Concentrated Solar Power on Demand

CSPonD

Liquid Salts as Direct Receiver and Storage Media

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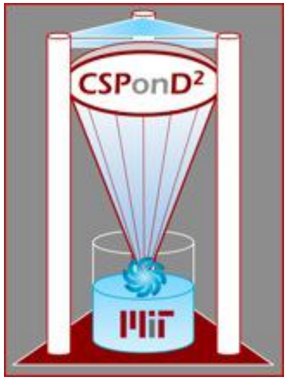
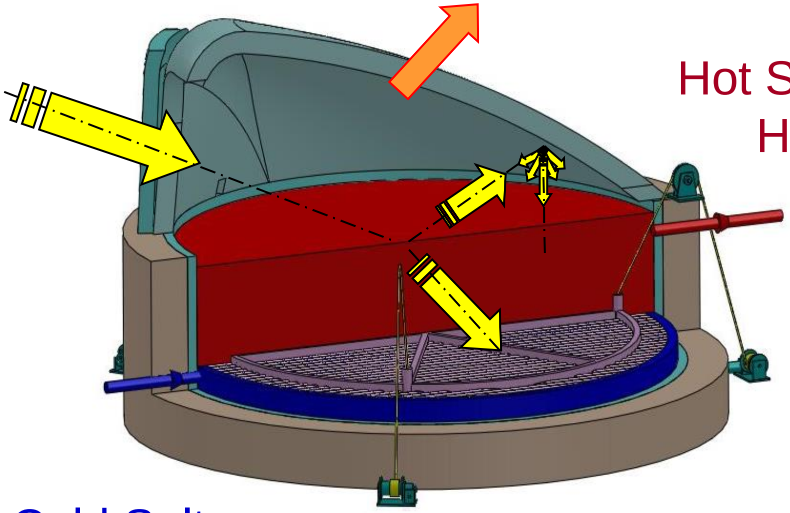


January 2015

CSPonD Summary

- Solar thermal power system
- Direct conversion of light from heliostats to heat by absorption in liquid salt bath
- Liquid salt provides heat storage
- 24 hour power production



Light from Heliostats Absorbed As Travel Through Molten Salt

Outline

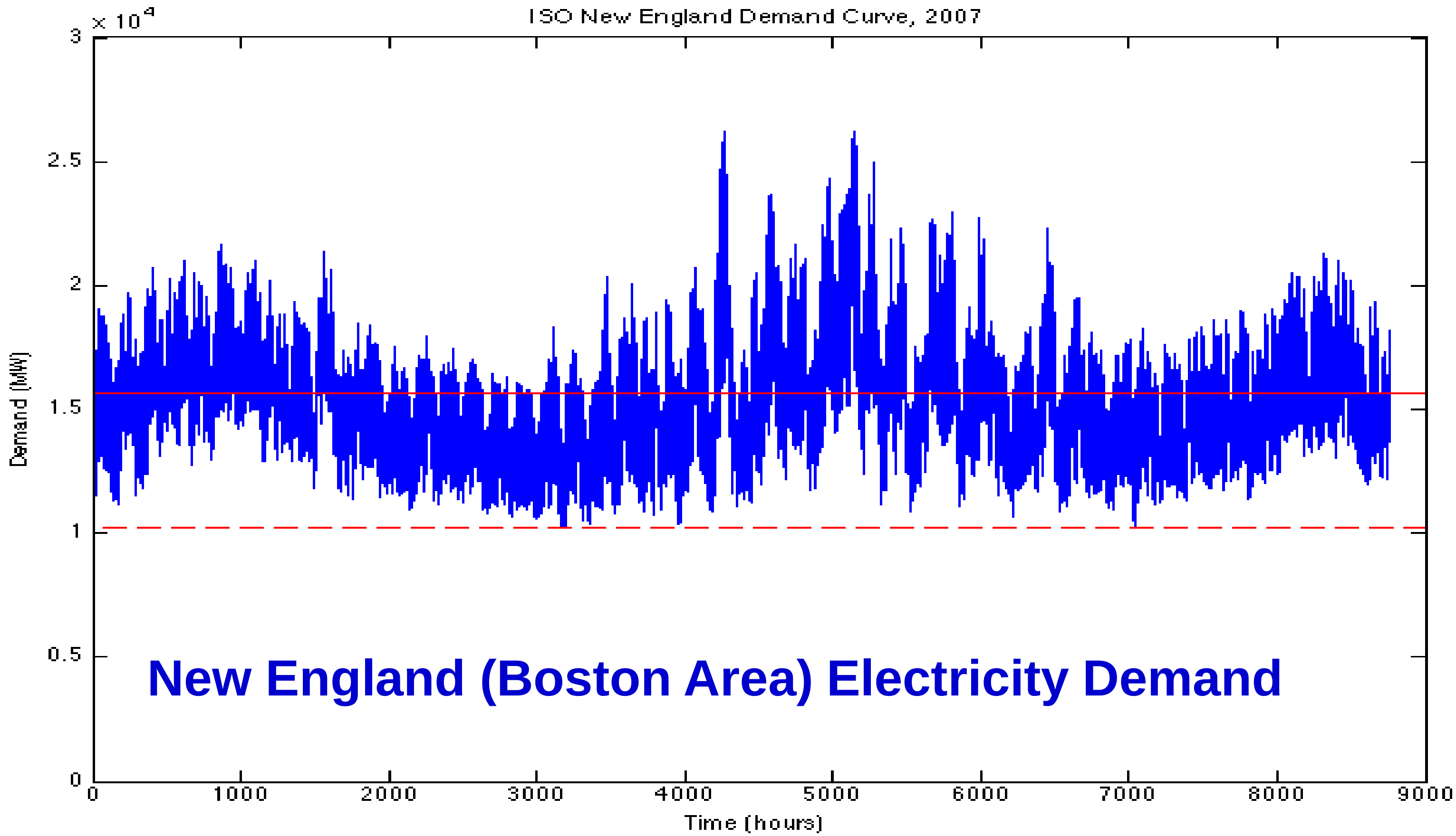
- The Electricity Market: Defining Requirements
- CSPonD
  - Description
  - Experimental Program
  - Status
- Backup Information

The Electricity Market

Starting Point for Design Goals

Electricity Demand Varies With Time

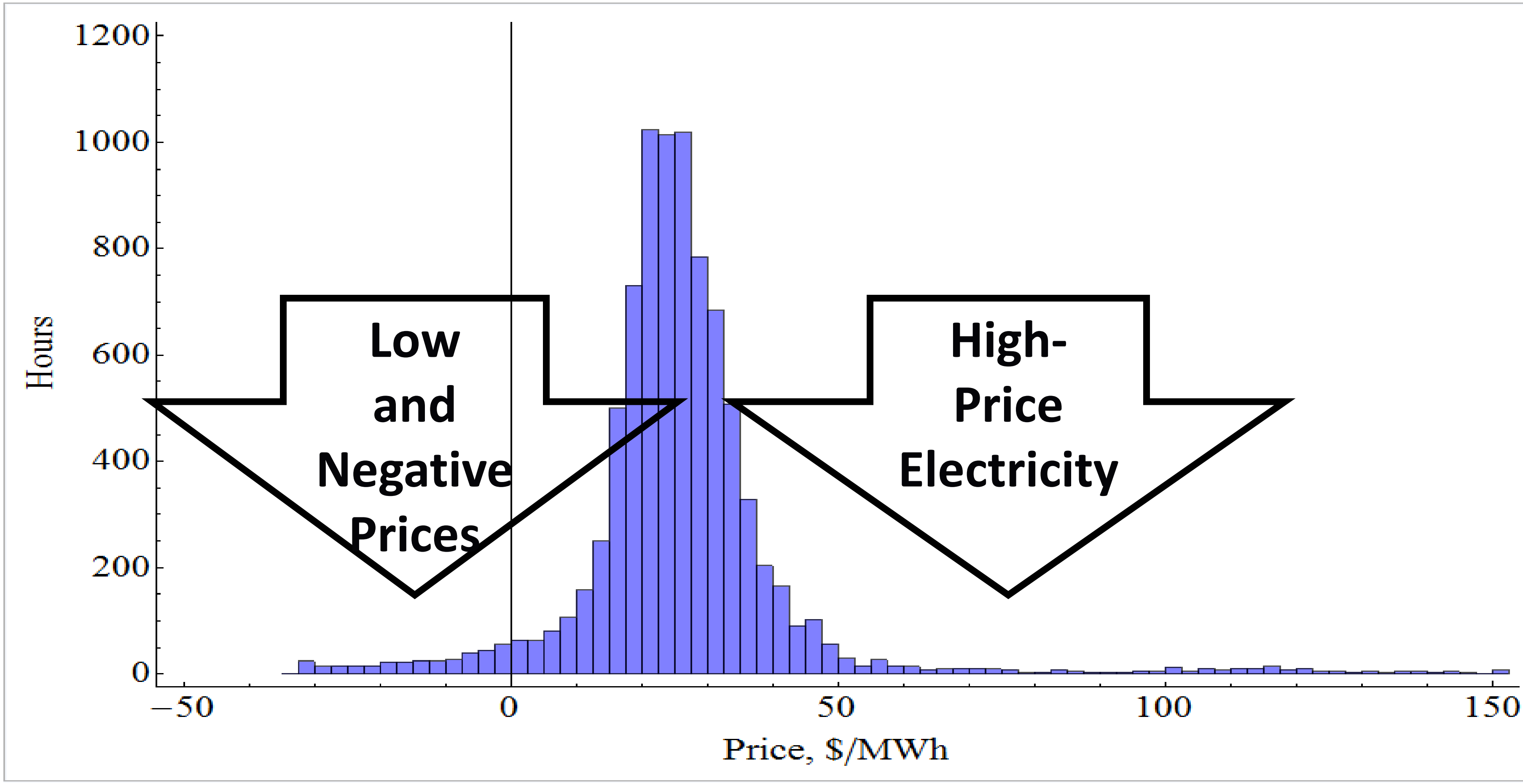
No Combination of Nuclear and Renewables Matches Electricity Demand



Demand (10^4 MW(e))

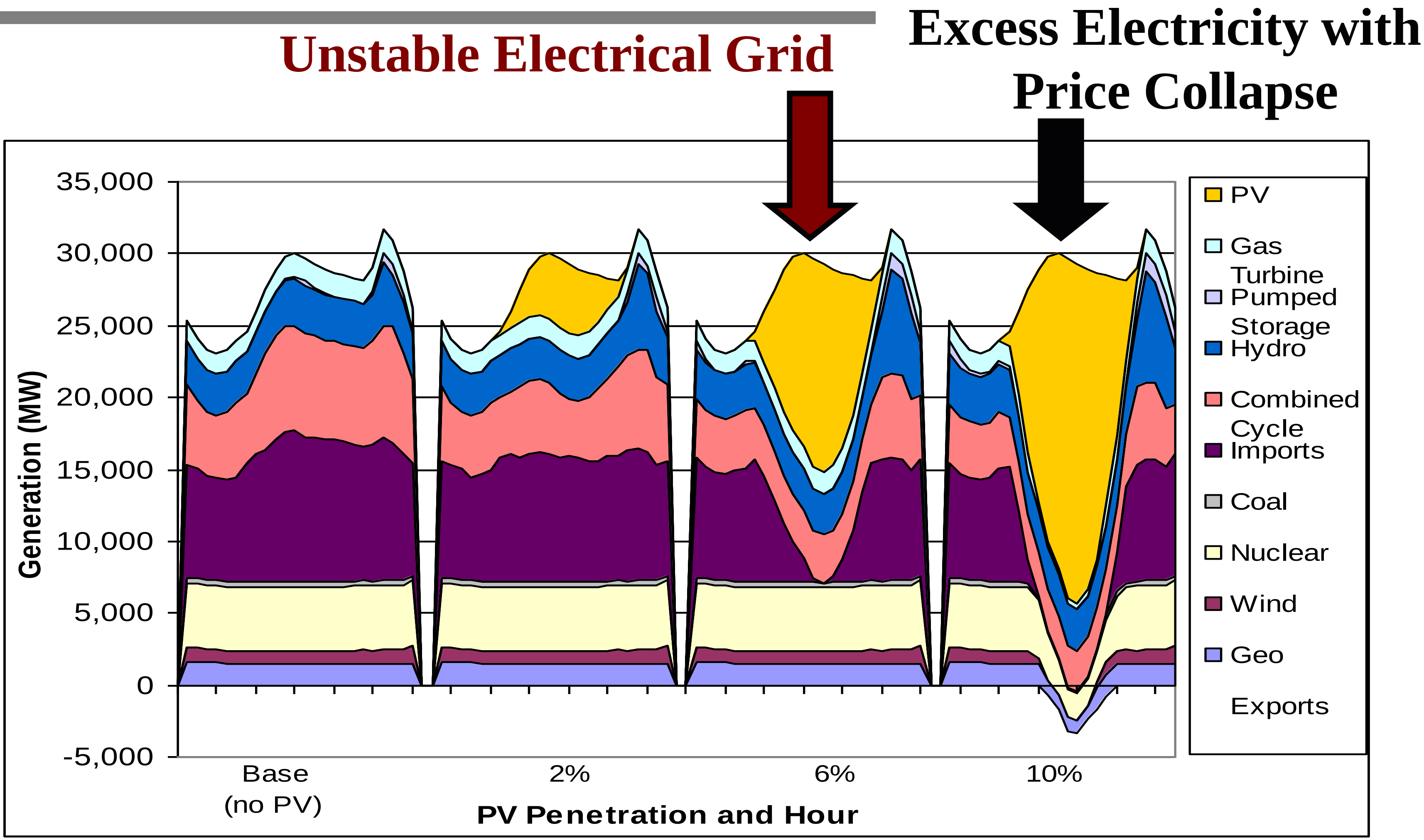
Time (hours since beginning of year)

In a Free Market Electricity Prices Vary



2012 California Electricity Prices

Adding Solar and Wind Changes Electricity Prices & Price Structure

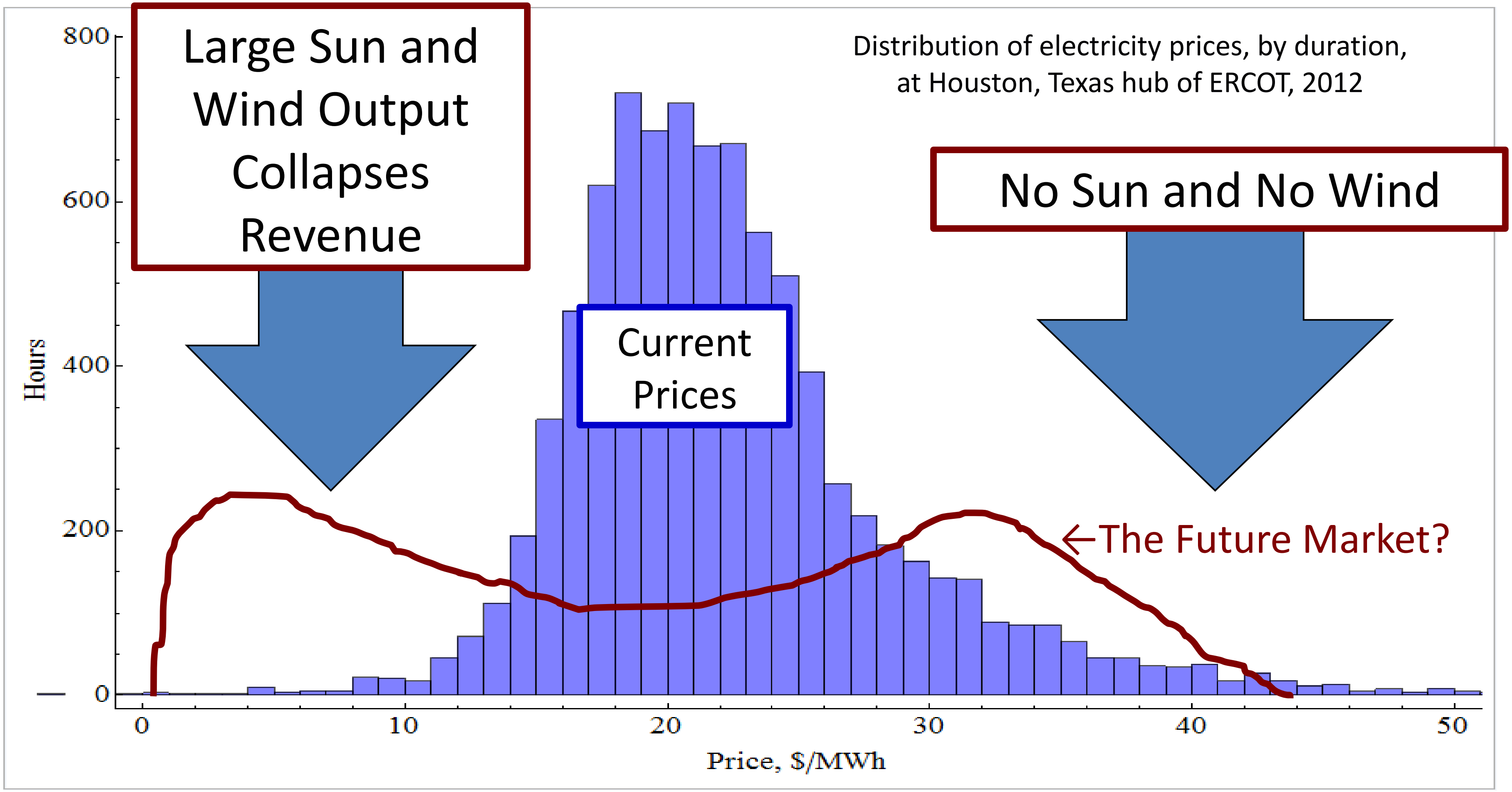


California Daily Spring Electricity Demand and Production with Different Levels of Annual Photovoltaic Electricity Generation

Notes on California Solar Production

- Far left figure shows mix of electricity generating units supplying power on a spring day in California. The figures to the right shows the impact on grid of adding PV capacity assuming it is dispatched first—low operating cost.
- Percent PV for each case is the average yearly fraction of the electricity provided by PV. The % of power from PV is much higher in late June in the middle of the day and is zero at night. Initially PV helps the grid because PV input roughly matches peak load. Problems first show up on spring days as shown herein when significant PV and low electricity load.
- With 6% PV, wild swings in power supply during spring with major problems for the grid. By 10% PV on low-electricity-demand days PV provides most of the power in the middle of many spring days.
- In a free market PV or producers with zero production costs will accept any price above zero. As PV grows, revenue to PV begins to collapse in the middle of the day. Collapsing revenue limits PV new build. Same happens if lots of wind is built. Large-scale PV or wind also damages base-load electricity market while increasing market for peak power when no sun or wind. In the U.S. that variable demand is getting filled with gas turbines with increases in greenhouse gas emissions.
- The revenue problem with renewables is similar to selling tomatoes in August when all the home-grown tomatoes turn red and the price collapses to near zero
- The other part of the story is the need for backup power when low wind or solar. For example, in Texas only 8% of the wind capacity can be assigned as dispatchable. That implies in Texas for every 1000 MW of wind, need 920 MW of backup capacity for when the wind does not blow—almost a full backup of wind. In the Midwest grid, only 13.3% of the wind capacity can be assigned as dispatchable. Consequently, with today's technologies large scale renewables implies large-scale fossil fuel usage

Low-Carbon Electricity Free Market Implies More Hours of Low / High Price Electricity



Future Solar Economics Poor If Sell When Sun is Out

MIT Concentrated Solar Power on Demand (CSPonD)

Description

Power Plus Storage

Joint Program Between MIT Mechanical and Nuclear Science and Engineering Departments

Alex Slocum leads the CSPonD Project. C. Forsberg leads the Fluoride-salt-cooled High-temperature Reactor (FHR) project—see appendix. Both projects both based on properties of high temperature salts with many common challenges.

A. Slocum, J. Buongiorno, C. W. Forsberg, T. McKrell, A. Mitsos, J. Nave, D. Codd, A. Ghobeity, C. J. Noone, S. Passerini, F. Rojas, "Concentrated Solar Power on Demand," *Journal Solar Energy*, **85**, 1519-1529, 2011

Existing Solar Power Technology

- Mirrors reflect sunlight to boiler
- Boiler tubes on top of tall tower absorb light
- Heat water and convert to steam
- Steam turbine produces electricity

PS-10, 11 MWe peak, image courtesy of N. Hanumara

The Challenge is Cost

- Low efficiency system
  - In theory high efficiency
  - In practice
    - Lower steam temperatures to avoid boiler-tube thermal fatigue from variable light
    - High heat loses from exposed boiler tubes
- Marginal economics
  - Need efficient light-to-electricity system
  - Peak power not match peak demand with peak electricity prices

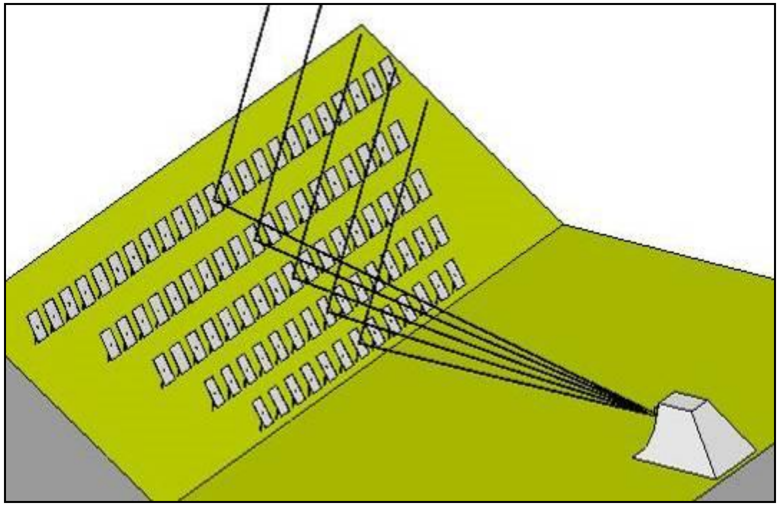
PS-10, Spain, 11MWe peak, image courtesy of N. Hanumara

CSPonD Description

Figure Next Page

- Mirrors shine sunlight to receiver
- Receiver is a high-temperature liquid salt bath inside insulated structure with open window for focused light
  - Light volumetrically absorbed through several meters of liquid salt
  - Structure minimizes heat losses by receiver
  - Enables salt temperatures to 900°C
- Small window minimizes heat losses but very high power density of sunlight through open window
  - Power density would destroy conventional boiler-tube collector
  - Light absorbed volumetrically in several meters in salt
- Requires high-temperature (semi-transparent) salt

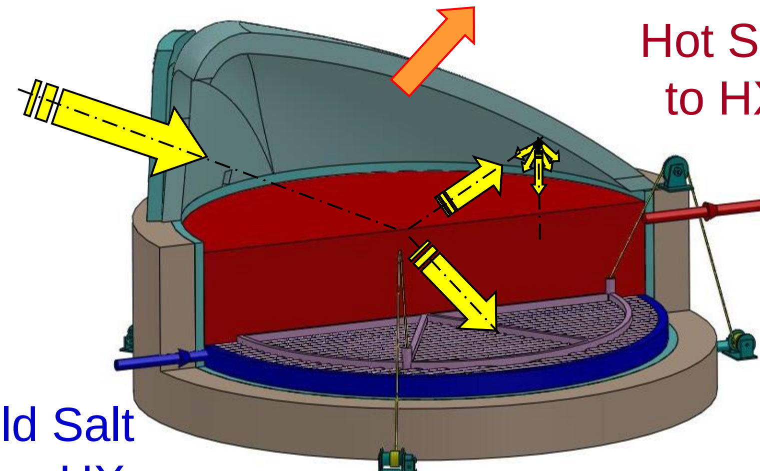
Two Component System



Light Reflected From Hillside Heliostats to CSPonD System

(Not to scale)

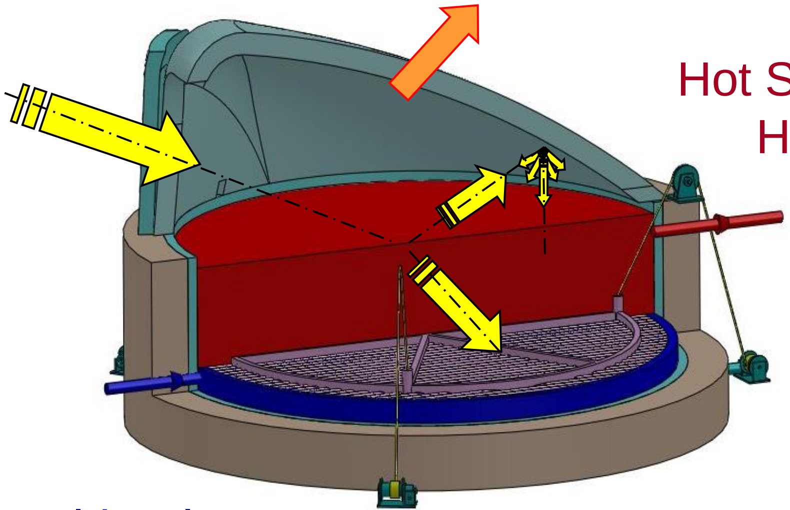
Flat Land Options Exist



Light Collected By Absorption in Liquid Salt Inside Insulated Building With Open Window

CSPonD Heliostats Shine Light Through "Pinhole" into Liquid-Salt Collector

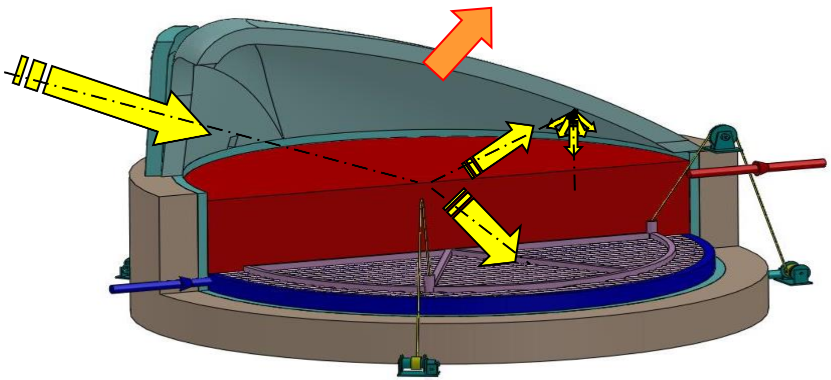
- Efficient light-to-heat collection
  - Concentrate light
  - Focus light through open window in insulated structure
  - Minimize heat losses
- Challenge
  - Light energy per unit area very high
  - Will vaporize solid collectors



Light Collected As Travel Through Molten Salt Similar to Sunlight Absorbed by the Ocean

Light Focused On "Transparent" Salt

- Light volumetrically absorbed through several meters of salt
- Molten salt experience
  - Metal heat treating baths (right bottom)
  - Molten salt nuclear reactor
- Advantages
  - No light-flux limit
  - No thermal fatigue
  - High efficiency
  - Energy storage



Like Ocean Absorption of Sunlight

Molten Chloride Salt Metallic Heat Treatment Bath (1100°C)

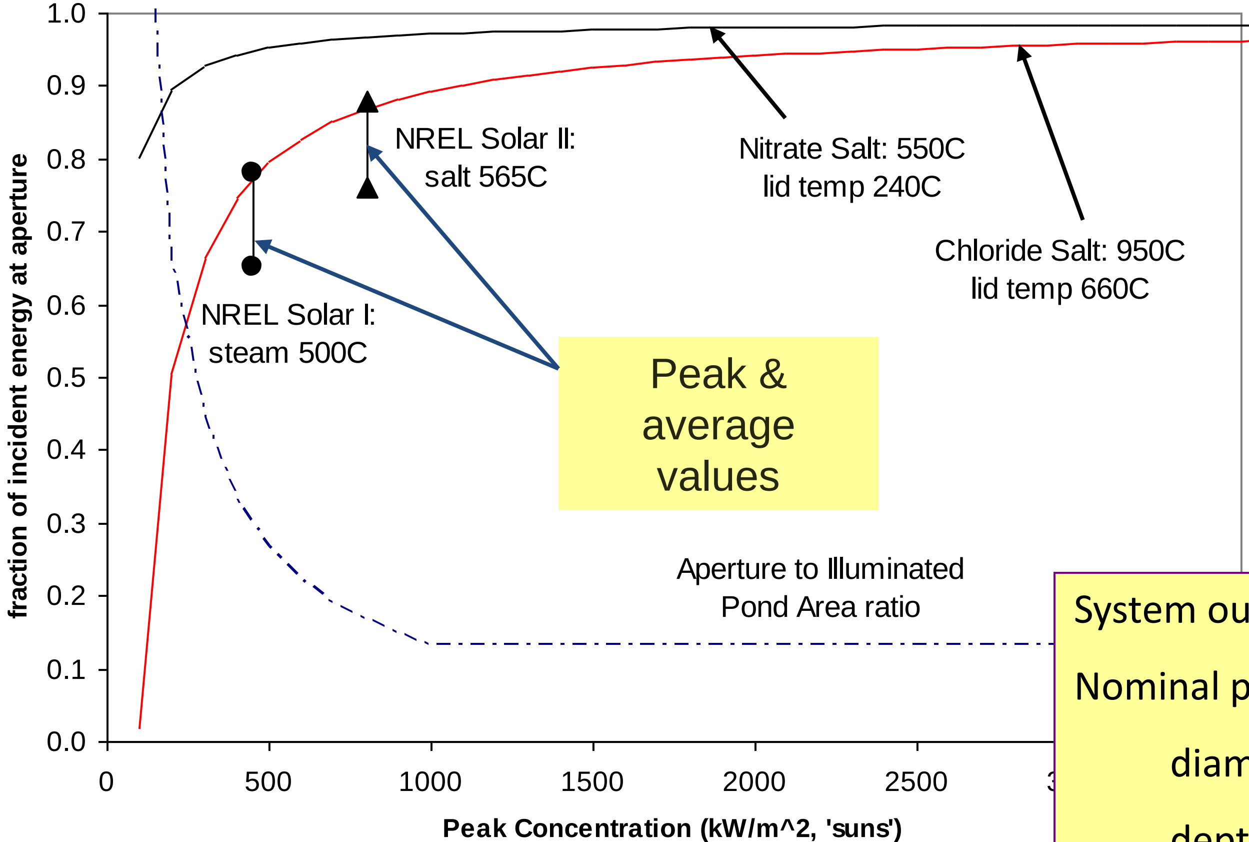
Two Classes Of Molten Salts

Appearance of molten

NaCl-KCl salt at 850°C

- Near-term: Nitrates
  - Used in some concentrated thermal solar systems
  - Off the shelf
  - Temperature limit of ~550°C (Decompose salt)
- Long-term: Chlorides and Carbonates
  - Thermodynamically stable
  - Peak temperatures > 1000°C

System Design Enables Efficient Light Collection and High Temperatures



NREL (2003)

Compares favorably with measured values for CSP Power Tower Systems

System output (MWe):	4
Nominal pond size	
diameter (m):	25.0
depth (m):	5.0
Avg beam down angle (deg):	21.4
Nitrate Salt, Lid peak temp (C):	550/240
Chloride, Lid peak temp (C):	950/660

Salt Selection

Salts Used in Commercial Metal Heat Treating Operations

Initial candidates (Other options to be examined):

- Binary nitrate mixture, KNO_3-$NaNO_3$, (eutectic 40-60 wt%, melting point 222°C)
  - Commercial in closed solar systems
  - Family of options with variable compositions
- Ternary carbonate salt, Li_2CO_3-Na_2CO_3-K_2CO_3 “cartecsal” (eutectic 32-33-35 wt%, melting point 397°C)
  - Used for heat treating metals
  - No experience in power cycles
- Binary chloride salt, NaCl-KCl (eutectic 50-50 wt%, melting point 657°C)—long term option

Properties At Operating Conditions

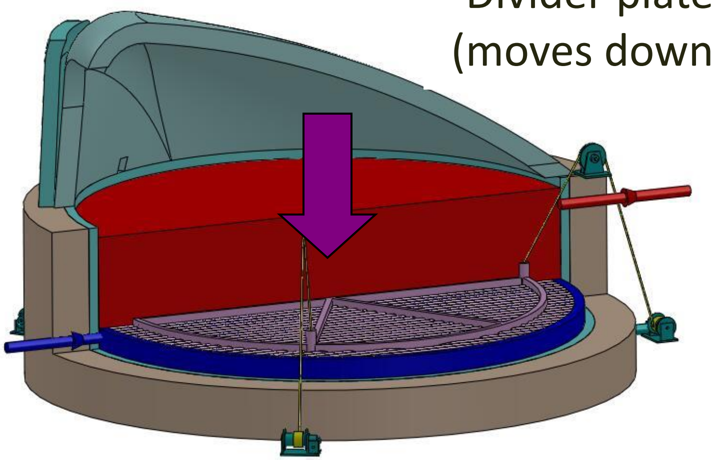
	NaCl-KCl at 800°C	Li_2CO_3-Na_2CO_3-K_2CO_3 at 800°C	KNO_3-$NaNO_2$-$NaNO_3$ at 350°C
Density kg/m^3	1520	1902	1850
Viscosity mPa·s	1.2	4.3	2.360
Thermal conductivity W/m-K	0.45	0.822	0.61
Specific heat J/kg-K	1090	1560	1560
Power Cycle Temp. °C	~800	~700	~500

CSPonD Integral Heat Storage

- Salt tank has insulated separator plate
- Plate functions
  - Separates hot and cold salt
  - Bottom light absorber creating mixing currents in hot salt
- Storage role
  - If excess heat input, plate sinks to provide cold salt to heat to become hot salt and storage
  - If power demand high, plate raised with cold salt return from power cycle stored under plate

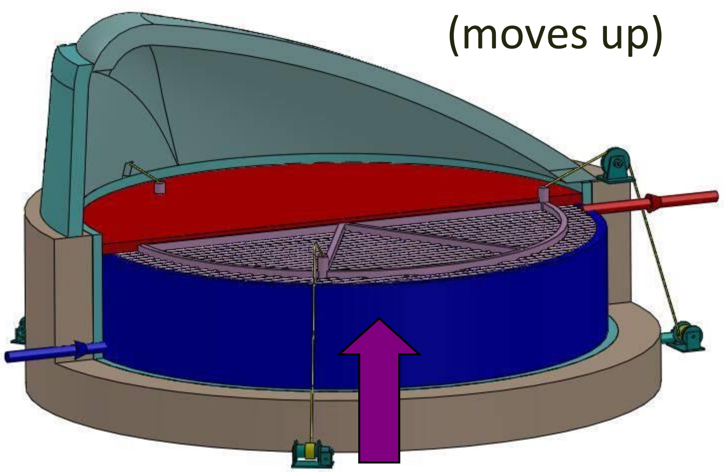
Daytime

Divider plate
(moves down)



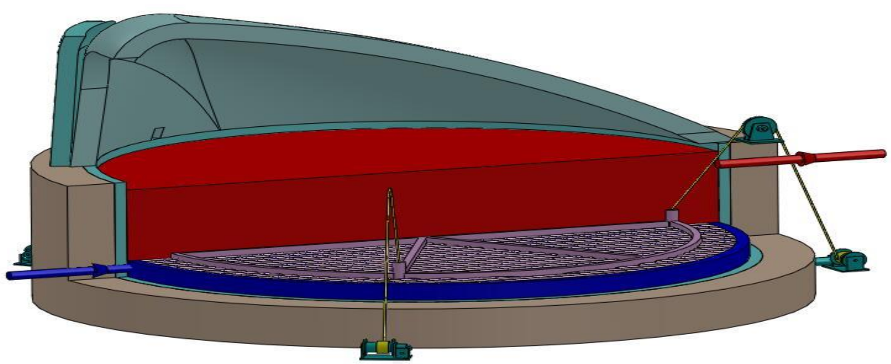
Nighttime

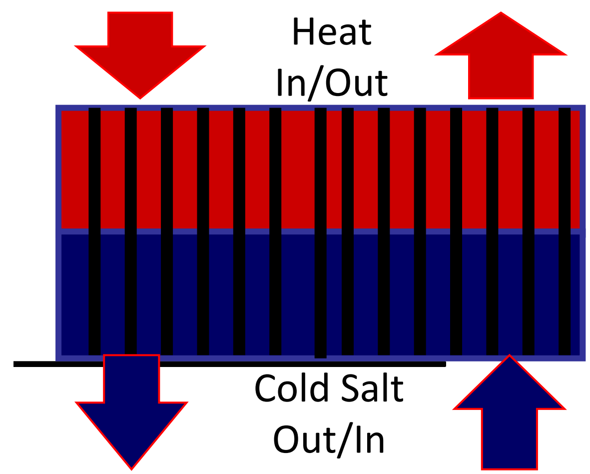
Divider plate
(moves up)



Alternative CSPonD Heat Storage

- Separate collector and heat storage tank
  - Liquid storage with solid fill (Several options)
  - May reduce required salt inventory
  - Centralized storage from several receivers with common power plant—lower power-cycle costs
- No definitive studies
  - New hot salt storage options (Backup materials)





Multiple Power Cycle Options

Salt Temperature: 500°C, 700°C, and 700+°C

- Steam (500 to 700°C)
  - Off-the-shelf technology
  - Expensive
- Air Brayton (700°C and up)
  - Existing technology
  - Small or limited cooling water requirements
  - Requires 700°C salt temperatures
- Supercritical carbon dioxide (600 to 700°C)
  - High efficiency
  - Very compact and potentially low-capital cost
  - Advanced technology: Not fully developed

Options for Power and Heat

- CSPonD has cooling systems in lid
  - Prevent overheating and equipment damage
  - Cooler temperatures than salt to provide condensing surface for salt vapors
    - Lowers salt losses at very high temperature operations
    - Creates “liquid” mirror reflective surface to minimize heat loses
- High temperature heat—not as hot as salt so options for use
  - Integrate into power cycle
  - Use for other uses such as water desalination

CSPonD

Experimental Program

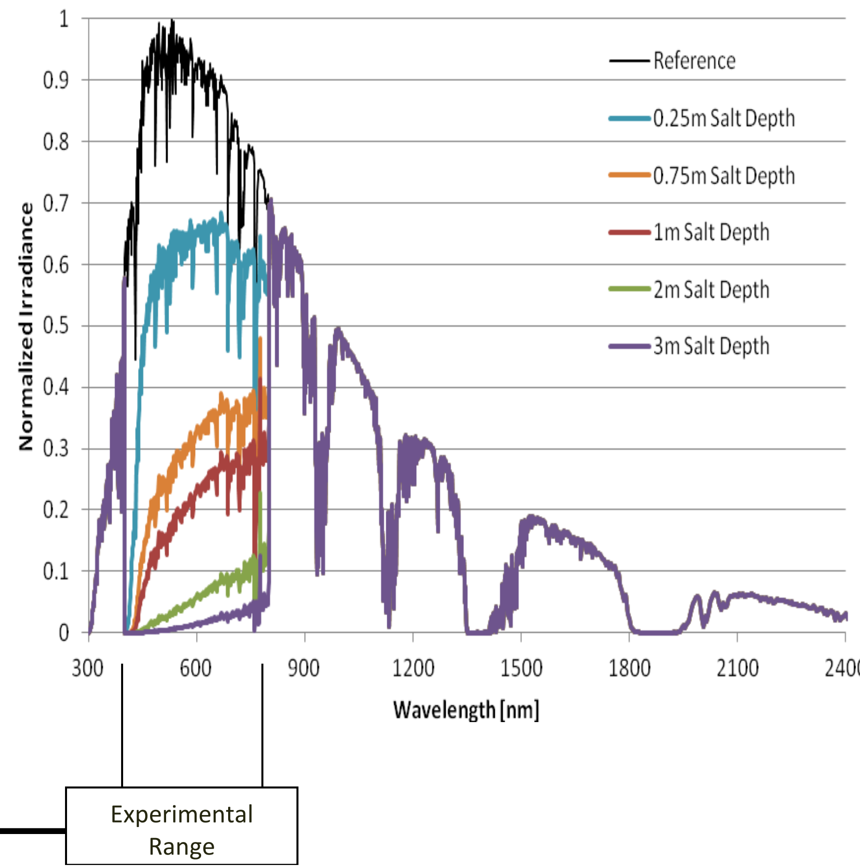
Salt Optical Characterization

Experimental Molten Salt Measurements

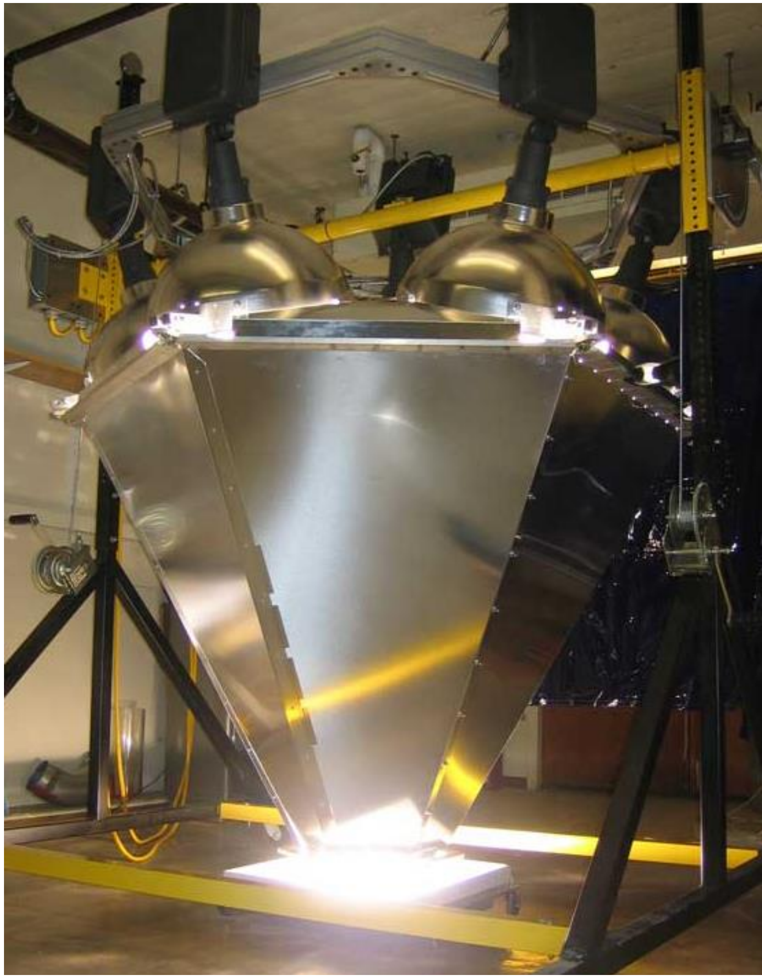
(l) Variable optical path length transmission apparatus

(r) Appearance of molten NaCl-KCl salt at 850°C

Solar Irradiance Attenuation of NaCl-KCl (50-50wt%) salt at 850°C

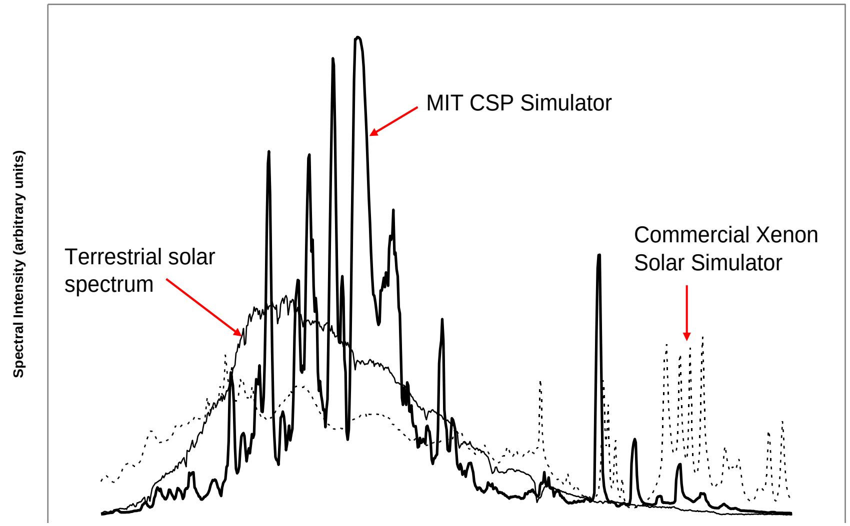


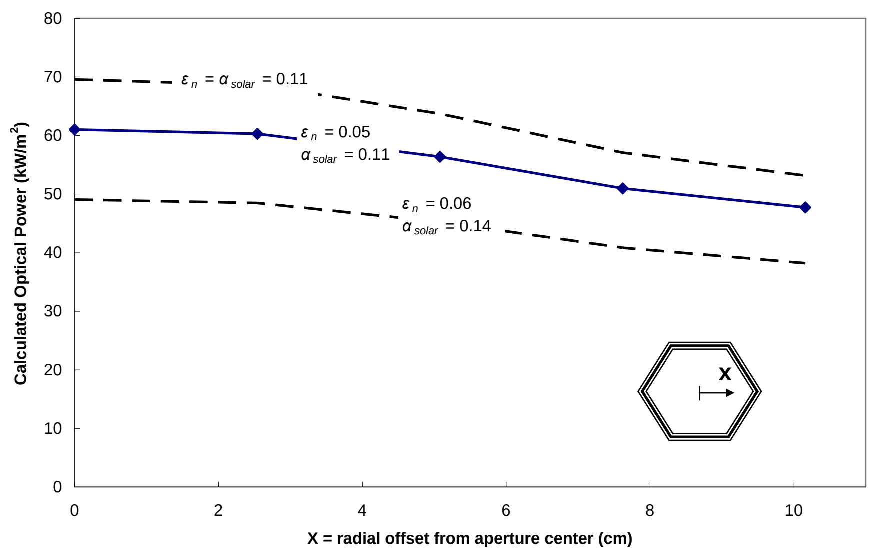
60-Sun Solar Simulator



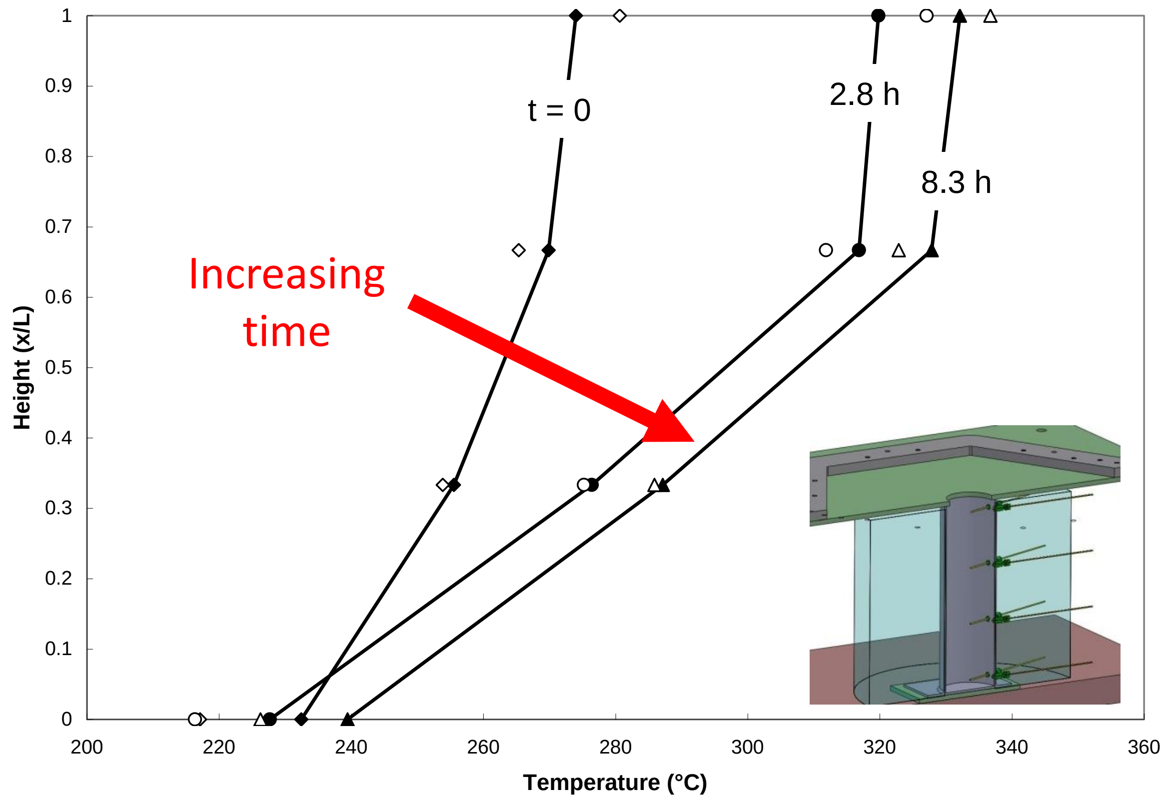
MIT CSP Solar Simulator

10.5 kW_e



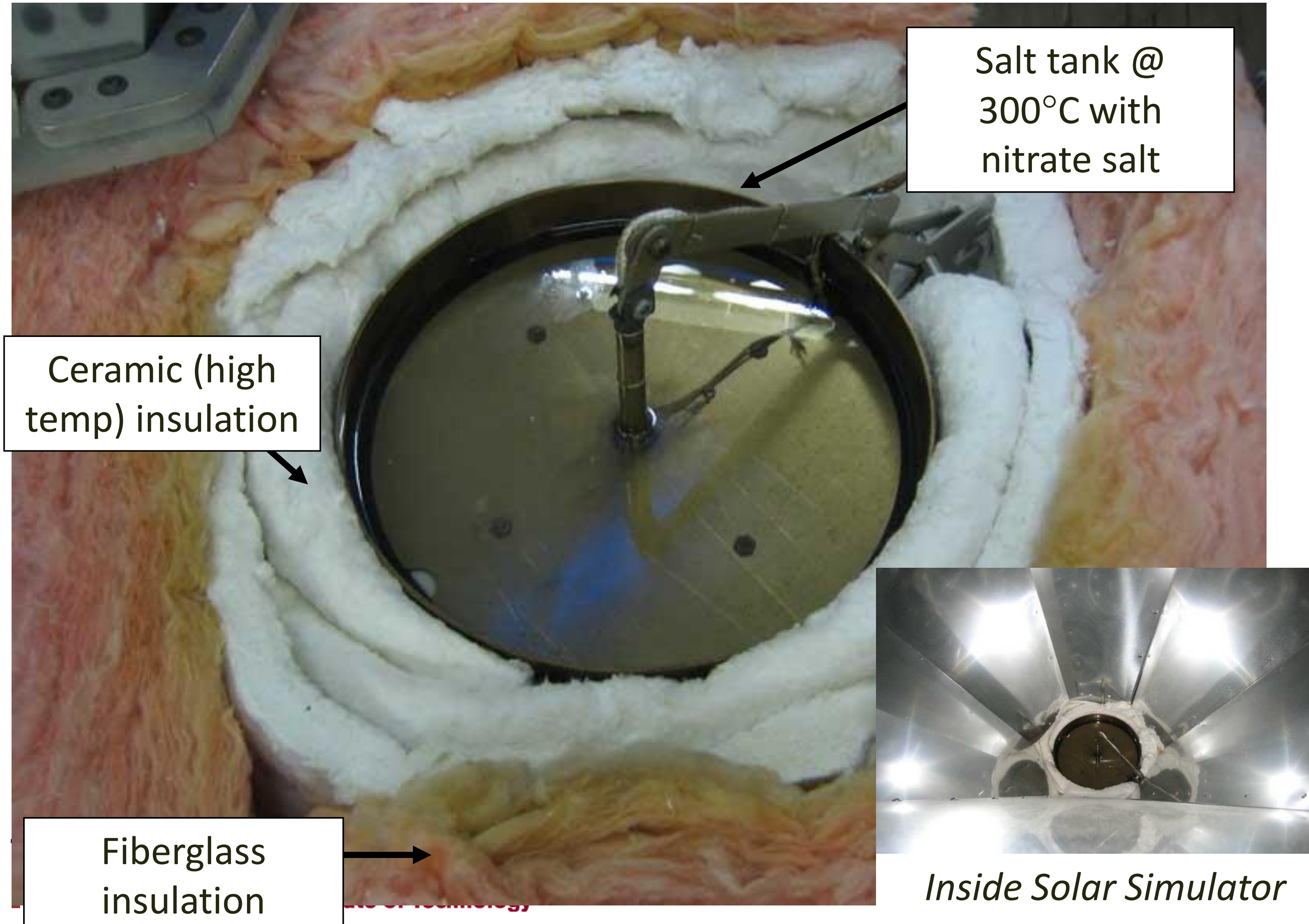


Volumetric Light Absorption Experiments



Temperature distribution of $NaNO_3$-KNO_3 (60-40wt%) heated optically

Virtual Two-Tank System Testing



Inside Solar Simulator

CSPonD Status

Joint Program Between MIT and Masdar Institute, Abu Dhabi, UAE

Joint Program Initiated 2014

- Design and deploy a pilot CSPonD experimental system in Abu Dhabi
- Field proof of principle using Masdar solar test facilities within 3 years
- Includes new Chinese partners

CSPonD Project

Masdar Test Facility

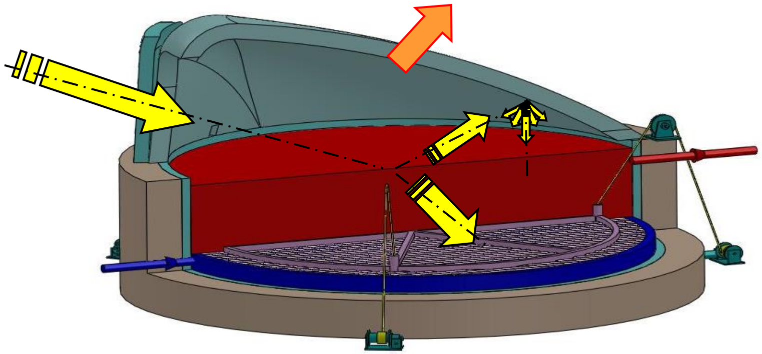
CSPonD Test Module

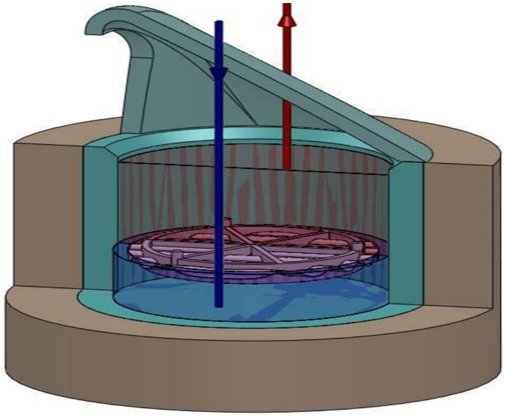
To Be Installed Under Tower

CSPonD Conclusions

- Analysis and experiments indicate better economics than existing concentrated solar thermal systems
  - Higher efficiency
  - Electricity when needed
- Significant uncertainties
  - Pilot plant to address many uncertainties
  - Large incentives for higher-temperature salt than nitrate but limited experimental data
- Experimental program between MIT and Masdar Institute to deploy small pilot plant at test facility in Abu Dhabi
- Recent discoveries indicate route to major improvements

Questions





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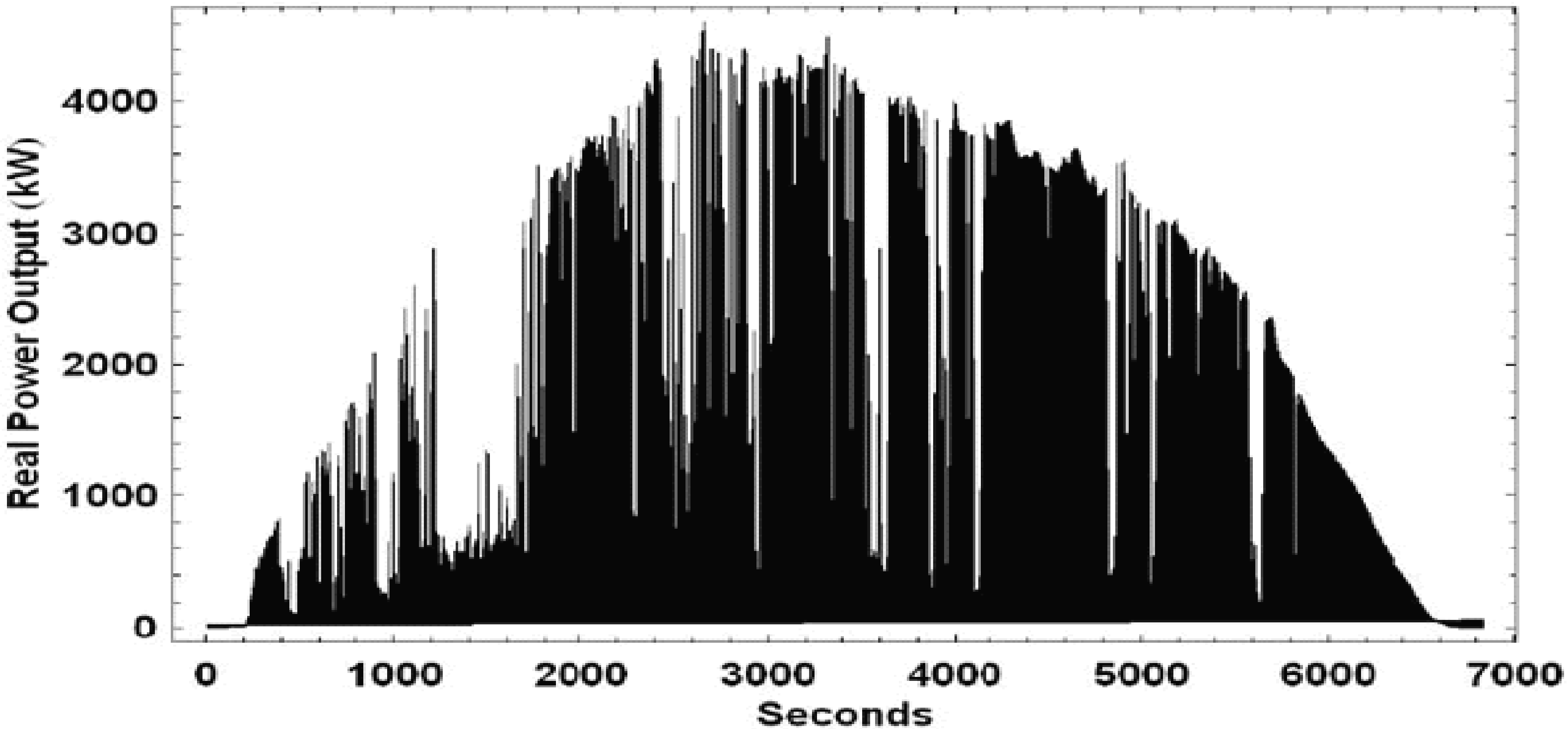
Biography: Charles Forsberg

Dr. Charles Forsberg is the principle investigator and director of the Fluoride-salt-cooled High-Temperature Reactor Project. He is a co-inventor and principle investigator for the Concentrated Solar Energy on Demand (CSPonD) system. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and the 2014 Seaborg Award from the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

Solar Cost Is Generation Plus Storage To Meet Electricity Demand

Photovoltaic Costs Include Backup Storage

Power output from a 4.6 MW PV system in Springerville, Arizona at 10 second time resolution for one day are shown



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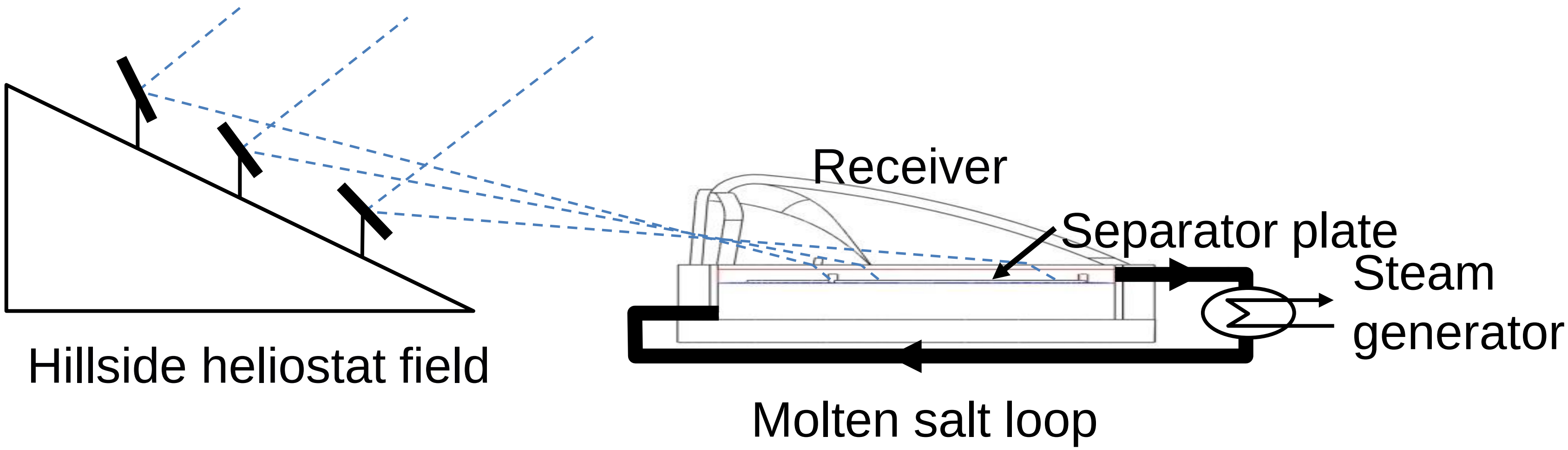
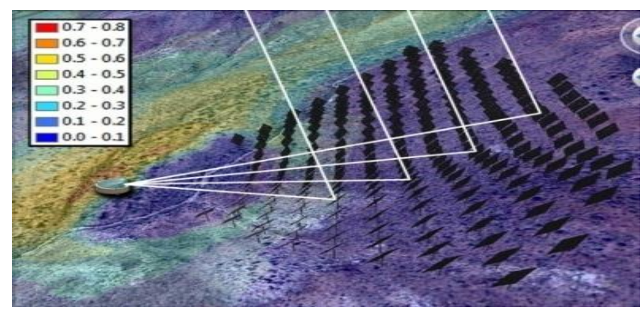
Apt, J. (n.d.). The Spectrum of Power from Utility-Scale Wind Farms and Solar Photovoltaic Arrays. *Carnegie Mellon Electricity Industry Center Working Paper CEIC-08-0*

Concentrated Solar Power on Demand (CSPonD)



Conventional CSP "Power Tower"



Hillside beam-down **CSPonD** System

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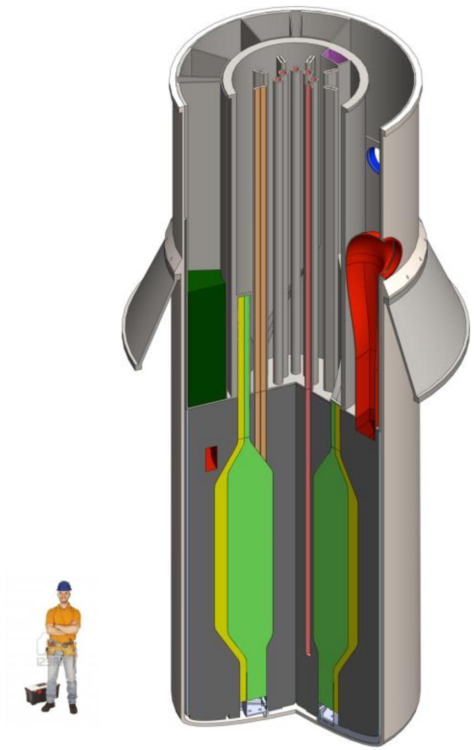
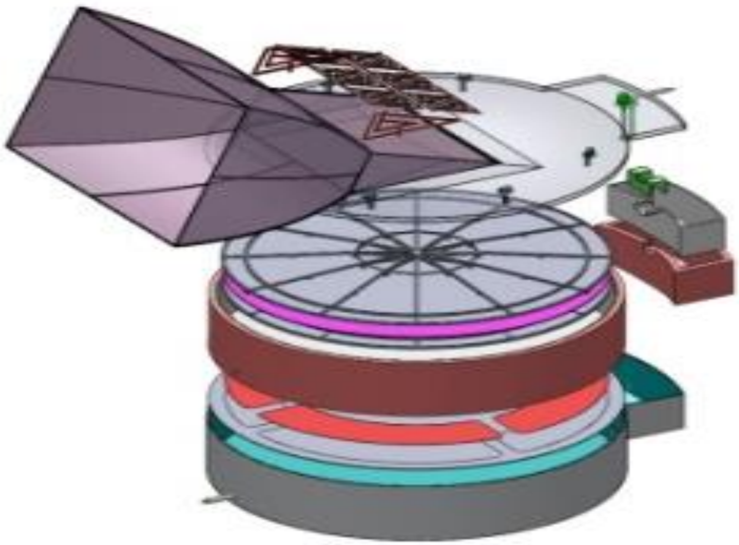
High-Temperature Salt Power Programs at MIT

MIT Has Two High-Temperature-Salt Electricity-Generation Projects

Shared Liquid-Salt Technology Base: Heat Transfer, Heat Storage, and Power Cycles



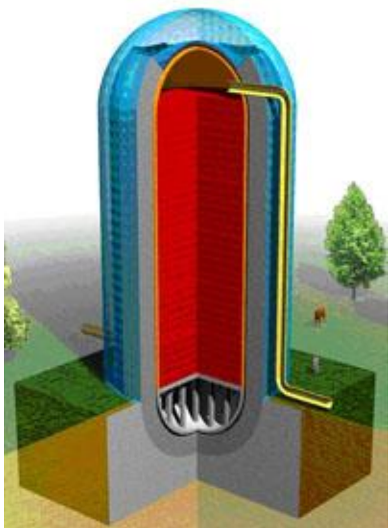
Fluoride-Salt-Cooled High-Temperature Reactor (FHR)



Concentrated Solar Power on Demand (CSPonD)

The Base-Load FHR Produces Variable Electricity to Match Market Needs

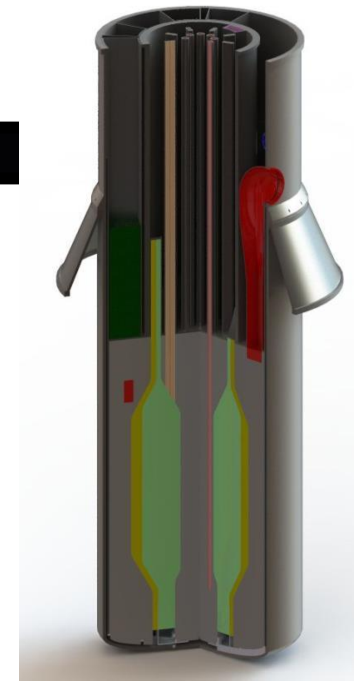
FIRES for Peak Electricity
Stored Heat

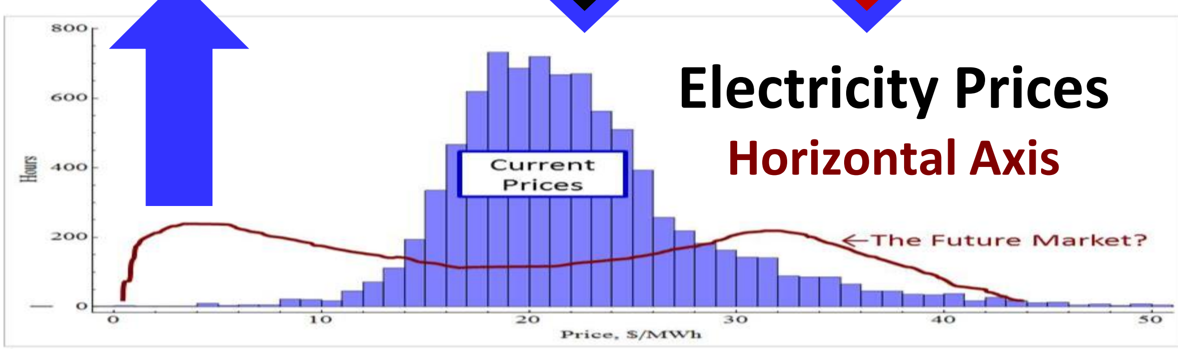


Combustible Fuels for Peak Electricity

Gas-Turbine (NACC)

Constant High-Temperature Heat (600 to 700 C)
Reactor (FHR)

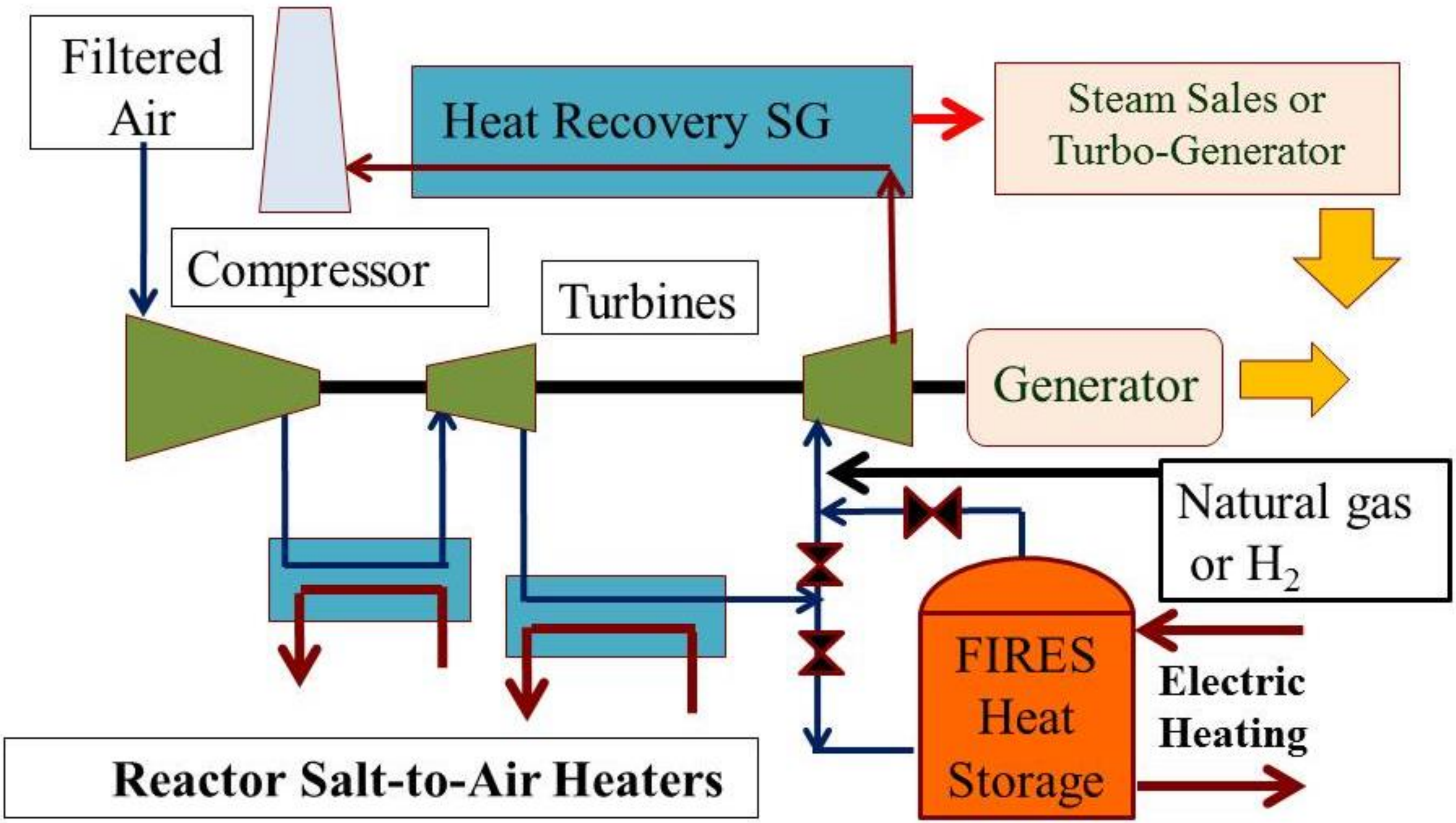




Electricity Prices
Horizontal Axis

NACC Power System

Base-load and Peak Electricity (Auxiliary Natural Gas or Stored Heat)



Notes on NACC (Long-term CSPond Option)

- With base-load operation, air is compressed, heated using heat from the FHR, sent through a turbine to produce electricity, is reheated using heat from the FHR to the same temperature (670C), sent through a second turbine to produce electricity and exhausted at low pressure to a heat recovery steam generator (HRSG)
- In the HRSG the warm air is used to produce steam to produce added electricity or steam for industrial sale.
- The base-load operations are very similar to a natural-gas fired combined cycle plant. The efficiency is ~42%. The cooling water requirements are about 40% of a conventional light water reactor. That is partly because of the higher efficiency and partly because some of the heat rejection is via warm air—similar to stand alone combined cycle natural gas plants.
- For peak power, after second reheat using nuclear heat, natural gas is injected into the hot air stream to raise compressed air temperatures. This increases electricity production from the second turbine and the HRSG.
- The system may also contain a Firebrick Resistance-Heated Energy Storage (FIRES) System. The firebrick is heated with electricity when the price of electricity is below that of natural gas. At times of high prices, compressed air after the second reheat is sent through FIRES to increase its temperature. This results in higher power output from the second turbine and the HRSG
- Peak heat to electricity efficiency is above 66% because it's a topping cycle above the lower-temperature 700C nuclear heat

FHR and CSPonD Share Liquid-Salt Heat-Transfer / Power-Cycle Technologies

Materials, Pumps, Power Cycles, Valves, Etc.

Nuclear

- New reactor concept
  - Forsberg, Peterson, and Pickard
- FHR (Joint MIT, Berkeley, Wisconsin program)
- High-temperature heat transfer loop between high-temperature reactors and power systems
- China to build first FHR (10 MWt) by 2020

Solar

- Drive to more efficient systems
- CSPonD
  - Near-term nitrate salts to 550°C
  - Next generation chloride or carbonate salts to 700°C
  - Nuclear systems only looking at 700°C systems