Lecture # 17
Solar Thermal Energy

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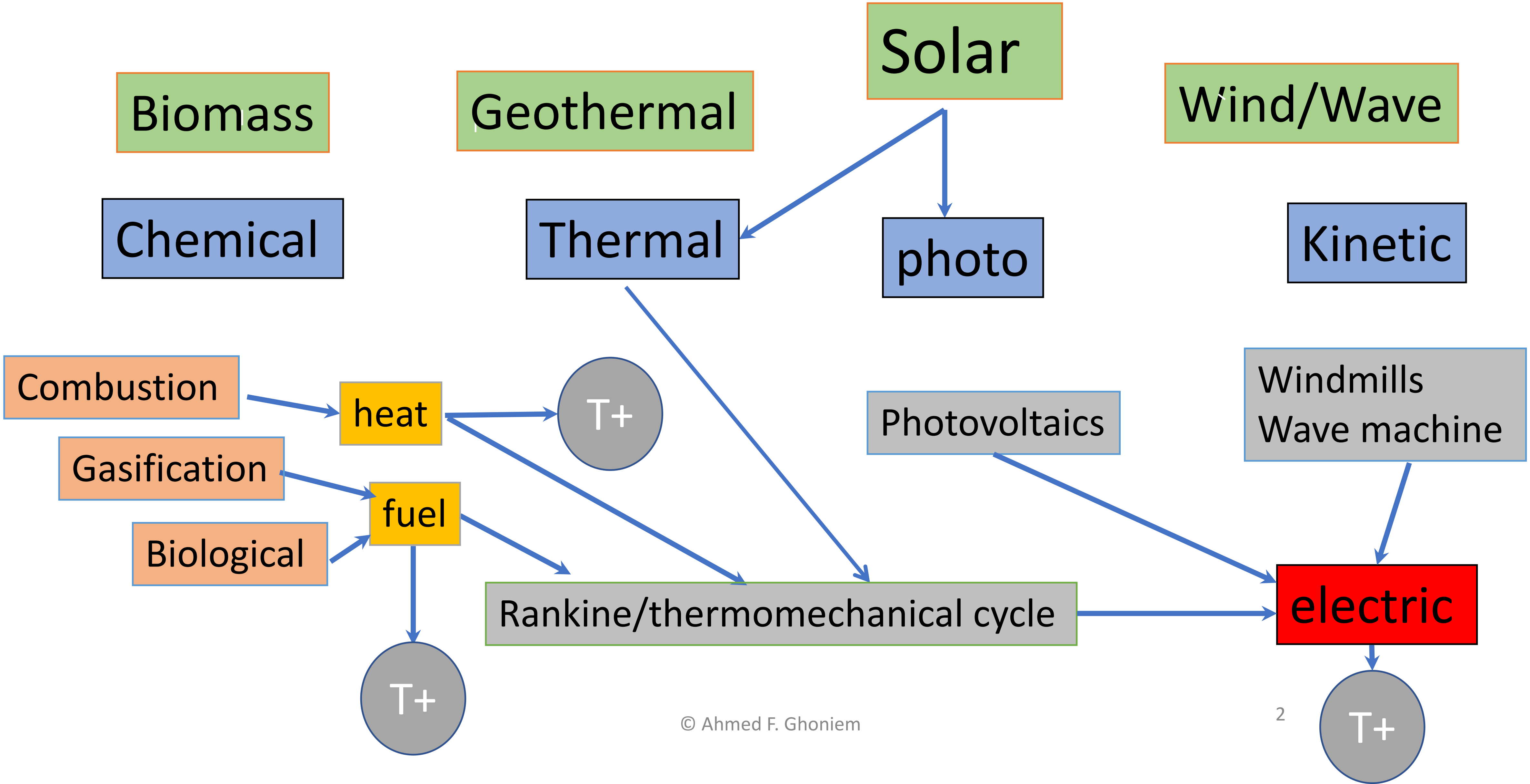
April 6, 2020

Renewables: Some characteristics and specifics.

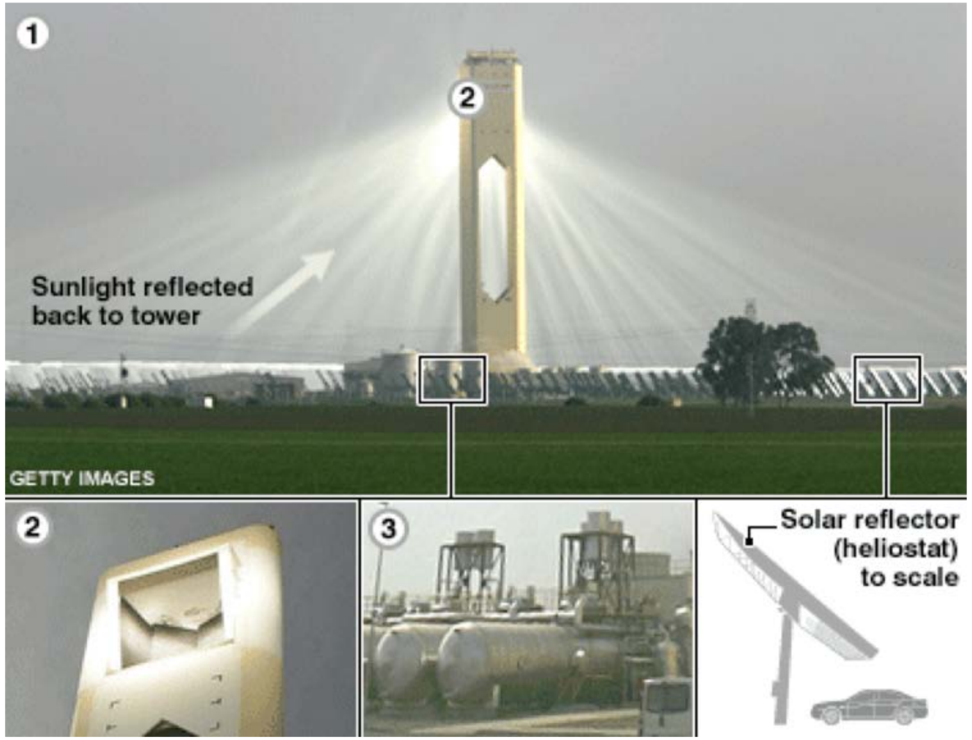
Historical Trends …

Solar Thermals: Concentrators and Plants

Renewable Sources and Their Utilization



Solucar, Outside Seville, 2007, 600 mirrors generate 11 MWe,



1. The solar tower is 115m (377ft) tall and surrounded by 600 steel reflectors (heliostats). They track the sun and direct its rays to a heat exchanger (receiver) at the top of the tower
2. The receiver converts concentrated solar energy from the heliostats into steam
3. Steam is stored in tanks and used to drive turbines that, eventually, will produce enough electricity for up to 6,000 homes

Aerial view of PS10 11MW solar plant

Designed for 10 MW, central receiver, to deliver 20-25 GWh/y (25-30% capacity)
Located in Sanlucar La Mayor (best area in Spain for solar), built and operated by Abengoa.

www.solucar.es
Cost estimated to be 3X higher
Capital cost: E3000/KWe

Saturated steam is generated at the receiver tower, fed directly to the turbine, or some stored in hot water tank for extending the hours of operation. The receiver is a forced circulation radiant boiler receiving ~ 55 MWt of concentrated solar radiation. Storage capacity is 20 MWht, sufficient to operate the turbines for 50 minutes at 50% capacity.

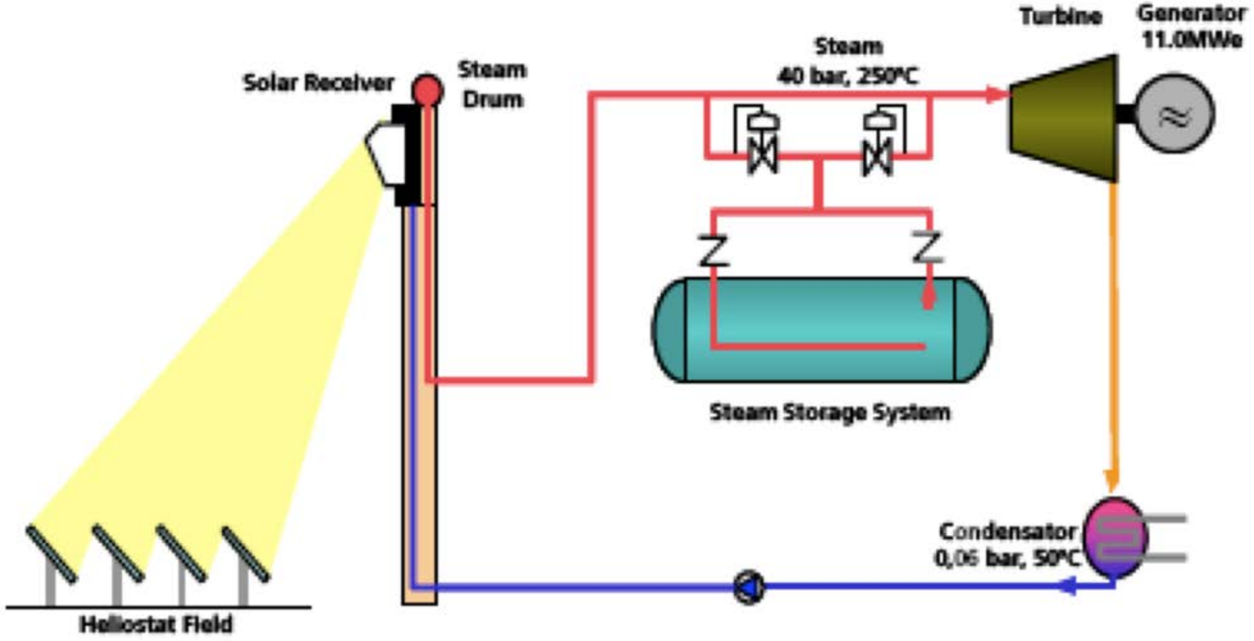
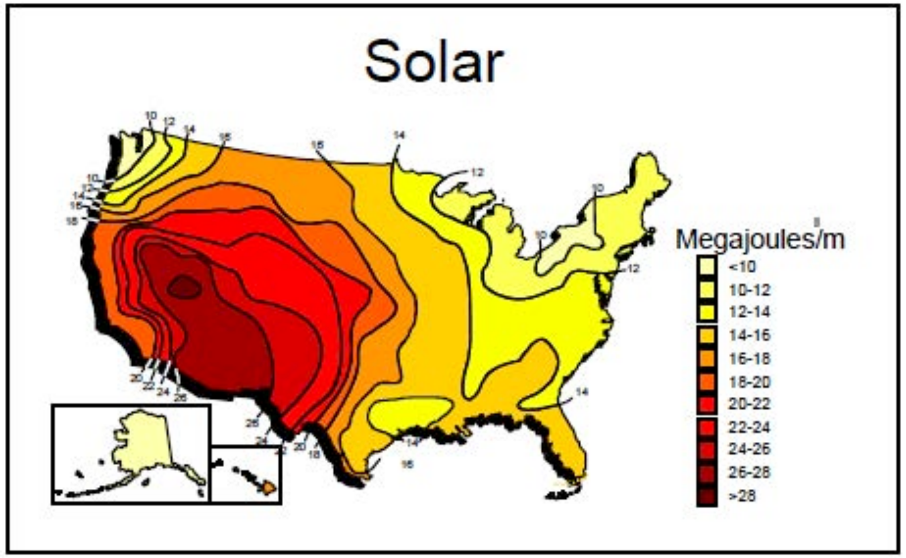


Image courtesy of DOE.

General characteristics of Renewable Sources (does not apply to hydropower and some geothermal):

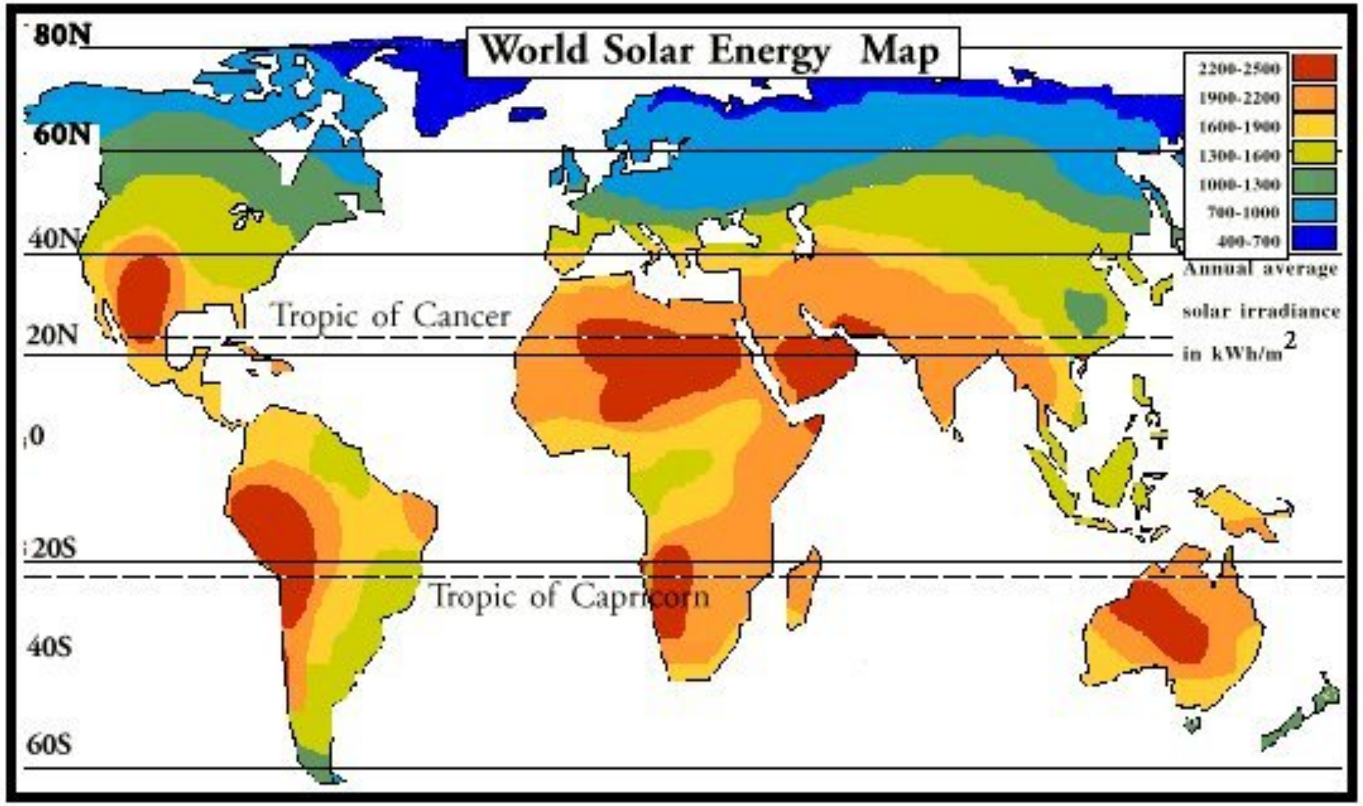
1. Ubiquitous, certainly with solar, less so with wind (more wind off-shore).
2. Low energy density, mostly surface area dependent, lower grade heat and low heating value for biomass.
3. Mostly intermittent, especially for solar, wind and wave, less so for hydropower and biomass (which has seasonal intermittency instead of daily).
4. Fuel cost is negligible (except for biomass and geothermal), but capital cost to collect the energy can be significant.
5. Carbon neutral (if all is kept renewable).

Solar Energy is "Everywhere", But Opportunities Vary
Distribution networks may have to look different



Average daily total irradiance on a horizontal surface in a clear day Source: US DOE

Image courtesy of DOE.



Historical Notes

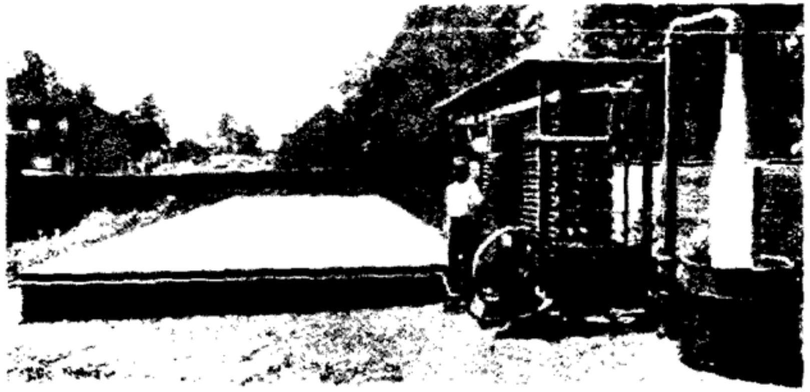
In 1780, 95% of total power used in commercial applications was from natural sources (wind and water). By 1911, all but 2% of power was generated from burning coal and harnessing steam. "Within a few generations at most, some other energy than that of combustion of fuel must be relied upon to do a fair share of the work of the civilized world." *Robert H. Thurston - 1901, the Smithsonian Institution annual report.*

"… the human race must finally utilize direct sun power or revert to barbarism because eventually all coal and oil will be used up. I would recommend all far-sighted engineers and inventors to work in this direction to their own profit, and the eternal welfare of the human race" *Frank Shuman – 1914*

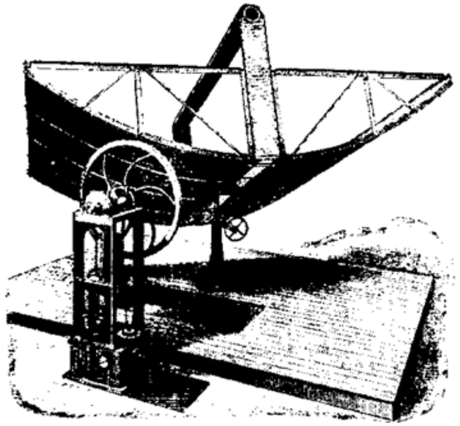
The conversion of solar energy into mechanical power was attempted as a commercial venture by **the Sun Power Company** in Pennsylvania by Frank Shuman, 1910. "The fact that … no fuel is required is such an enormous advantage as to entirely offset the increased initial cost, and in addition cause great profits." *Frank Shuman - 1911*.

Source: The power of Light by Frank T. Kryza, McGraw Hill, 2003

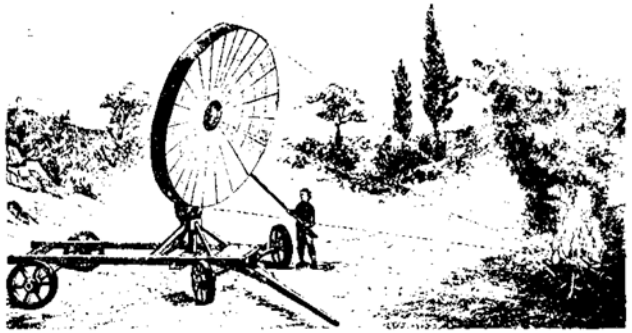
Leonardo Da Vinci and his drawing of a 4-mile burning mirror to be set in the ground.



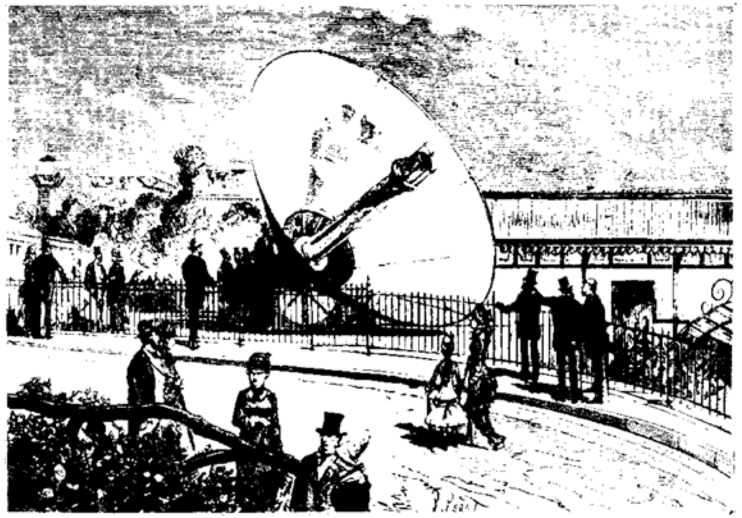
Shuman's first Tacony solar plant. Note the water gushing out of the pipe at right.



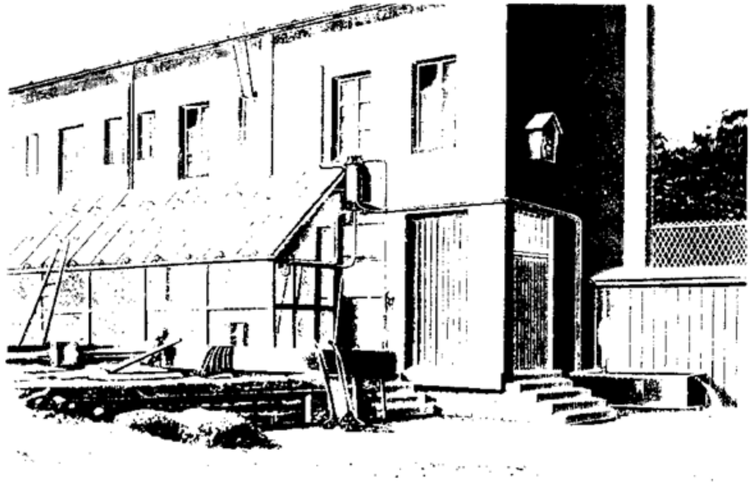
John Ericsson's solar motor, the first to use a "parabolic trough" collector (the curved shape that looks like a section of metal barrel). Frank Shuman later enlarged and adapted this design for his solar machine in Egypt.



A large, lightweight German burning mirror of the late 1700s being used to set fire to a pile of wood at a distance of about 30 feet. This compound parabolic mirror used scores of flat pieces of thin brass plate nailed onto a parabolic armature or frame made of wood. Mirrors of this type, often 10 feet or more in diameter, were by far the most powerful solar reflectors yet developed and could focus the concentrated rays of the sun on a target area less then 1 inch in diameter. Wood burst into flame almost instantly. Copper ore melted in 1 second, lead in the blink of an eye.

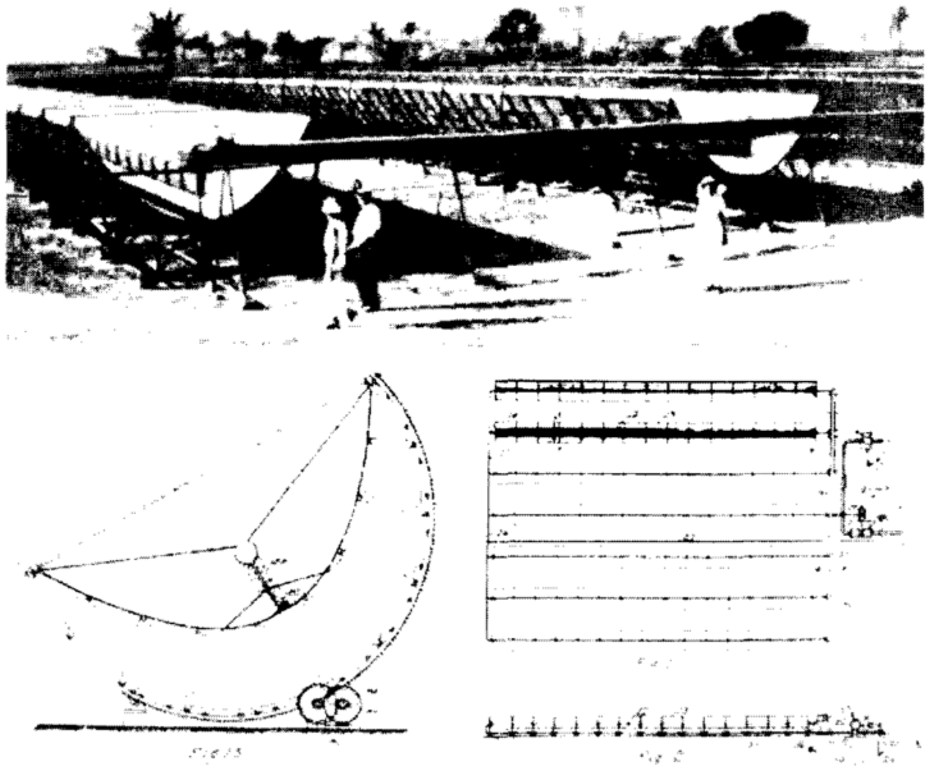


One of the largest Mouchot devices ever built on display at the Universal Exposition in Paris in 1878 on the banks of the Seine. It was a prototype of this device that so intrigued Napoleon III in 1867 and spurred him to provide Mouchot with financing.

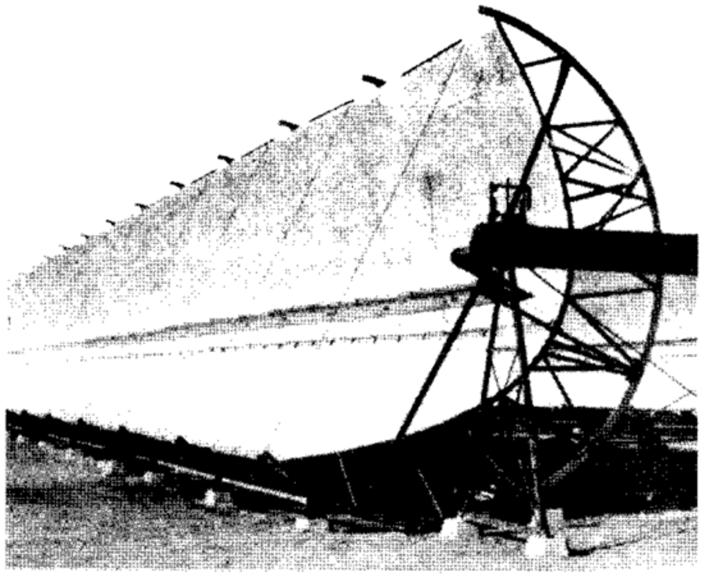


Large cast-iron solar hot boxes (numbered 1 through 10 in the diagram) built on the side of Charles Tellier's Paris workshop. The thick metal plates were needed because the working fluid was ammonia under pressure. Tellier hooked up the pump powered by the ammonia to lift water from his well.

Solar Powered Irrigation in Egypt -1913

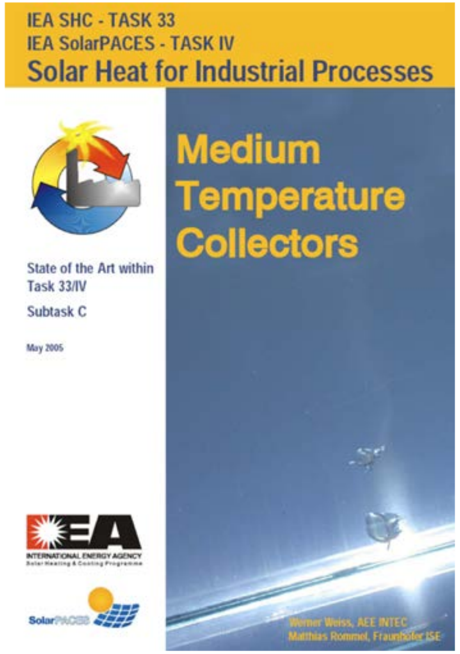


Frank Shuman's Maadi plant in Egypt, with cutaway diagram of the parabolic trough collectors.



Frank Shuman's Maadi parabolic troughs, close up.

Fast forward to 21st Century



	Collector Type	Operating Temperature [°C]	Heat Transfer Medium	Contact person within Task 33/IV	Page
	Fix Focus Trough	100 - 200	water, steam, thermal oil, air	Klaus Hennecke DLR Institute for Technical Thermodynamics D-51170 Köln Germany	21
	Linear Concentrating Fresnel Collector	100 - 400	Water, steam, thermal oil	Andreas Häberle PSE Solar Info Center 79072 Freiburg Germany	22
	CHAPS Combined Heat and Power Solar collector	80 - 150	Water	Joe Coventry The Australian National University Centre for Sustainable Energy Systems Department of Engineering, Canberra ACT 0200 Australia	24

The Combined Heat and Power Solar (CHAPS) collector

Authors:

Dr Joe Coventry
Prof Andrew Blakers

Research Institution(s) involved in the development

The Australian National University
Centre for Sustainable Energy Systems
Department of Engineering
Canberra ACT 0200 Australia

Prototype CHAPS system

300m² Bruce Hall system under construction

Description of collector, operating temperature range and stagnation temperature

The CHAPS collector is a parabolic trough system consisting of glass-on-metal mirrors that focus light onto high efficiency monocrystalline silicon solar cells to generate electricity. Water, with anti-freeze and anti-corrosion additives, flows through a conduit at the back of the cells to remove most of the remaining energy as heat. The thermal energy may be used via a heat exchanger for industrial applications, building heating and domestic hot water.

Operating temperature level:

The operating temperature of the collector is limited by the inclusion of solar cells. The electrical efficiency of the system reduces as operating temperature increases. Therefore the system is ideally suited to lower temperature applications (<80°C) where electrical system efficiency is maintained above 10%; however, temperatures up to around 150°C are feasible, with electrical efficiency still in the order of 8%.

Stagnation temperature:

Not applicable. The receiver is destroyed well below the stagnation temperature, so preventative measures are included to avoid the possibility of stagnation conditions occuring. For example, the tracking system uses a dc actuator with battery backup. This is combined with automatic collector 'parking' in case of over-temperature conditions.

Dimensions of the prototype collectors

Width of single trough: 1.55 m
Length of single trough: 24 m
Focal length: 0.85 m

Collector parameters based on aperture area

The thermal efficiency parameters are estimated, but based on data measured at operating temperatures lower than 80°C. It is assumed that the insulation is improved for higher temperature applications. Efficiencies are based on DNI (direct normal irradiation) and on the total aperture area of the mirror.

	Thermal efficiency	Electrical efficiency[1]
η_0	0.56	0.126
a_{1a}	0.0325 W/(m² K)	0.355
a_{2a}	0.00313 W/(m² K²)	

1 Although it is not strictly correct to plot electrical efficiency on the same axes as for a therml efficiency curve, this has been done for the sake of comparison. The parameters are based on 1000 W/m² assuming ambient temperature of 25°C. Actually, the absolute temperature of the receiver is what matters for electrical performance, so technically the temperature difference (Tm-Tamb) should be in reference to a baseline Tamb.

Linear Concentrating Fresnel Collector

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Research Institution(s) involved in the development

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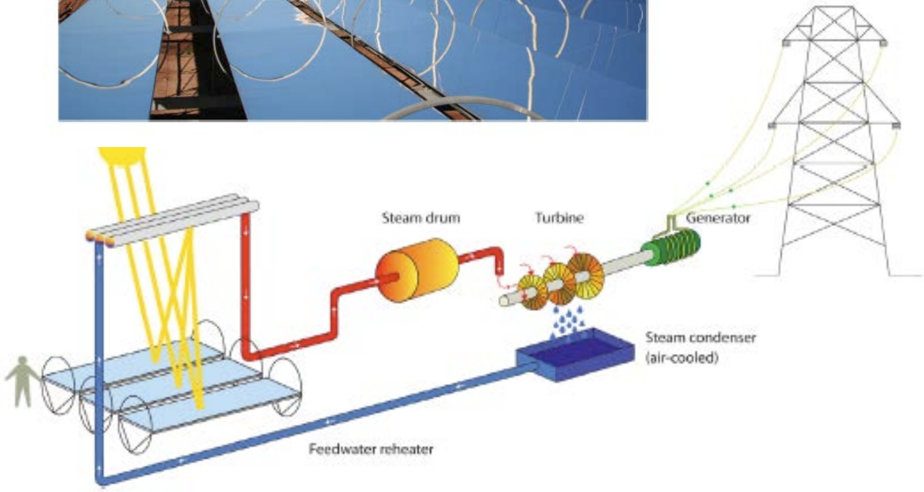
DLR
Institute for Technical Thermodynamics
Lindner Höhe
51170 Köln, Germany

Companies involved in the development

Solarmundo, PSE GmbH

A similar concept is being pursued by the Australian company SHP (Solar Heat and Power) and SHP-Europe in co-operation with the University of Sidney.

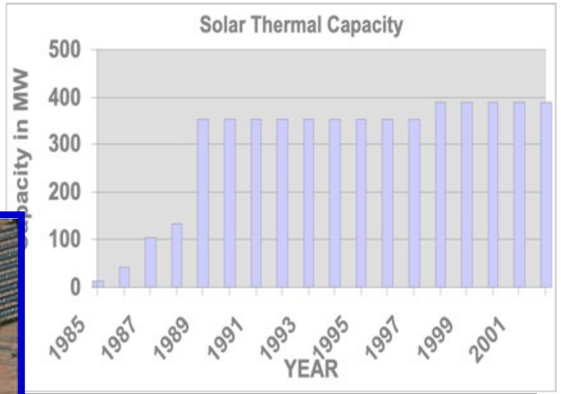


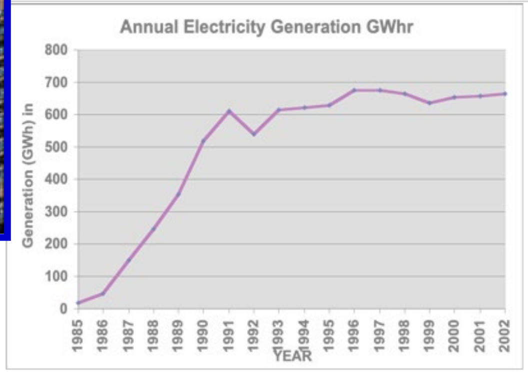
Ausra's CLFR technology builds on the experience with troughs and towers. Ausra's core technology, the Compact Linear Fresnel Reflector (CLFR) solar collector and steam generation system, was originally conceived in the early 1990s by Ausra's founders in Australia. The CLFR system retains a key advantage of troughs – fewer foundations and positioning motors per square meter of mirror – and a key advantage of the PS-10 tower system – direct steam generation and energy storage. Compared to trough systems, the CLFR system reduces costs by replacing special heat-curved reflectors with standard flat glass, and keeps all mirrors close to the ground, lowering wind loads and steel usage.

Solar Thermal Electric Generation Stations (SEGS) 1985-2002
Modern plants 2006-2014

Nine SEGS Plants in the Mojave Desert (350MW)

Image courtesy of NREL.





- In 2006, Nevada Solar 1 was commissioned, 64 MWe, built over 250 acres (1.3 sq km), using 760 troughs. Expected power 130 million kWh/y, capacity factor ~ 25%). Cost $250M (~$110M for IGCC and ~$35M for NGCC).
- Ivanpah solar plant (2014), Dry Lake, CA, world largest CSP, 392 MW, capacity factor 28.72% . 4000 acres, 173,500 heliostats, $2.2 B ($1.6 B loan guarantees, total cost $2.2B), doubles US solar electricity

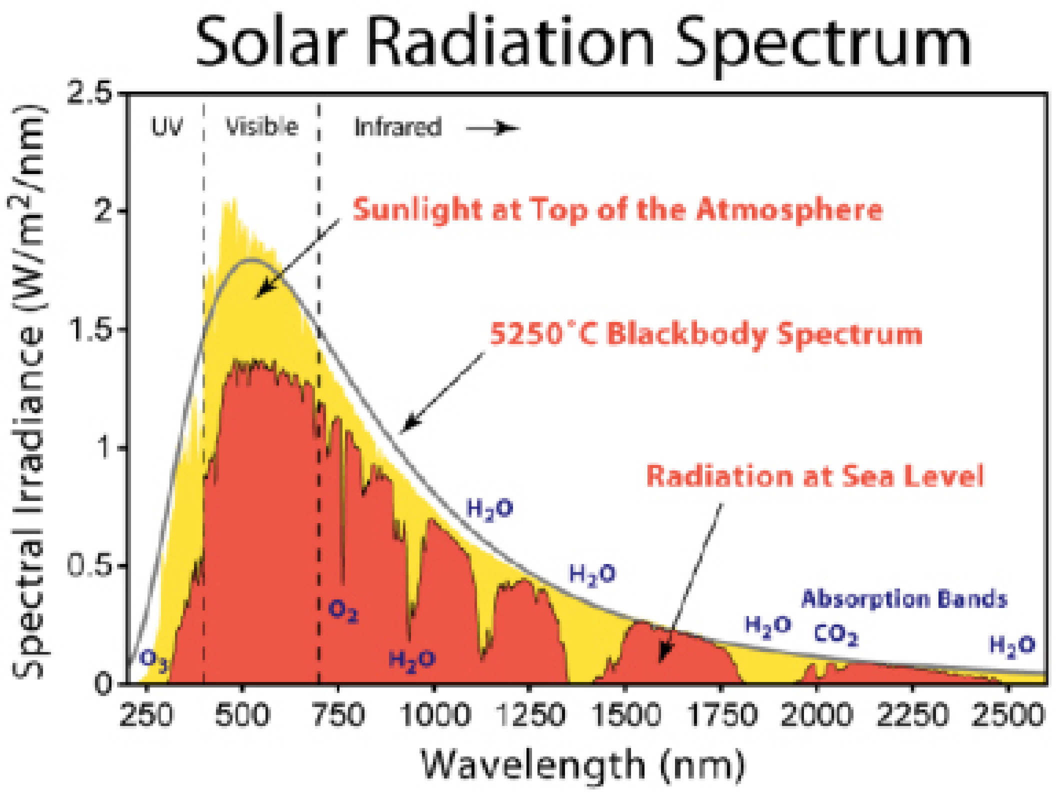
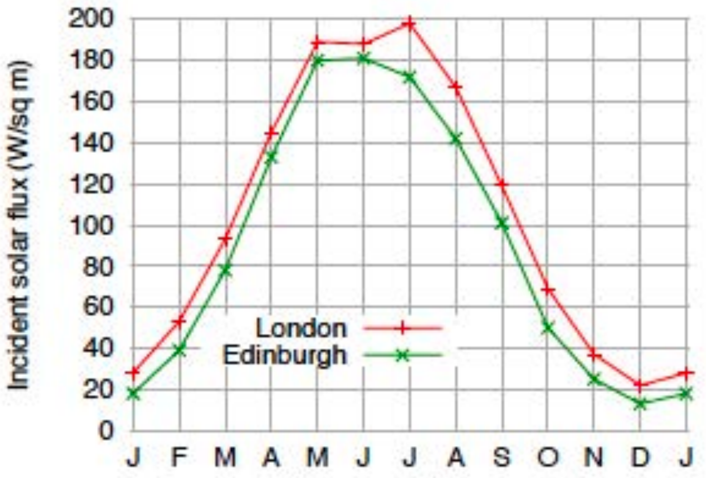
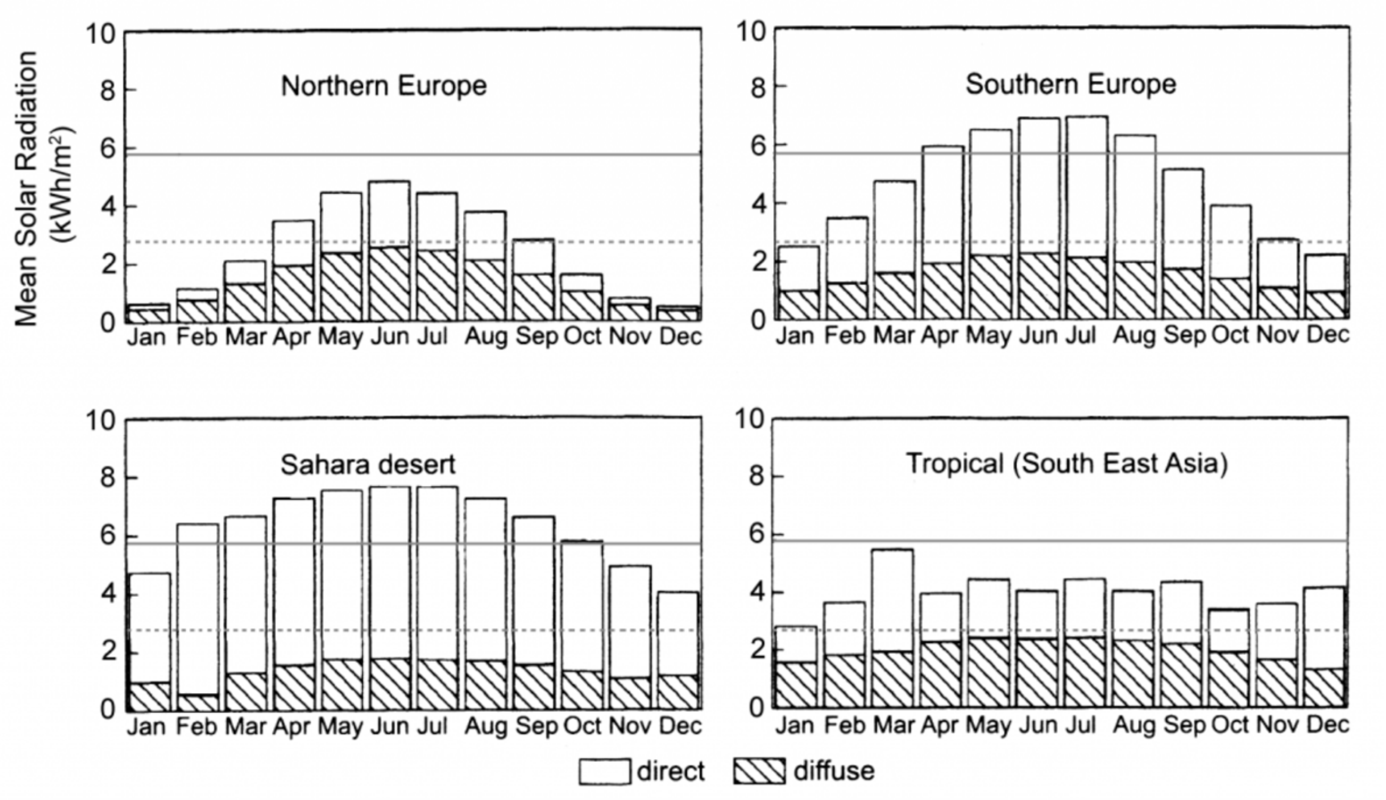


Figure 3: The solar spectrum above the atmosphere and at sea level

- Extra-terrestrial total irradiance (insolation: incident solar radiation) ~ 1367 W/m^2
- Irradiance at Earth's surface is made of beam (direct) and diffuse components
- Total terrestrial irradiance depends on location (north, south, ..), hours/days of sun, cloud coverage, etc. When averaged over one day:
  - Clear ~ 590 - 1000 W/m^2
  - Cloudy days ~ 120 W/m^2
  - Average ~ 300 W/m^2 (strong function of location)



In London, solar intensity, average over the year is ~ 100 W/m^2 from MacKay



The yearly variation of the mean total daily solar radiation (total per day) for different locations, the dashed lines is at 2.88 kWh/m^2day, and solid line is at 5.75 kWh/m^2day, showing both direct and diffuse radiation. Location affects number of hours/day of sun, solar angle, weather conditions, ..

Intermittency is tricky! Role of storage, backup and multiple sources/technologies

How Much? On average

2.7 MWh/m^2/y total incident radiation

~ 7 kWh/m^2/day total

~ 0.3 kW/m^2 total

@ ~ 15% conversion efficiency, ~ 0.05 kW/m^2, therefore for a house using ½ kW, you need ~ 10 m^2.

@ 20% (overall: field x cycle) efficiency (CSP), generate 60 MW/km^2, for a power plant)

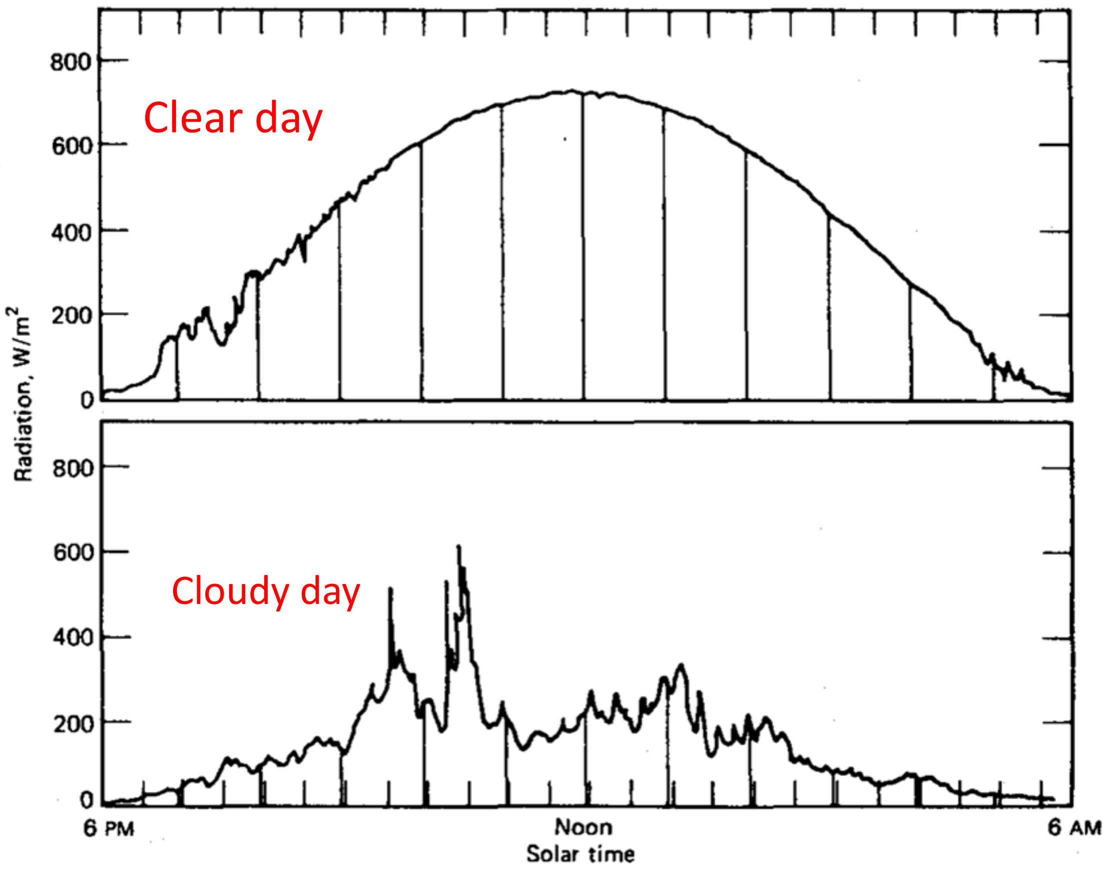


Figure 2.5.1 Total (beam and diffuse) solar radiation on a horizontal surface vs. time for clear and largely cloudy day, latitude 43°, for days near the equinox.

Energy Balance of collectors and their fluid temperature

(1) Flat Collectors:

$$q = \beta I - \hat{h}\left(T_c - T_a\right)$$

q net flux collected by a fluid passing through the collector

I Irradiance $< 1\ kW/m^2$

β fraction absobed, depends on orientation & transmissivity < 0.8

$\hat{h}$ overall heat transfer coefficient

T_c collector T T_a environment T

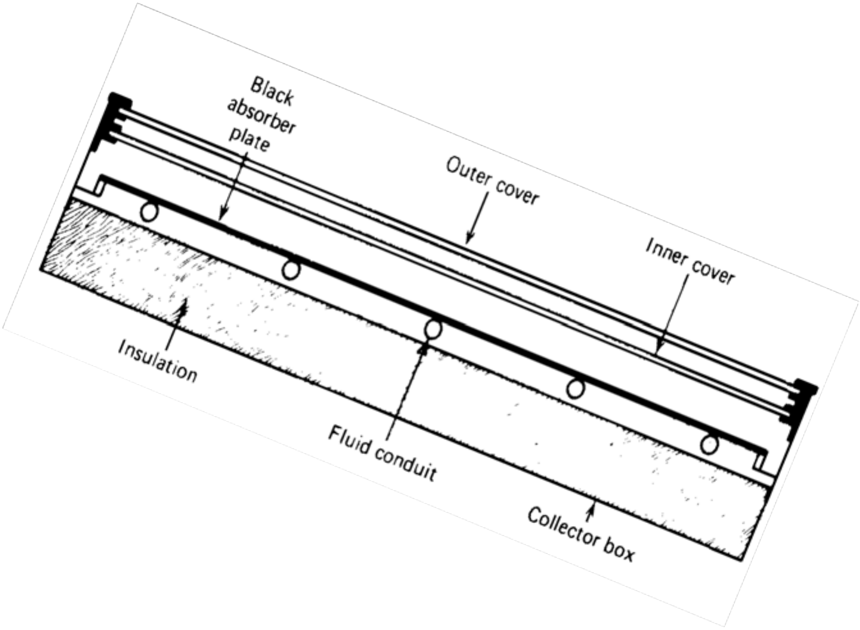
$at\ q = 0$ $$(T_c)_{\max} = T_a + \frac{\beta I}{\hat{h}}$$

for high $(T_c)_{\max}$, $\hat{h}$ must be very low (insulation < 0.1 kW/m^{2}K)

Typical value $T_c \sim 80$ C

$$\eta_{col} = \frac{q}{I} = \beta - \frac{\hat{h}\left(T_c - T_a\right)}{I} \leq \beta$$

goes down linearly with temperature! must limit heat loss



Flat collectors:

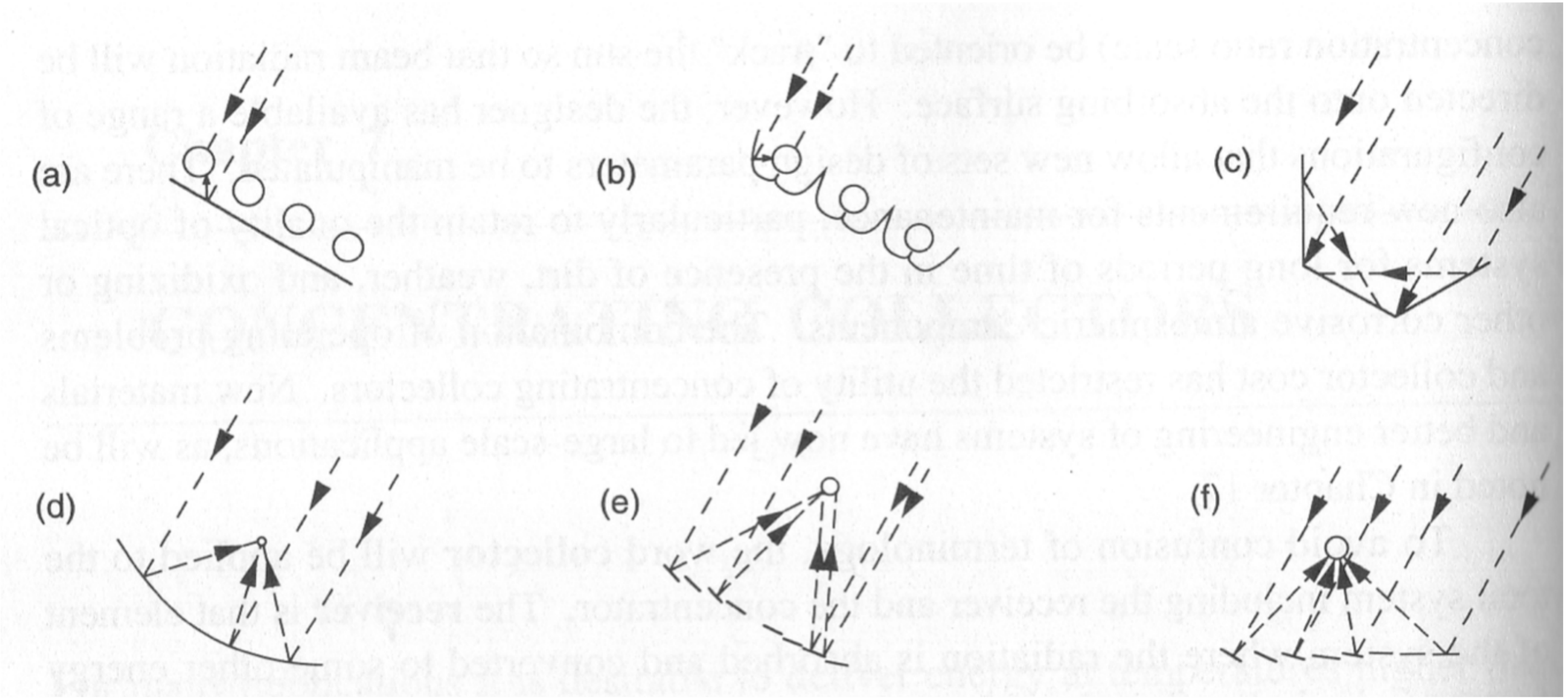
limit heat transfer fluid tempertaure.

Typical values of β, is 80%,

Collection efficiency at $T_c \sim 60$ C, ~ 50%.

Concentrating Collectors:

1. Trough
2. Tower
3. Cone



(a) Flat collector, (b) with local curved mirrors, (c) concave, (d) parabolic,
(e) Fresnel reflector (f) Array of heliostats with central receiver
Goal: Increasing the flux of radiation on receivers

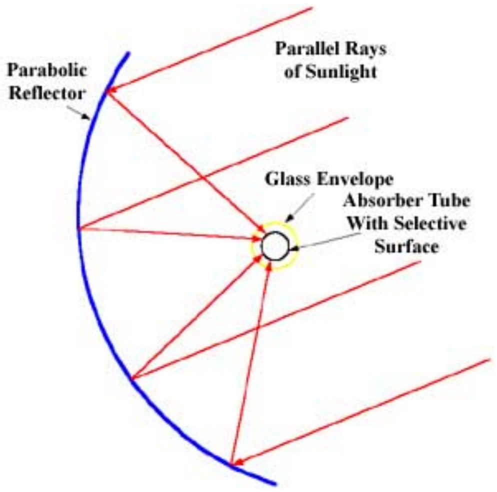
Focusing Collectors : increases the collector temperature and collection efficiency:

- Project the collected energy onto a small area (from Sun to mirror/reflector to collector) to increase T.
- Energy is collected from the *large area of the concentrator*, and lost from the *small area of the collector* only.
- Concentration Ratio C_R is the ratio between irradiance on the collector (at the focal point of the concentrator) and incident irradiance, *I*, is (also the area ratio):

$$C_R = 107.5 \frac{D_m}{F} \text{ for cylindrical}$$

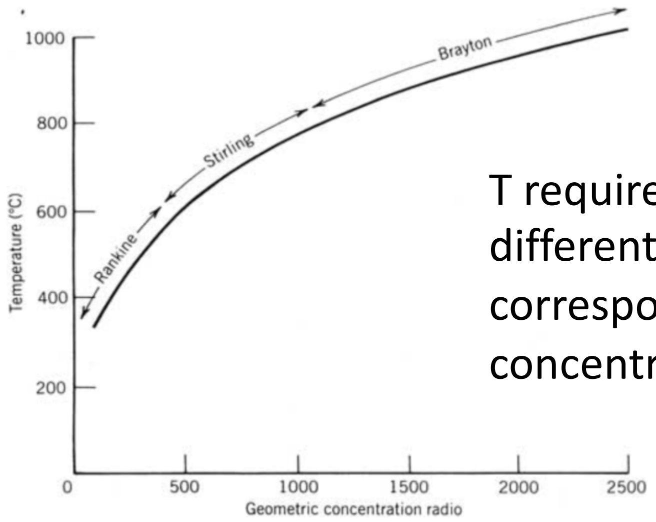
$$= 11560 \left(\frac{D_m}{F} \right)^2 \text{ for spherical}$$

D_m : mirror dimension, F : focal length



Concentrating Collectors

- Thermal energy at *T* higher than those possible with flat-plate collector; using a concentrator and a receiver.
- Increasing the concentration ratio: the ratio of collector area to absorber area, raises *T* at which energy is delivered.
- Spherical (3D) collectors deliver higher *T* than cylindrical (2) collectors.



T requirements for different engines and the corresponding concentration ratio

net absorbed flux: $qA_{col} = \beta A_{conc} I - \hat{h} A_{col} \left(T_c - T_a\right)$

define: $C_R = A_{conc} / A_{col}$

then: $q = \beta C_R I - \hat{h}\left(T_c - T_a\right)$

β depends on reflective and transmissive properies of glass cover and absorbative properties of collector surface ~ 80% (best)

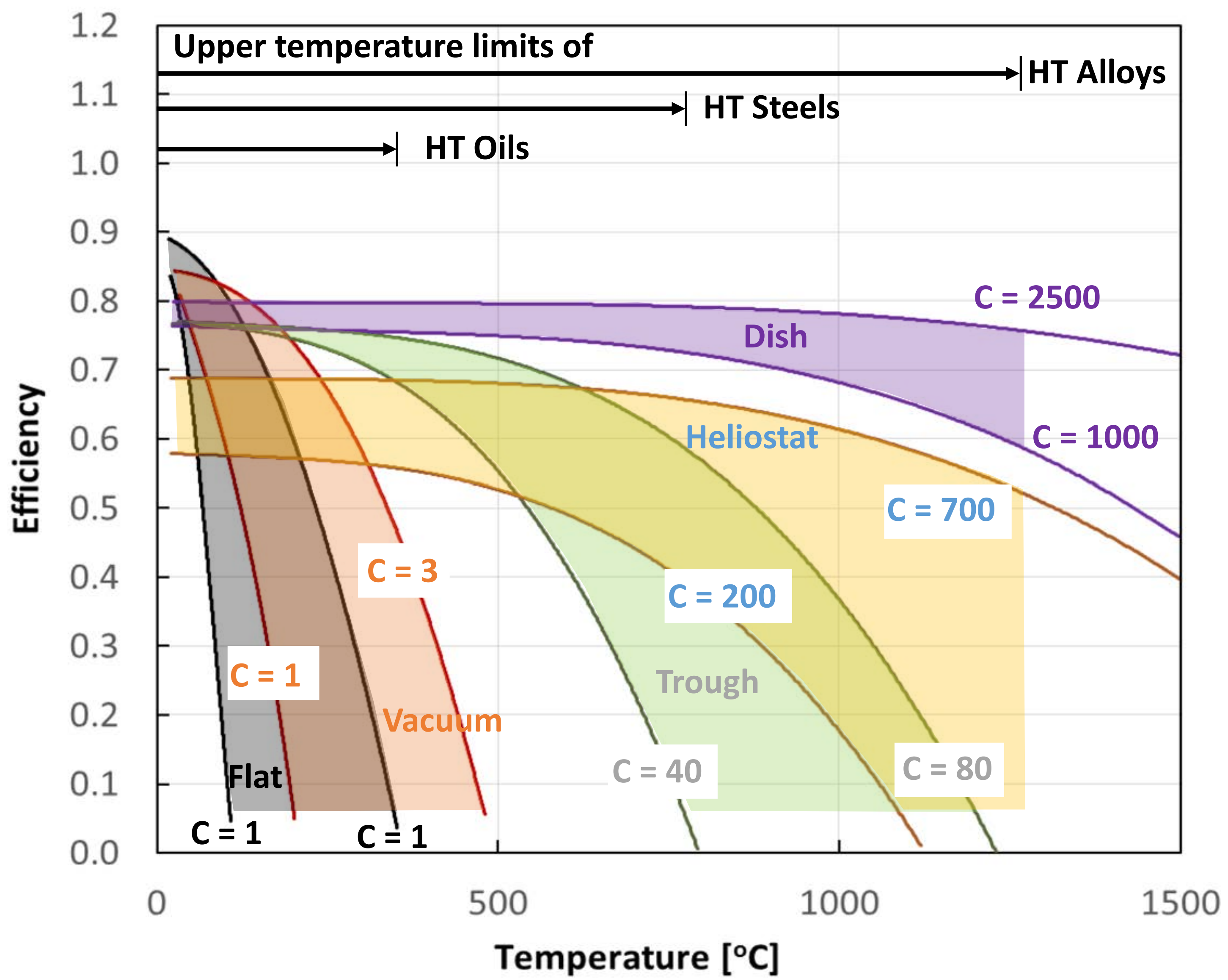
max imum collector/fluid temperature is when $q = 0$,

$$\left(T_c\right)_{\max} = T_a + \frac{\beta I C_R}{\hat{h}}$$

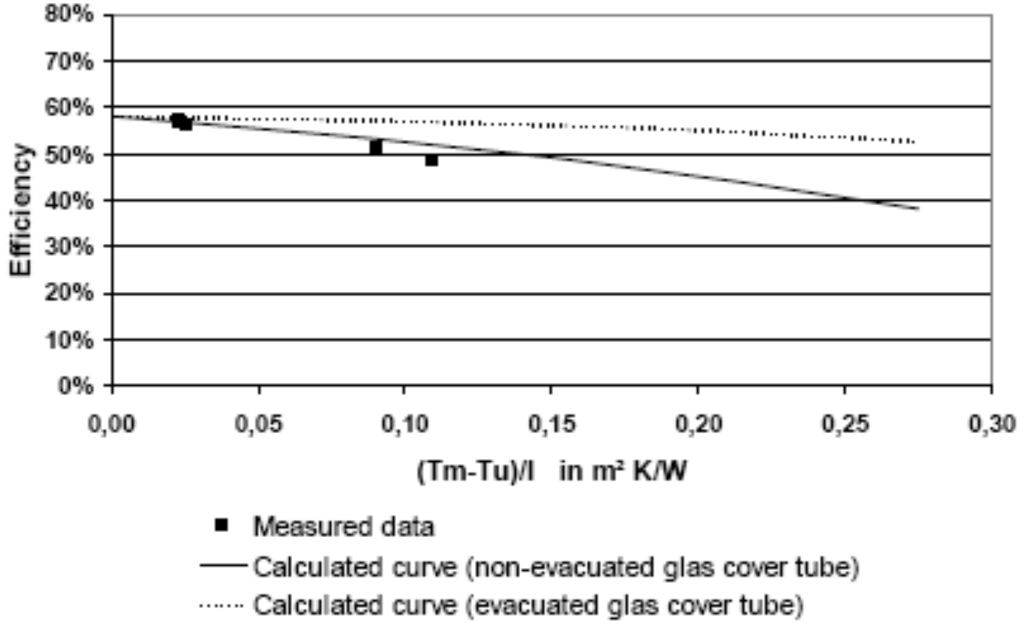
collector efficiency: $$\eta_{col} = \frac{qA_{col}}{IA_{conc}} = \frac{q}{IC_R} = \beta - \frac{\hat{h}\left(T_c - T_a\right)}{I\,C_R}$$

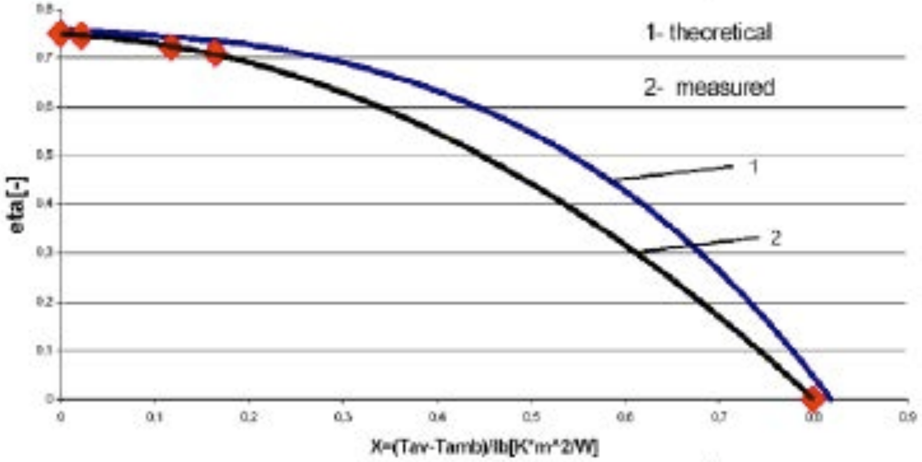
note how it increses with the concentration ratio

Solar field efficiency:



C: concentration ratio





$\eta_0 = 0.75$

$a_{1a} = 0.1123$ W/(m² K)

$a_{2a} = 0.00128$ W/(m² K²)

$$\eta = \eta_0 - a_{1a} \cdot \frac{\Delta\overline{T}}{DNI} - a_{2a} \cdot \frac{\Delta\overline{T}^2}{DNI}$$

The power is about 1 kW. The efficiency curve is shown in figure 2. The collector has an efficiency of around 60% at a radiation of 800 W/m² and a temperature of 300°C.

Optimizing the Solar Field-Power Block System

Using oil as a heat transfer fluid.
Or direct steam generation in the collectors.

By X.G. Casala, Jan 2000, “Modeling and Optimizing the use of Parabolic Trough Technology with Rankine Cycles for Electricity Productions” Escela Tecnica Superior de Ingeniera, Madrid.

DSG: direct steam generation

$$\eta_{col} = \frac{q}{I} = \beta - \frac{\hat{h}\left(T_c - T_a\right)}{I\,C_R} \leq \beta$$

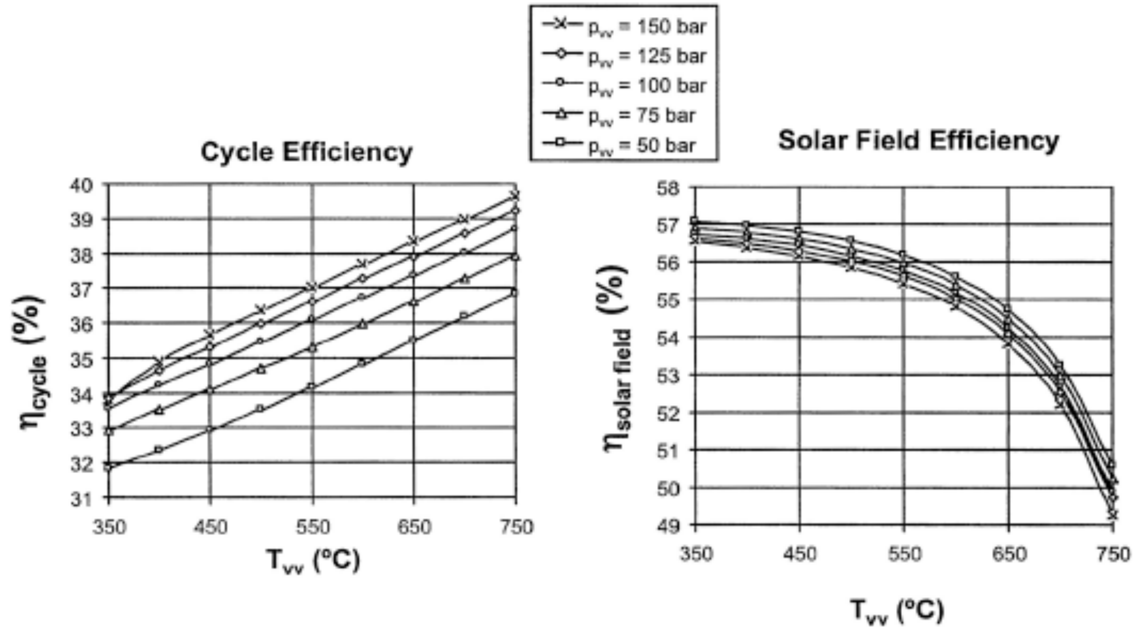


Fig.27: Effect of turbine inlet pressure on cycle and solar field efficiencies. Rankine water cooled.

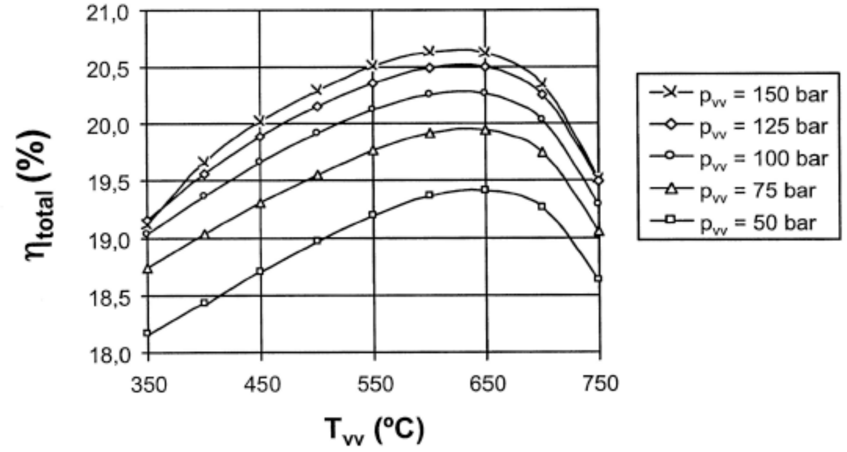
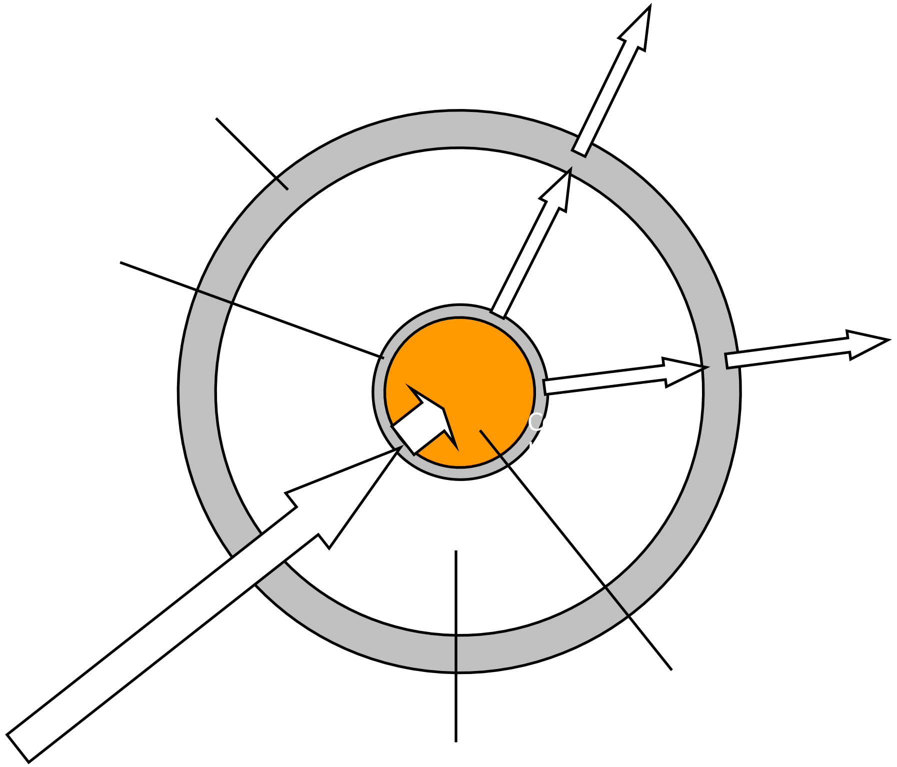


Fig.28: Total conversion efficiency as function of turbine inlet temperature and pressure. Rankine cycle water cooled.

Heat-Collection Element (HCE)

Space between absorber pipe and glass shield is evacuated
• Reduces convective losses



Glass shield has a spectrally selective coating
• Lets solar radiation in
• Blocks thermal radiation

Solar thermal Electric Power systems

Source: US DOE 2005

Characteristics of solar thermal electric power systems.

	Parabolic Trough	Power Tower	Dish/Engine
Size	30-320 MW*	10-200 MW*	5-25 kW*
Operating Temperature (°C/°F)	390/734	565/1,049	750/1,382
Annual Capacity Factor	23-50%*	20-77%*	25%
Peak Efficiency	20%(d)	23%(p)	29.4%(d)
Net Annual Efficiency	11(d')-16%*	7(d')-20%*	12-25%*(p)
Commercial Status	Commercially Available	Scale-up Demonstration	Prototype Demonstration
Technology Development Risk	Low	Medium	High
Storage Available	Limited	Yes	Battery
Hybrid Designs	Yes	Yes	Yes
Cost			
$/m^2	630-275*	475-200*	3,100-320*
$/W	4.0-2.7*	4.4-2.5*	12.6-1.3*
$/W$_p$ †	4.0-1.3*	2.4-0.9*	12.6-1.1*

* Values indicate changes over the 1997-2030 time frame.

† $/W$_p$ removes the effect of thermal storage (or hybridization for dish/engine).

(p)=predicted; (d) = demonstrated; (d') = has been demonstrated, out years are predicted values

Table courtesy of DOE.

Parabolic-Trough Technology

Parabolic Trough systems use parabolic trough-shaped mirrors to focus sunlight on thermally efficient receiver tubes that contain a heat transfer fluid (Figure 1). This fluid is heated to 390°C (734°F) and pumped through a series of heat exchangers to produce superheated steam which powers a conventional turbine generator to produce electricity. Nine trough systems, built in the mid to late 1980's, are currently generating 354 MW in Southern California. These systems, sized between 14 and 80 MW, are hybridized with up to 25% natural gas in order to provide dispatchable power when solar energy is not available.

Developed by Luz Int., and installed in Kramer Junction in 1991, company failed commercially in 92 (low NG prices), but plant is still in operation.

Image courtesy of DOE.

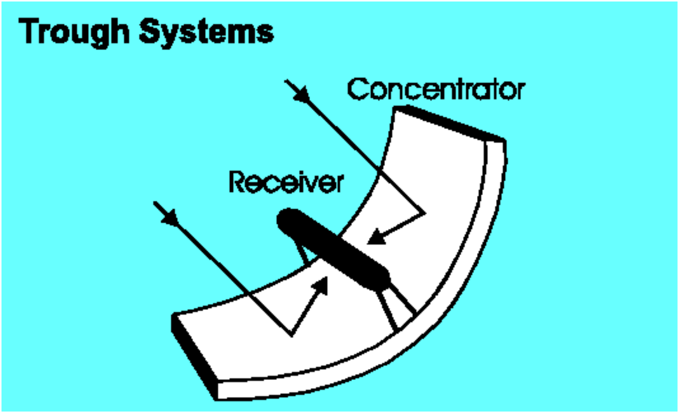


Image courtesy of DOE.

Solar Energy Generating System (SEGS)

- Nine SEGS Plants in the Mojave Desert (350MW)
- Parabolic-Trough Collectors, single axis tracking.
- Hybrid Design with Auxiliary Boiler
- Conversion Efficiency
  - 24% Peak
  - 8%-13% Annualized
- Levelized Cost of Electricity
  - 13 ¢/kWh (Hybrid)
  - 17 ¢/kWh (Solar Only)

Image courtesy of DOE.

Hybrid Combined Cycle SEGS Plant

- Would boost thermal efficiency to 54-58%
- Total annual average solar-to-electric efficiency at 10-14%.
- Plants use conventional equipment and are “hybridized” for dispatchability (25%)

Image courtesy of NREL.

- Total reflective area > 2.3 M. m^2
- More than 117,000 Heat Collecting Elements
- 30 MW increment based on regulated power block size

Hybridized Parabolic-Trough System

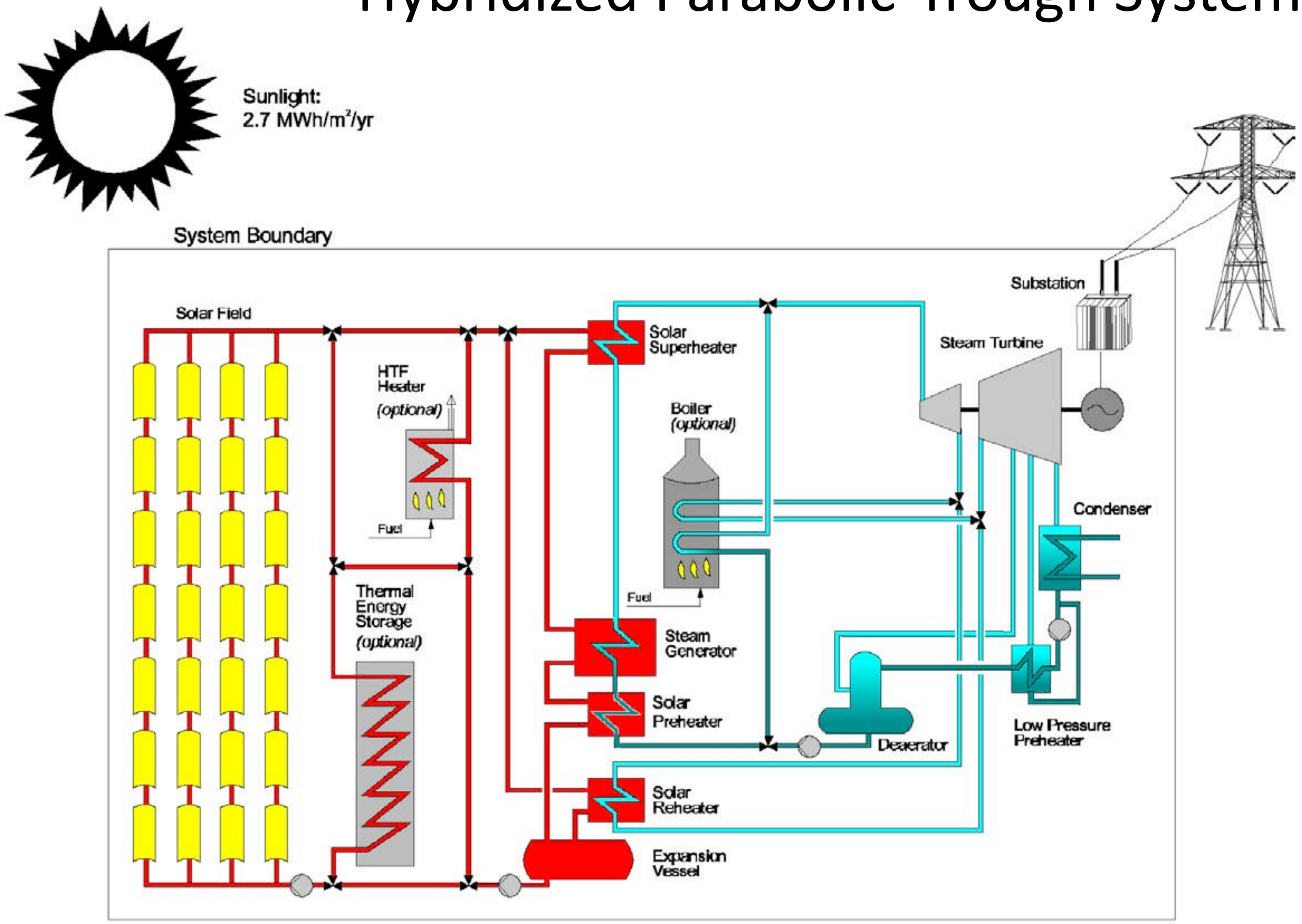
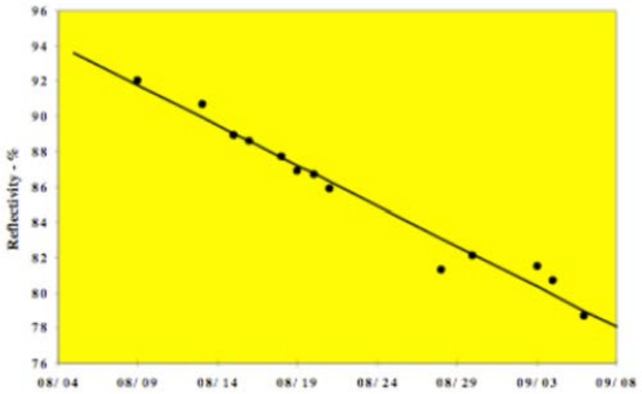


Figure 1. Solar/Rankine parabolic trough system schematic [1].

Image courtesy of DOE.

Critical to keep the reflectors clean ……



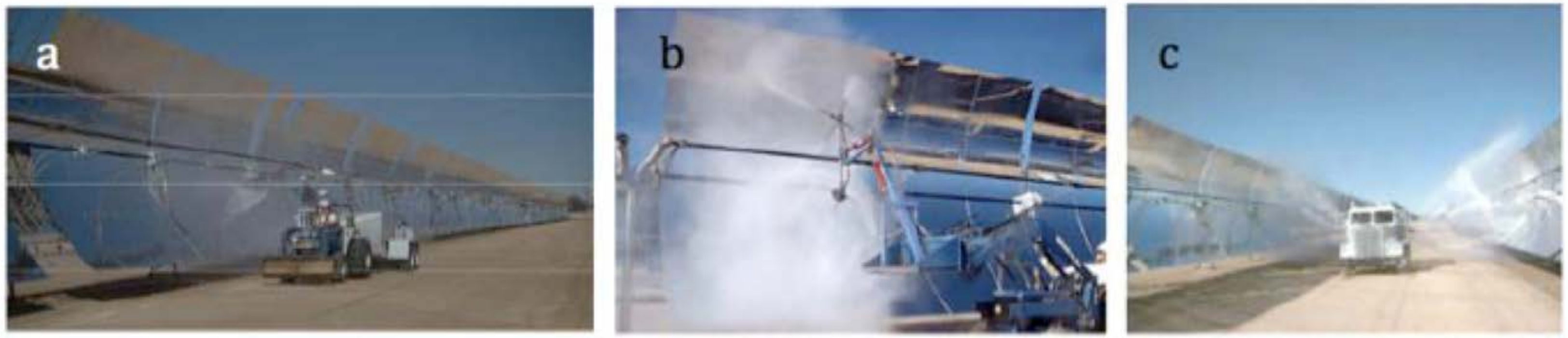


Figure 2: Water wash methods used in the solar-thermal industry [1]. (a) Traditional spray (b) High-pressure spray (c) Deluge-type cleaning

[1] G.E. Cohen, D.W. Kearney, and G.J. Kolb, "Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants," Sandia Lab Report on CSP SAND99-1290.

Power Tower Technology

During daylight hours, 2000 mirrors at Solar Two track the sun and store its energy as heat in molten salt. This energy can then be used to generate electricity when needed, such as during periods of peak demand for power.

Image courtesy of DOE.

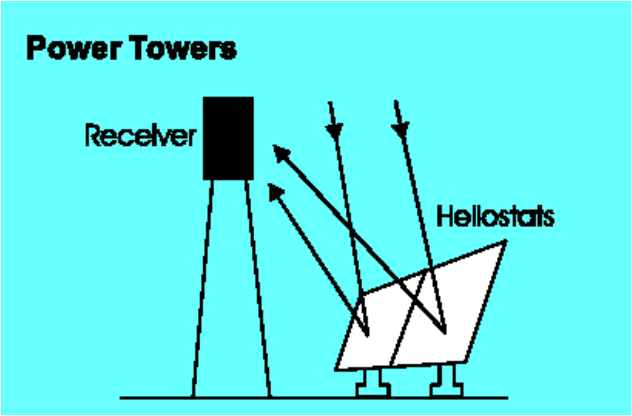


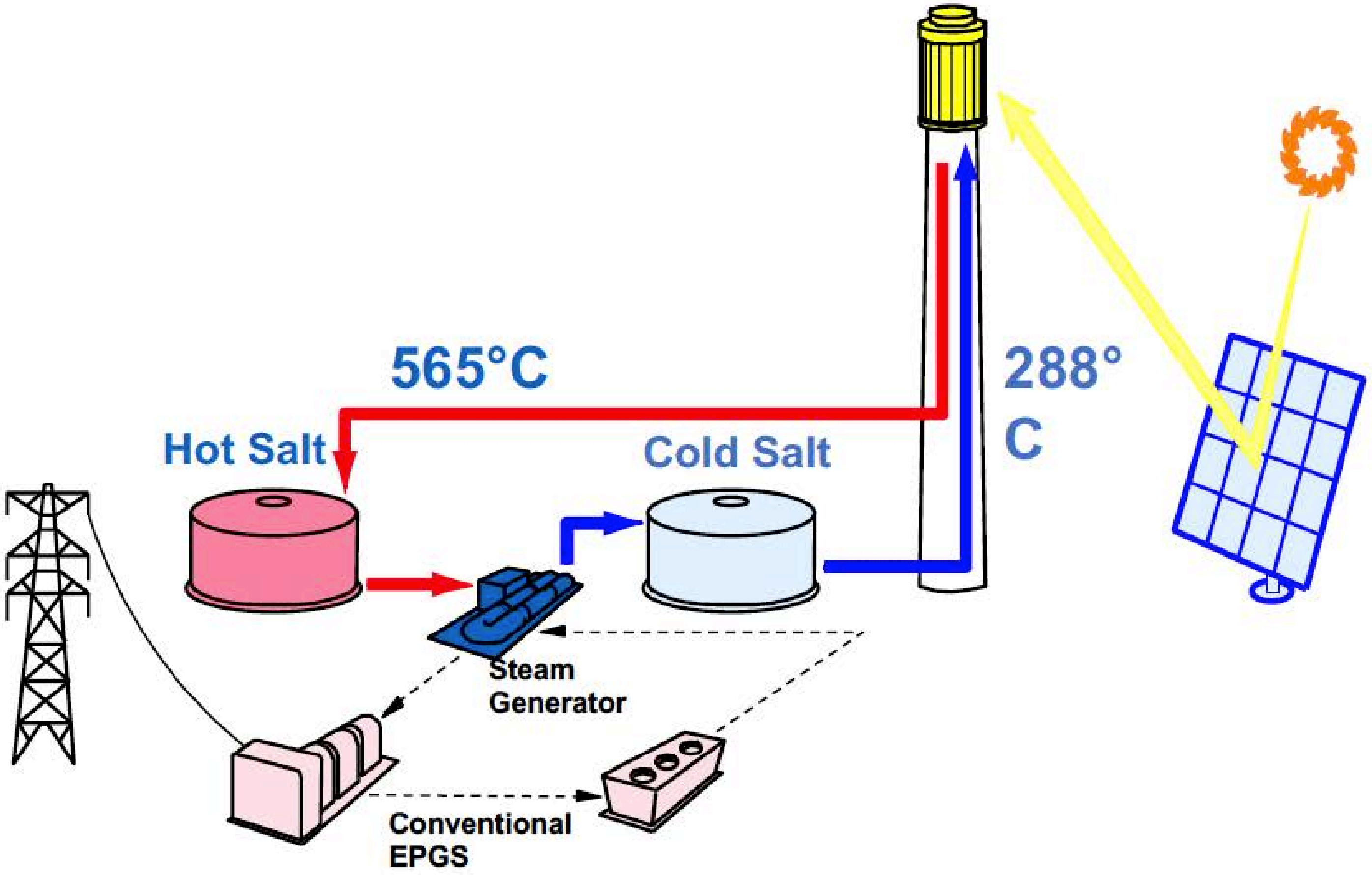
Image courtesy of DOE.

Power Tower systems use a circular field array of heliostats (large individually-tracking mirrors) to focus sunlight onto a central receiver mounted on top of a tower (Figure 2). The first power tower, Solar One, which was built in Southern California and operated in the mid-1980's, used a water/steam system to generate 10 MW of power. In 1992, a consortium of U.S. utilities banded together to retrofit Solar One to demonstrate a molten-salt receiver and thermal storage system.

The addition of this thermal storage capability makes power towers unique among solar technologies by promising dispatchable power at load factors of up to 65%. In this system, molten-salt is pumped from a "cold" tank at 288ºC (550ºF) and cycled through the receiver where it is heated to 565ºC (1,049ºF) 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.

"Solar Two" first generated power in April 1996, and is scheduled to run for a 3-year test, evaluation, and power production phase to prove the molten-salt technology. The successful completion of Solar Two should facilitate the early commercial deployment of power towers in the 30 to 200 MW range.

Dispatchable Power Requires Storage



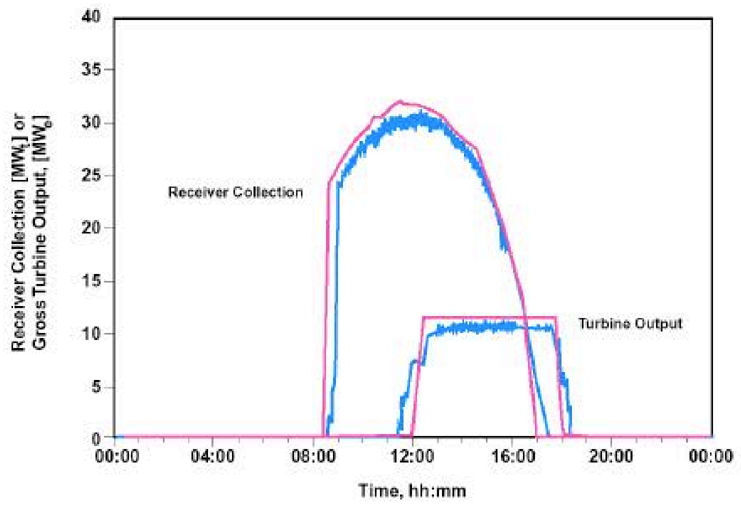


Image courtesy of DOE.

2009, Near Lancaster, CA

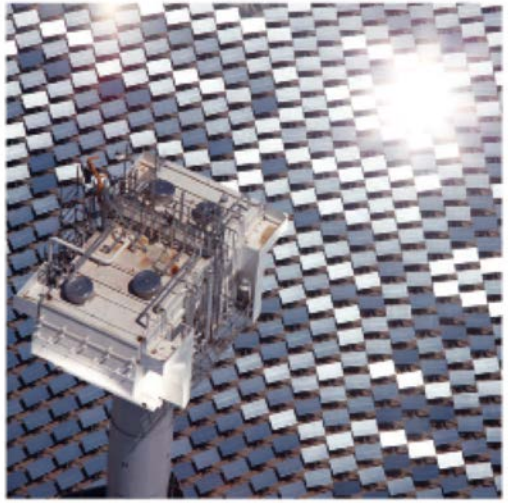
The eSolar Module

- 10 acres
- 1 tower
- 1 thermal receiver
- 12,000 mirrors reflecting the power of 10,000 suns
- 2.5 MW powering 2,000 households with clean, renewable energy

Sierra SunTower Quick Facts

- 2 modules
- 20 acres
- 2 towers
- 2 65-ton thermal receivers
- 1 refurbished 1947 GE steam turbine generator
- 24,000 mirrors reflecting the power of 20,000 suns
- 5 MW of clean, renewable energy supplied to 4,000 Southern California Edison households through a power purchase agreement
- Only operating solar thermal power tower plant in the US

eSolar is a responsible steward of our shared natural resources.



Solar Dish + Stirling Engine/Micro turbine

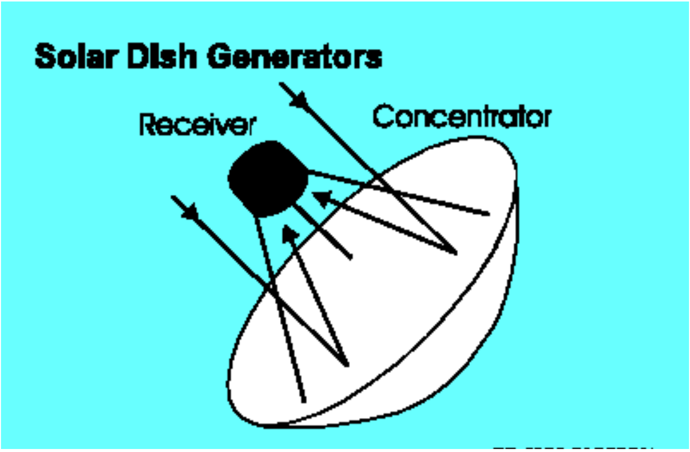
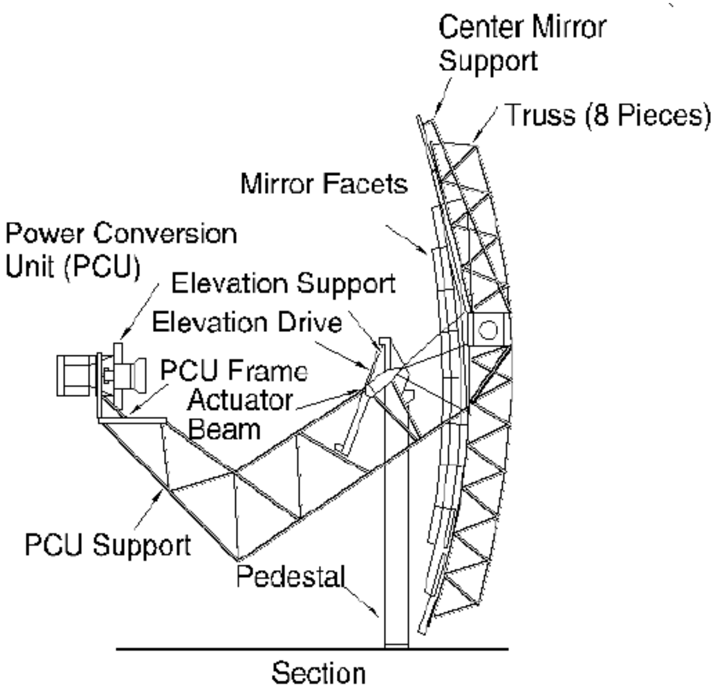


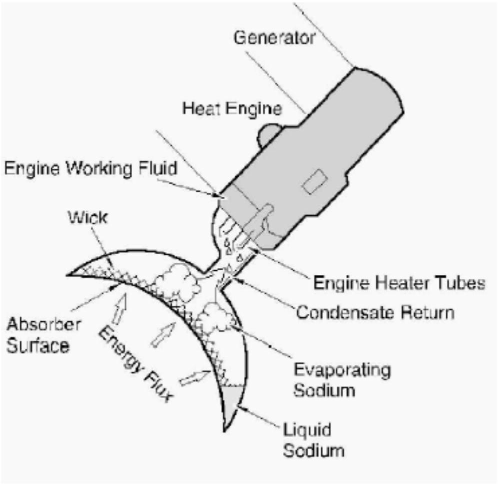
Image courtesy of DOE.

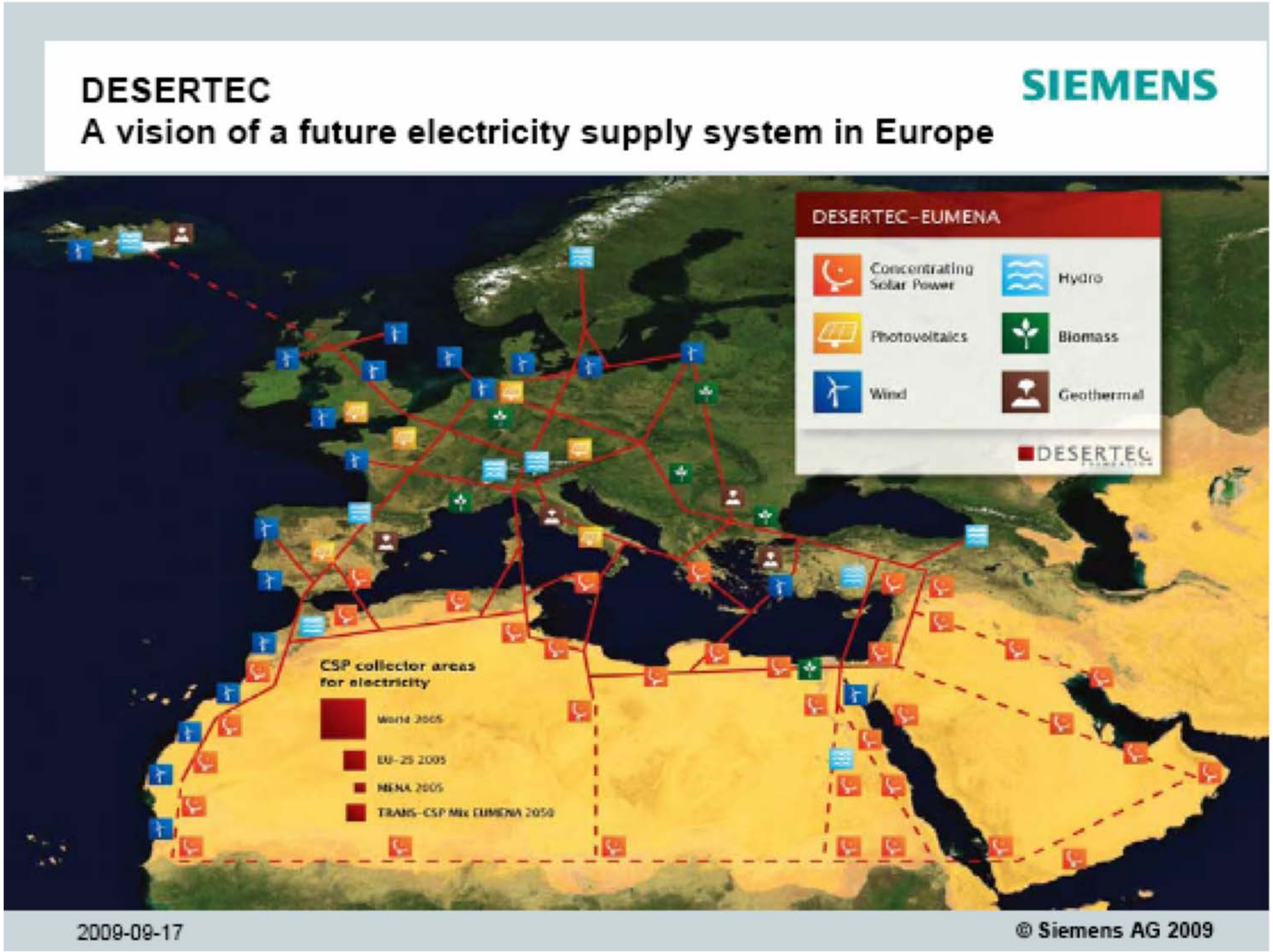


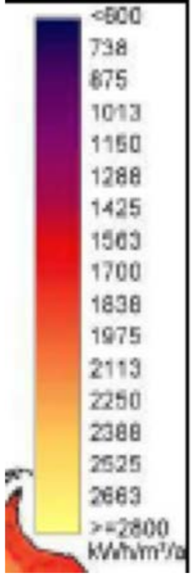
A parabolic dish mirror concentrates the energy onto the engine hot side. T ~ 750 C is achievable. Stirling engines or micro gas turbine could be used with 10-25 kW. Overall efficiency close to 30%

CSP Dish/Converter Systems

- Technology Features:
  - High efficiency (Peak > 30% net solar-to-electric)
  - Modularity (10, 25kW)
  - Autonomous operation
  - Hybrid capabilities (no storage)
  - Stirling and, in future, Brayton engines and CPV




DESERTEC
A vision of a future electricity supply system in Europe
SIEMENS
DESERTEC-EUMENA
Concentrating Solar Power
Hydro
Photovoltaics
Biomass
Wind
Geothermal
DESERTEC
CSP collector areas for electricity
World 2005
EU-25 2005
MENA 2005
TRANS-CSP Mix EUMENA 2050
2009-09-17
© Siemens AG 2009



The solar potential in the MENA Region

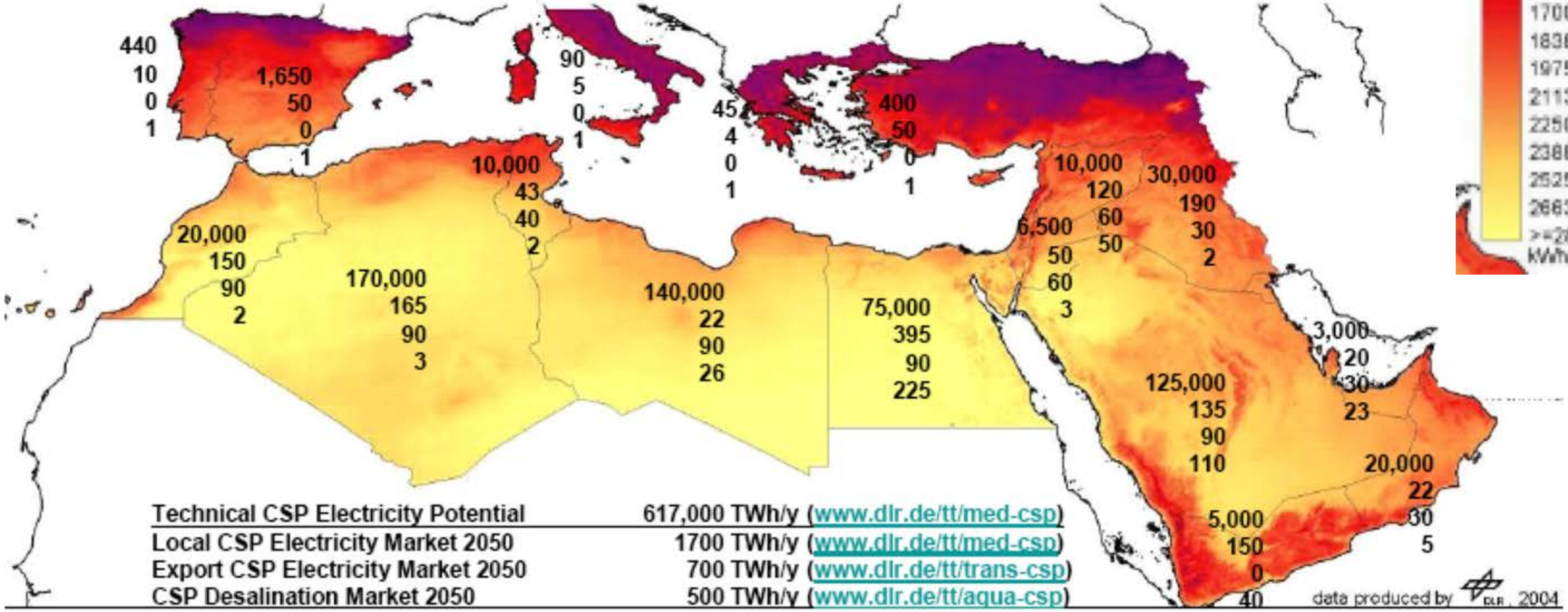


Figure 4-1: Concentrating Solar Power Potentials until 2050 in TWh/y. Techno-economic supply-side potential (top), potential for local electricity (second from top), potential for electricity export from MENA to Europe (third from top) and potential for seawater desalination (bottom). For better comparison, desalination potentials have been converted to electricity required by reverse osmosis. Background: Fig. 1-13.

AQUA-CSP: Concentrating solar power for seawater desalination
German Aerospace Center (DLR) http://www.dlr.de/tt/aqua-csp

Operating Hybrid Combined Cycle Solar Plant

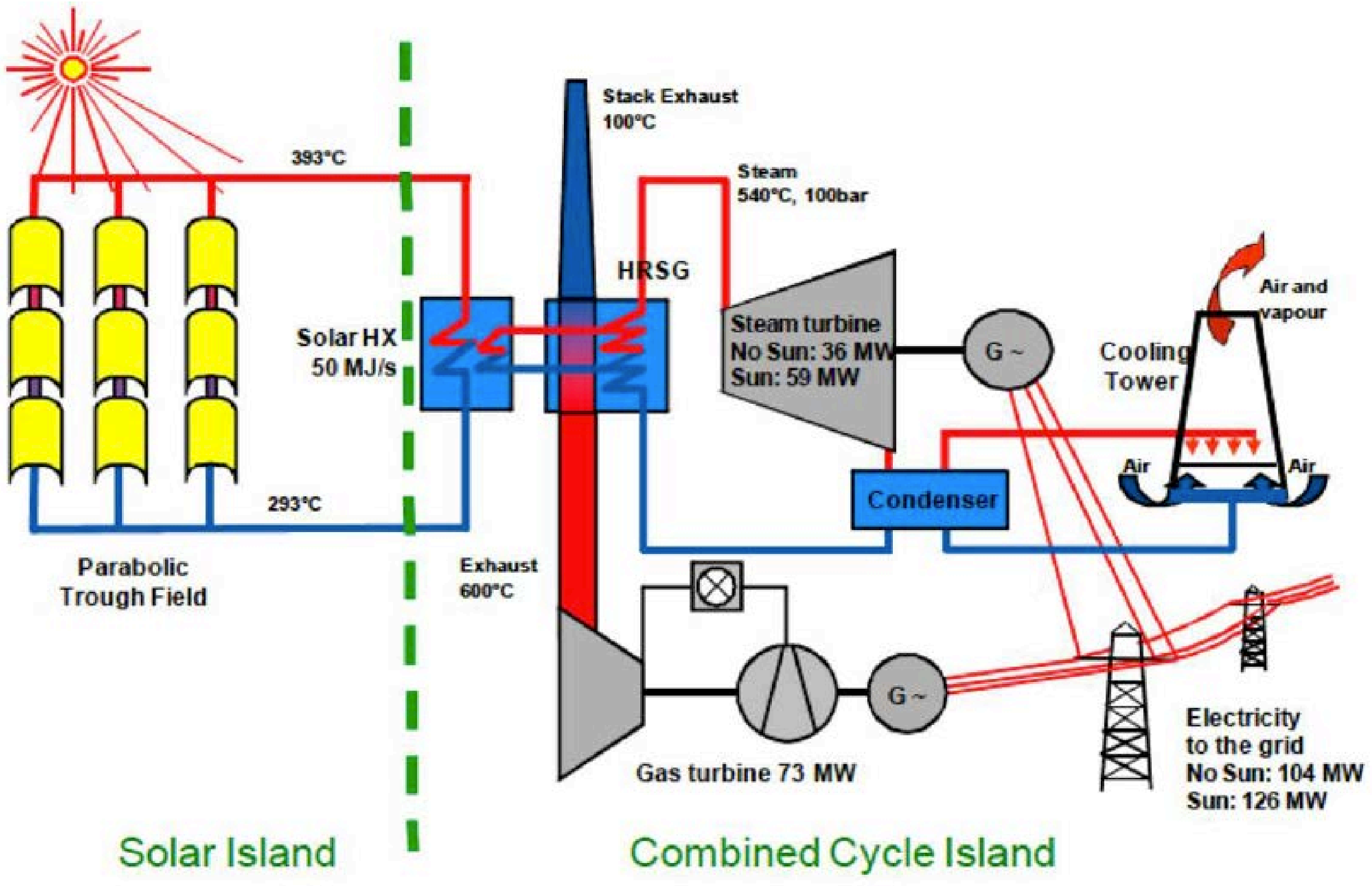


Figure 3-1 Scope Split and General Concept of the ISCC Kuraymat

Table 1 shows the technical key data for the ISCC Kuraymat according to the EPC contract and the latest construction design. The design thermal power of the Solar Island will be reached for DNI values between 700 and 800 Watt/m² depending on incident angle and status of the solar field (Number of loops in operation, tracking accuracy, mirror reflectivity etc.).

Key Technical Data		
	Unit	**Value**
Solar Field total Aperture Area	m^2	130800
Number of Collectors	N°	160
Number of Collector Loops	N°	40
Design Irradiation	W/m^2	700
Solar Field Design Thermal Power at Reference Conditions	MJ/s	50
Hot Leg HTF Temperature	°C	393
Cold Leg HTF Temperature	°C	293
Gas Turbine Generator Rated Power Output	MWe	74,4
Steam Turbine Generator Rated Power Output	MWe	59,5

Table 1 Key Technical Data

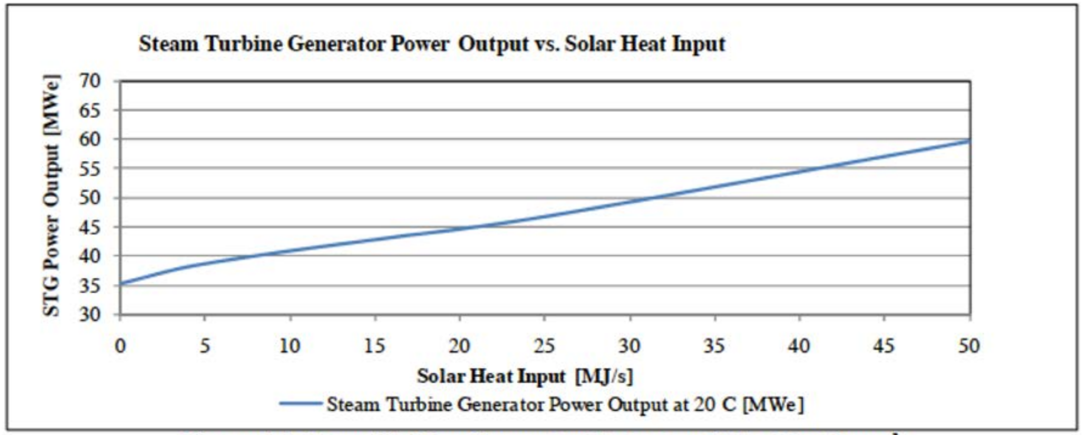
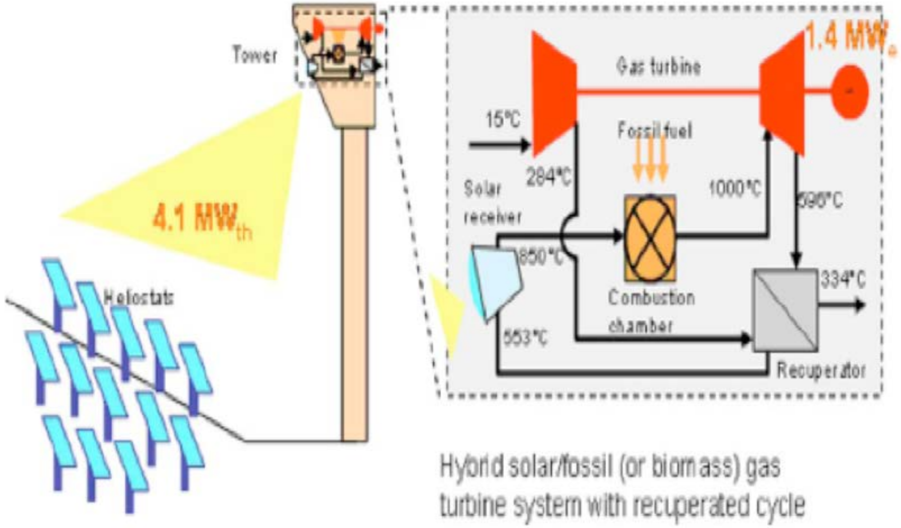


Figure 5-1 Steam Turbine Generator Output vs. Solar Heat Input[1]

AORA solar gas turbine hybrid system
100 kW electricity
170 kW heat

No longer operating, problems with the concentrator and heliostat



Hybrid solar/fossil (or biomass) gas turbine system with recuperated cycle

Located in the Western Region of Abu Dhabi, the 100-megawatt, grid connected power plant generates clean energy to power 20,000 homes in the UAE (**2012**).

Shams 1 was designed and developed by Shams Power Company, a joint venture between Masdar (60 percent), Total (20 percent) and Abengoa Solar (20 percent).

Covering an area of 2.5 km^2 – or 285 football fields – Shams 1 incorporates the latest in parabolic trough technology and features more than 258,000 mirrors mounted on 768 tracking parabolic trough collectors.

The CSP project reduces the UAE's carbon emissions, displacing approximately 175,000 tonnes of CO_2 per year, an equivalent to planting 1.5 million trees, or taking 15,000 cars off the road.

Solar Chimney

the Hydroelectric Power for the desert”

$$V_{ch} = \sqrt{\frac{\Delta T}{T} 2gH_{ch}}$$

Operated in Spain, 1982-89
From Encyclopedia of Physical Science and Technology, 2000
Article by J Schlaich and W Schiel

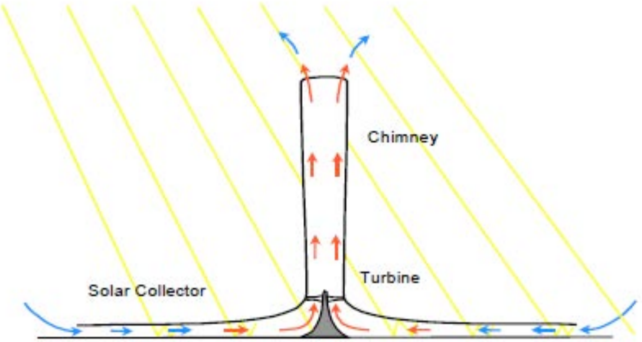


Fig. 1. Principle of the solar chimney: glass roof collector, chimney tube , wind turbines.

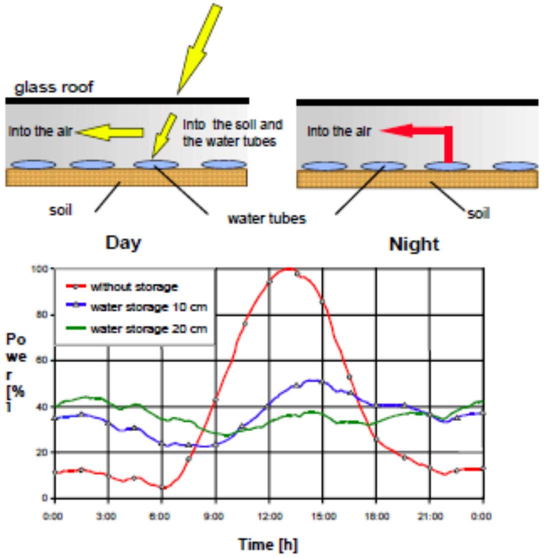


Fig. 2. Principle of heat storage underneath the roof using water-filled black tubes.

The principle dimensions and technical data for the facility are:

- Chimney height: HT = 194.6 m
- Chimney radius: RT = 5.08 m
- Mean collector radius: RC = 122.0 m
- Mean roof height: HC = 1.85 m
- Number of turbine blades: 4
- Blade: length 5 m, profile FX W-151-A tip-to-wind speed ratio: 1 : 10

- Transmission ratio: 1 : 10
- Operation: stand-alone or grid connection mode
- Heating in collector: ΔT = 20° C
- Nominal output: 50 kW
- Roof covered with plastic: 40,000 m²
- Roof covered with glass: 6000 m²

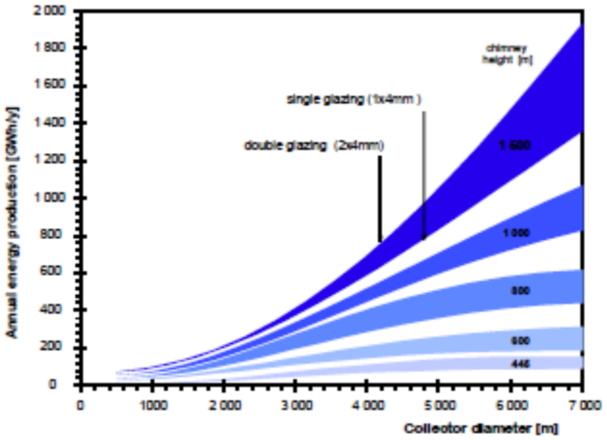


Fig. 3. Annual energy production by a Solar Chimney (at 2300kwh/m²/a global insolation) dependent on collector diameter and chimney height.

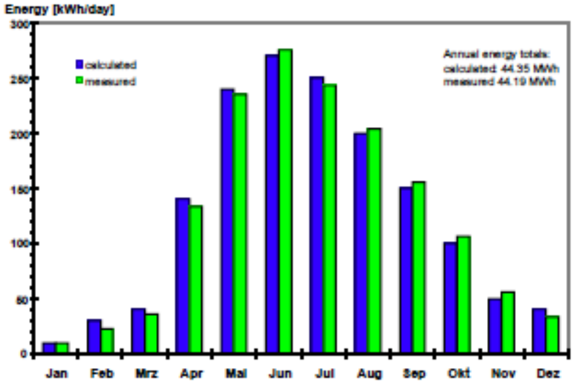
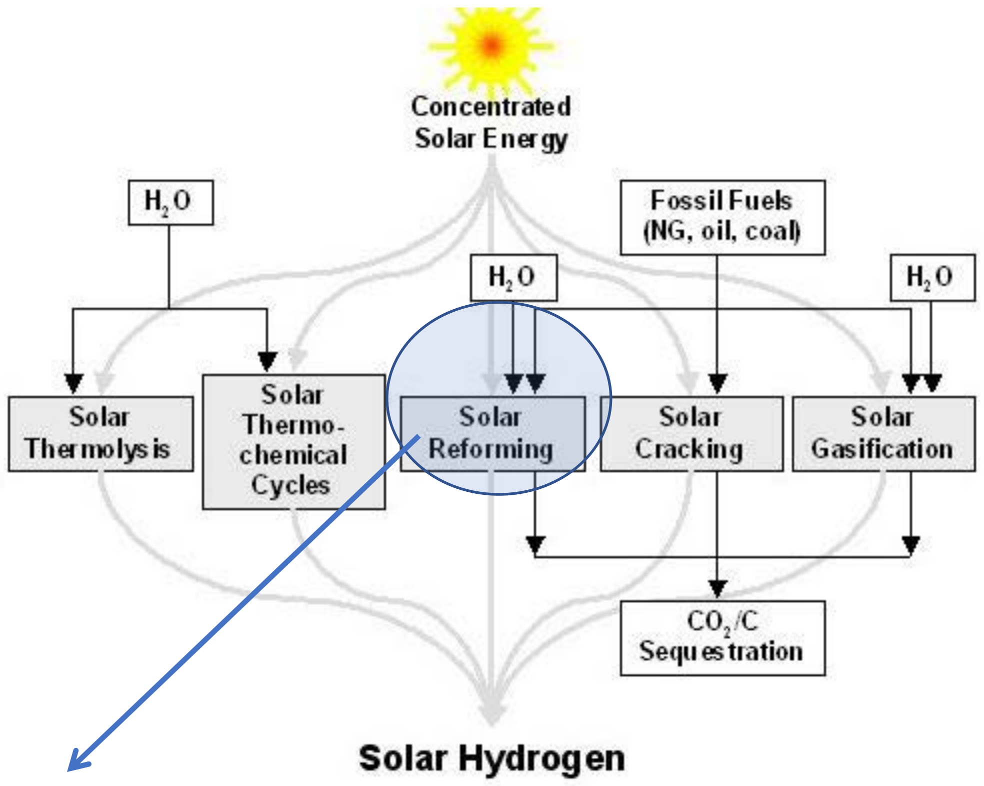


Fig. 9. Comparison of measured and calculated monthly energy outputs for the Manzanares plant.

Many trends in Solar Chemical Hybrid Systems

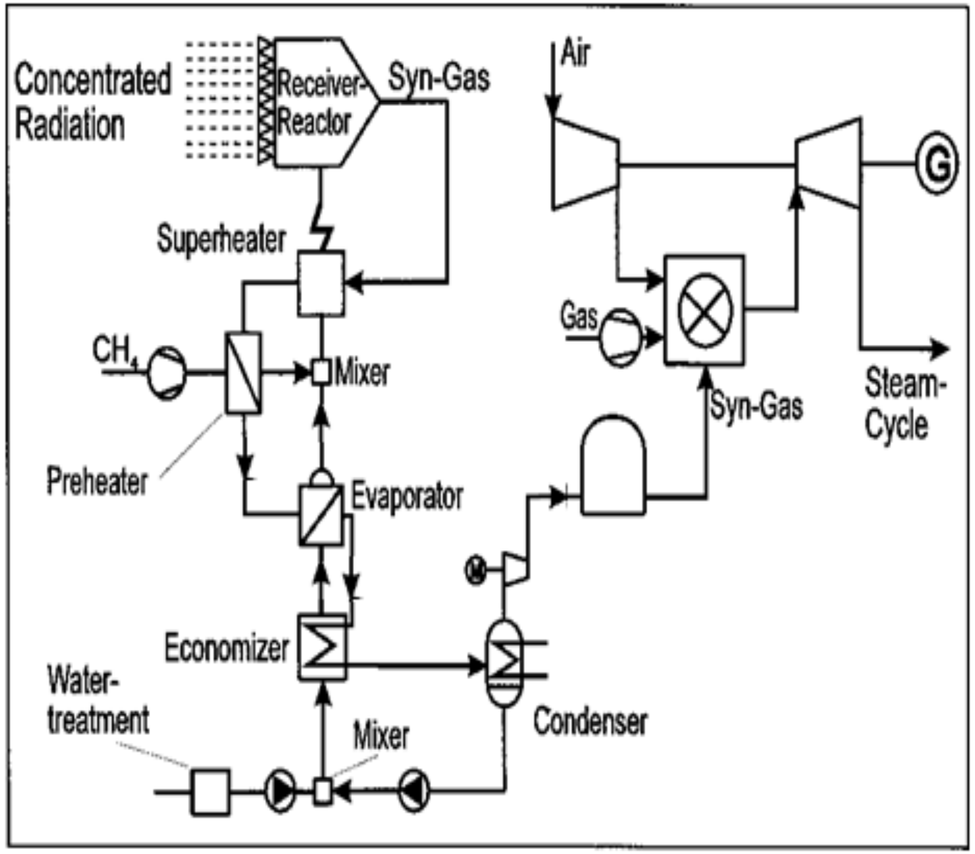
Water splitting using solar heat, or steam reforming, cracking or gasification of fuels (gas, liquid and solids).

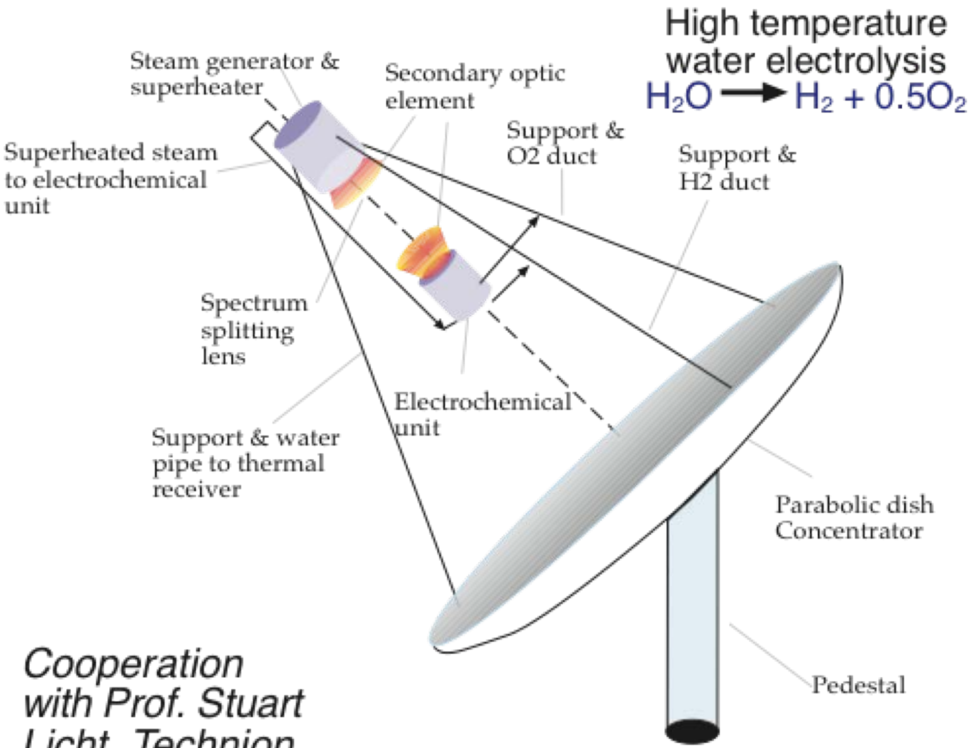


"Solar fuels" is a very active research area in many leading institutions and the subject on newly awarded large centers in the US>

Potential: Low temperature solar thermal chemical process

H_2 or Syngas Production Using Solar Energy

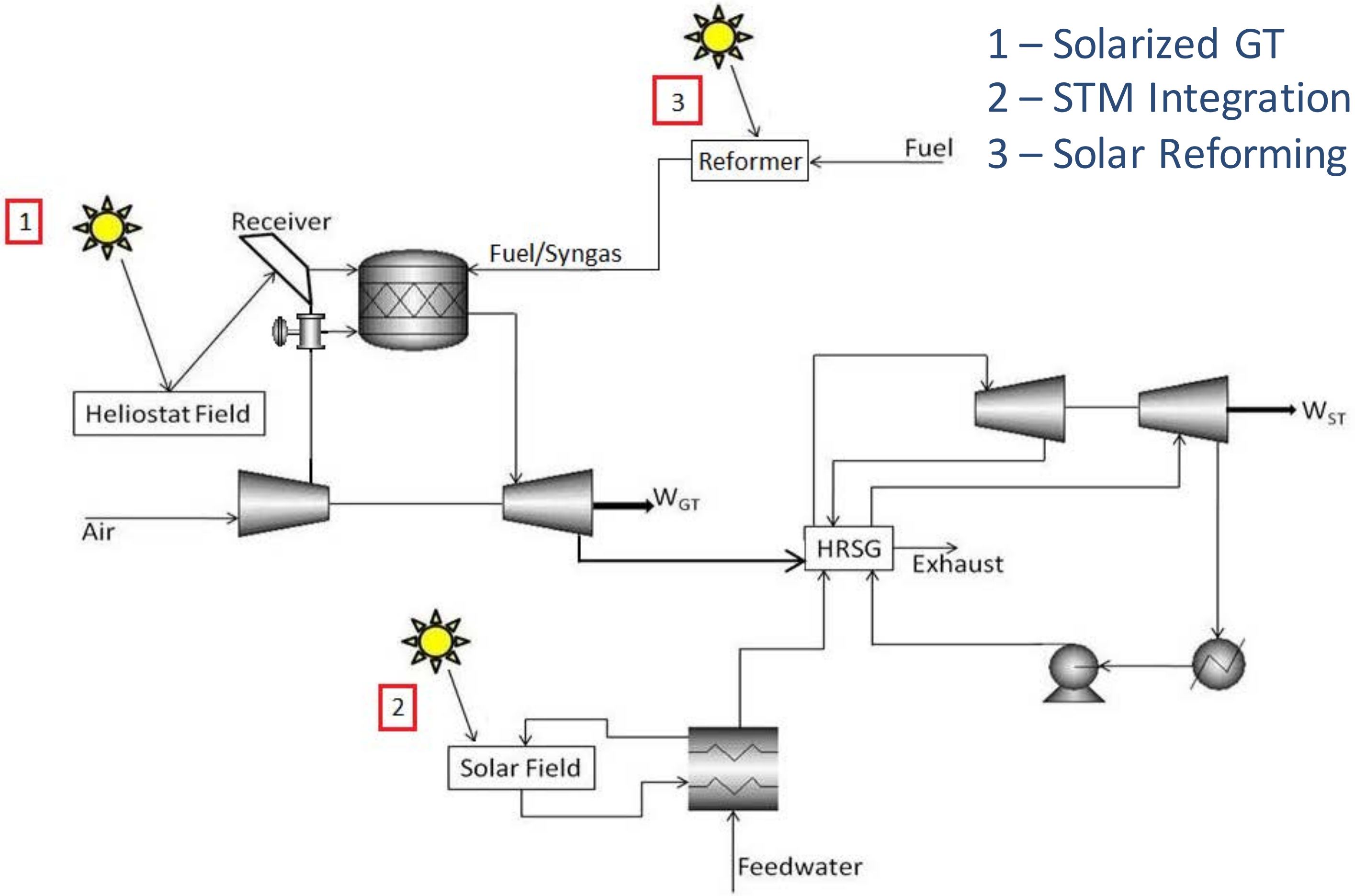




Cooperation with Prof. Stuart Licht, Technion

Three Hybridization Schemes

1 – Solarized GT
2 – STM Integration
3 – Solar Reforming

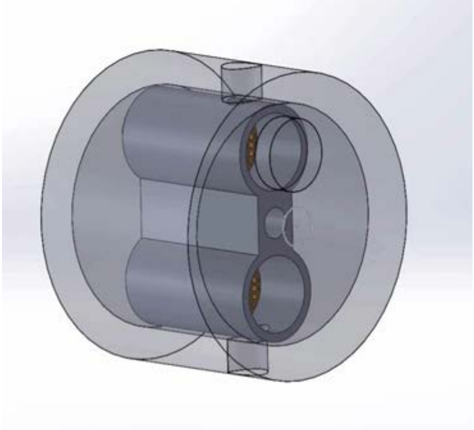


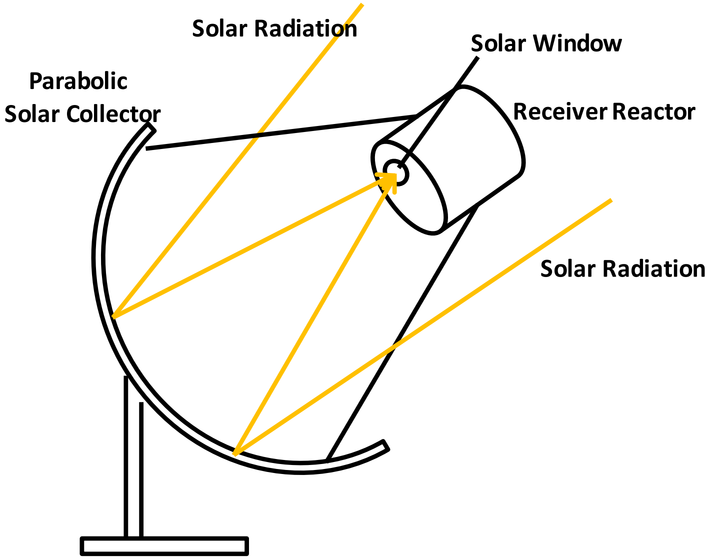
J. Sheu and A. F. Ghoniem. *International Journal of Hydrogen Energy*, 39(27): 14817-14833, 2014
E. J. Sheu, E. M. A. Mokheimer, and A. F. Ghoniem, *Journal of Hydrogen Energy*, 40(7): 2939-2949, 2015

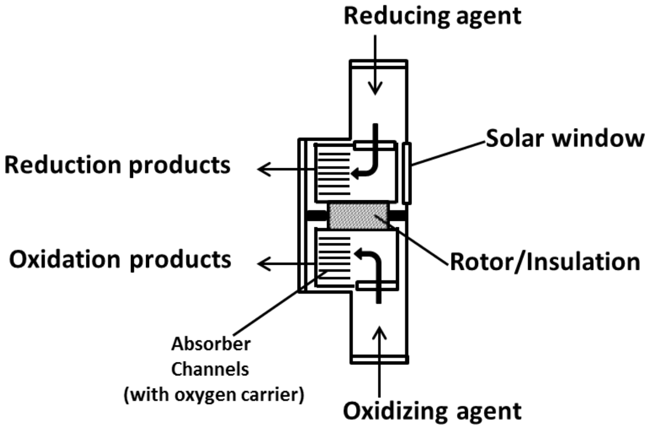
Solar Fuels?

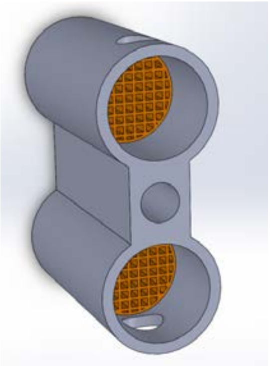
Metal	Reduction/oxidation reactions
Copper	$CuO + CH_4 \rightarrow Cu + CO + 2H_2 \quad \Delta H^o = 120.40$ kJ/mol
	$Cu + H_2O(v) \rightarrow CuO + H_2 \quad \Delta H^o = 85.77$ kJ/mol
Nickel	$NiO + CH_4 \rightarrow Ni + CO + 2H_2 \quad \Delta H^o = 204.03$ kJ/mol
	$Ni + H_2O(v) \rightarrow NiO + H_2 \quad \Delta H^o = 2.125$ kJ/mol
Iron	$\frac{1}{4}Fe_3O_4 + CH_4 \rightarrow \frac{3}{4}Fe + CO + 2H_2 \quad \Delta H^o = 243.93$ kJ/mol
	$\frac{3}{4}Fe + H_2O(v) \rightarrow \frac{1}{4}Fe_3O_4 + H_2 \quad \Delta H^o = -37.77$ kJ/mol

Novel, looping based reformer









E. J. Sheu, E. M. A. Mokheimer, and A. F. Ghoniem. *International Journal of Hydrogen Energy*, 40(38): 12929-12955, 2015
E. J. Sheu and A. F. Ghoniem*Solar Energy*, 125 (2016) 339-359. and 134 (2016), pp. 23-31.