Solar Energy Conversion Devices and Plants

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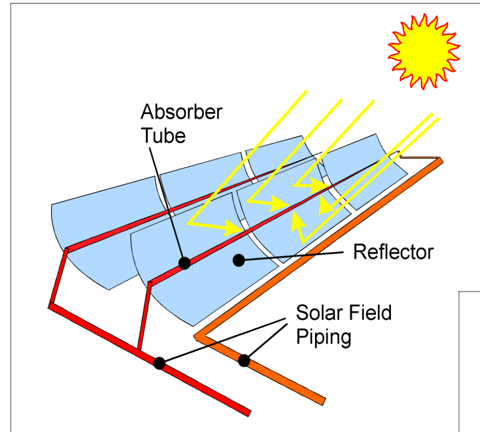
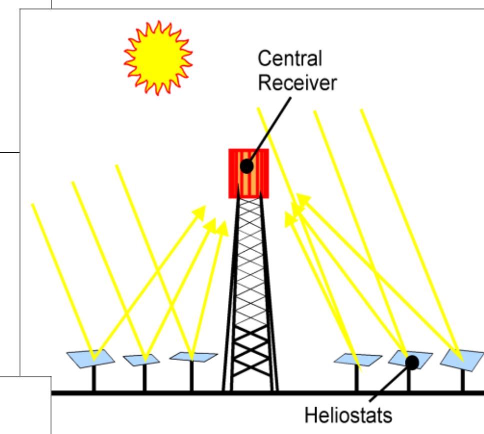
Solar Thermal Electricity Generation

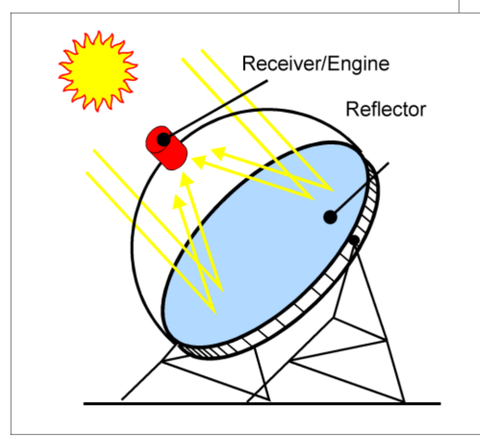
CSP = Concentrated Solar Power

Solar Concentrating Technologies

- Trough systems
- Tower systems
- Dish systems

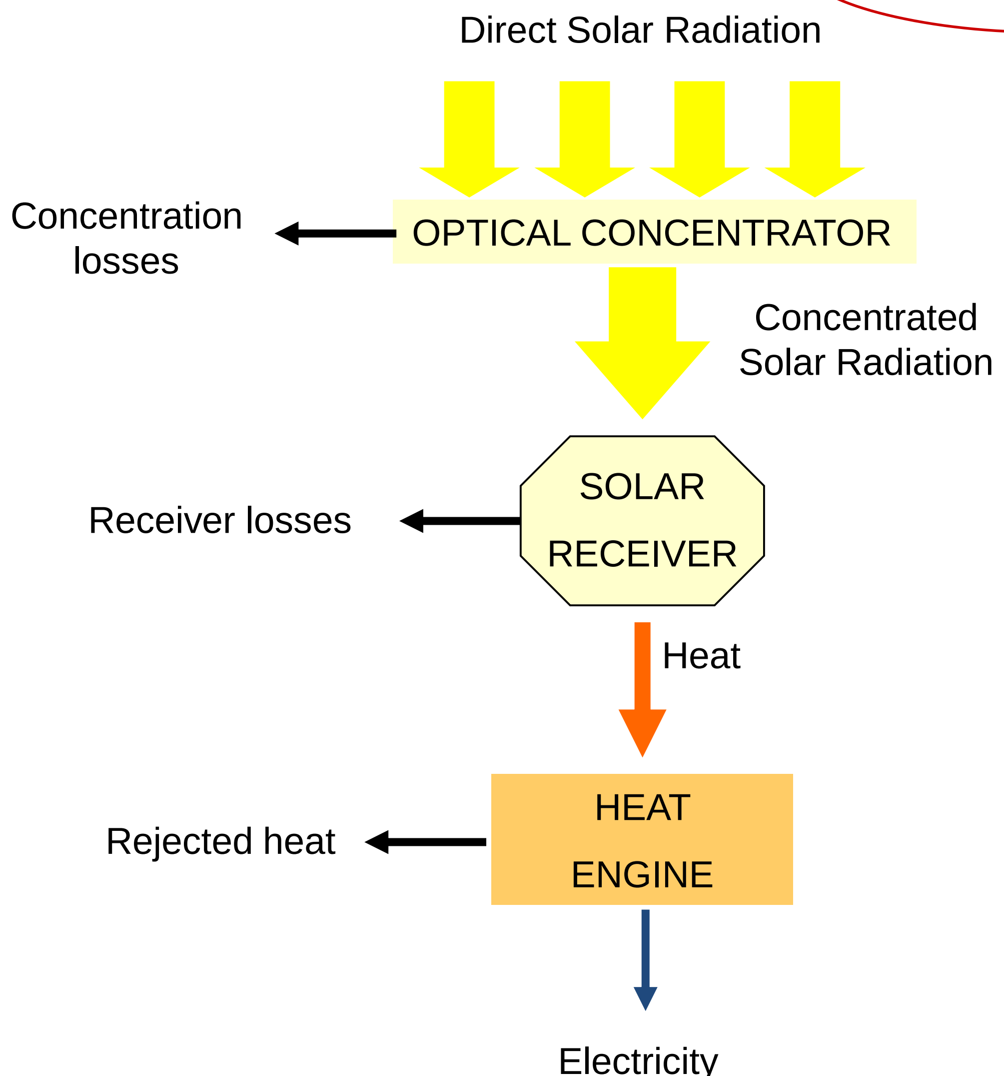




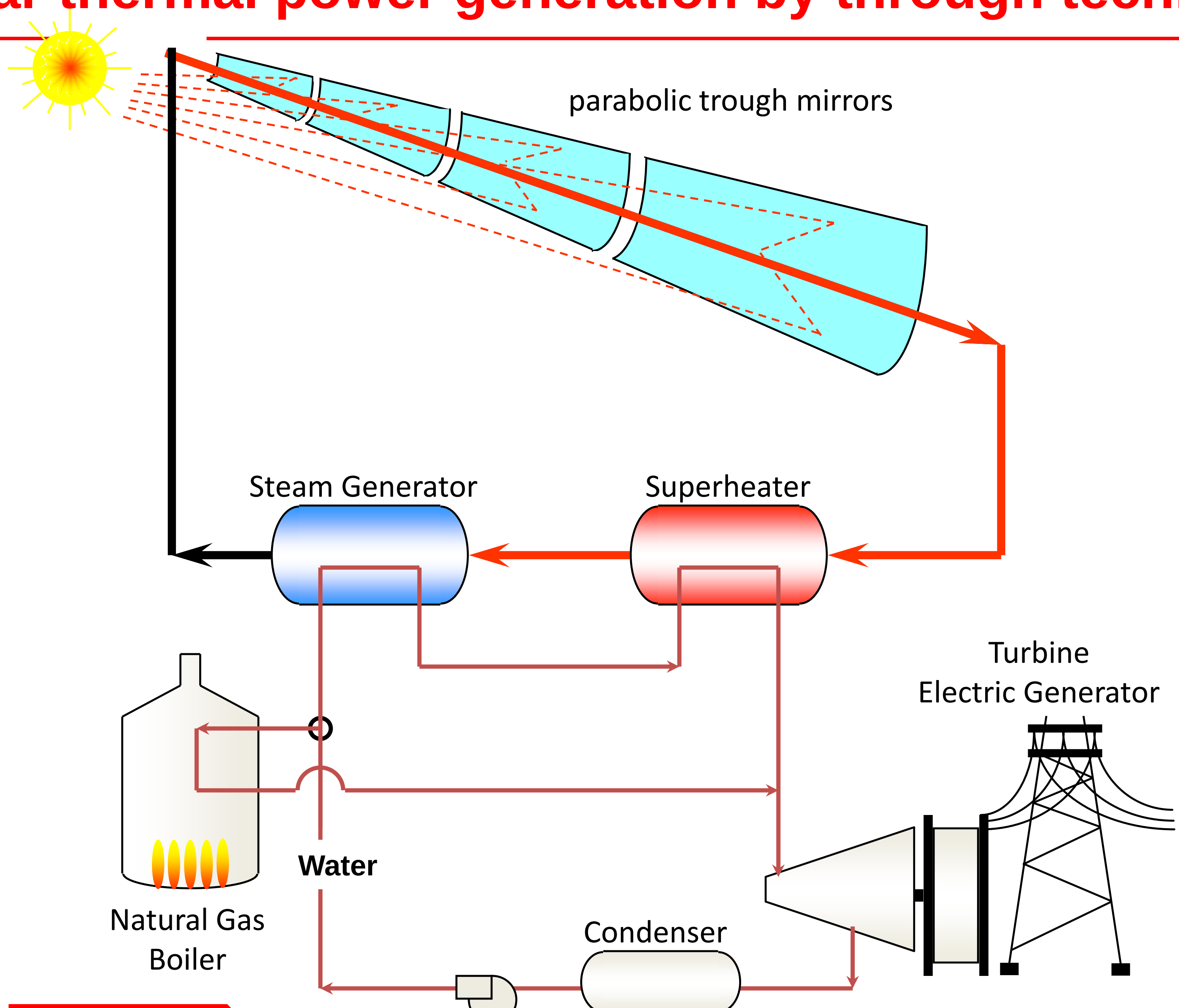


$$\eta_{solar-to-electrcity} = \eta_{optics} \cdot \underbrace{\eta_{receiver}}_{<\eta_{absorption}} \cdot \underbrace{\eta_{heat-to-electricity}}_{<\eta_{Carnot}}$$

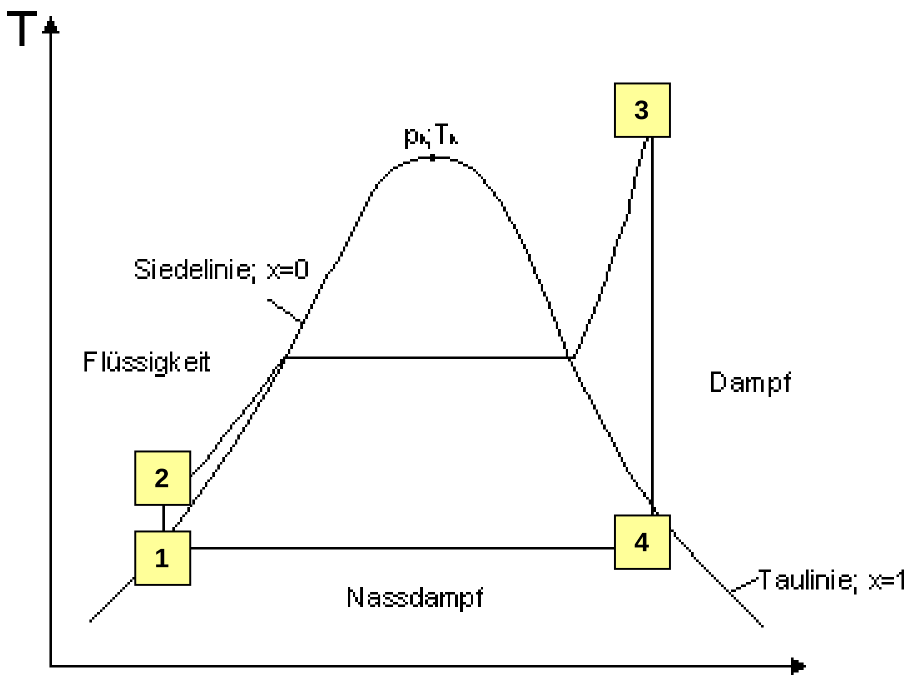
$$\eta_{absorption} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right)$$



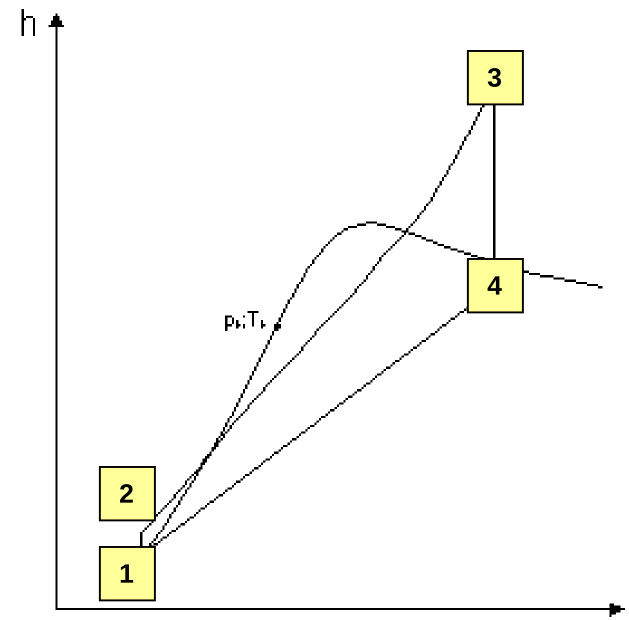
Solar thermal power generation by through technology



Clausius-Rankine Cycle



T-s-Diagramm



h-s-Diagramm

Changes of heat transfer fluid:

1 after the condenser: liquid at given *p* and T

1-2 Isentropic compression in the liquid phase (entropy remains constant)

2 after the feed pump: compressed liquid at high pressure

2-3 Isobaric heat input (preheating, evaporation and superheating)

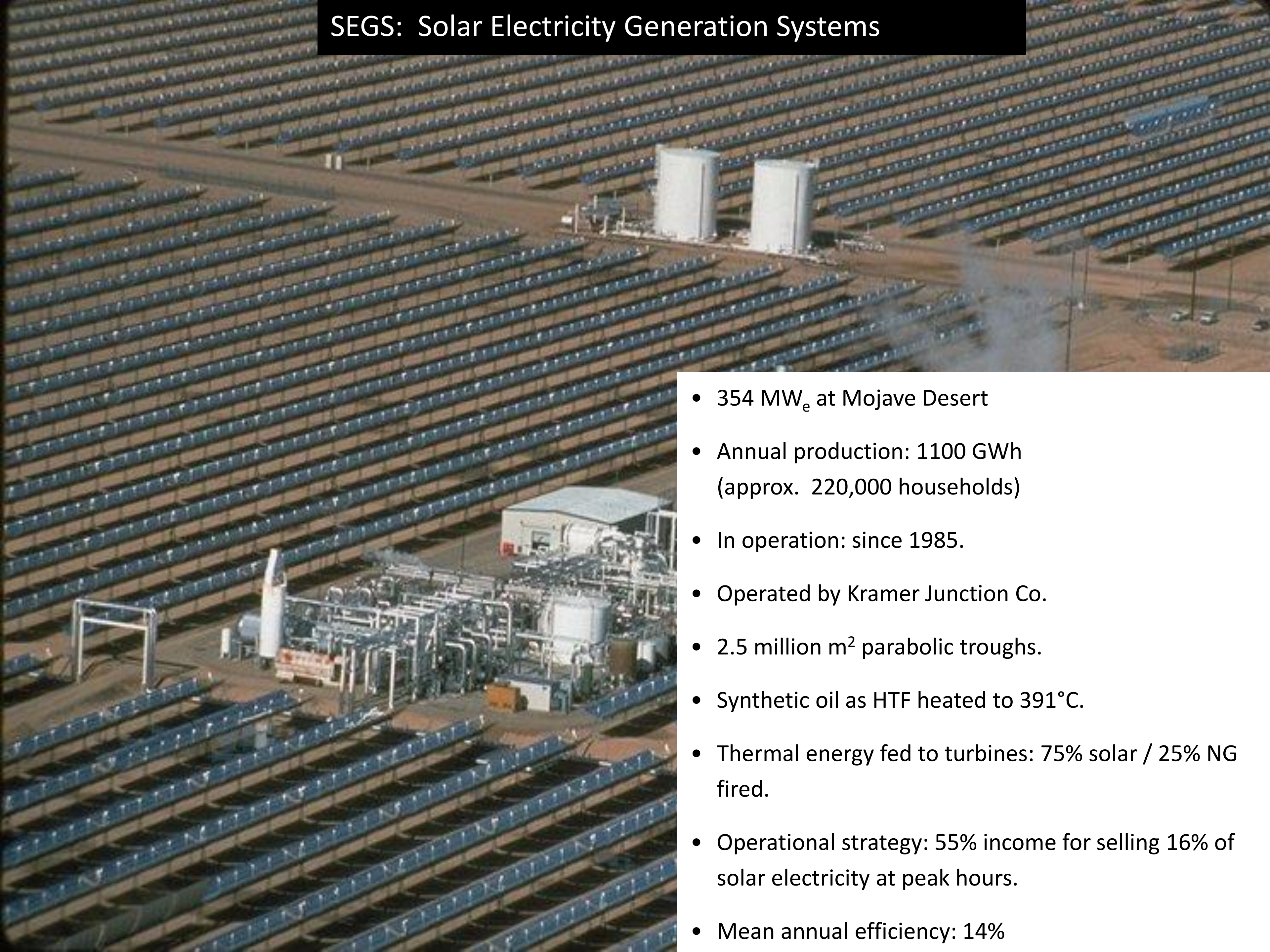
3 after the solar receiver: superheated steam

3-4 Isentropic expansion

4 after the turbine: mixture of liquid and steam; condition given by steam quality *x*

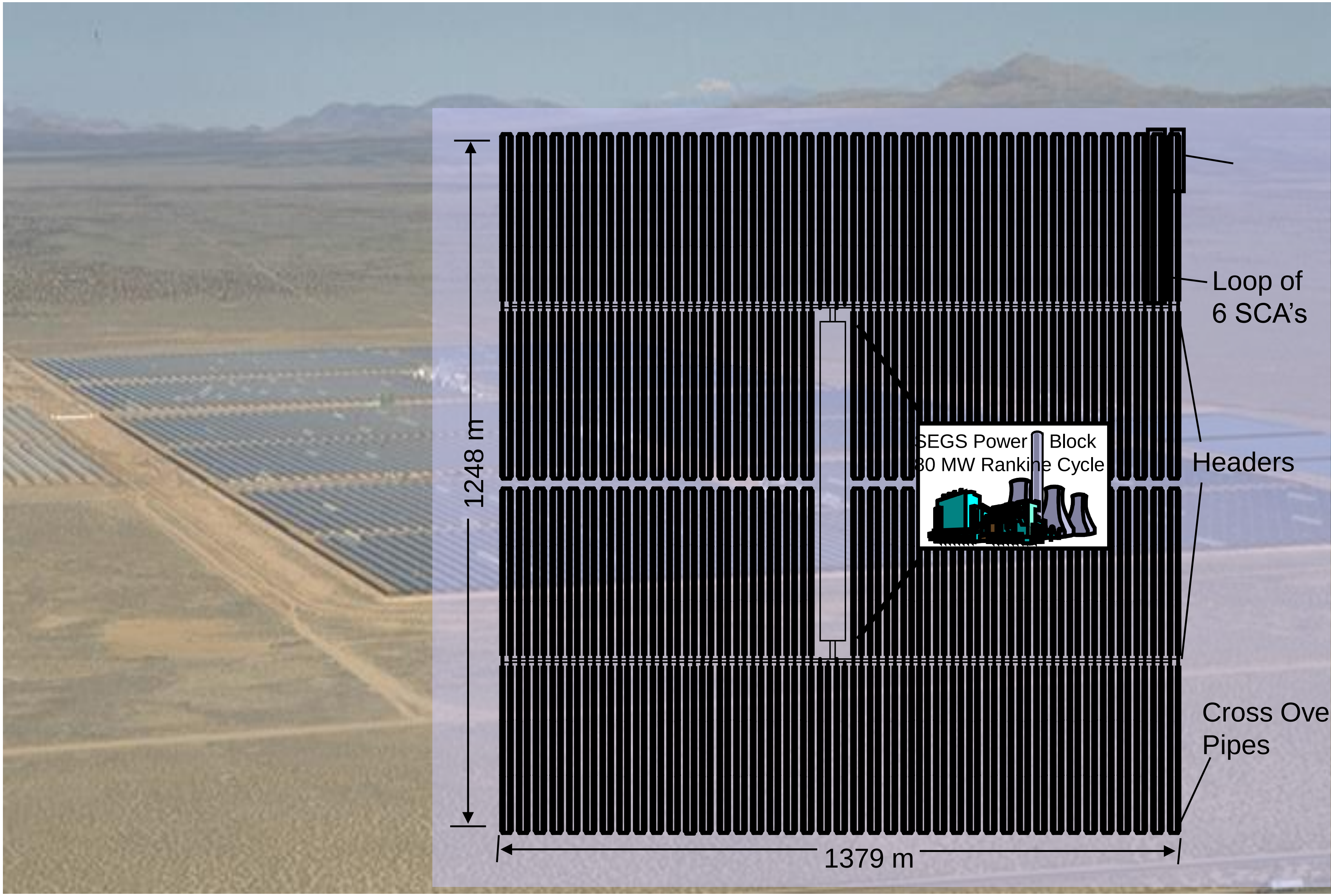
4-1 Isobaric heat removal and condensation

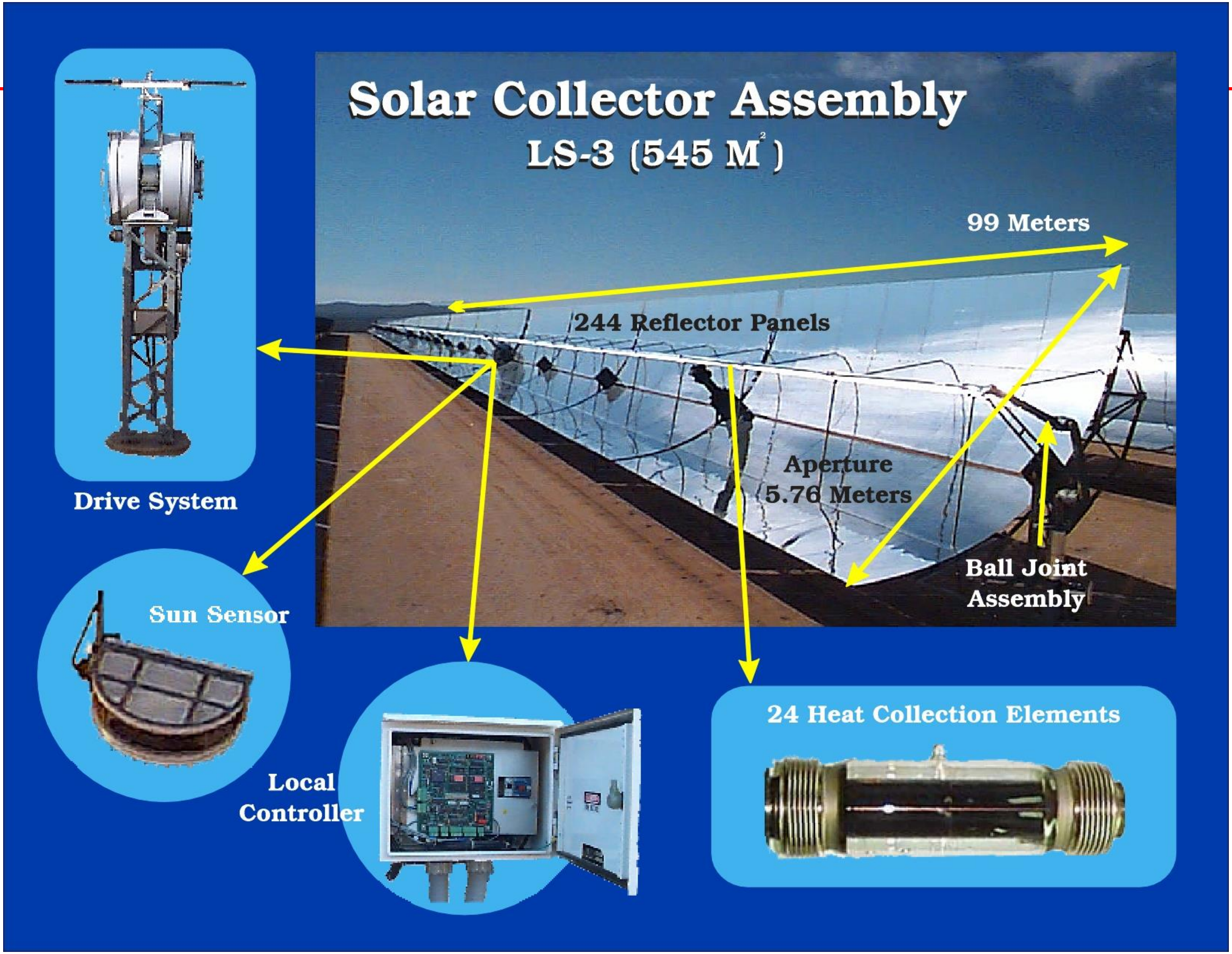
SEGS: Solar Electricity Generation Systems



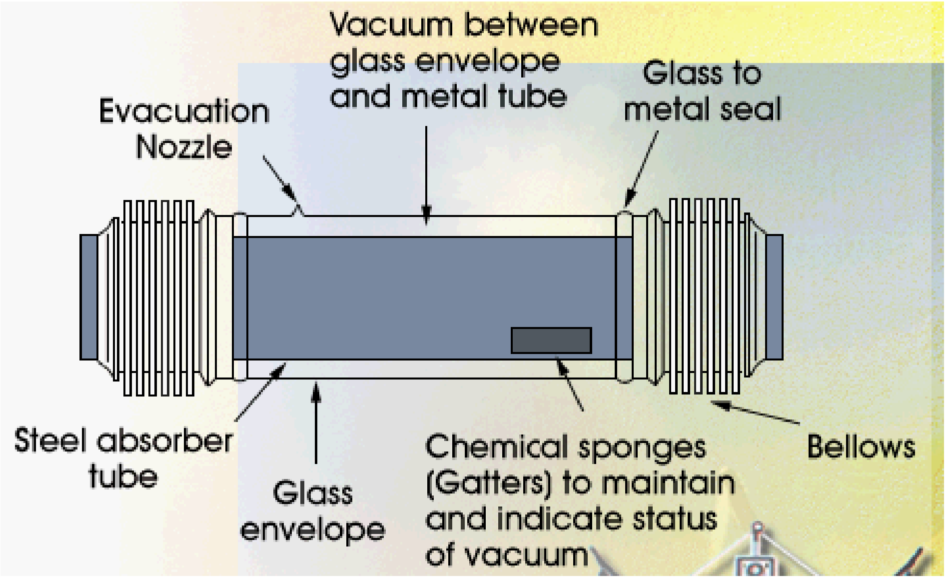
- 354 MW_e at Mojave Desert
- Annual production: 1100 GWh (approx. 220,000 households)
- In operation: since 1985.
- Operated by Kramer Junction Co.
- 2.5 million m^2 parabolic troughs.
- Synthetic oil as HTF heated to 391°C.
- Thermal energy fed to turbines: 75% solar / 25% NG fired.
- Operational strategy: 55% income for selling 16% of solar electricity at peak hours.
- Mean annual efficiency: 14%

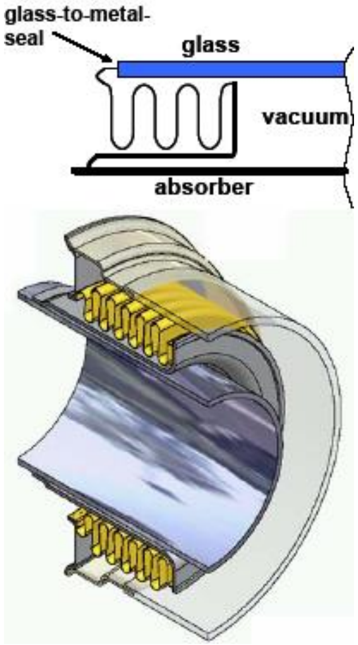
Typical Layout of SEGS Plant




Solar Collector Assembly
LS-3 (545 M²)
99 Meters
244 Reflector Panels
Aperture
5.76 Meters
Ball Joint
Assembly
Drive System
Sun Sensor
Local
Controller
24 Heat Collection Elements

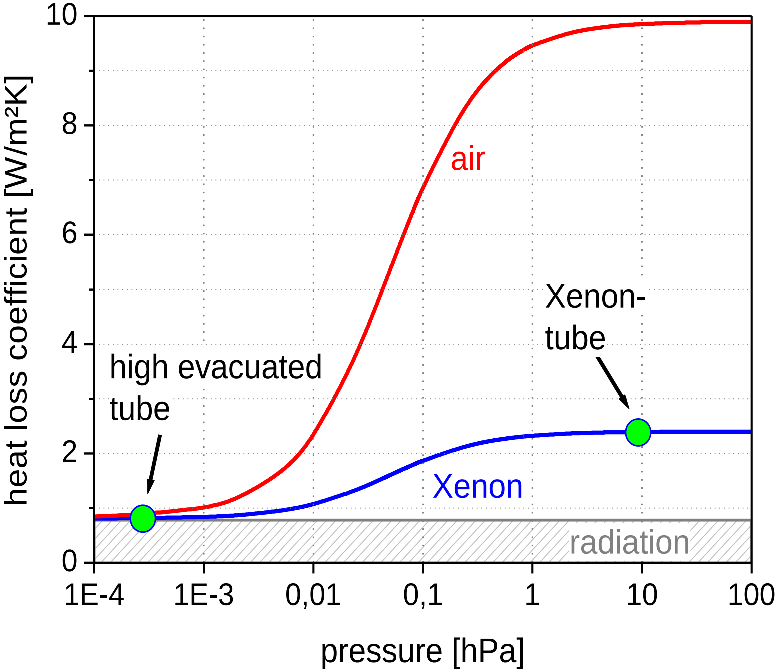
Solar Absorber



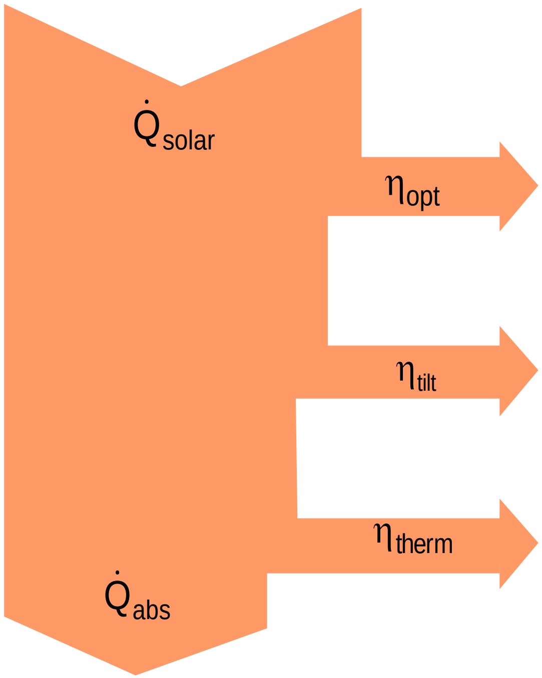


Vacuum isolation:

- The evacuated tube collector can be manufactured in a low-pressure-Xenon and in a high vacuum version (< 10^{-3} mbar)
- Heat conduction is strongly reduced (Xenon) or even suppressed (high vacuum)



Efficiency of parabolic through



Optical losses at normal incidence

Optical losses due to non-normal irradiation

Thermal losses

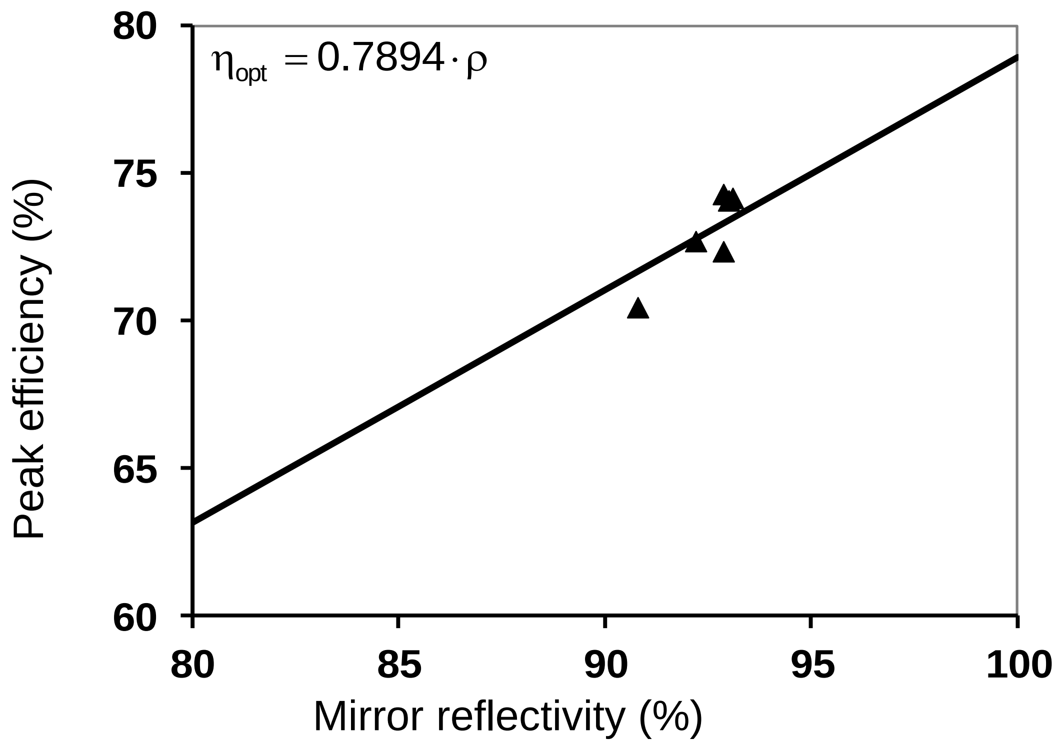
$$\eta = \frac{\dot{Q}_{abs}}{\dot{Q}_{solar}} = \eta_{opt} \cdot \eta_{tilt} \cdot \eta_{therm}$$

$$\eta_{opt} = \rho \cdot \tau \cdot \alpha \cdot IC$$

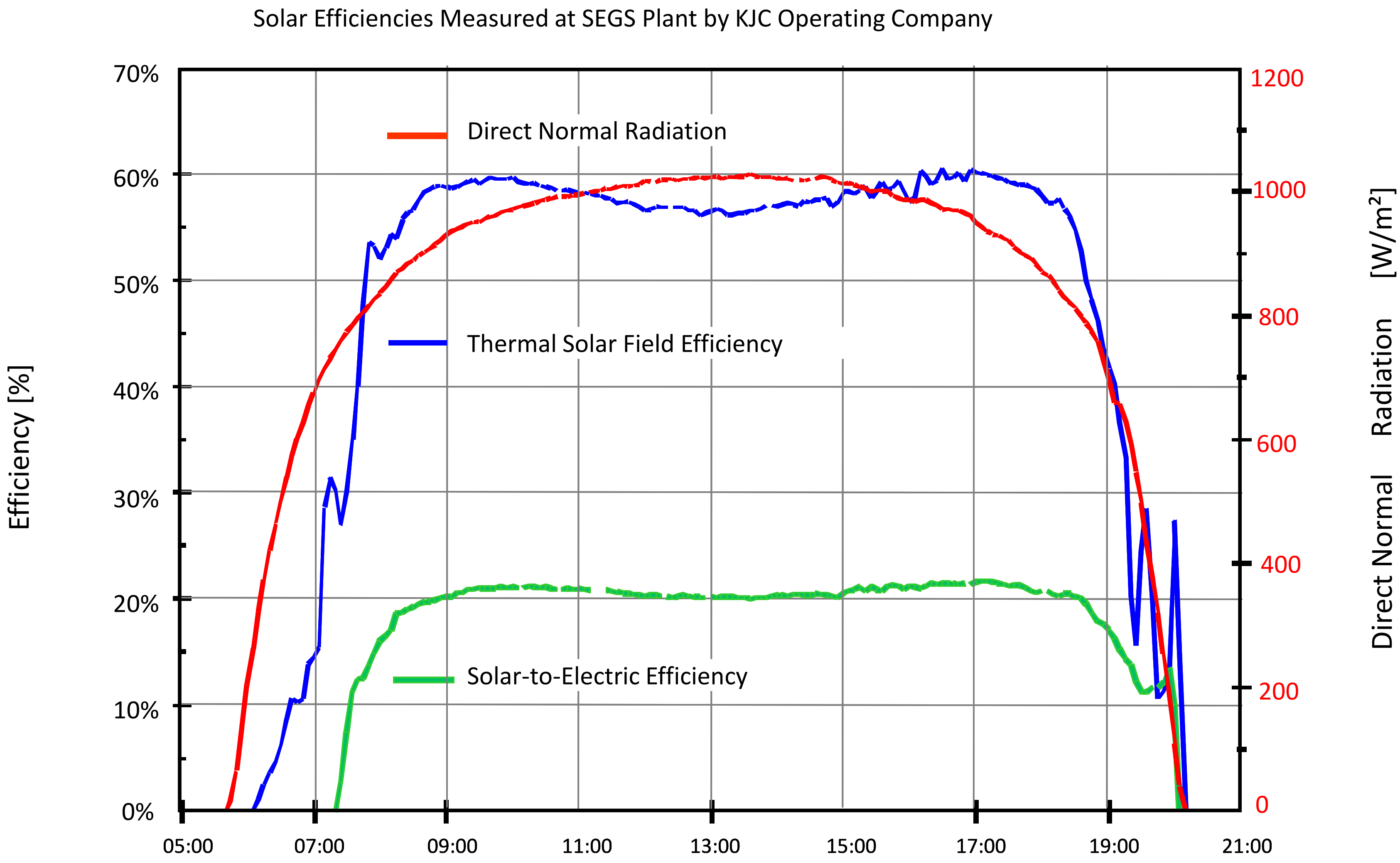
ρ reflectivity mirror
τ transmissivity quartz
α absorptivity absorber
IC interception factor

IC - Intercept-Faktor includes all losses due to

- optical imaging properties
- Shadows
- Manufacturing tolerances
- Tracking inaccuracies

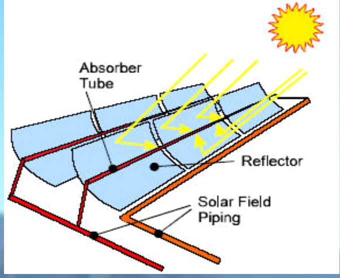


Solar efficiency

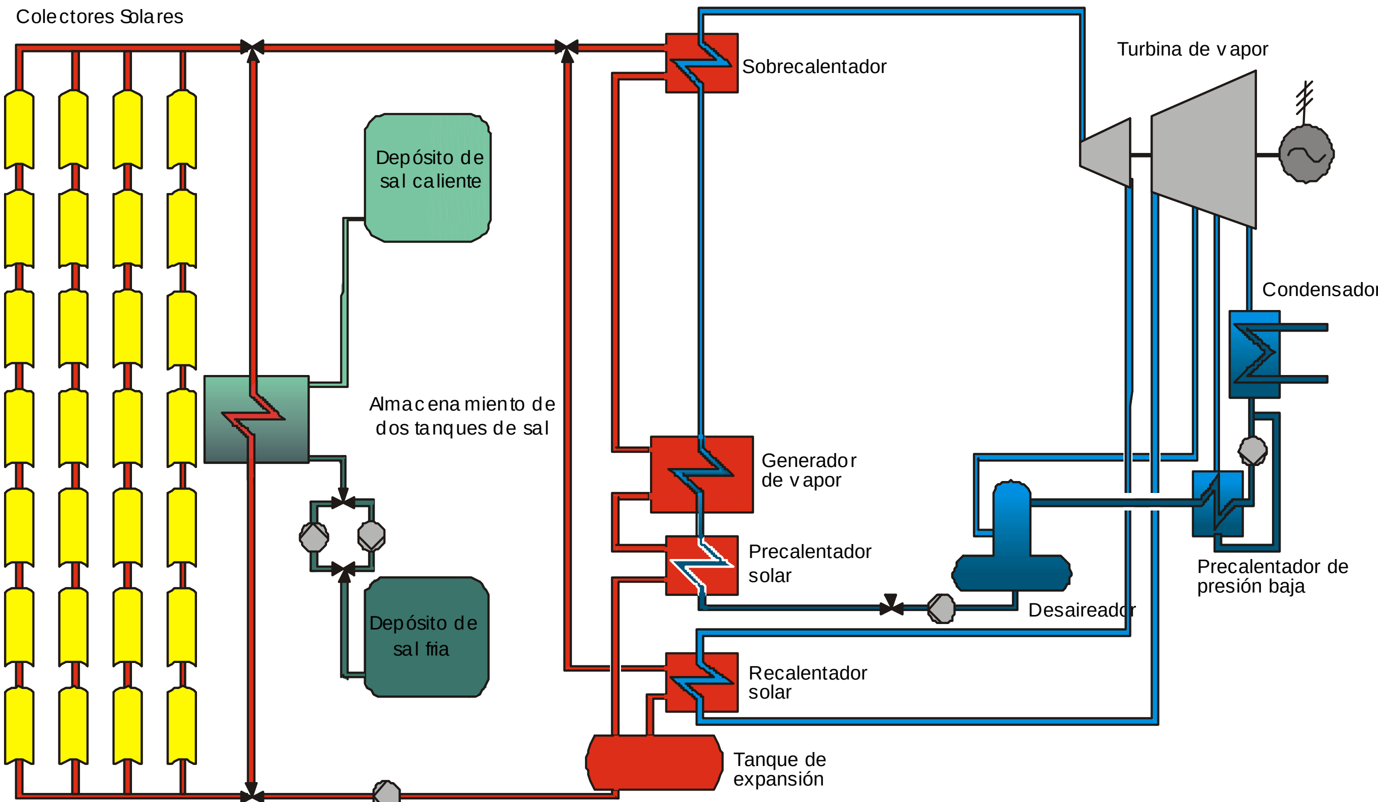


50 MW_e AndaSol 1 (Spain)

- **510,120 m² solar field**
- **180 GWh annual production**
- **Start-up Nov. 2008**
- **Annual production: 176 GWh (approx. 35,000 households)**
- **7.5 hours storage (molten salt)**
- **12% natural gas (NG) backup**
- **Investment: 260 Mio. EUR**



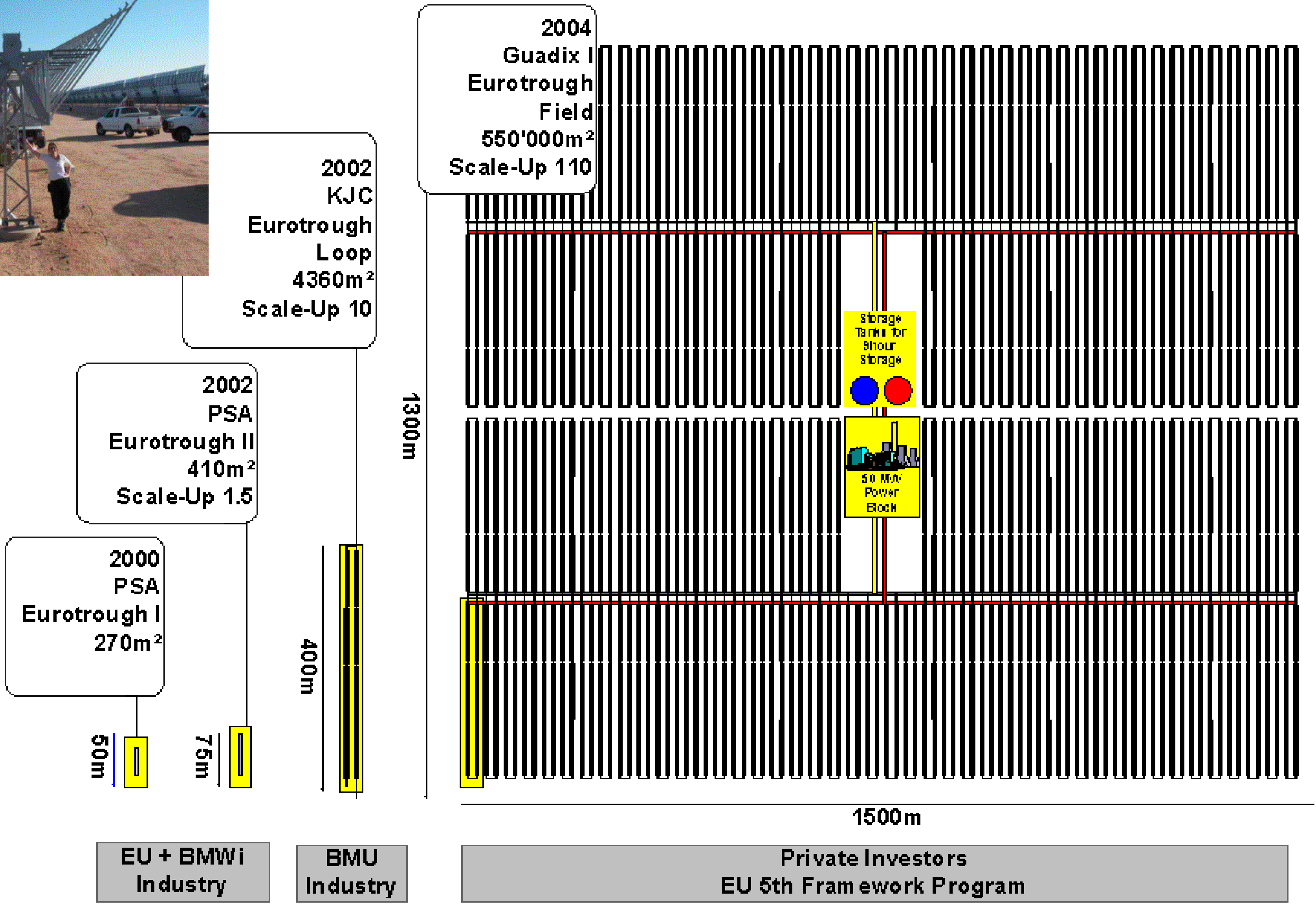
50 MW_e Andasol Plant in Spain



- 672 trough collectors
- 150 m long each
- 8 m aperture diameter

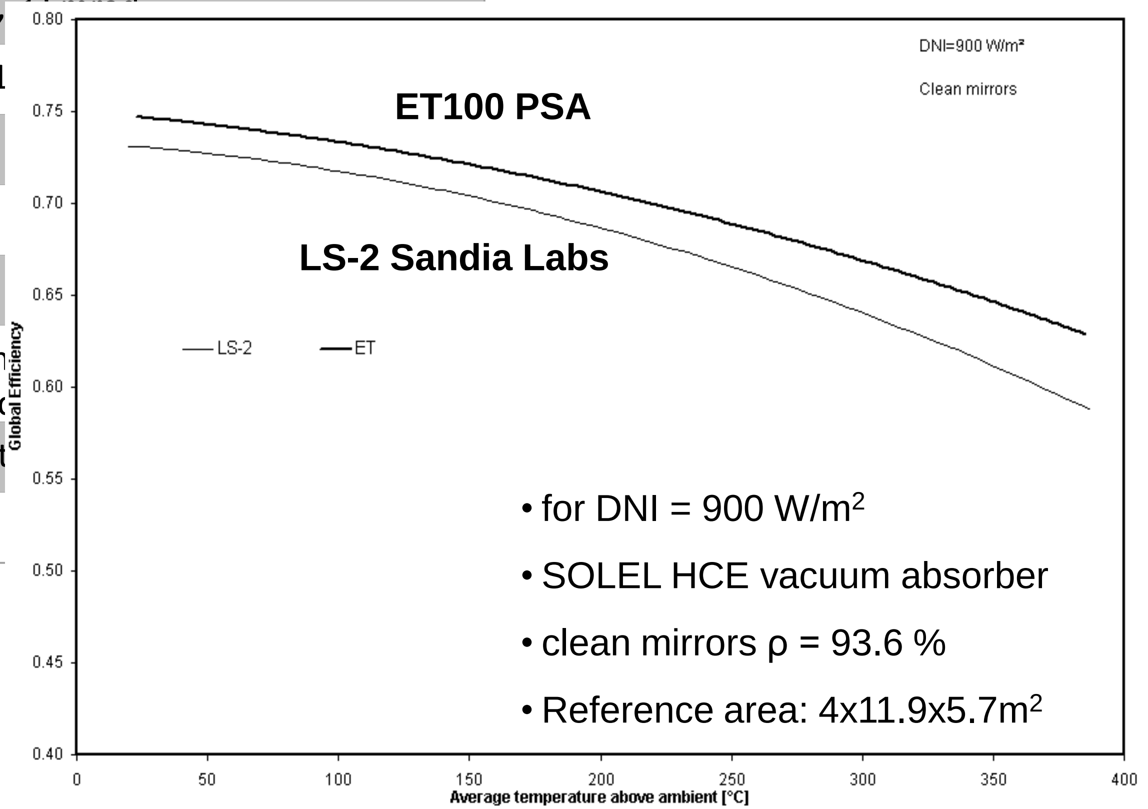
	50 MW_e Solar Only 9 h heat storage
Required land (km²)	1.8
Investment cost	260 Mio €
Annual electricity production (GWh_e)	181.7
LEC (€/kWh)	0.15

50 MW$_e$ Andasol Plant in Spain



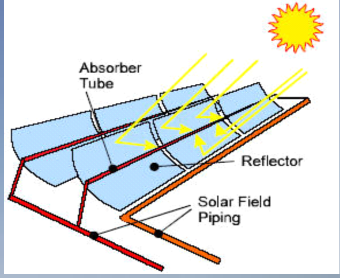
50 MW_e Andasol Plant in Spain

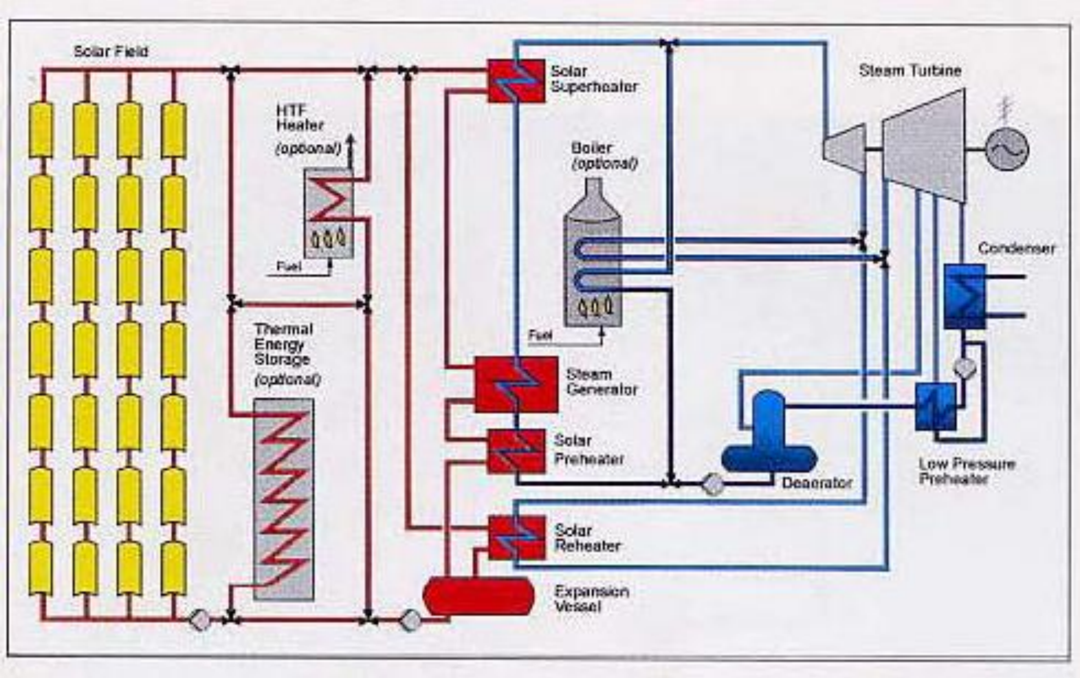
Layout	parabolic trough collector
support structure	steel frame work, pre-galvanized, three variants; light weight, low torsion
collector length	12 m per element; 100 - 150 m collector length
drive	hydraulic drive
max. wind speed	operation: 14 m/s, stow: 40 m/s
Tracking control	clock + sun sensor,
parabola	$y = x^2/4f$ with f = 1
aperture width	5.8 m
Reflector	4 glass facets
optical efficiency	0.80 (design)
absorber tube	evacuated glass en application depend
Fluid	oil, steam, applicat
cost	< 200 Euro/m^2



64 MW_e Solar One (Nevada, USA)

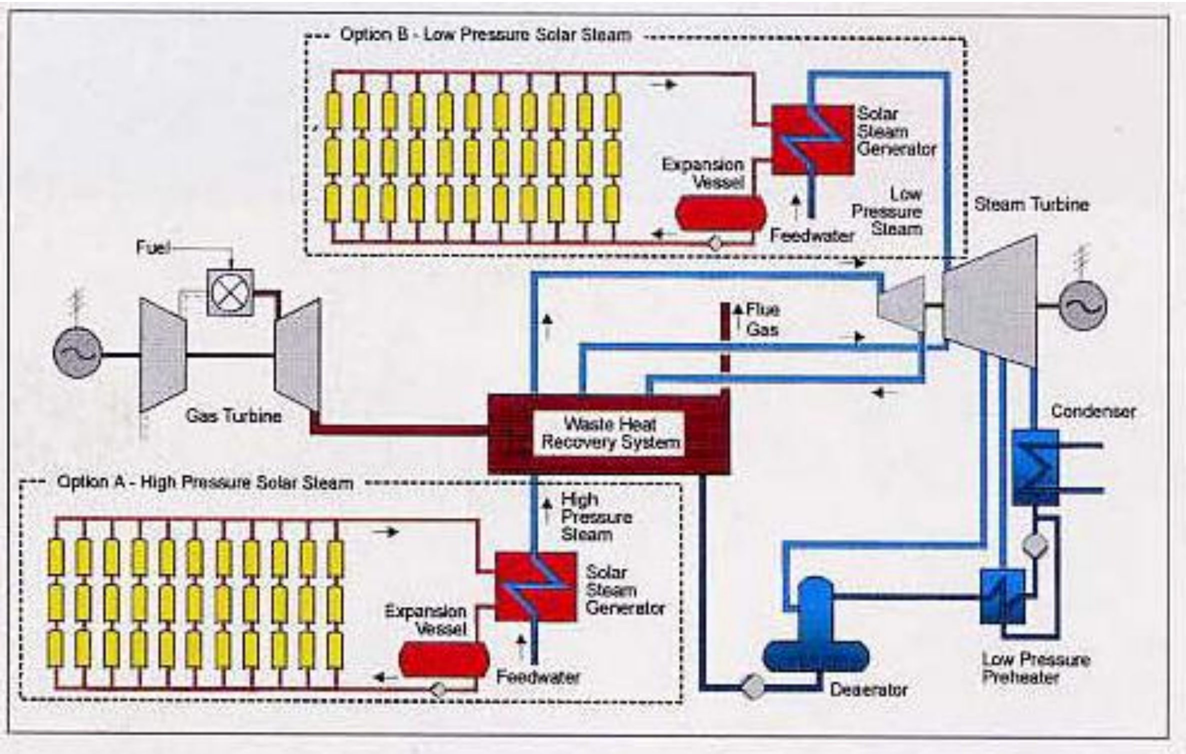
- **357,200 m² solar field**
- **130 GWh annual production**
- **Start-up in June 2008**



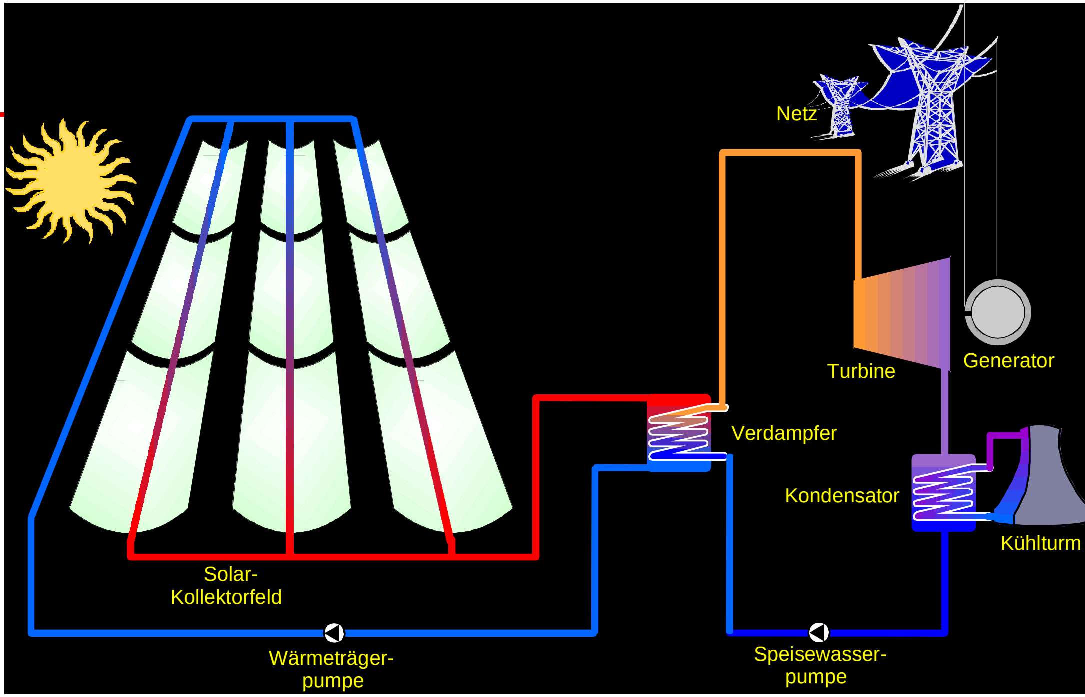


Solar Rankine-Cycle

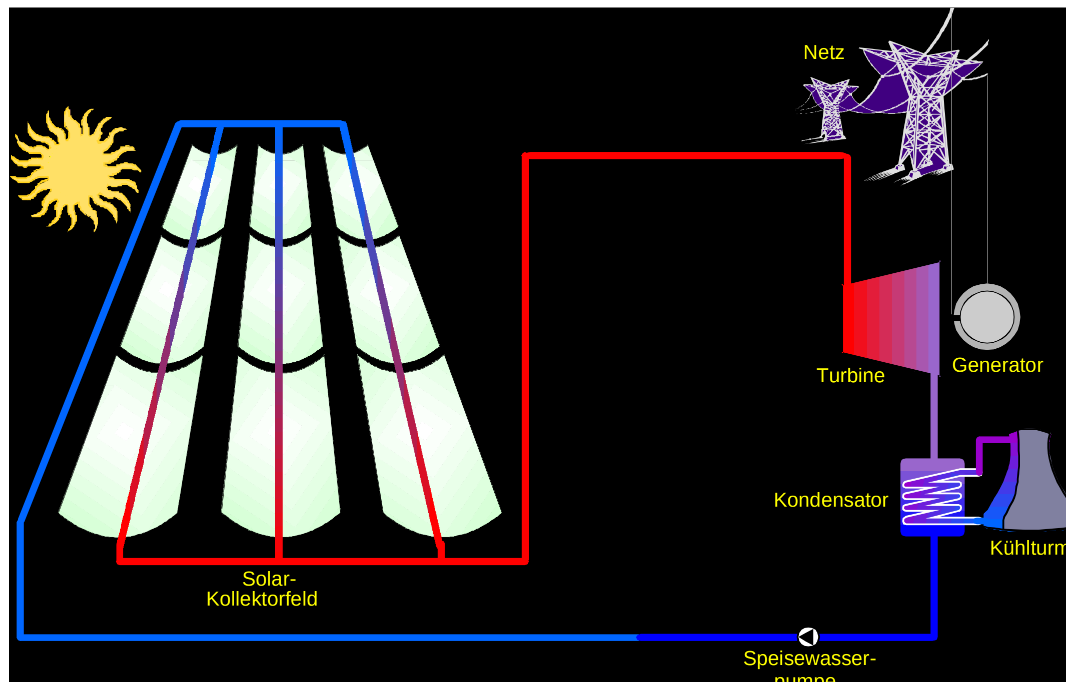
Solar Combined-Cycle



Indirect Steam Generation



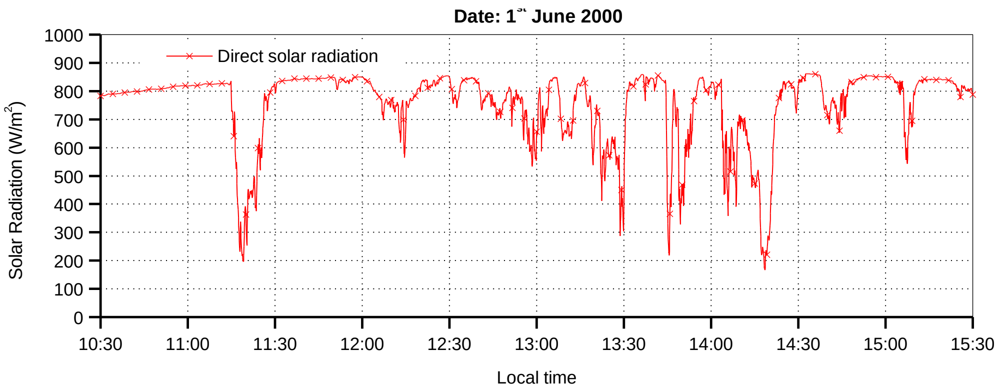
Direct Steam Generation

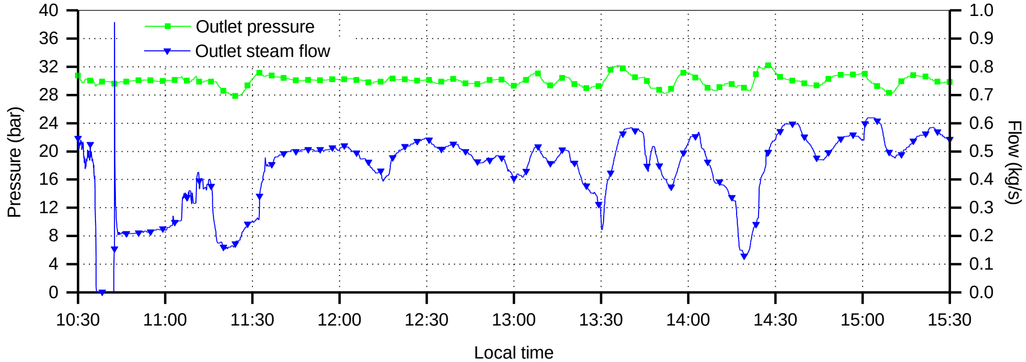


Direct Steam Generation

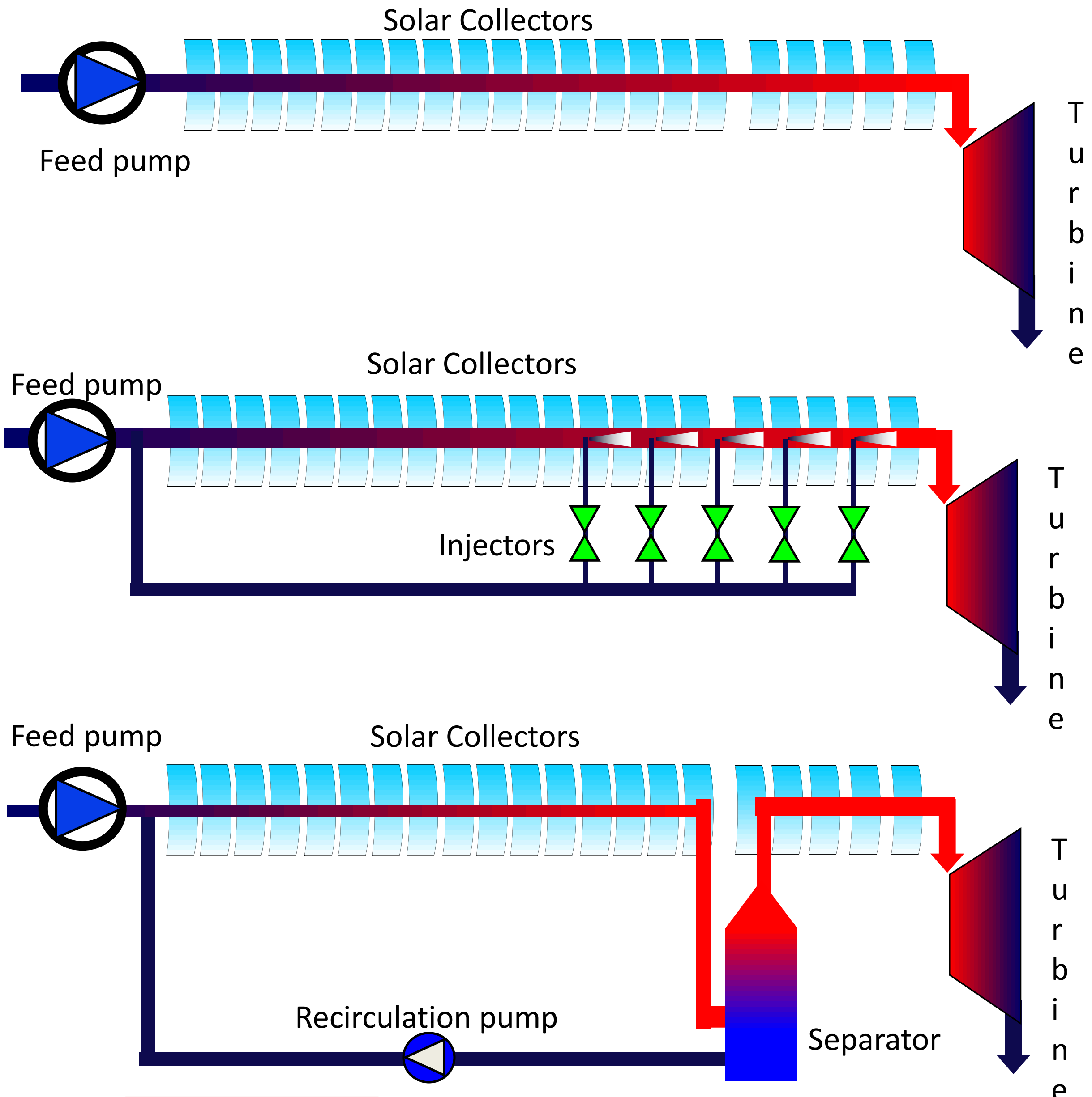
Technical Data:

- Length: 550 m
- Number of Modules: 40
- Sizes of Modules: 5,8 x 12 m²
- Diameter Absorber Tubes: 70 mm
- Mass Flow: 1.2 kg/s
- Temperature: 375 C
- Pressure: 30 - 100 bar





Direct Steam Generation

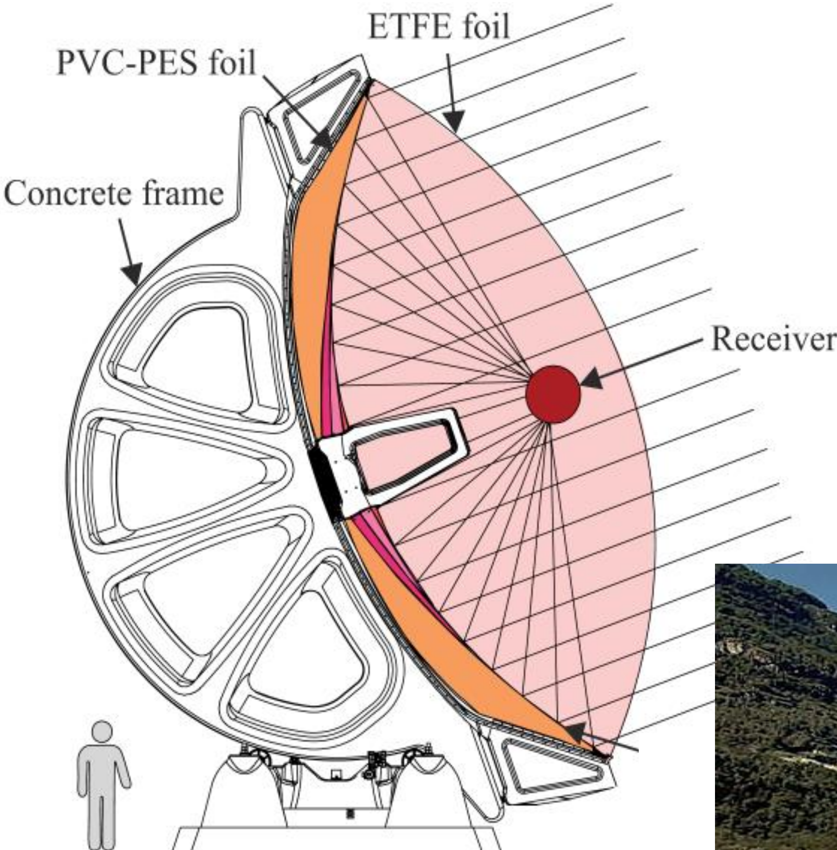


Once Through Boiler
- Lowest Costs
- Least complexity
- Best Performance
- Controllability ?
- Flow Stability ?

Injection Process
- Better Controllability
- Flow stability equally good
- More complex
- Higher investment costs

Recirculation Process
- Better Flow Stability
- Better Controllability
- More complex
- Higher investment costs
- Higher parasitics

Airlight Energy

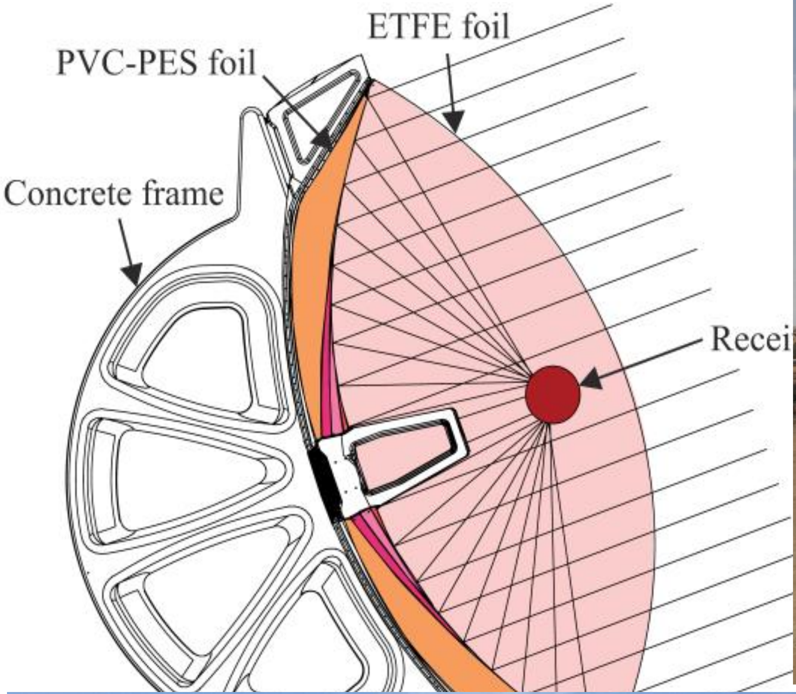


- Pre-cast concrete durable and rigid
- Wind induced vibrations eliminated
- Small structural deformation → ap = 10 m
- Self-cleaning scratch/UV-resistant ETFE
- High-quality mirror foils protected
- Low costs per m^2

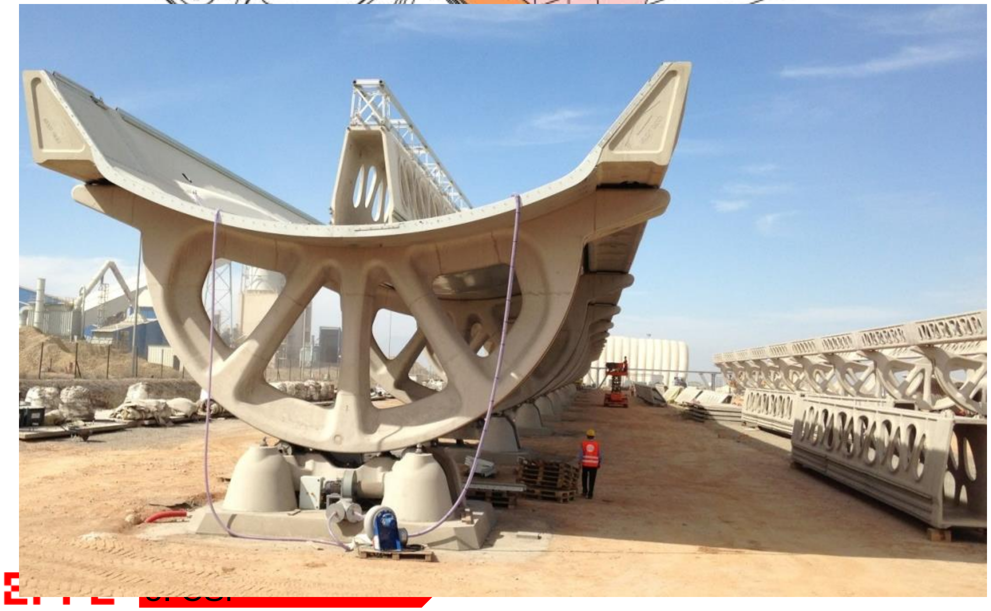
- J. Solar Energy Engineering 134, 021002-1/8, 2012.
- Solar Energy 95, pp. 308–318, 2013.

Airlight Energy

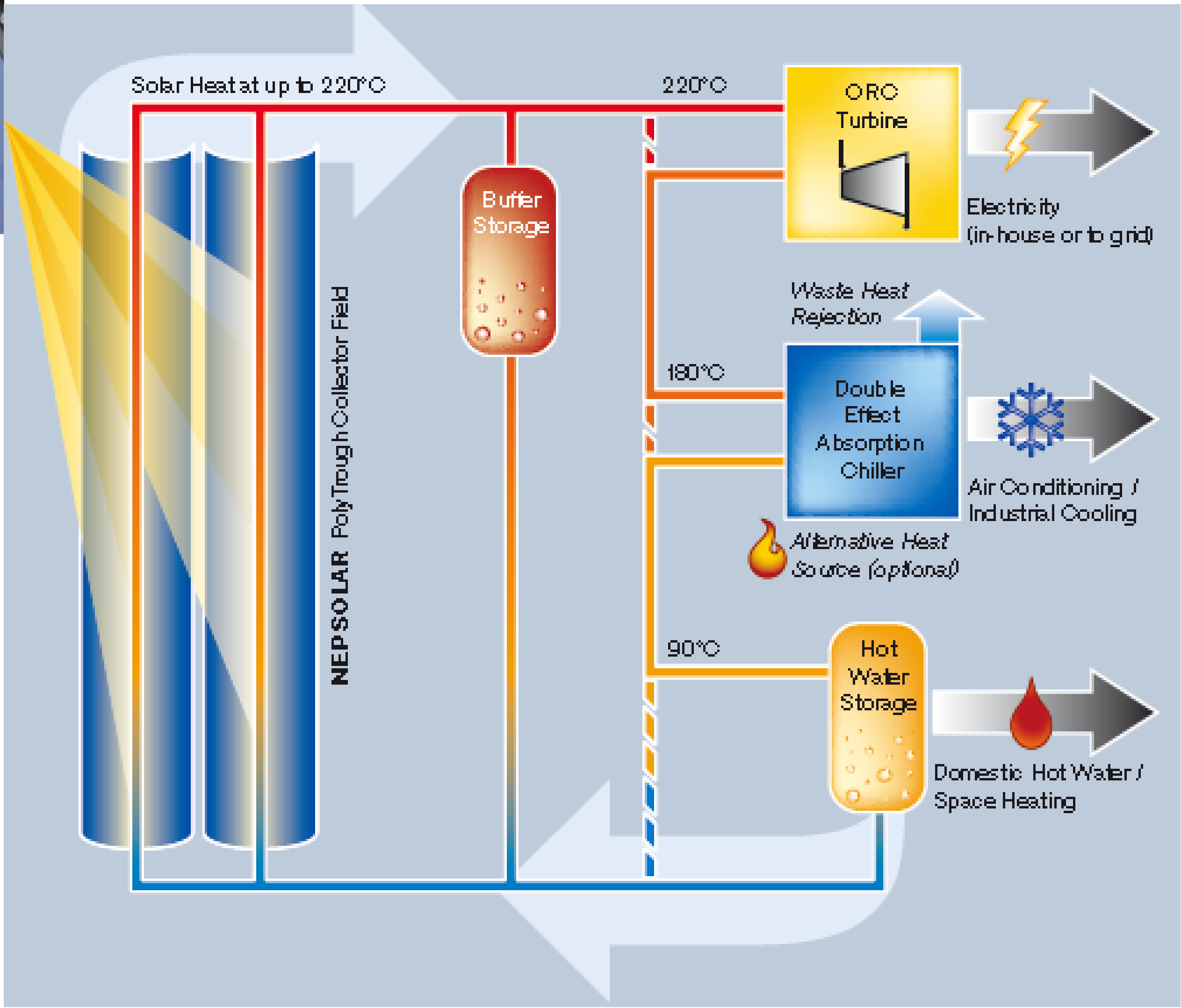
airlight energy



- 4 MW$_{th}$ solar thermal power
  Ait Baha, Morocco

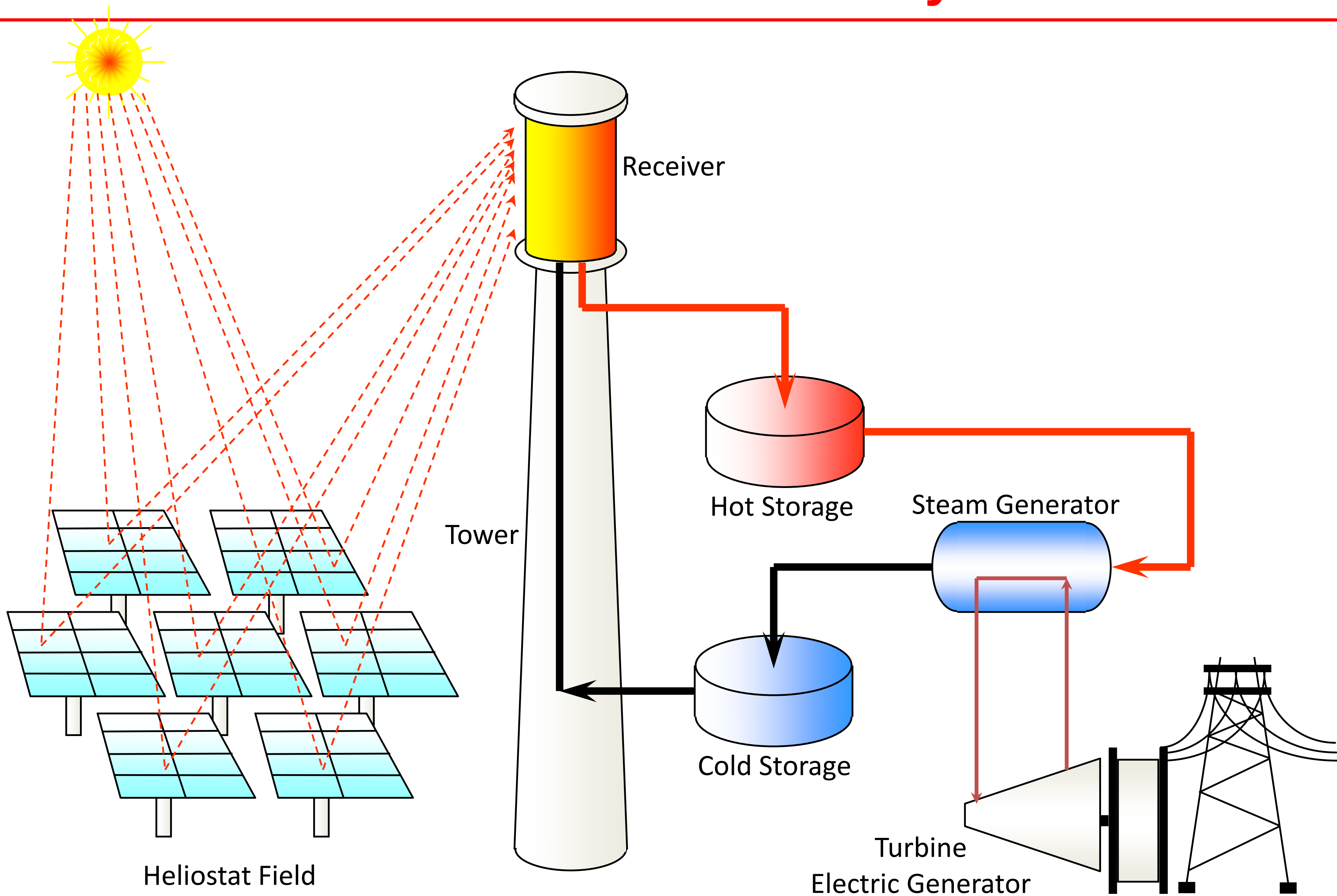


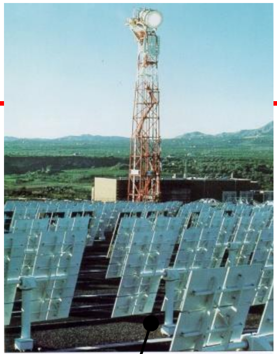
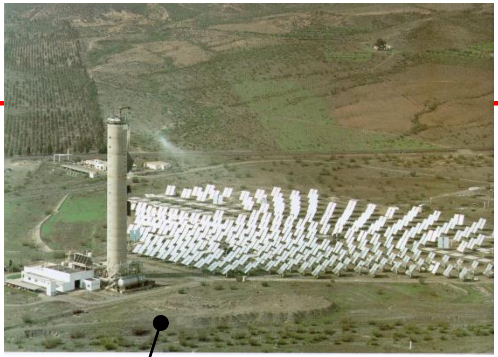
Nepsolar



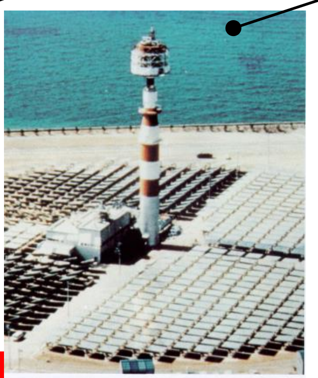
Solar Heat at up to 220°C
220°C
ORC
Turbine
Electricity
(in-house or to grid)
Buffer
Storage
NEPSOLAR PolyTrough Collector Field
Waste Heat
Rejection
180°C
Double
Effect
Absorption
Chiller
Air Conditioning /
Industrial Cooling
Alternative Heat
Source (optional)
90°C
Hot
Water
Storage
Domestic Hot Water /
Space Heating

Solar Thermal Power Generation by Solar Towers

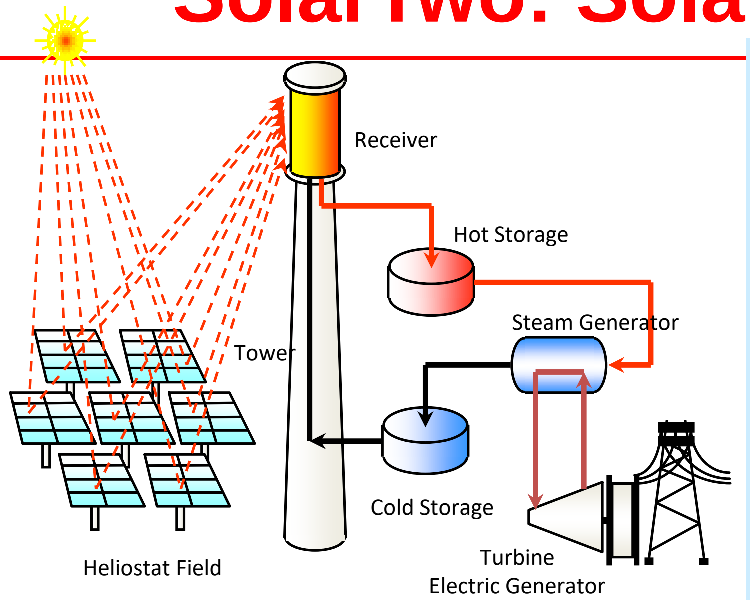


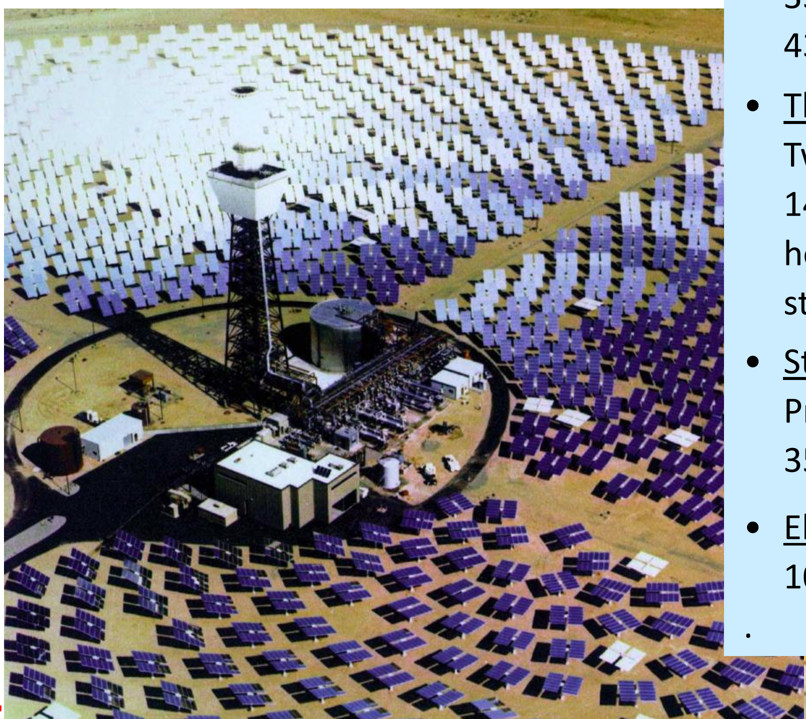





Name	SSPS-CRS	EURELIOS	SUNSHINE	CESA-1	THEMIS	Solar One	Solar Two	SPP-5
Location	Almería	Adrano (Sicily)	Nio Town	Almería	Targasonne	Barstow	Barstow	Shchelkino (Crimea)
Country	Spain	Italy	Japan	Spain	France	USA	USA	Russia
Start of Operation	1981	1981	1981	1983	1982	1982	1996	1986
Electric Output	500 kW_e	1 MW_e	1 MW_e	1 MW_e	2-2.5 MW_e	10 MW_e	10 MW_e	5 MW_e
Heliostat field reflective surface area	3655 m²	6216 m²	12912 m²	11880 m²	10794 m²	71447 m²	71447 m²	40000 m²
Receiver heat-transfer fluid	Liquid Sodium	Steam	Steam	Steam	Molten salt (HITEC)	Steam	Molten Salt	Steam
Receiver heat-transfer fluid temperature	530 °C	512 °C	249 °C	525 °C	450 °C	516 °C	565 °C	250 °C
Storage medium	Sodium	HITEC salt / hot water	HITEC salt / hot water	HITEC salt	Molten salt (HITEC)	Oil/rock	Molten Salt	Water / steam
Storage capacity (full power hours)	2	0.5	3	3.5	5	3	3	not available


SolarTwo: Solar Towers with Molten Salt





<u>Facts</u>:

- Operated by Sandia National Laboratories at Barstow, CA.
- Solar One (steam) operated 1982-1988.
- Solar Two (molten salt) operated 1996-1999.
- <u>Heliostats</u>:
  1,818 heliostats of 39 m^2 each, 108 heliostats 95 m^2 each;
  total reflective area = 81,162 m^2.
- <u>Solar receiver</u>:
  Cylindrical shape of 5.1-m ϕ x 6.2-m high;
  33 25-mm ϕ tubes in each of 24 panels;
  43 MW$_{th}$ solar thermal power with 800-sun peak flux.
- <u>Thermal Storage</u>:
  Two 12-m f x 8-m high storage tanks;
  1400 tons molten nitrate salt (K, Na) as HTF; m.p. 240 °C;
  hot storage @ 565°C; cold storage @ 280 °C;
  storage capability: 24 hr. power delivery.
- <u>Steam Generator</u>:
  Preheater, evaporator, superheater vessels;
  35.5 MW thermal rating at 538 °C, 100 bar.
- <u>Electric Power Generation System</u>:
  10 MW$_e$ net electric power rating Rankine-cycle.

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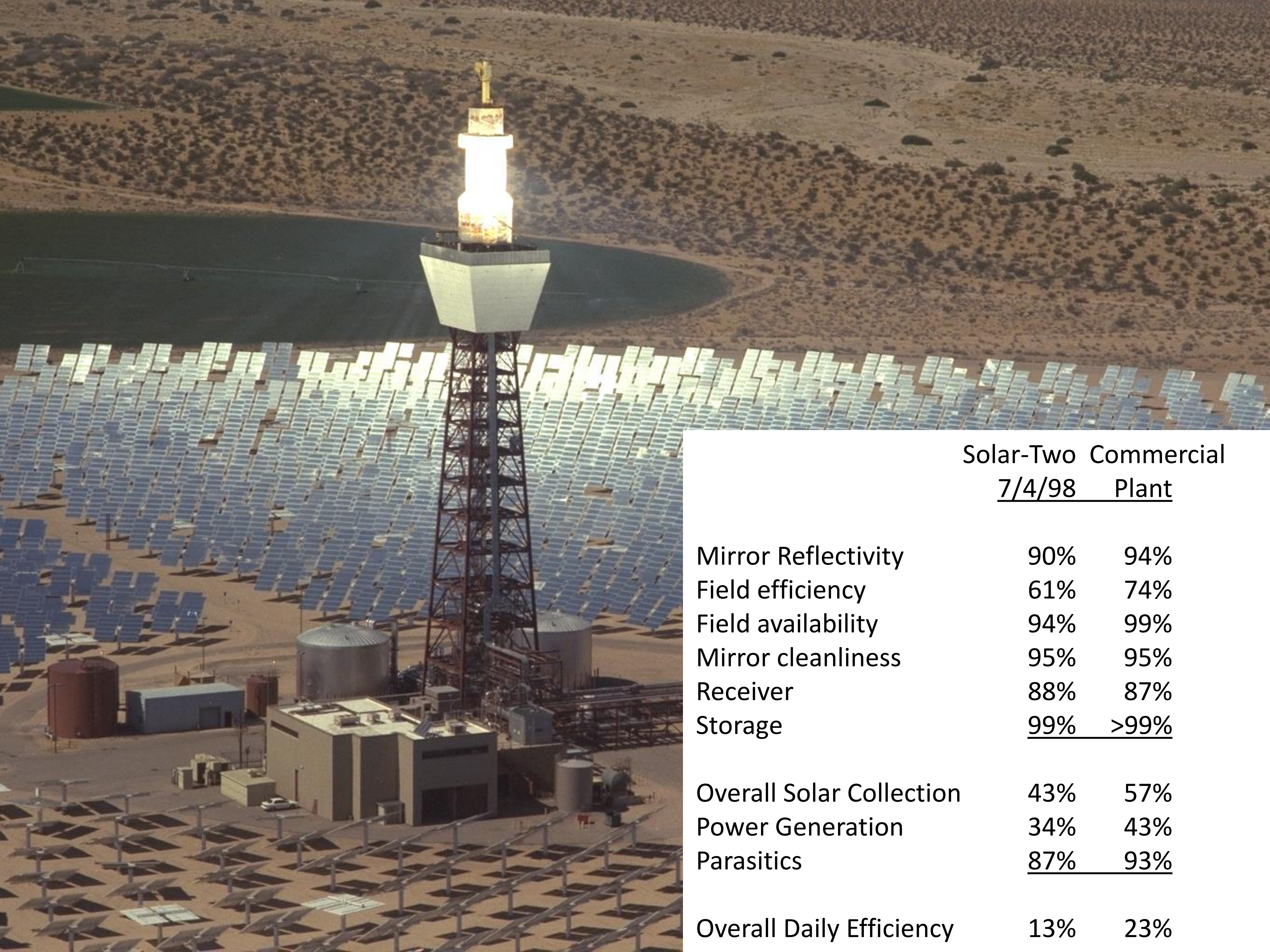
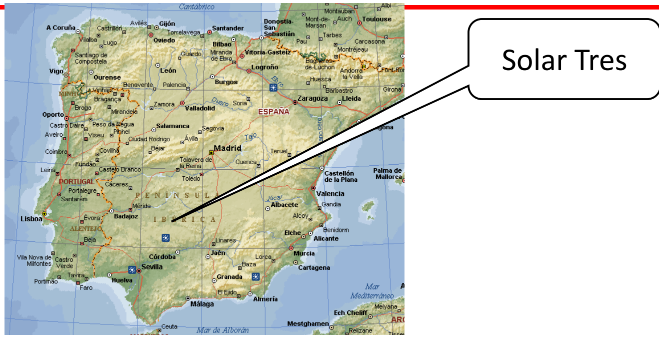
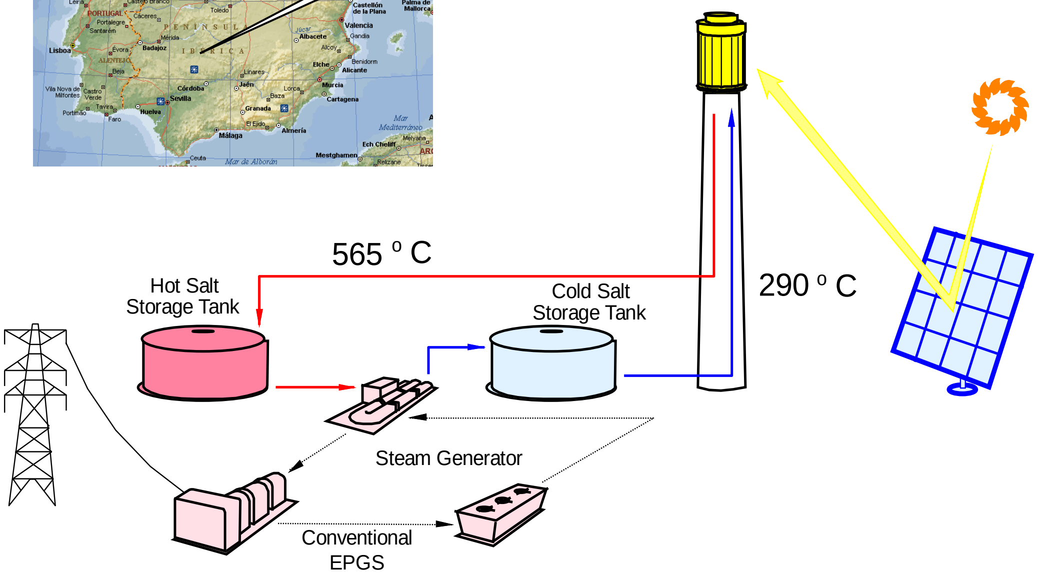
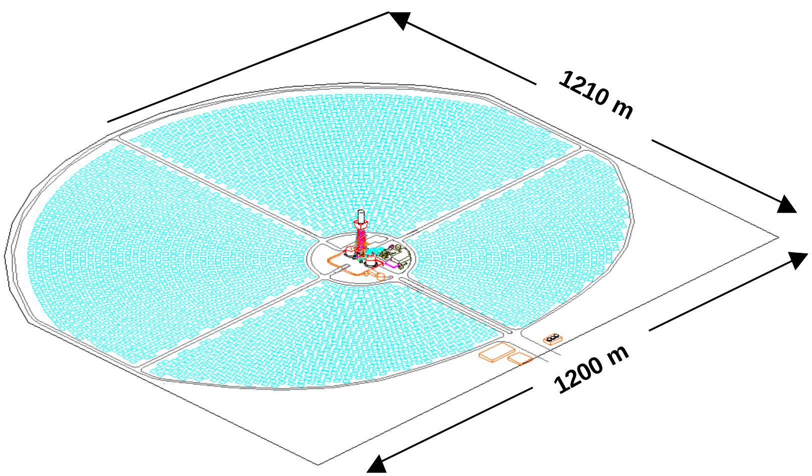


	Solar-Two 7/4/98	Commercial Plant
Mirror Reflectivity	90%	94%
Field efficiency	61%	74%
Field availability	94%	99%
Mirror cleanliness	95%	95%
Receiver	88%	87%
Storage	99%	>99%
Overall Solar Collection	43%	57%
Power Generation	34%	43%
Parasitics	87%	93%
Overall Daily Efficiency	13%	23%

15 MW_e SolarTres in Spain







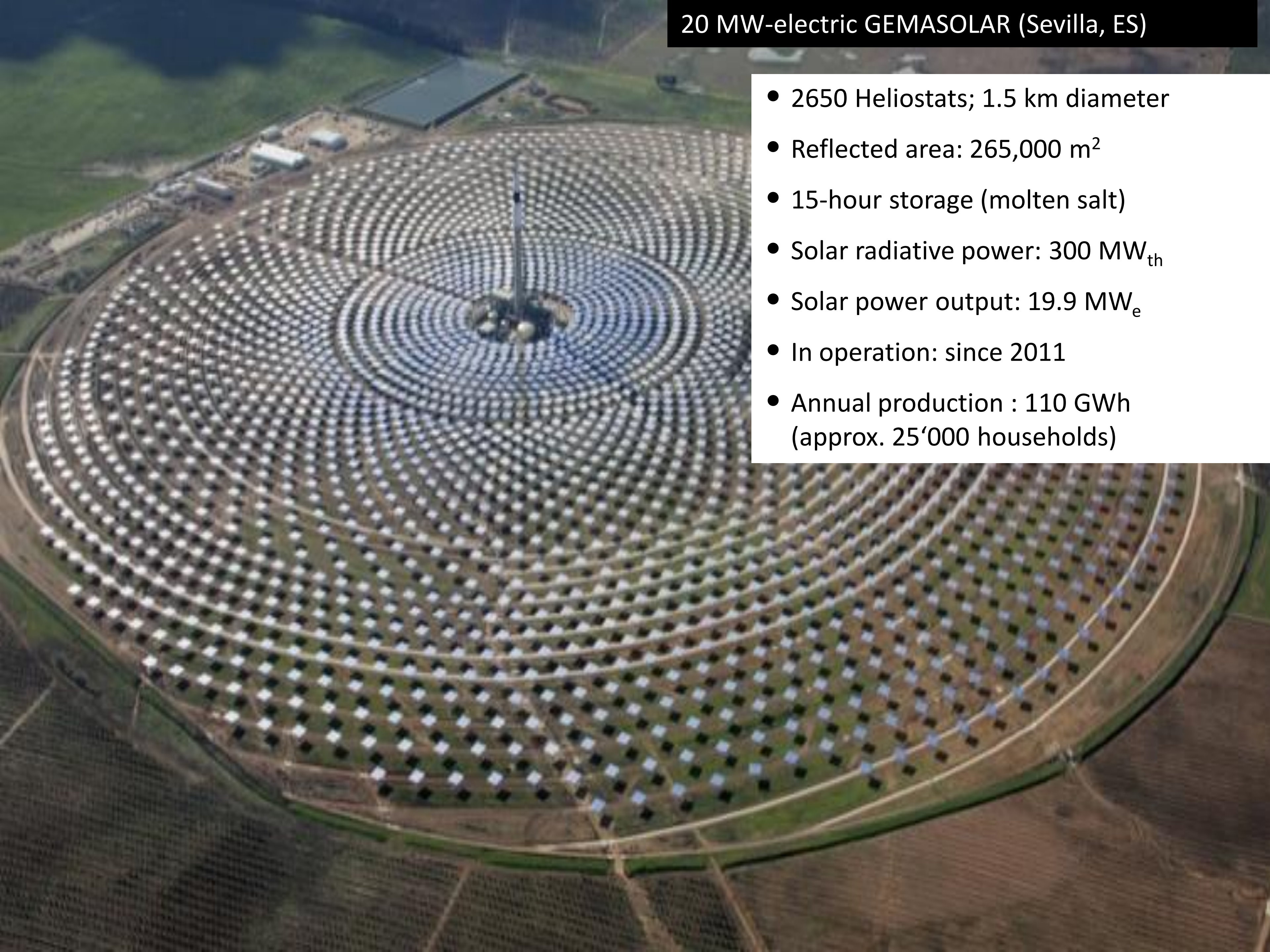
Technical specifications	
Heliostat field reflectant surface	264825 m^2
Number heliostats	2750
Land area	142.31 Ha
Receiver thermal power	120 MWt
Tower height	120 m
Heat storage capacity	15 hours
Power at turbine	17 MWe
Power NG burner	16 MWt

Operation	
Solar irradiance onto heliostats	2062 kWh/m^2
Electricity dispatched	105566 MWhe
Production from fossil (annual)	15%
Capacity factor	71%

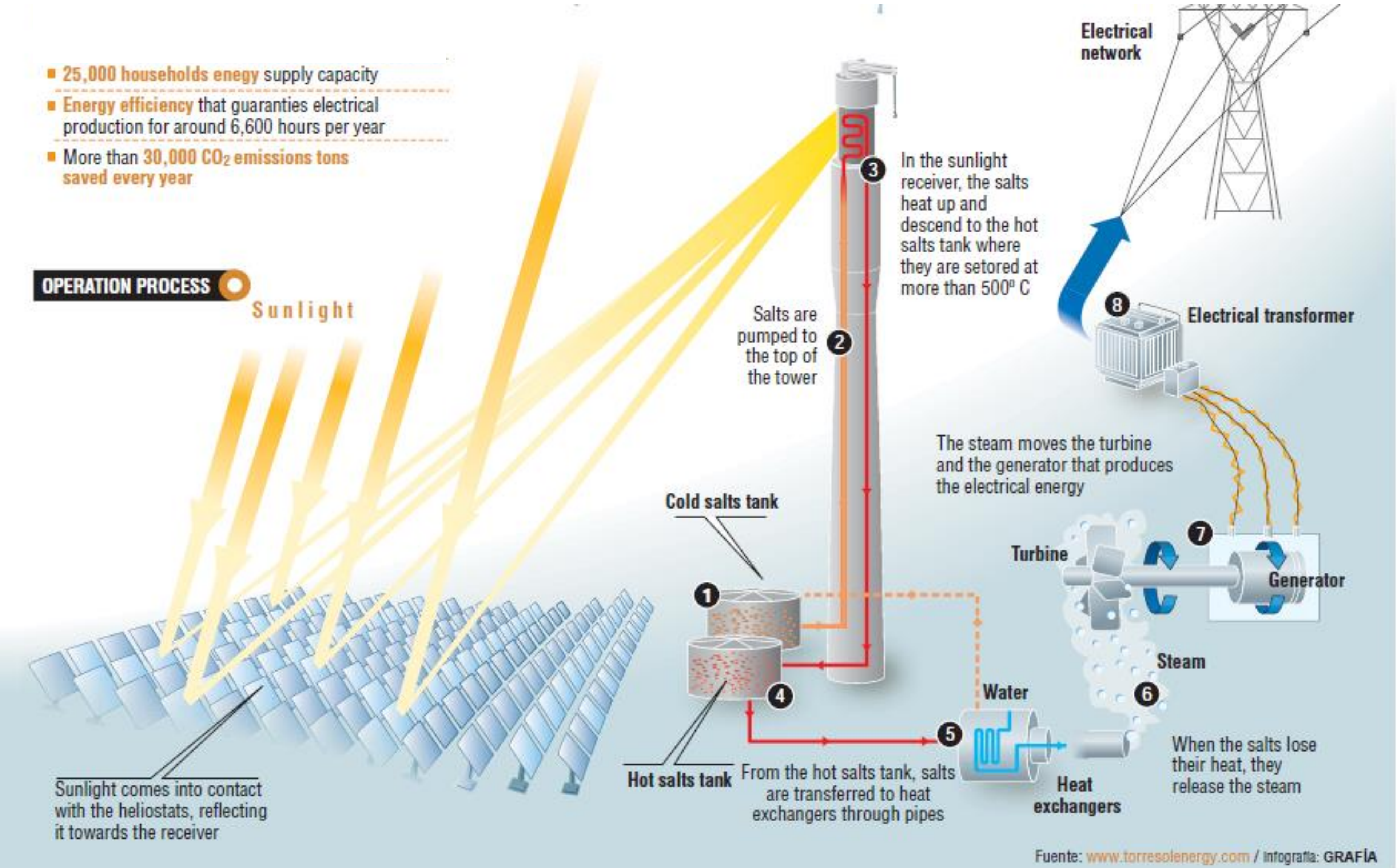
- 16-hour storage (580 MWh_t) with 6,250 salt tons
- 24 hours/day solar-only power production
- 84 GWh annual production
- Investment: 147 M€

20 MW-electric GEMASOLAR (Sevilla, ES)

- 2650 Heliostats; 1.5 km diameter
- Reflected area: 265,000 m^2
- 15-hour storage (molten salt)
- Solar radiative power: 300 MW_{th}
- Solar power output: 19.9 MW_e
- In operation: since 2011
- Annual production : 110 GWh (approx. 25‘000 households)



20 MW$_e$ Gemasolar in Spain



11 MW-electric/ 55 MW-thermal(Sevilla, ES)

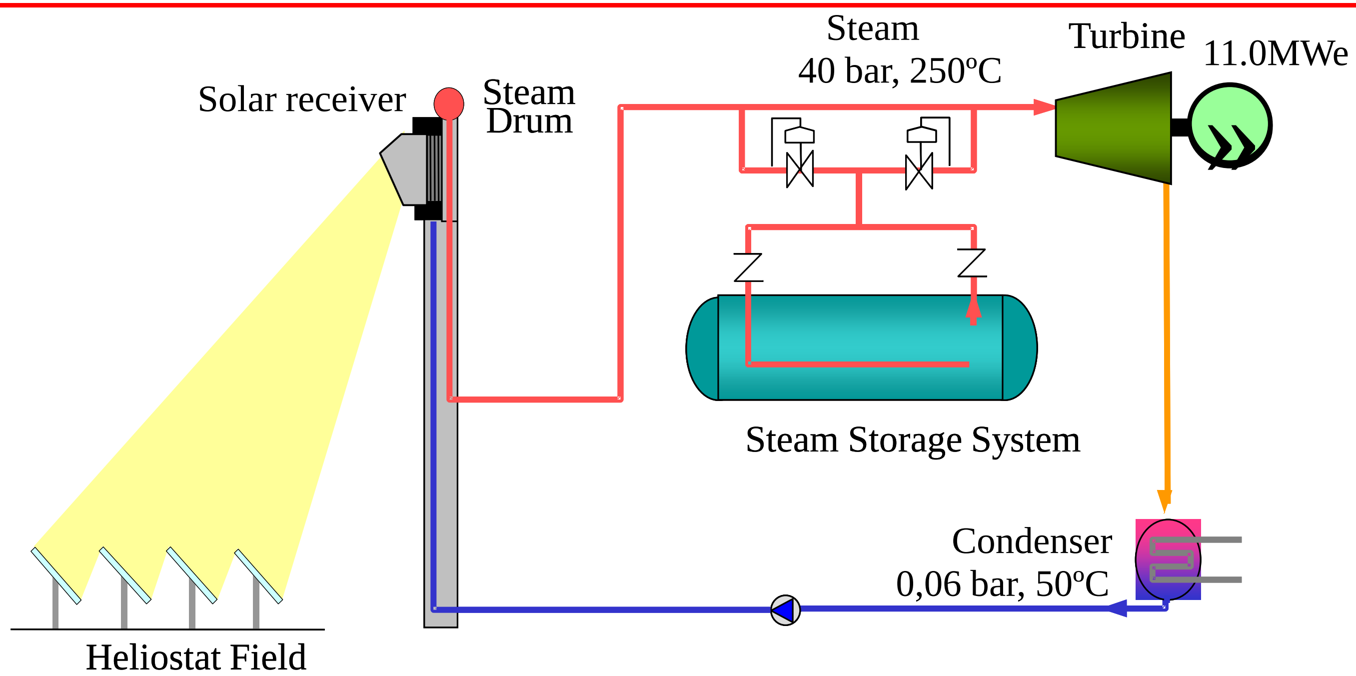
- 624 Heliostats; each 120 m^2
- Tower height: 100 m
- Costs (incl. power block): 35 M€
- Efficiency solar-to-electricity: peak 21%, mean annual 17%
- In operation: since 2007
- Annual production : 23 GWh (approx. 15‘000 households)
- 1 hour storage (steam)

20 MW-electric/ 100 MW-thermal (Sevilla, ES)

- Costs (incl. power block): 80 M€
- Efficiency solar-to-electricity: peak 21%, mean annual 17%
- In operation: since 2009
- Annual production : 46 GWh
- 12-15% NG backup

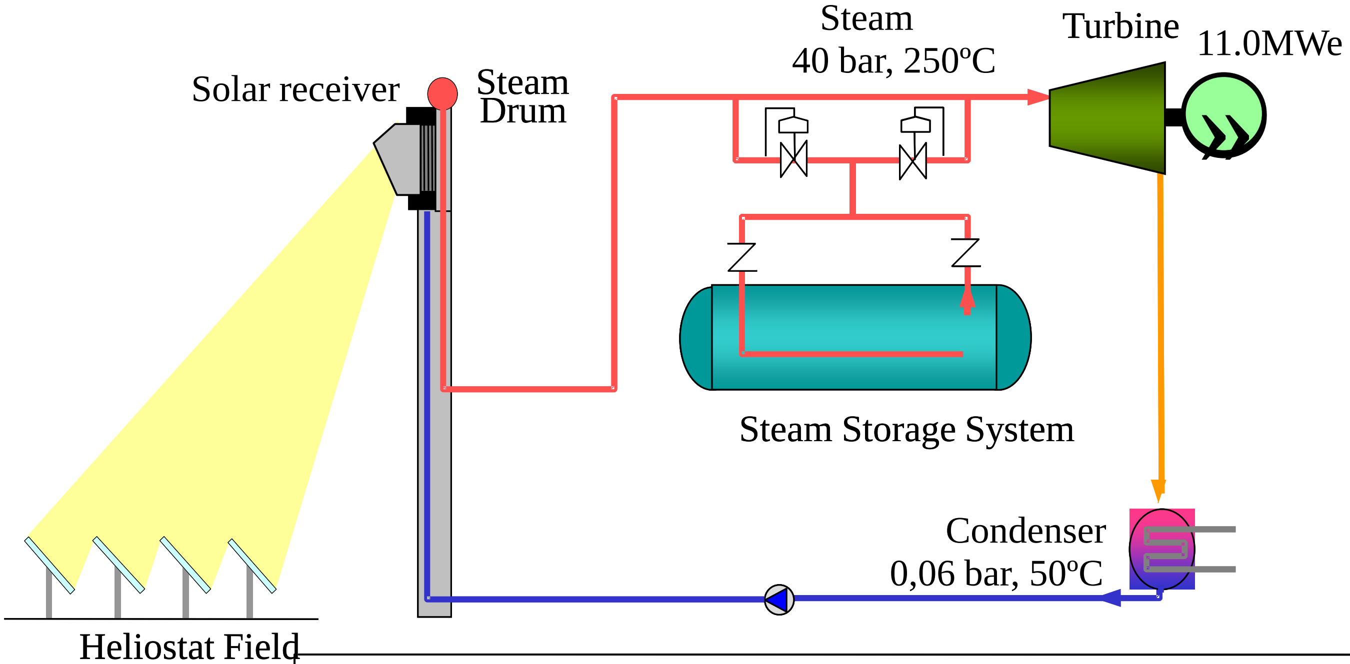
11 MW_e in Sevillia, Spain

PS10
Sanlucar Solar Project



General Description	
Emplacement	Sanlúcar M. (Sevilla), Lat 37.4º, Lon 6.23º
Nominal Power	11.02MWe
Tower Height	100m
Receiver Technology	Saturated Steam
Receiver Geometry	Cavity180º, 4 Pannels 5m x 12m
Heliostats	624 @ 121m2
Thermal Storage Technology	Water/Steam
Thermal Storage Capacity	15MWh, 50min @ 50% Rate
Steam Cycle	40bar 250ºC, 2 Pressures
Electric Generation	6.3kV, 50Hz -> 66kV, 50Hz
Land	60Has
Annual Electricity Production	23.0GWh

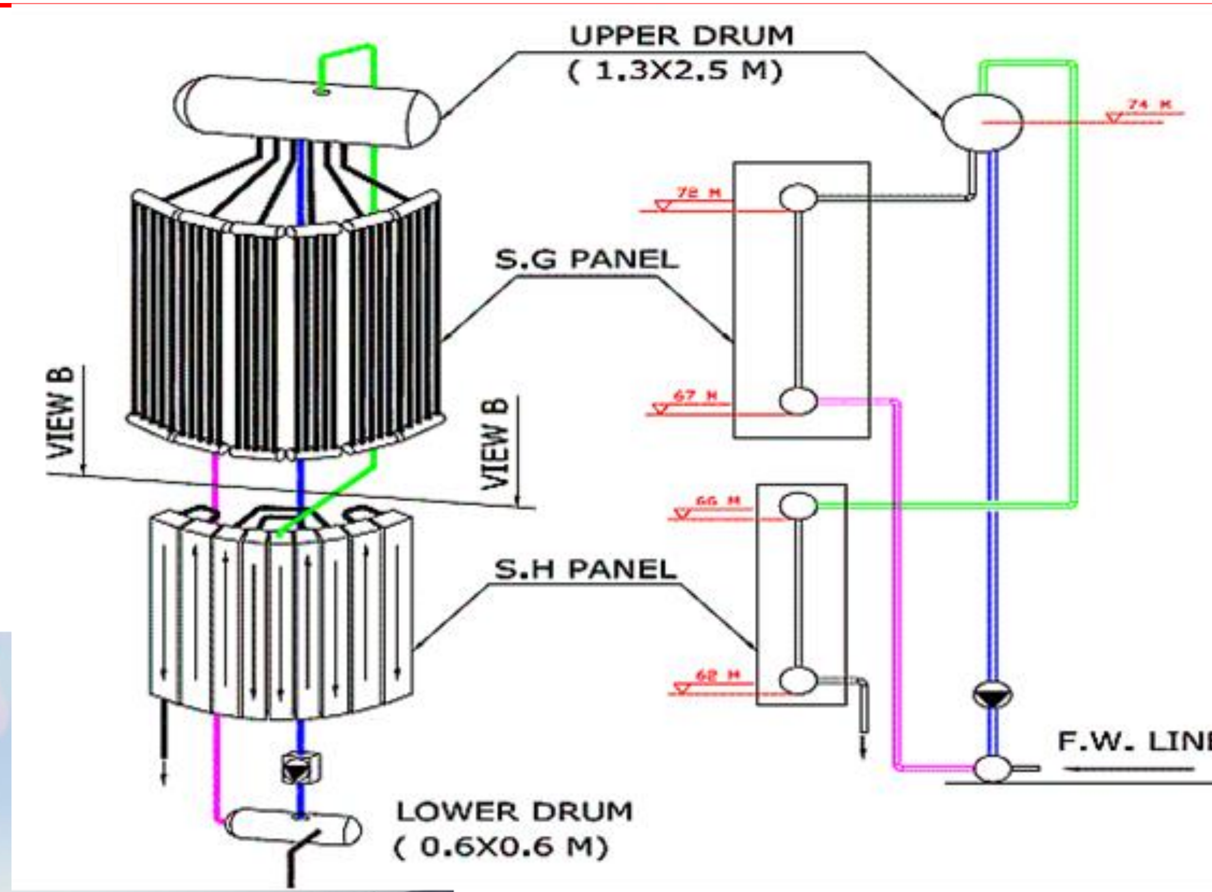
11 MW_e in Sevillia, Spain

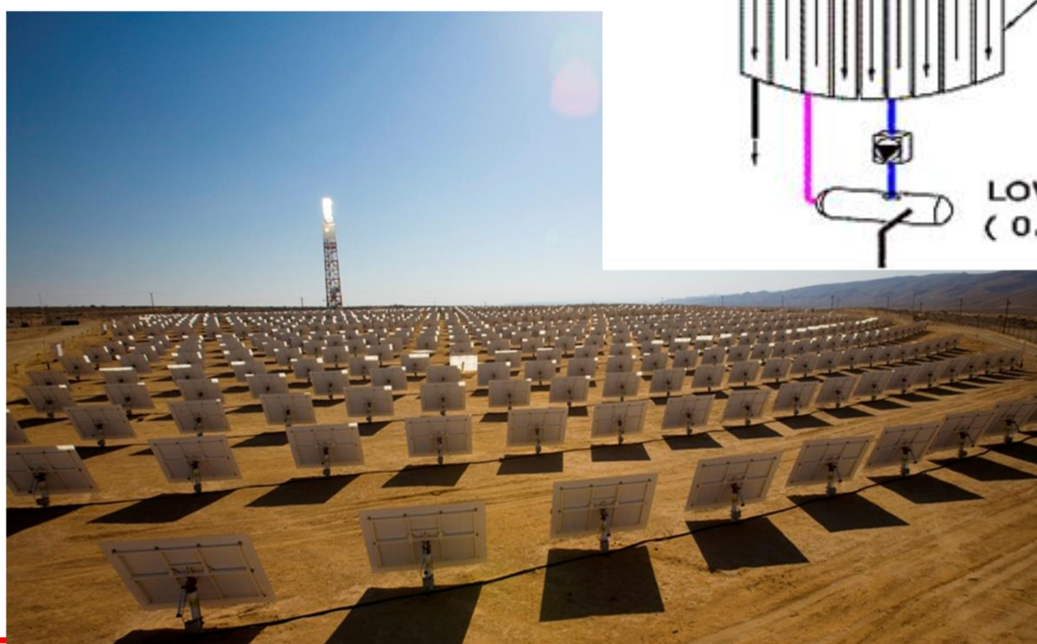


Nominal Rate Operation		
Optical Efficiency	77.0%	67.5MW -> 51.9MW
Receiver and Heat Handling Efficiency	92.0%	51.9MW -> 47.7MW
Thermal Power to Storage		11.9MW
Thermal Power to Turbine		35.8MW
Thermal Pow. -> Electric Pow. Efficiency	30.7%	35.8MW -> 11.0MW
Total Efficiency at Nominal Rate		21.7%
Energetical Balance in Annual Basis		
Mean Annual Optical Efficiency	64.0%	148.63GWh(useful) -> 95.12GWh
Mean Annual Receiver&Heat Handling Efficiency	90.2%	95.12GWh -> 85.80GWh
Operational Efficiency (Starts Up/Stops)	92.0%	85.80GWh -> 78.94GWh
Operational Efficiency (Breakages, O&M)	95.0%	78.94GWh -> 75.00GWh
Mean Annual Thermal Ener. -> Electric Efficiency	30.6%	75.00GWh -> 23.0GWh
Total Annual Efficiency		15.4%

BrightSourceEnergy™

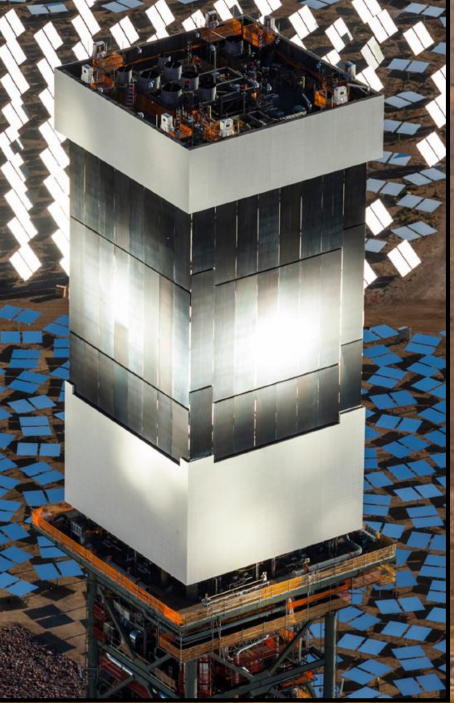
Brightsource Dual External





- Direct solar-to-steam at 550^0 C
- Air-cooled power block
- 15 m^2 heliostat mirrors

Ivanpah Solar Electric Generating System



Solar Field

- Heliostat Solar-Field Aperture
- Area: 2,600,000 m^2
- # of Heliostats: 173,500
- Heliostat Aperture Area: 15.0 m^2
- Tower Height: 459 ft
- Receiver Type: steam generator
- Heat-Transfer Fluid Type: Water
- Receiver Inlet Temp: 480F
- Receiver Outlet Temp: 1050F

Power Block

- Turbine Capacity: 392.0 MW
- Turbine Manufacturer: Siemens
- Output Type: Steam Rankine
- Power Cycle Pressure: 160.0 bar
- Cooling Method: Dry cooling
- Annual Efficiency: 28%
- Fossil Backup Type: Natural gas
- Thermal Storage: None

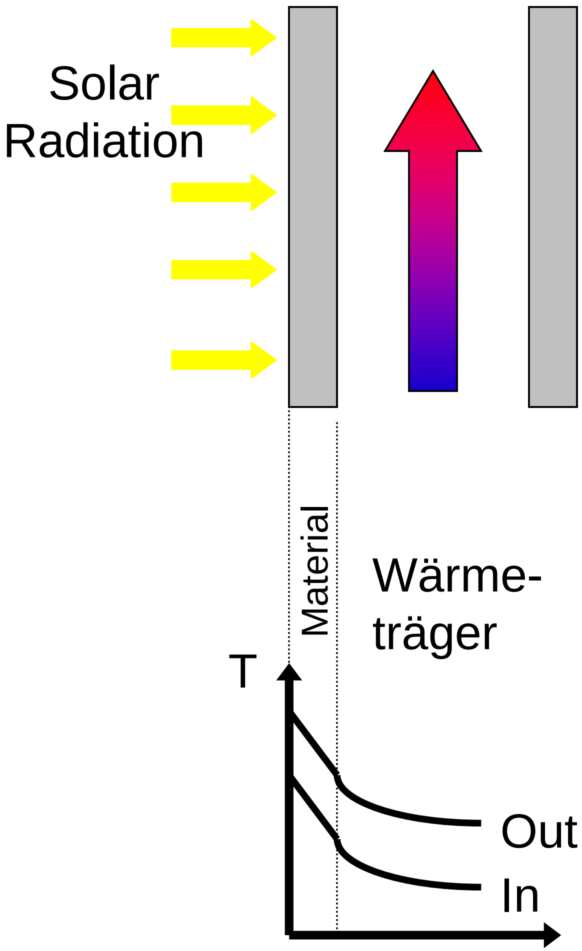
eSolar

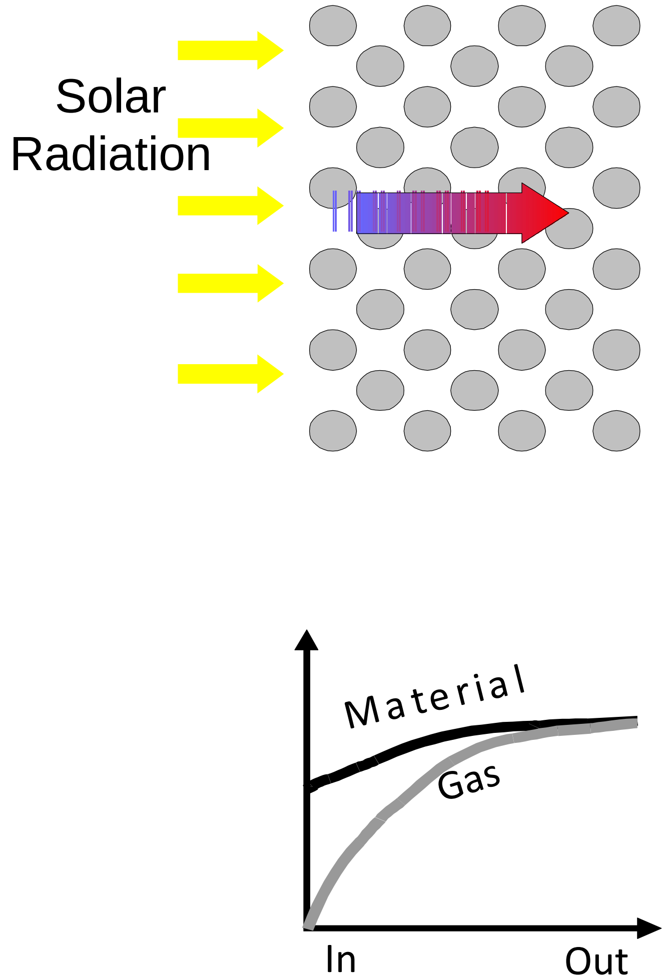
eSolar Sierra SunTower

- 2 modules, 20 acres
- 2 towers, 2 x 65-ton thermal receivers
- 1 GE steam turbine generator
- 24,000 mirrors reflecting the power of 20,000 suns
- 5 MW of clean, supplied to 4,000 Southern California Edison households

Double-Cavity

Tube vs. Volumetric Absorber

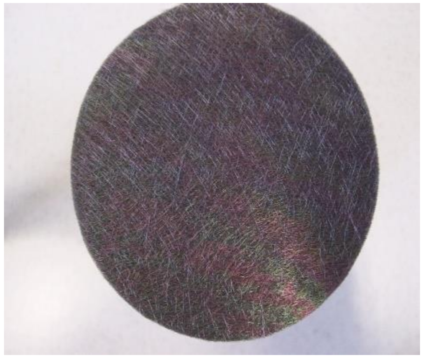




Properties:

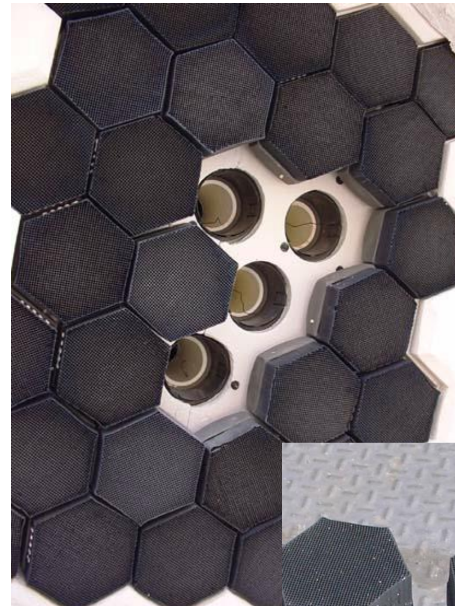
- Higher incident flux
- Improved absorption
- Lower extinction
- Higher heat transport
- Higher thermal stability
- Lower cost

Volumetric Absorber

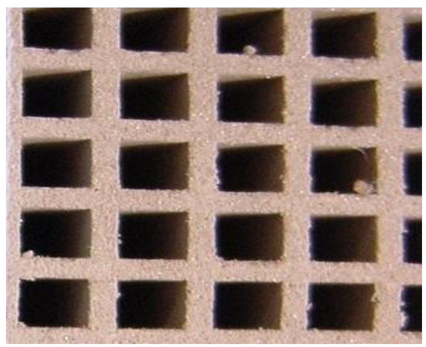


Metallic wire mesh

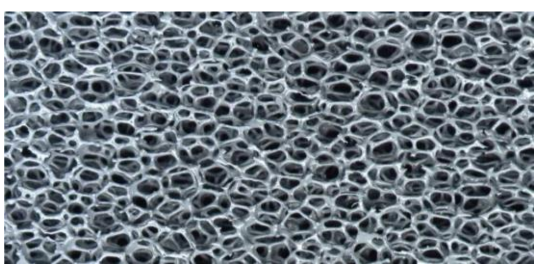
Parallel metallic channels



Sponge

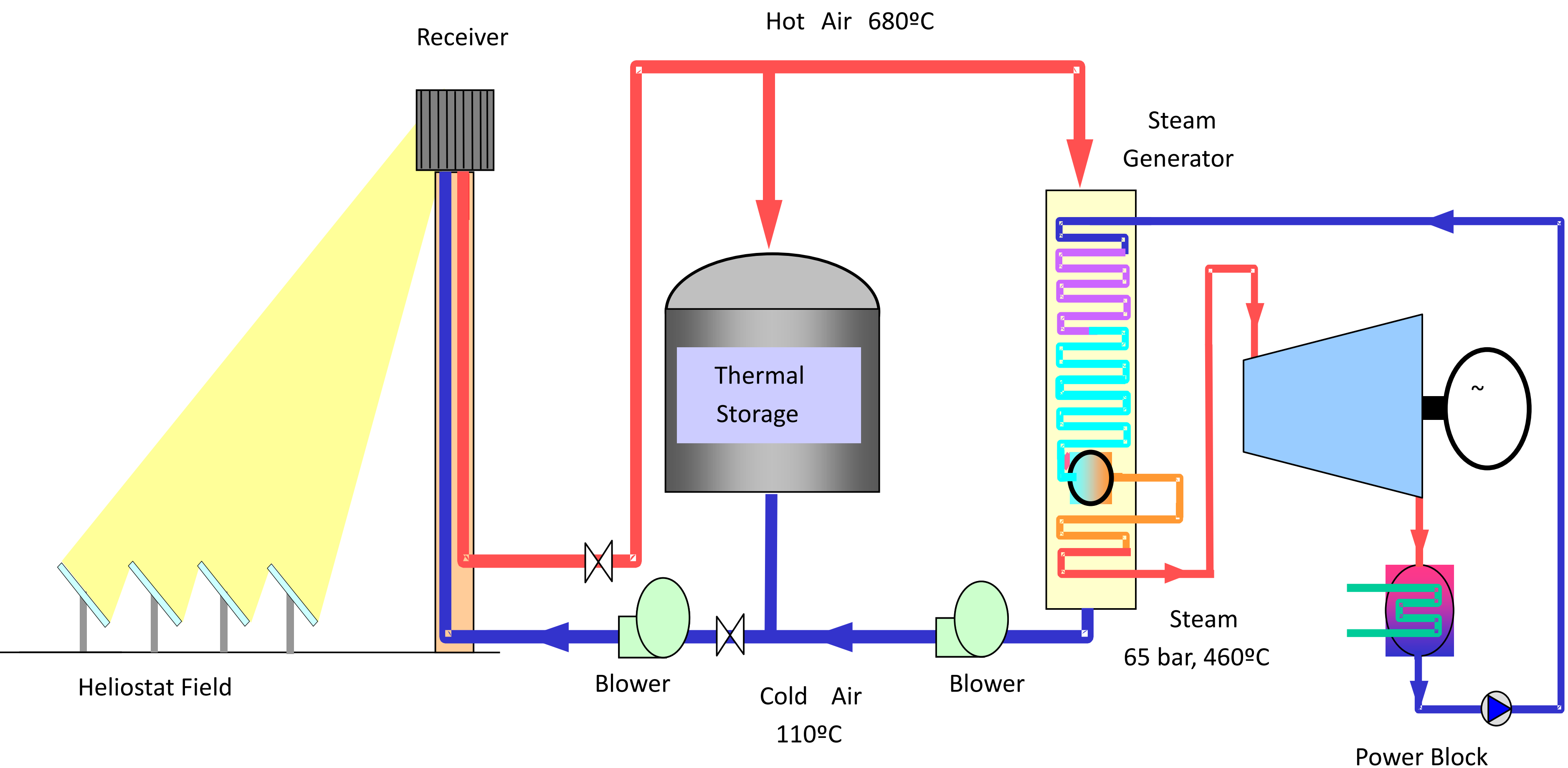


Parallel ceramic channels



RPC

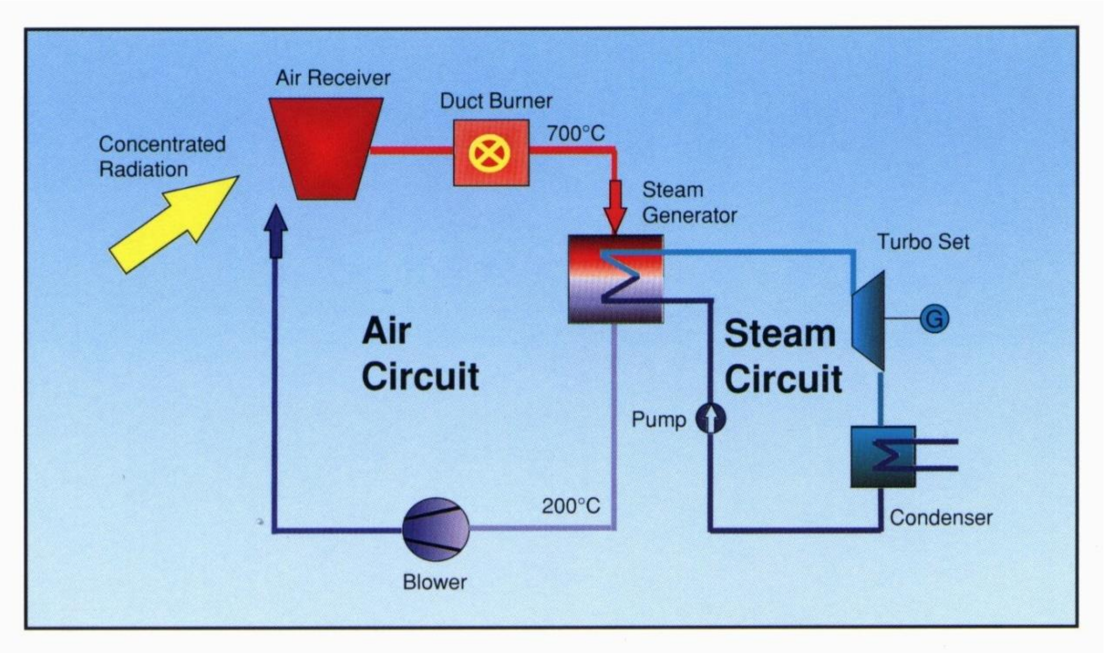
Air-Based Solar Tower Scheme

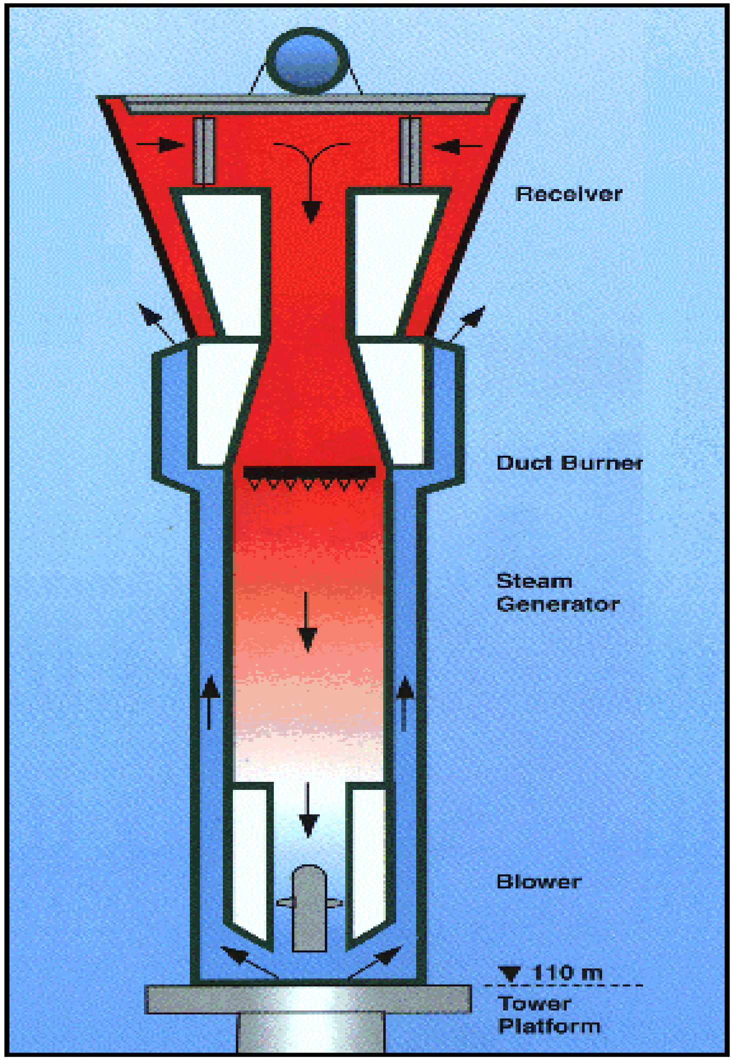


Solar Air Receiver

Technical Sheet

- Steam Parameters: 700°C, 100 bar
- Heat Transfer Medium: Air
- Backup Options: Thermal Storage, Duct Burners
- Backup Fuels: Natural Gas, Oil
- Technology Status 3 MW Demonstration at PSA





Heliostats

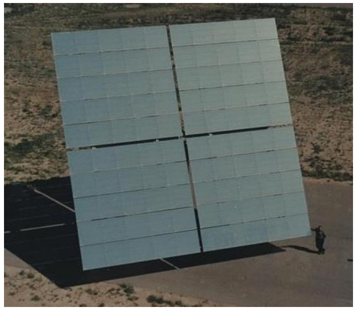
Faceted

Streched-membrane

GM-100

SAIC-170

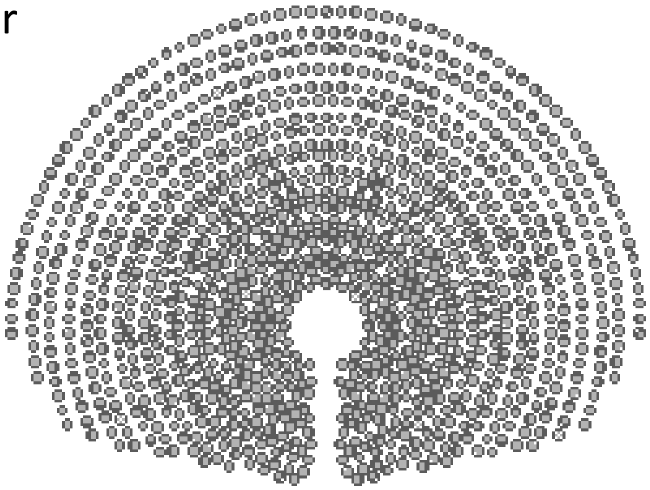
ATS-150



ASM-150

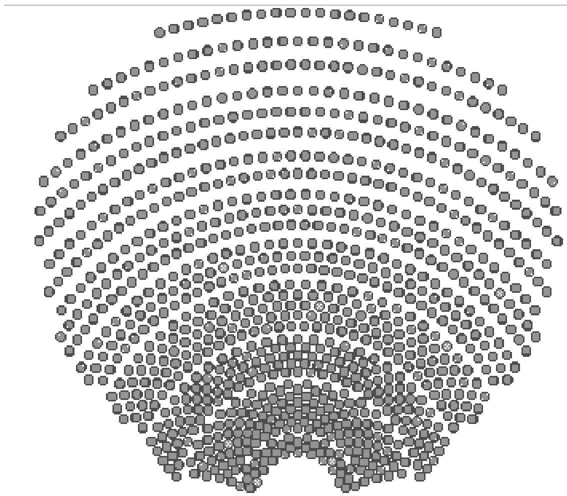
Heliostat Field

Circular



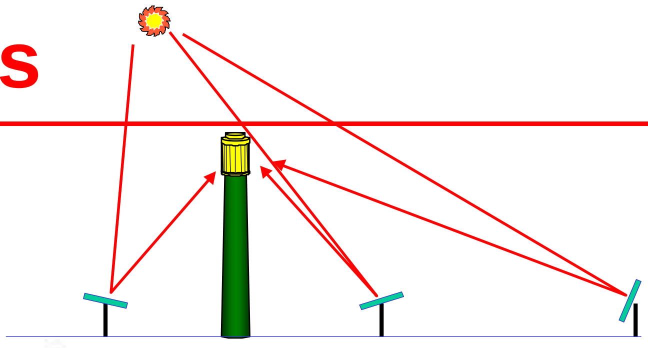
Land use factor: 0,20

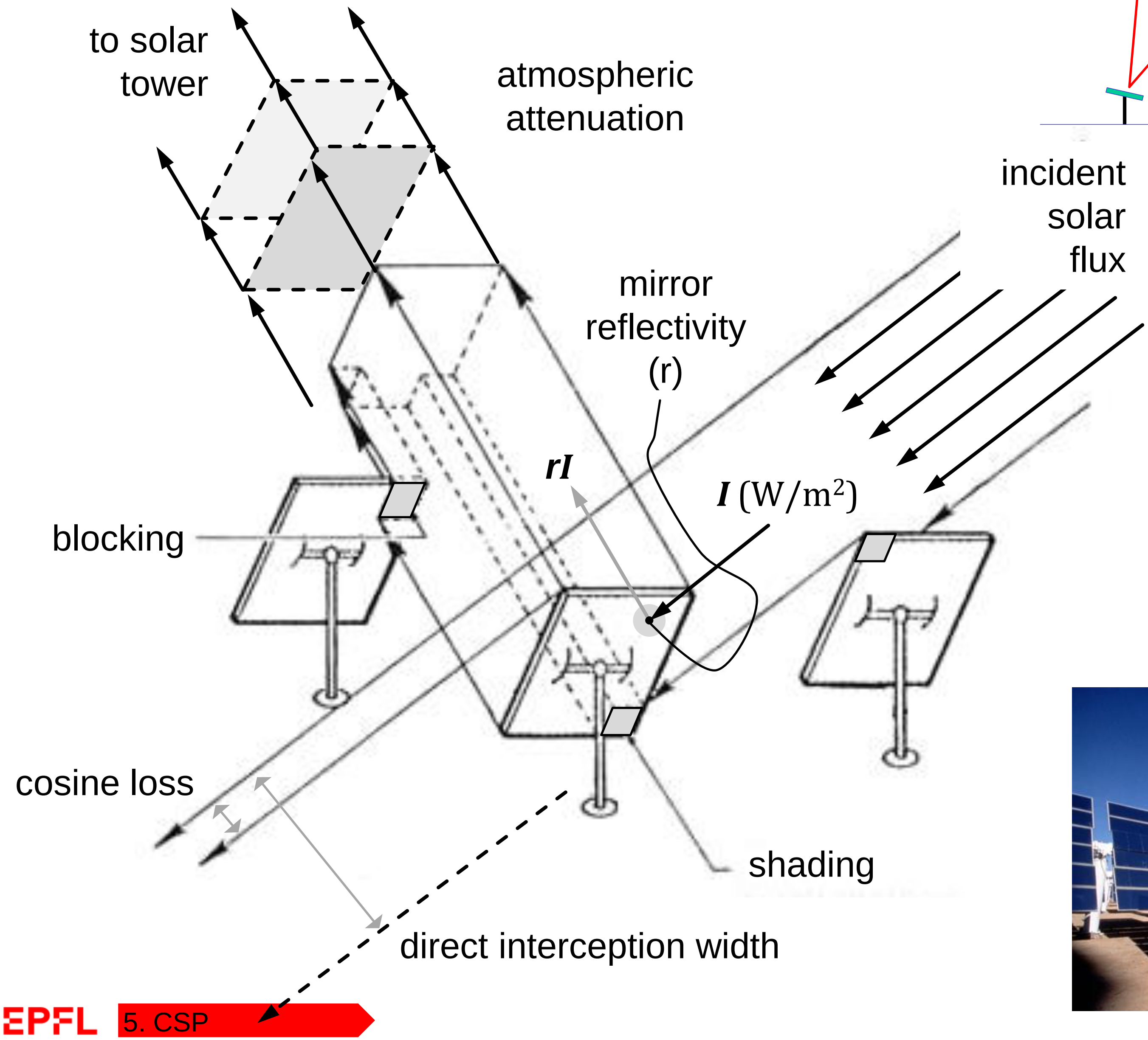
North

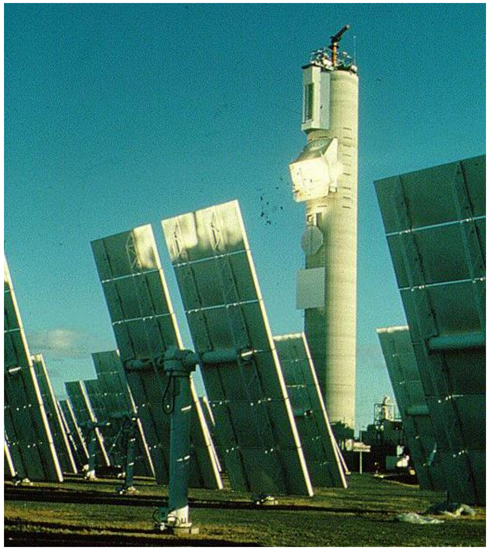


Land use factor: 0,25

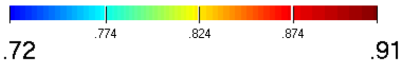
Heliostat Losses



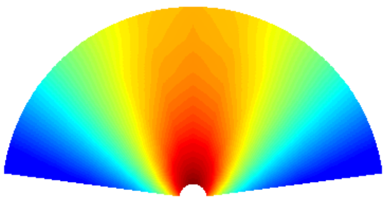


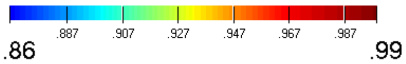


Optical Efficiency

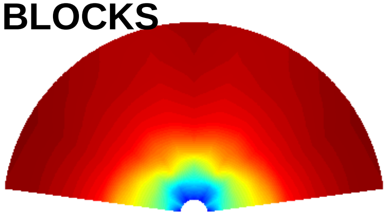


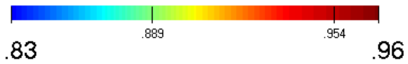
COSINE FACTOR



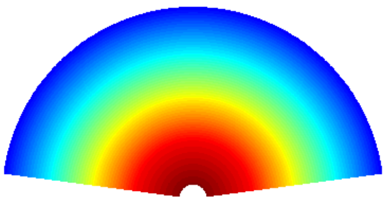


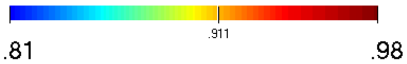
SHADOWS + BLOCKS



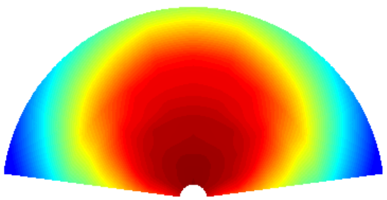


AIR TRANMITTANCE





SPILLAGE FACTOR



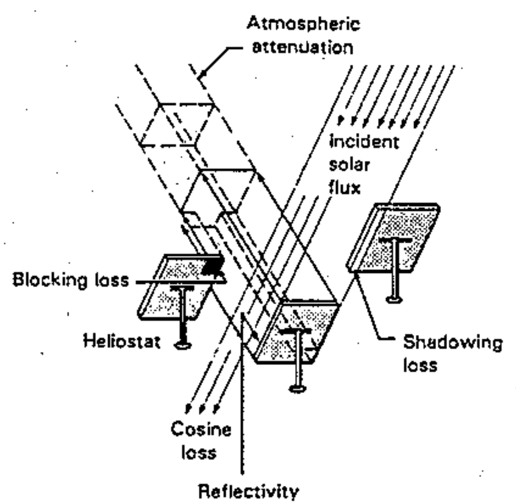
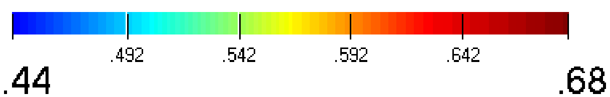
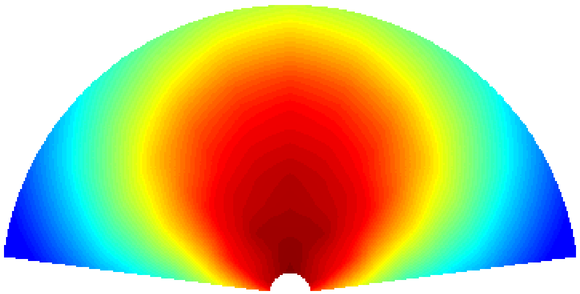


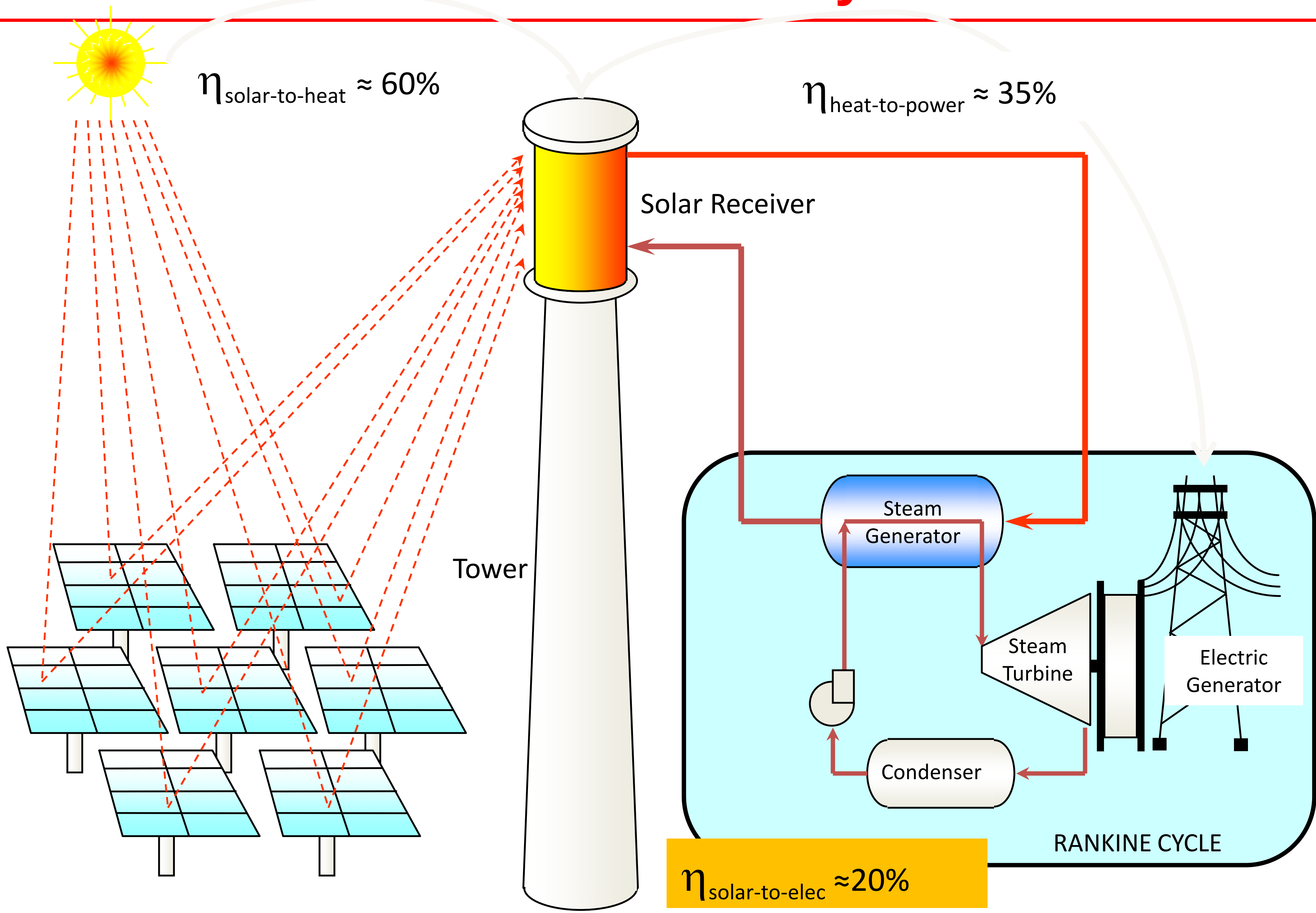
Figure -3 Collector Field Optical Loss Processes



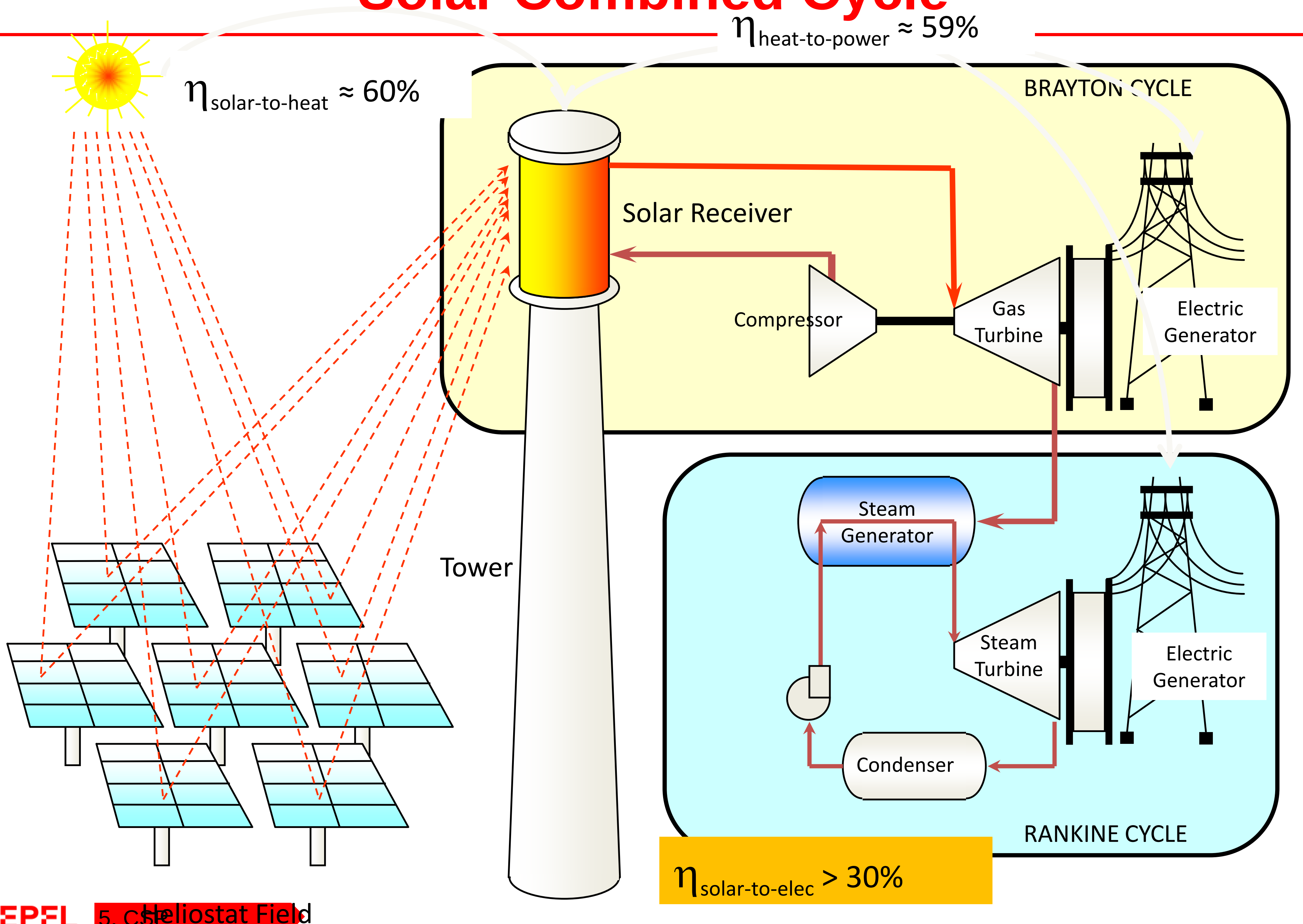
TOTAL OPTICAL FIELD EFFICIENCY



Solar Rankine Cycle



Solar Combined Cycle

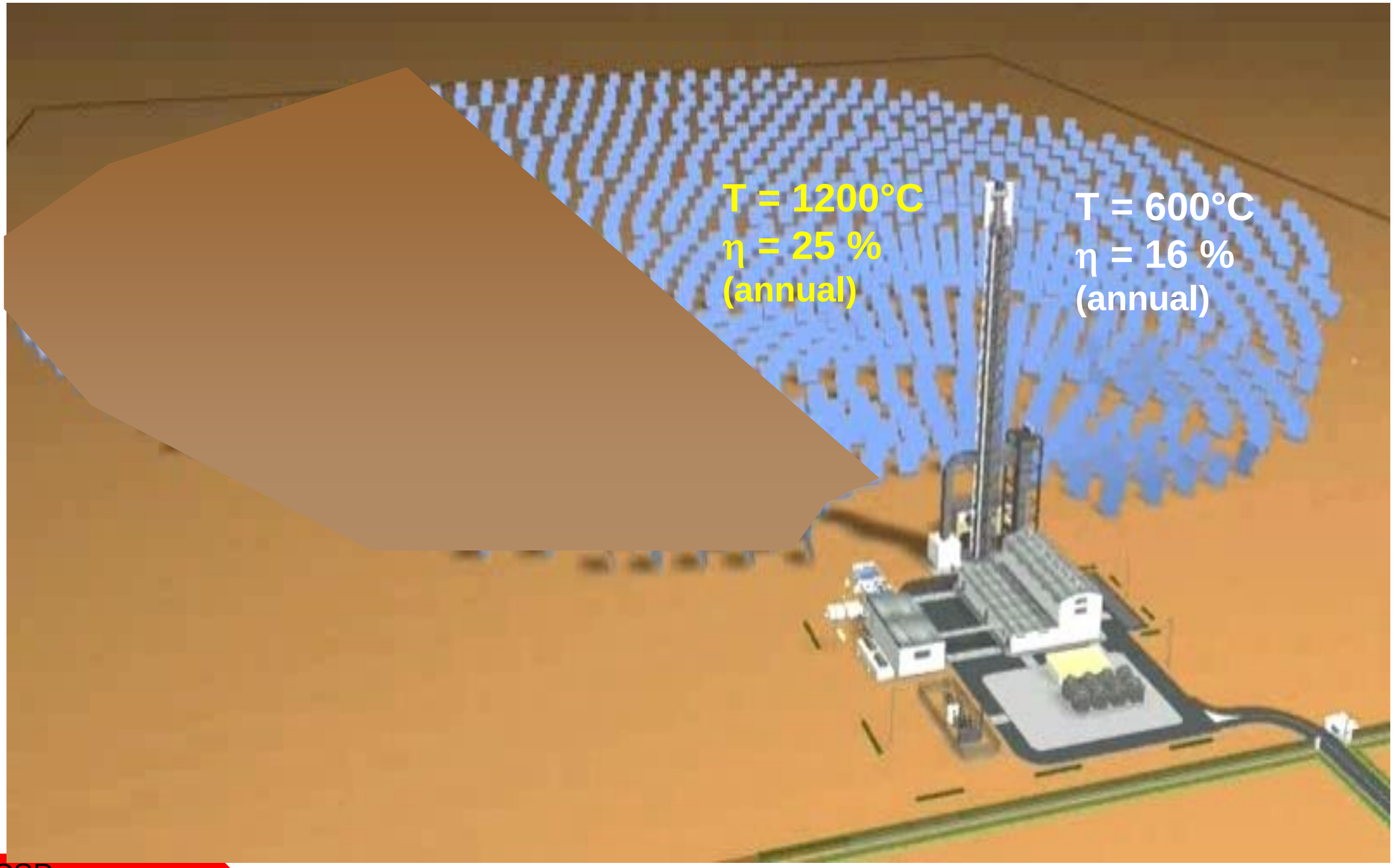


Solar Thermal Combined Cycle Power Generation

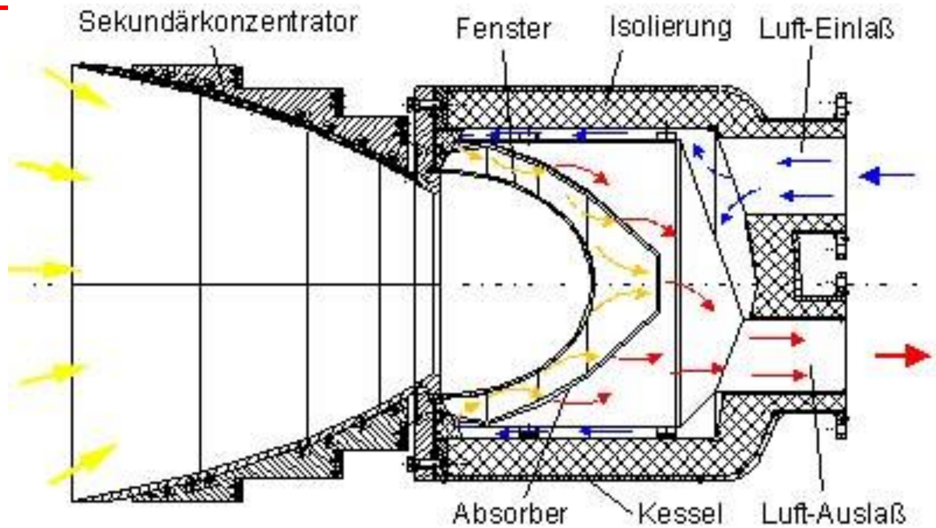
Improved Performance = Cost reduction

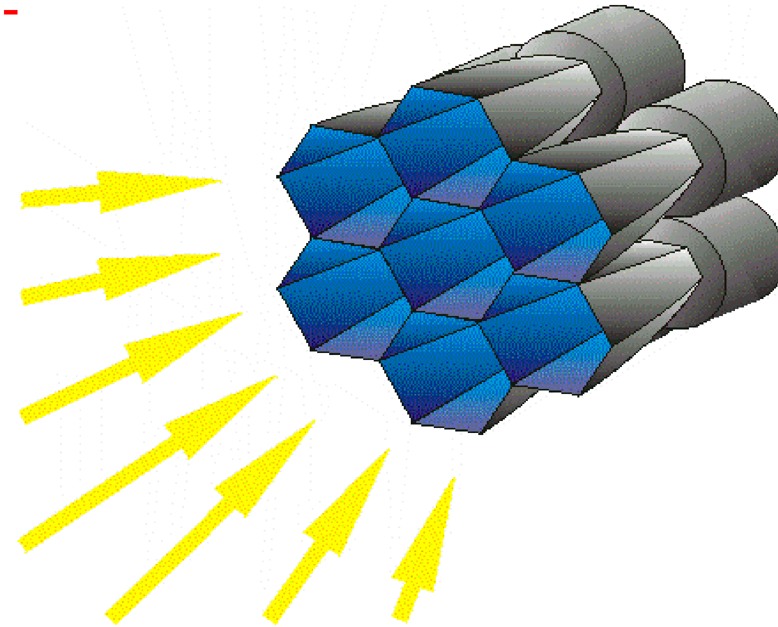
– High Temperature

– High Concentration

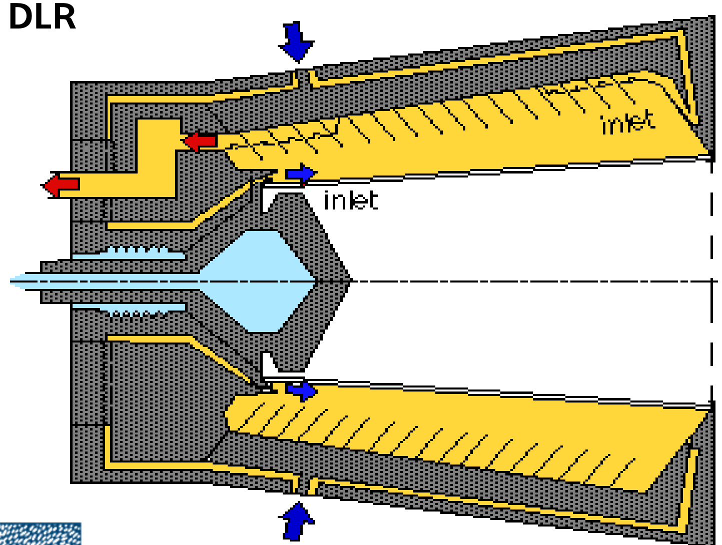


Solar Receiver Technology for CC Plants





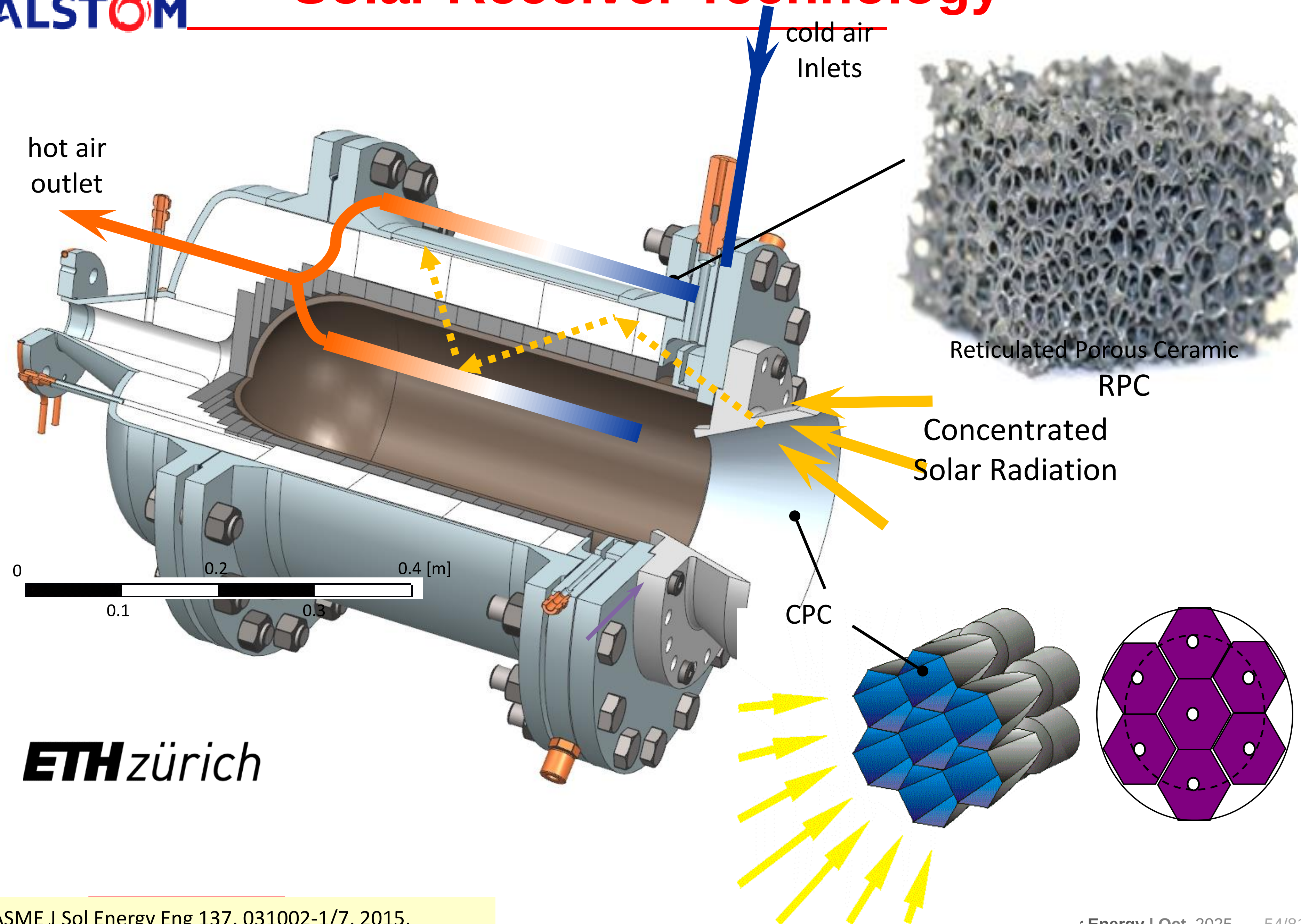
DLR



WIS

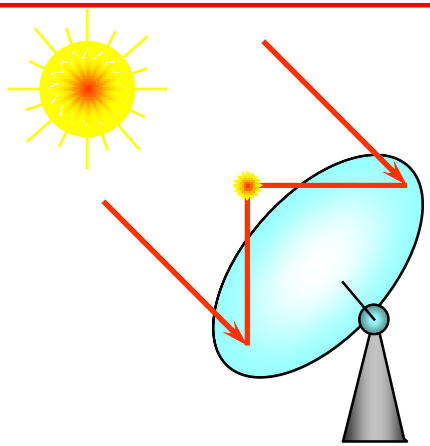
- 100 kW electricity
- 170 kW heat
- 1,600 sq. meter

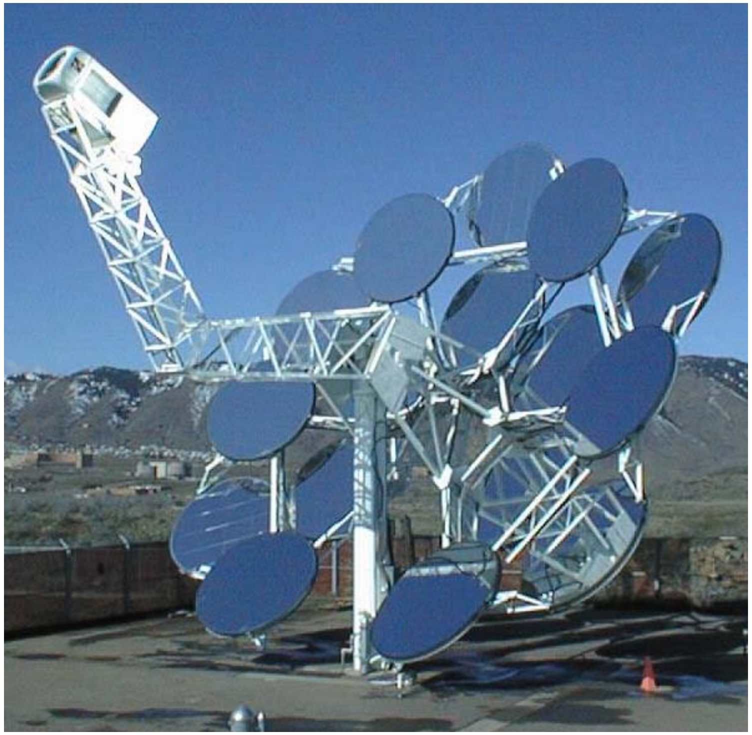
Solar Receiver Technology



ASME J Sol Energy Eng 137, 031002-1/7, 2015.

Solar Thermal Power Generation by Dish Technology



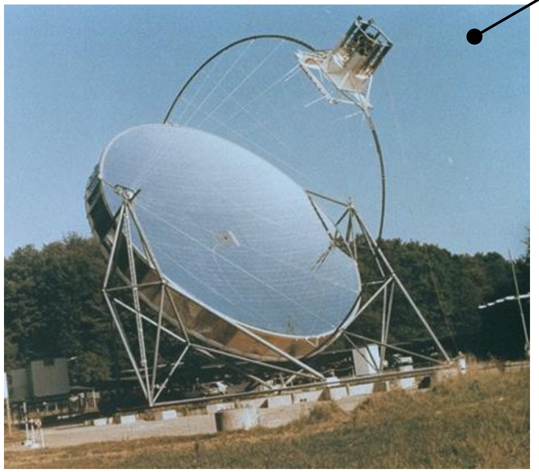


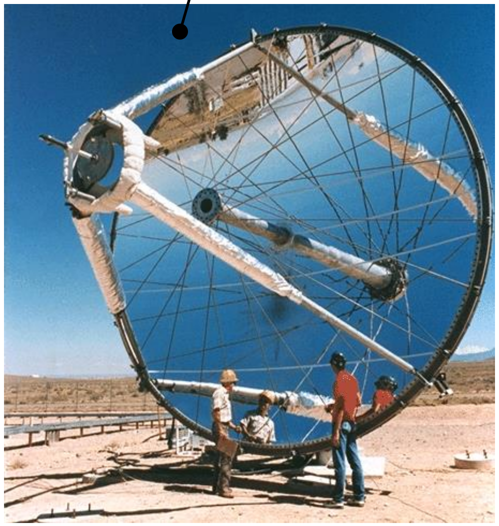
Solar dish Technology: Glass-Facet Concentrators

Name	JPL-TBC	Vanguard I	MDAC
Manufacturer	E-Systems	Advanco Corp.	McDonnell Douglas
Year	1979	1984	1984
Aperture Diameter/Area	11 m	10.6 m	10.6 m
Concentration Ratio (geometric)	1500-3000	2700	2793
Output at 1000 W/m² insolation	82 kW	73.1 kW	70-80 kW
Optical Efficiency	89%	89%	88%
Number Built	2	1	8
http://solstice.crest.org/renewables/dish-stirling/index.html			

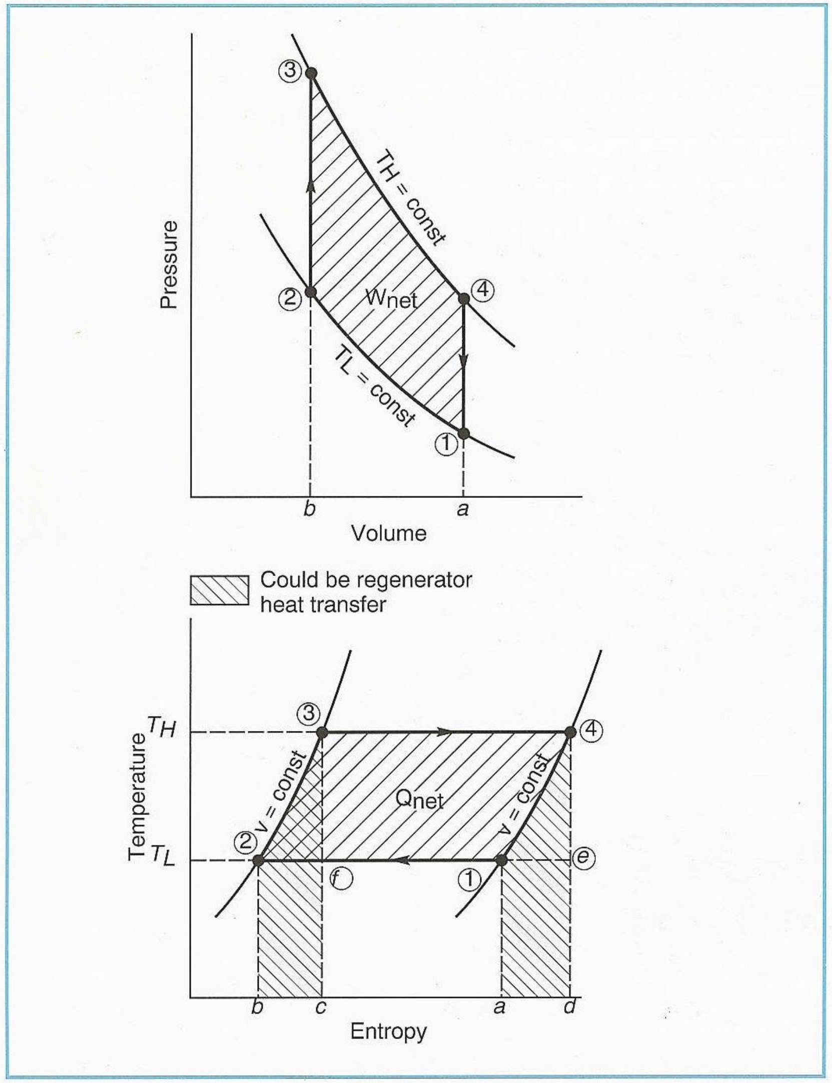
Solar Dish: Single-Facet Stretched-Membrane Concentrators

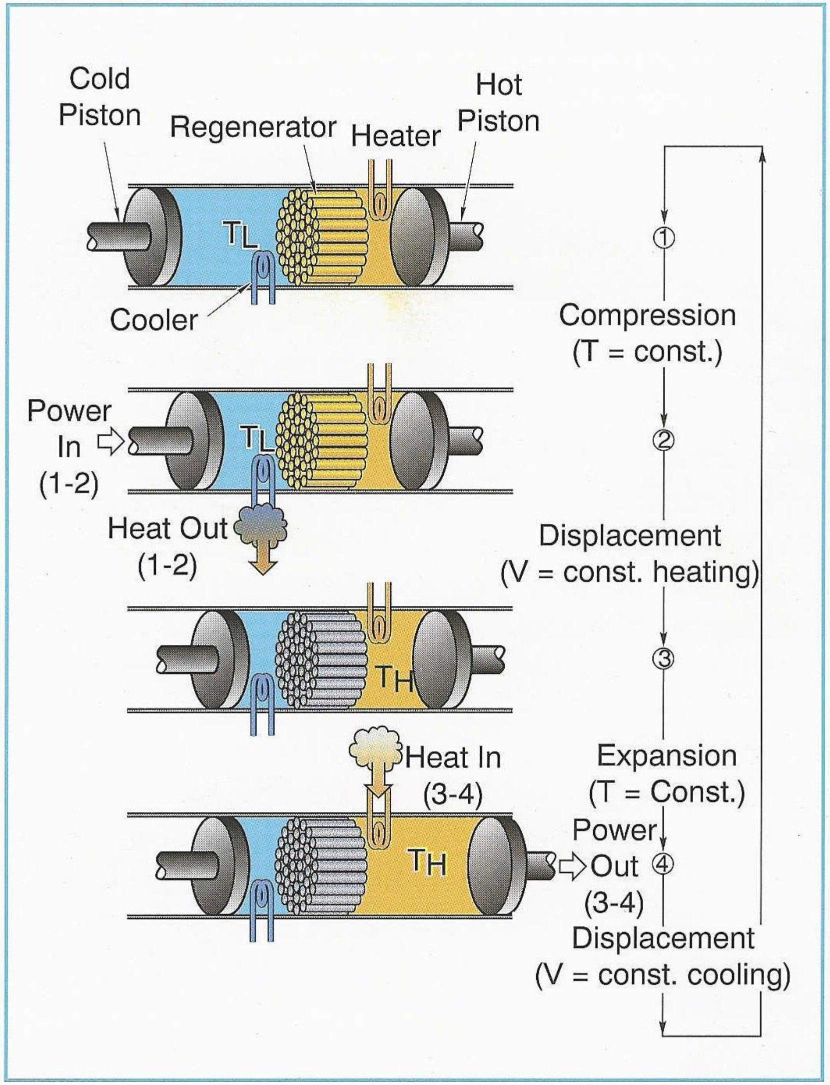
Manufacturer	Schlaich Bergermann und Partner	Schlaich Bergermann und Partner	Solar Kinetics Inc.
Year	1984	1989 / 1997	1990
Aperture Diameter/Area	17 m	7.5 m / 8.5 m	7 m
Concentration Ratio (geometric)	600	4000 / 4000	
Output at 1000 W/m² insolation	179 kW	36 kW / 45 kw	23.3 kW
Optical Efficiency	79%	82%	67%
Number Built	3	6 and 3	1
http://solstice.crest.org/renewables/dish-stirling/index.html			





Stirling Heat engine

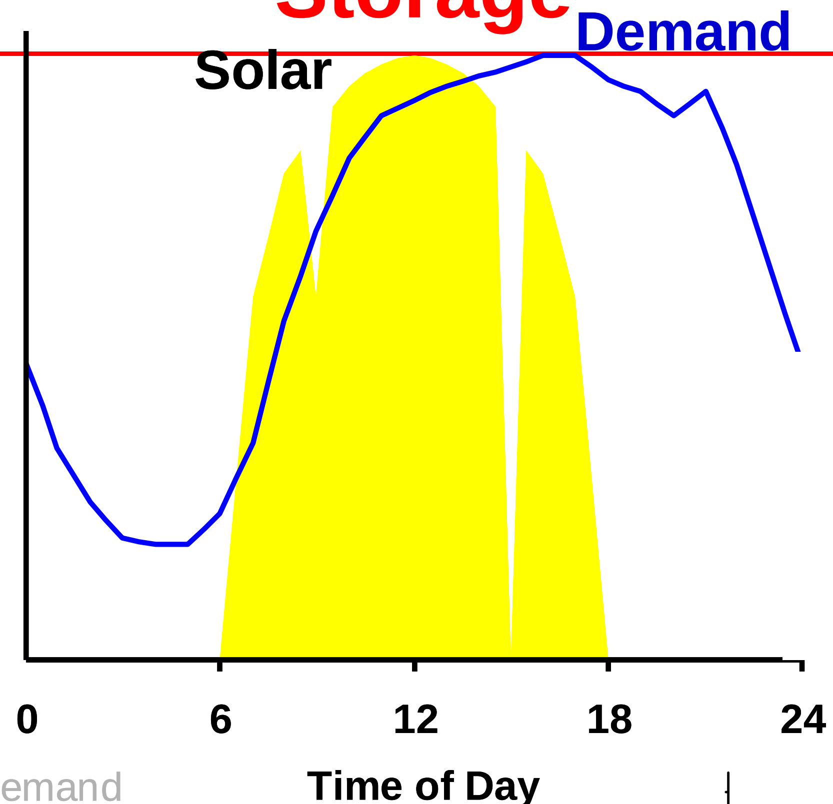




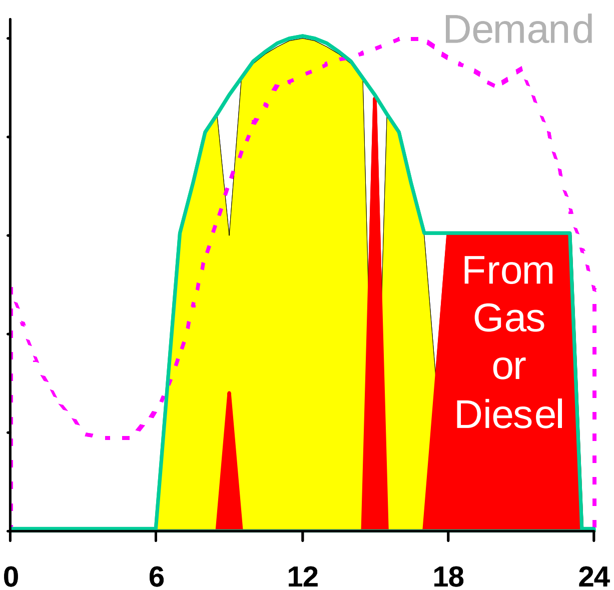
The Big Dish

Manufacturer	Anutec Ltd
Year	1995
Aperture Diameter/Area	23 m/400 m²
Output	350 kW_{th} / 55 kW_{el} (in test runs) expect to achieve between 60 and 80 kW_{el} at full operation
Number Built	2 MW_{el} power plant soon to be established at Tennant Creek (Northern Territory) using this dish technology
http://www.anutech.com.au/physci/opps/bigdish.html	

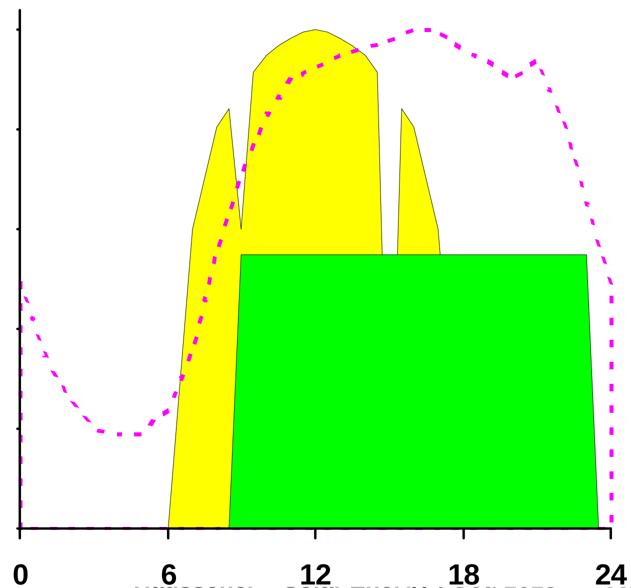
Storage



Hybridization

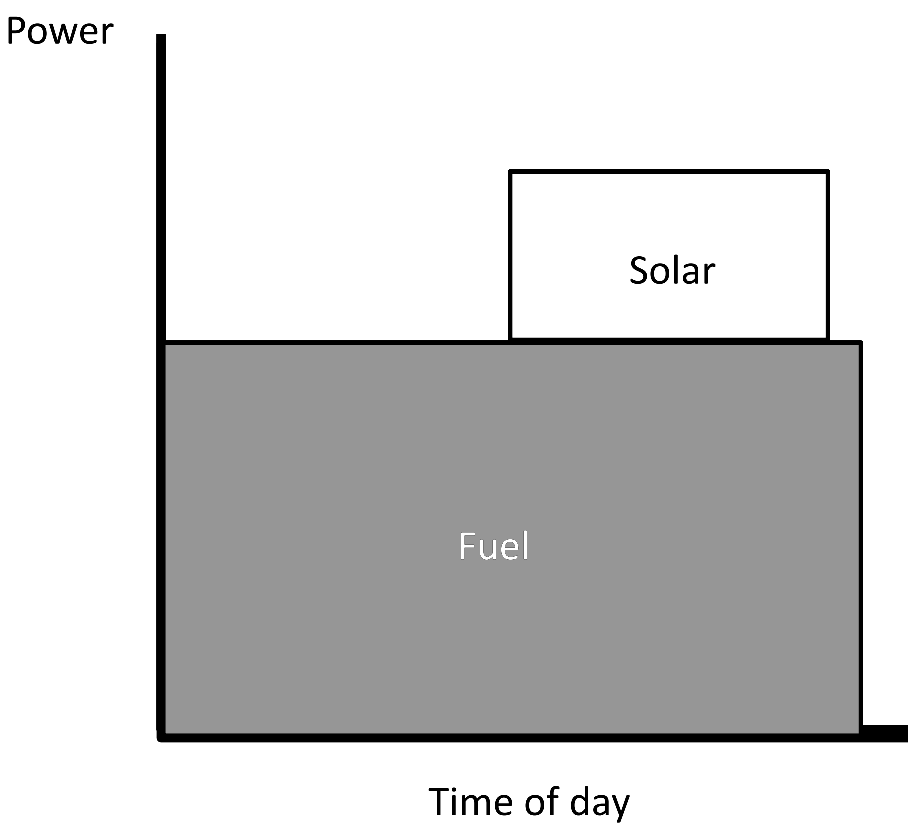


Storage

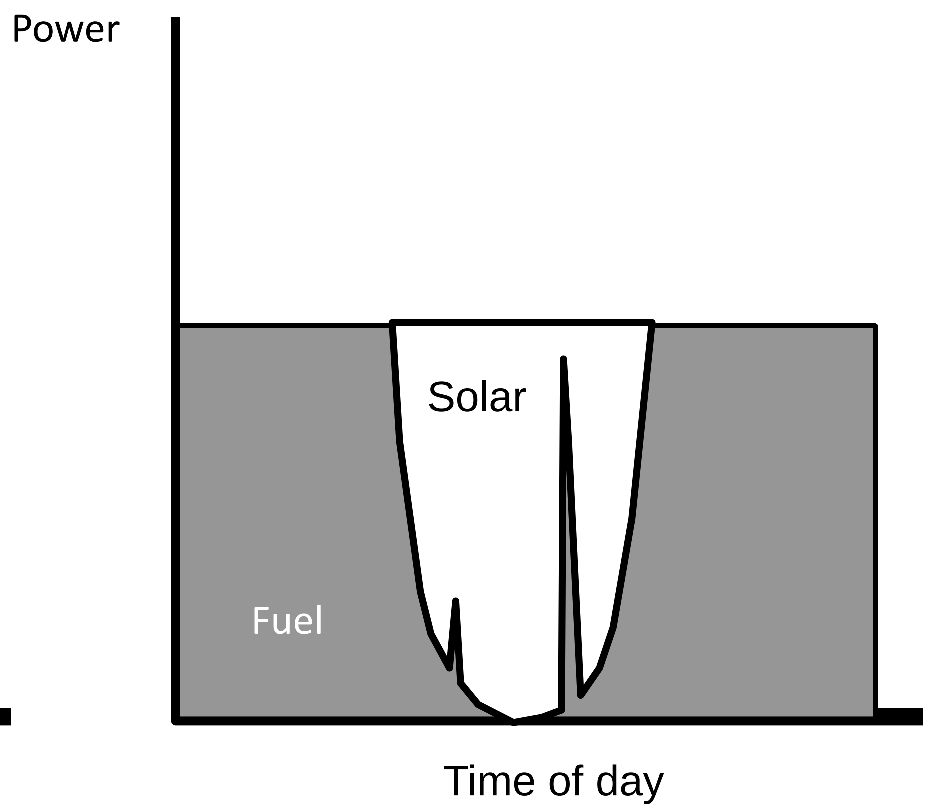


Storage

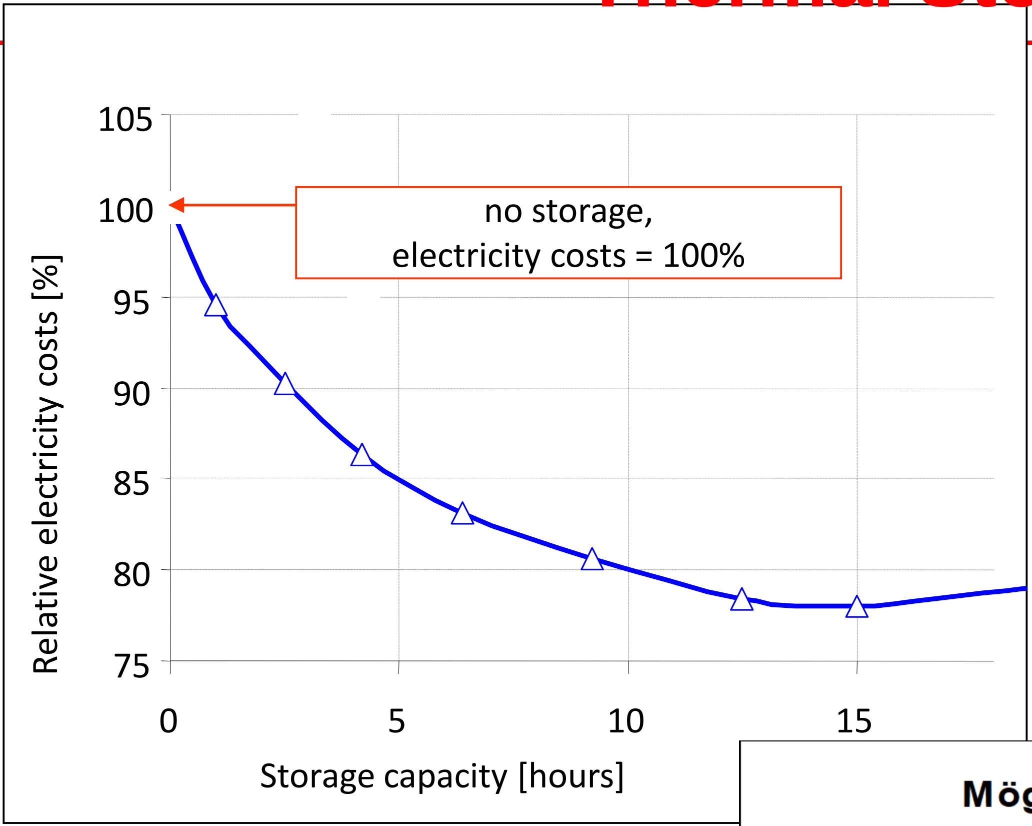
Power booster



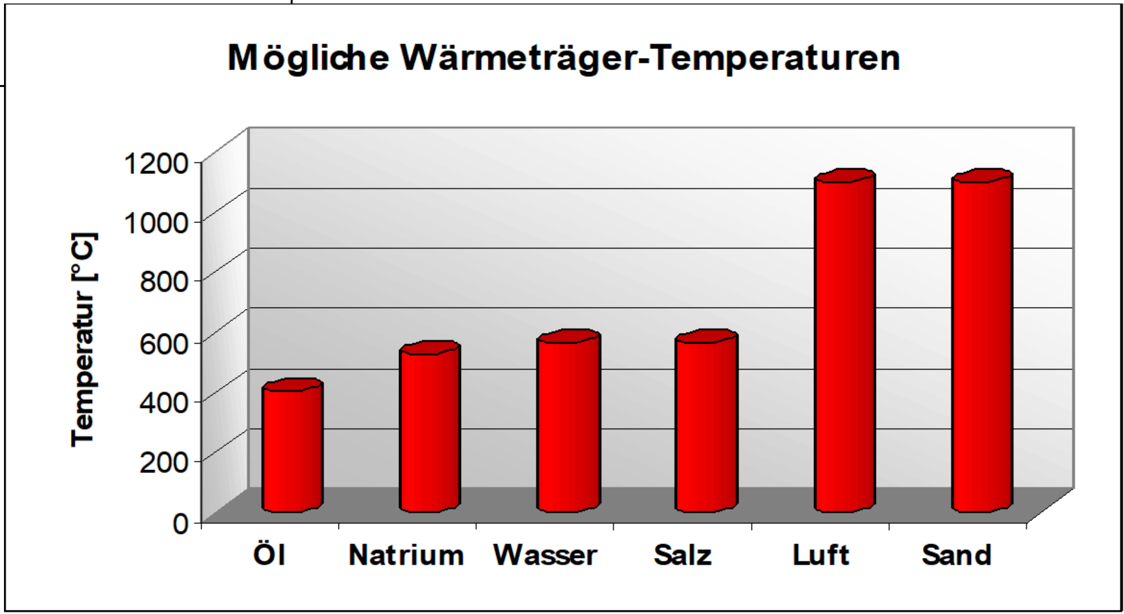
Fuel saver



Thermal Storage

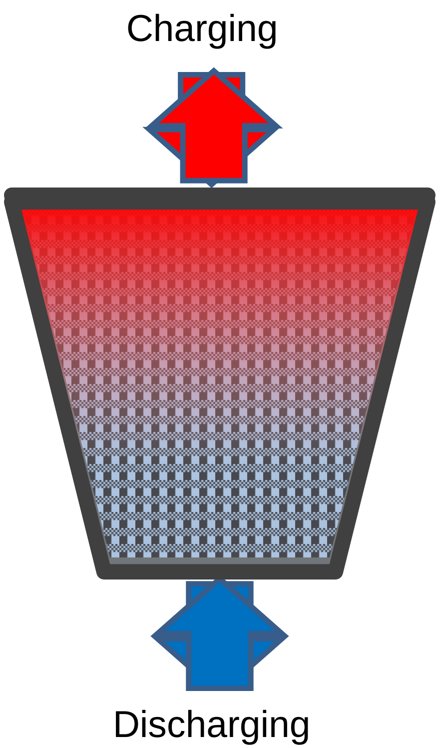


* assuming specific investment costs for the storage of 10 Euro/kWh



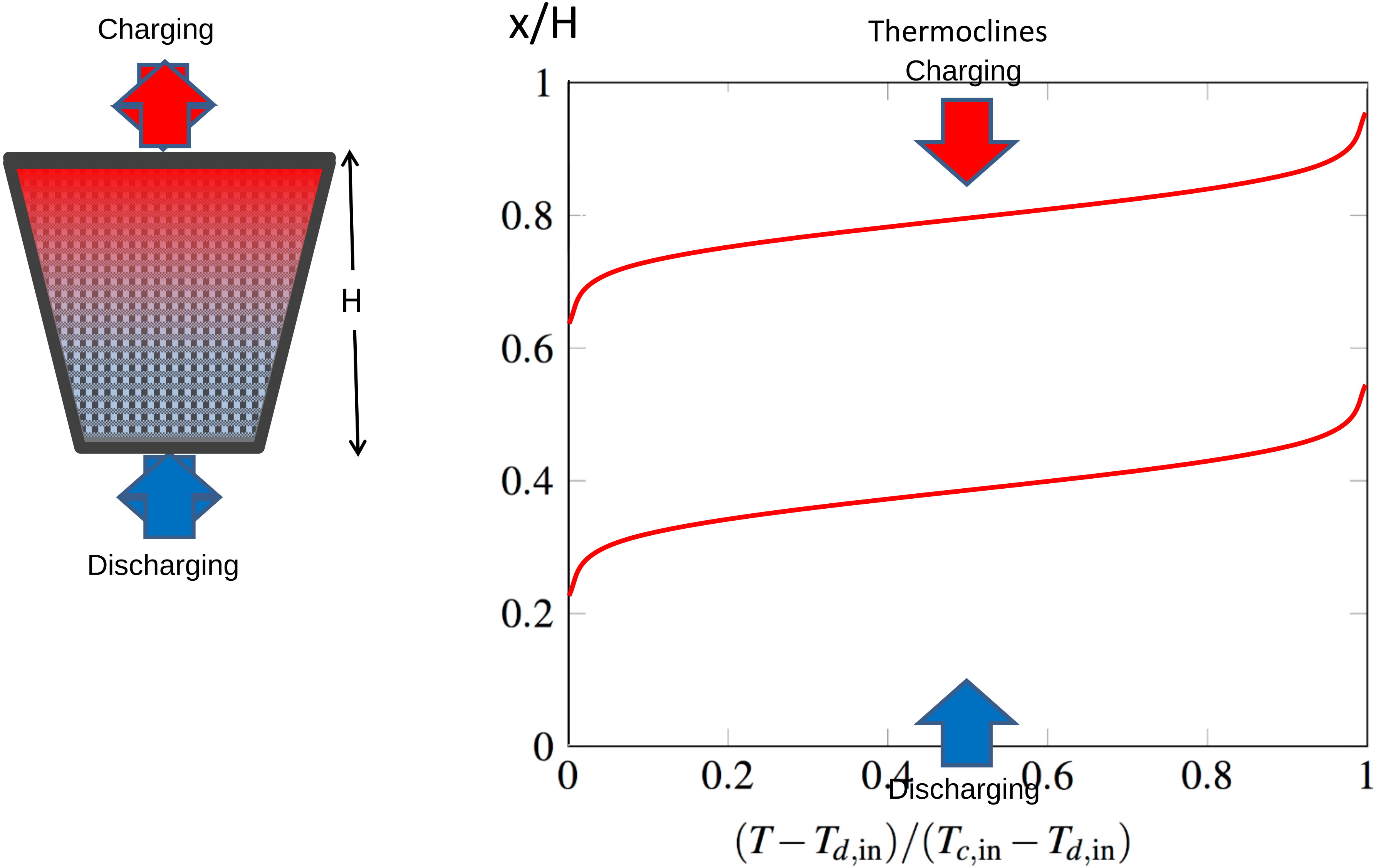
	Temperature		Average density	Average heat conduc-tivity	Average heat capacity	Volume specific heat capacity	Media costs per kg	Media costs per kWh_t
	Cold	**Hot**						
Storage Medium	°C	°C	kg/m^3	W/mK	kJ/kgK	$kWht/m^3$	\$/kg	$\$/kWh_t$
Solid media								
Sand-rock-oil	200	300	1,700	1	1.30	60	0.15	14
Reinforced concrete	200	400	2,200	1.5	0.85	100	0.05	1
NaCl (solid)	200	500	2,160	7	0.85	150	0.15	1.5
Cast iron	200	400	7,200	37	0.56	160	1.00	32
Cast steel	200	700	7,800	40	0.60	450	5.00	60
Silica fire bricks	200	700	1,820	1.5	1.00	150	1.00	7
Magnesia fire bricks	200	1,200	3,000	5	1.15	600	2.00	6
Liquid media								
Mineral oil	200	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil	250	350	900	0.11	2.3	57	3.00	43
Silicone oil	300	400	900	0.10	2.1	52	5.00	80
Nitrite salts	250	450	1,825	0.57	1.5	152	1.00	12
Nitrate salts	265	565	1,870	0.52	1.6	250	0.70	5.2
Carbonate salts	450	850	2,100	2	1.8	430	2.40	11
Liquid sodium	270	530	850	71	1.3	80	2.00	21
Phase change media								
$NaNO_3$	308		2.257	0.5	200	125	0.20	3.6
KNO_3	333		2.11	0.5	267	156	0.30	4.1
KOH	380		2.044	0.5	150	85	1.00	24
Salt-ceramics	500-850		2.6	5	420	300	2.00	17
(Na_2CO_3-$BaCO_3$/MgO)								
NaCl	802		2.16	5	520	280	0.15	1.2
Na_2CO_3	854		2.533	2	276	194	0.20	2.6
K_2CO_3	897		2.29	2	236	150	0.60	9.1

Packed Bed Rocks - Concept



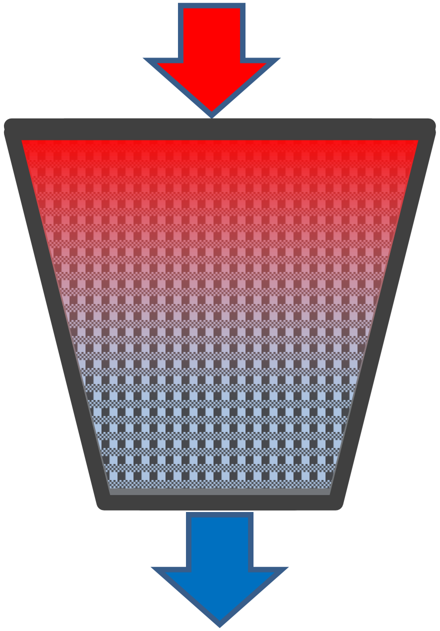
• Applied Energy 137, pp. 812–822, 2015.

Packed Bed Rocks - Concept



- Applied Energy 137, pp. 812–822, 2015.

Packed Bed Rocks - Concept



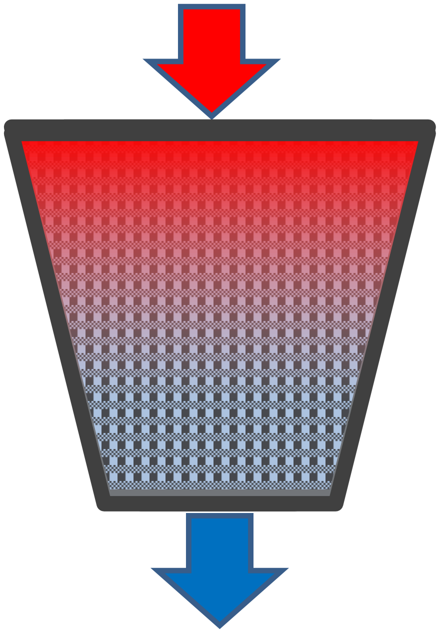
- Air as HTF
- Applicability in a wide range of temperatures
- No degradation or chemical instability
- No safety concerns
- Mechanical stability due to conical shape
- Direct heat transfer between storage material and HTF
- High efficiency charging-discharging
- Low-cost (~15 SFr/kWh)

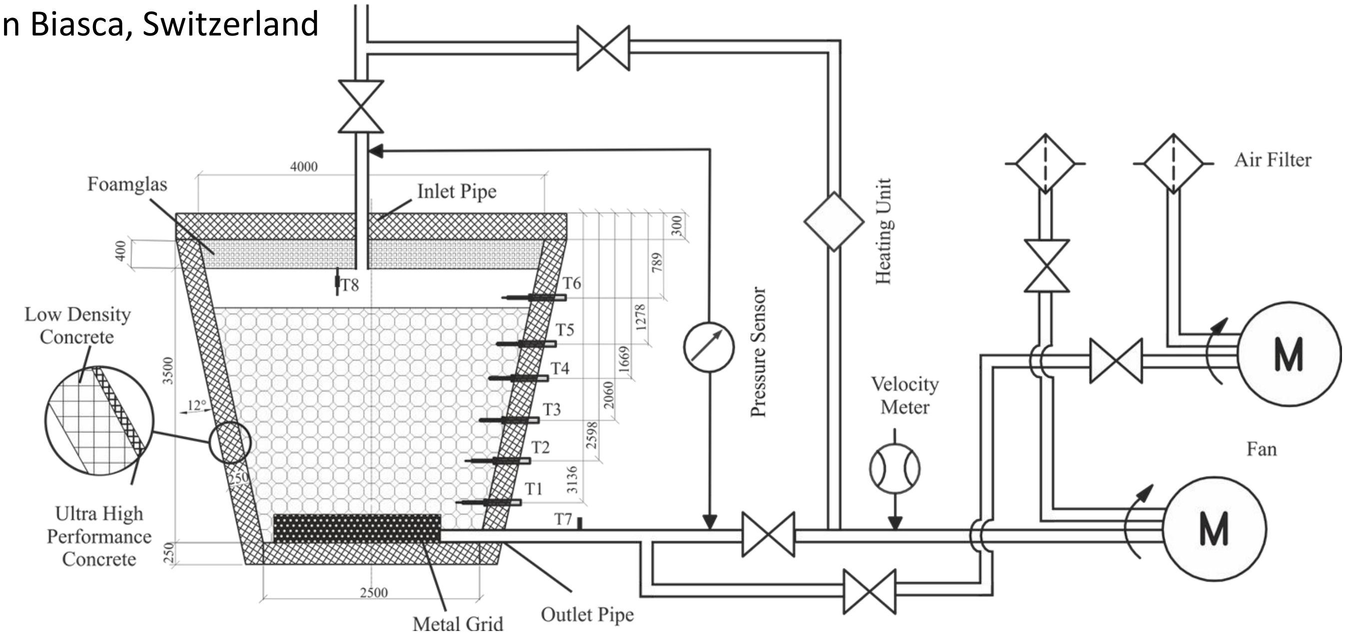
- Applied Energy 137, pp. 812–822, 2015.

Packed Bed Rocks - Concept

airlight energy

6.5 MWh_{th} Thermal Storage Pilot in Biasca, Switzerland

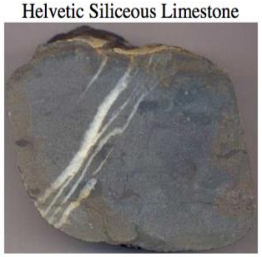


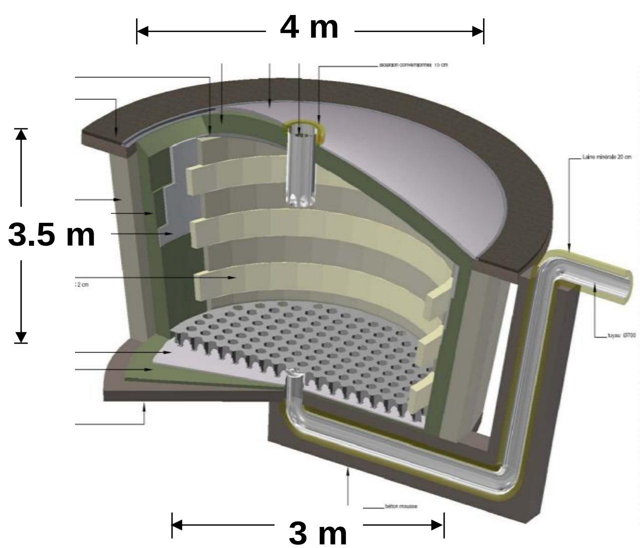


$T_{out} = 640°C$

$\eta = 95\%$

Helvetic Siliceous Limestone



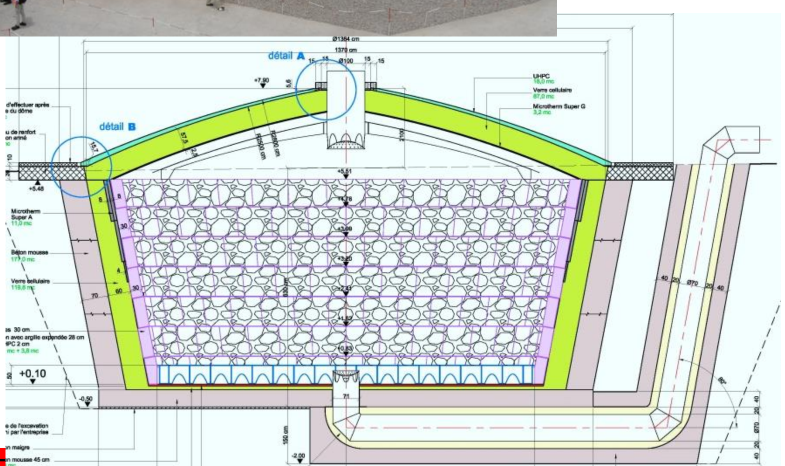


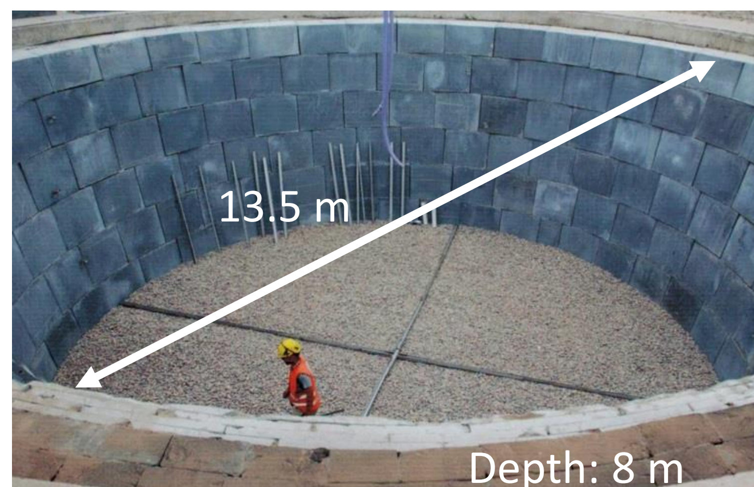
Packed Bed Rocks - Concept

airlight energy

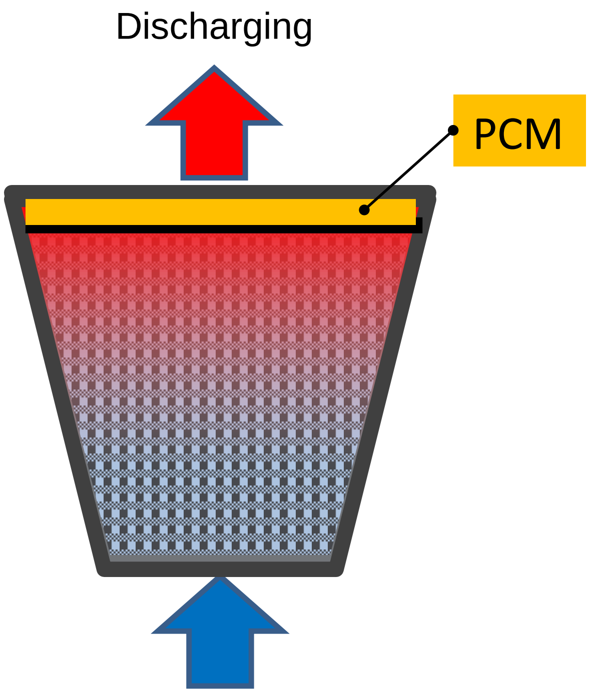
7 GWh$_{th}$ Thermal Storage in Ait Baha, Morocco

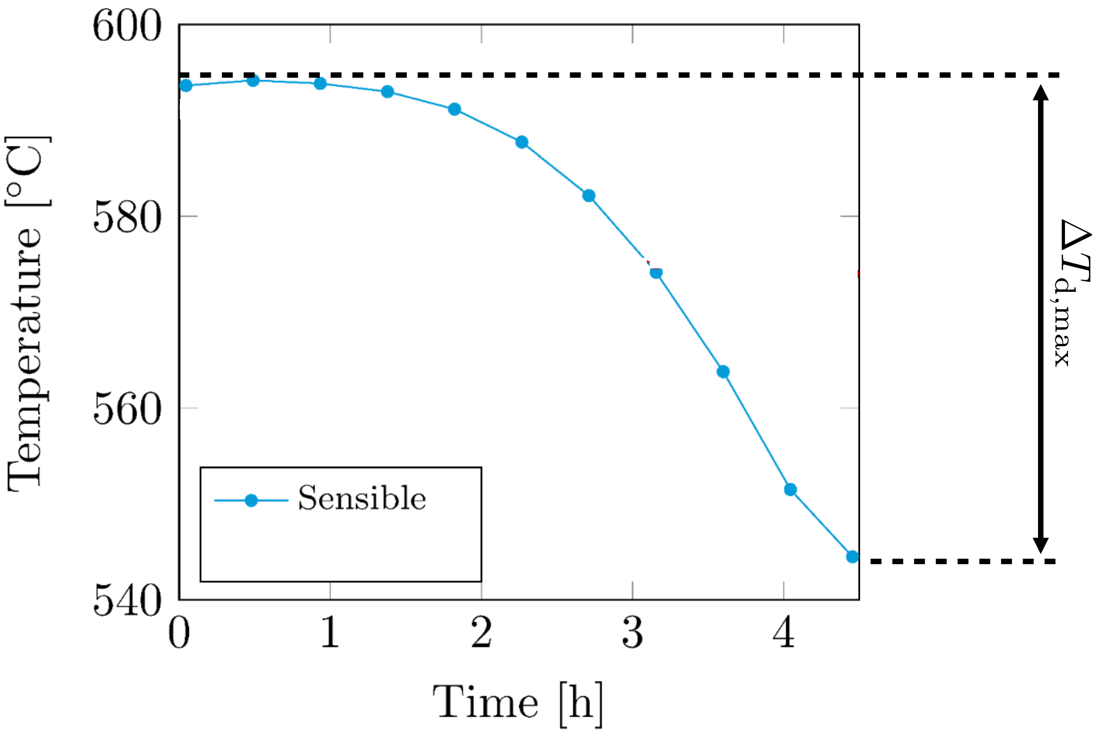
- 4 MW solar thermal power





Combined Sensible/Latent Heat Storage

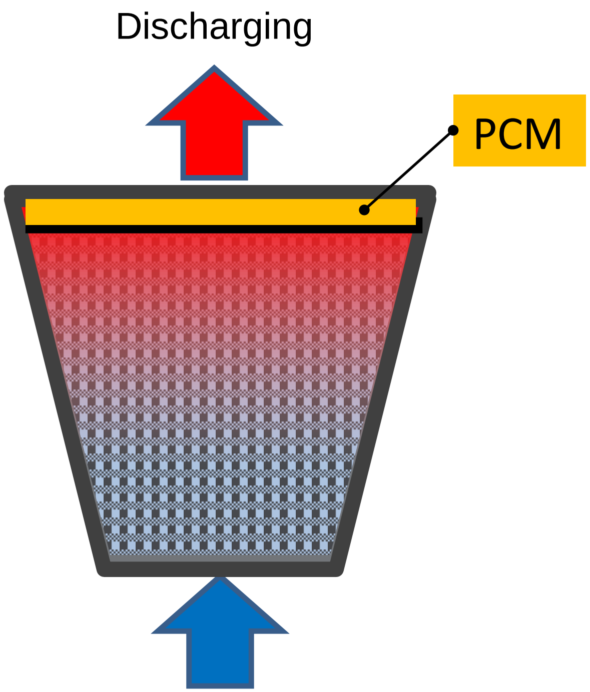


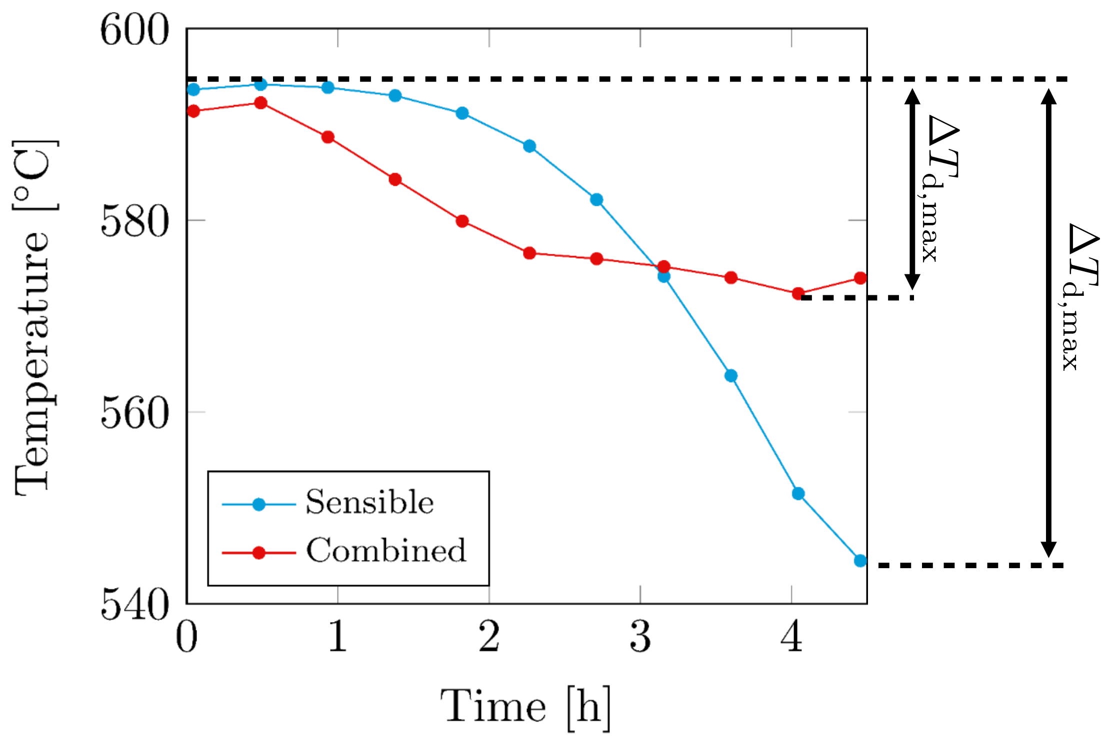


- $AlSi_{12}$ (m.p. 572 C)
- Heat of fusion = 466 kJ/kg
- Encapsulation: steel (316 mm i.d., 1 mm thick)
- m_{PCM} = 9.6 kg
- m_{rocks} = 245 kg

- Applied Thermal Engineering 70, pp. 316-320, 2014.
- Applied Thermal Engineering 101, pp. 657–668, 2016.

Combined Sensible/Latent Heat Storage





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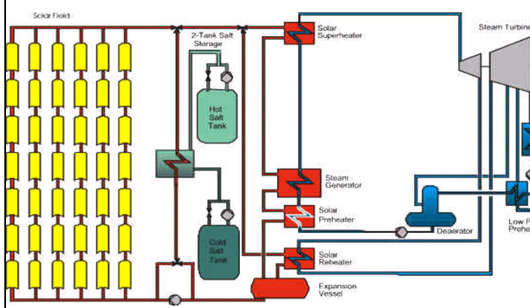
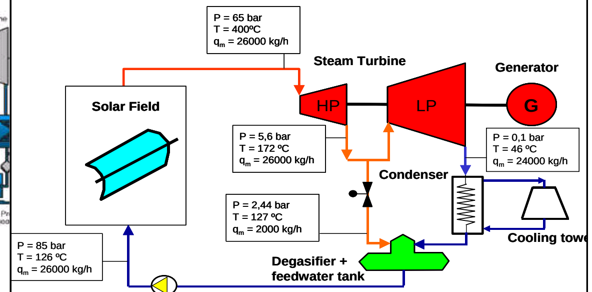
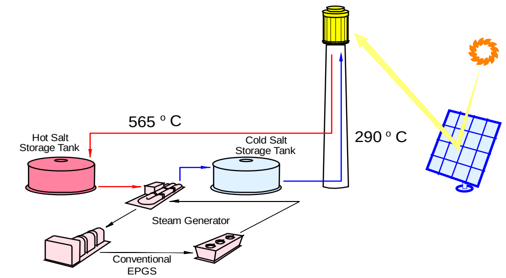
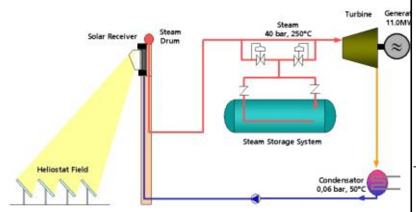
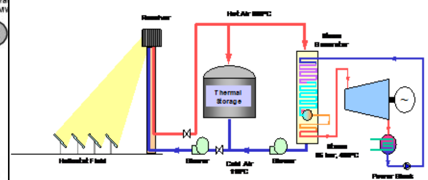
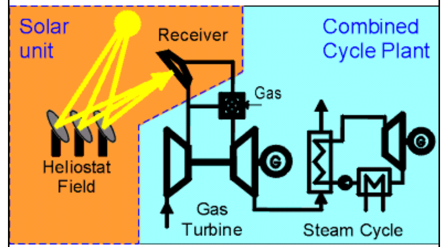
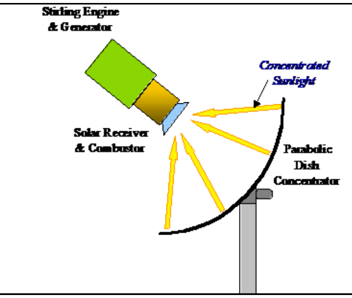
Characteristics of CSP Systems

Ref.: “Concentrating Solar Power in 2001”, Tyner at al., SolarPACES

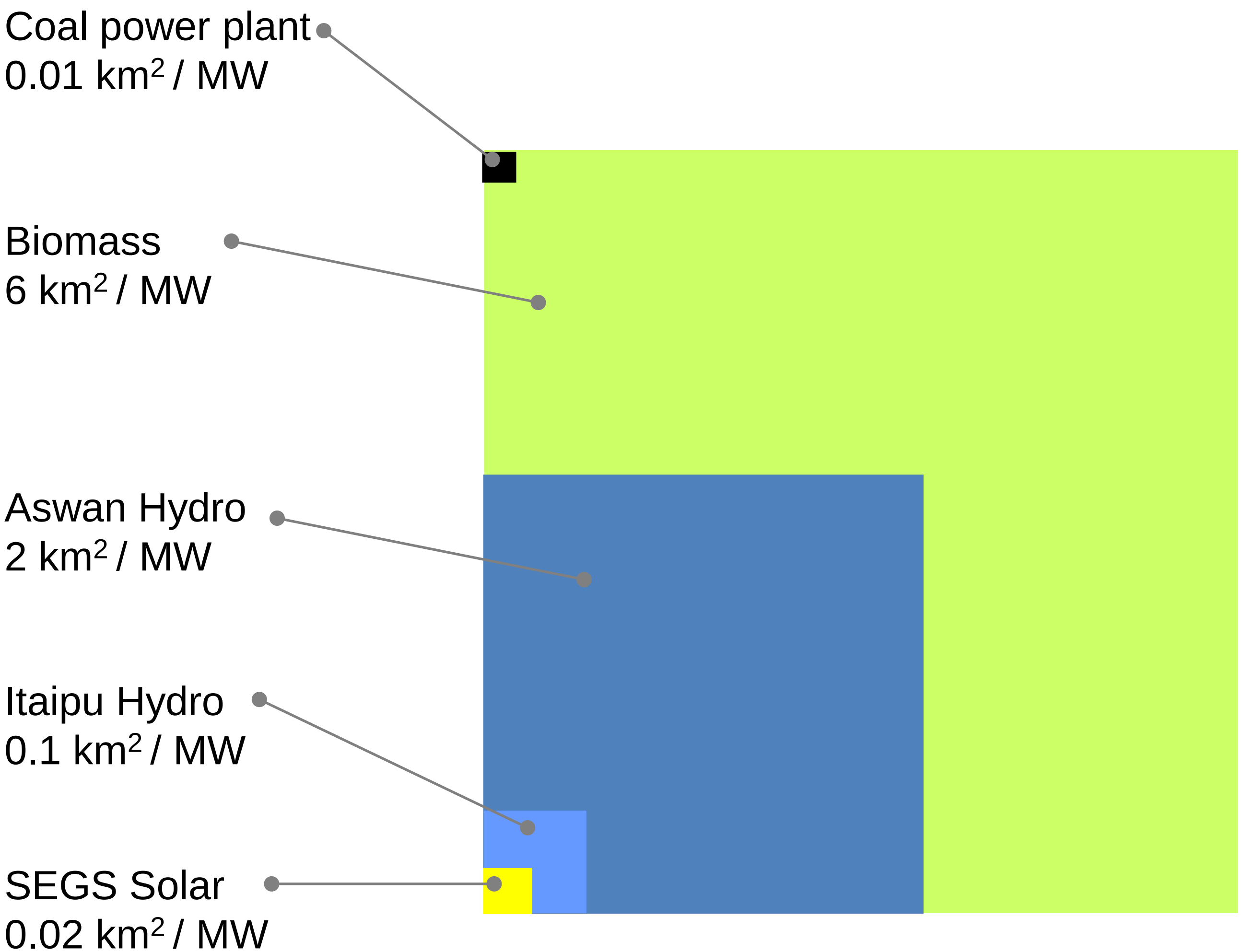
Concentrating Solar Power System		Peak Efficiency	Annual Efficiency	Annual Capacity Factor
Trough		21 %	10 - 12 %	25 - 100 %
Tower		23 %	14 - 20 %	25 - 100 %
Dish		29 %	18 - 23 %	25 %

- A.C.F = fraction of year the technology can deliver solar energy at rated power

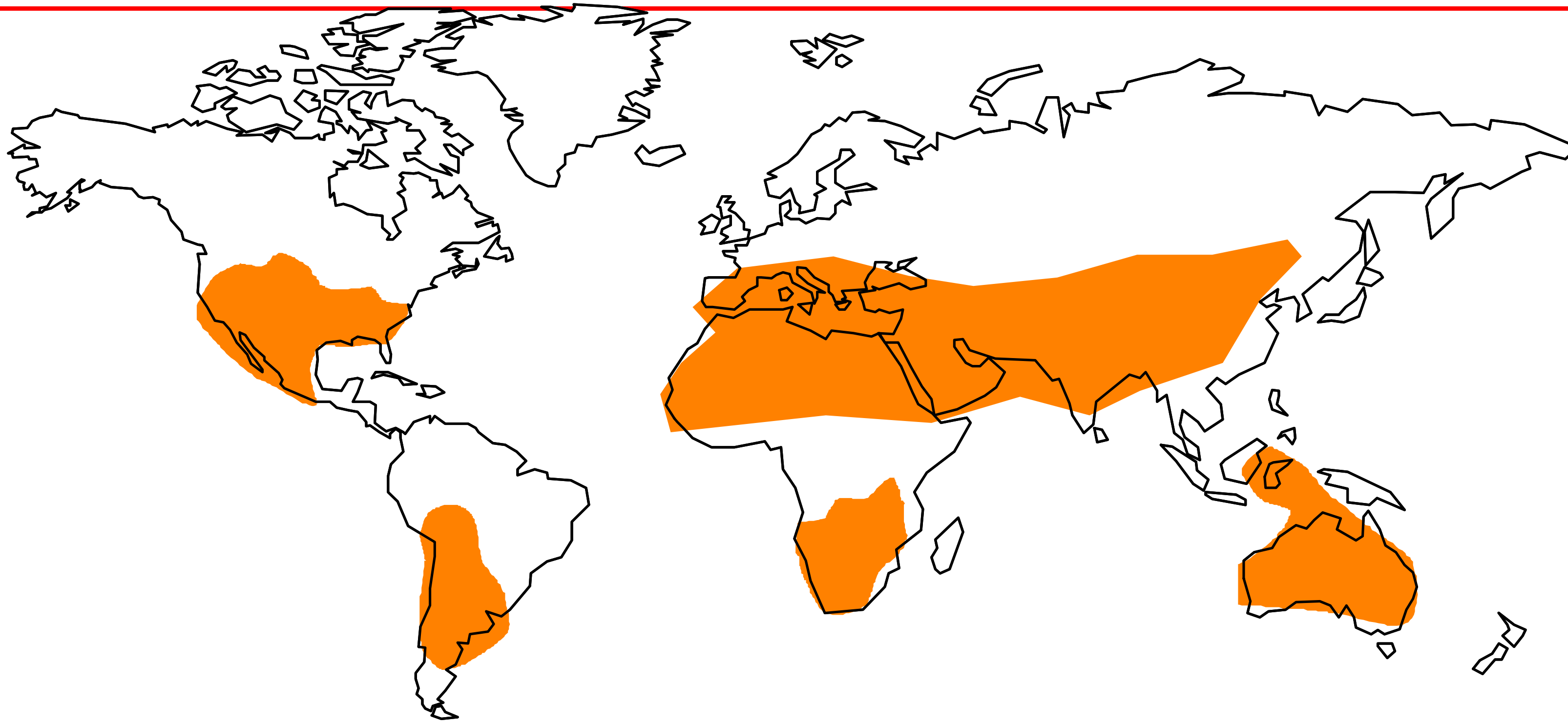
Technology	Parabolic trough / HTF	Parabolic trough DSG	Molten salt Central receiver system
			
Technical design parameter:			
Collector	Parabolic trough	Parabolic trough	Heliostat field
Receiver	Linear receiver (tubes)	Linear receiver (tubes)	Molten salt receiver
Storage system	2-tank-molten-salt storage	No storage system available up to date	2-tank-molten-salt storage
Cycle	Rankine steam cycle	Rankine steam cycle	Rankine cycle
Planed / built power size			
	50 MW Andasol I & II, under preparation, Spain	4.7 MW INDITEP study	Solar Tres (17MW), planed, Spain
Maturity	Several commercial units up to 80 MW_e are in operation in southern USA	Single row experimental plant in Spain	Solar 2 (11 MW) experimental plant in California in the 1990ies
Temperature	393°C	411°C	565°C
Size ref sys	50 MW_e	10 × 4.7 MW_e	3 × 17 MW_e
Capacity factor	29 %	22 %	33 %
LEC for a single ECOSTAR reference system, solar-only			
	0.172 €/kWh_e	0.187 €/kWh_e	0.183 €/kWh_e
LEC for power plant park consisting of several reference systems with total capacity of 50 MW, solar-only			
	0.172 €/kWh_e	0.162 €/kWh_e	0.155 €/kWh_e

Technology	Saturated steam central receiver system	Atmospheric air central receiver system	Pressurized air central receiver system	Dish engine System
				
Technical design parameter:				
Collector	Heliostat field	Heliostat field	Heliostat field	Parabolic dish
Receiver	Saturated steam receiver	Volumetric atmospheric air-cooled receiver	Pressurized air receiver	Cavity receiver with tube bundle
Storage system	Water/steam buffer storage	Ceramic thermocline thermal storage	No storage system available up to date	No storage system available up to date
Cycle	Rankine cycle	Rankine cycle	Combined cycle	Stirling engine
Planed / built power size				
	PS 10 (11MW), under construction, Spain	PS 10 conceptual design study	Solgate study 14.6 MW_e	22 kW_e
Maturity	Several experimental plants up to 2 MW_{th} have been tested	2.5 MW_{th} experimental plant tested in Spain in 1993	2 × 200 kW_e under construction in Italy	About 30 units up to 25 kW_e are in operation at different sites
Temperature	250°C	750°C	800°C	800°C
Size of the reference system	5 × 11 MW_e	5 × 10 MW_e	4 × 14.6 MW_e	2907 × 25 kW_e
Solar capacity factor	26%	33 %	11 % (55%)[1]	22%
LEC for a single ECOSTAR reference system, solar-only				
	0.241 €/kWh_e	0.234 €/kWh_e	0.147 €/kWh_e (0.1 €/kWh_e)	0.281 €/kWh_e
LEC for a power plant park consisting of several reference systems with total capacity of 50 MW, solar-only				
	0.169 €/kWh_e	0.179 €/kWh_e	0.139 €/kWh_e (0.082 €/kWh_e)	0.193 €/kWh_e

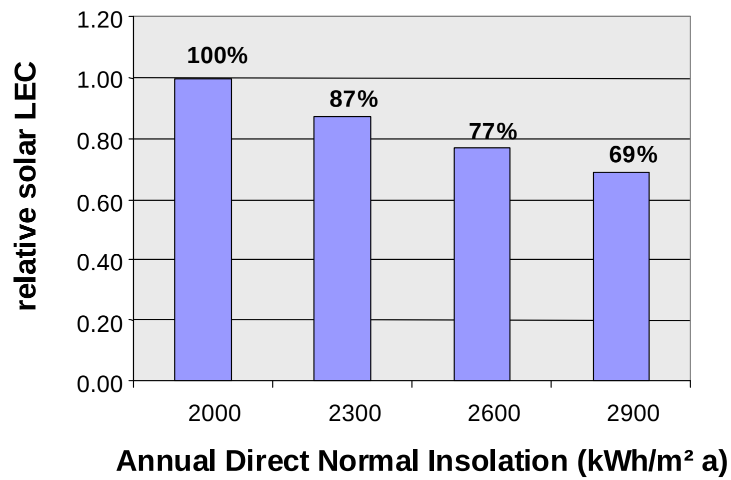
Land Use


Coal power plant
0.01 km2 / MW
Biomass
6 km2 / MW
Aswan Hydro
2 km2 / MW
Itaipu Hydro
0.1 km2 / MW
SEGS Solar
0.02 km2 / MW

Zones for Development of CSP



1. Global solar radiation on earth	(TWh/year)	240 * 10 [6]
2. Dessertic areas (7% of earth surface)	(TWh/year)	16 * 10 [6]
3. Solar fraction of DNI available (70%)	(TWh/year)	11,2 * 10 [6]
4. Efficiency of CSP plants (15%)	(TWh/year)	1,68 * 10 [6]
5. Percentage a rea with good infrastructures (1% of dessert areas)	(TWh/year)	16,8 * 10 [3]
6. World electricity demand year 2000	(TWh/year)	15 * 10 [3]



1% of arid/semi-arid areas are enough to supply annual world demand of electricity

Applications

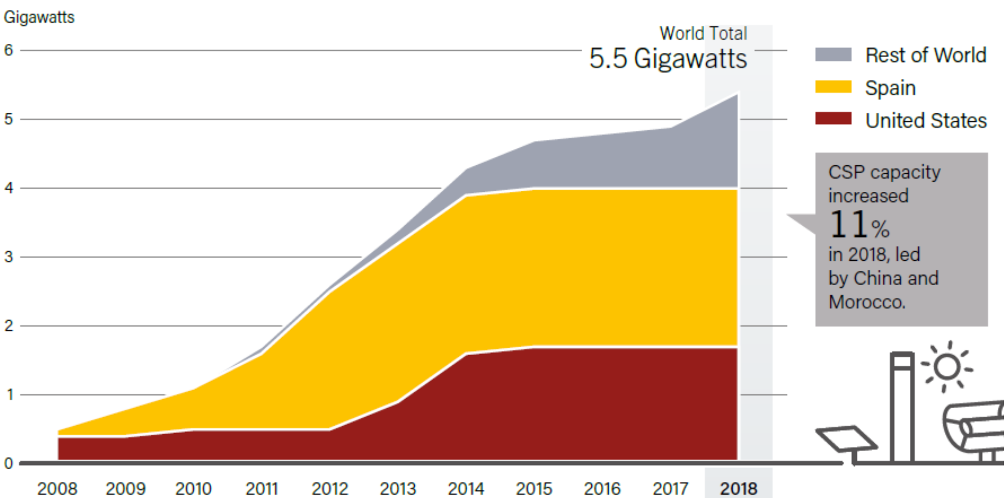
Table 2: Comparison of Solar Thermal Power Technologies

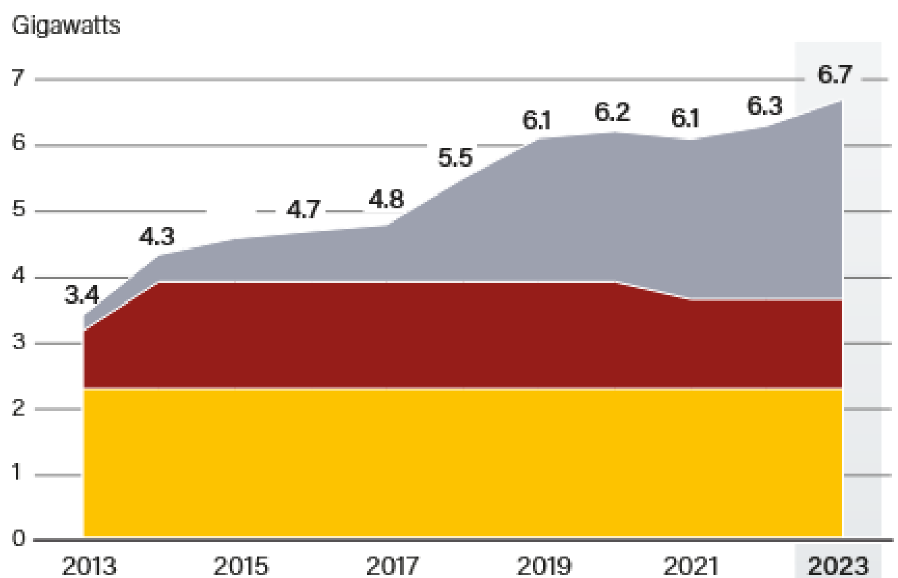
	Parabolic Trough	Central Receiver	Parabolic Dish
Applications	Grid-connected plants, process heat (Highest solar unit size built to date: 80 MWe)	Grid-connected plants, high temperature process heat (Highest solar unit size built to date: 10 MWe)	Stand-alone applications or small off-grid power systems (Highest solar unit size built to date: 25 kWe)
Advantages	• Commercially available – over 10 billion kWh operational experience; operating temperature potential up to 500°C (400°C commercially proven) • Commercially proven annual performance of 14% solar to net electrical output • Commercially proven investment and operating costs • Modularity • Best land use • Lowest materials demand • Hybrid concept proven • Storage capability	• Good mid-term prospects for high conversion efficiencies, with solar collection; operating temperature potential up to 1000°C (565°C proven at 10MW scale) • Storage at high temperatures Hybrid operation possible	• Very high conversion efficiencies – peak solar to electric conversion of about 30% • Modularity • Hybrid operation possible • Operational experience of first prototypes
Disadvantages	• The use of oil based heat transfer media restricts operating temperatures to 400°C, resulting in moderate steam qualities • Land availability, water demand	• Projected annual performance values, investment and operating costs still need to be proved in commercial operation	• Reliability needs to be improved • Projected cost goals of mass production still need to be achieved

Conversion pathways: Solar to thermal

- Solar to thermal: concentrated radiation
  - Application: concentrated solar power
  - 6.7 GW_{el} world wide installed capacity in 2023
    Mostly parabolic through and towers

FIGURE 30. Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2008-2018

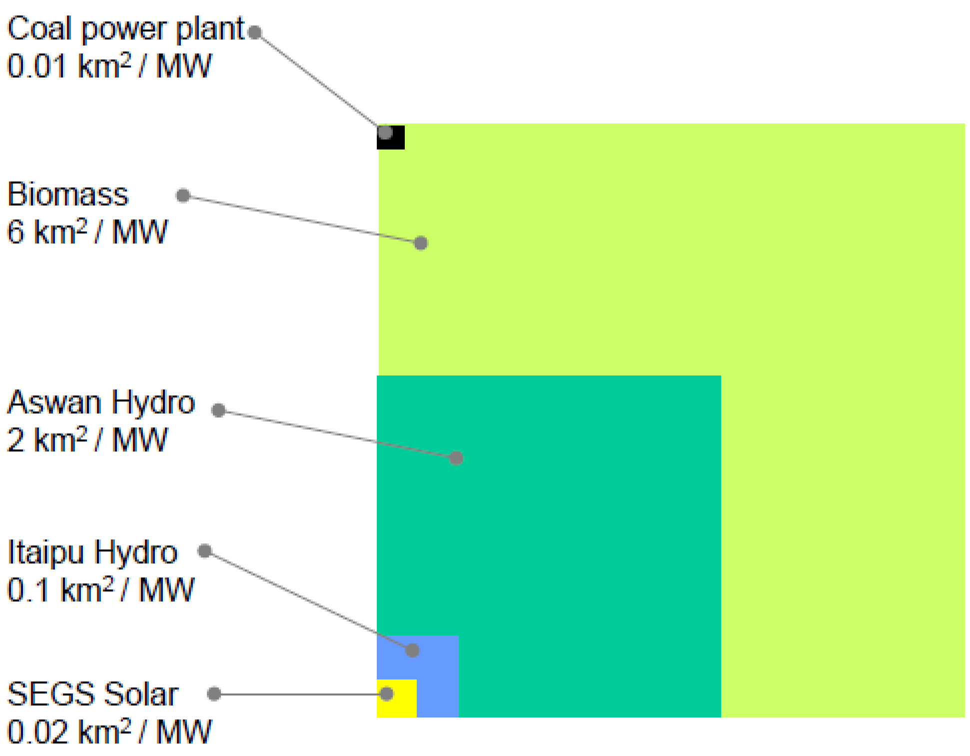




REN21, Renewable 2019 / 2024 Global Status Report

Conversion pathways: Solar to thermal

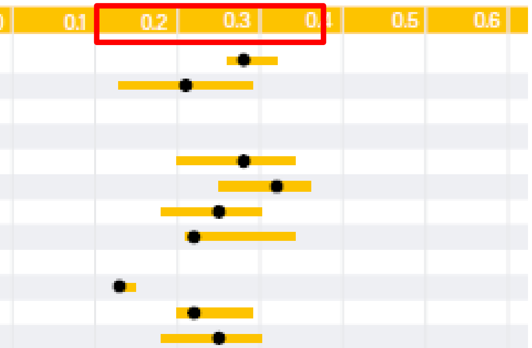
- Solar to thermal: concentrated radiation
  - Application: concentrated solar power, land use



Conversion pathways: Solar to thermal to electrical

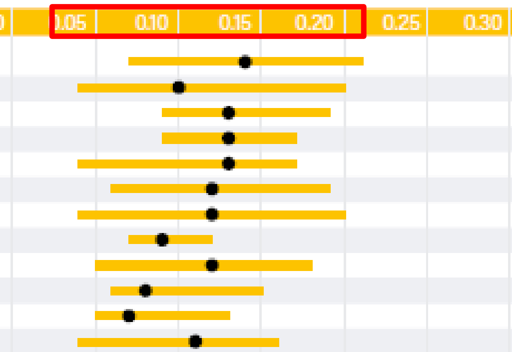
- CSP and PV, cost and capacity factor comparison

CONCENTRATING SOLAR THERMAL POWER (CSP)



Region	Capacity Factor → min	max	wa
Africa	0.36	0.53	0.39
Asia	0.21	0.54	0.28
Central America and the Caribbean			
Eurasia			
Europe	0.23	0.41	0.32
Middle East	0.24	0.39	0.29
North America	0.27	0.52	0.35
Oceania	0.11	0.23	0.12
South America			
China	0.28	0.29	0.28
India	0.21	0.54	0.28
United States	0.27	0.52	0.35

SOLAR PV

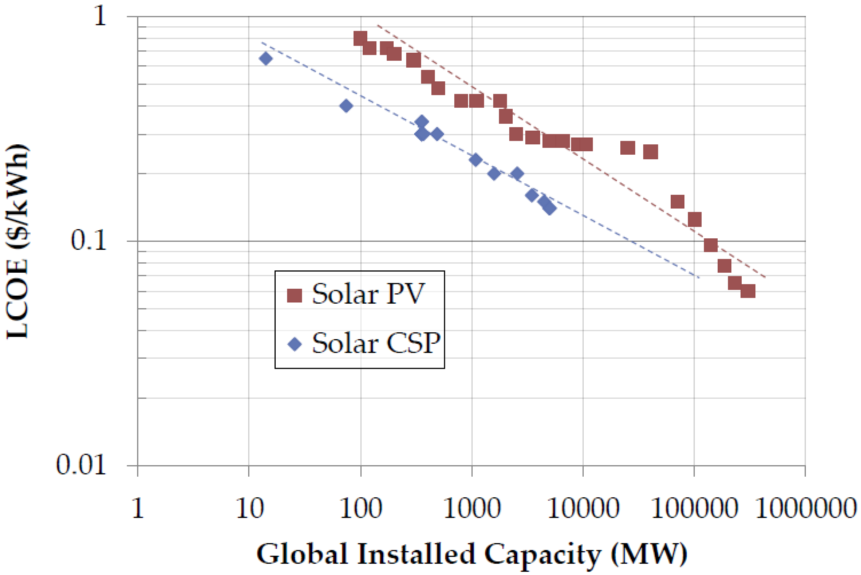


Region	Capacity Factor → min	max	wa
Africa	0.14	0.28	0.18
Asia	0.1	0.23	0.17
Central America and the Caribbean	0.16	0.19	0.17
Eurasia	0.1	0.18	0.14
Europe	0.11	0.18	0.12
Middle East	0.18	0.35	0.22
North America	0.14	0.32	0.2
Oceania	0.2	0.26	0.22
South America	0.12	0.34	0.2
China	0.1	0.19	0.17
India	0.15	0.22	0.19
United States	0.14	0.32	0.2

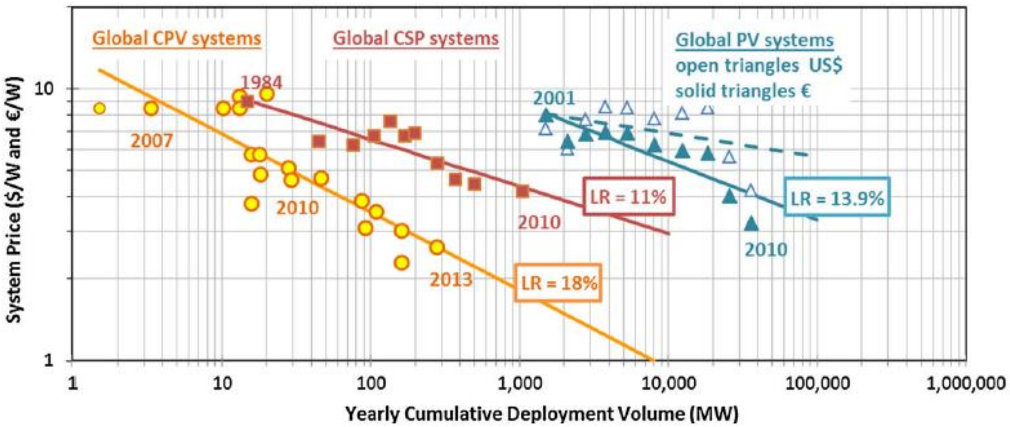
REN21, Renewable 2018 Global Status Report

Conversion pathways: Solar to thermal to electrical

- CSP and PV, learning curve comparison



Norwich Technologies, confidential



Haysom et al., Progress in Photovoltaics, 2015

Solar Chimney