Agenda

- Intro

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

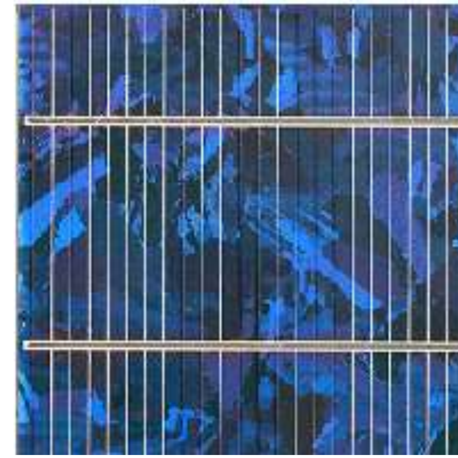
- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Photo sensitive materials, silicon cell manufacture
  - Materials and emissions in construction

- US installations and performance, system cost and incentives
- Solar power strategic issues

Most Common Commercial Solar Cells

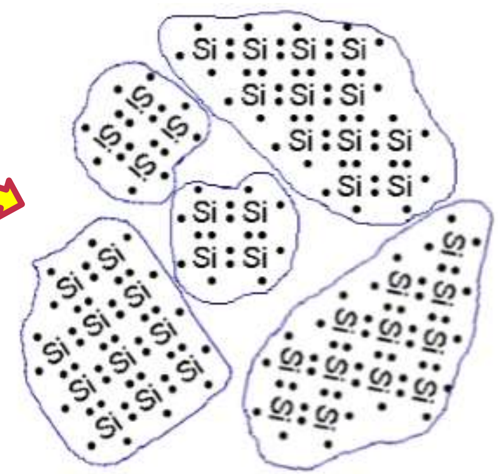
Silicon single-crystals:
Continuous, repetitive structure.
Rare in nature, needs to be grown in lab. → expensive for large crystals.

Solar cells made from single crystal, (200-300)μ wafers. Mono-crystalline cells, most efficient, most expensive.



Multi-crystalline silicon:
Pieces made of more than one single-crystal, multiple domains.

Constituent crystals relatively small, easier to grow and cheaper.
Also less efficient, free charge carriers have to cross boundaries.



Amorphous ***a*-Si:H** $\langle\varepsilon_G\rangle$=1.7eV, high absorbance.

New: Thin-film cells (1 μ thick), technique saves material.
Heterojunction cells: CdTe,..
Multi-layer cells
Organic semiconductors.

Thin-Film PV Solar Cells: CIGS

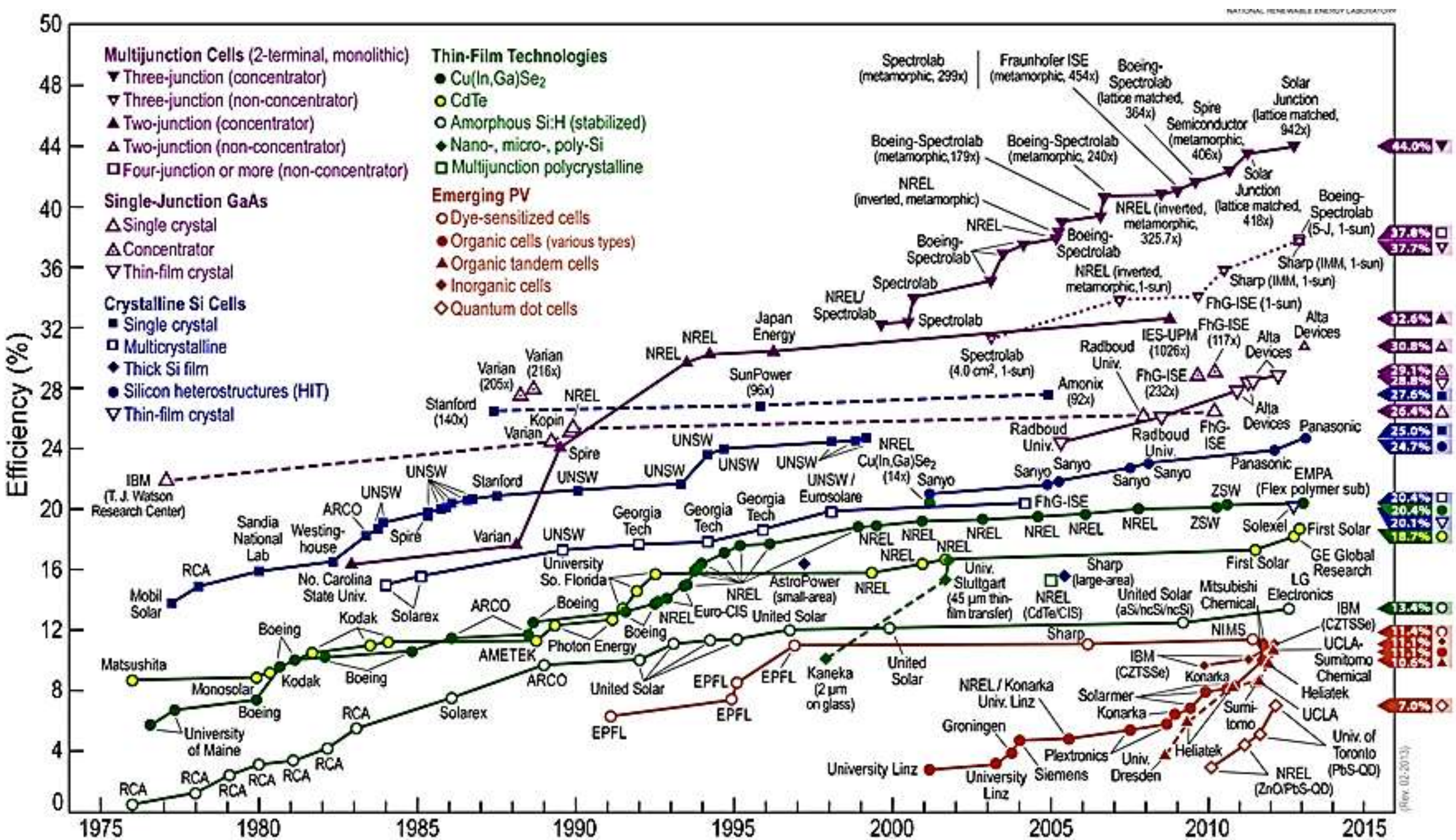
The ZSW institute's building in Stuttgart-Vaihingen has a façade with CIGS panels.

Nano-particles embedded in plastic.

2019: CIGS (Copper, Indium, Gallium and Selenium) cell efficiencies have surpassed all other thin film PV technologies, achieving 23.4% on the cell and 17.5% on the module level.
CIGS has also been deployed in ultra-high efficiency tandem cells, potential to achieve 30% efficiency.
Future efficiency development via band-gap tuning: Perovskite/CIGS tandem

Ongoing R&D: Efficiencies of Solar Cells

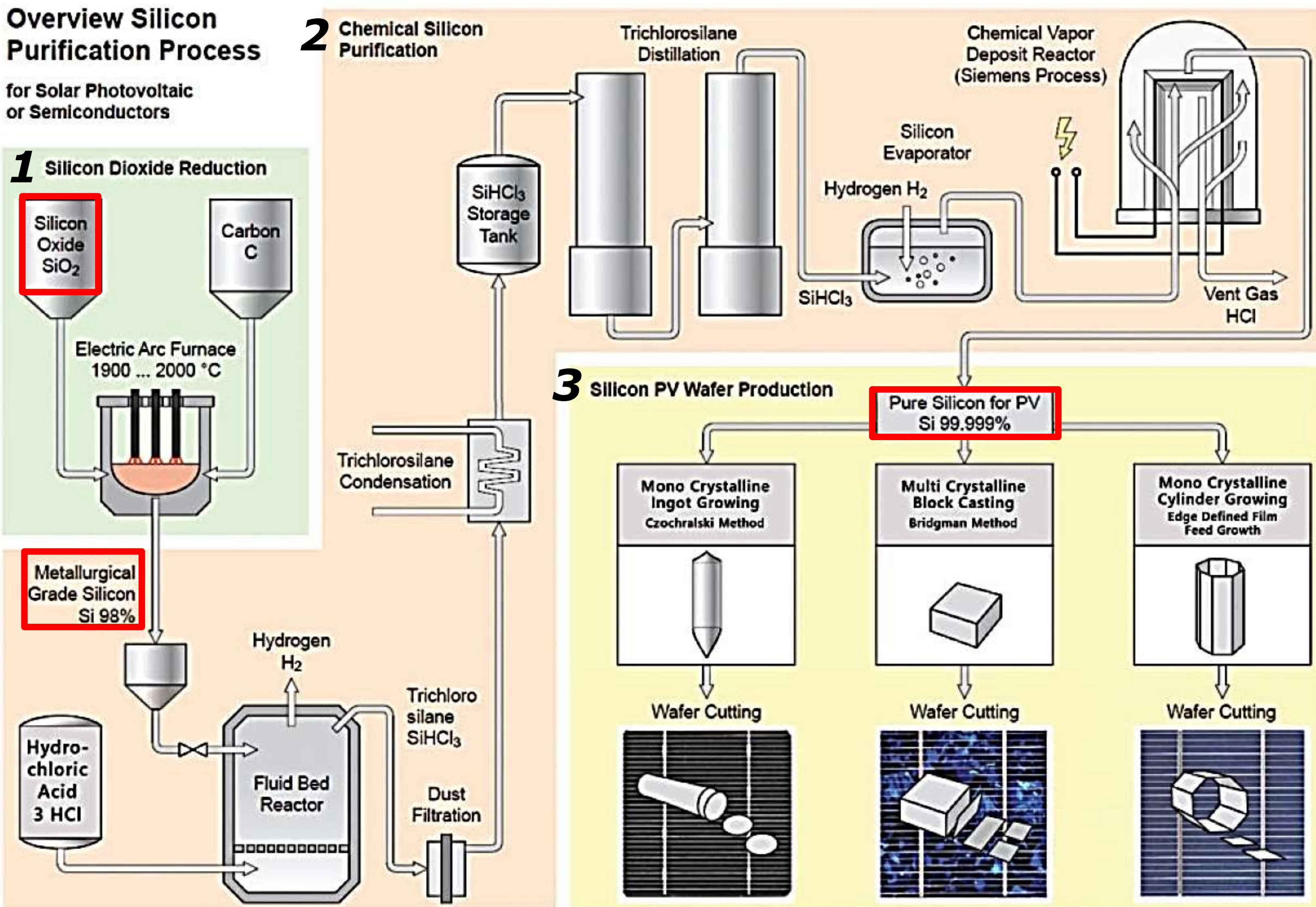
Standard with conventional processes: flat-panel multi-crystalline cells (240-250)W, e ≤ 20%.



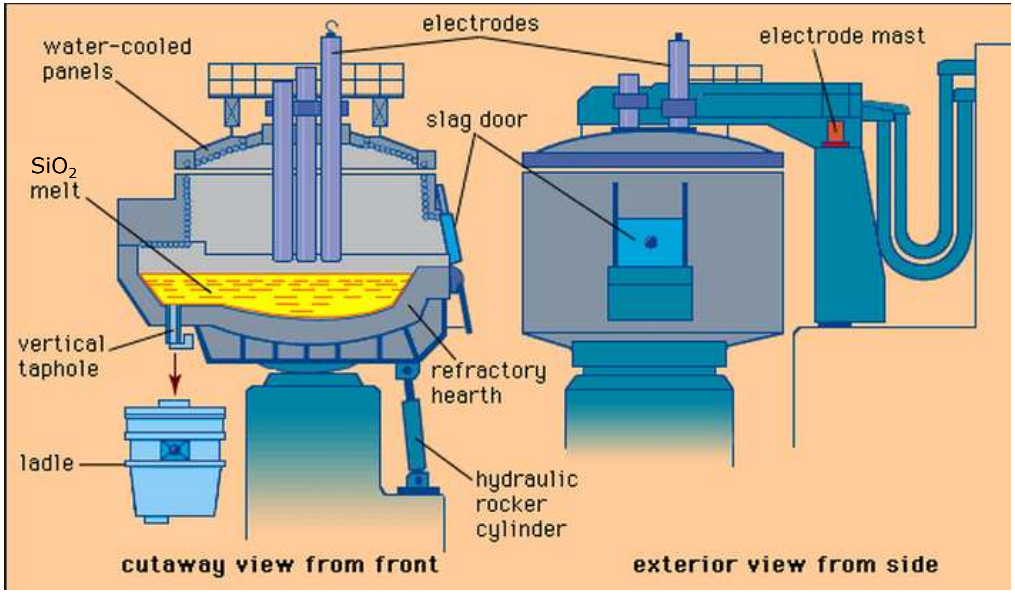
http://theenergycollective.com/ericwesoff/208316/first-solar-crushes-solar-pv-efficiency-record, Acc. April 2013.

Mainstay Si cell production

PV Cell Manufacture Chain



Semiconductor Grade Silicon Fabrication



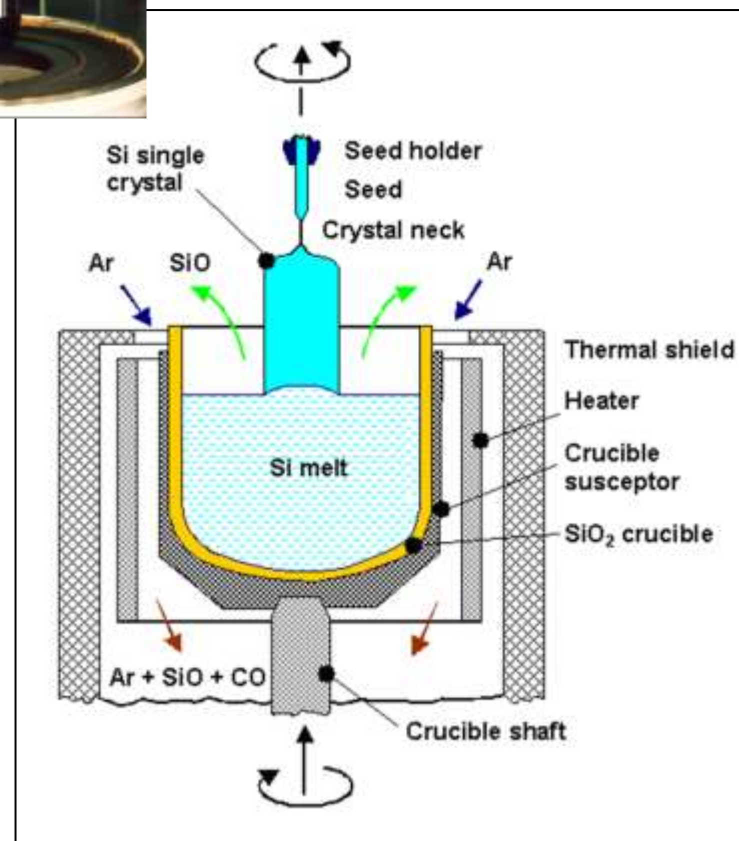
Steps to Obtaining Semiconductor Grade Silicon (SGS)

Step	Description of Process	Reaction
1	Produce metallurgical grade silicon (MGS) by heating silica with carbon	C (s) + SiO_2 (s) → Si (l) + SiO (g) + CO (g)
2	Purify MG silicon through a chemical reaction to produce a silicon-bearing gas of trichlorosilane ($SiHCl_3$)	Si (s) + 3HCl (g) → $SiHCl_3$ (g) + H_2 (g) + heat
3	$SiHCl_3$ and hydrogen react in a process called Siemens to obtain pure semiconductor-grade silicon (SGS)	2$SiHCl_3$ (g) + 2H_2 (g) → 2Si (s) + 6HCl (g)

Arc furnace for processing materials with high melt temperatures, e.g., T_{fus} = SiO_2: 1,600^{0}C.

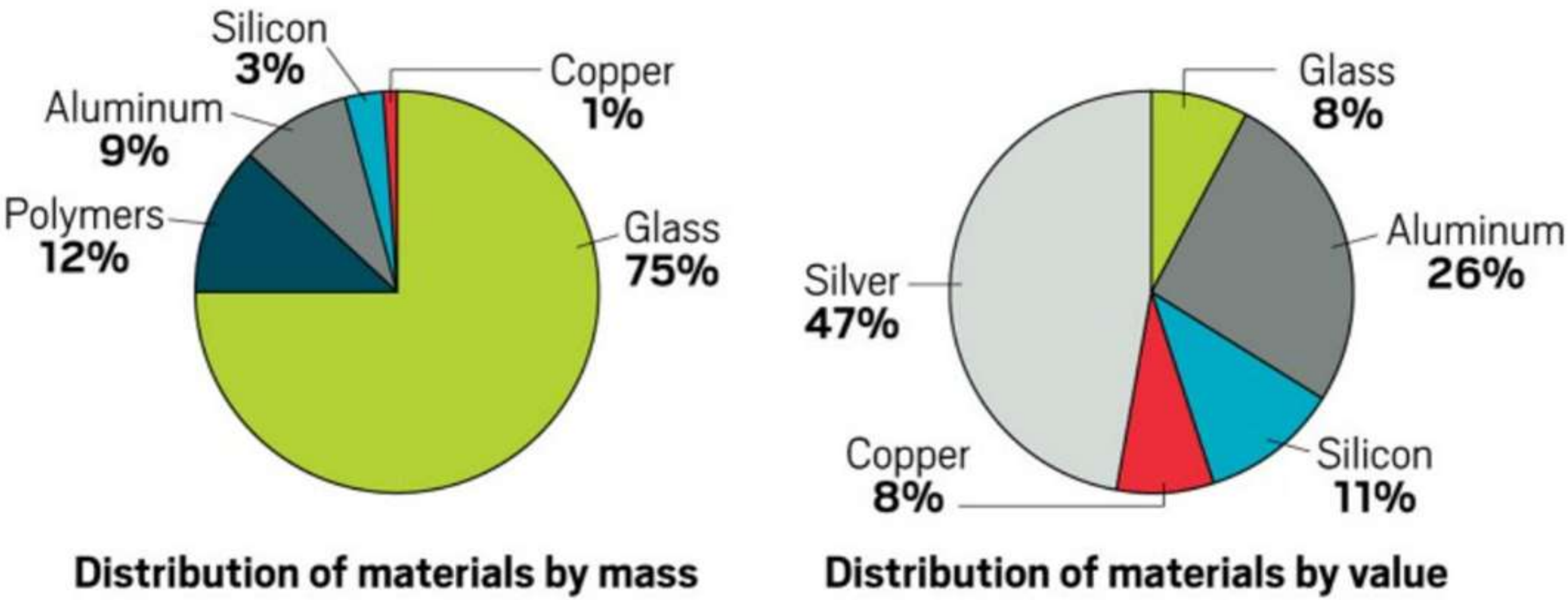
Czochralski Process

Metallurgical Si is melted in quartz crucible, seed Si crystal dipped into melt, slowly drawn while rotated. Impurities remain in melt, oxygen from crucible → Si crystal, stabilizes.



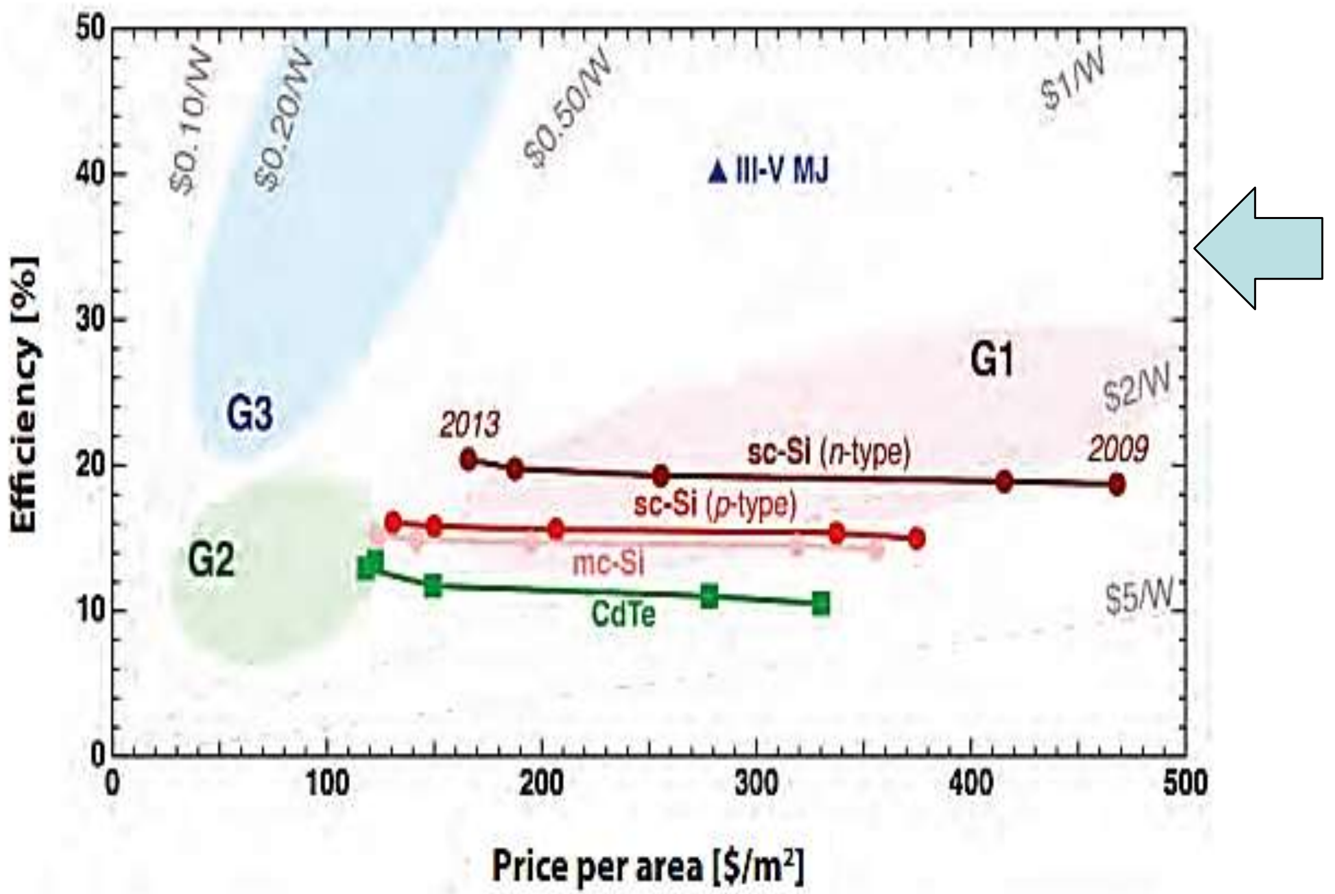
Large single-crystal suspended by thin **Si** seed crystal (inset, arrow). Seed crystal supports weight of the crystal and the torque needed to rotate crystal during its growth

Si-PV Cell Materials



Source: Martin Bellman/Icarus. **Note:** Silver is less than 1% of the mass.

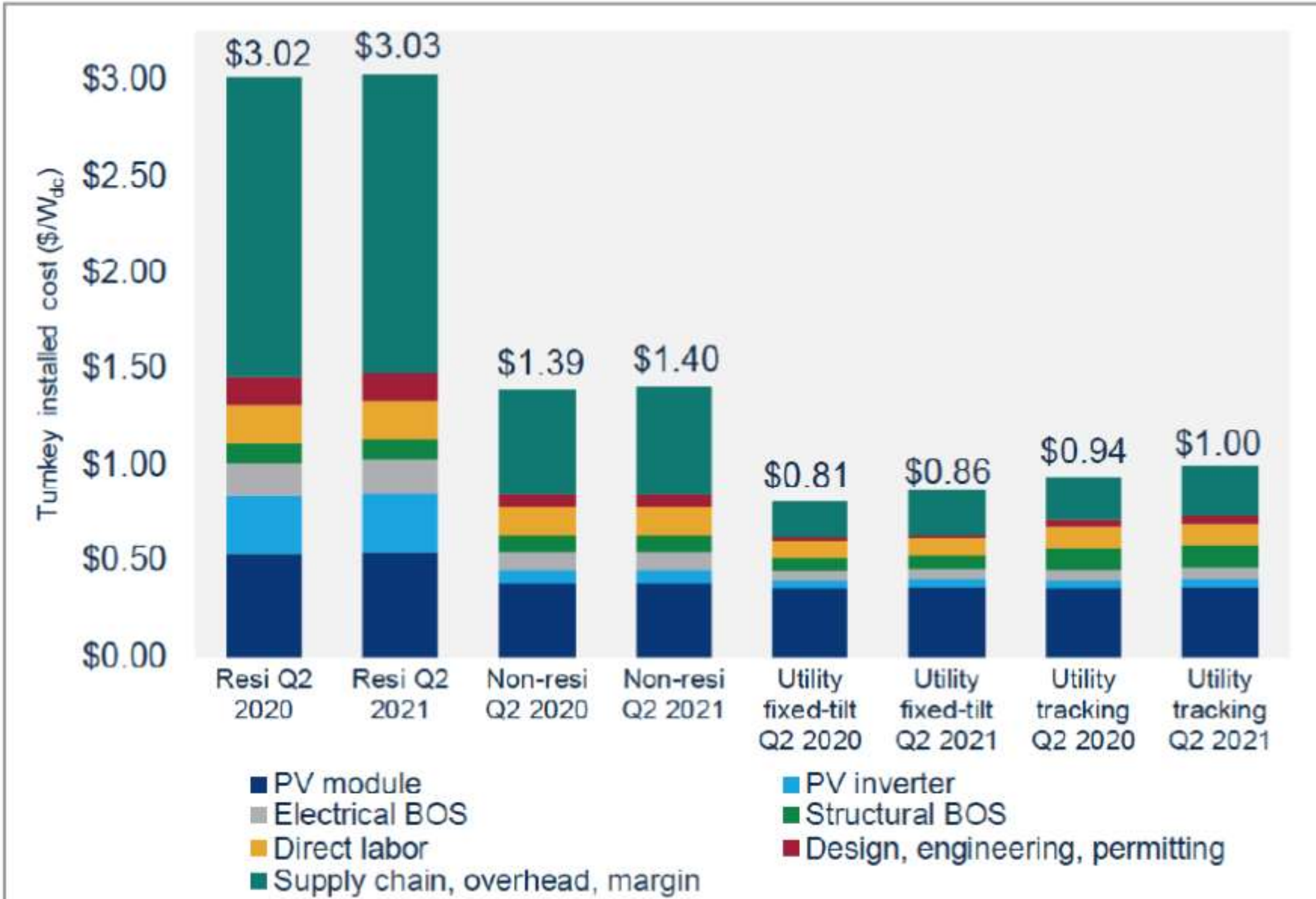
Trends in Commercial PV Price/Performance



PV module efficiency and price per area (period 2009-2013).Conventional generations: G1 in red, G2 in green, and G3 in blue.

Current G1 and G2 modules cluster near the region originally defined as G2.

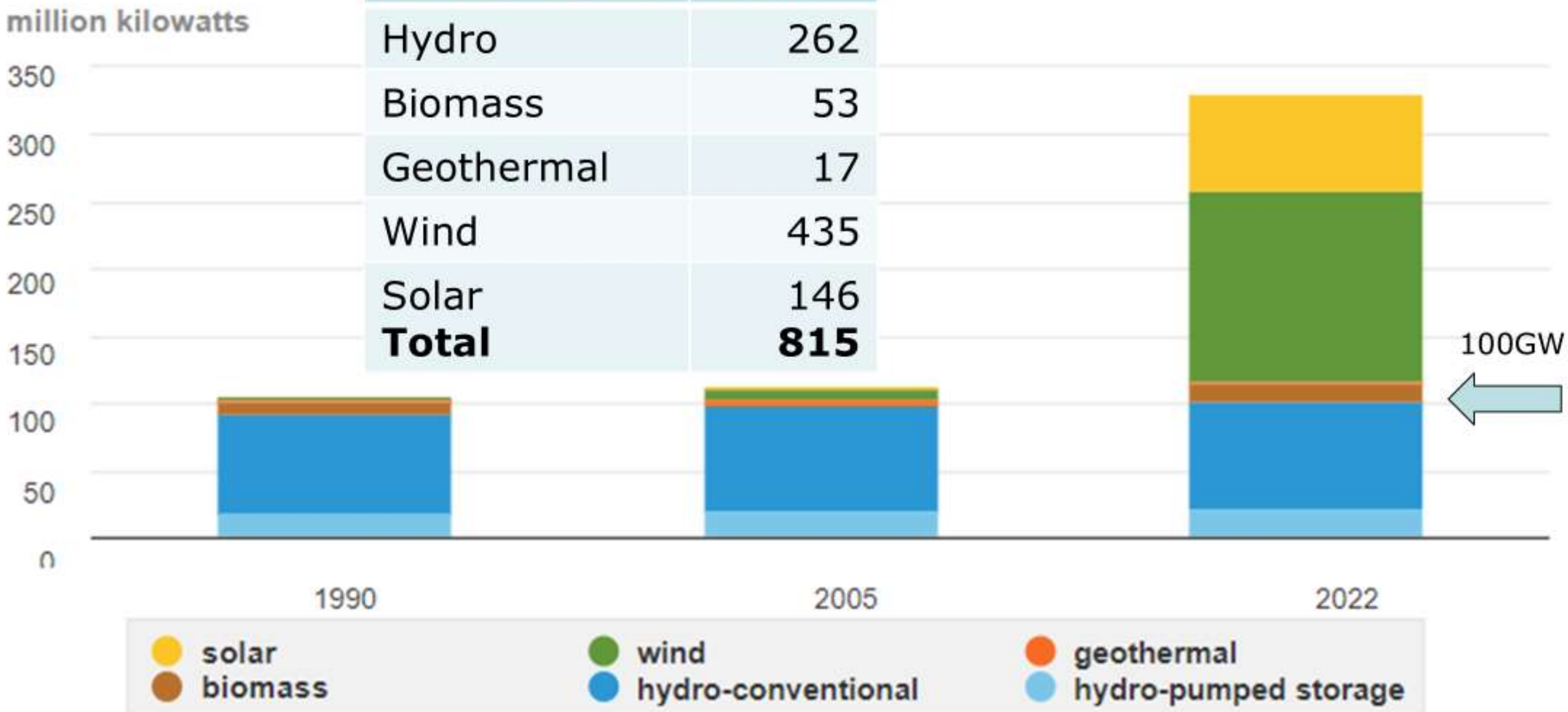
US Average PV System Cost



Source: Wood Mackenzie

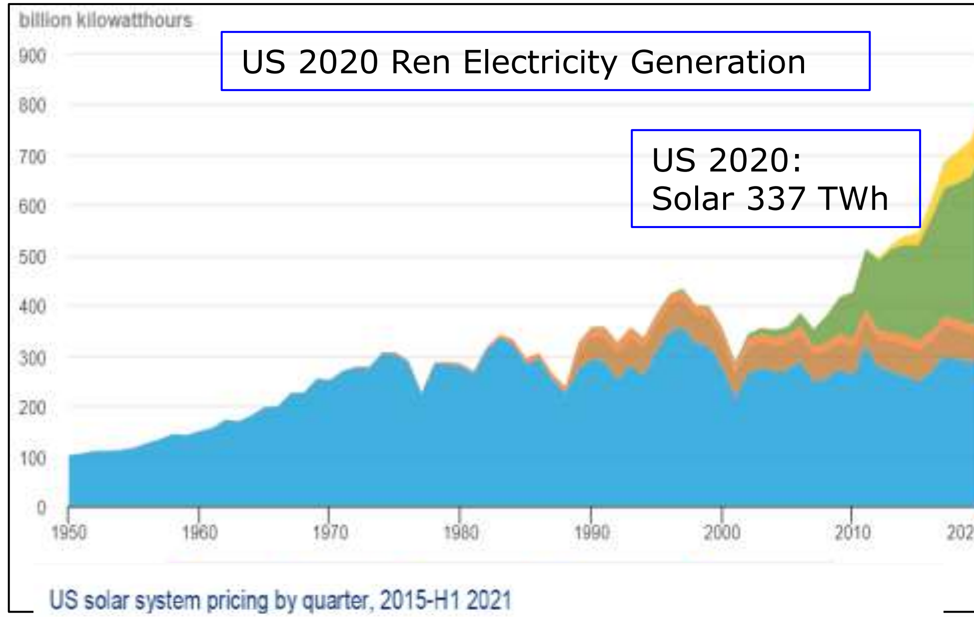
U.S. Renewable Generation Capacity & Production

2022 Source	TWh
Hydro	262
Biomass	53
Geothermal	17
Wind	435
Solar	146
Total	**815**



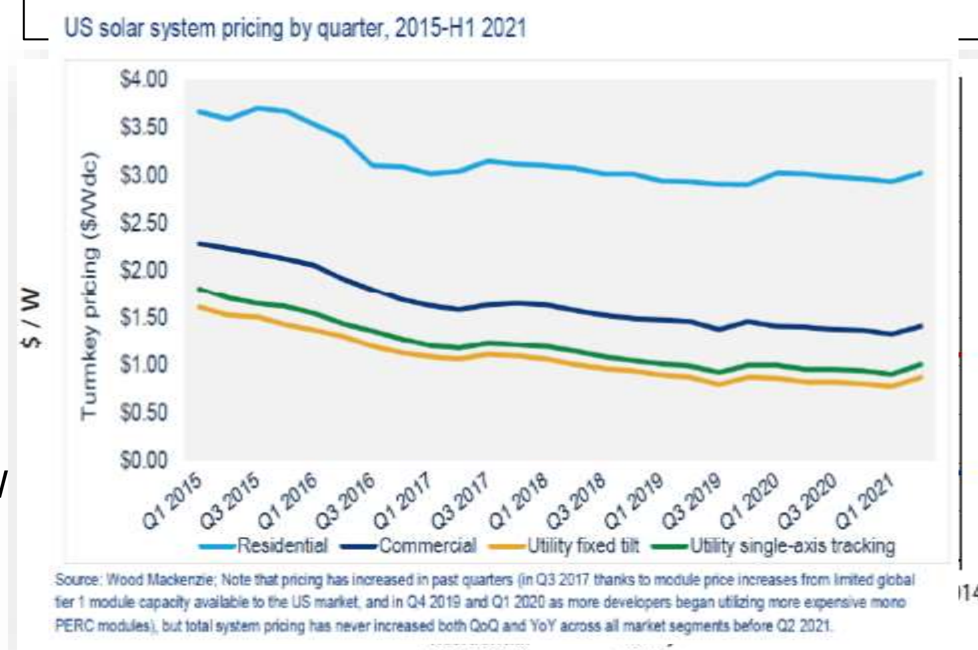
U.S. PV Installations

Net Electric Power (2020)	
Coal:	19%
Nat Gas:	40%
Nuclear:	20%
Hydro:	7.3%
Wind:	8.4%
Solar:	2.3%
Total:	**4,000 TWh**



Levelized costs for residential PV are (170%) higher than utility-scale PV because of much higher residential Balance Of System costs (in US). Result of high per-kWh subsidies. Grid-connected solar electricity relies on subsidies at various levels.

Cash incentives range: \$(0.90-1.2)/W for systems (installed in 2011). (MIT Report)



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- Concentrated (thermal) solar power technologies
- Solar th/PV power strategic issues

Next: Geothermal, Wind Power

Concentrated Solar Power (Thermal)

US: Ivanpah (CA) Solar Installation

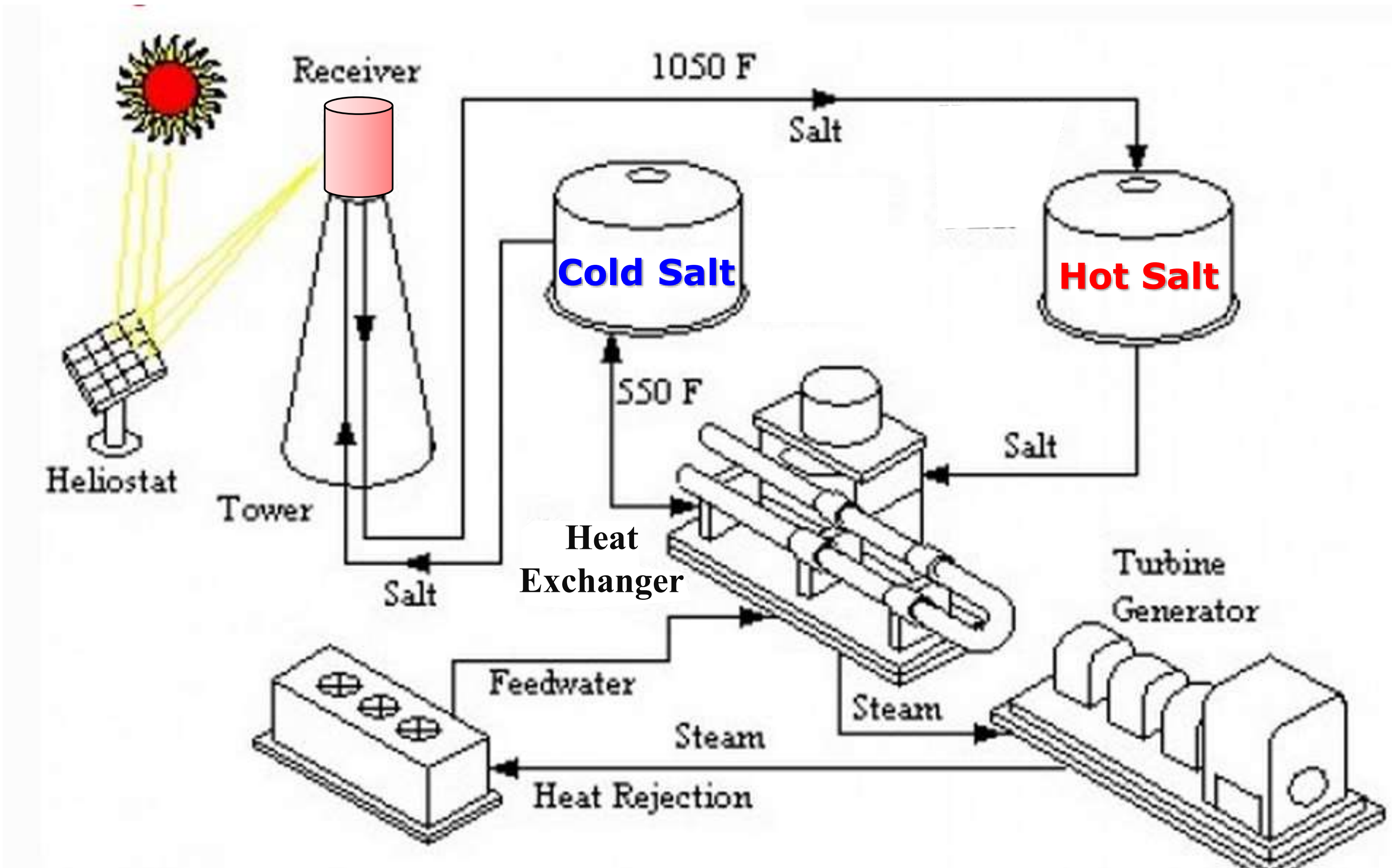
377 MW **plant** located on $2.6 \cdot 10^6$ m^2, 173,500 heliostats, cost \$6.2/W.
→730 GWh annual production, LCOE \$0.19/kWh

The biggest (2014) solar thermal energy plant in the world is located near Ivanpah in California. Working fluid water. 1896 man-years construction (4 years). Construction costs came down Crescent Dunes (> \$9/W) on public land. In 2010, the project was scaled back from its original 440 MW design to avoid disturbing the habitat of the 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).

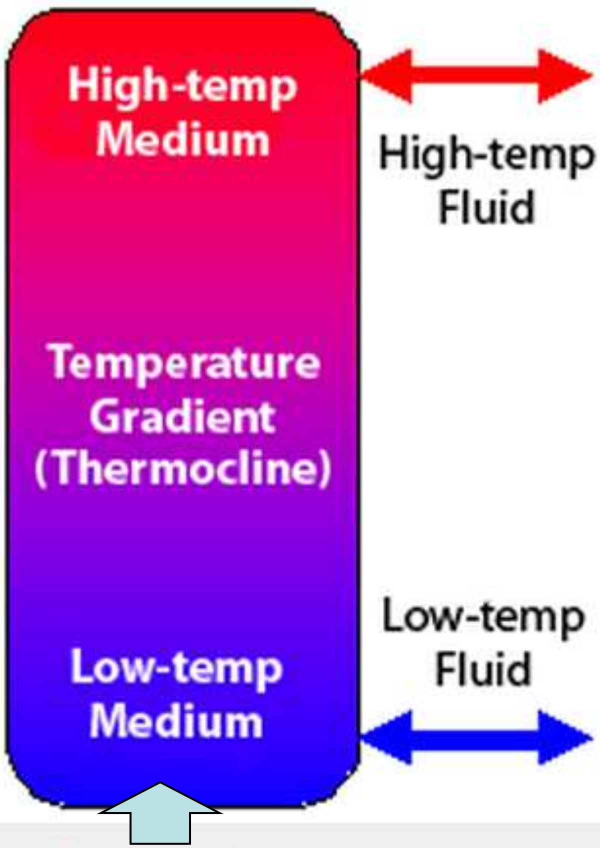
Concentrated Solar Plant: Working Medium Flow



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

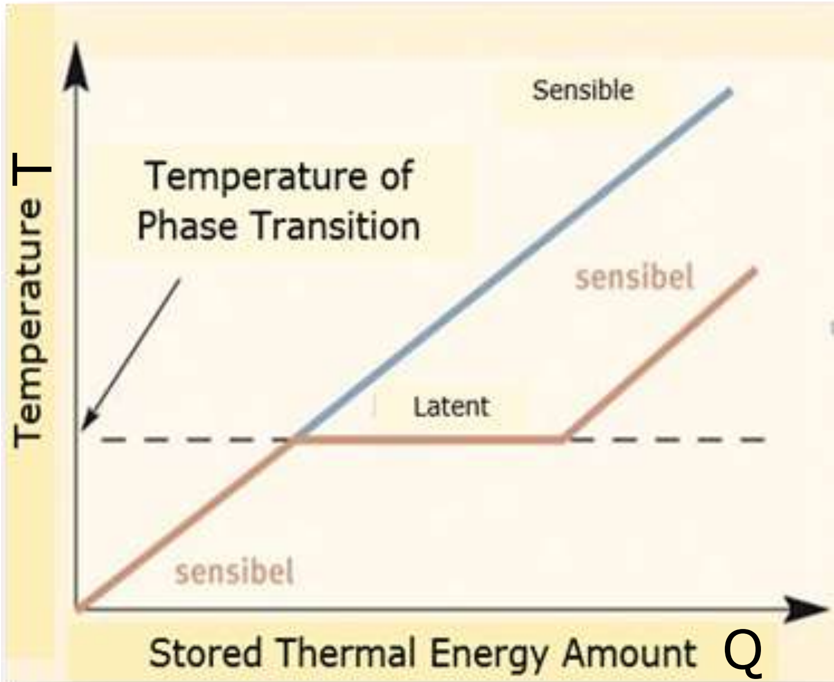
Thermal storage and heat exchange in solid material: Silica sand, ceramic.

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 phase-transition temperature.
(ii) High latent heat of transition.
(iii) Good heat transfer.

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

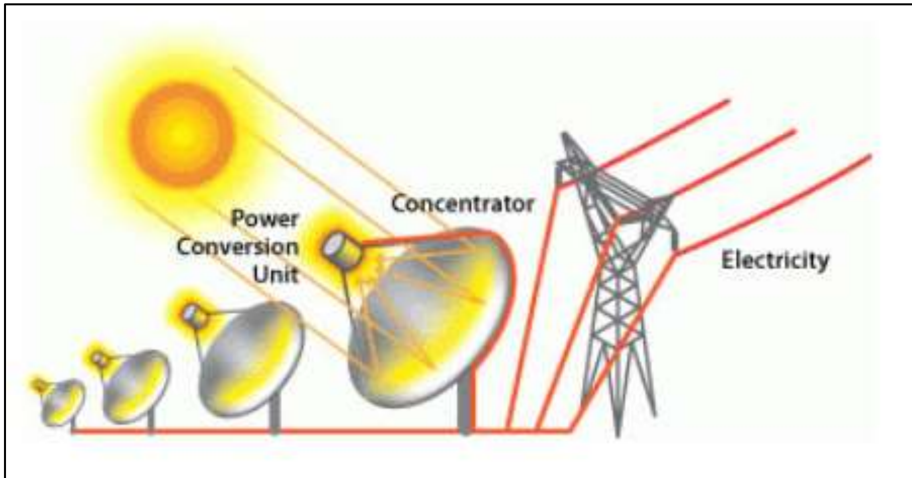
(i) Long-term chemical stability.
(ii) Compatibility construction materials
(iii) No toxicity.
(iv) No fire hazard.

Economics

(i) Abundant.
(ii) Available.
(iii) Cost effective.

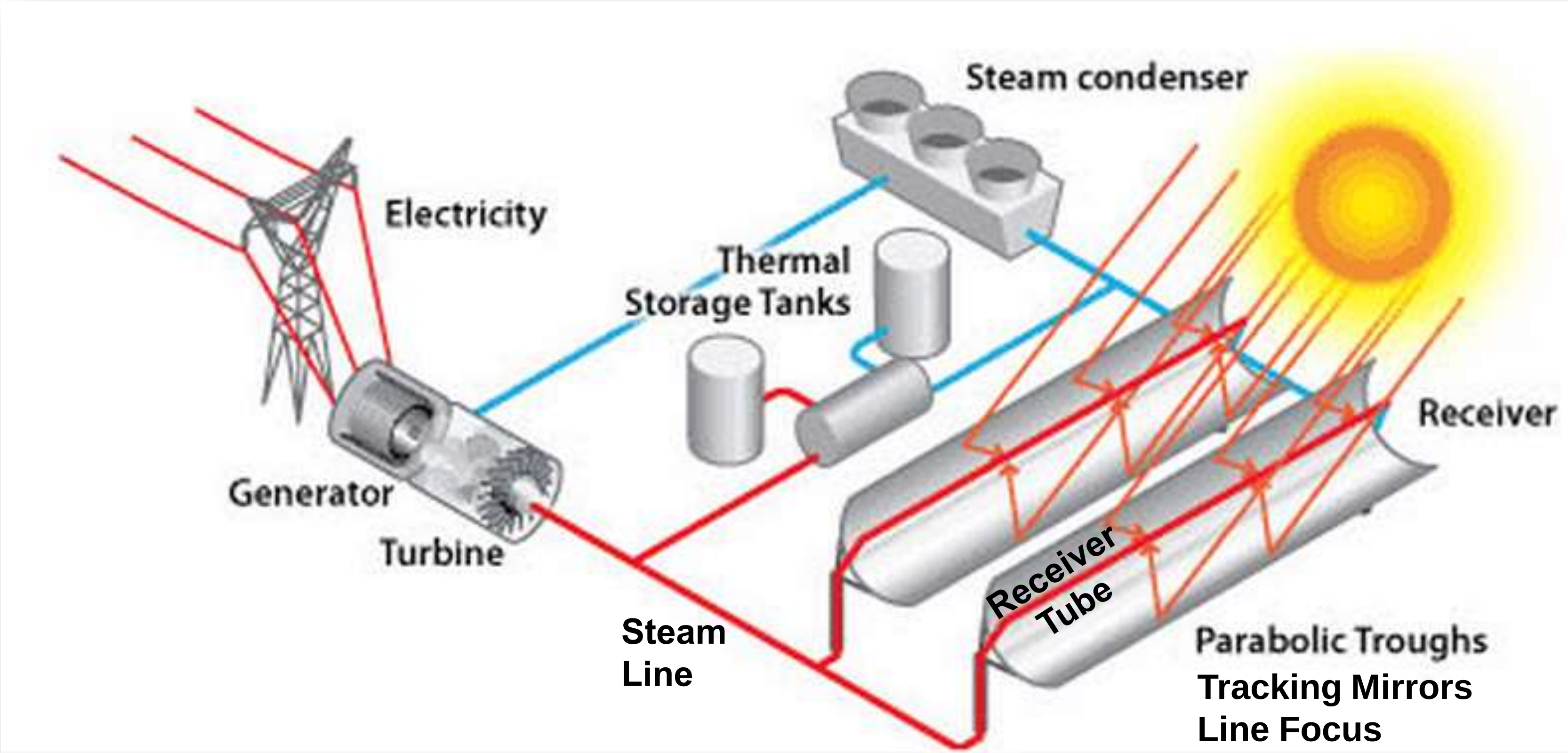
Competing storage technologies: Batteries, electrolyzer-H_2, pumped pV & gravitational, thermal, mechanical,…

Dish Engine Systems



The dish/engine system is a concentrating solar power (CSP) technology that produces smaller amounts of electricity than other CSP technologies—typically in the range of 3 to 25 kilowatts—but is beneficial for modular use. The two major parts of the system are the solar concentrator and the power conversion unit.

Line-Focus CSP Collectors



A linear concentrator power plant using parabolic trough collectors. → $\Delta T = 50^0 - 400^0C$

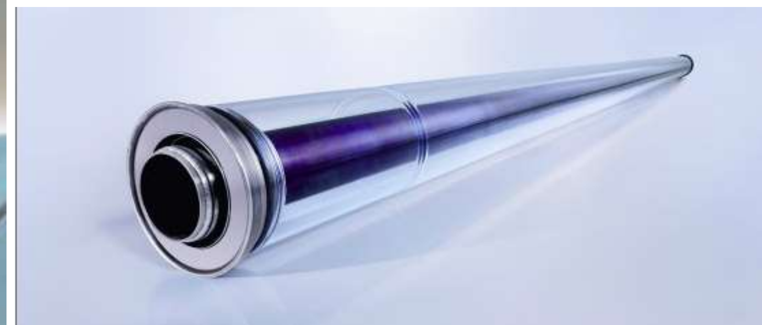
Typically, collector fluid=oil, produces superheated steam in a heat exchanger

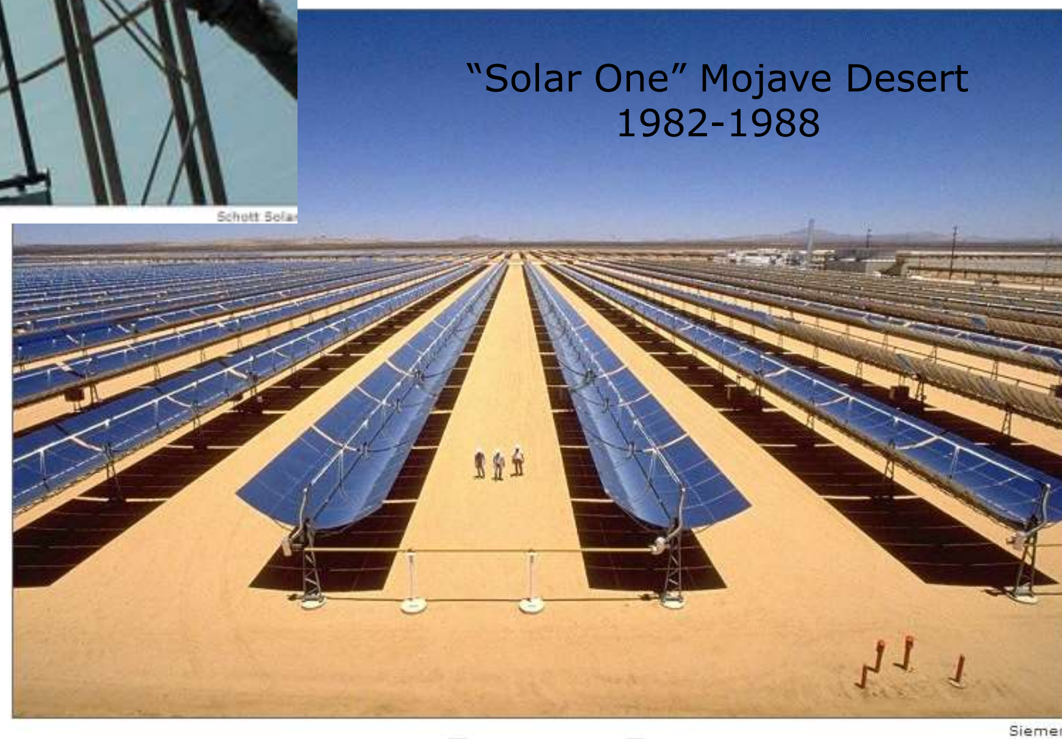
Currently largest trough systems → generate 80 MW_e. Overnight heat storage in molten salt (K/Na nitrate) storage tanks (remains liquid in large T range, large heat capacity)

After DOE Energy Efficiency and Renewable Energies.

Line-Focus CSP Collector

Receiver Tube (oil)





Planned: 9 power plants in Mojave Desert (3 sites), total 354 MW_e, $2 \cdot 10^6$ m^2 collector area.

Efficiencies e = 0.16-0.18

In 2010 the largest concentrating solar power plant since the 1980s was completed when Florida Power and Light installed a 75 MWAC CSP plant near Indiantown, Florida.

75-MW Martin Solar Plant near Indiantown, Florida

Solar Performance in SW U.S.

Electricity generation Mesquite Solar 1-3 in 2017-2019. Location: Arlington, Maricopa County, Arizona → optimum capacity factors.

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**

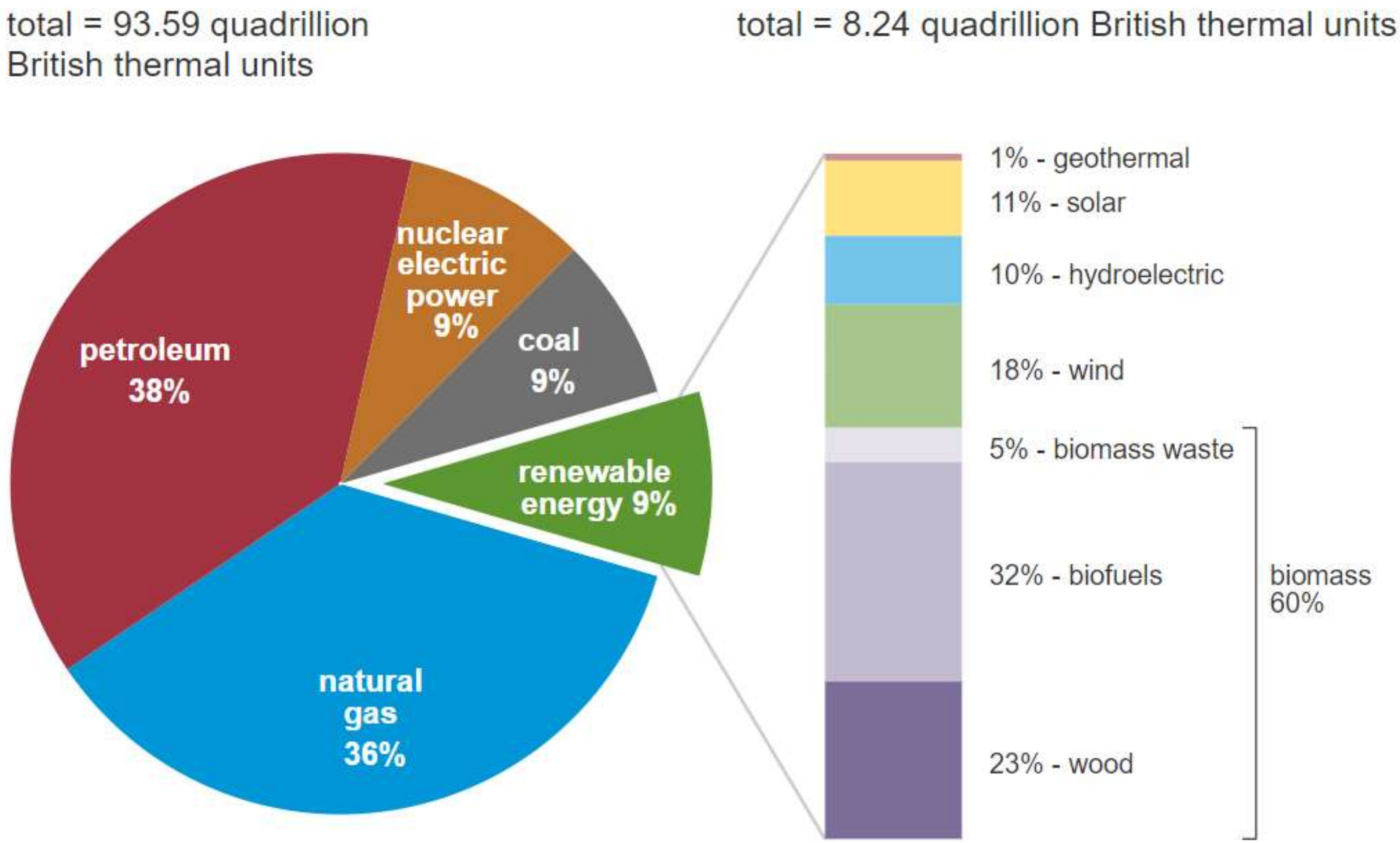
Generation (MW·h) of Mesquite Solar 2 (100MW with tracking)

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)

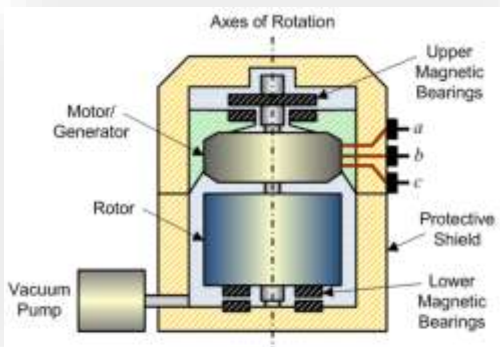
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016												21,060	**21,060**
2017	22,673	25,705	40,558	43,985	48,952	49,978	44,174	43,447	39,846	35,670	23,425	22,187	**440,600**
2018	25,678	28,450	38,984	43,517	50,609	48,203	44,817	44,342	39,830	31,777	27,684	21,898	**445,789**
2019	25,460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

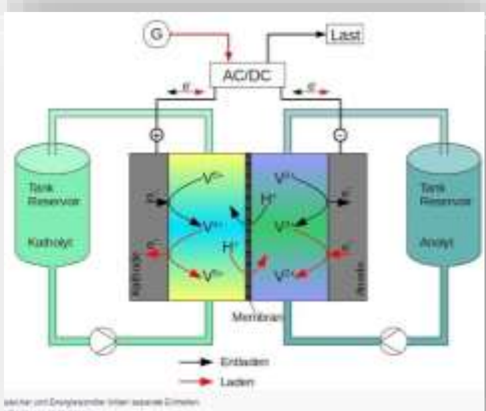
U.S. Energy Consumption 2023

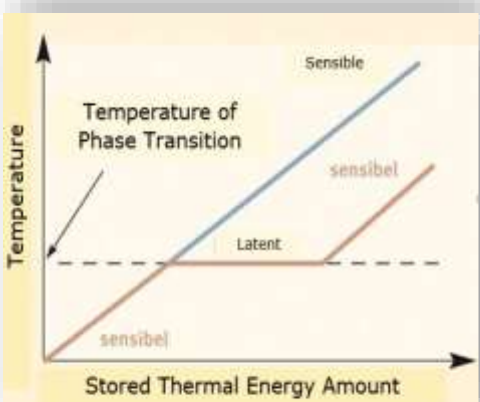


Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2024, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

Distributed Energy Storage Techniques







Mechanical energy storage

Gravitational, pumped hydropower, compressed-air, flywheels

Electrical/Electrochemical storage

Super capacitors, supercon magnets

Batteries: Lead-acid, Ni-Cd, Li-ion, redox-flow/fuel cells

Chemical energy storage→ H electrolizer

Water dissociation → hydrogen

Thermal energy storage

Change in internal heat energy ("sensible heat"),

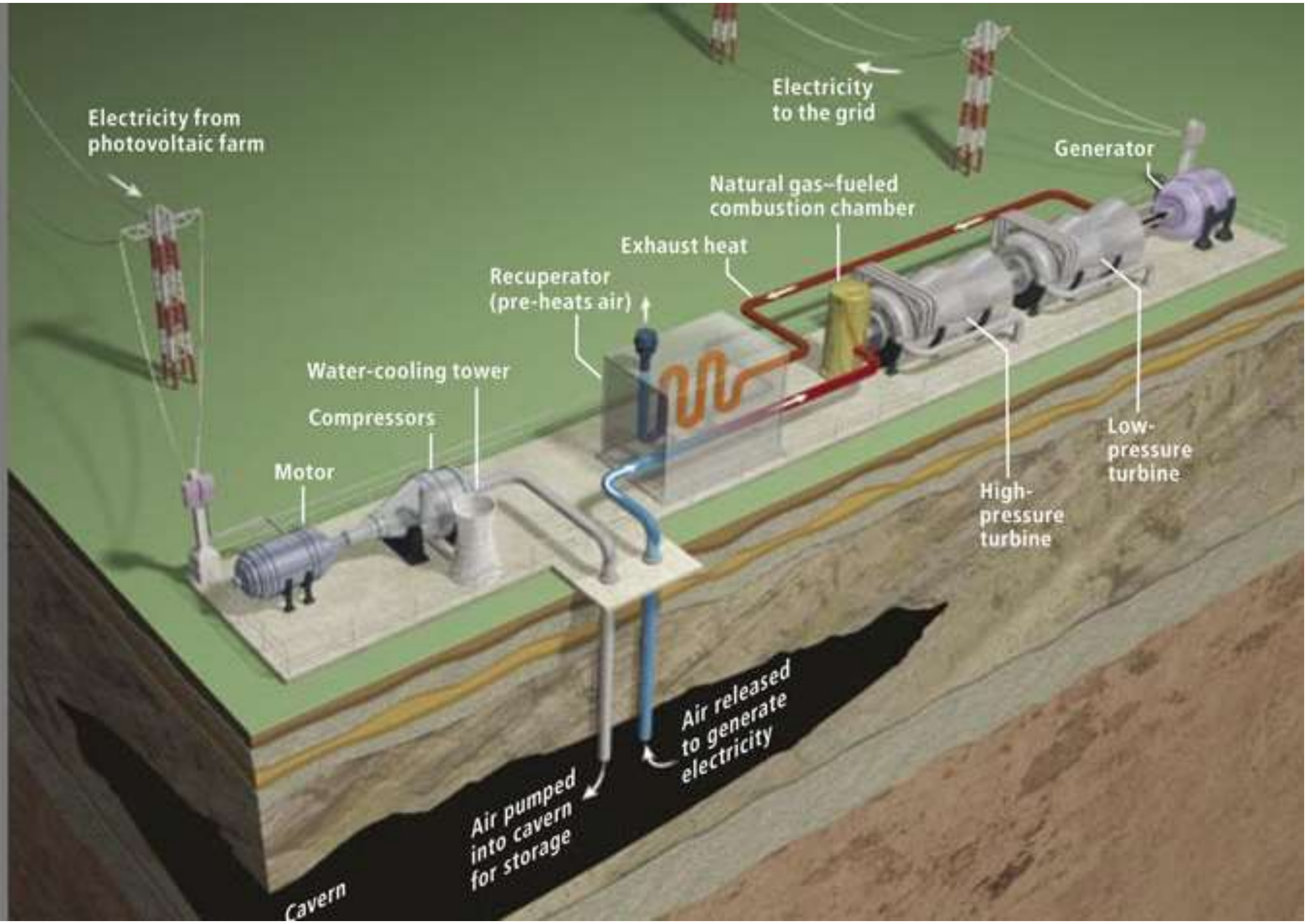
High heat capacity materials (C, concrete,..)

Phase change (transition) → latent heat
→ molten salt storage, thermo-chemical heat

Energy Storage

Underground Storage

Excess electricity produced during the day by photovoltaic farms would be sent over power lines to compressed-air energy storage sites close to cities. At night the sites would generate power for consumers. Such technology is already available; the PowerSouth Energy Cooperative's plant in McIntosh, Ala. has operated since 1991 (the white pipe sends air underground). In these designs, incoming electricity runs motors and compressors that pressurize air and send it into vacant caverns, mines or aquifers (*right*). When the air is released, it is heated by burning small amounts of natural gas; the hot, expanding gases turn turbines that generate electricity.



Solar Power Technologies: Strategic Issues

1. Intermittency, subject to local weather, diurnal and seasonal variations
2. Low power densities and efficiencies, in particular solar thermal, thin-film PV cells
3. Impact on local ecosystems, large land use
4. Controllability, voltage/power depend on insolation, temperature coefficients.
5. Converters DC → AC, feed-in synchronization/connection with utility e-grid
6. Geographic limitations, distance from consumption centers, transmission losses
7. Emissions (CO_2, H_2S, SF_6…) & toxic acids, chemicals
8. Needs efficient energy storage, “smart” grid for feed-in
9. Economics ($$/kWh, “energy pay-back” times), adoption requires incentives
10. Minor role in current US energy mix (ramp up time for scaling to ~(10-20)%)

Sustainable Energy Strategy

Goals: Maximum possible energy security and independence

Criteria for a sustainable energy strategy (based on existing reality)

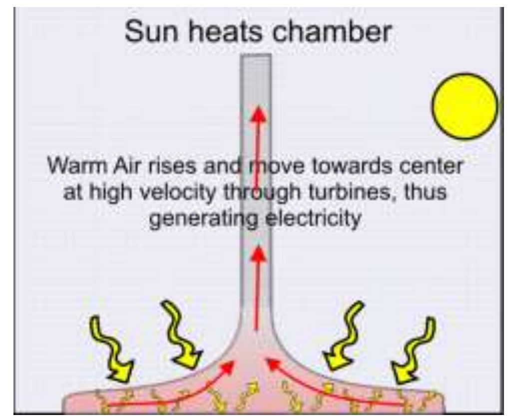
- provides safe energy supply;
- enhances energy independence;
- allows for flexible response to a variable mix of energy demands;
- accounts for existing infrastructure and its evolutionary inertia;
- does not rely on future technological breakthroughs, but is adaptable;
- does not waste useful resources;
- is acceptable to the public.

→ Diversity of technologies desirable, ramp up most potent candidates now.

Dynamical update of strategy in time

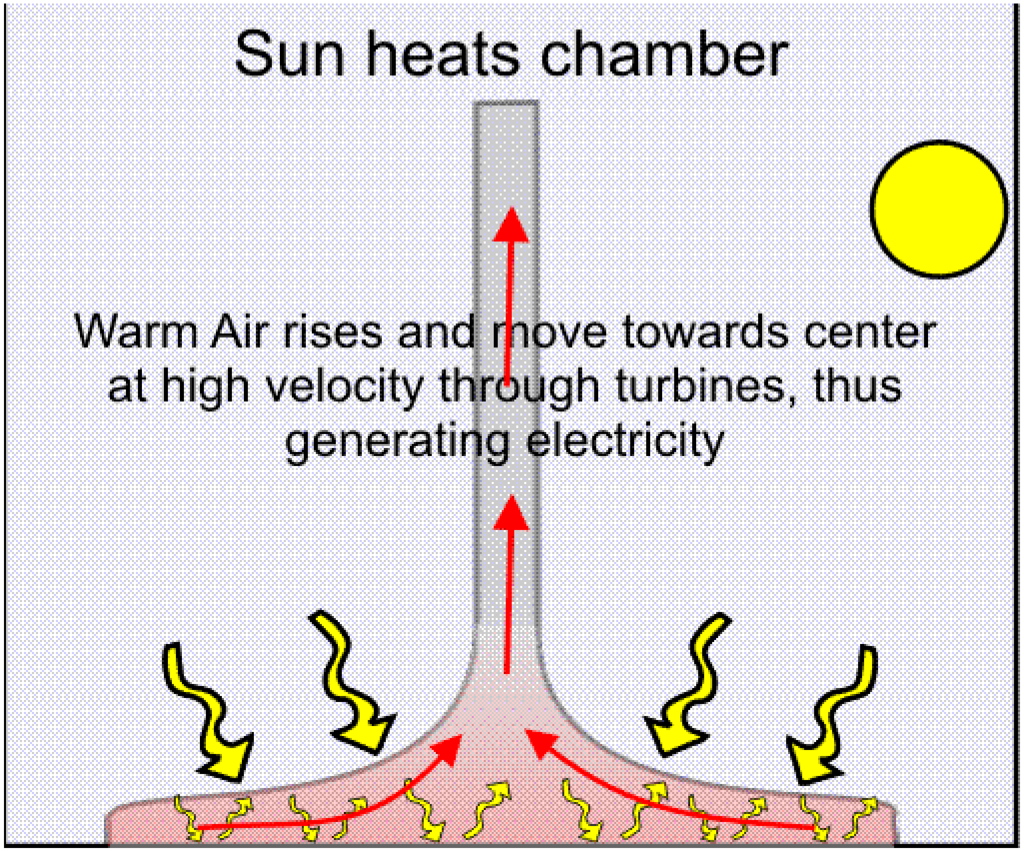
Hot-Air Updraft Towers

Principle of operation: Sunlight collector dome produces hot air underneath, which escapes through chimney and produces draft driving a turbine.



An Australian plan: construct (world's first large-scale) solar thermal power station Buronga in New South Wales. 200-MW 'Solar Mission' should produce enough electricity to power 200,000 homes, reducing CO_2 emissions by 750,000 t

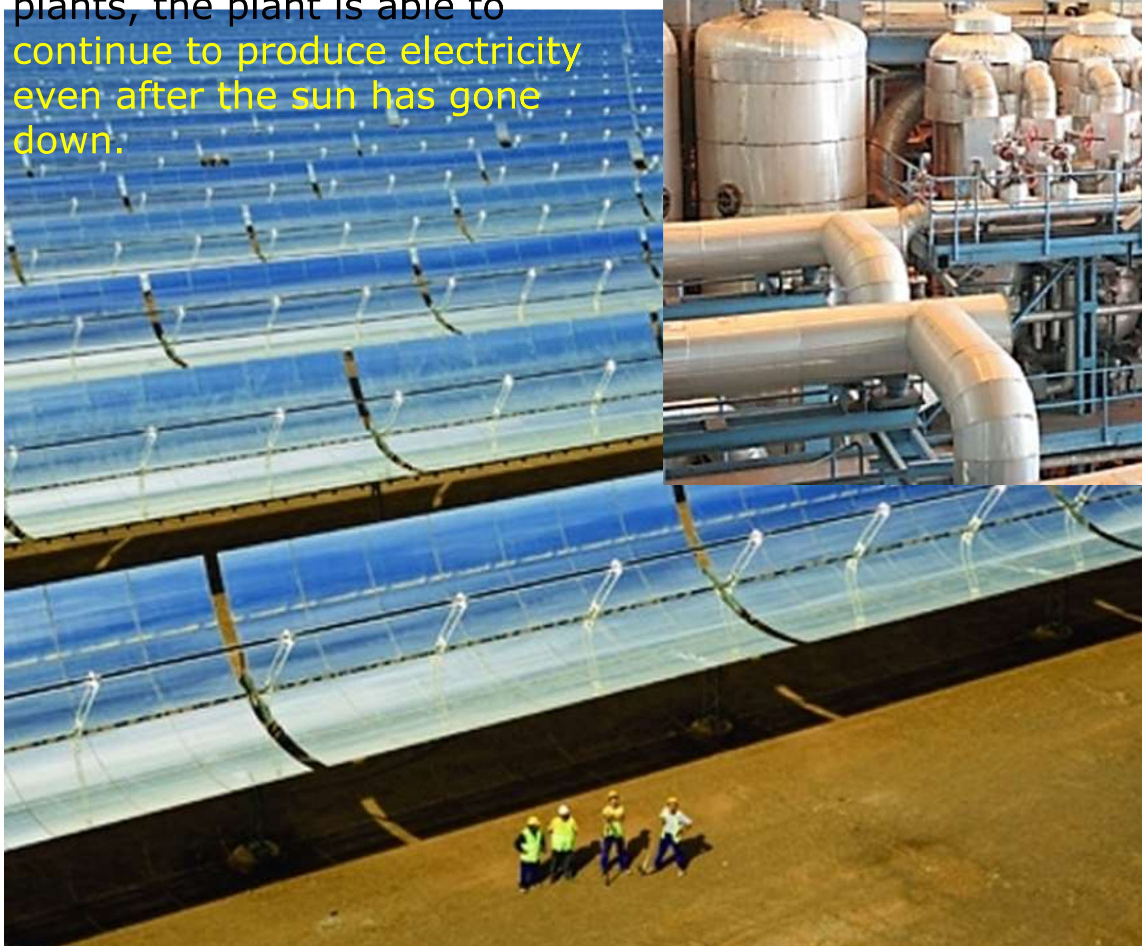
Turbines are driven by heat rising with the hot air trapped under the transparent "collector" dome around the tower.



333.55 J/g (heat of fusion of ice) = 333.55 kJ/kg = 333.55 kJ for 1 kg of ice to melt
PLUS

Sicily: CSP Plant (Molten Salt)

Since 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.



Some CSP plants use molten salt storage in order to extend their operation, but collectors rely on oil as the heat collection medium. → 2 heat transfer systems (oil-to-molten-salt +molten-salt-to-steam) increases the complexity, decreases efficiency of the system. The salts used in the system are also environmentally benign, unlike the synthetic oils used in other CSP systems.

Raw Materials Used in Energy Technologies

Materials (kg) needed for generating 1-GWh of electricity in various technologies, including basic resources. (1GWa = 8.7TWh)

Plant → Materials	Coal 45,5 %	Lignite 44 %	natGas 58 %	Nucl	Hydro 3 MW	Wind 1,5 MW, Off-sh	Solar thermal	Solar PV roof top
Iron	2.000	2.00	1.200	420	2.400	**5.200**	**3.470**	**5.200**
Bauxite	16	18	2	27	4	44	6	**2.000**
Copper	2	7	1	6	5	**65**	**252**	**230**
Limestone	7.000	20.000	6.400	800	6.000	2.490	2.100	10.000
Nickel	1,4	1,1	0,4	**15,5**	0,4	0,4	0,5	**14**
Coal	**501.300**	3.500	255	880	2.860	3.840	2.700	14.000
Lignite	5.180	**1.017.000**	300	500	2.750	5.100	745	32.900
natGas	1.160	800	**185.705**	1.070	730	1.560	440	5.690
Crude Oil	3.760	1.200	2.220	610	580	720	1.750	4.300
Uranium	0,34	0,2	0,003	**26,5**	0,007	0,02	0,03	0,92