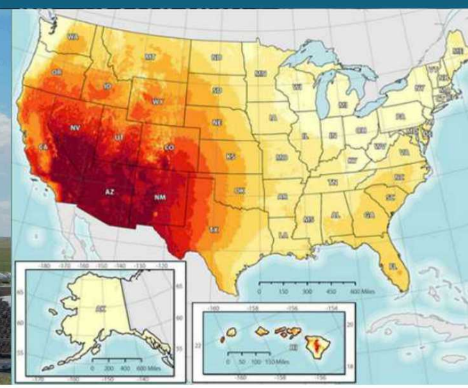
SAND2019-4701PE

Next Generation Concentrating Solar Energy for the 21st Century



PRESENTED BY

Kenneth M. Armijo, Ph.D.

National Solar Thermal Test Facility (NSTTF)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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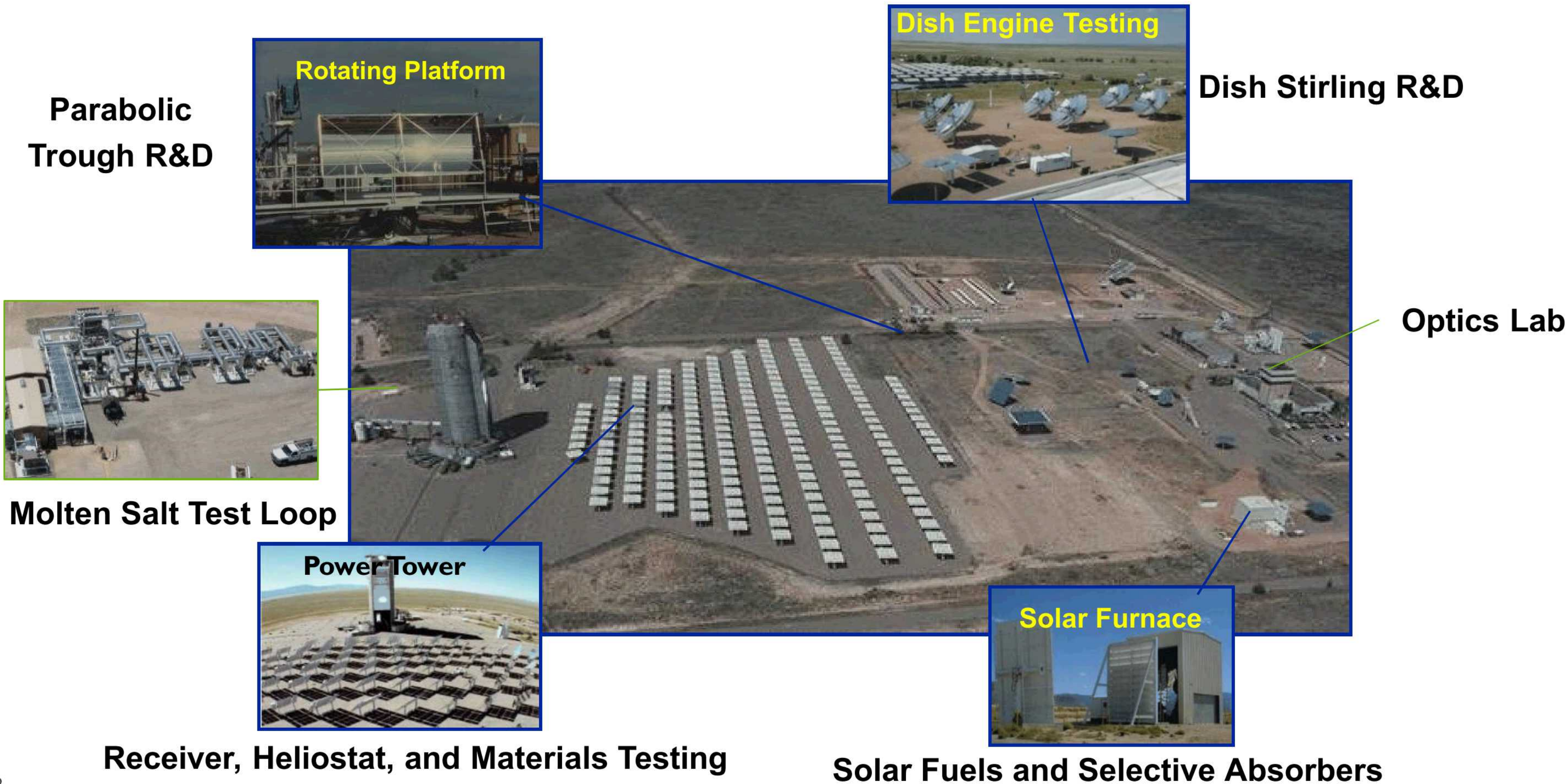
Sandia's National Solar Thermal Test Facility (40 Years of CSP R&D)

- Birthplace of Concentrating Solar Power (CSP) Industrial-Scale Research & Development
- Develop next-generation CSP technologies to provide dispatchable, clean solar-thermal generated electricity at higher conversion efficiencies.
- Realize significant reductions in Levelized Cost of Energy (LCOE) by making fundamental advances in CSP systems and power cycles to achieve the intent of the SunShot goals by 2020.



From Farmer to Labs Researcher

- From Sabinal, New Mexico
- USDA Organic Chile, Vegetable and Chile Farm
- SMTS @ Sandia Labs, NASA Shuttle Program Engineer & PhD at Berkeley
- Understanding water scarcity, engineering & energy from a personal perspective
- Changes in farming practices over the last 30 years

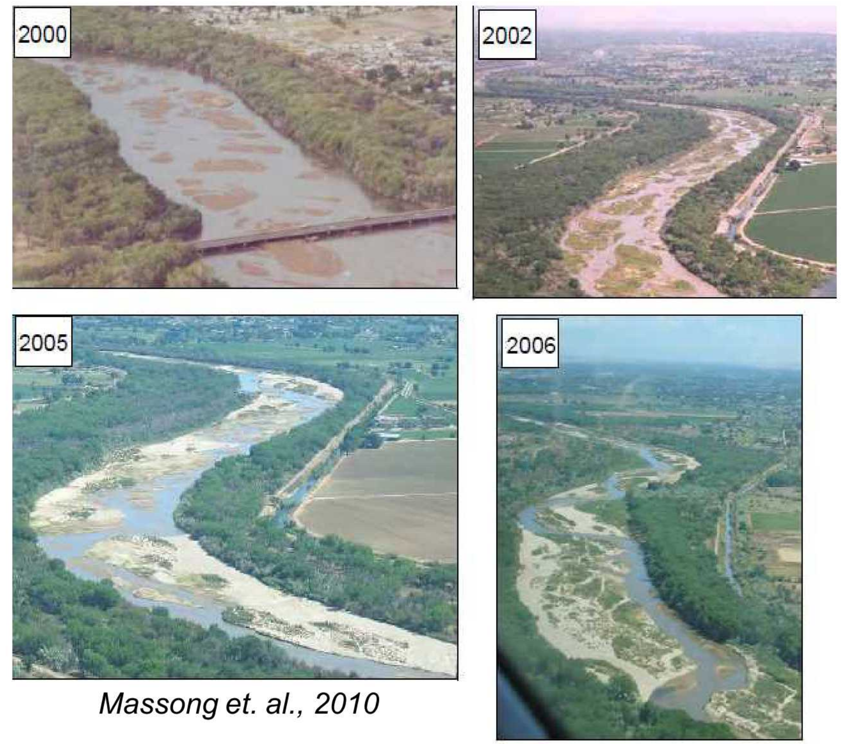


Sandia National Laboratories

Implications of Energy & Water in NM

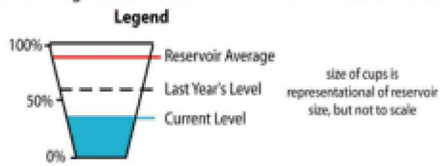
From a Central New Mexico Chile Farm

- Historical Struggles with Water and Necessity to Adapt
- Rio Grande by Belen, NM 2000-2006



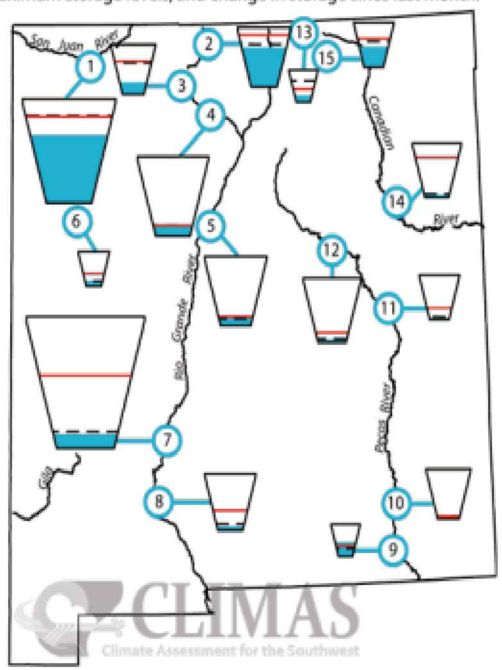
Massong et. al., 2010

New Mexico reservoir levels for July as a percent of capacity. The map depicts the average level and last year's storage for each reservoir. The table also lists current and maximum storage levels, and change in storage since last month.



Reservoir Name	Capacity Level	Current Storage*	Max Storage*	Change in Storage*
1. Navajo	69%	1175.9	1,696.0	-66.9
2. Heron	64%	257.5	400.0	-7.0
3. El Vado	19%	37.1	190.3	-31.2
4. Abiquiu	12%	147.2	1,192.8	-10.3
5. Cochiti	10%	51.2	491.0	2.1
6. Bluewater	12%	4.8	38.5	-0.4
7. Elephant Butte	8%	177.4	2,195.0	-89.0
8. Caballo	6%	20.7	332.0	-0.1
9. Lake Avalon	35%	1.4	4.0	-0.2
10. Brantley	1%	5.9	1008.2	-1.1
11. Sumner	2%	2.2	102.0	-1.9
12. Santa Rosa	1%	6.4	438.3	-0.2
13. Costilla	12%	1.9	16.0	-1.0
14. Conchas	3%	7.2	254.2	-2.6
15. Eagle Nest	43%	34.1	79.0	-2.1

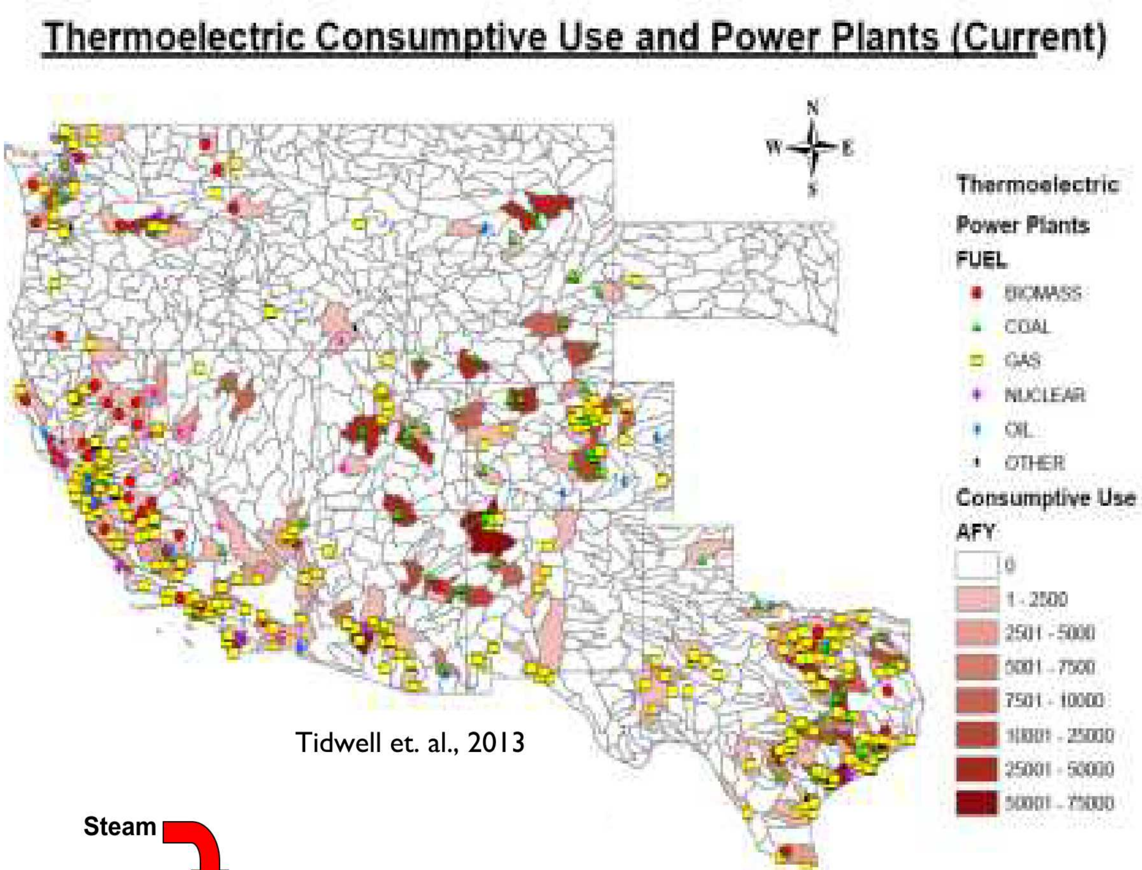
* thousands of acre-feet



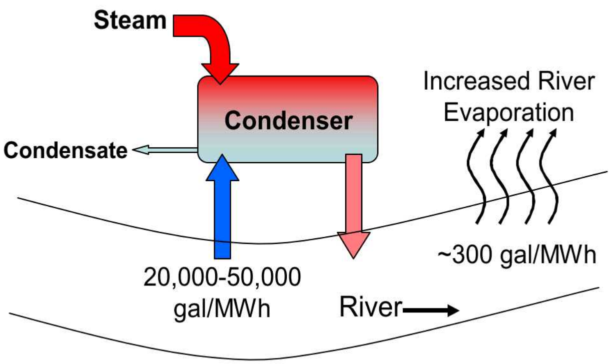
www.climas.arizona.edu

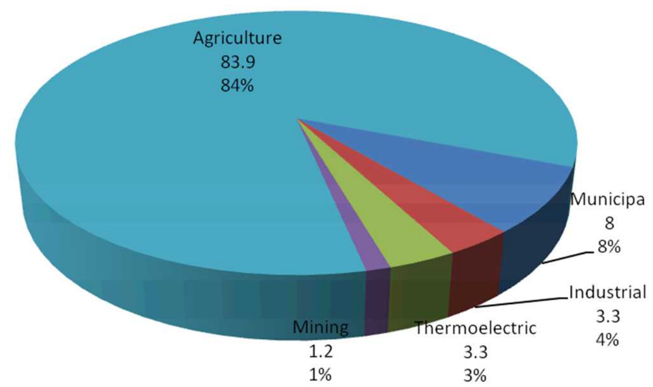
Energy & Water Consumption

Thermoelectric Consumption

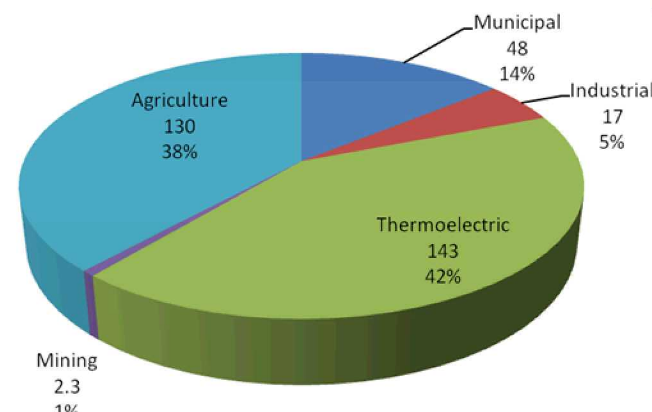


Tidwell et. al., 2013





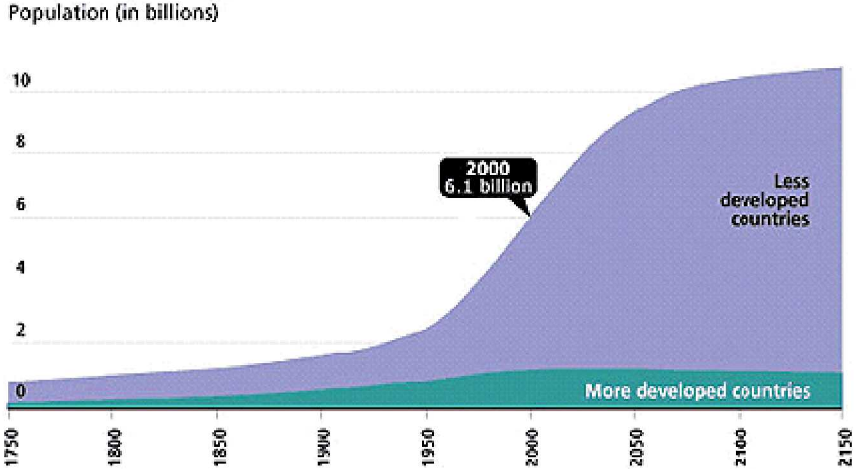
U.S. Water Withdrawal (BGD)
2005



U.S. Water Withdrawl (BGD), 1995

Energy Challenges & Implications

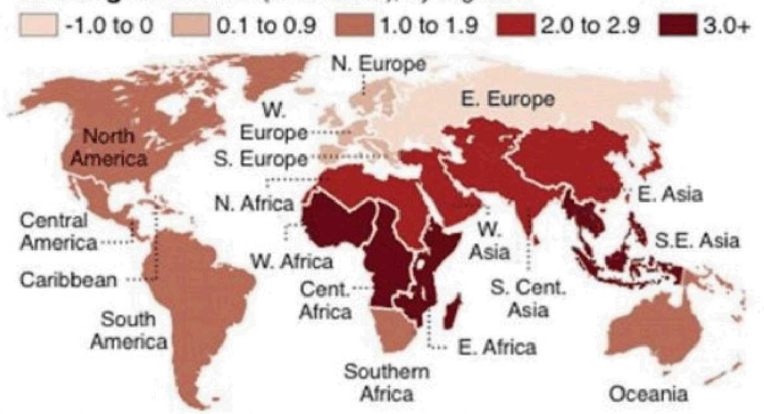
World Population Growth, 1750–2150



Source: United Nations, *World Population Prospects, The 1998 Revision*; and estimates by the Population Reference Bureau.

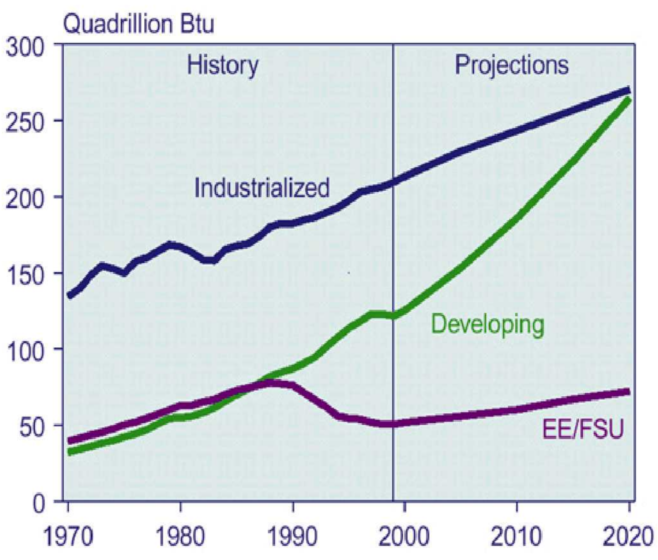
Birth rates raising urban population

More than half the world's population will be living in cities next year, according to the U.N.

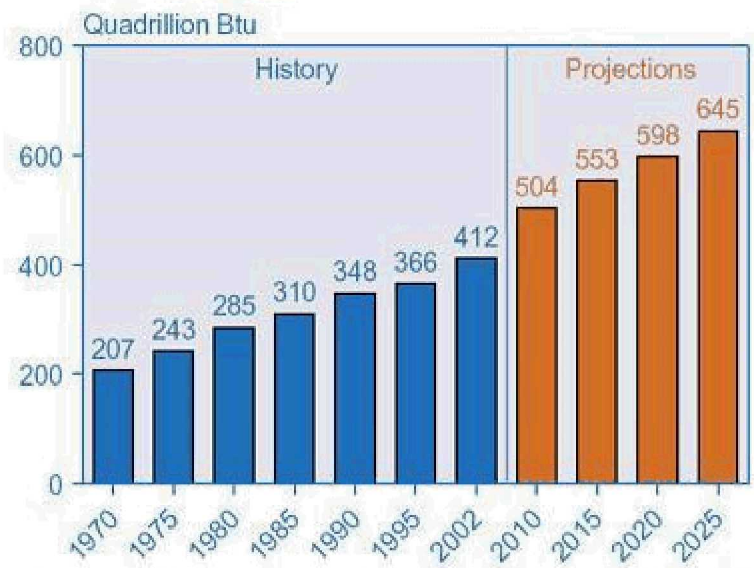


SOURCE: U.N. Population Fund AP

Figure 3. World Energy Consumption by Region, 1970-2020

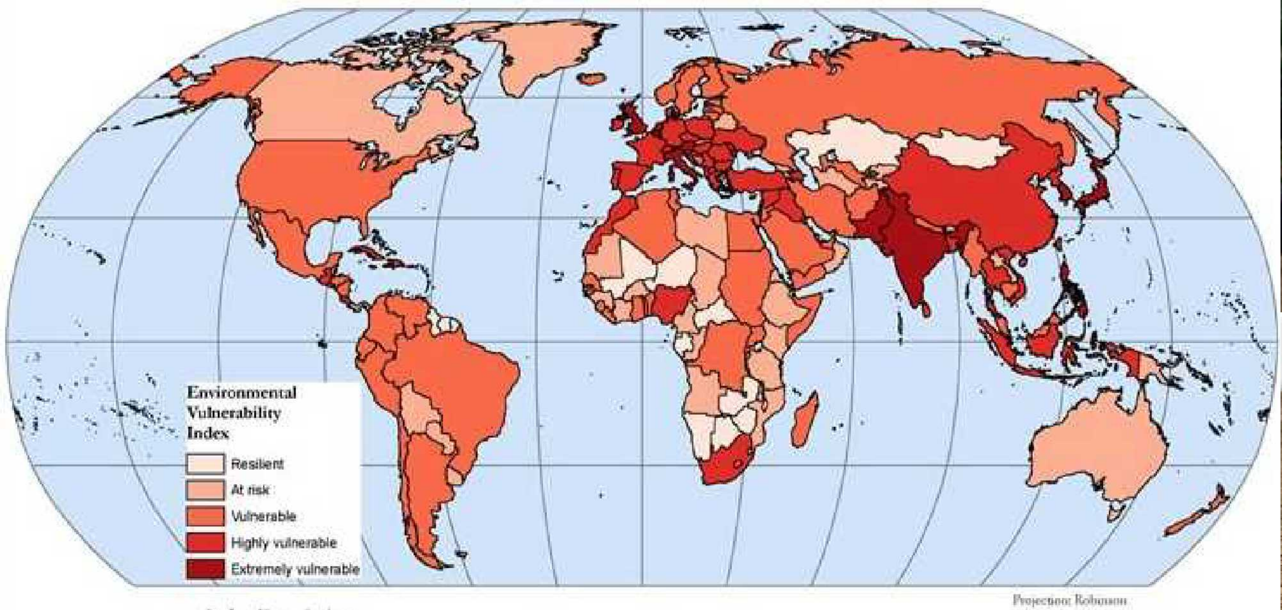


World Marketed Energy Consumption, 1970-2025



Social Implications – The Climate

Environmental Vulnerability Index



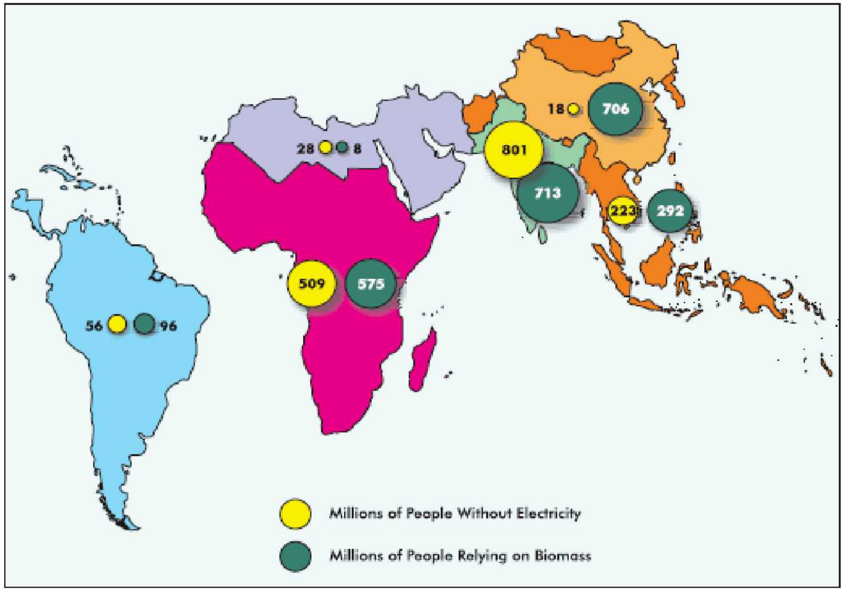
Index Description:

The Environmental Vulnerability Index (EVI) is a unitless index score ranging from 174 (for low vulnerability) to 450 (for high vulnerability). The EVI has been designed to reflect the extent to which the natural environment of a country is prone to damage and degradation.

The EVI is based on 50 indicators for estimating the vulnerability of the environment of a country to future shocks.

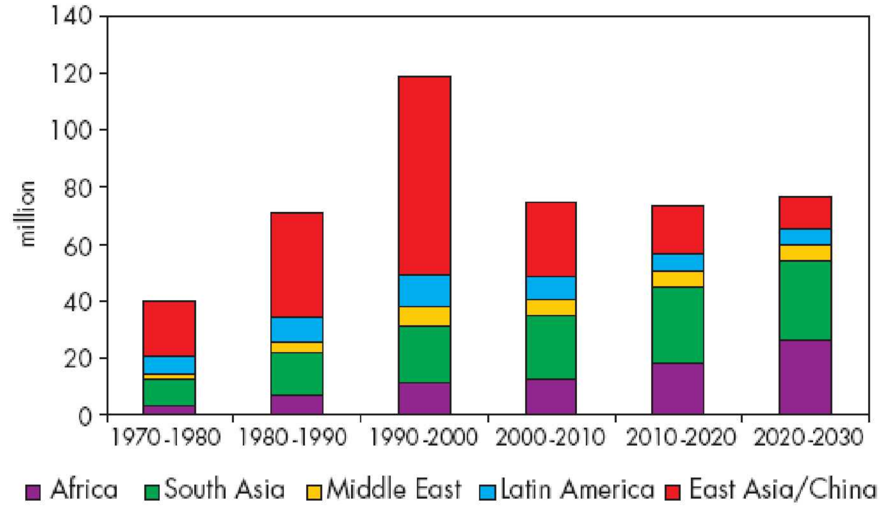
Source:
Kaly, U.L., Pratt, C.R. and Mitchell,
Demonstration Environmental Vuln
(EVI) 2004. SOPAC Technical Repo

Global Energy Poverty



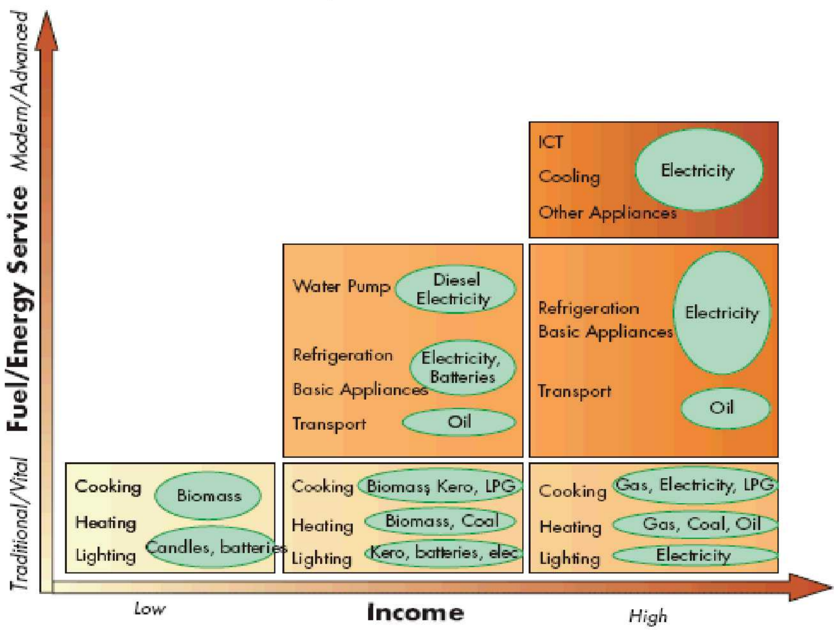
Source: IEA analysis.

Annual Average Number of People Gaining Access to Electricity

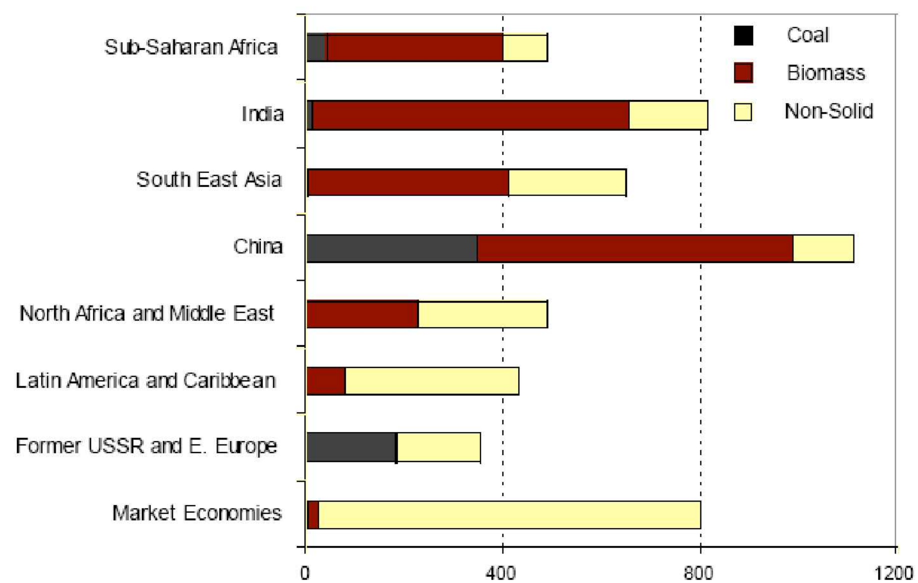


Source: IEA analysis.

Illustrative Example of Household Fuel Transition



Note: ICT is information and communication technology.
Source: IEA analysis.



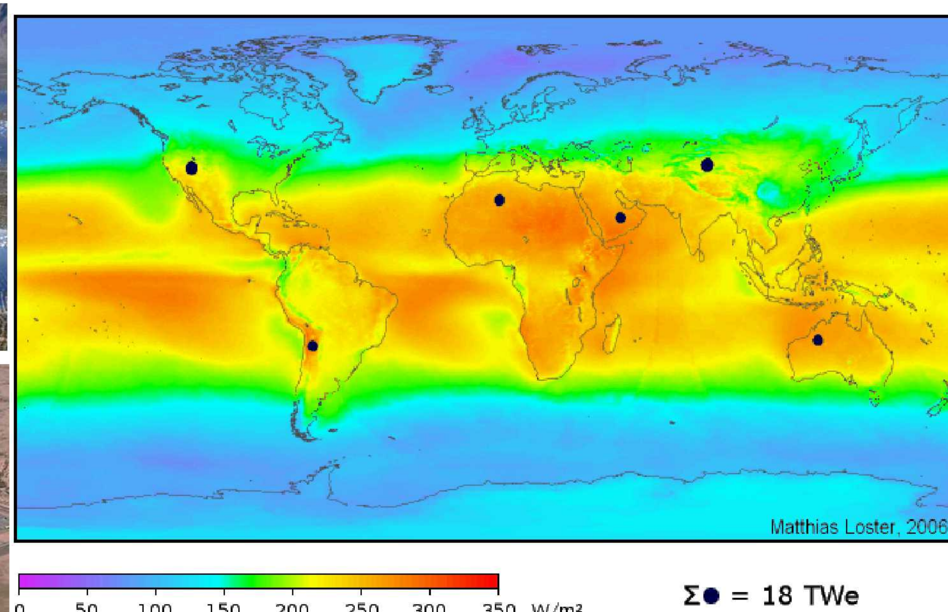
1990 Population (million)

WHO *Air Quality Guidelines*, 1999

Solar Energy Potential

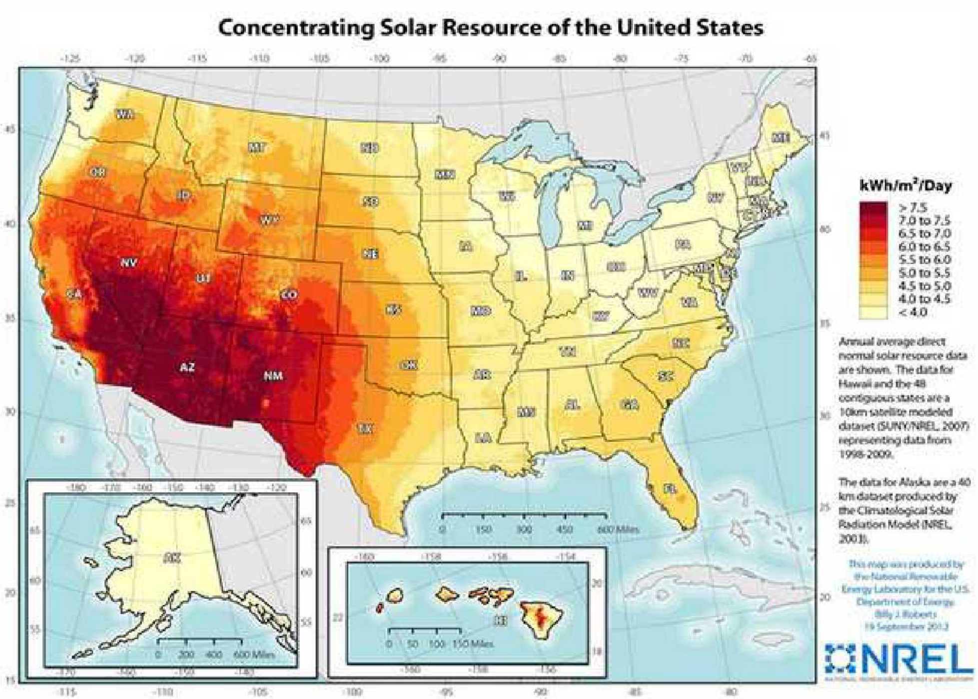
- Total Solar Constant (Earth) 1370 W/m^2
- Earth Albedo (Ability to Reflect Light): $\Omega = 0.37$
- Thus, for the whole Earth, with a cross section of 127,400,000 km², the power is 1.74x1017W, ±3.5%
- 6 Boxes at 2.5 TWe each (2008 Worldwide Energy Consumption of 1.50x1013W – "Consumption by Fuel Statistical Review of World Energy" 2009, Energy Information Agency (EIA)
- Solar concentration to scale boxes

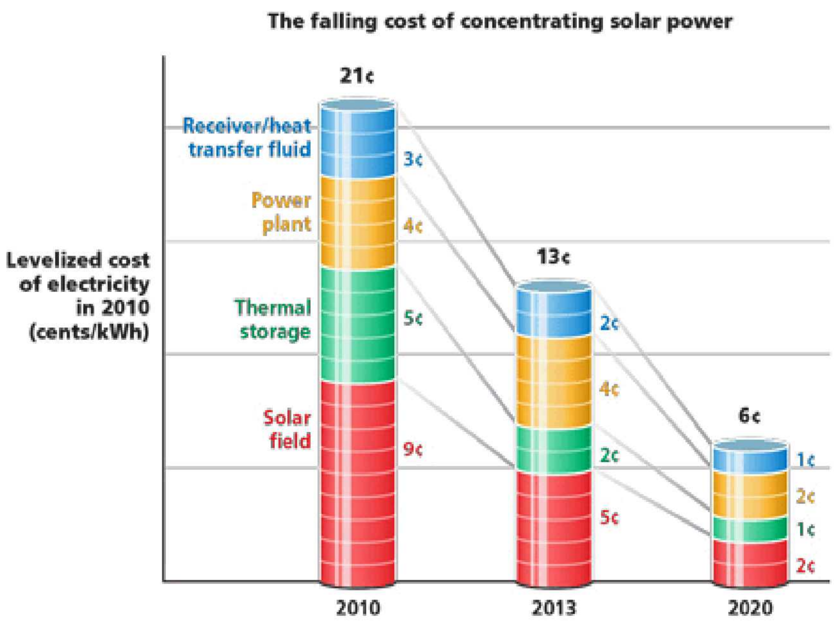
Kamman, 2010



The Potential for Solar in New Mexico

- New Mexico has very high renewable energy resource potential.
- Both Solar and Wind Energy resources are large enough to not only provide power to New Mexico, but provide a substantial export that could help boost the economy in the form of electricity from power purchasing agreements to other states.
- The cost of solar energy is rapidly decreasing to a Levelized Cost of Electricity (LCOE) of approximately $0.06/kWh, required to meet parity goals by the U.S. Department of Energy
- New Mexico solar energy researchers at Sandia National Laboratories are equipped to help the nation and New Mexico achieve this objective.





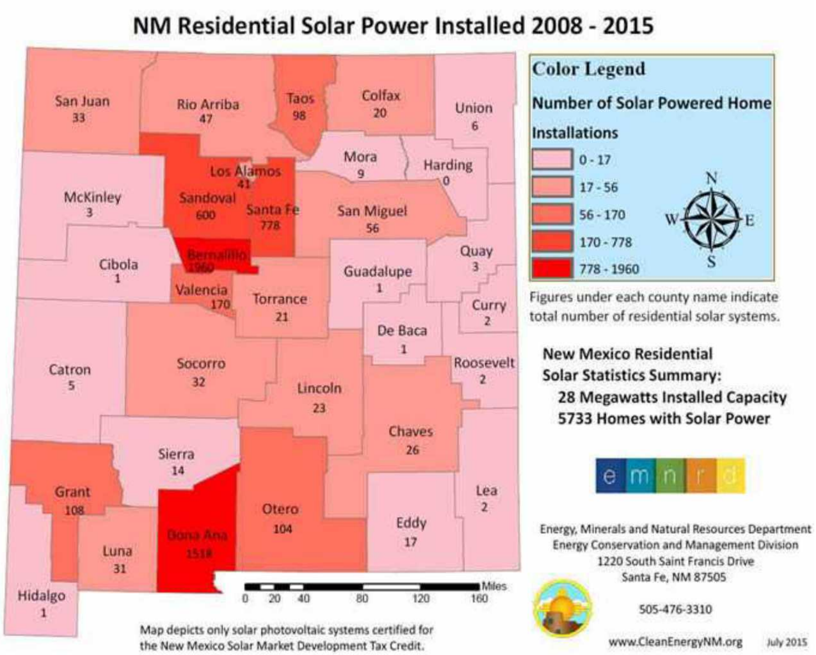
U.S. DOE SunShot Initiative 2016

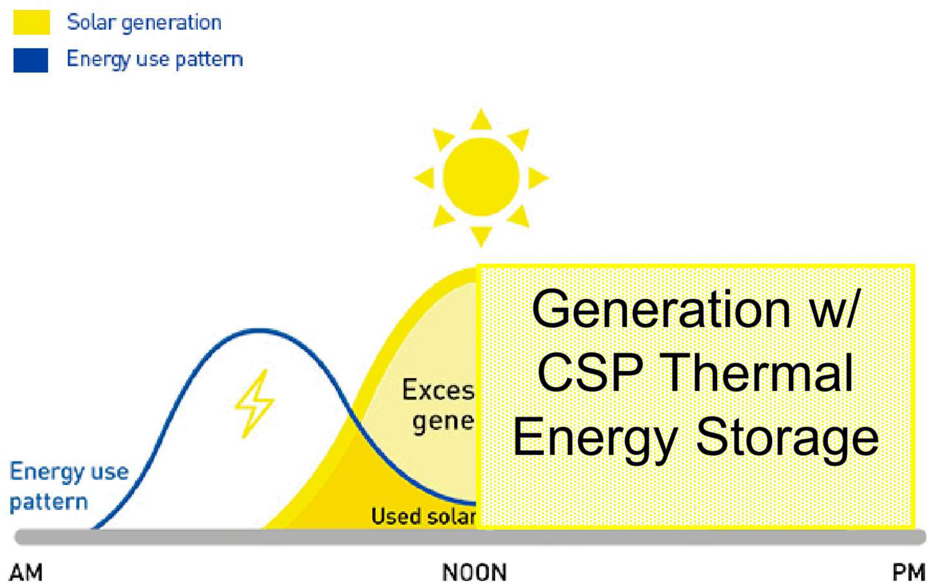
Value of Dispatchable Power Meeting Utility Power Demands

- Current energy demand peaks in the early morning and late evening, where solar energy storage is required to provide power before and after peak times the sun is out.
- Current battery storage is only good for a few hours (~3-4hrs. max), where solar thermal systems can provide > 15 hours of energy storage.
- CSP Energy Storage provides:

  higher value because power production can match utility needs

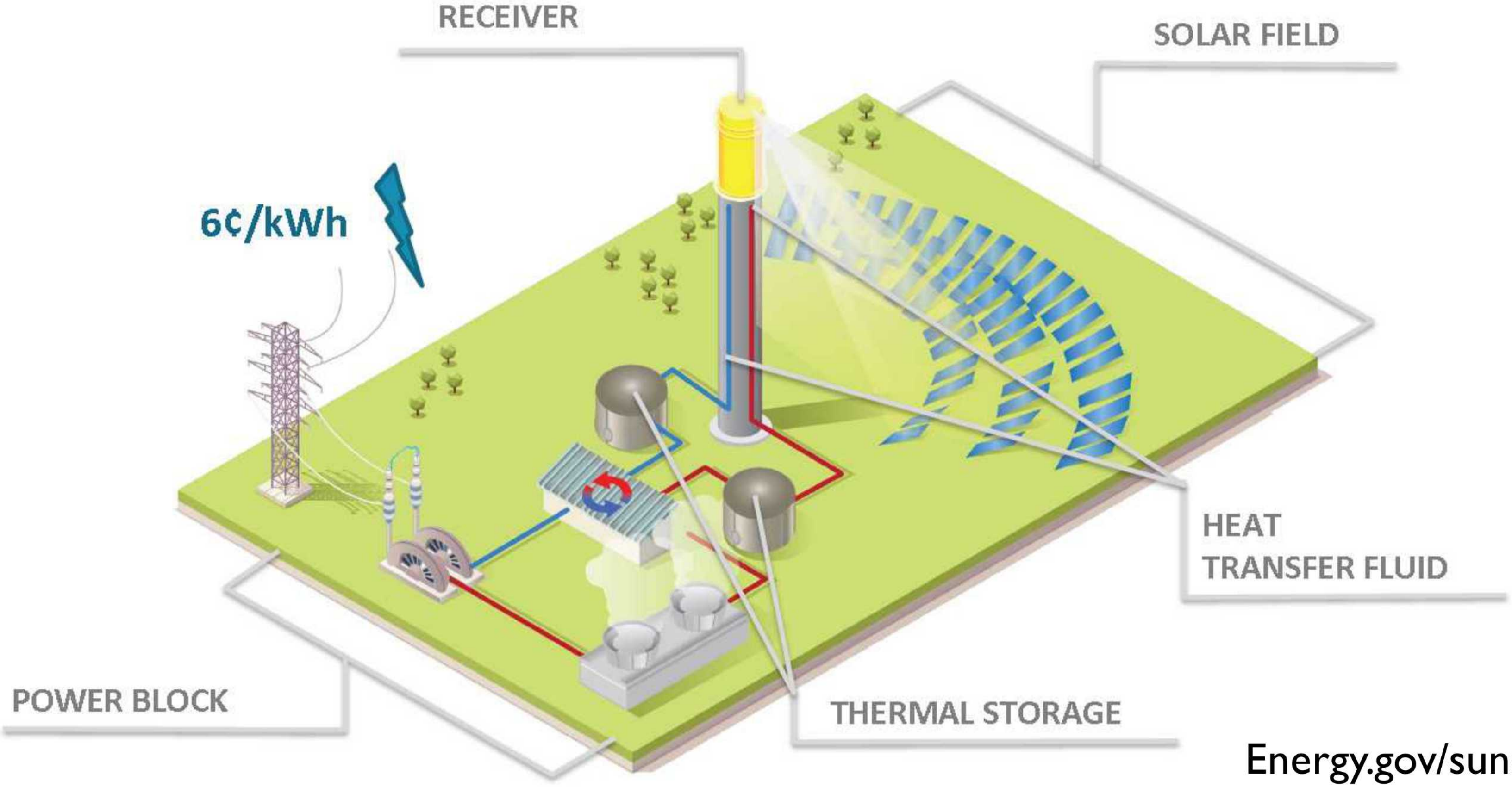
  lower costs because storage is cheaper than incremental turbine costs





Concentrating Solar Power (CSP) Systems

- Unlike solar (photovoltaic) cells, which use light to produce electricity, concentrating solar power (CSP) systems generate electricity from thermal energy.
- CSP uses mirrors and lenses to concentrate and focus sunlight onto a thermal receiver, similar to a boiler tube. The receiver absorbs and converts sunlight into heat.
- Heat is then transported to a steam generator or engine where it is converted into electricity.



Energy.gov/sunshot

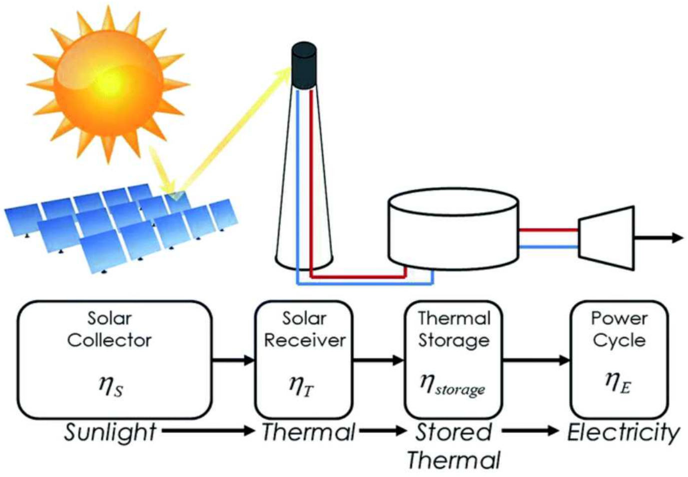
Types of Concentrating Solar Power Technologies

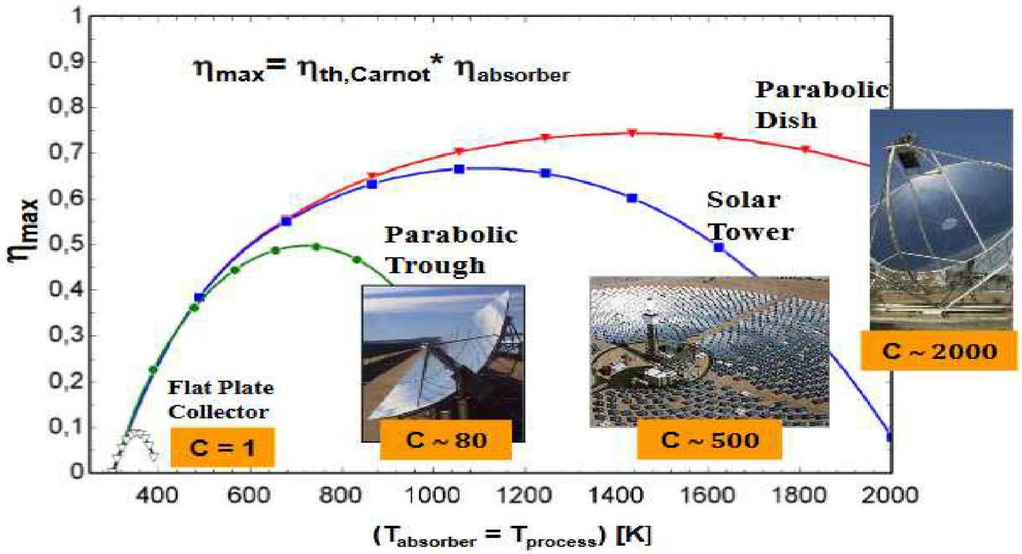
- Concentrating, or focusing, receivers intercept direct radiation over a large area and focus it onto a small absorber area.
- Receivers can provide high temperatures more efficiently than flat-plate collectors, since the absorption surface area is much smaller.
- Most concentrating receivers require mechanical equipment that constantly orients the collectors toward the sun and keeps the absorber at the point of focus.

Four primary types of CSP collectors:

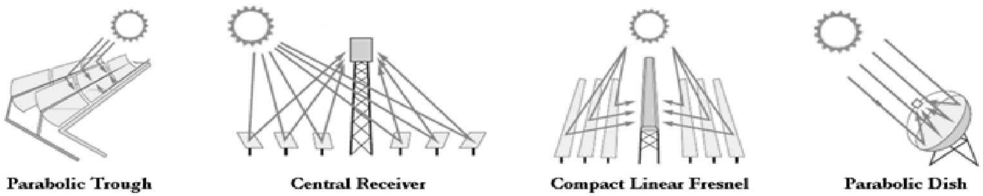
- Parabolic trough system
- Parabolic dish
- Power tower
- Linear Fresnel Reflector

Key Features of CSP Solar Technologies.





Armijo, SAND2016-11399



	Parabolic Trough	Central Receiver	Compact Linear Fresnel	Parabolic Dish
Operating Temperature [ºC]	350-550	250-565	390	550-750
Plant Peak Efficiency [%]	14-20	23-35 Note – 35% achieved with combined cycle	18	30
Annual Capacity Factor [%]	25-28 (no TES) 29-43 (with TES)	55 (with 10h TES)	22-24	25-28
Collection Concentration [suns]	70-80	>1,000	>60 suns (with secondary reflector)	>1,300
Steam Conditions [ºC/bar]	380-540 / 100	540 / 100-160	260/50	N/A
Water Requirement [m^3/MWh]	3 (wet cooling) 0.3 (dry cooling)	2-3 (wet cooling) 0.25 (dry cooling)	3 (wet cooling) 0.2 (dry cooling)	0.05-01 (mirror washing)

CSP Systems Currently in the U.S.

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	February 2016	January 2015
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

Commercial Parabolic Trough Systems

50MW AndaSol-1 Parabolic Trough Plant
w/ 7-hr Storage
Andalucia, Spain

64 MWe Solargenix
Parabolic Trough Plant

Concentrating Solar Power:
Non-Dispatchable Central Station/Distributed Power

Dish/Stirling: Pre-commercial,
pilot-scale deployments

Concentrating PV: Pre-commercial,
pilot-scale deployments

Modular (3-25kW)

High solar-to-electric efficiency

Commercial Power Tower Systems

Ivanpah, Solar Facility, San Bernadino, CA
392 MWe

Crescent Dunes, Solar Facility, Tonopah, NV
110 MWe

Advanced CSP for the 21st Century

- U.S. DOE & Sandia Labs are developing a 3rd generation of CSP technologies with temperatures and thermal energy transfer capabilities for high efficiency & lower cost power cycles, such as with an sCO2 Brayton cycle.
- To achieve the targeted cycle efficiency of greater than 50%, solar energy collected by the receiver and stored in TES is expected to be delivered to a turbine at or above 700 °C to achieve a DOE SunShot cost target of 6 ¢/kWh$_e$
- Thermal systems that are capable of achieving temperatures beyond 700°C will enable the opportunity to realize efficiency gains beyond 50% from sCO_2 and increase the adoption of solar energy globally.

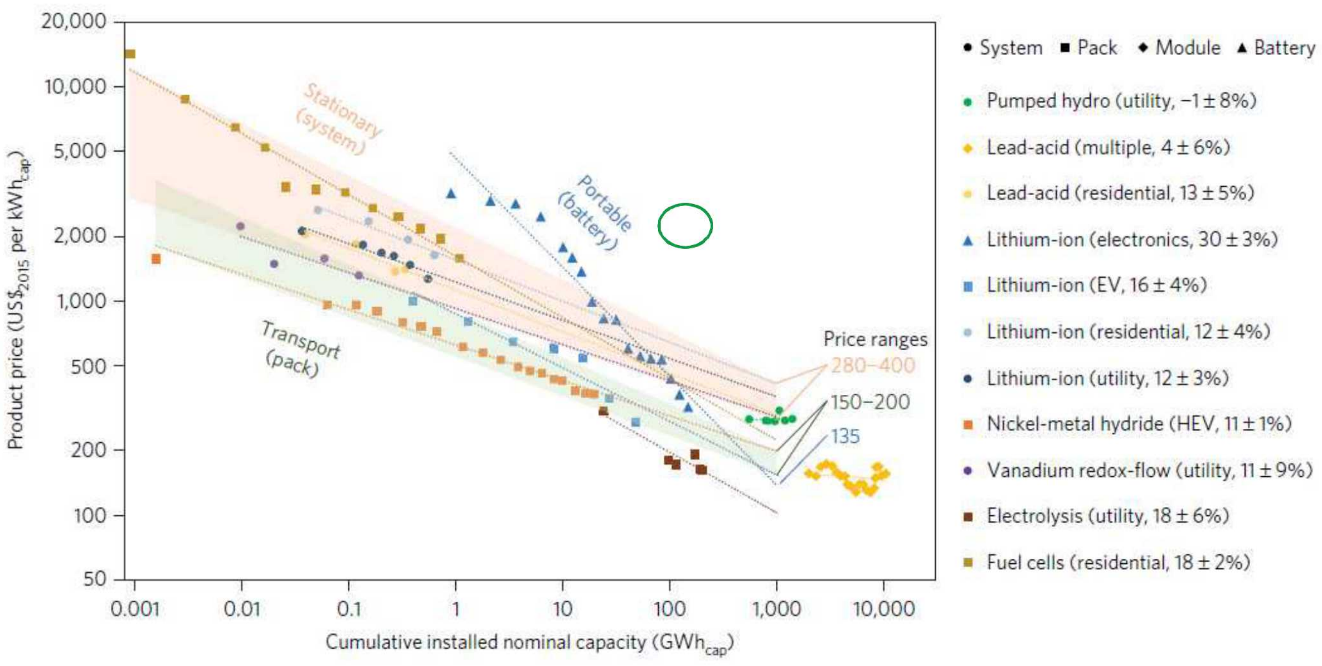
COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	• Thermal Efficiency: • Particle Loss • Flow Velocity Control and Monitoring	• Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation	• Charging and Discharging Particle loss, Efficiency, Scalability	• Particle Attrition • Optimized Performance Character	• Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients	
MOLTEN SALT	• Thermal Conductivity • Thermal Stability • Tube Strength and Durability	• Pipe Material Compatibility • Freeze Recovery • Pumps Valves Seals • Leak Detect	• Corrosion Behavior • Chemistry Monitoring and control • Tank Cost	• Characterize Material Properties • Cost / Supply Chain	• Material Compatibility w/ salt & CO_2 • Freeze Protection • Thermal Ramp Rates	
GAS	• High Pressure Fatigue • Absorptivity Control and Thermal Loss Management	• Recirculator Cost & Operating Power • Large Pipes High Cost	• Storage Concept not Determined	• Low Thermal Conductivity • Low Heat Capacity	• Requires High Area • Multiple Heat Exchangers • Cascading Temperature	

www.energy.gov/eere/solar/

Why Gen 3, why not Gen 2.1?

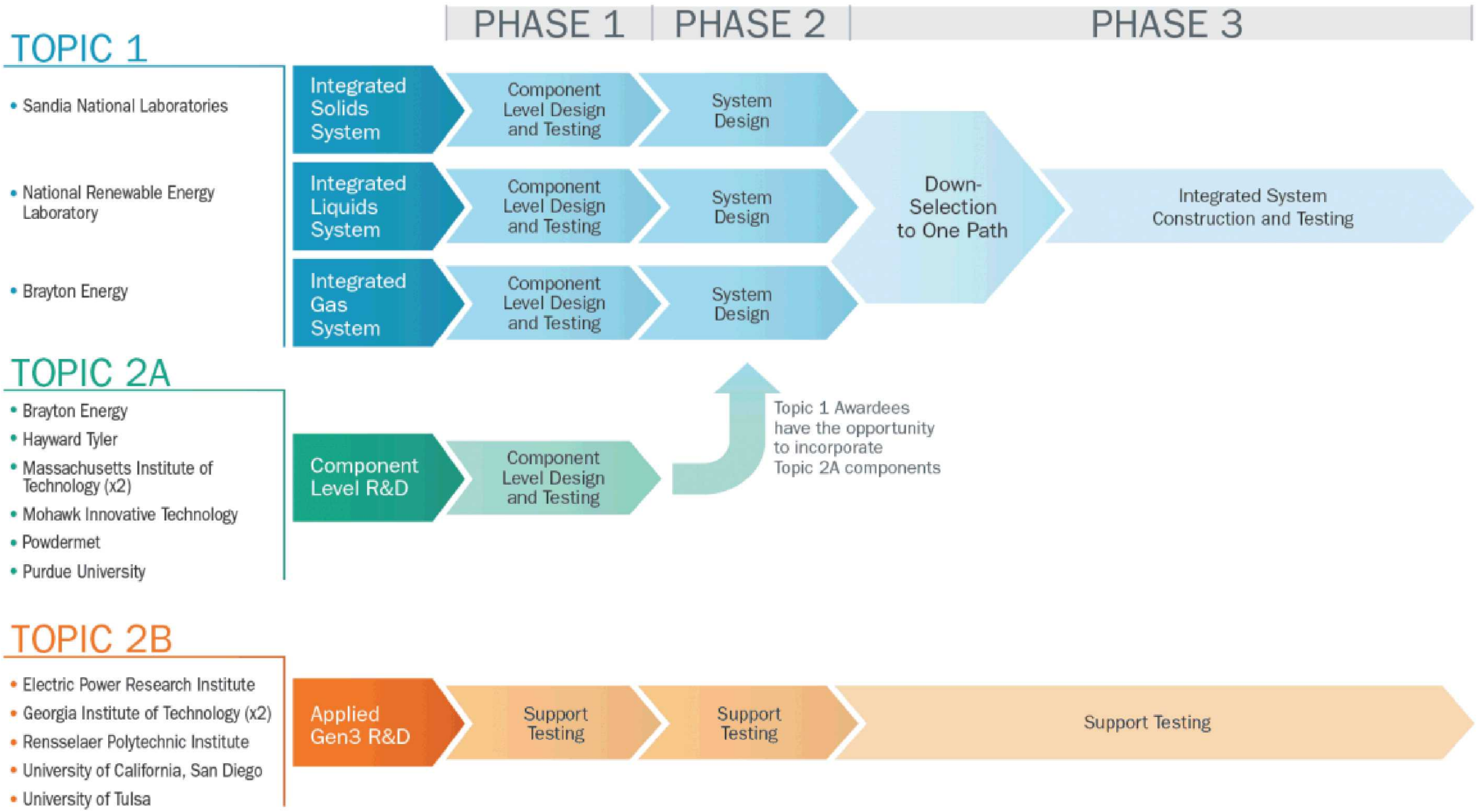
- CSP's value is based on efficient energy storage.
- CSP costs must decline to compete
- Goal: De-risk high-temp components and develop integrated-system designs with thermal energy storage at >700°C

Energy Storage Costs vs. Installed Capacity



Schmidt et al., "The future cost of electrical energy storage based on experience rates," *Nature Energy*, July 2017.

Generation 3 CSP Research – A competition to make the world better



www.energy.gov/eere/solar/

Gen3 Liquid Pathway

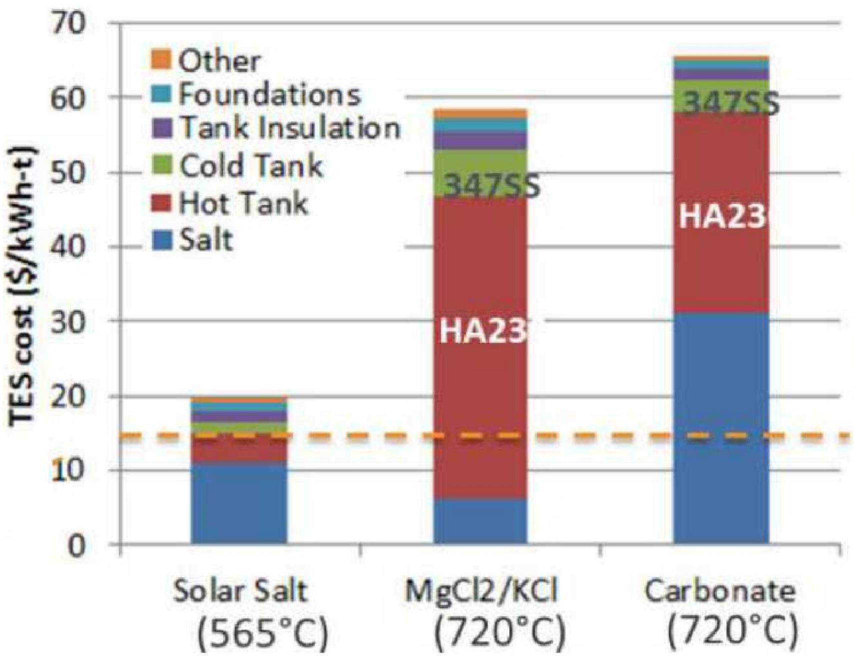
- Leverage expertise with liquid-HTF towers
- Examine two, alternative high-temp liquids
- Use low-cost, thermally stable energy storage media
- Design for sCO_2 Brayton-cycle integration

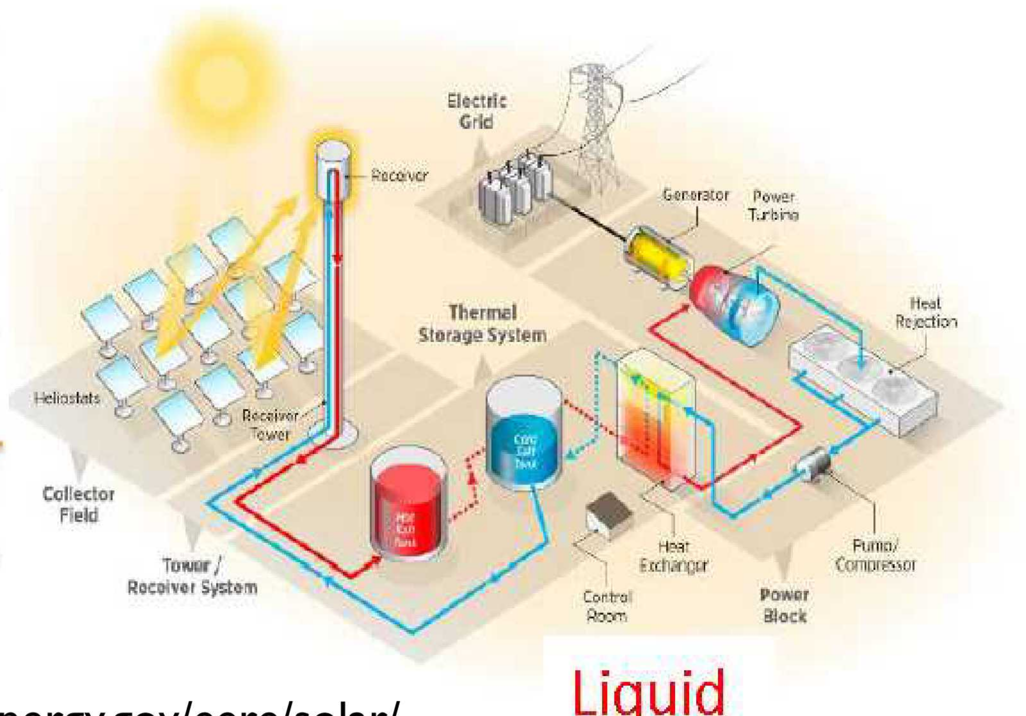
Vast Solar Jemalong
Sodium-HTF pilot facility (Australia)

SolarReserve Crescent Dunes
Molten-salt HTF plant (USA)

Advanced CSP – **High-Temp. Liquids** for Next Generation CSP

- The next generation of liquid-phase concentrating solar thermal power technologies have the potential to advance CSP power systems to higher efficiencies.
- Salts have great heat capacitance capabilities with over 10 hours of storage possible, however corrosion and wetting issues still persist that are being addressed with current research.
- Chloride salts have much higher decomposition and operation temperatures, while sodium is capable of much higher receiver efficiencies, due to its larger thermal conductivity.





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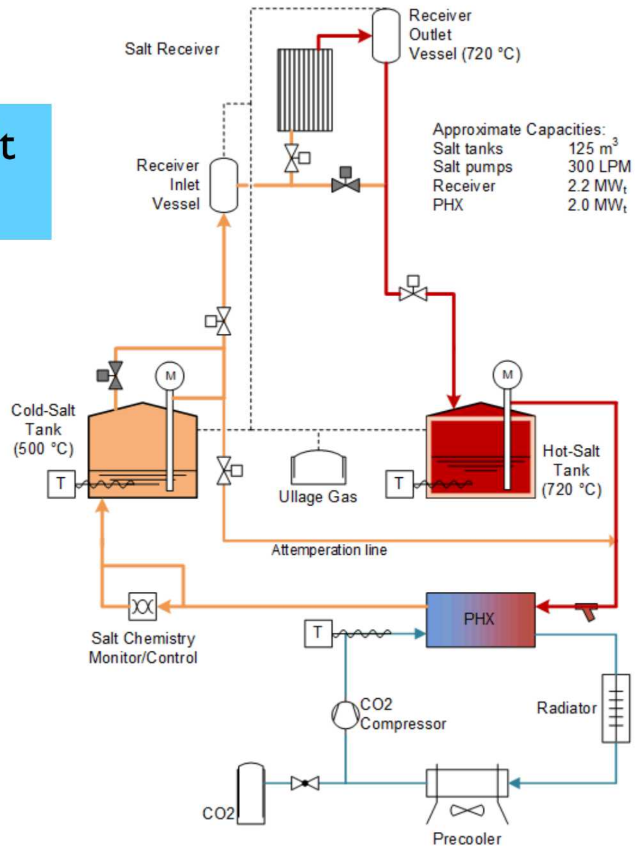
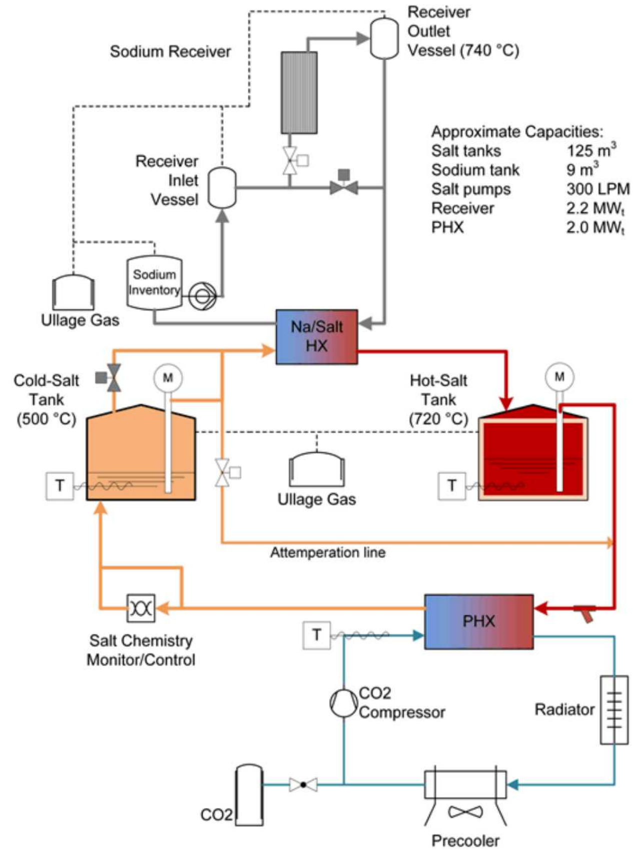
Liquid-HTF Alternatives

Cl-Salt HTF





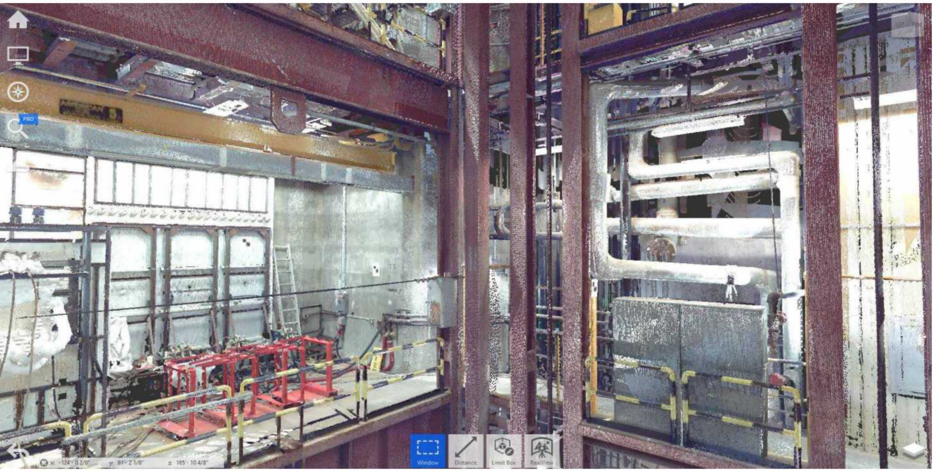
Sodium HTF

Direct-storage Na thermocline also considered

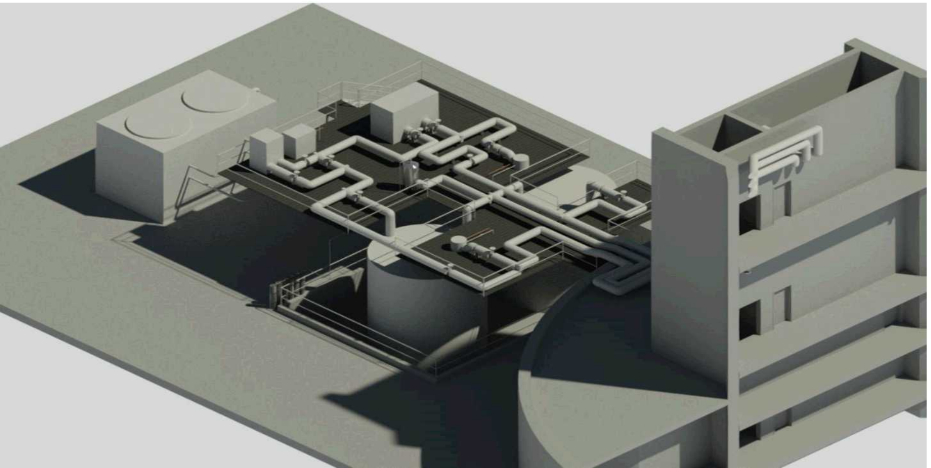
Parameter	Solar Salt (Gen2)	Chloride Salt*	Sodium
Mass composition	60% $NaNO_3$ 40% KNO_3	Ternary $MgCl_2$-KCl-NaCl blend	100% Na
Solidification Temp (°C)	238	426	98
Stability Limit (°C)	600	>1418	882
Density (kg/m³)	1770 @ 500°C	1590 @ 700°C	835 @ 700°C
Specific Heat (J/g-K)	1.53 @ 500°C	1.1 @ 700°C	1.26 @ 700°C
Viscosity (cP)	1.30 @ 500°C	1.4 @ 700°C	0.24 @ 700°C
Thermal Cond. (W/m-K)	0.54 @ 500°C	0.4 @ 700°C	64.2 @ 700°C

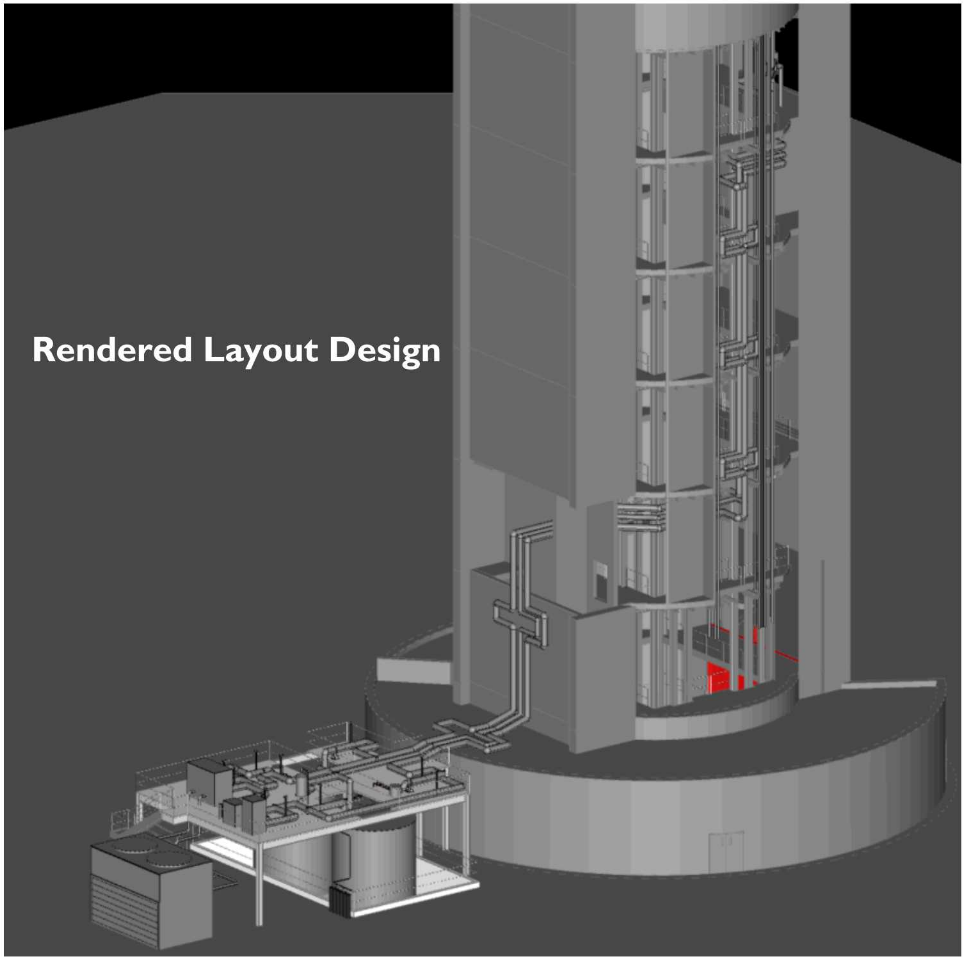
- The Gen 3 Liquid-Phase project aims to design, develop, and test a 2 MWt system consisting of advanced liquid CSP system components (solar receivers, thermal energy storage tanks and associated pumps, heat exchangers, piping, valves, sensors, and heat tracing).
- If selected for the third phase, the system will be validated in a pilot-scale test facility Sandia National Labs.

220 ft Point Cloud Tower Level



Rendered Revit 3D Model

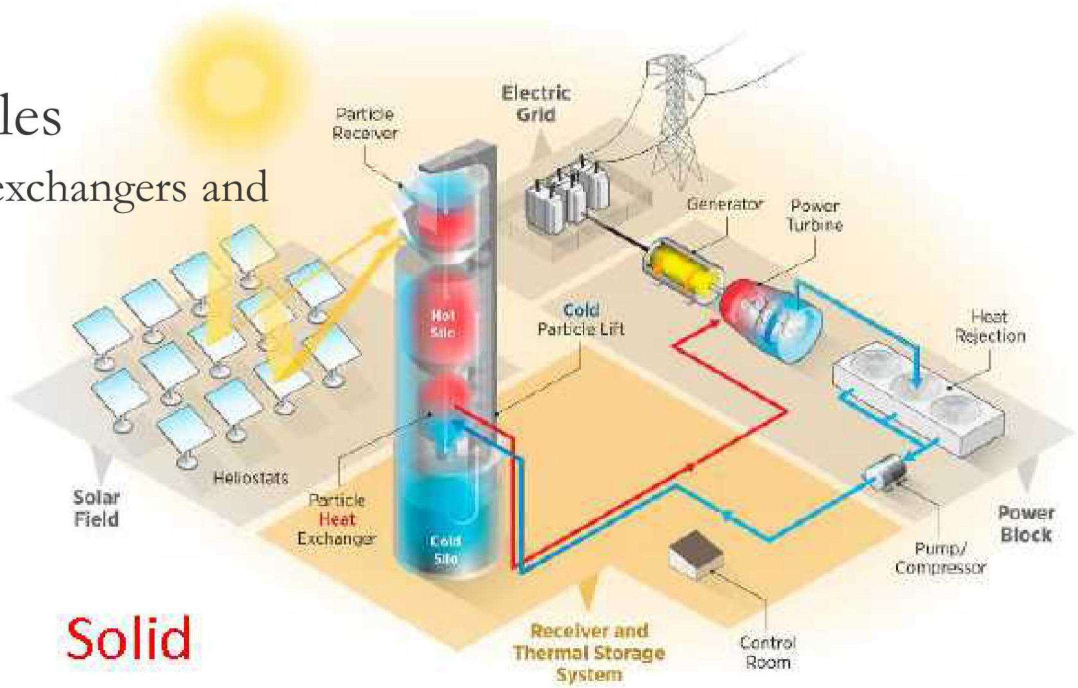




Advanced CSP – **Solid Particles** for Next Generation CSP

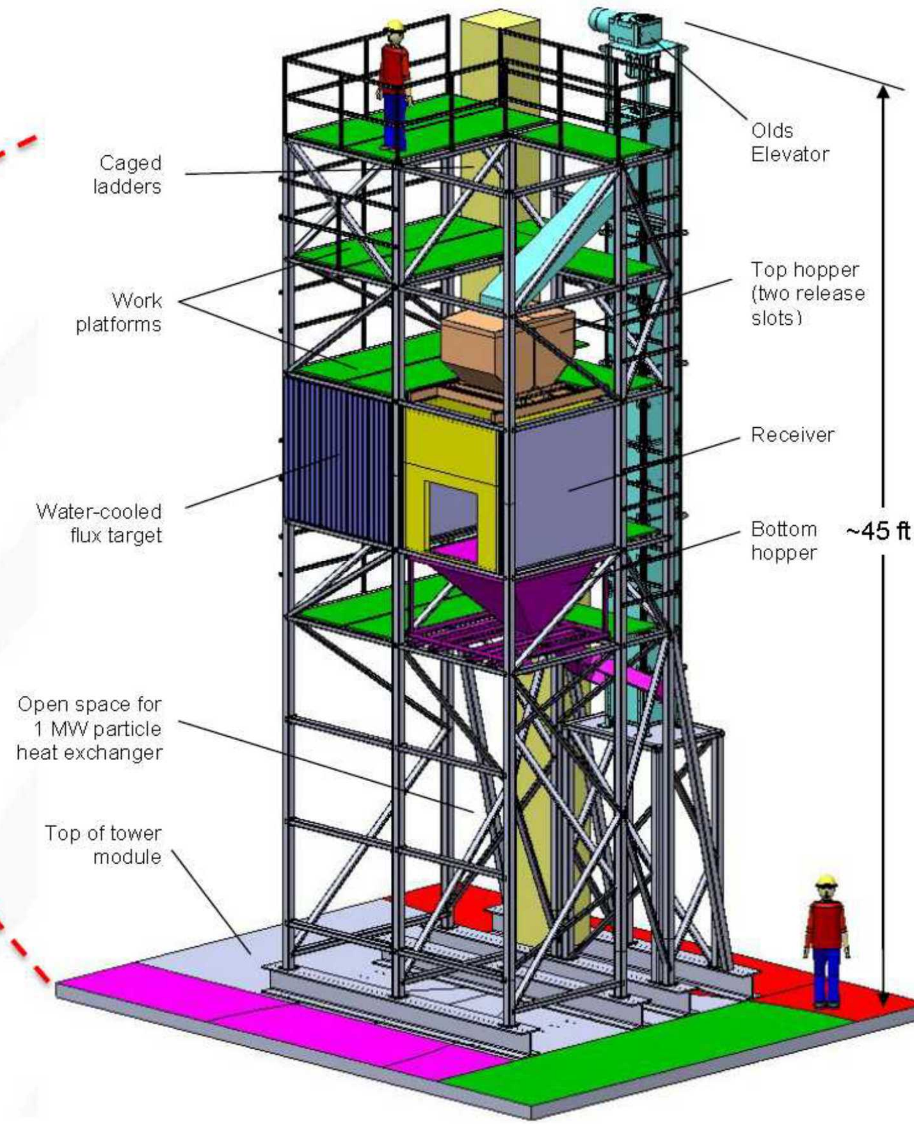
- Solid particles can achieve higher temperatures (>1000C) than molten salts
  - Enables more efficient power cycles
- Direct heating of particles vs. indirect heating of tubes
  - Higher solar flux levels for increased receiver efficiency
- No freezing of decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles
  - Reduced costs without extra heat exchangers and separate storage media

CARBO ceramic particles ("proppants")



Solid

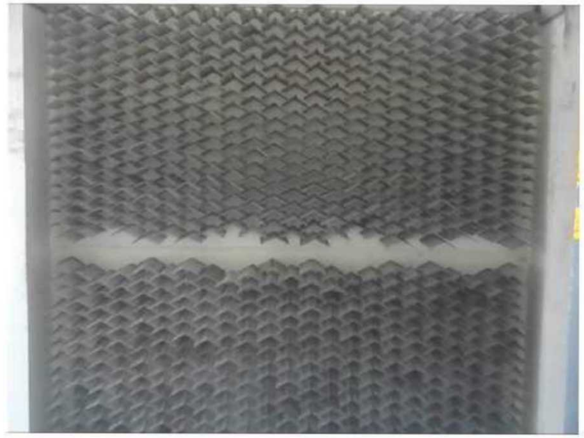
Sandia Falling Particle Receiver



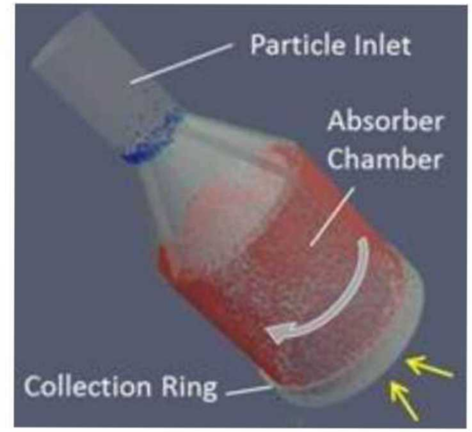
R&D 100
55 Years of Invention

Solid Particle Receiver Designs

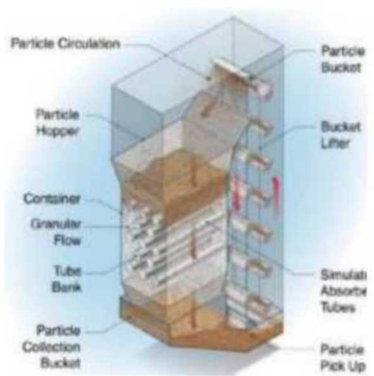
Free-Falling (SNL)



Obstructed Flow (GT)



Centrifugal (DLR)



Enclosed Flow (NREL)

Solid Graphite (Graphite Energy)

Fluidized Bed/Tubes

Solid Particles Varieties

Material	Image	Compositi on	Properties		Advantag e	Dis-advantage
			Density (kg/m^3)	Specific Heat (J/kg-K)		
Silica sand		SiO_2	2,610	1,000	Stable, abundant, low cost	Low solar absorptivity and conductivity
Alumina		Al_2O_3	3,960	1,200	Stable	Low absorptivity
Coal ash		SiO_2, Al_2O_3, + minerals	2,100	720 at ambien t temp	Stable, abundant, No/low cost	Identify suitable ash
Calcined Flint Clay		SiO_2, Al_2O_3, TiO_2,Fe_2O_3	2,600	1,050	Mined abundant	Low absorptivity
Ceramic proppants		75% Al_2O_3, 11%SiO_2, 9%Fe_2O_3,3 %TiO_2	3,300	1,200 (at 700°C)	High solar absorptivi ty, stable	Synthesized , higher cost

C. Ho, 2017

Advanced CSP - **Supercritical Gases** for Next Generation CSP

Gas-phase heat transfer fluid

- Can behave approximately as an ideal gas
- Operation in the range of 60-120 bar
- Balances wall thickness requirements with heat transfer characteristics

Closed-loop Configuration

- Enables high thermodynamic efficiency by allowing power cycle to accept heat at a high average temperature

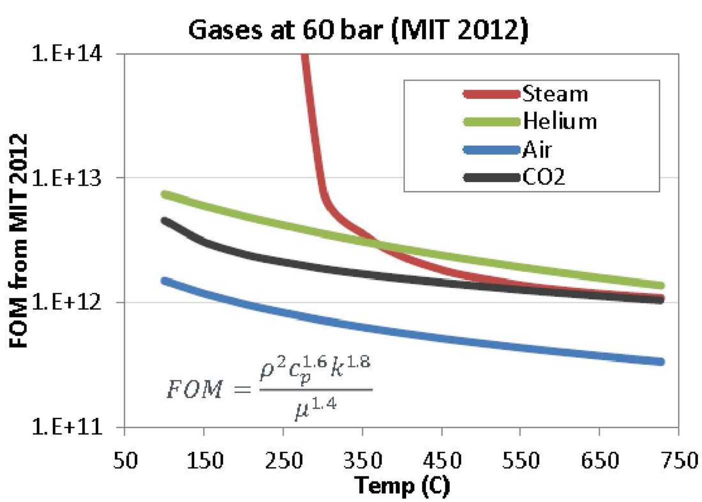
Indirect thermal energy storage

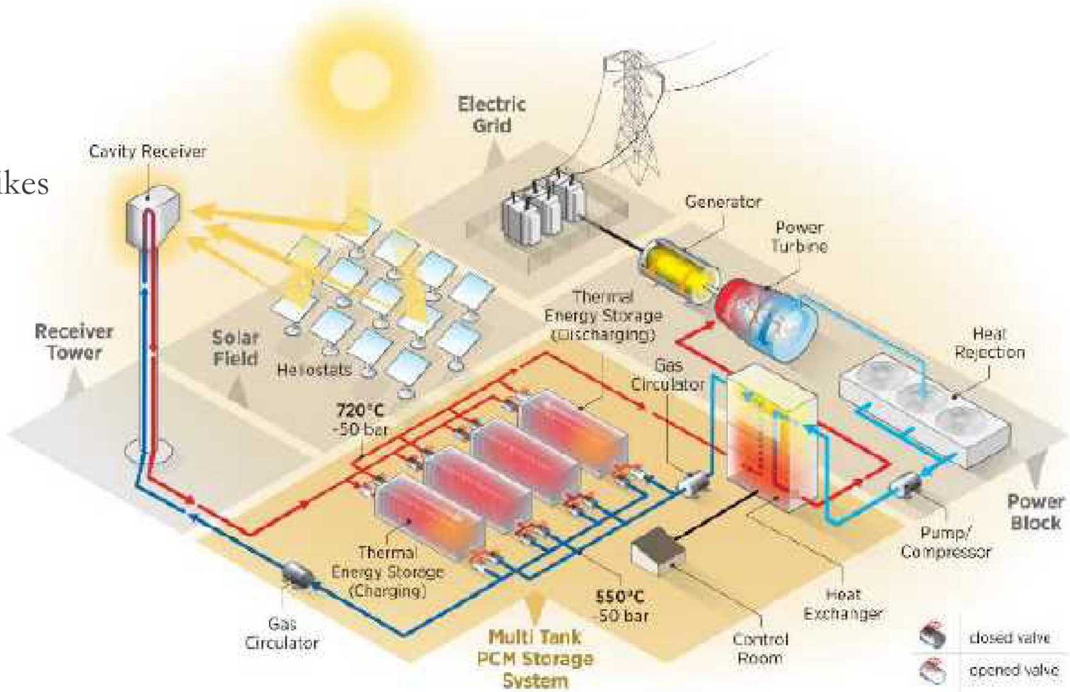
- Secondary storage media
- Enables a variety of TES technologies
- Low Corrosion issues

Power generation decoupled from production

- Allows the system to dispatch to demand / price spikes without affecting energy collection subsystem.

www.energy.gov/eere/solar/





Gas

CSP Supercritical Gas Heat Transfer Fluids

Advantages

- **Thermally stable**
  - No phase change
  - Eliminates heat-trace, attrition, chemistry management equipment
  - Simplifies system startup and shutdown
- **Inert**
  - Reduces corrosion
  - Minimal environmental or safety hazards
- **Low cost and high thermal efficiency**
  - 89-95% receiver, <200$/kWt
- **Builds on existing designs**
- **Simple primary heat-exchanger**
- **Enables advanced TES concepts**

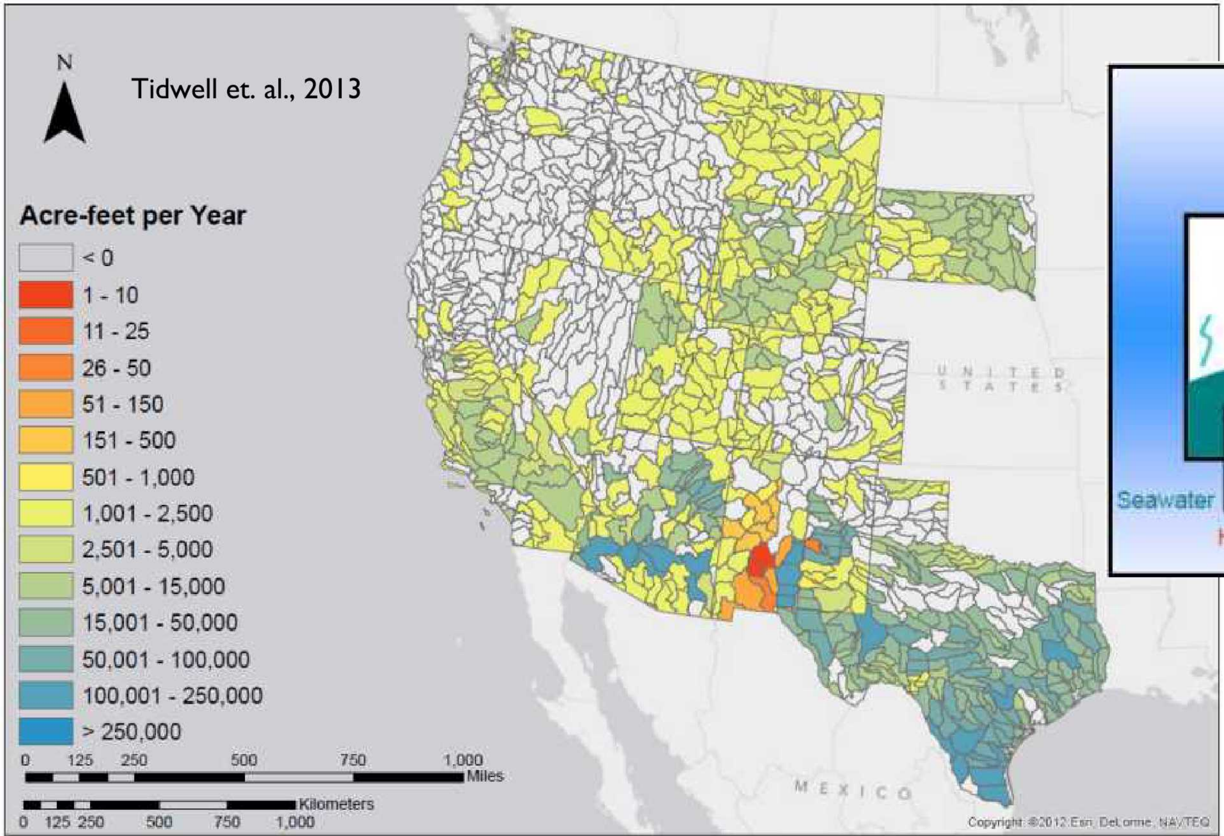
Challenges

- **Inferior heat-transfer to liquids**
  - Optimization of operating pressure
  - Transient response sensitivity
- **Indirect TES technology**
  - System integration
- **Power consumption for fluid circulation**
- **Selection of appropriate pressure and temperature targets**
  - Balance wall material cost with parasitic losses
- **Flow path complexity**

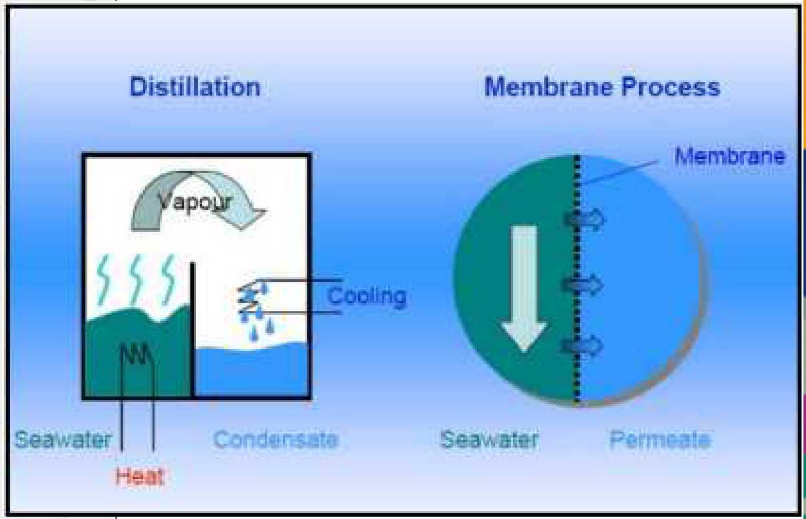
Opportunities for CSP – Desalination

- CSP systems generate a lot of waste heat that can be utilized for other functions, such as with thermal desalination technologies.
- Thermal Distillation, among other technologies, are being investigated for application with CSP plants to help facilitate both electricity and fresh water production.

Brackish Groundwater Metric

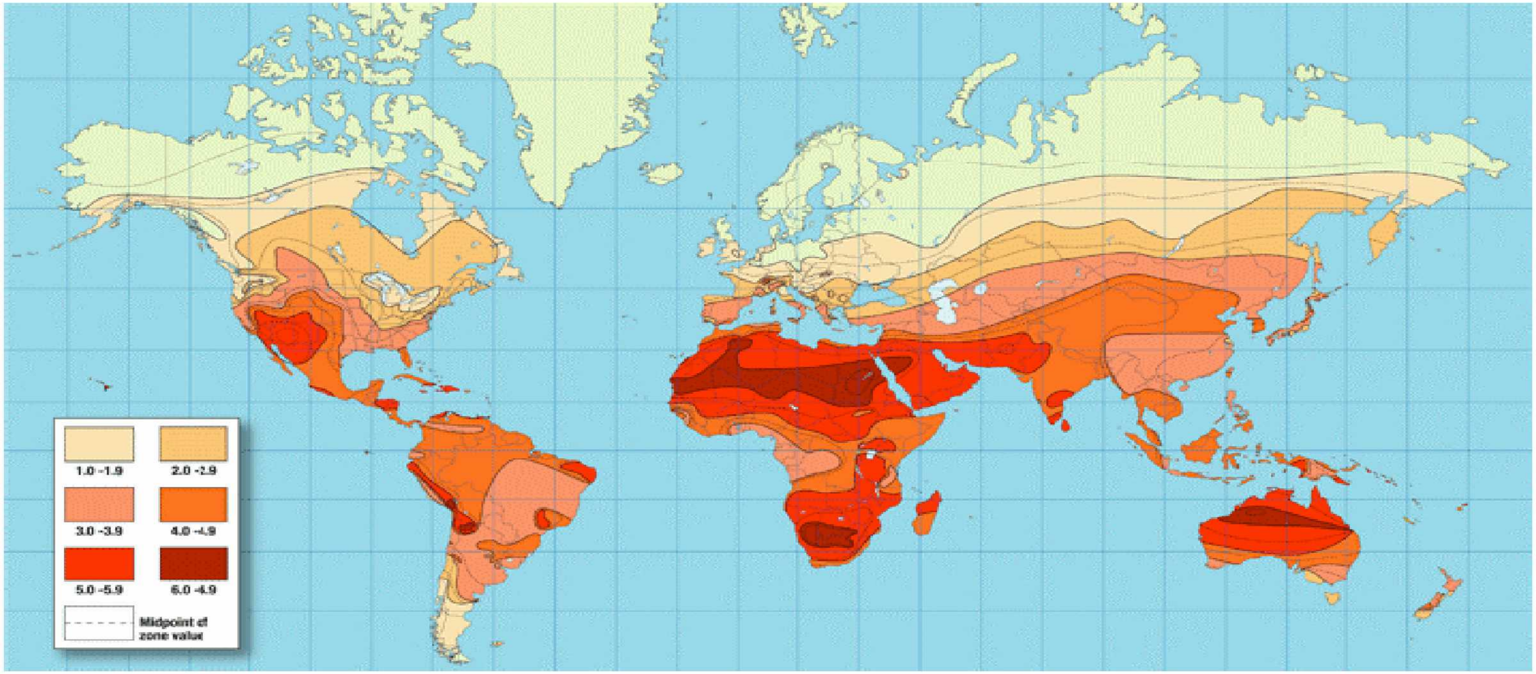


Desalination Approaches



Conclusions

- Sandia National Laboratories is positioned as a R&D institution to conduct on-sun renewable energy research for concentrating solar thermal energy research, where our solar energy facilities and technical staff will promote the development of next generation power plants & solar energy industry.
- The ability to use CSP with storage to cover for times when PV will not work is even leading some developers to consider combining the two in a single, hybrid system.
- Current installed solar and wind energy capacity is increasing, but with the tremendous potential NM has, federal and state legislation to promote residential, commercial and utility-scale solar energy generation could offset energy demands related to increasing power utility costs, water purification and a growing demand for electric vehicles, to name a few.



M. Mehos et al., 2008

Acknowledgements

Sandia Nat'l Labs – National Solar Thermal Test Facility (NSTTF)

Department of Energy

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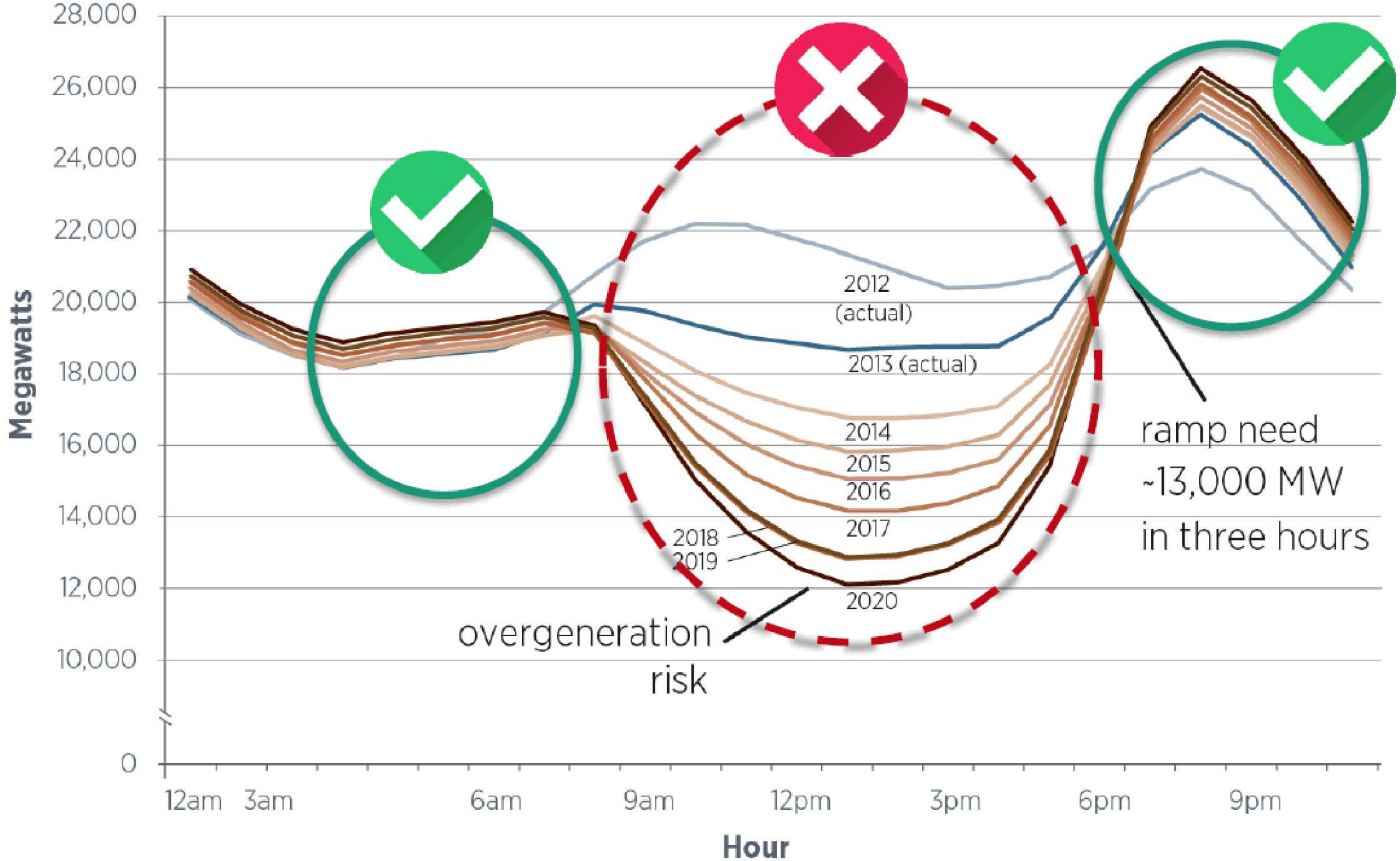
Questions?

Extra Slides

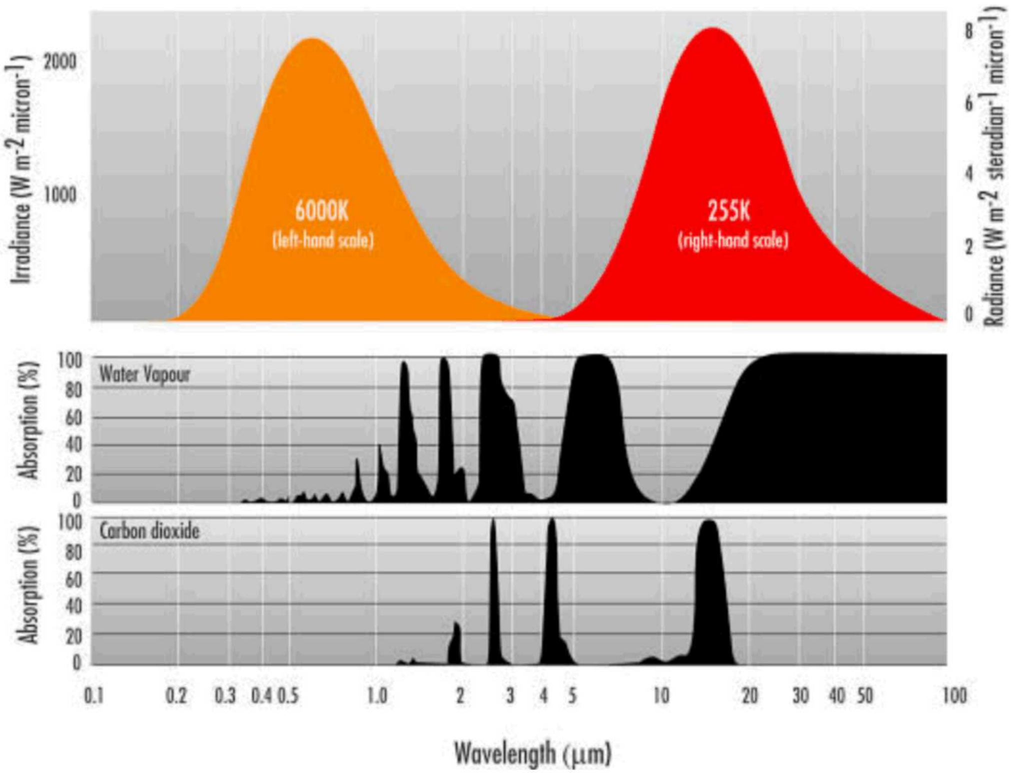
Near Terms Opportunities for CSP: Flexible, Renewable, Dispatchable Energy



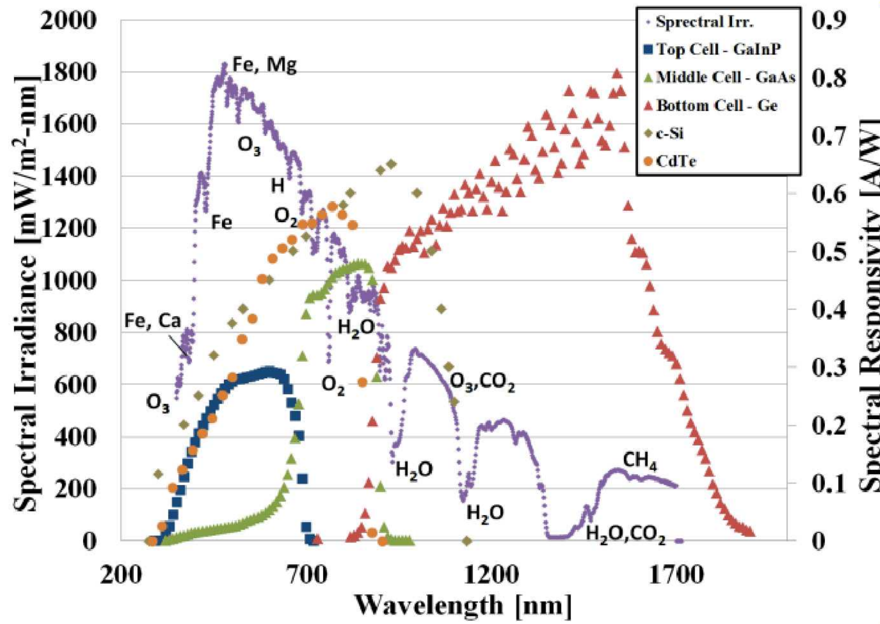
CSP can readily be configured to meet uncertain demands of the future grid by varying the relative sizes of the solar field, storage, and power block

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

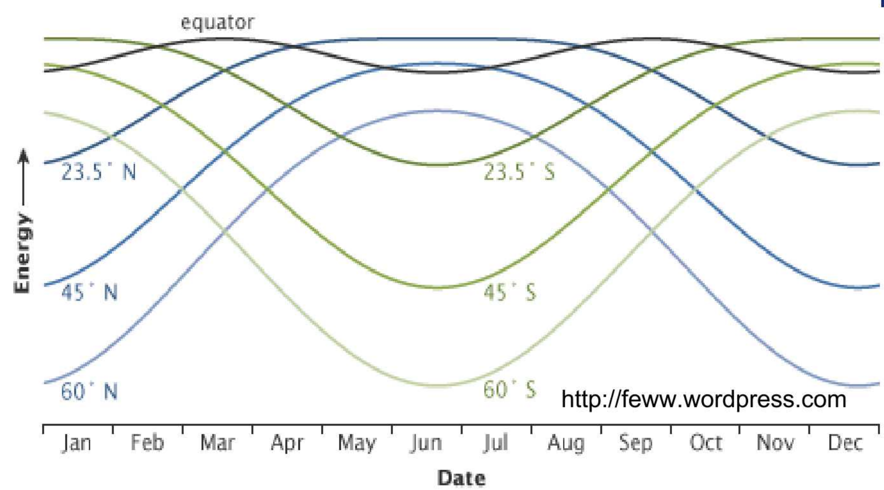
Radiative Absorption & Forcing



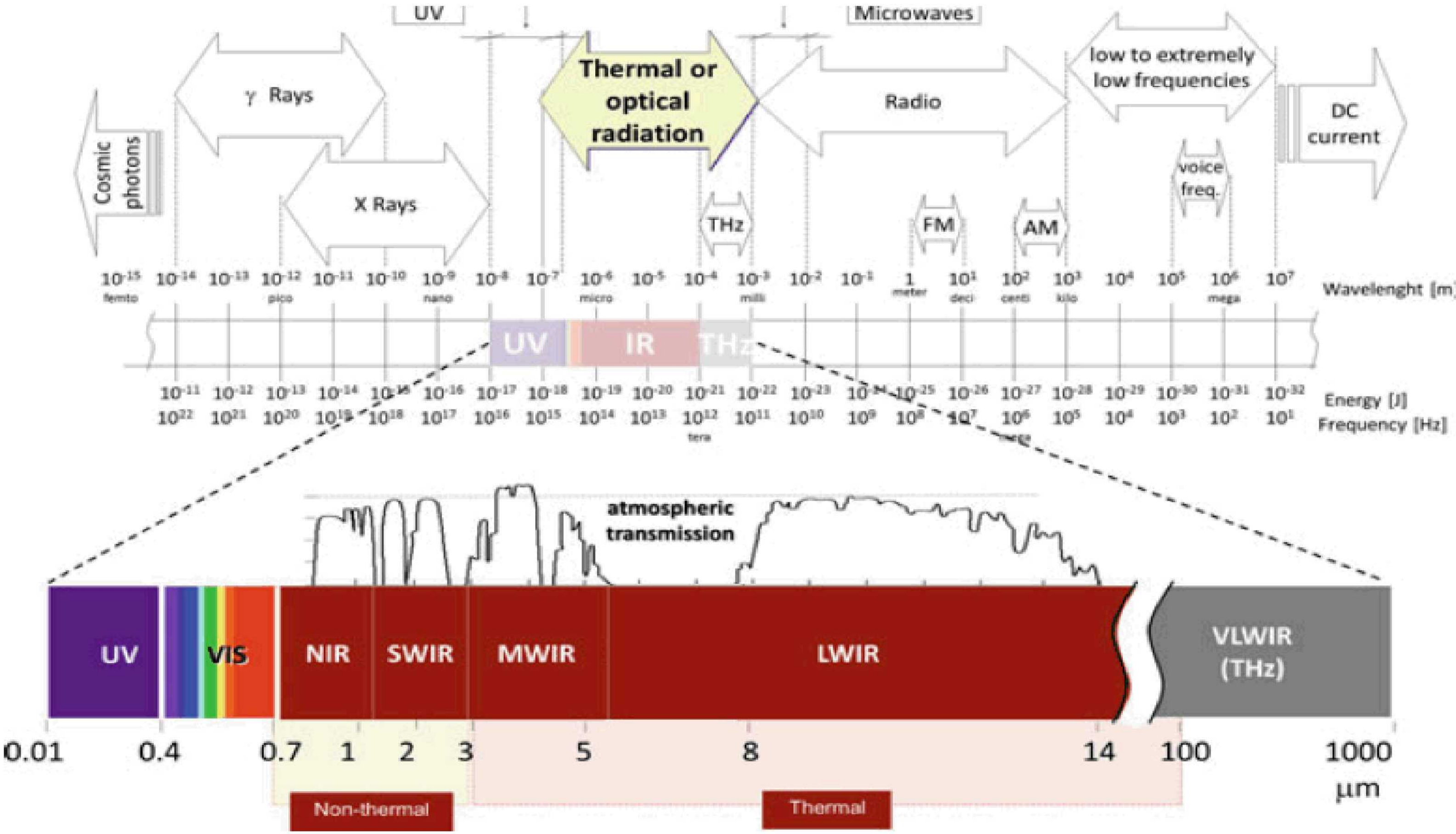
http://www.bom.gov.au/info/climate/change/gallery/14.shtml



Seasonal Radiative Energy based on Latitude



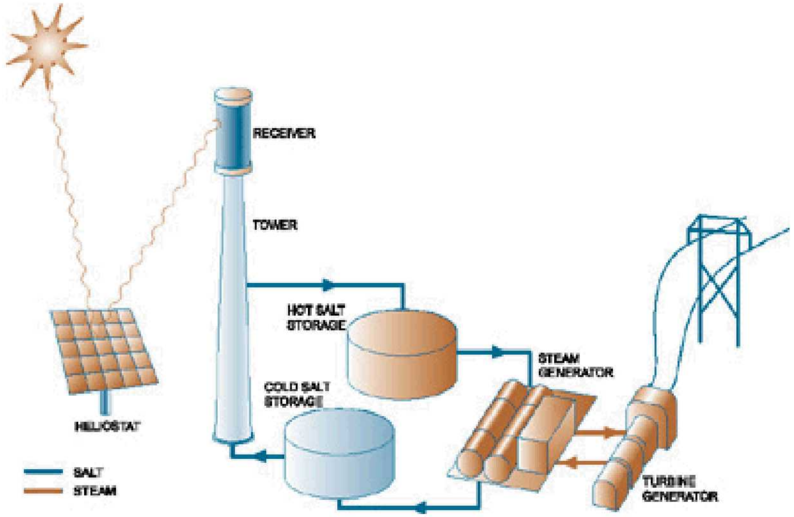
http://feww.wordpress.com



Source: Incropera DeWitt

Power Tower Systems

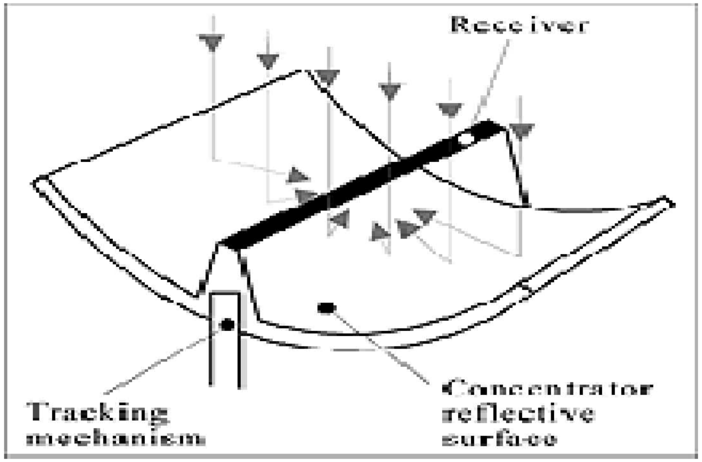
- A CSP Power Tower has a field of large mirrors that follow's the sun's path and concentrate sunlight onto a receiver on top of a high tower.
- Computer tracking keeps the mirrors aligned so the reflected rays of the sun are always aimed at the receiver, where temperatures over 1000°C can be reached. High-pressure steam is generated to produce electricity.
- Molten salt storage system retains heat efficiently, so it can be stored for hours before being used to generate electricity.
- Molten-salt is pumped from a "cold" tank at 288°C and cycled through the receiver where it is heated to 565°C and returned to a "hot" tank. The hot salt can then be used to generate electricity when needed. Current designs allow storage ranging from 3 to 13 hours.



www.energy.gov/eere/solar/

Parabolic Trough Systems

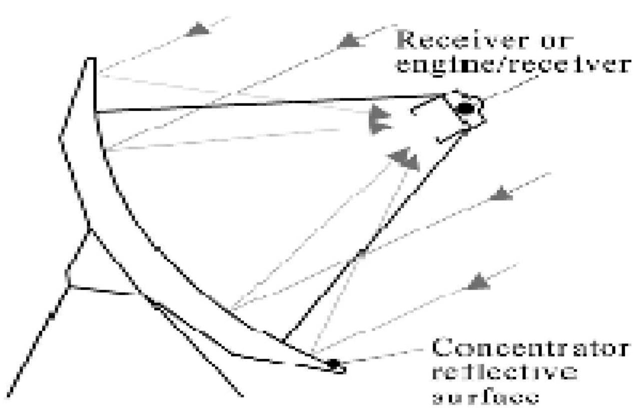
- Parabolic troughs systems concentrate sunlight onto a line-focused receiver tube positioned along the focal line of a trough. Sometimes a transparent glass tube envelops the receiver tube to reduce heat loss.
- Parabolic trough systems comprise approximately 85% of the CSP market.
- Systems typically use water or high-temperature oils, where temperatures at the receiver can reach up to 400C and produce steam for generating electricity.
- Troughs in the field are all aligned along a north-south axis to track the sun from east to west, ensuring the sun is continuously focused on receiver pipes.
- Many parabolic (as well as tower) systems use natural gas at startup for initial heating as well as for cogeneration.



Parabolic Dish Systems

- A parabolic dish collector is similar in appearance to a large satellite dish, but has mirror-like reflectors and an absorber at the focal point.
- Dish systems use dual-axis tracking to concentrate light onto a receiver located at the focal point in front of the dish.
- A Stirling engine is linked to the receiver to generate electricity. Parabolic dish systems can reach 1000 C at the receiver, and achieve the highest efficiencies for converting solar energy to electricity in the small-power capacity range.
- Each dish produces 5 to 50 kW of electricity and can be used independently or linked together to increase generating capacity. A 250-kW plant composed of ten 25-kW dish/engine systems requires less than an acre of land.

Crossection of Parabolic Dish.



6-Dish Prototypes - Sandia

- Research at Sandia Labs has investigated the development of sodium heat pipes with a phase change material (PCM) for Dish energy storage