Solar Thermal Conversion

Major Functions:

- Solar Radiation collection and concentration
- Conversion to heat
- Storage of energy
- Generation of electricity
- Use of waste heat in refrigeration and air-conditioning

Collection

The temperature to which a surface is heated by a certain flux of incident solar energy is determined by the balance of incident radiation and loss by conduction, convection and radiation.

The use of selective surfaces that absorb visible sunlight but do not lose energy by infrared radiation will achieve high temperatures.

The temperature obtained can be increased by boosting the flux of incident sunlight by use of concentrating mirrors or lenses.

A fairly low concentration ratio, obtainable with simple optics, can be combined with a selective surface to efficiently produce temperatures high enough for electrical power generation.

Three basic collection geometries of sunlight for solar thermal conversion: non-concentrating, concentrating to a line, and concentrating to a point.

Collection

Non concentrating collectors: Industrial process heat at moderate temperatures *(About 18% of the fuel consumption in the United States is for generation of industrial process heat at moderate temperatures (process steam) and another 11.5% is used for high-temperature process heat).* Low temperature heat for domestic water heating.

Concentration to a line: concentration ratios up to 20 with selective surfaces to achieve high enough temperatures for electrical generation

Point focusing: concentration ratios up to 1000, with out the need for use of selective surfaces. *(Thermochemical conversion - splitting of water to produce hydrogen)*

Focusing Systems

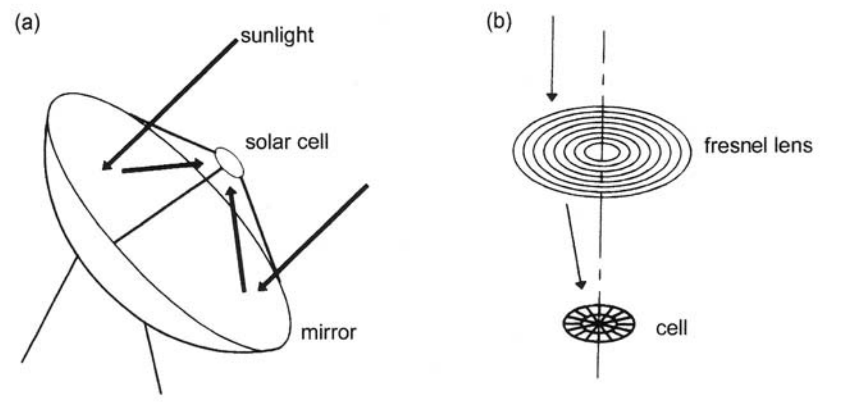


Fig. 7.5 Point-focus systems with rotational symmetry, (a) Dished parabolic mirror; (b) Fresnel lens

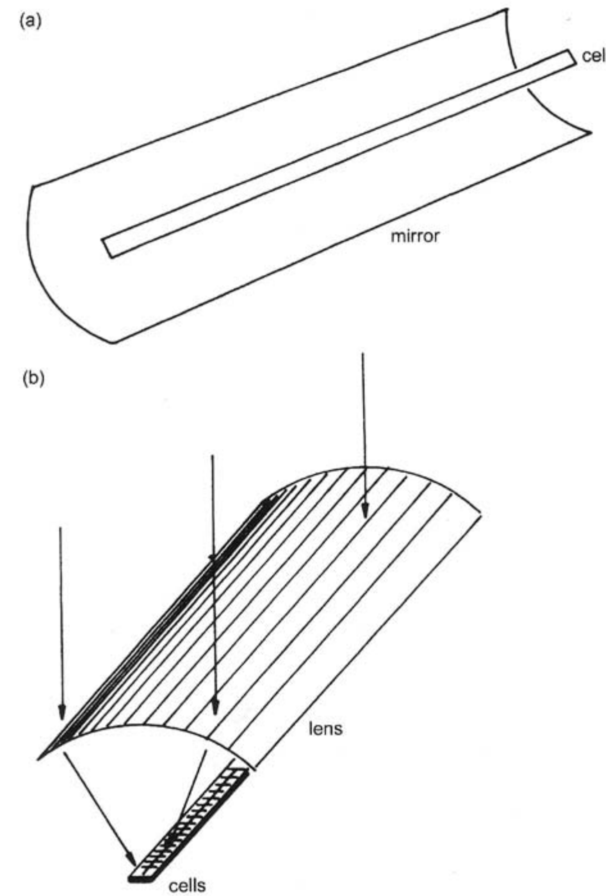
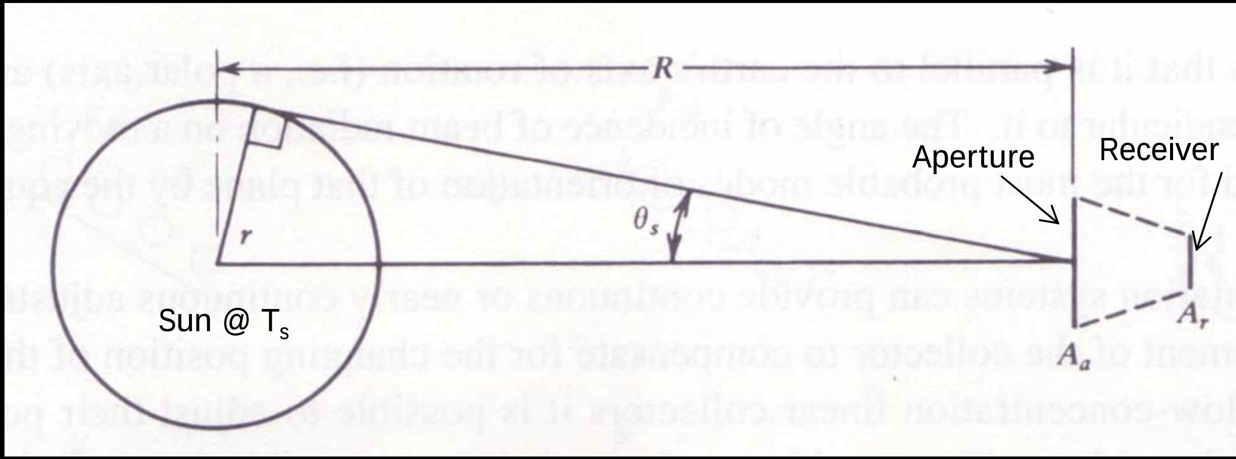


Fig. 7.6 Line-focus systems with linear symmetry. (a) Parabolic mirror; (b) Curved Fresnel lens

Concentration Ratio

Area concentration ratio (geometric):

$$C = \frac{A_a}{A_r}$$



Optical concentration ratio:

$$C_O = \frac{\frac{1}{A_r}\int I_r dA_r}{I_a}$$

I_r is the averaged irradiance

I_a is the insolation incident on the collector aperture

Historical Notes

"That 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

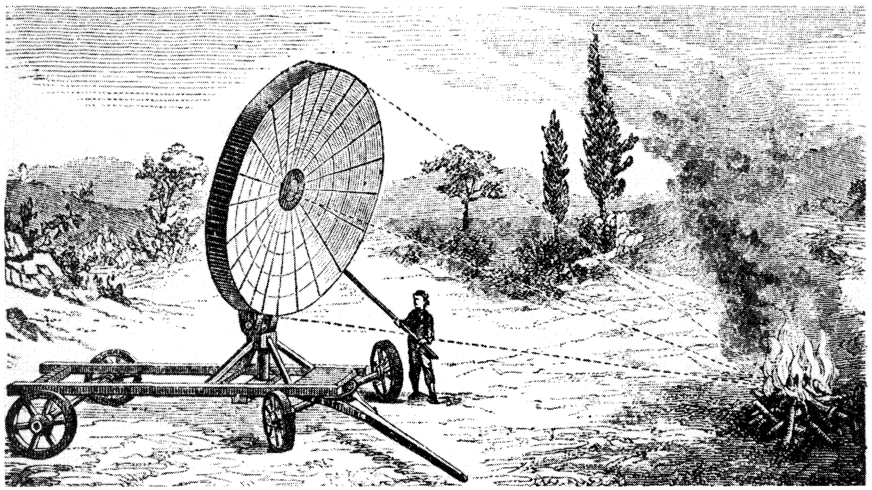
Between 1880 and 1910, there were 48 articles on solar energy as a world energy source in the pages of *Scientific American* magazine.

In 1780, 95% of total power used in commercial applications was from natural sources (wind and water).

In 1911, all but 2% of power was generated from burning coal and harnessing steam.

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

Historical Notes



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.

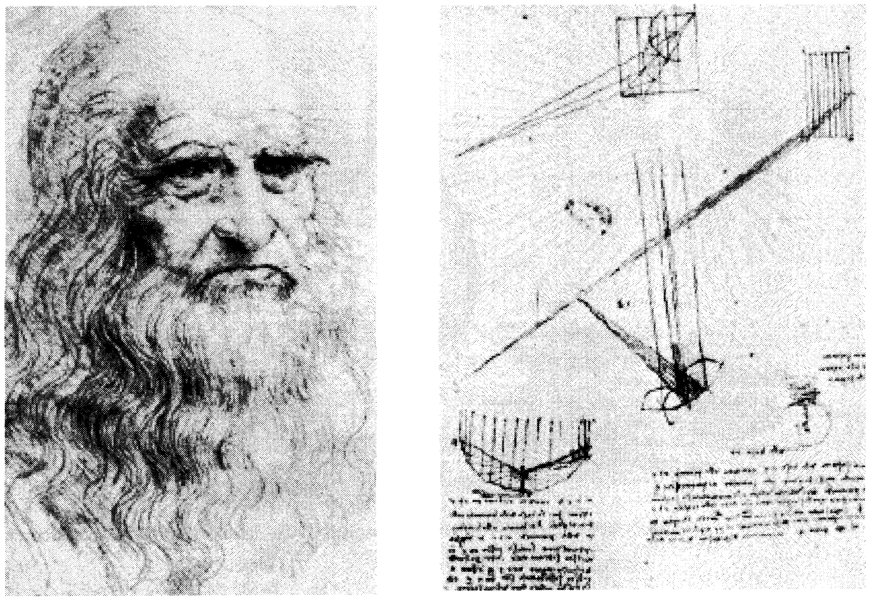
The idea that the sun's heat could be harnessed in some way as a source of immense power was not a new one even in 1900's. The power of concentrated sunlight was a theme that ran through history, going back some thousand of years.

In Mesopotamia, the temple priests may have used polished golden bowls as crude parabolic mirrors to ignite altar fires.

Abu Ali al-Hasan al-Haitham work on light and optics during 1000AD helped the development of focusing mirrors (burning mirrors).

In Rome in 1640's Father Athanasius Kircher had shown that sunlight could be concentrated at a distance using a focusing lens and mirror to ignite fires.

Leonardo Da Vinci



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

Proposed (~1515AD) to build a concave mirror 4 miles in diameter to be built in an excavated bowl-shaped recess in the ground - a source of heat and power to run commercial enterprises, not as a weapon of war. The focal point of the giant mirror was to be 13 feet. A tall pole on a central axis would hold the materials to be heated.

Performed experiments with models of giant concave mirrors made up of a mosaic of flat pieces of mirrored glass glued to the bottom of a bowl.

Used varnish to silver concave mirrors to improve their reflectivity and calculated to quantify the degree to which the sun's rays could be concentrated.

The Sun Power Company - 1910

The conversion of solar energy into mechanical power was attempted as a commercial venture by the Sun Power Company in Pennsylvania by Frank Shuman.

Alfred Ackerman, a Londoner and an engineer suggested that the following criteria must be met to have a successful solar power plant.

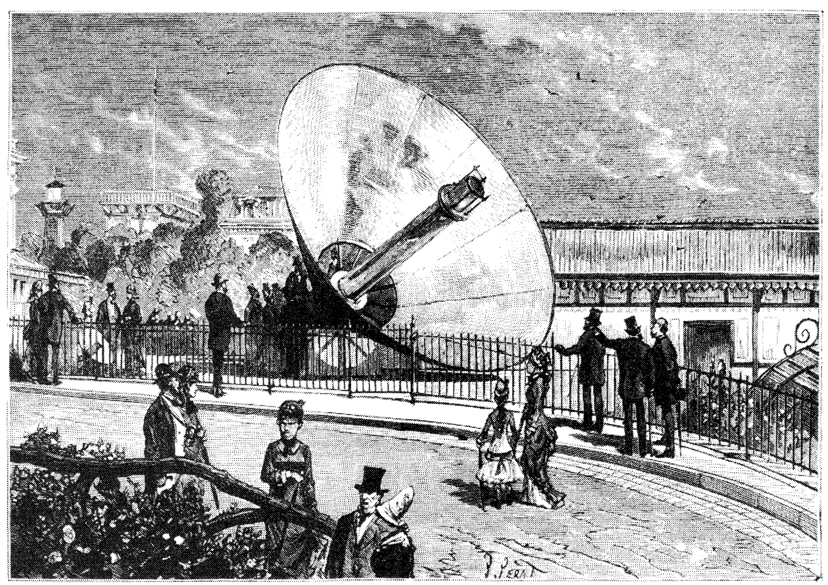
It should be sold as a complete package to the consumer as an inexpensive and reliable mechanical power, not solar energy collection.

If sun power was to be put to practical use, that some method for storing energy was essential.

Simplifying construction of heat absorbers to lower their cost.

First Solar Powered Machine

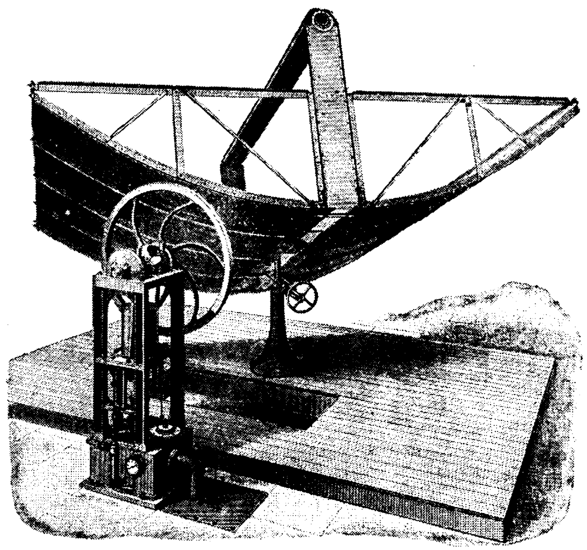
Augustin Mouchot in 1878 built a solar powered machine to power a printing press. The inverted cone shaped solar reflector made of copper sheets coated with burnished silver had a total reflecting surface of 56 ft^2. A small central boiler located along the axis of the collector produced the steam to drive a 1/2 horse power engine at 80 strokes per minute. To store energy for future use, Mouchot had tried breaking water into its atomic components, hydrogen and oxygen.



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.

Ericsson Solar Motor- 1880

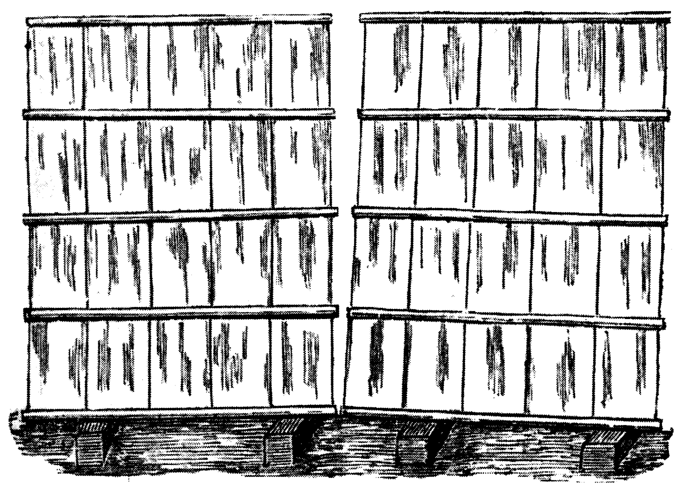
John Ericsson devised a hot-air engine to run on solar heat, that took cool air into a cylinder, heated it, and used its expansive force to move a piston. Pistons could push its flywheel at 400 rpm. He also invented the solar calorimeter for measuring the intensity of solar radiation.



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.

William Adams-1860

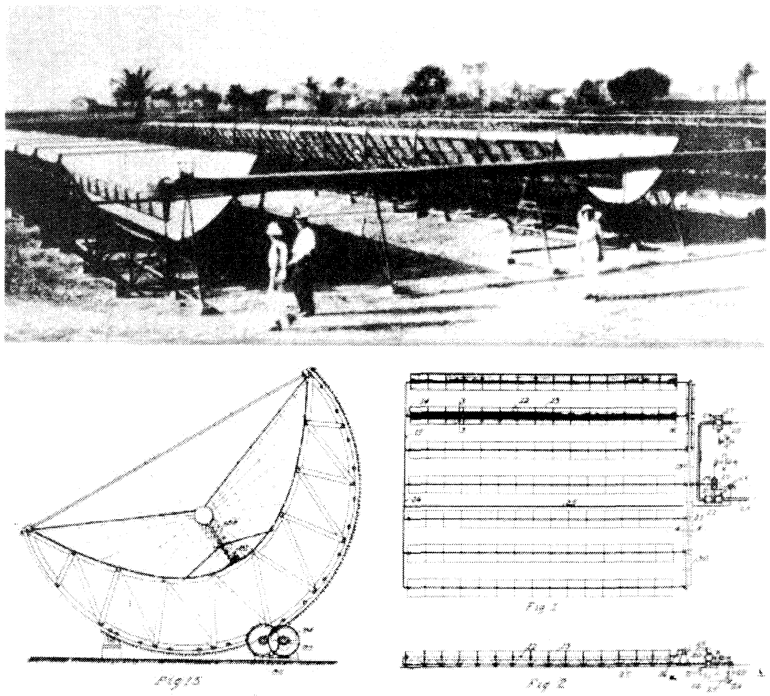
Solar Heat - a substitute for fuel in tropical countries - 1878



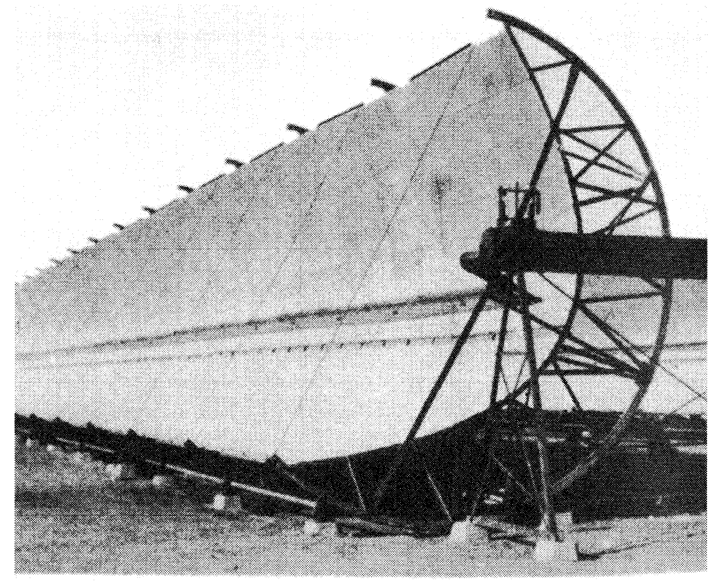
Two banks of the giant compound concave mirror Adams built to heat a 12-gallon boiler.

Bombay, India

Solar Powered Irrigation in Egypt -1913

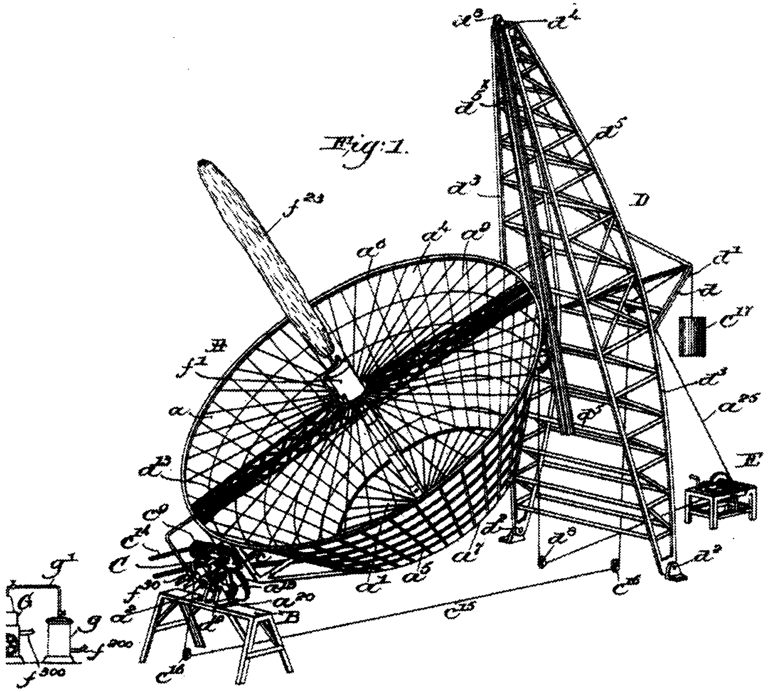


Frank Shuman's Maadi plant in Egypt, with cutaway diagram of the parabolic trough collectors.

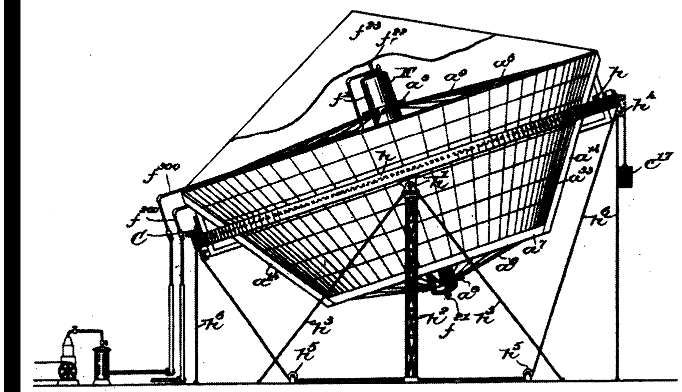


Frank Shuman's Maadi parabolic troughs, close up.

Irrigating Arizona Desert - 1903

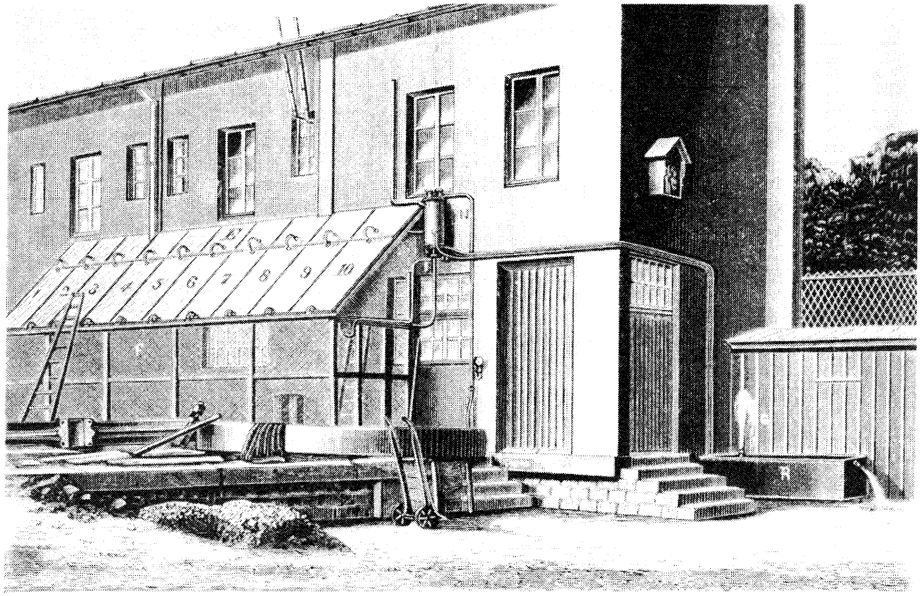


Patent drawing for Aubrey Eneas's second solar motor, 1899. To follow the sun's motion, the truncated cone mirror was moved along a track in tower scaffolding at right.



the Eneas solar collector.

Tellier Flat-Plate Collector - 1885



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.

Two iron sheets riveted together to form a watertight seal. Ammonia was used as a working fluid under pressure, because of its lower boiling point.

Henry Willsie and John Boyle - 1904

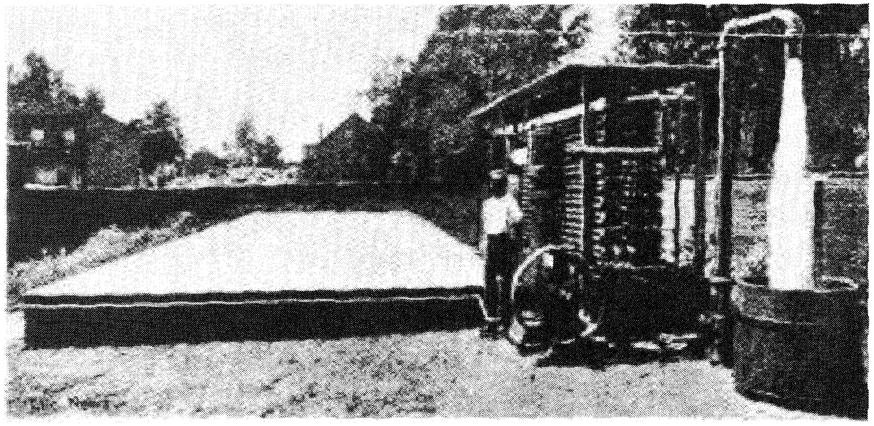
A simple hot box collector (a shallow, rectangular wooden box covered by two panes of glass and filled with three inches of water) in which warmed water vaporized liquid sulfur dioxide to power a small engine. Use hot water (~190^{o}F) to transfer solar heat from the collector to a low boiling point liquid in a separate system of pipes. The heat would be transferred from the hot water under atmospheric conditions to the high-pressure vapor in a separate sealed system.

On Commercial Viability

A sun-power plant in order to be practicable, must possess, first, high efficiency; low cost of installation and maintenance; well marked length of service; and should require no specially trained mechanics for its operation.

The fact that after installation 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


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

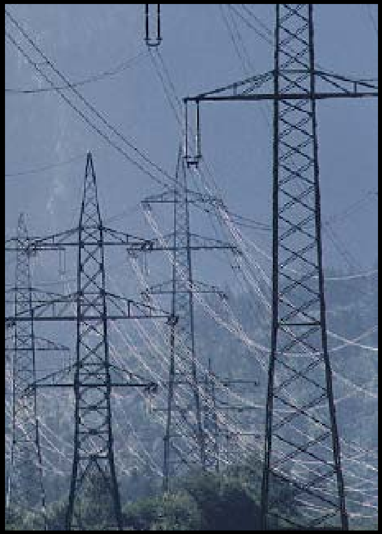
Concentrating Solar Power - Today

Heat from concentrating solar thermal collectors drive steam, gas turbines or piston engines to deliver electricity or combined heat and power.

Steam

Power

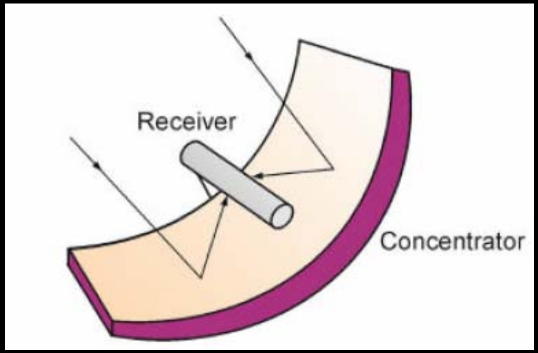
Reject Heat



Parabolic Trough

Solar Electricity Generating System (SEGS)

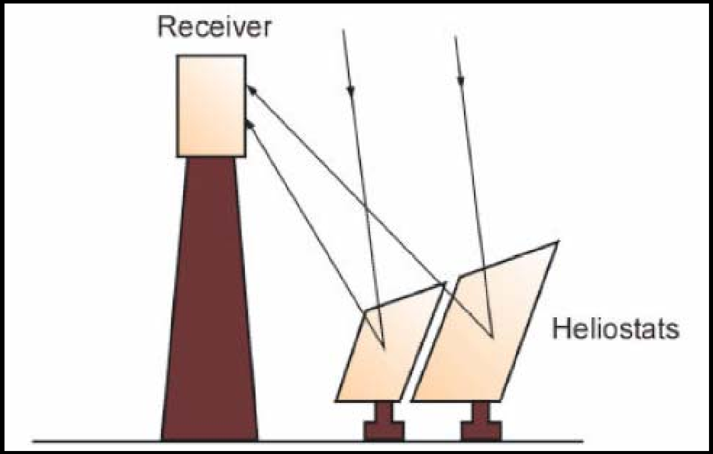
cycle: steam turbine, CHP
status: commercial, 80 MW
projects ahead:
50 - 150 MW, Spain, India, Mexico, Egypt, Morocco, Crete, Jordan, USA, South Africa ....



oil (1-3 bar / 390 °C)
steam (100 bar / 390 - 550 °C)

Source: Dr. Franz Trieb, German Aerospace Center (DLR)

Solar Power Tower

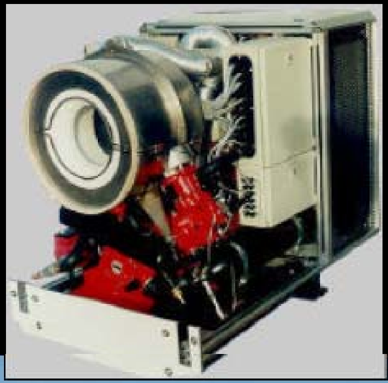


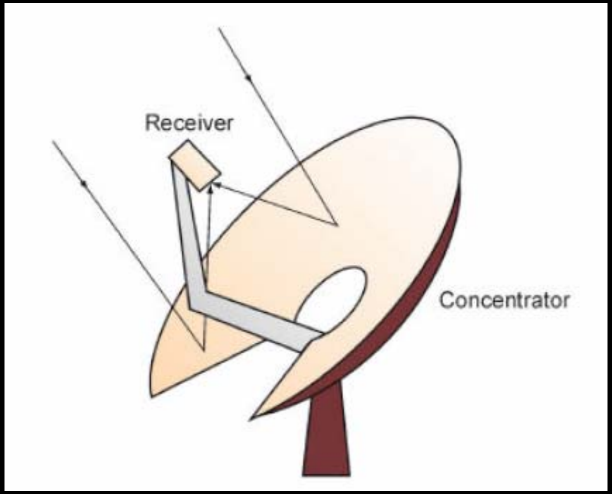
air (1 - 15 bar / 800 - 1200 °C)

cycle: steam turbine, gas turbine, combined cycle, CHP (Combined Heat & Power)
status: prototype, demonstration
projects ahead: Spain
PS10 (10 MW steam cycle)
SOLGATE (250 kW gas turbine)

Source: Dr. Franz Trieb, German Aerospace Center (DLR)

Parabolic Dish



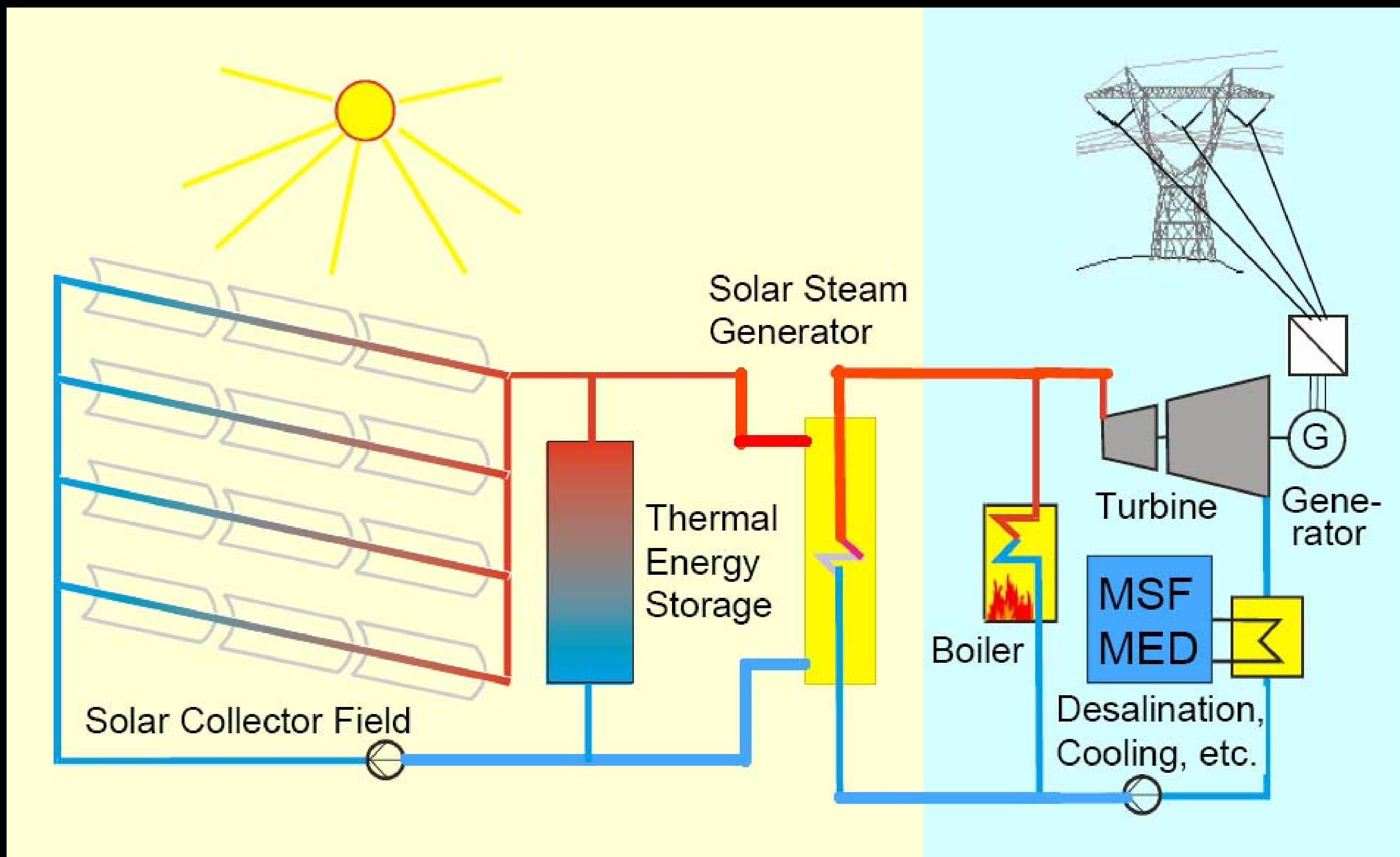


helium (50 - 200 bar / 600 - 1200 °C)

cycle: Stirling engine
status: prototype, demonstration
projects ahead:
EURO-DISH, 10 kW series

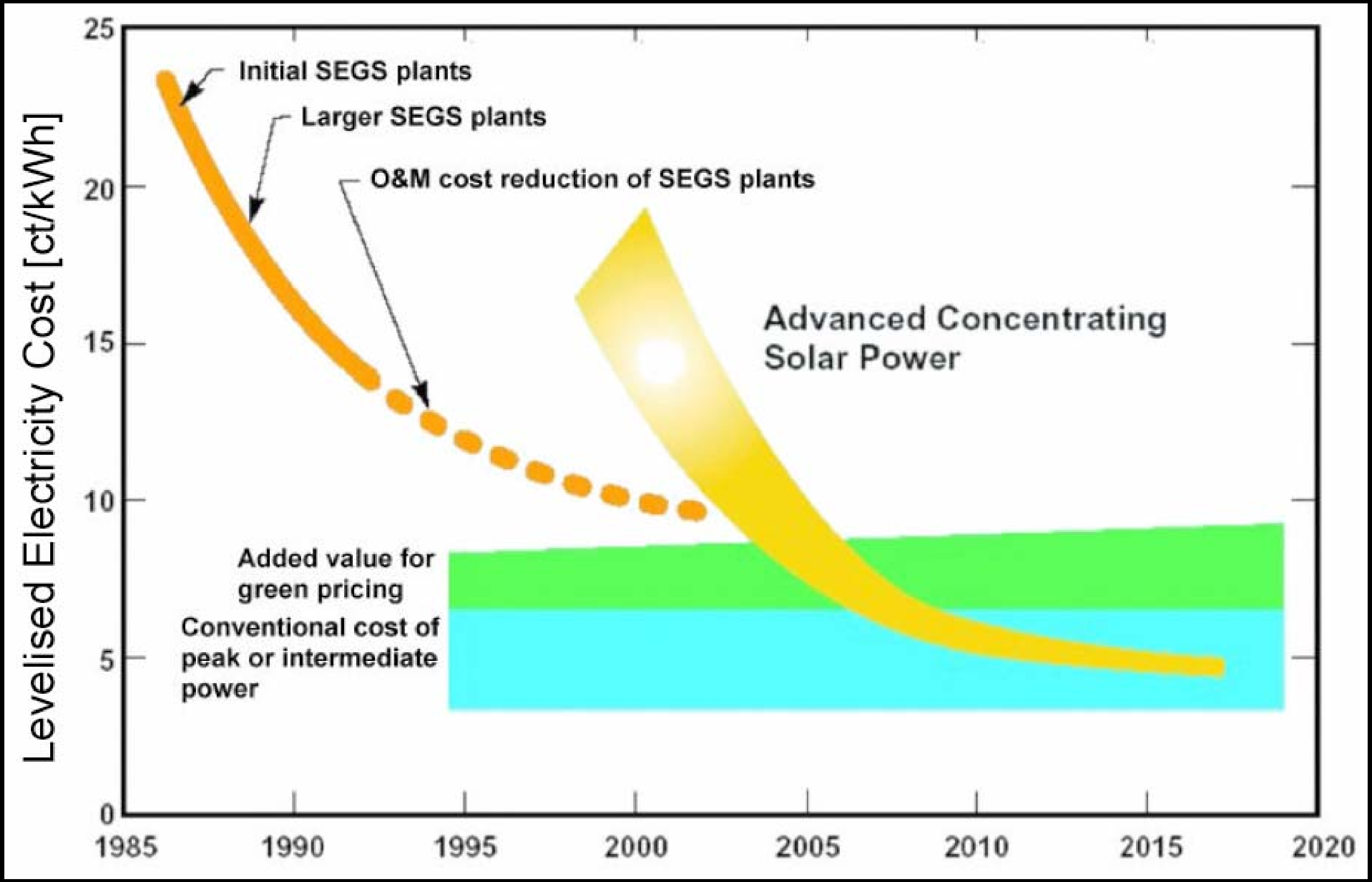
Source: Dr. Franz Trieb, German Aerospace Center (DLR)

CHP Plant



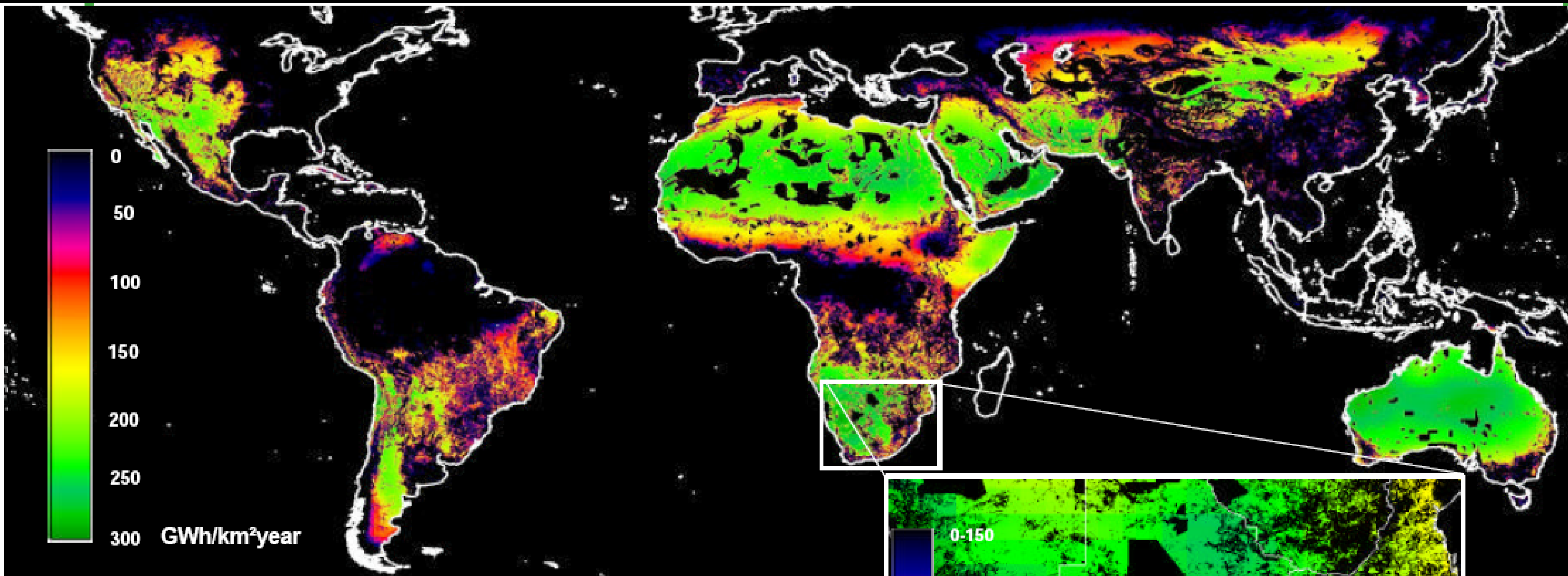
Source: Dr. Franz Trieb, German Aerospace Center (DLR)

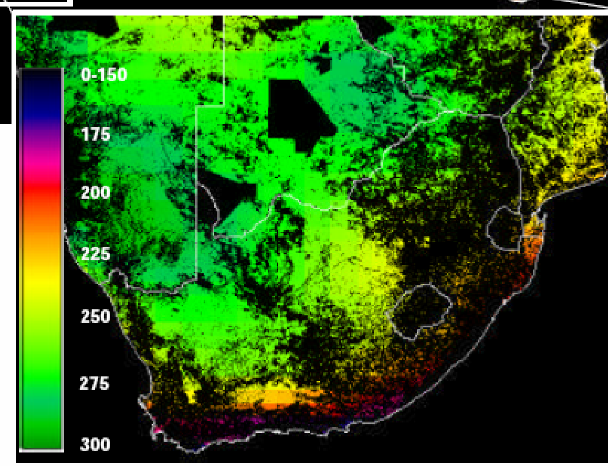
CSP Costs



Source: Dr. Franz Trieb, German Aerospace Center (DLR)

CSP Potential





- 1 km² yields up to 200 - 300 GWh_e/year
- 1 km² equals 50 MW coal or gas plant
- 1 km² saves 500,000 bbl of oil / year
- 1 km² avoids 200,000 tons CO_2 / year

Source: Dr. Franz Trieb, German Aerospace Center (DLR)

Solar Thermal Conversion

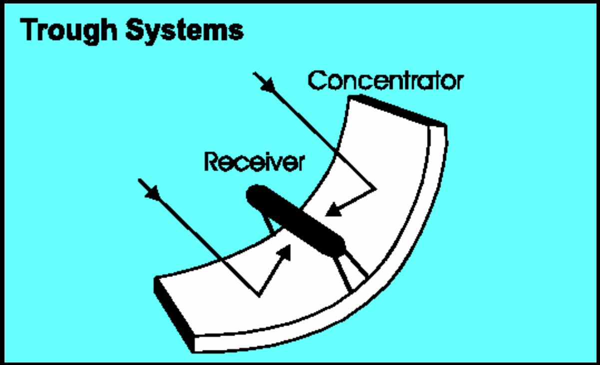
Solar energy is collected as high-temperature heat, generally by means of mirrors or lenses that track the motion of the sun and direct a concentrated solar flux onto a receiver. Temperatures up to 1000 K can be generated by this means, high enough to produce the high-pressure steam used in modern steam turbines to generate electricity.

Can solar thermal conversion become economically competitive with combustion of fossil fuels as a source of high-temperature heat?

What are the best designs for the collection and conversion of sunlight in a solar thermal facility?

What are the best uses of the high-temperature heat from solar thermal conversion?

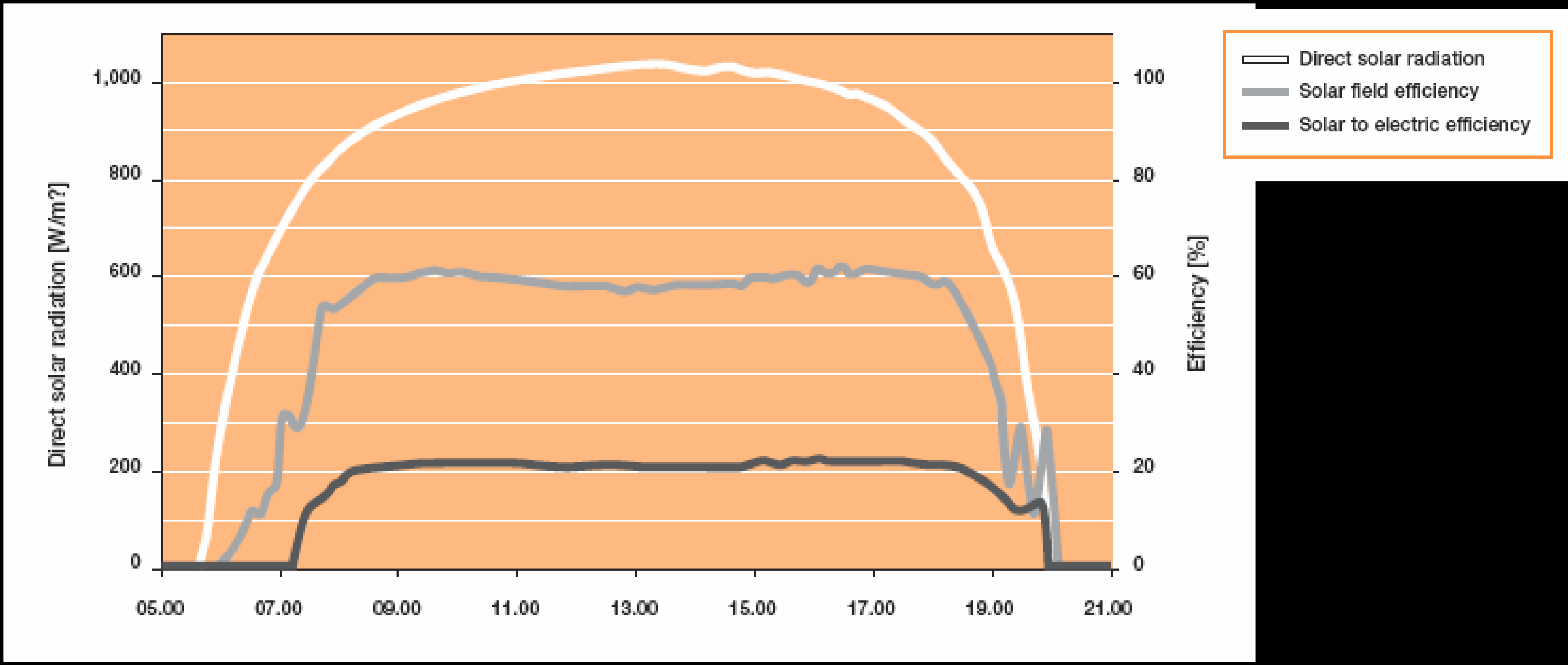
Parabolic-Trough Technology



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.

Source: US DOE

Daily Summer Output Pattern at the SEGS IV Plant in Kramer Junction, CA



Parabolic-Trough System

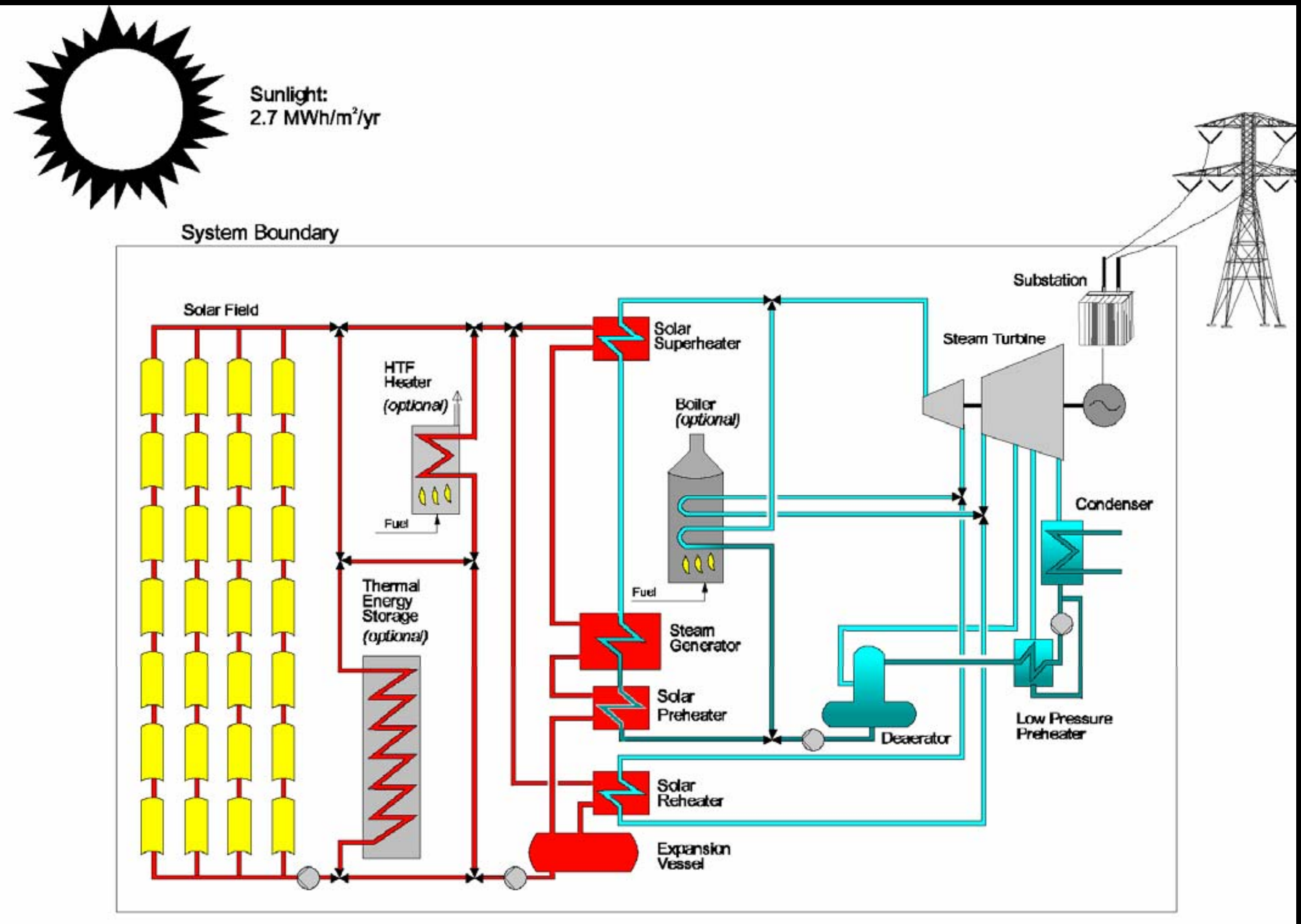


Figure 1. Solar/Rankine parabolic trough system schematic [1].

Source: US DOE

Parabolic-Trough System

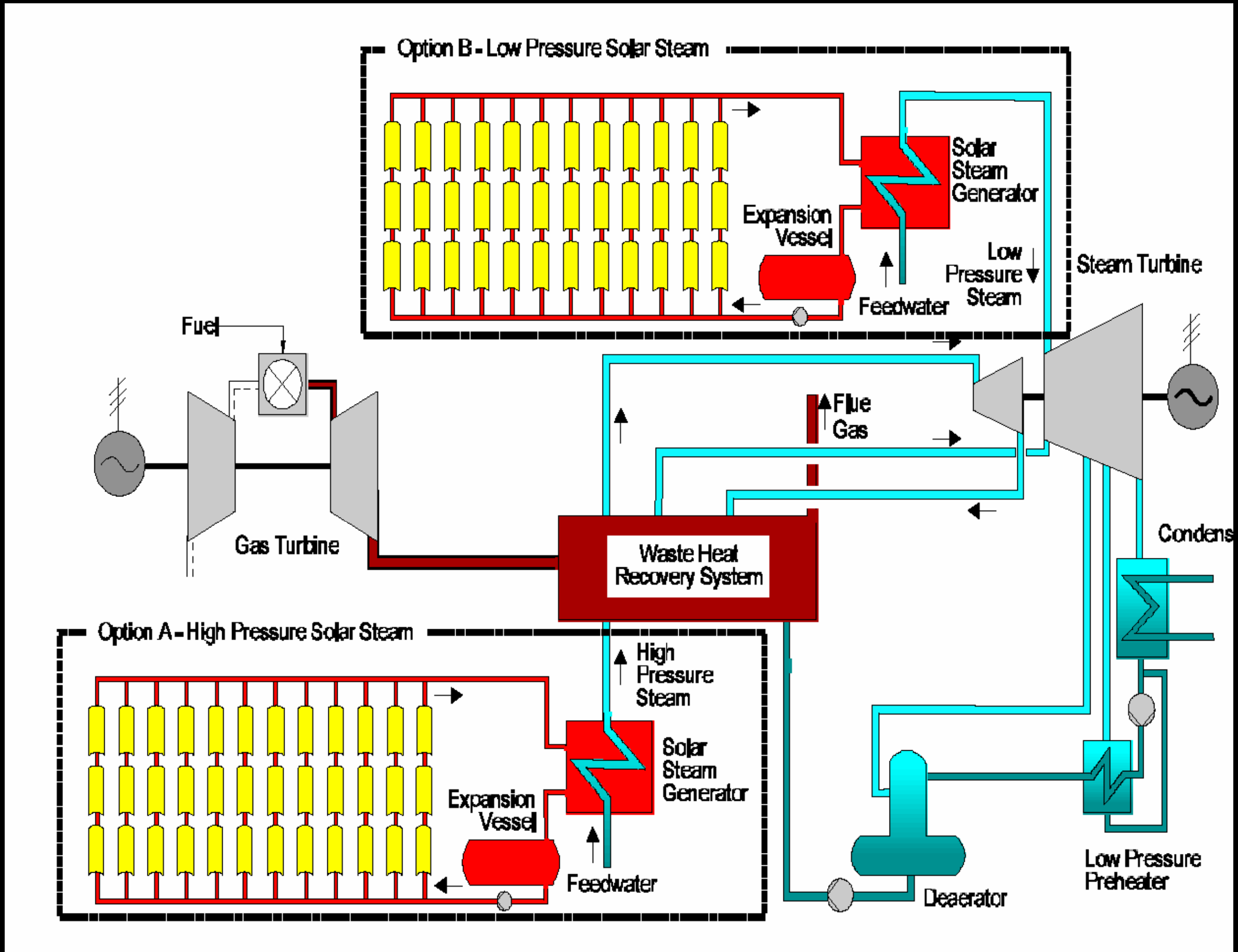
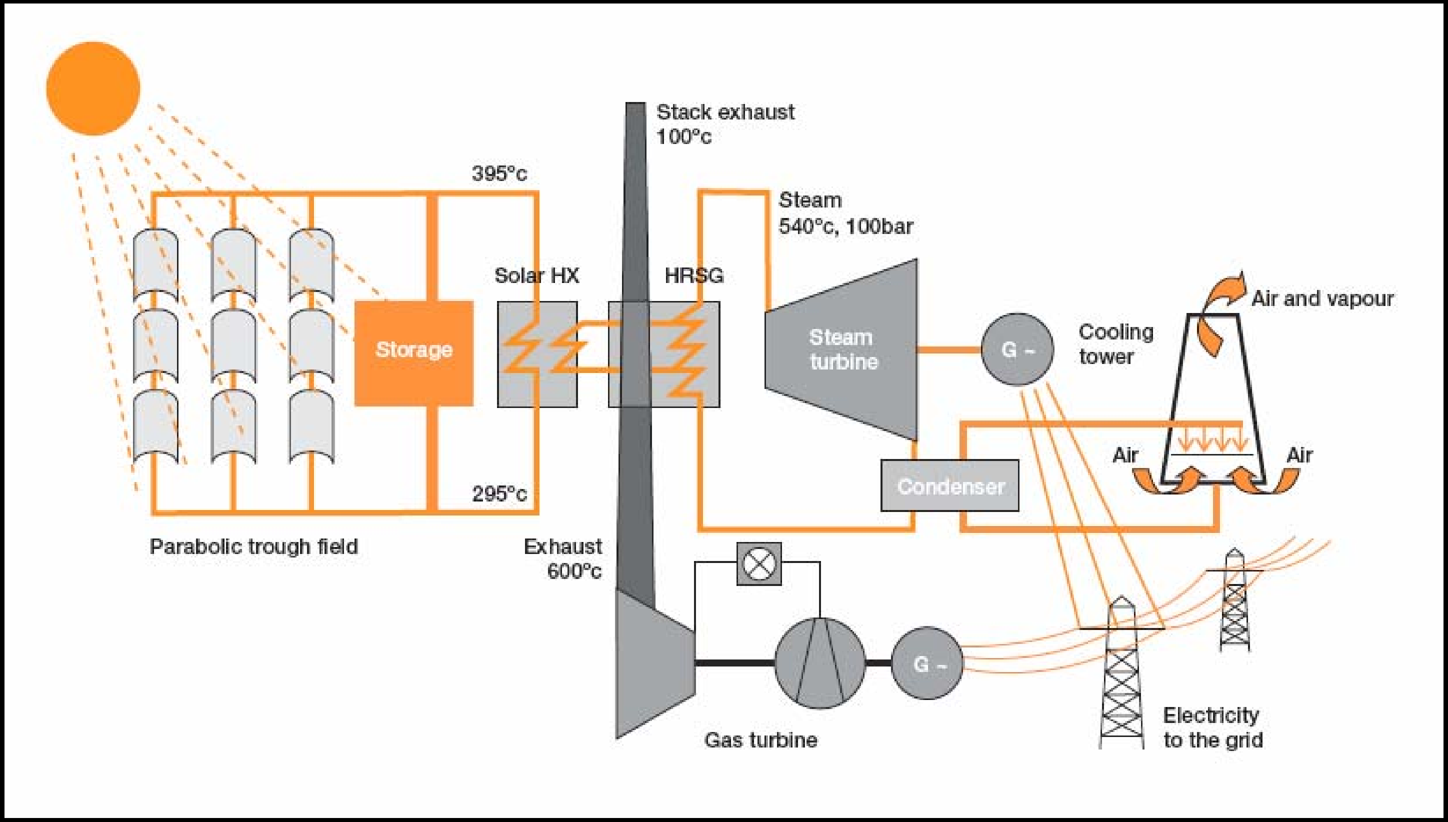


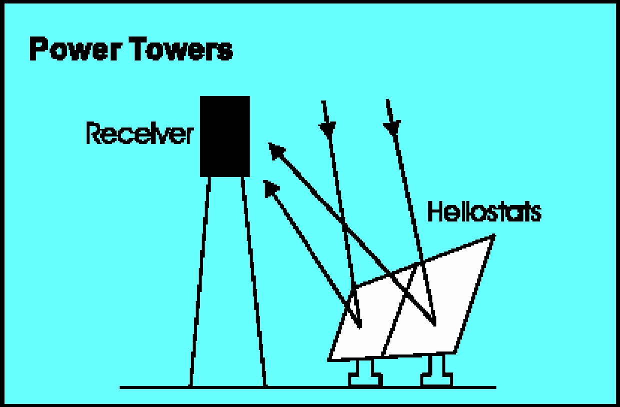
Figure 2. Integrated Solar Combined Cycle System [1].

Source: US DOE

Integrated Solar/Combined Cycle System



Power Tower



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.

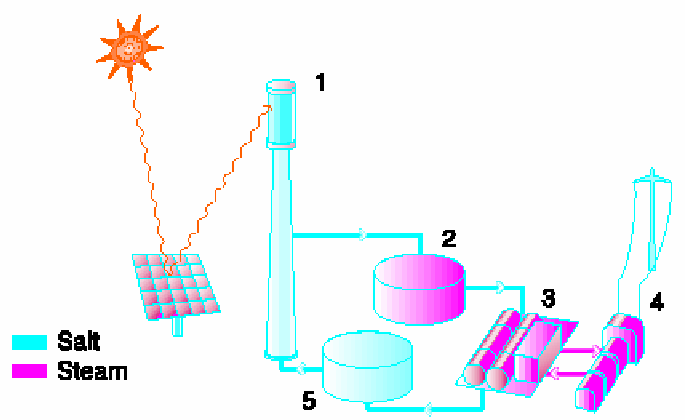
Power Tower systems use a circular field array of heliostats (large individually-tracking mirrors) to focus sunlight onto a central receiver mounted on top of a tower (Figure 2). The first power tower, Solar One, which was built in Southern California and operated in the mid-1980's, used a water/steam 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 288°C (550°F) and cycled through the receiver where it is heated to 565°C (1,049°F) 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.

Power Tower

Solar Power Towers



Schematic of electricity generation using molten-salt storage:

1) sun heats salt in receiver;
2) salt stored in hot storage tank;
3) hot salt pumped through steam generator;
4) steam drives turbine/generator to produce electricity;
5) salt returns to cold storage tank to be reheated in the receiver.

A new SAIC faceted membrane heliostat is on test at the National Solar Thermal Test Facility.

Source: US DOE

Power Tower

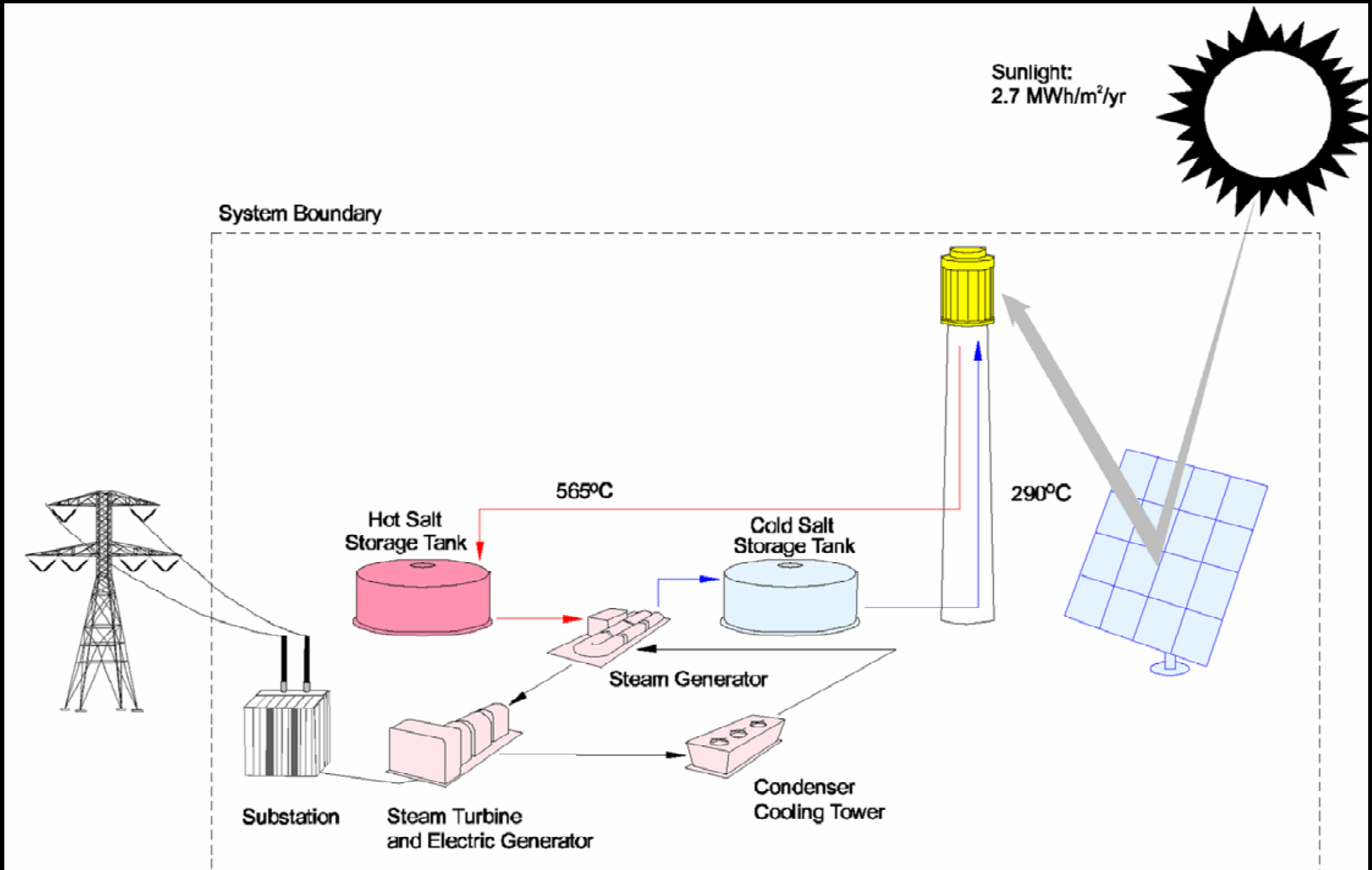
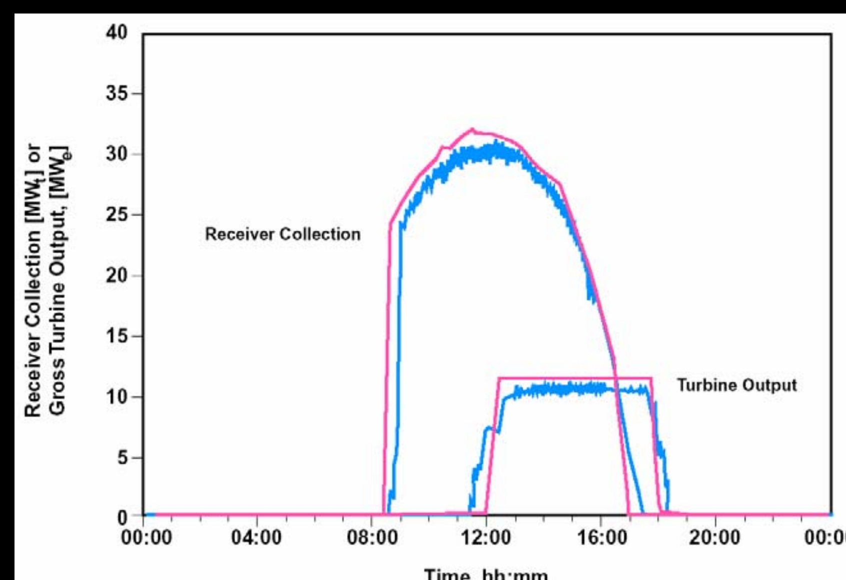


Figure 1. Molten-salt power tower system schematic (Solar Two, baseline configuration).

Power Tower - Solar two

Power Output: Solar Two produced 1633 MWh over a 30-day period, exceeding its one-month performance measure of 1500 MWh of power production; the plant also produced a record turbine power output of 11.6 megawatts.



Source: US DOE

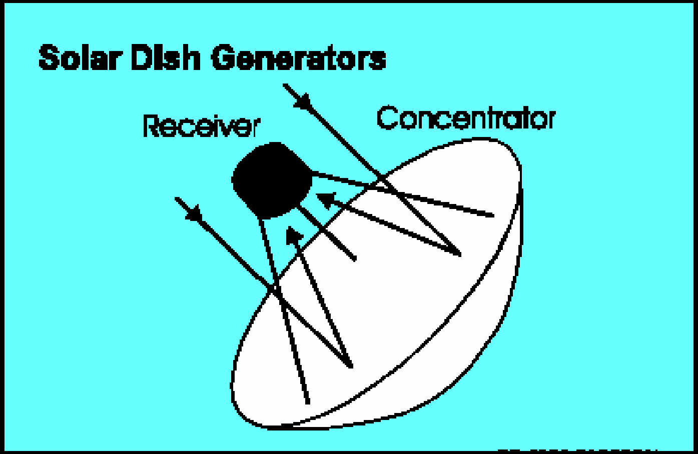
Power Towers

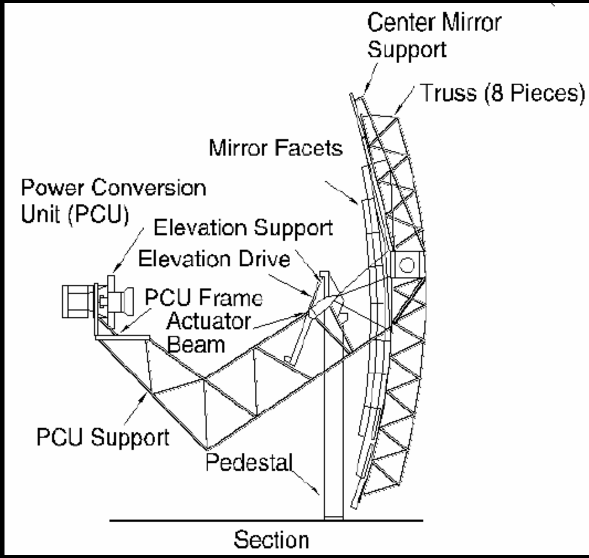
Table 1. Experimental power towers.

Project	Country	Power Output (MWe)	Heat Transfer Fluid	Storage Medium	Operation Began
SSPS	Spain	0.5	Liquid Sodium	Sodium	1981
EURELIOS	Italy	1	Steam	Nitrate Salt/Water	1981
SUNSHINE	Japan	1	Steam	Nitrate Salt/Water	1981
Solar One	USA	10	Steam	Oil/Rock	1982
CESA-1	Spain	1	Steam	Nitrate Salt	1983
MSEE/Cat B	USA	1	Molten Nitrate	Nitrate Salt	1984
THEMIS	France	2.5	Hi-Tec Salt	Hi-Tec Salt	1984
SPP-5	Russia	5	Steam	Water/ Steam	1986
TSA	Spain	1	Air	Ceramic	1993
Solar Two	USA	10	Molten Nitrate Salt	Nitrate Salt	1996

Source: US DOE

Solar Dish-engine

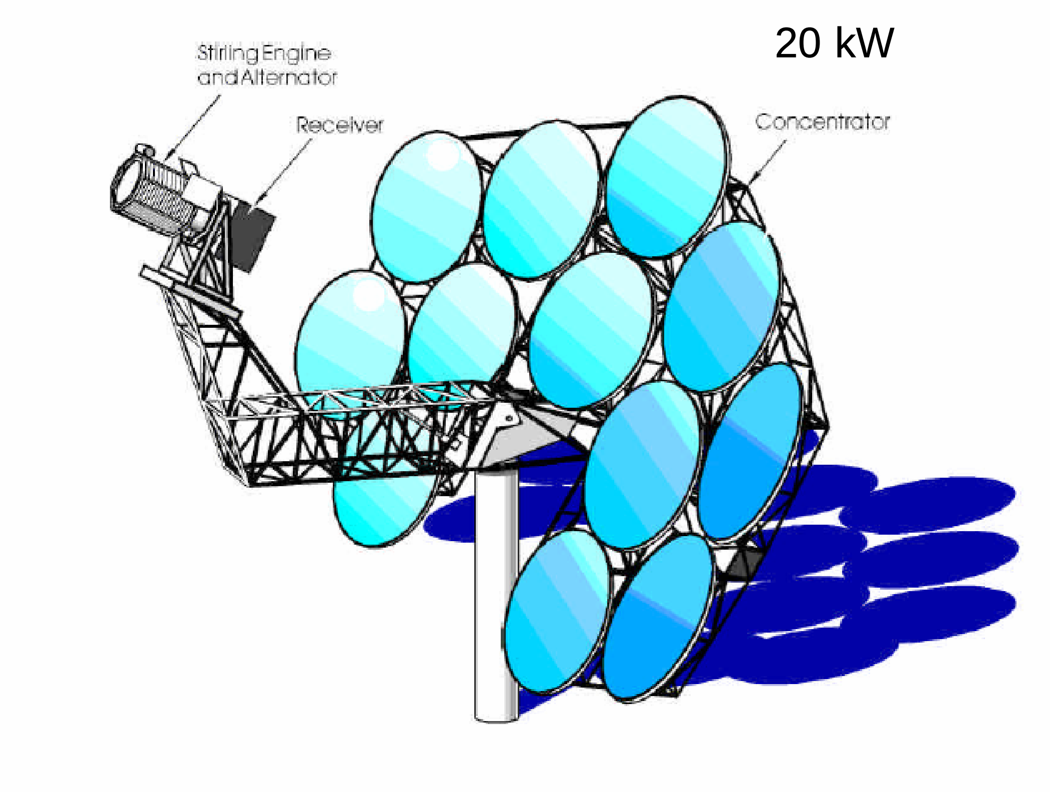


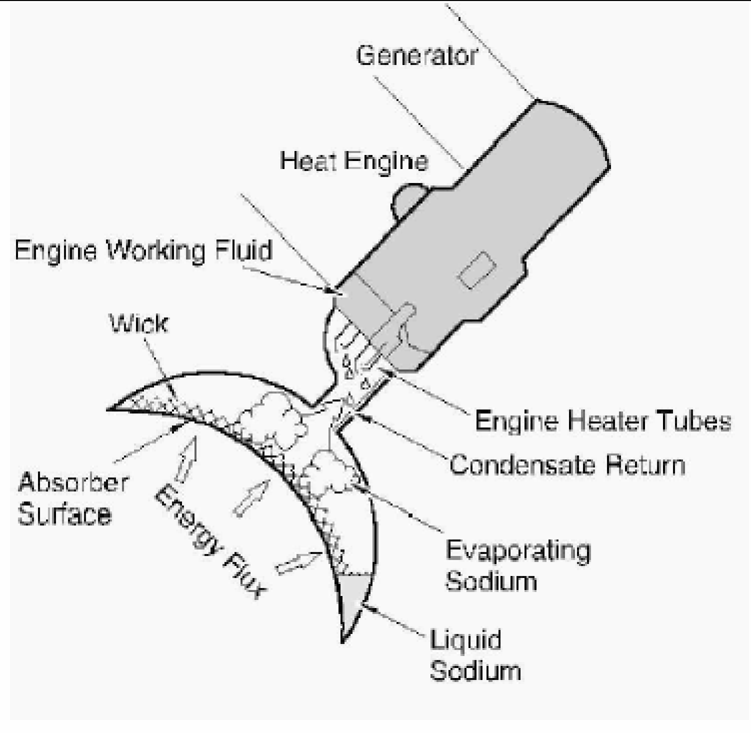


Dish/Engine systems use an array of parabolic dish-shaped mirrors (stretched membrane or flat glass facets) to focus solar energy onto a receiver located at the focal point of the dish (Figure 3). Fluid in the receiver is heated to 750°C (1,382°F) and used to generate electricity in a small engine attached to the receiver. Engines currently under consideration include Stirling and Brayton cycle engines. Several prototype dish/engine systems, ranging in size from 7 to 25 kW_e, have been deployed in various locations in the U.S. and abroad.

High optical efficiency and low startup losses make dish/engine systems the most efficient (29.4% record solar to electricity conversion) of all solar technologies. In addition, the modular design of dish/engine systems make them a good match for both remote power needs in the kilowatt range as well as hybrid end-of-the-line grid-connected utility applications in the megawatt range. If field validation of these systems is successful in 1998 and 1999, commercial sales could commence as early as 2000.

Solar Dish-engine





Source: US DOE

Solar Thermal Electric Power Systems

Table 1. 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 (ºC/ºF)	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*

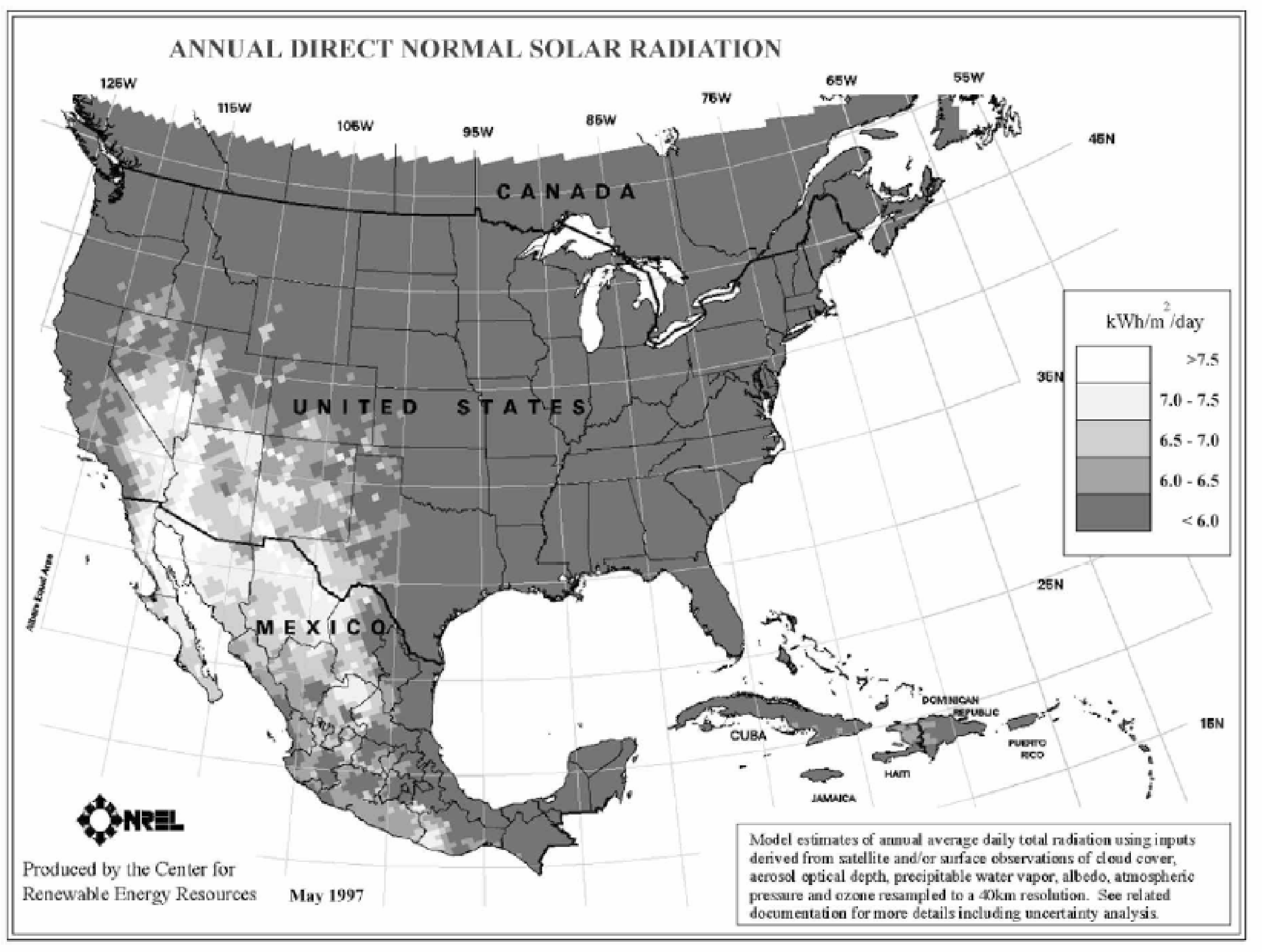
* Values indicate changes over the 1997-2030 time frame.

† $\$/W_p$ removes the effect of thermal storage (or hybridization for dish/engine). See discussion of thermal storage in the power tower TC and footnotes in Table 4.

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

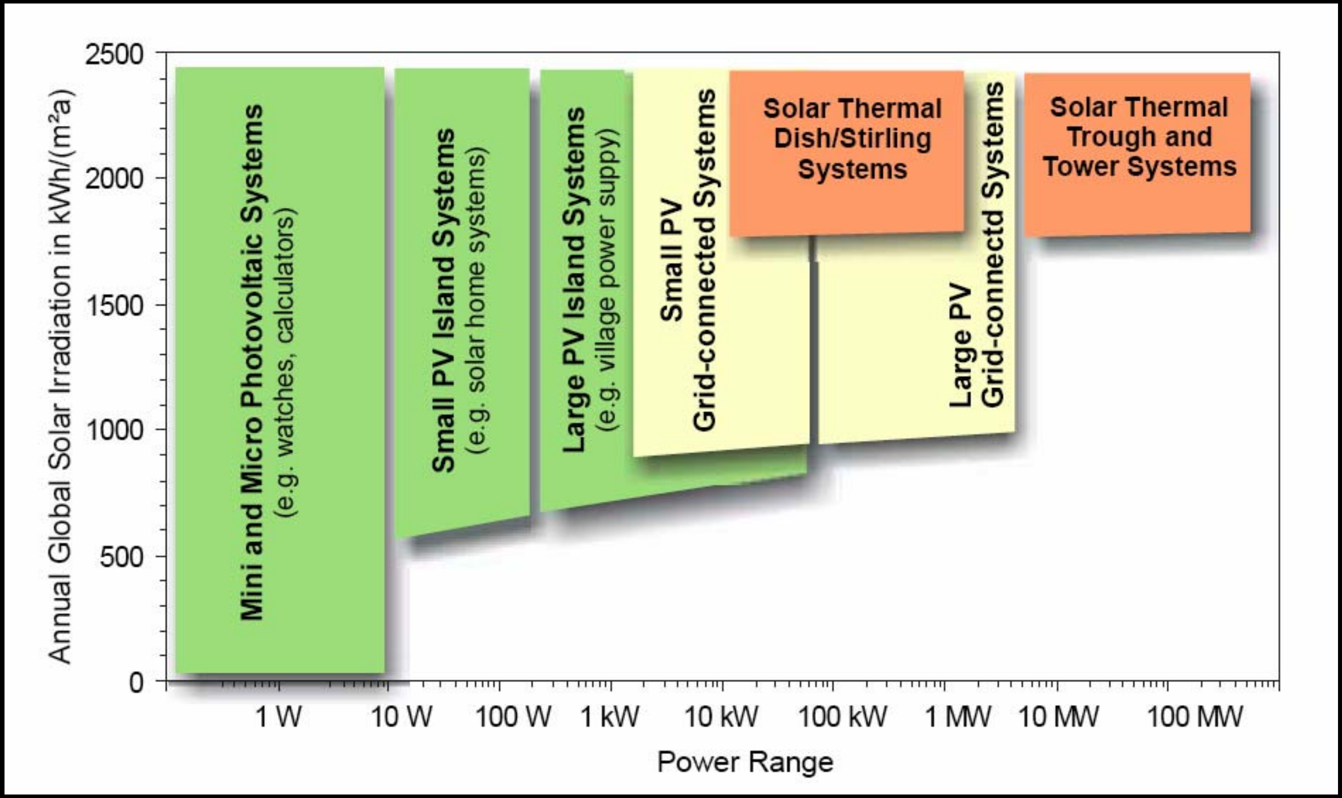
Source: US DOE

US Solar Radiation Map



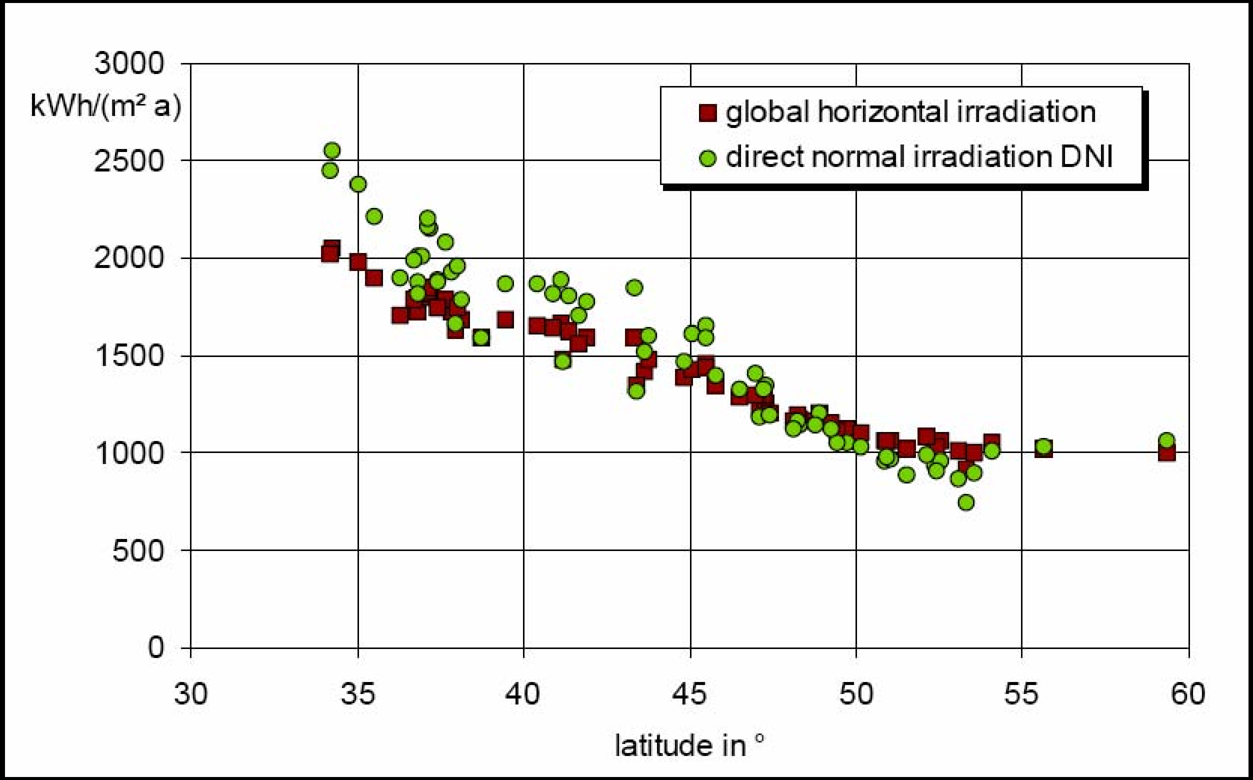
Source: US DOE

PV-CSP Power Ranges



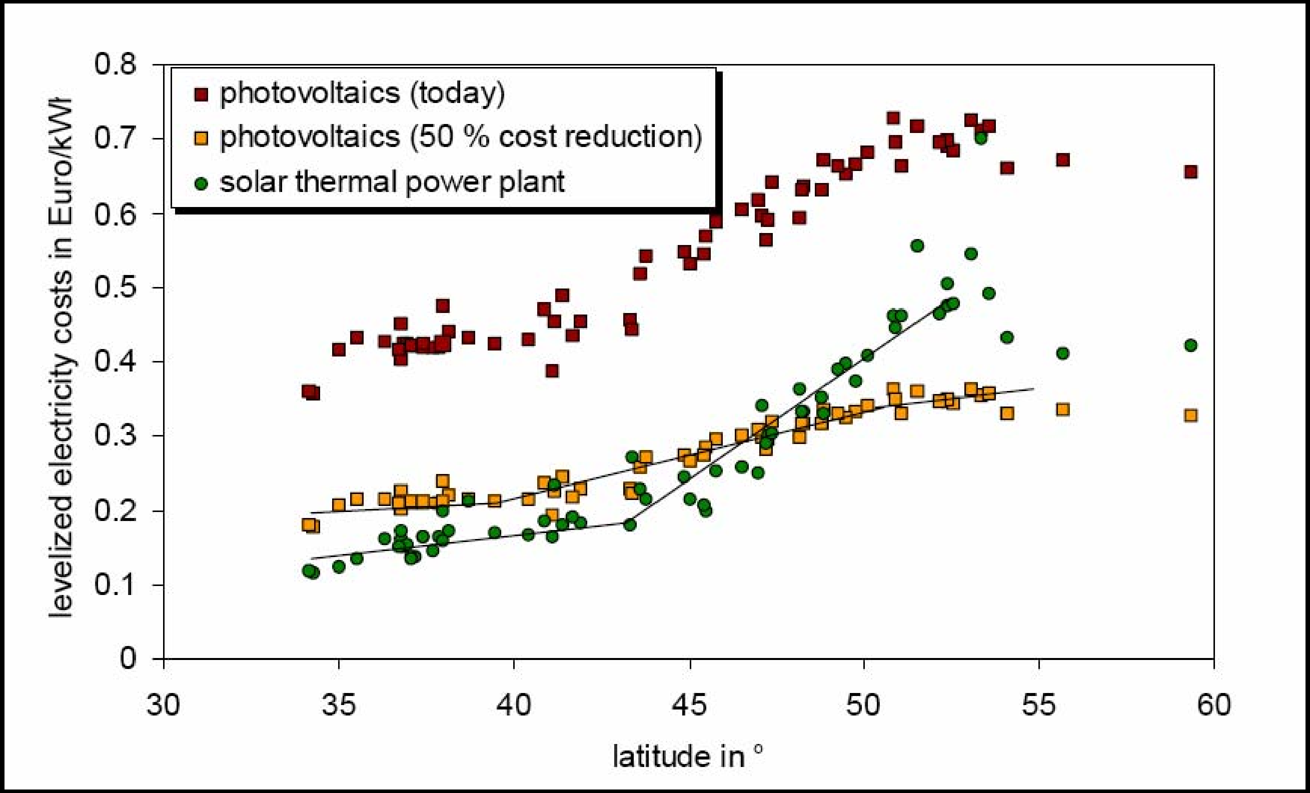
Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain

Annual Global Irradiation in Europe & USA



Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain

Levelized Energy Costs



Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain