Concentrated Solar Power (Thermal)

Agenda

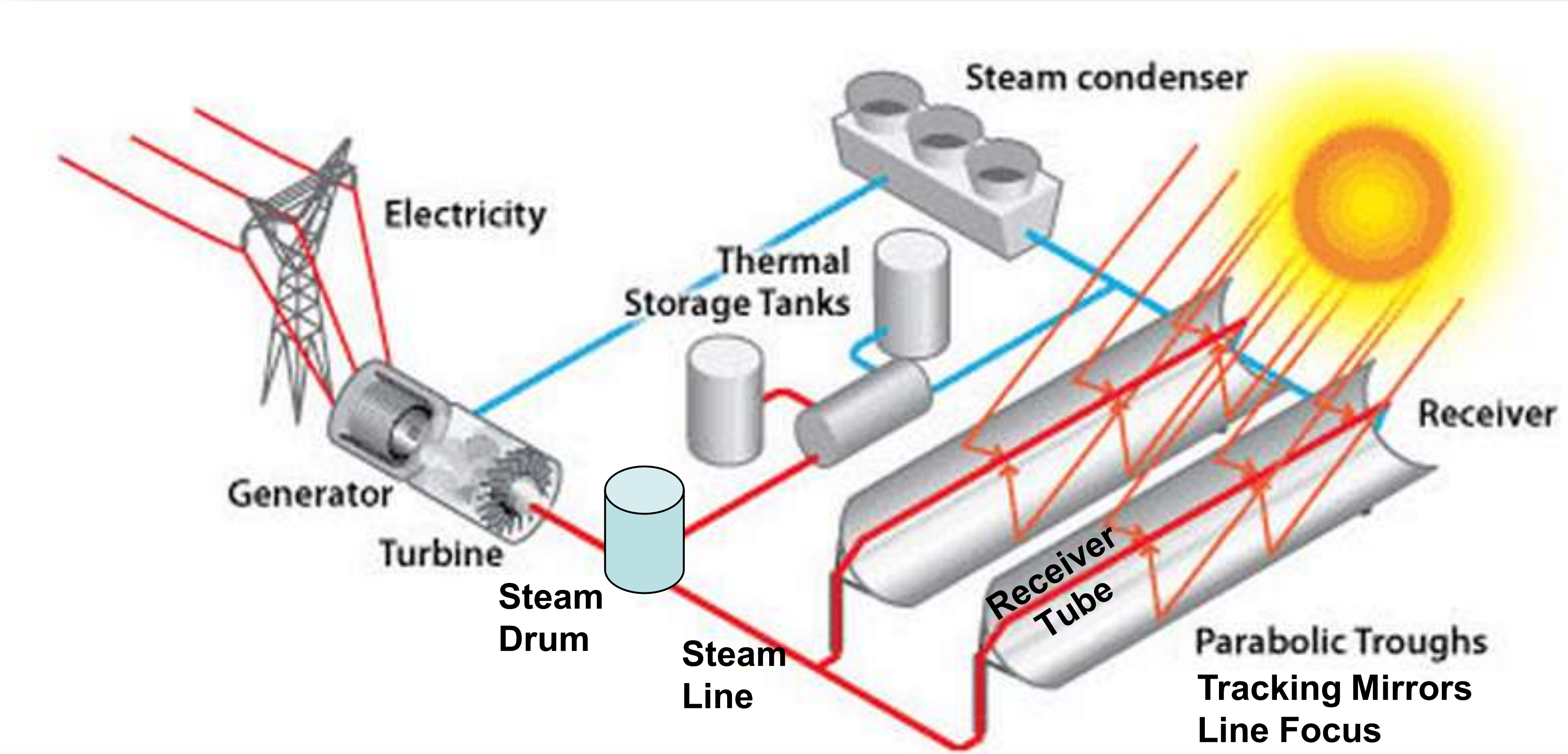
- Intro
- Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays

- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Solar-PV cell design R&D
  - Silicon wafer, cell manufacture
  - Materials and emissions in construction

- Concentrated solar power (CSP) technology
- Solar power strategic issues
- US installations and performance

Next: Wind Power

Line-Focus CSP Collectors



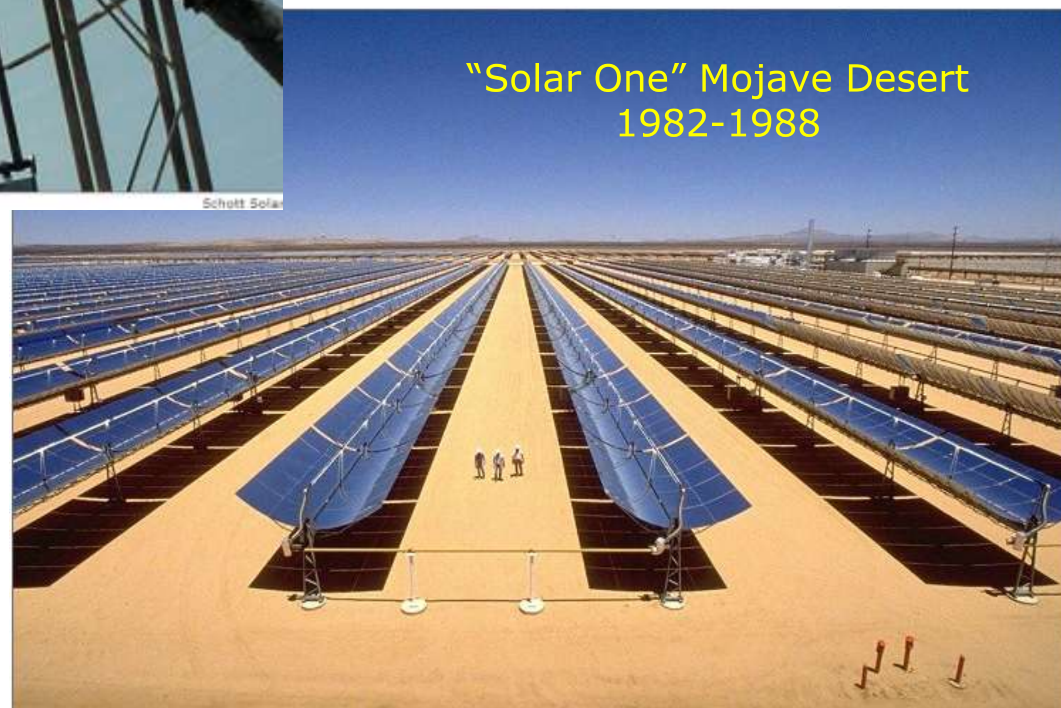
A linear concentrator power plant using parabolic trough collectors. **→ ΔT = 50^0- 400^0C**

Receiver/collector fluid=oil → heat exchanger →steam driven turbine generator

Largest trough systems: ∽ 400 MW_e. Overnight molten salt (K/Na nitrate) heat storage tanks (large heat capacity). After: DOE Energy Efficiency and Renewable Energies.

Line-Focus CSP Collector

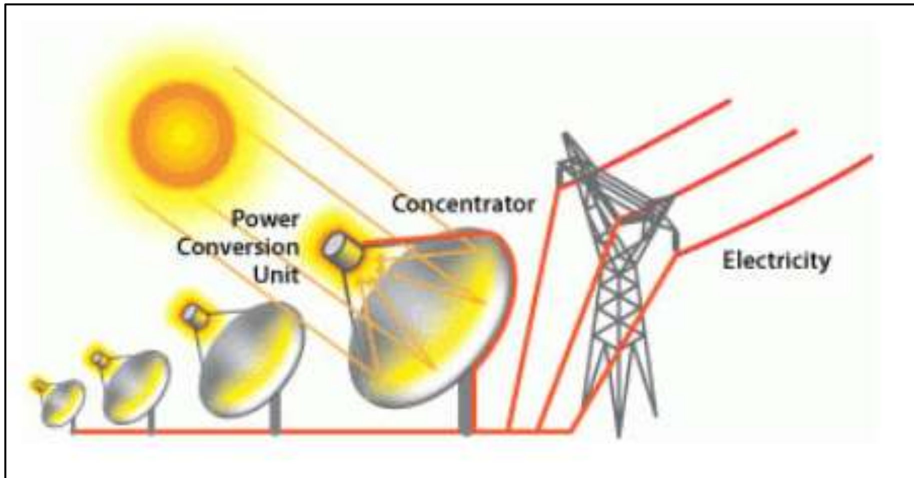
Receiver Tube (oil)



Mojave Desert power plants (3 sites), Location: Barstow, CA total 354 MW_e, $2 \cdot 10^6$ m^2 collector area, synthetic oil. Efficiency $\varepsilon = 0.16\text{-}0.18$

Solana, 2013, Location: Gila Bend, AZ
Capacity: 280 MW_{th}, tubes with molten salt storage (6 hrs).
Efficiency $\varepsilon = 0.34$
Genesis, 2013, Blythe, CA

Dish Engine Systems (Sterling Thermal Engine)



Concentrating solar power (CSP) technology for low power applications (3 - 25 kW).

Compact dish/engine system: solar concentrator (parabolic mirror) plus power converter unit (thermal engine).

Minimal support infrastructure, flexible modular use, .

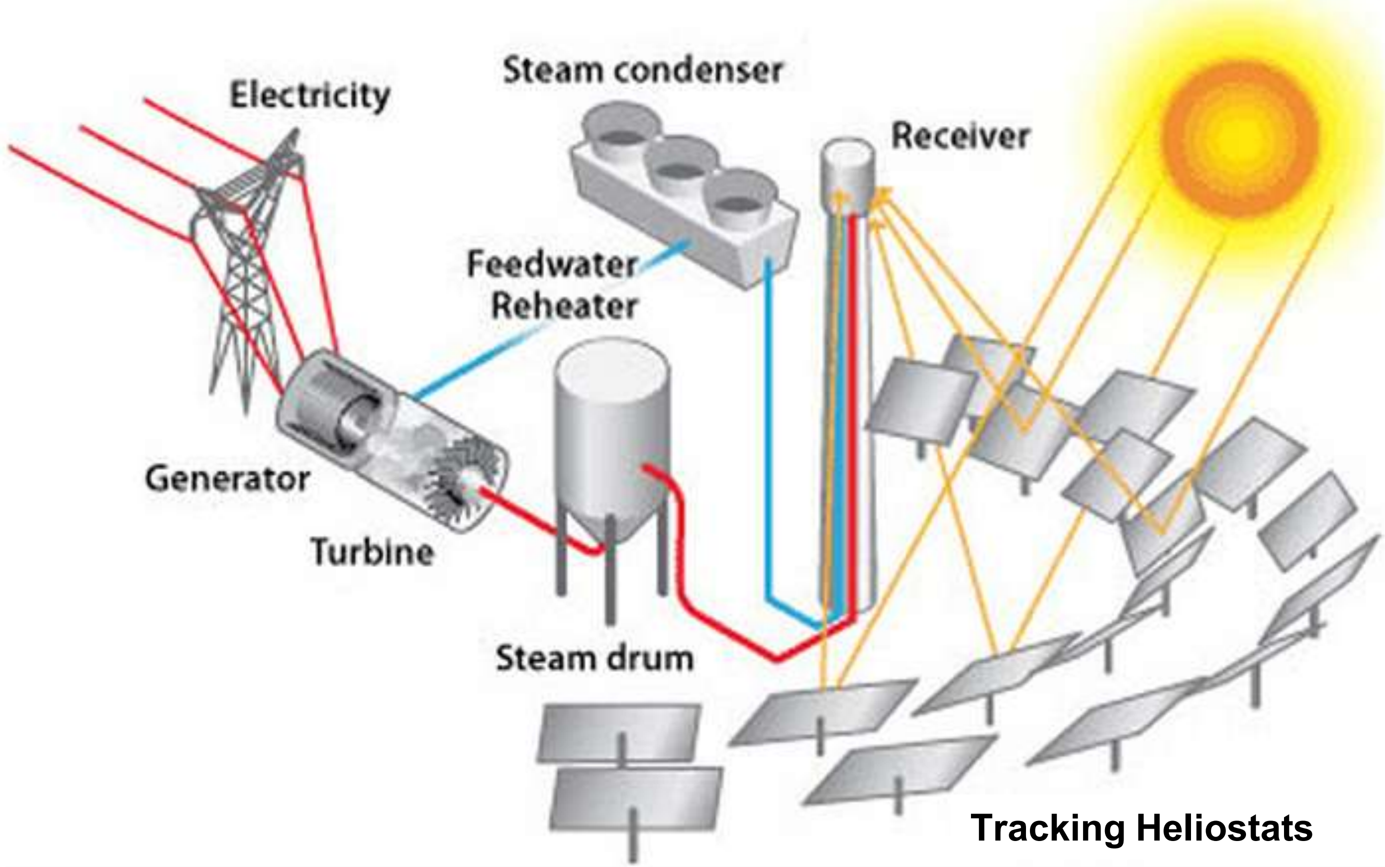
US: Ivanpah (CA) Solar Thermal Power Plant

Largest (2013-2026?) solar thermal power plant on public land. Working fluid water, natgas start up. Construction: 1896 man-years (4 years). Construction costs > $5.5/W, down from Crescent Dunes (> $9/W) . 2010, project reduction from 440 MW→ 377 MW environmental concerns (desert tortoise).

Heliostat Tracking Mirrors

The Solar One “proof of principle” project produced 10 MW of electricity. Used 1,818 heliostat tracking mirrors, each covered area of 40 m² (430 ft²). Total area = 72,650 m² (782,000 ft²).

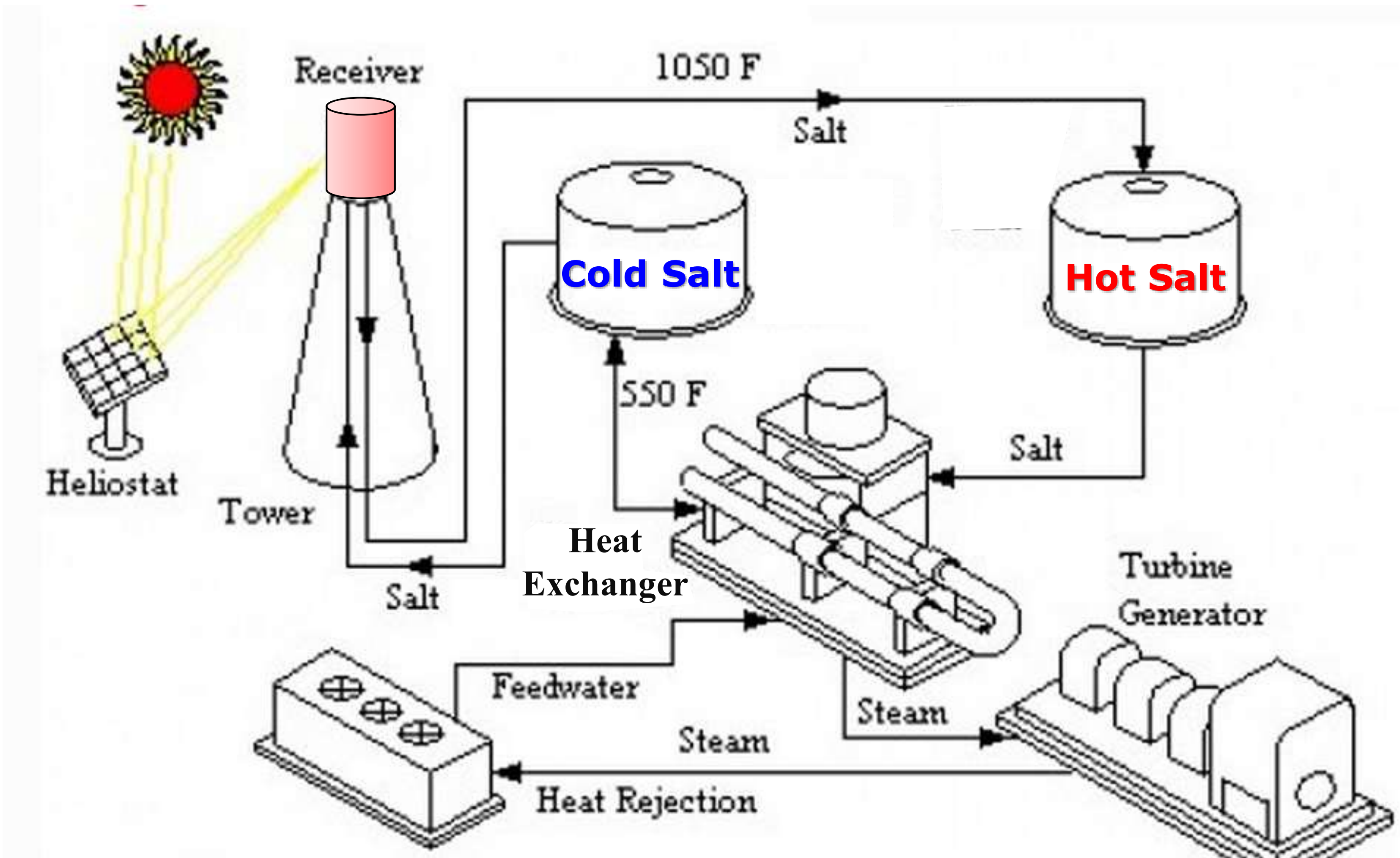
Solar Tower Power Plant



A power tower power plant.

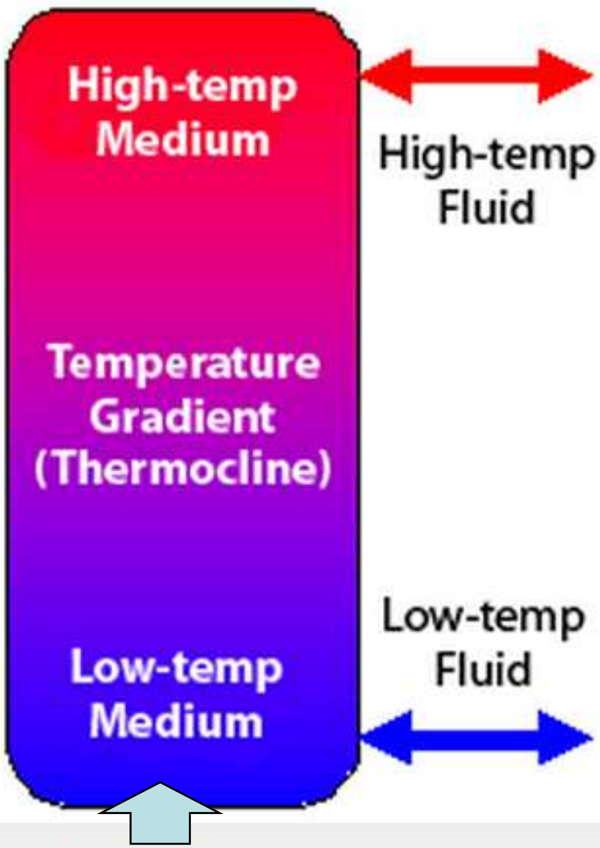
1982-1988: "Solar One", 10-MW plant (Barstow/CA).
1996-1999: "Solar Two", 10-MW, molten nitrate salt as primary medium.
Spain: several operational thermal (water/steam) tower plants, 11-20 MW

Concentrated Solar Power Plant: Working Medium Flow



Molten salt is able to reach very high temperatures (over 1000 degrees Fahrenheit) and can hold more heat than the synthetic oil used in other CSP plants, the plant is able to continue to produce electricity even after the sun has gone down.
Startup needs external heating, e.g., with nat gas boiler.

Heat Transfer/Storage



A single-tank thermocline thermal energy storage system.

SINGLE-TANK THERMOCLINE SYSTEM

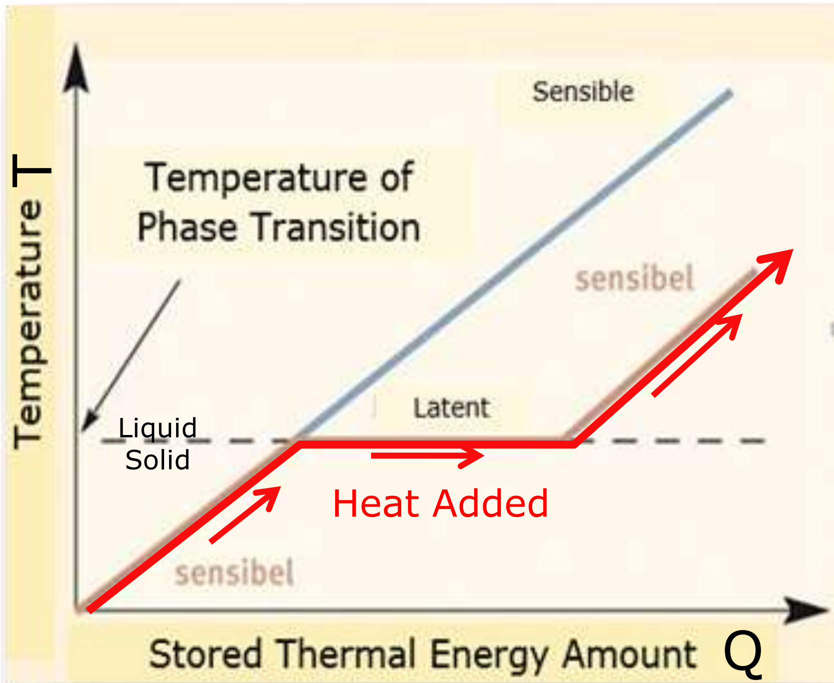
Thermal storage and heat exchange in solid material: Silica sand, ceramic.

Can be driven directly (store thermal energy by heating silica material), or in reverse (withdraw thermal energy to heat cold fluid)

The early trough plants used mineral oil as the heat-transfer and storage fluid;
Solar Two: used molten salt (K/Na Nitrates, ΔH of fusion, phase change heat conductivity)

The two-tank direct molten-salt thermal energy storage system at the Solar Two power plant.

Thermal Work Media/Energy Storage Materials



Thermal properties

(i) Suitable, low phase-transition temperature.

(ii) High latent heat of transition, thermal inertia.

(iii) Efficient heat transfer mode.

Recent review of PCM storage materials: A. Sharma et al., Renewable and Sustainable Energy Reviews 13 (2009) 318–345

Physical properties

(i) Favorable phase equilibrium.

(ii) High density.

(iii) Small volume change.

(iv) Low vapor pressure.

Kinetic properties

(i) No supercooling.

(ii) Sufficient crystallization rate.

Chemical properties

(i) Long-term chemical stability.

(ii) Compatibility construction materials

(iii) No toxicity.

(iv) No fire hazard.

Economics

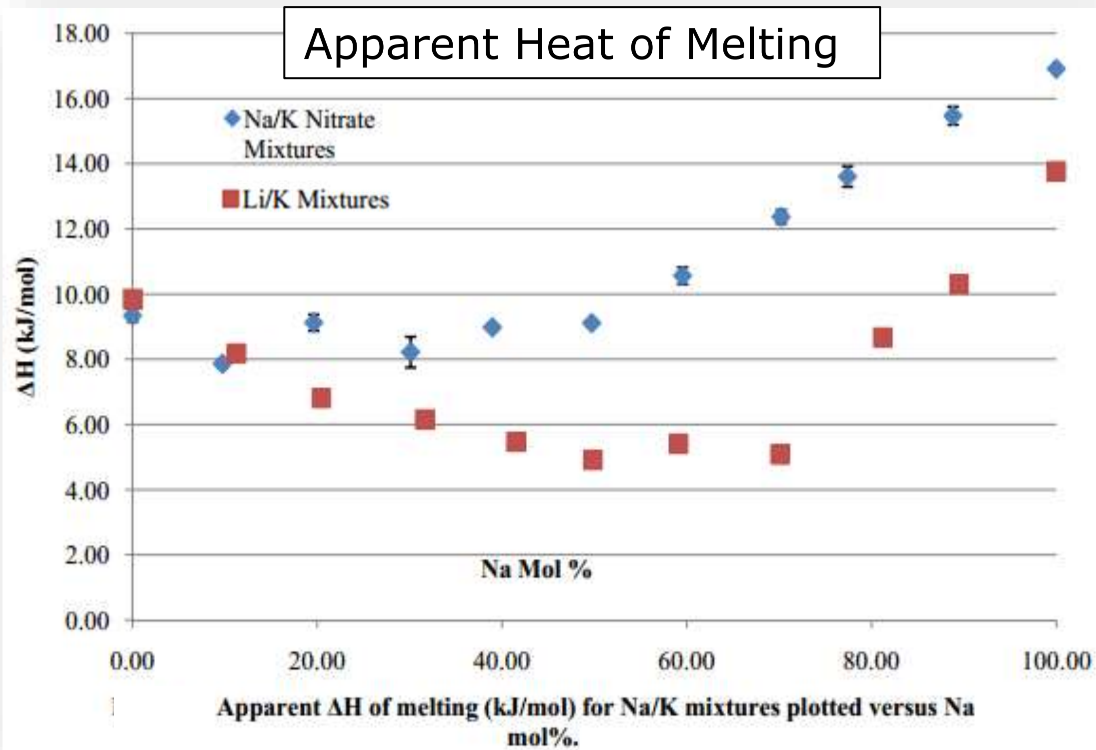
(i) Abundant.

(ii) Available.

(iii) Cost effective.

Competing storage technologies: Batteries, electrolyzer-H_2, pumped pV & gravitational, thermal, mechanical,…

Nitrate Salts: Thermodynamic Properties



Cordaro et al., Sandia Lab, 1980s.

Water: $c_p(H_2O)$= 4.184 J/(g·°C)
$C_v(H_2O)$= 74.539 J/(mol·K) (25 °C)
Heat of fusion ΔH_f = 333.6 J/g =6.01kJ/mol
Latent heat of vaporization ΔH_v = 40.7 kJ/mol

Non-ideal mixtures: Non-linear behavior, not proportional to mole fraction.

Large enthalpy of fusion → capacity to store large amount of energy in molten phase, recover upon fusion (solidification).

Na/K nitrates ($NaNO_3$, (KNO_3) have good (suitable) thermodynamic properties.

Fluor compounds, molten salt, FLIBE

Heat Transfer/Thermal Storage Materials

For design of large production facilities, accurate physical and thermodynamic properties of must be known.

Required data:

a) melting point;
b) viscosity;
c) apparent heat of fusion;
d) thermal conductivity;
e) heat capacity;
f) density;
g) volumetric expansion;
h) vapor pressure.

"Designer materials" for heat transfer: mixtures of salts, control various thermodynamic parameters.
Water or oil have limited temperature range for liquid phase → vapor requires pressure vessels, pipes.
Molten salts = good compromise.

Cordaro et al., Sandia Lab, 1980s.

Salt	Cp (J/mol/K) (this work)
$LiNO_3$	142.99 ± 1.68 (550-655K)
$NaNO_3$	140.58 ± 0.27 (590-655K)
KNO_3	138.41 ± 1.10 (610-655K)
$Ca(NO_3)_2$	140 - 160 (550 – 655 K)
$NaNO_2$	110.48 ± 1.14 (625-675K)
KNO_2	120.42 ± 1.43 (745-800 K)

Water: $c_p(H_2O)$= 4.184 J/(g·°C)
$C_v(H_2O)$= 74.539 J/(mol·K) (25 °C)
Heat of fusion ΔH_f = 333.6 J/g =6.01kJ/mol
Latent heat of vaporization ΔH_v = 40.7 kJ/mol

Solar Electricity Generation: Performance in SW U.S.

$$CF := \frac{Energy\ Generation\,(period)}{Nameplate\ power \cdot period}$$

Mesquite Solar 1-3 PV (2017-2019). Arlington, AZ
→ optimum Capacity factor 2024: ***CF***(=ε) ≈ 35%

Generation (MW·h) of Mesquite Solar 1 (150MW)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2017	18,968	23,127	39,542	43,048	45,896	51,628	31,943	39,425	40,513	37,184	22,096	20,363	**413,734**
2018	23,598	25,234	32,580	38,786	48,925	47,774	42,202	42,713	41,106	29,406	25,482	17,198	**415,004**
2019	21,519	21,215	33,843	40,244	42,179	47,752	42,113	45,612	36,747	37,825	21,338	16,959	**407,345**

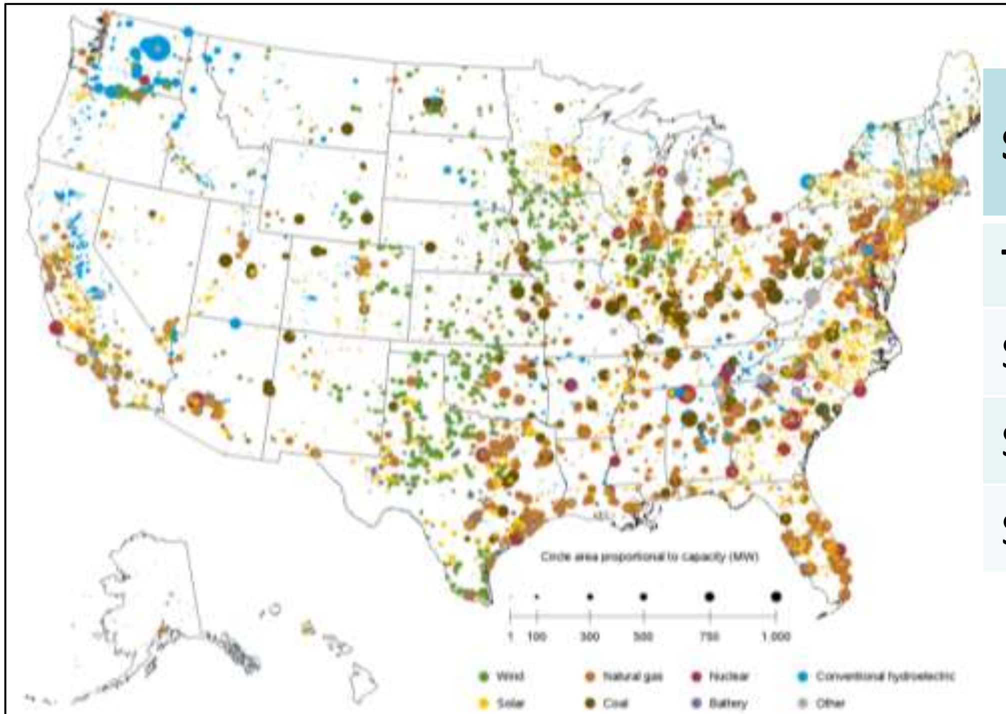
Generation (MW·h) of Mesquite Solar 2 (100MW with tracking)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016												13,255	**13,255**
2017	15,016	16,794	26,698	29,176	31,992	32,486	29,490	28,681	26,392	23,857	15,275	15,040	**290,897**
2018	17,201	18,569	24,484	28,562	32,739	31,729	29,461	29,075	26,015	16,891	15,900	14,396	**285,023**
2019	16,090	14,280	19,916	21,340	22,983	30,941	29,656	29,898	23,634	23,723	13,615	9,971	**256,047**

Generation (MW·h) of Mesquite Solar 3 (150MW with tracking)

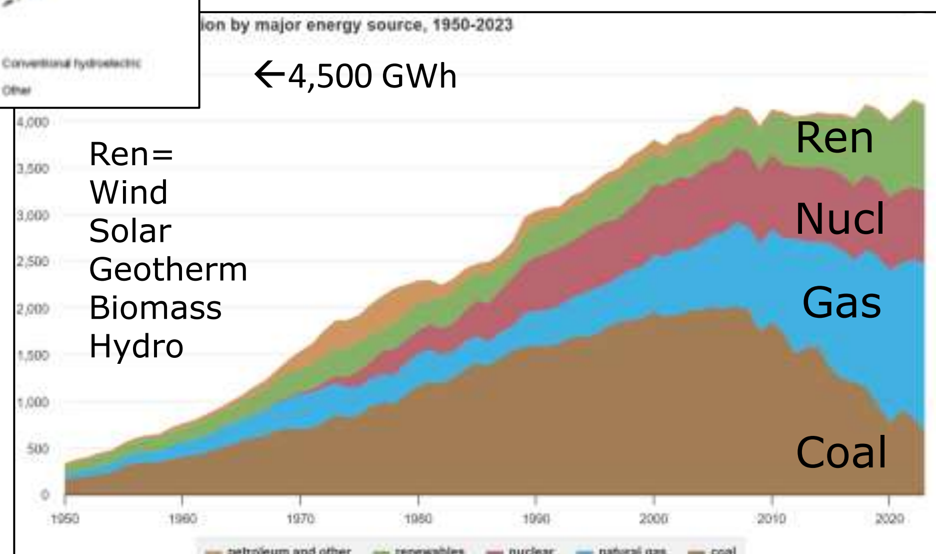
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016												21,060	**21,060**
2017	22,673	25,705	40,558	43,985	48,952	49,978	44,174	43,447	39,846	35,670	23,425	22,187	**440,600**
2018	25,678	28,450	38,984	43,517	50,609	48,203	44,817	44,342	39,830	31,777	27,684	21,898	**445,789**
2019	25,460	26,613	38,070	43,410	47,869	48,938	45,483	45,652	39,165	39,109	25,772	20,096	**445,637**

US 2024: Utility Scale Electric Generators

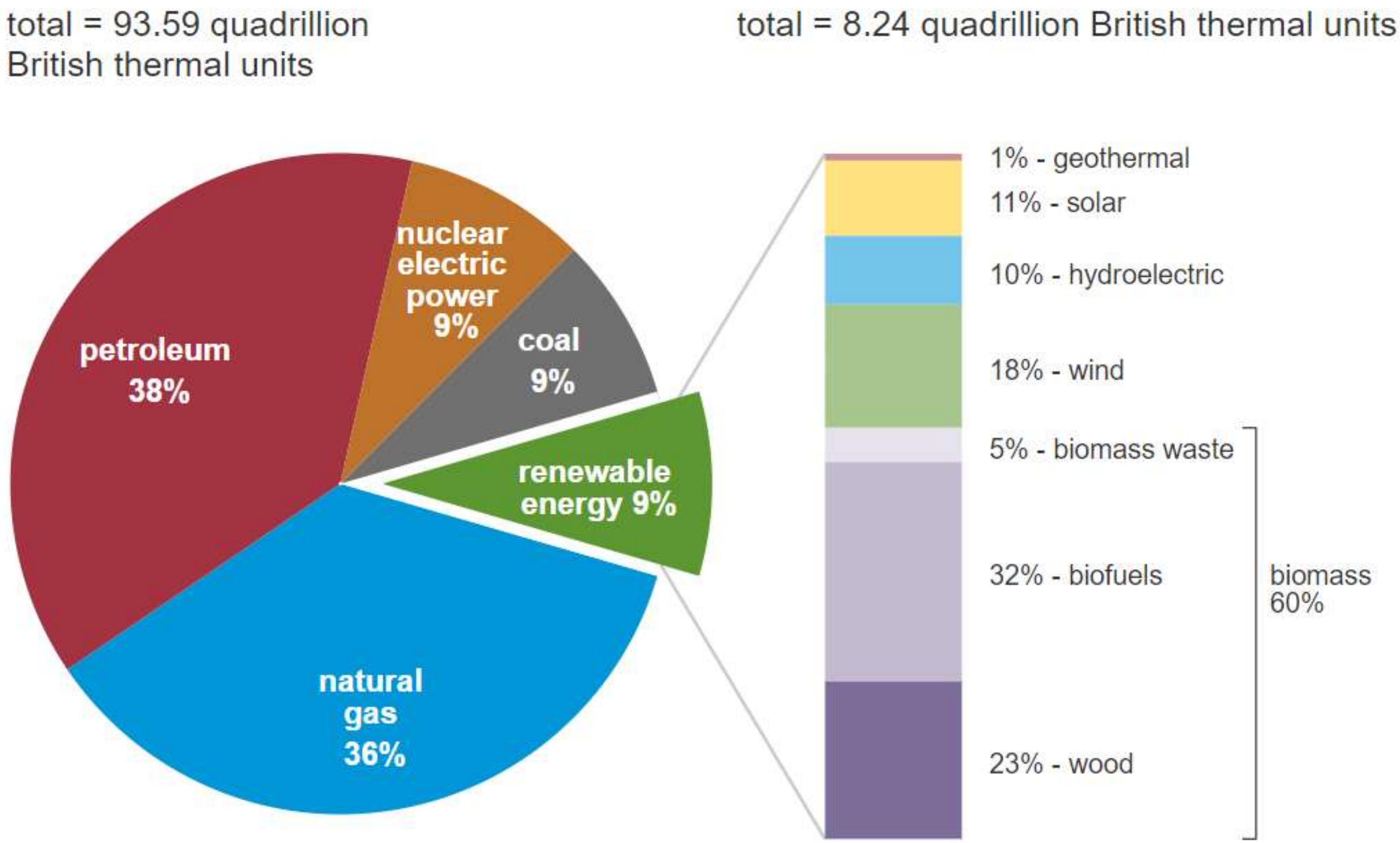


Source	Electricity (GWh)	Share
Total U.S.	**4,308,634**	100%
Solar **PV**	300,634	**6.98%**
Solar **CSP**	3,118	**0.07%**
Solar (PV + CSP)	303,752	7.05%

US 2024: 12,538 utility-scale power plants (>1MW), generation capacity 1.3 TW with 401 major coal-fired plants and 94 nuclear reactors.

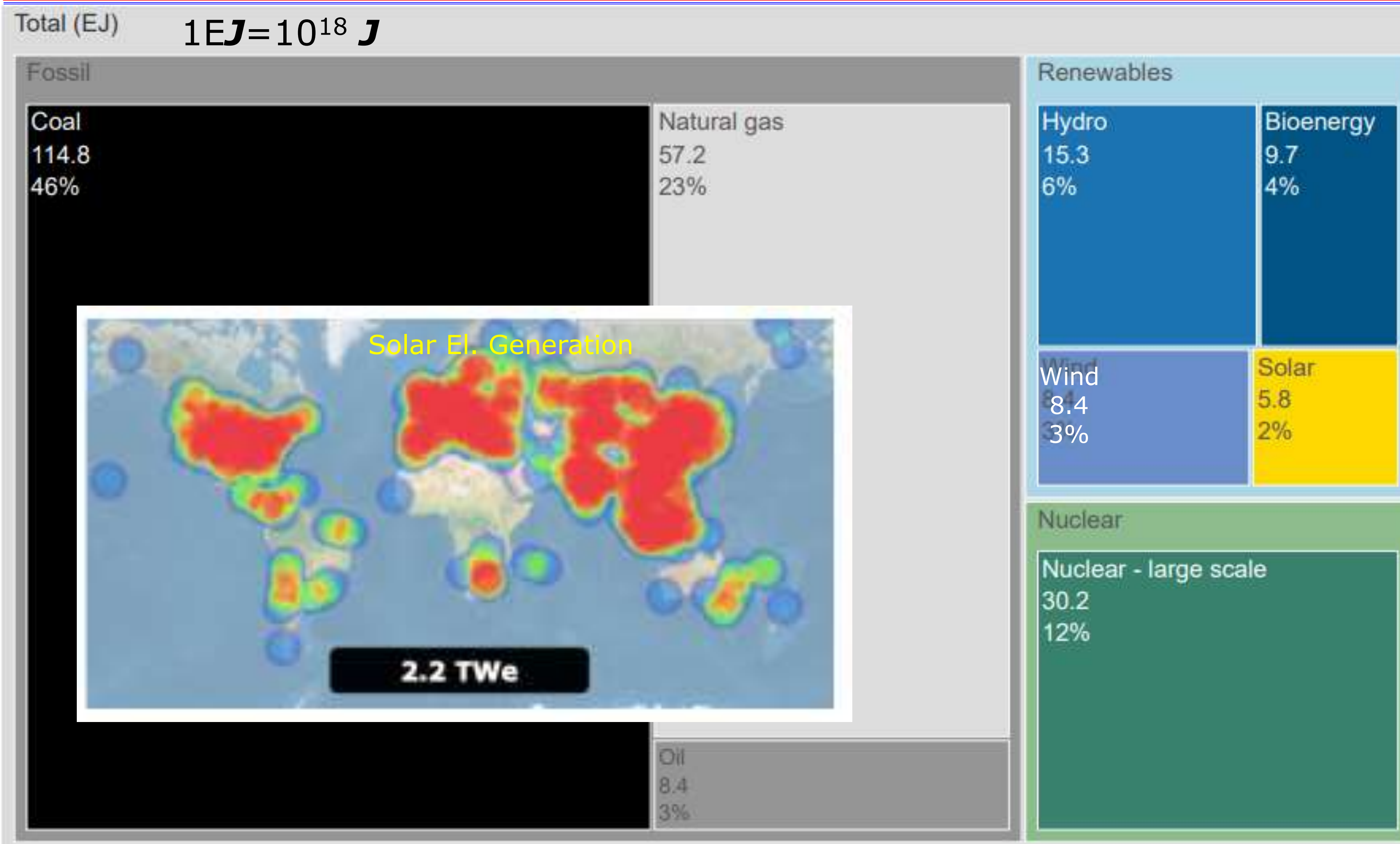


U.S. Total Energy Consumption 2023



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2024, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

2024 Global Electricity Production



Source: NEA figure based on IEA World Energy Outlook (IEA, 2024).

Still dominant coal power plants. Many are likely to be closed and replaced by other technologies. Various rationales: useful life, amortization, pollution. → What to scale?

Solar Power Technologies: Strategic Issues

1. Intermittency, subject to local weather, diurnal (“duck curve”) and seasonal variations,
2. Controllability, voltage/power depend on insolation, temperature coefficients,
3. Low power densities and efficiencies, in particular solar thermal,
4. Geographic limitations, resource-consumption distance, transmission losses,
5. Long term stability, thin-film PV cells,
6. Converters DC → AC, feed-in synchronization/connection/management utility e-grid,
7. Impact on local ecosystems, large land use per W, metal (Cu) mining,
8. Emissions (CO_2, H_2S, SF_6…) & toxic acids, chemicals in PV cell or film production,
9. Needs efficient energy storage over dark periods, “smart” grid for feed-in,
10. Economics ($$/kWh, “energy pay-back” times), incentives required for adoption,
11. Minor role in current global & US energy mix (ramp time for scaling to ~(10-20)%).
12. Skilled manpower, sufficient for scaling.