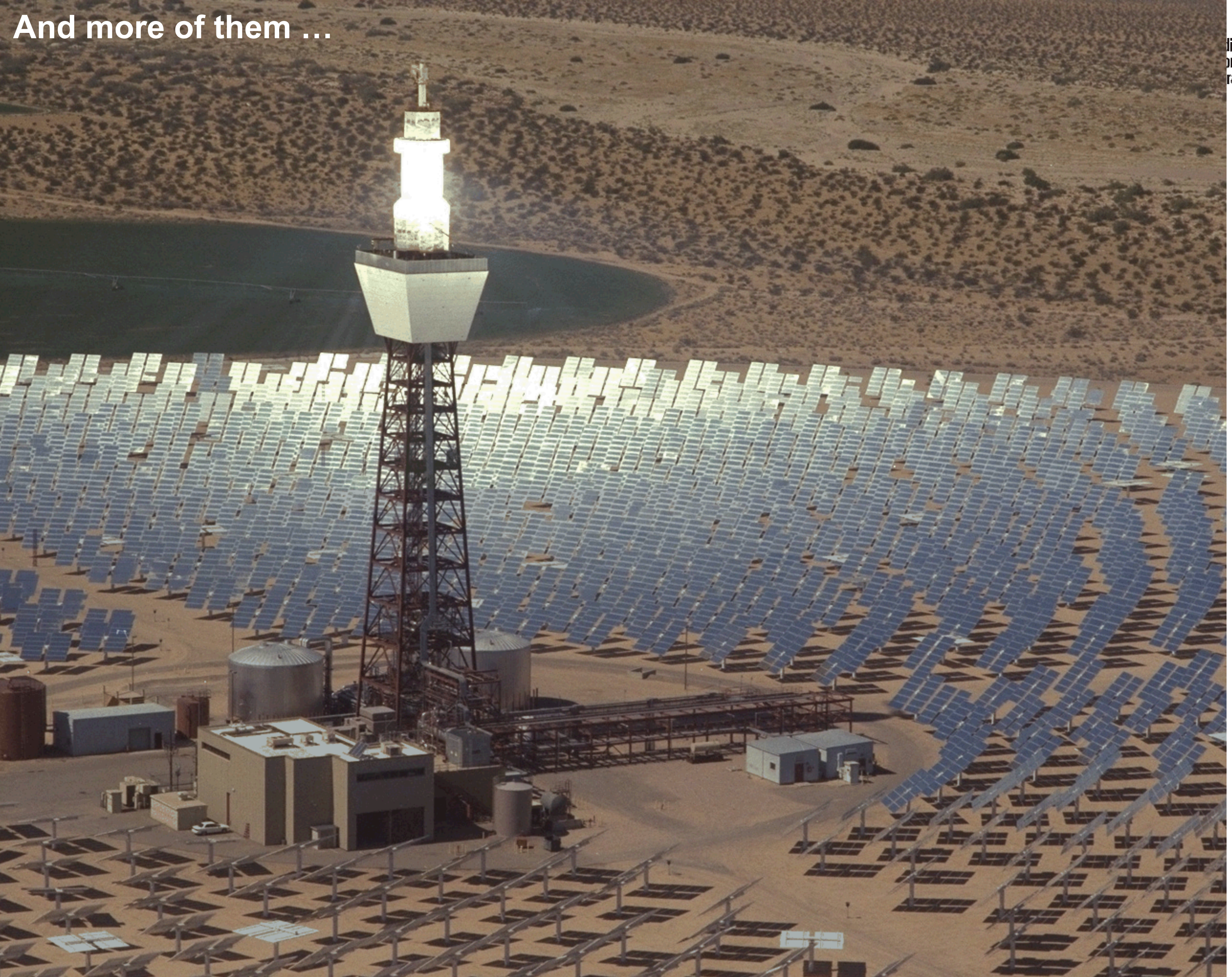
So what is CSP?



Now, think of bigger mirrors…



And more of them …




Many more of them …
Producing gigawatts of power …
That's CSP …

The basic concept…

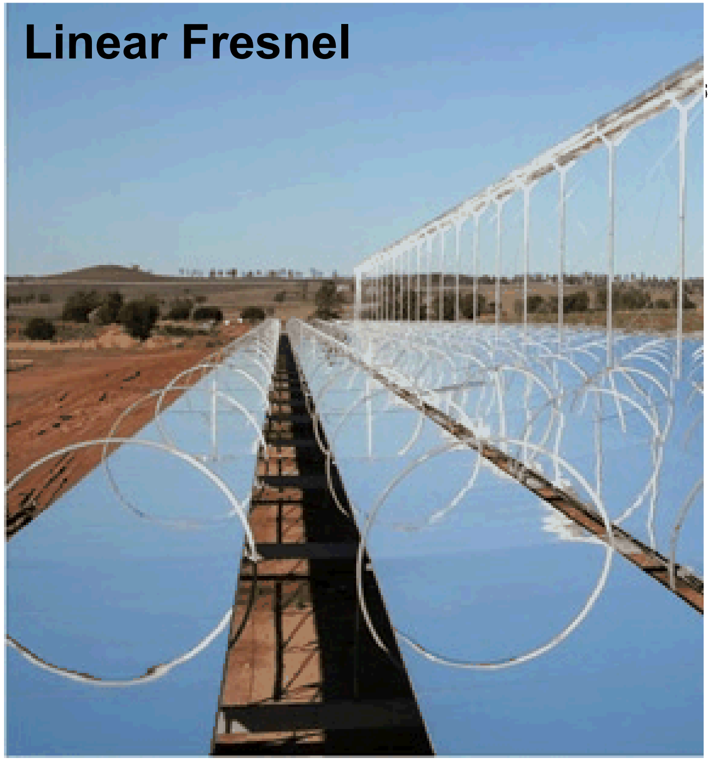
- Mirrors track the sun to concentrate solar energy onto a receiver (tubes, porous mesh, heatpipe, etc.)
    - …to heat a working fluid (water/steam, air or other gas, molten salt, sodium, etc.)
        - …to power a heat engine (Rankine, Brayton, Stirling, or other)
            - …to drive a generator to produce electricity (usually for the grid, but sometimes for remote or stand-alone applications)

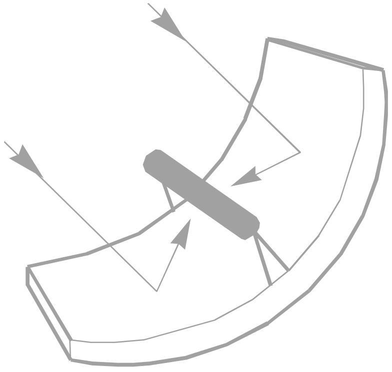
Overview of CSP Plants

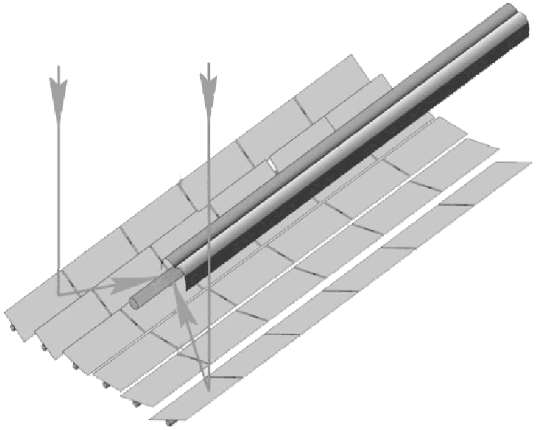
- Several CSP plants are in operation around the world
  - 540 MW in the US
  - 1180 MW in Spain
  - 655 MW the rest of the world
  - Gigawatts under construction and planned
- Power towers are emerging and the first commercial plants are coming on-line.
- Parabolic trough is the most mature and prevalent.
- Dish engine systems have higher efficiency and the potential for significant cost reductions.
- Compact linear Fresnel concentrator show low cost potential and are emerging.

Line Focus Technologies

- Low concentrations (<100 suns)
- Usually lower temperatures (<400°C, with exceptions)

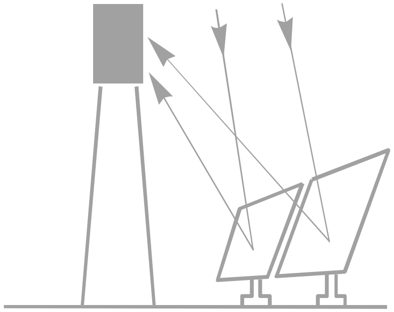






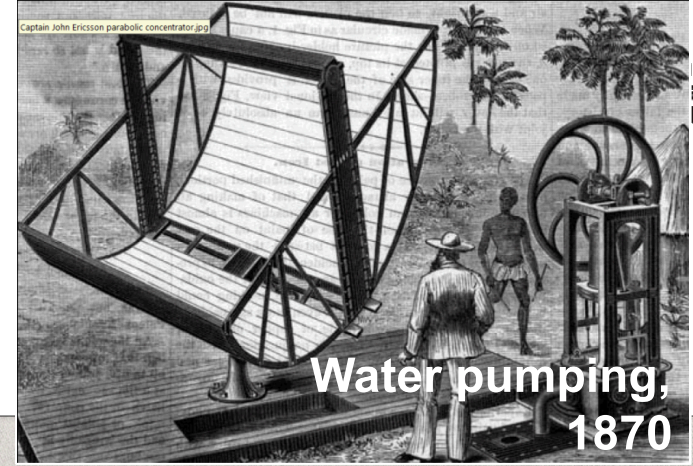
Point Focus Technologies

- Higher concentrations (200 to > 5000 suns)
- Usually higher temperatures (440 to >1000°C)



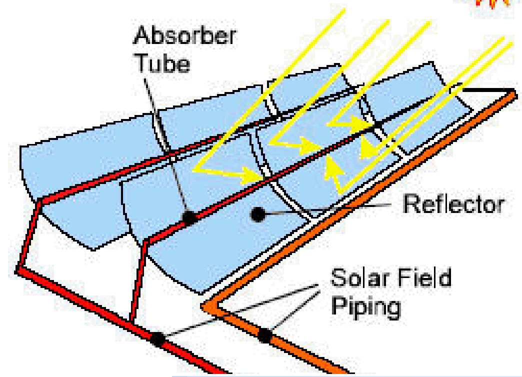
Parabolic Troughs

- Demonstrated, mature technology
  - Over 25 years of commercial operation
  - 1100 MW in commercial operation (plus 1300 MW under construction worldwide)
- Hybridization and storage options
- Limited opportunities for cost reduction or performance improvement



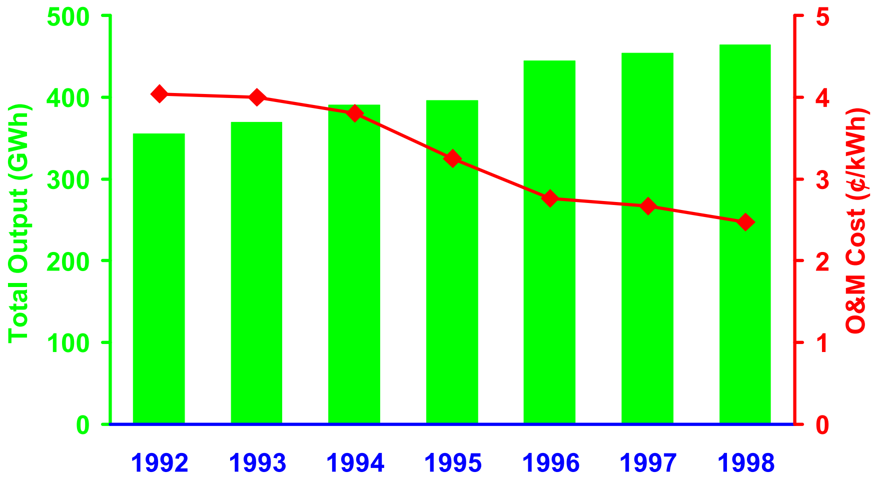
Trough Technology

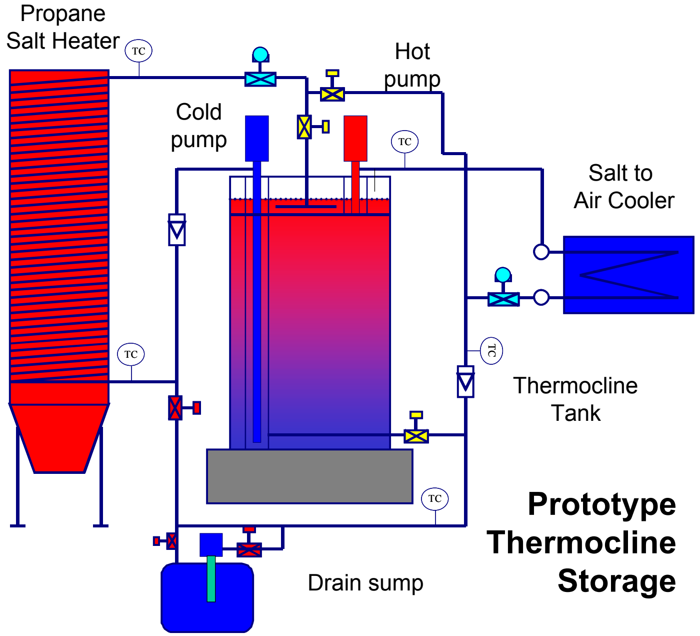
- Technology features
  - Proven receivers (HCEs)
    - Limited to 390°C by therminol HTF and low concentration ratios
    - Glass envelope and selective coating enhance efficiency and offset low concentration ratios
  - Molten Salt Storage
    - Two tank system leveraged from Solar Two experience
    - Heat transferred via oil-to-salt heat exchanger
    - Implemented commercially at Andasol and elsewhere
  - Steam generator system produces 100 bar, 370ºC superheated steam for reheat turbine
- But…
  - Limited ΔT (~100°C) results in high storage cost
  - Long-term development has already achieved the biggest cost reductions



Trough Technology

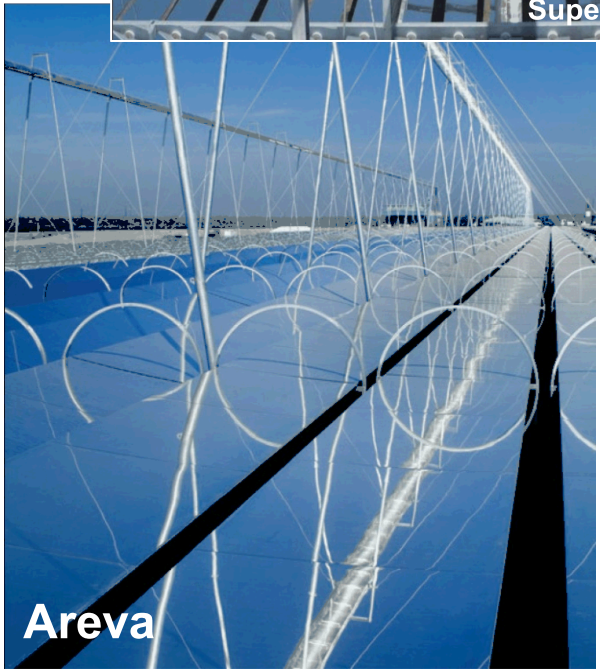
- Proven O&M costs and performance
- Continuing development
  - Direct molten salt HTF
  - Direct steam generation in receivers
  - Advanced single-tank thermocline molten salt storage





Linear Fresnel

- Fundamentally similar to troughs
- Uses long mirrors and fixed receivers to produce saturated or superheated steam
- Low thermal and power conversion efficiency (relative to troughs), but potentially low system costs
- Storage costly and challenging



Dish/Engine

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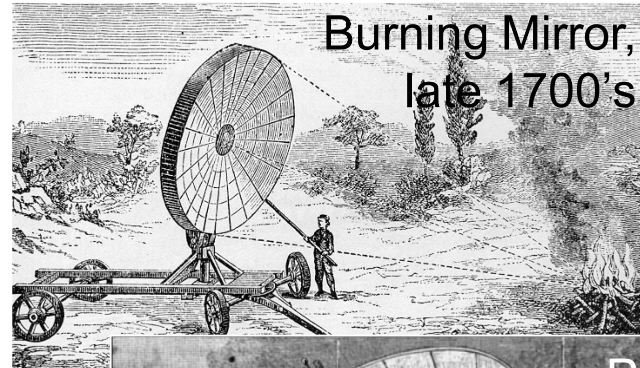
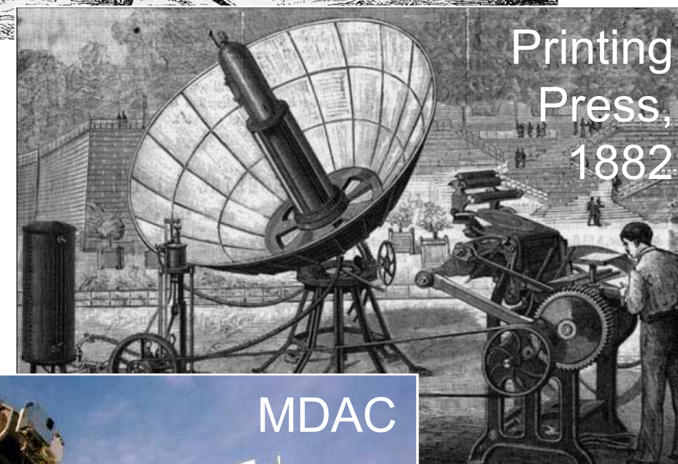
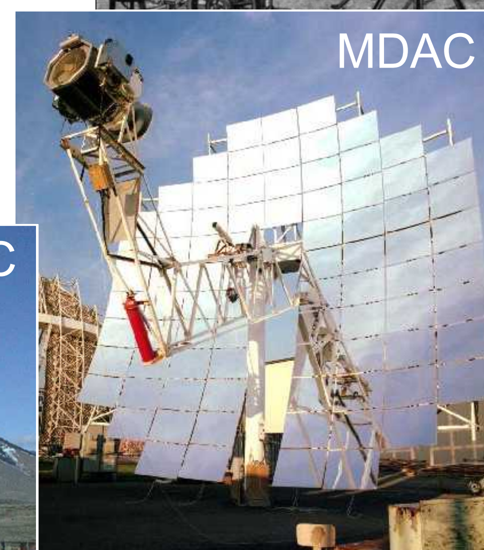
- Two-axis tracking parabolic dish focuses 1000+ suns on a cavity receiver
- Hydrogen (or other) gas in receiver powers a Stirling (or other) engine
- Highest solar-to-electric efficiency, but also highest cost
- Need high volume production to reduce the costs
- Storage options limited







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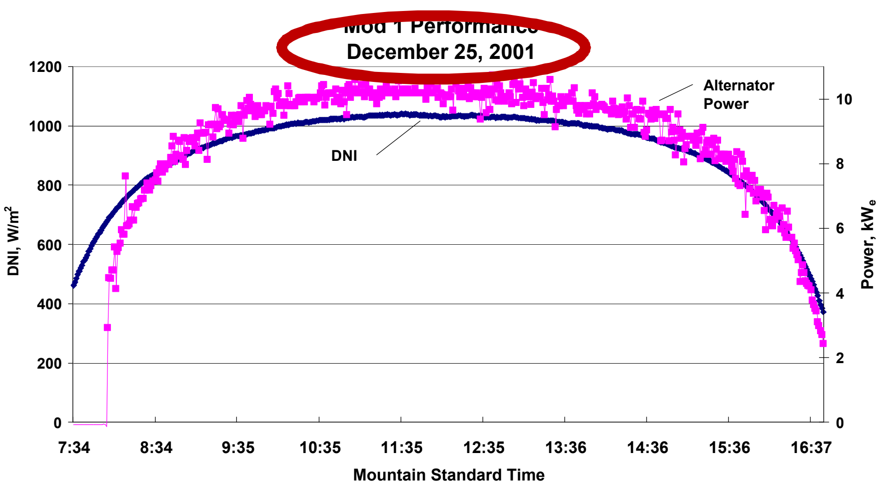
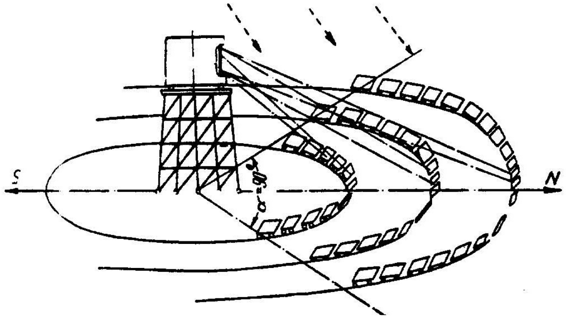
Dish/Engine

- Technology features
  - High efficiency (> 31% demonstrated)
  - Modularity (3 - 25kW)
  - Hybrid capability (but no little or no storage)
  - Autonomous operation (on- and off-grid)
- But…
  - Unproven reliability
  - High cost
  - Major SES projects cancelled



Power Towers

- Dispatchable power w/ cost-effective storage or hybridization
- Successfully demonstrated at Solar One and Solar Two, and more recently by Abengoa, BrightSource, and eSolar



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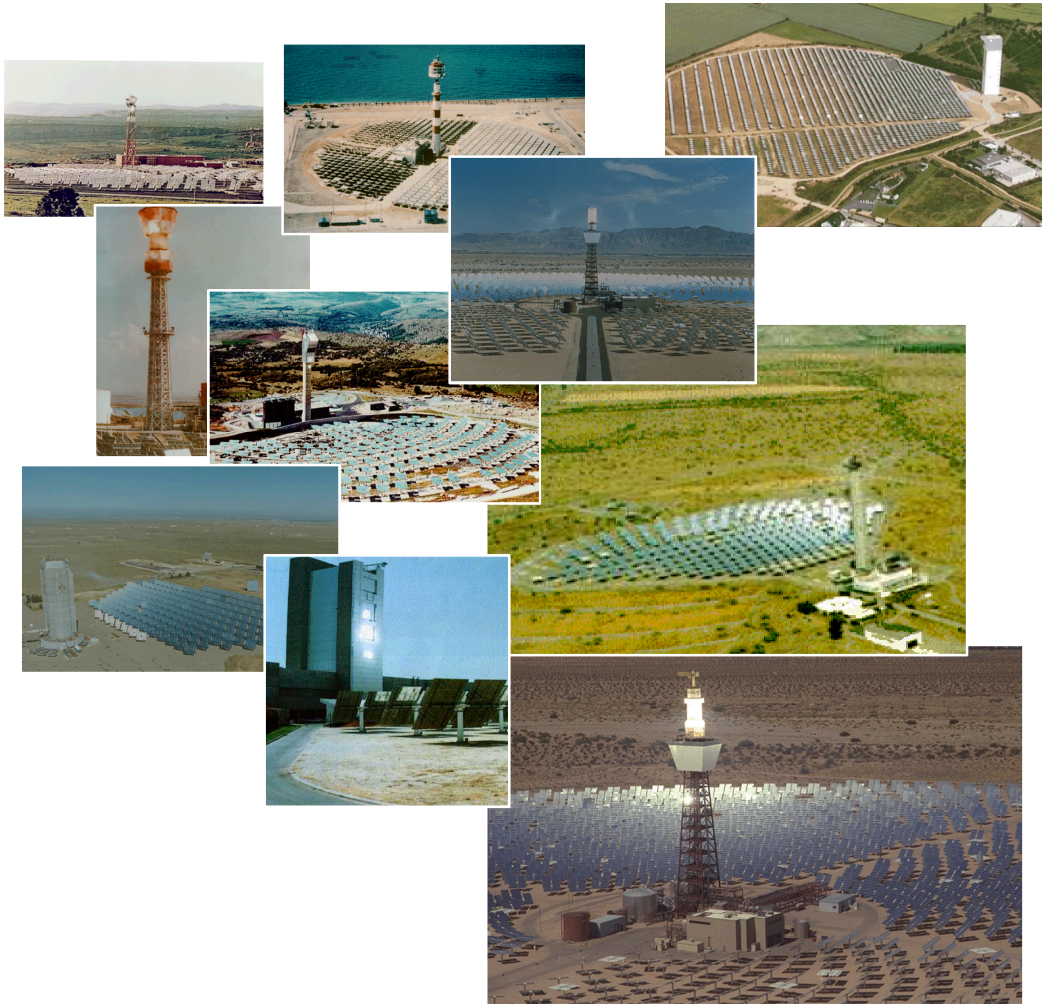
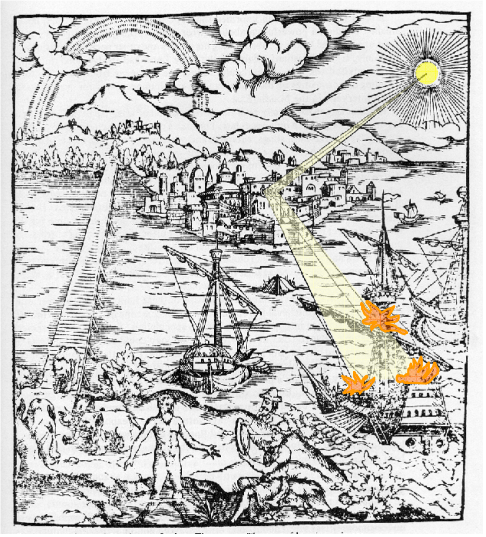
Baum, et al, 1956, "The optical system of the installation consists of 1,293 mirrors of 3 x 5 m, mounted on carriages which move on rails, positioned around a boilershield, on which the solar rays are focused."



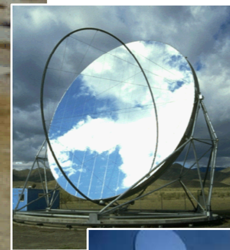


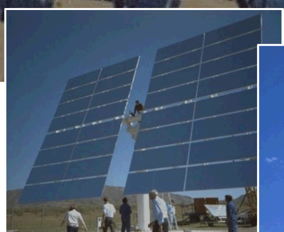
Archimedes "Heat Ray", c. 200BC

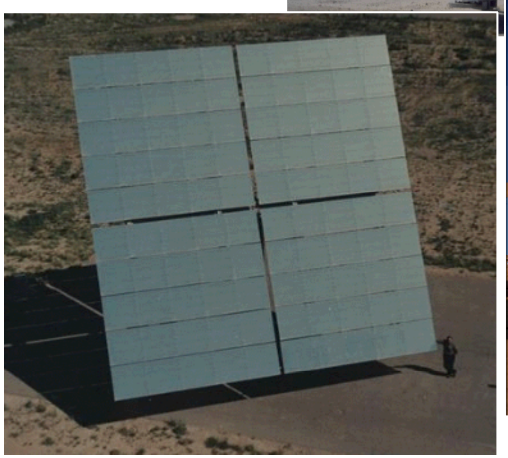
Power Towers

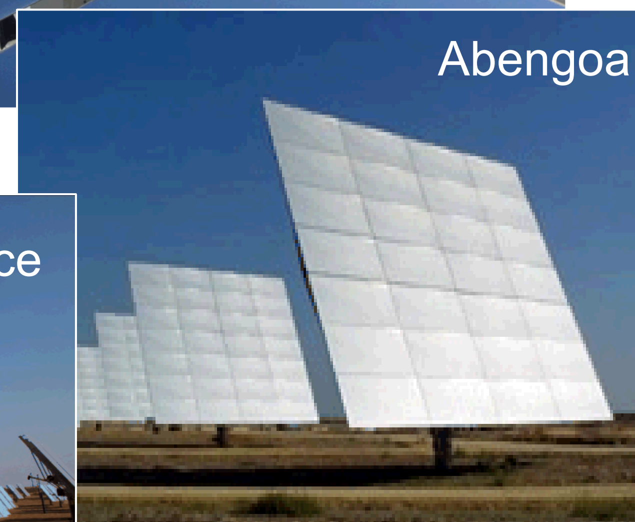
- Technology features
  - 50-200MW (and larger) plants for peaking and bulk power
  - Low-cost molten salt storage offers load-following and capacity factors >75%
  - Component performance well-established
- But…
  - Scale-up risk on key components
  - Large initial project cost & risk

Heliostats









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Receivers

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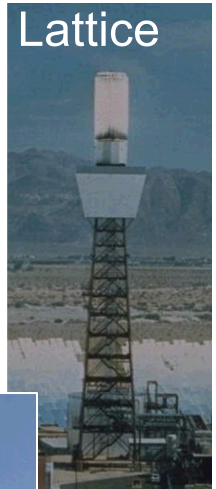

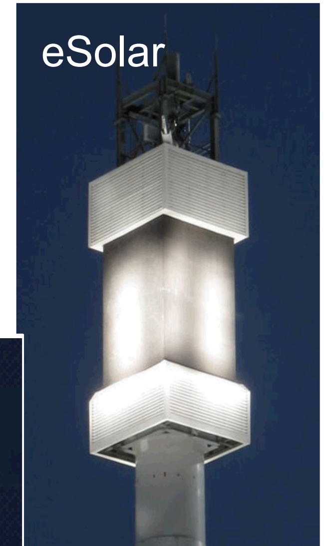

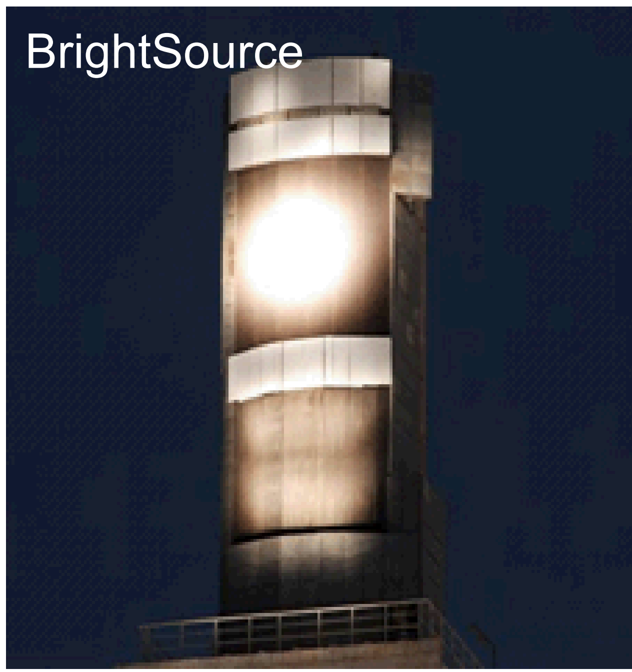

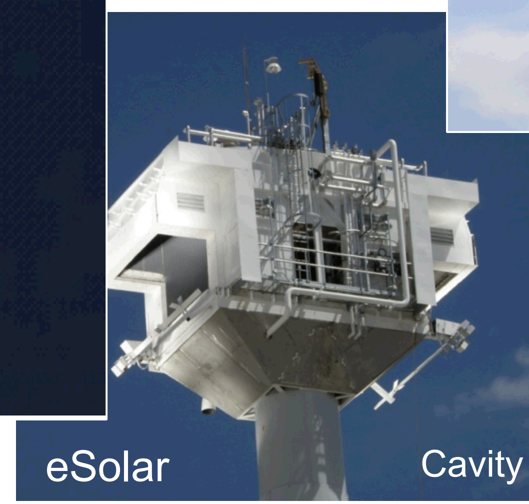

Towers

Commercial Power Tower Plants

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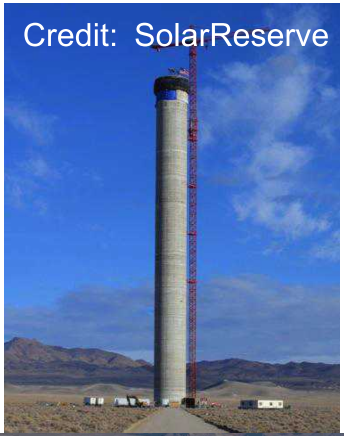
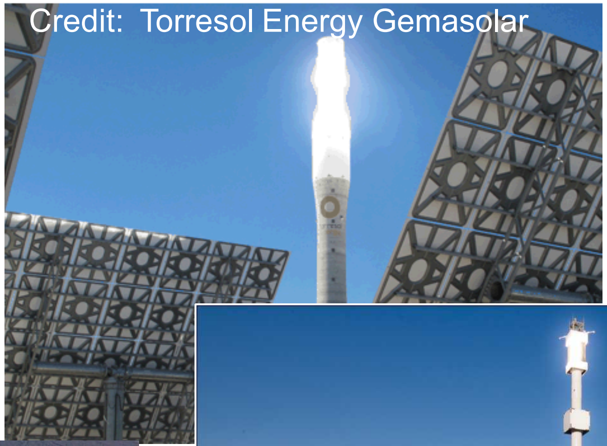
- BrightSource Ivanpah
  - **390 MWe** direct steam generation
  - Three plants under construction in Ivanpah, CA
- Gemasolar Thermosolar Plant
  - **20 MWe** molten salt power tower
  - Operational in Andalucía, Spain
- Solar Reserve Crescent Dunes
  - **110 MWe** molten salt
  - Under construction in Tonopah, NV
- Abengoa PS10 and PS20
  - 10 and 20 MWe direct steam power towes
  - Seville, Spain
- eSolar Sierra SunTower
  - **5 MWe** direct steam
  - Operational in Lancaster, CA

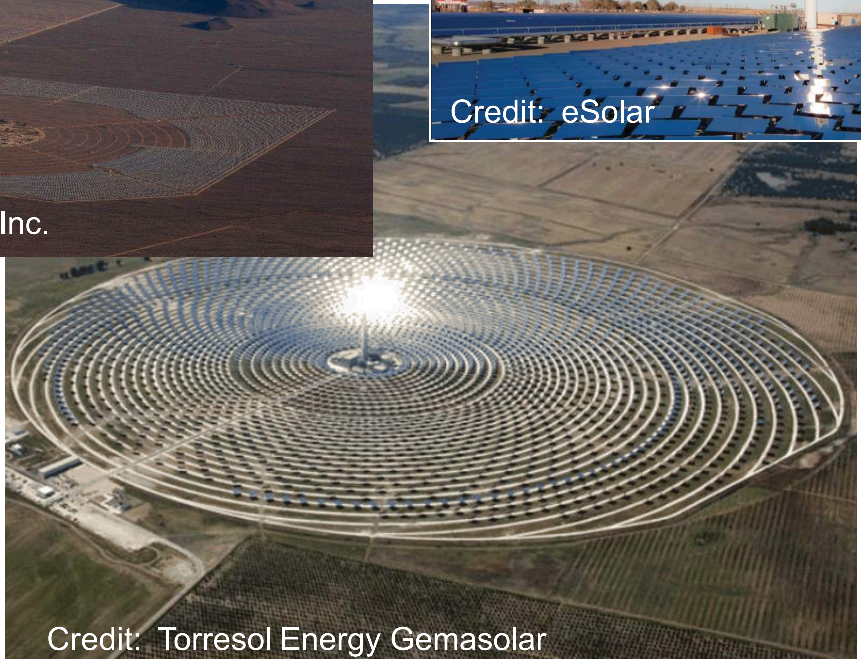

Credit: SolarReserve


Credit: Torresol Energy Gemasolar


Credit: eSolar


Credit: BrighSource Energy, Inc.

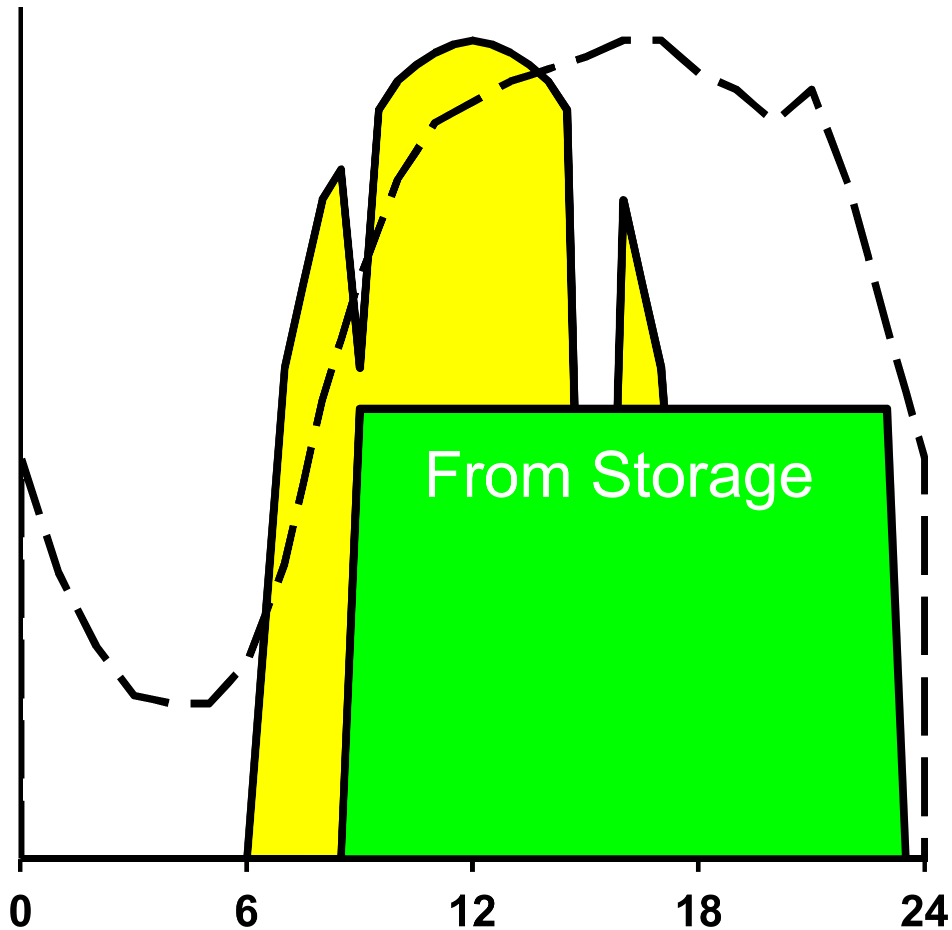

Credit: Abengoa


Credit: Torresol Energy Gemasolar

Molten Salt Power Towers

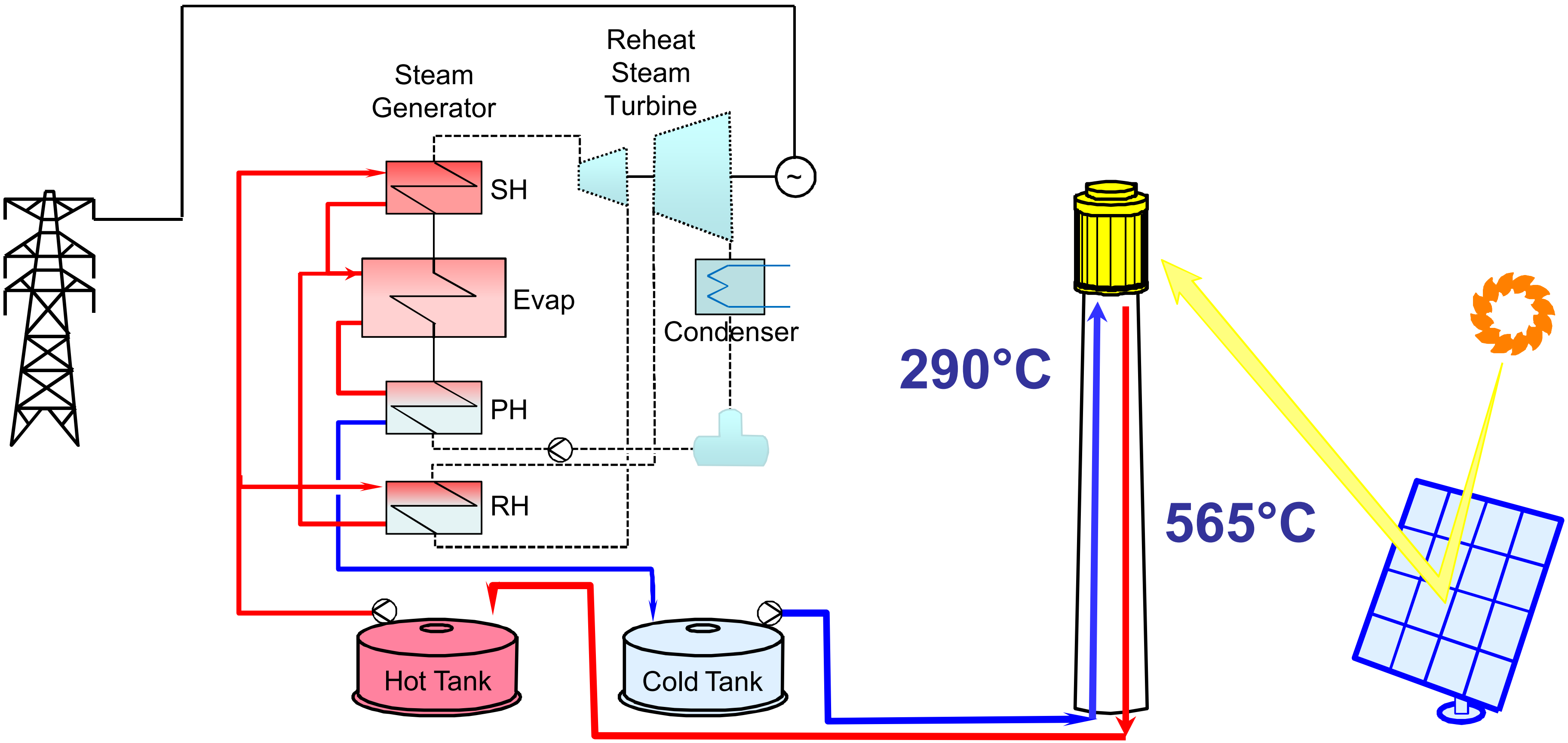
- Why molten salt?
  - Enables cost effective thermal storage
  - Dispatchable power generation
  - Decouples solar collection from power generation
- Attributes of molten salt
  - High temperature stability
  - Operates over temperatures well suited for Rankine cycles (290-565°C)
  - Low vapor pressure
  - Low cost
  - Good compatibility with common materials
- Examples:
  - 20 MWe Gemasolar
  - 110 MWe SolarReserve Crescent Dunes

Shifting Power Output with Molten Salt Storage



- Storage provides
  - decoupling of energy collection and generation
  - lower costs because storage is cheaper than incremental turbine costs
  - higher value because power production can match utility needs
  - No emissions

Schematic of Molten Salt Power Tower



Molten Salt Power Tower Advantages and Challenges

Advantages

- Low-cost thermal storage
- Decoupling collection from power generation
  - Grid stability
  - Load following
- Can be designed to target afternoon-to-evening peak loads or even baseload power

Challenges

- High freezing point of molten salt
- High perceived technical risk
  - No long-term operational performance
  - Long-term reliability
- Scale-up risk
- Learning curve

Volumetric-Air Power Towers

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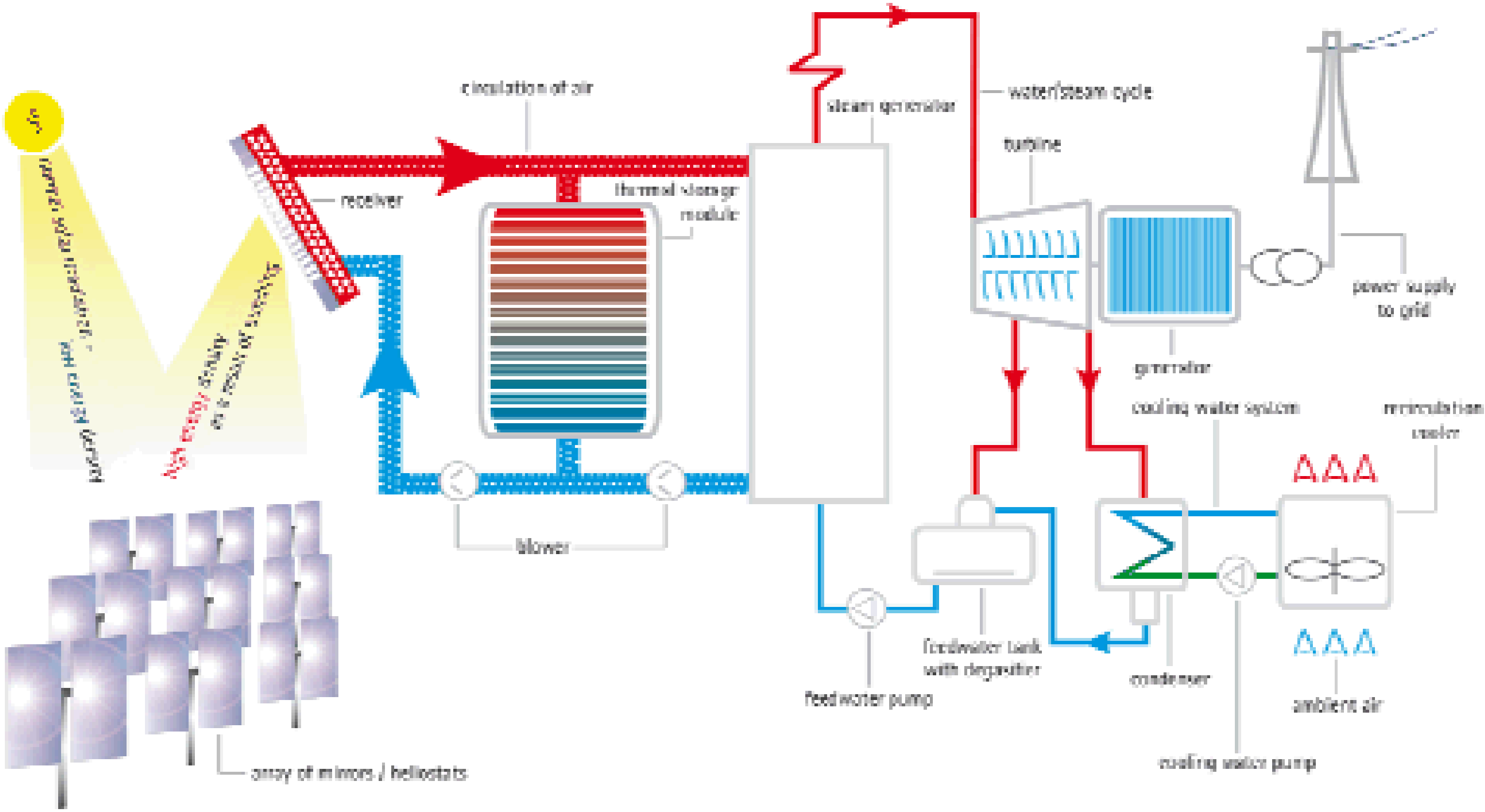
- Why air?
  - Obtain high temperatures
  - Can be coupled with storage
  - Relatively easy to handle
  - Simple system designs
- Attributes of air
  - Abundant
  - High temperature stability
  - Good compatibility with common materials
- Example:
  - 1.5 MWe Jülich demo plant in Germany

Source: Koll, G., "The Solar Tower Jülich – A Research and Demonstration Plant for Central Receiver System", SolarPACES 2009, Berlin, Germany, Sept 2009

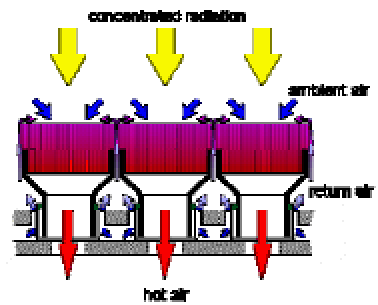
Schematic of Volumetric-Air Power Tower

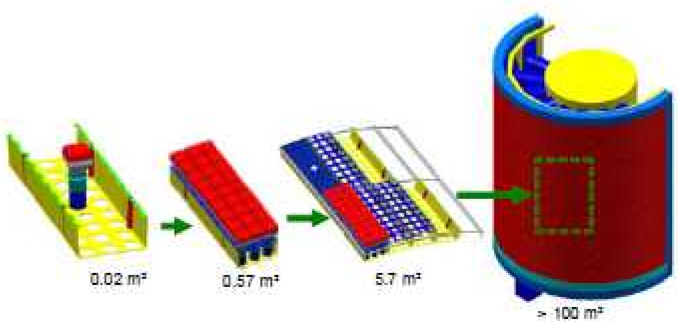


Source: Koll, G., “The Solar Tower Jülich – A Research and Demonstration Plant for Central Receiver System”, SolarPACES 2009, Berlin, Germany, Sept 2009

Receiver and Thermal Storage for Volumetric Air System

- Receiver
  - Made from porous ceramic modules
  - Sunlight concentrated and penetrates structure
  - Air drawn through to heat air
  - Recirculation improve efficiency of system
- Thermal Storage
  - Porous ceramic brick
  - Operates like a thermocline





Source: Koll, G., "The Solar Tower Jülich – A Research and Demonstration Plant for Central Receiver System", SolarPACES 2009, Berlin, Germany, Sept 2009

Volumetric-Air Power Tower Advantages and Challenges

Advantages

- High temperature output
- Reasonably-cost thermal storage
- Simple heat transfer fluid
  - Benign
  - Operate over large temperature difference
  - Open loop
- Steam generator can be similar to HRSG

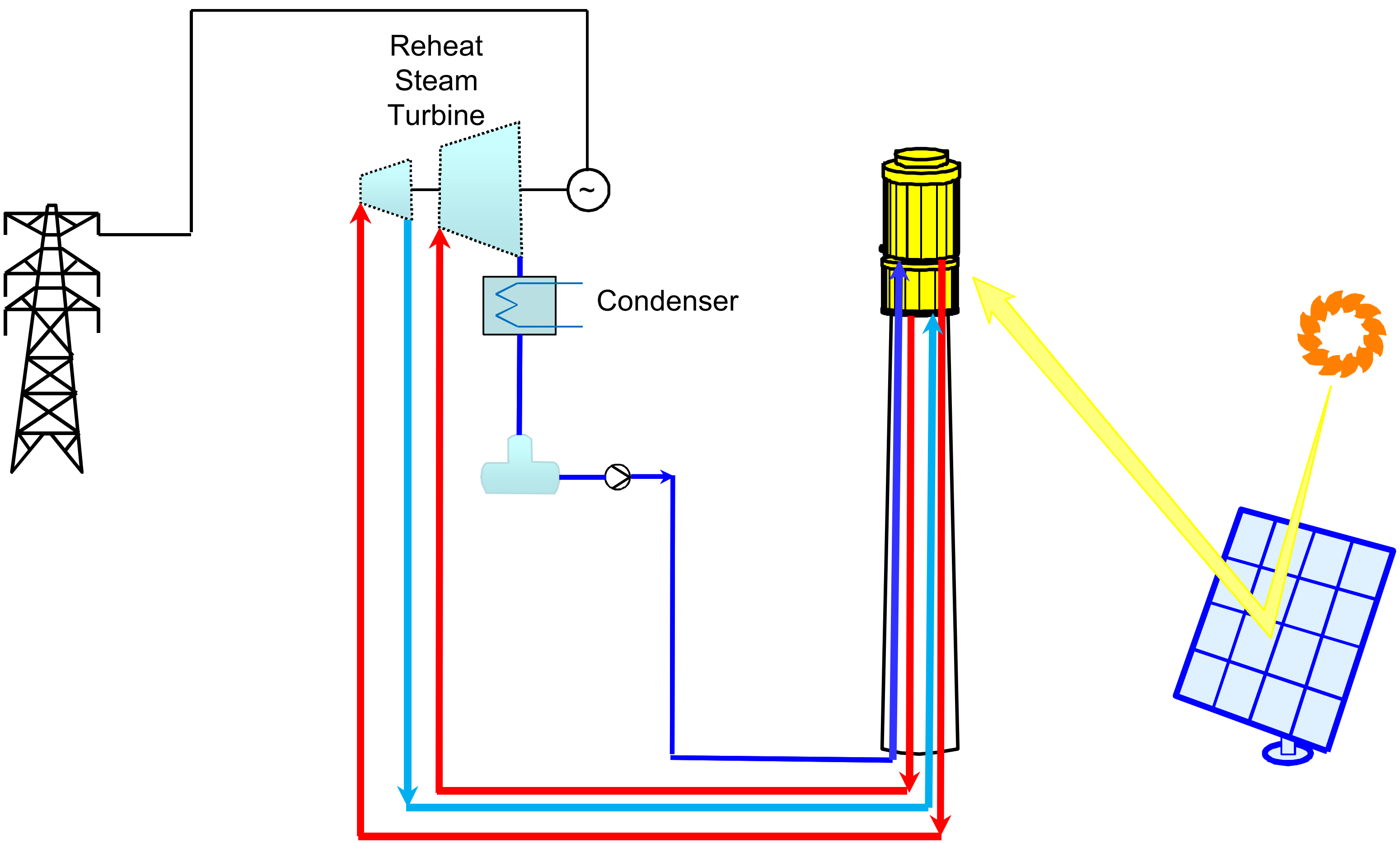
Challenges

- Pressure losses moving air
- Lower efficiency receiver
- Low heat transfer coefficient
- Less effective thermal storage
- High perceived technical risk
  - Receiver durability
  - Scale-up risk
- Learning curve

Direct Steam Power Towers

- Why direct steam?
  - Well understood boiler technology
  - High reliability
  - Relatively easy to handle
- Attributes of steam
  - Wide temperature use
  - High temperature stability
  - Good compatibility with common materials
- Examples:
  - 390 MWe BrightSource Ivanpah
  - 10 MWe Abengoa PS10 & 20 MWe PS20
  - 5 MWe eSolar Sierra

Schematic of Direct Steam Power Towers



Direct Steam Power Tower Advantages and Challenges

Advantages

- Builds off established steam technology from fossil industry
- Potentially high reliability receiver
- High efficiency receiver
- Uses common materials
- Can be hybridized
- Can incorporate storage
- Lower perceived technical risk

Challenges

- Turbine output directly tied to solar irradiance (unless mitigated with storage or hybridization
- Less effective thermal storage
- Boiler maintenance in an elevated environment
- Learning curve on how to operate