

# Solar Thermal Conversion

Major Functions:

- Solar Radiation collection and concentration
- Conversion to heat
- Storage of energy
- Generation of electricity

# 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?

# 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.

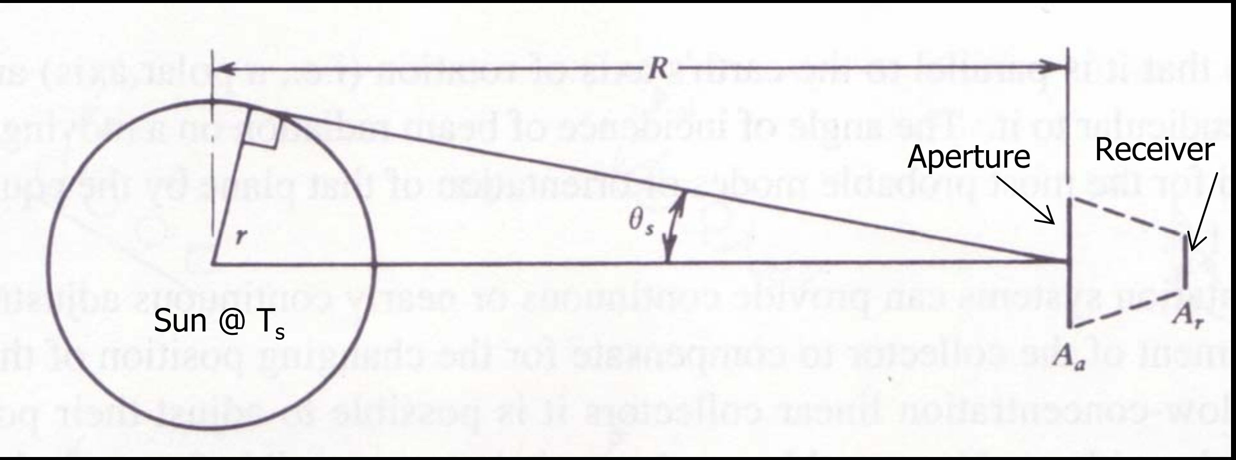
Concentration to a line: concentration ratios up to 20 with selective surfaces to achieve high enough temperatures for electrical generation

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

# Concentration Ratio

Area concentration ratio (geometric):

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




Optical concentration ratio:

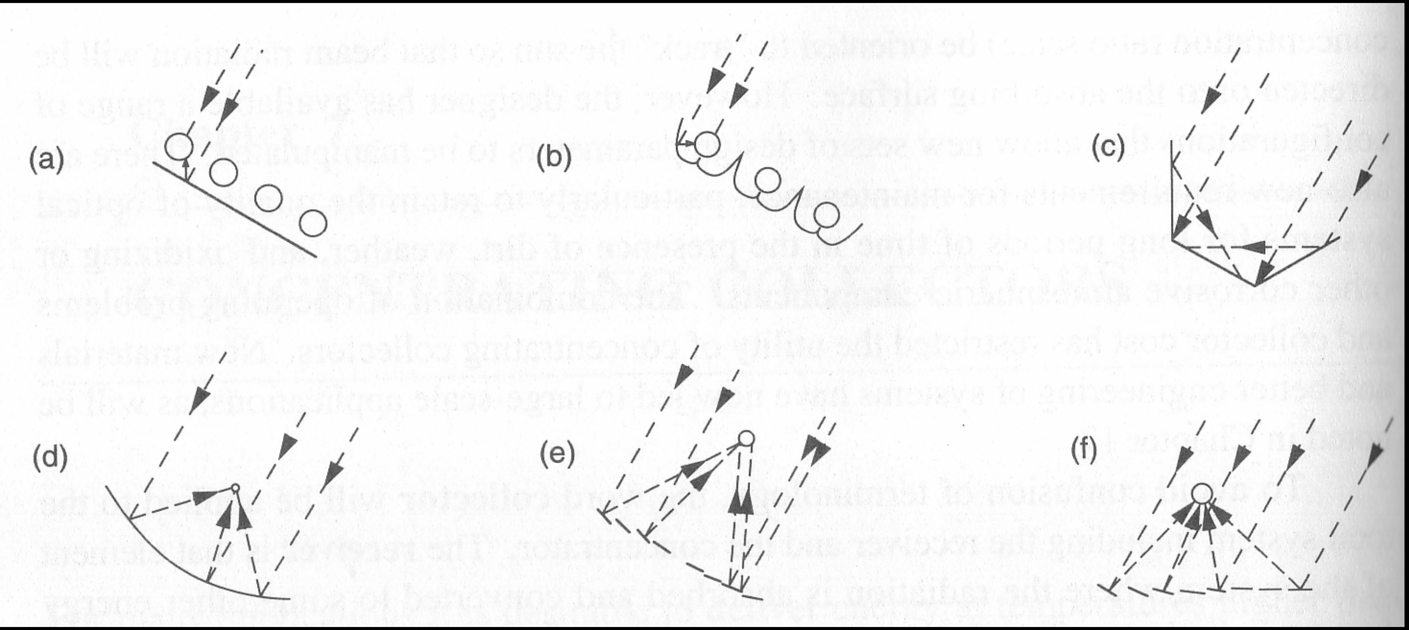
$$C_O = \frac{\frac{1}{A_r}\int I_r dA_r}{I_a}$$

$I_r$ is the averaged irradiance

$I_a$ is the insolation incident on the collector aperture

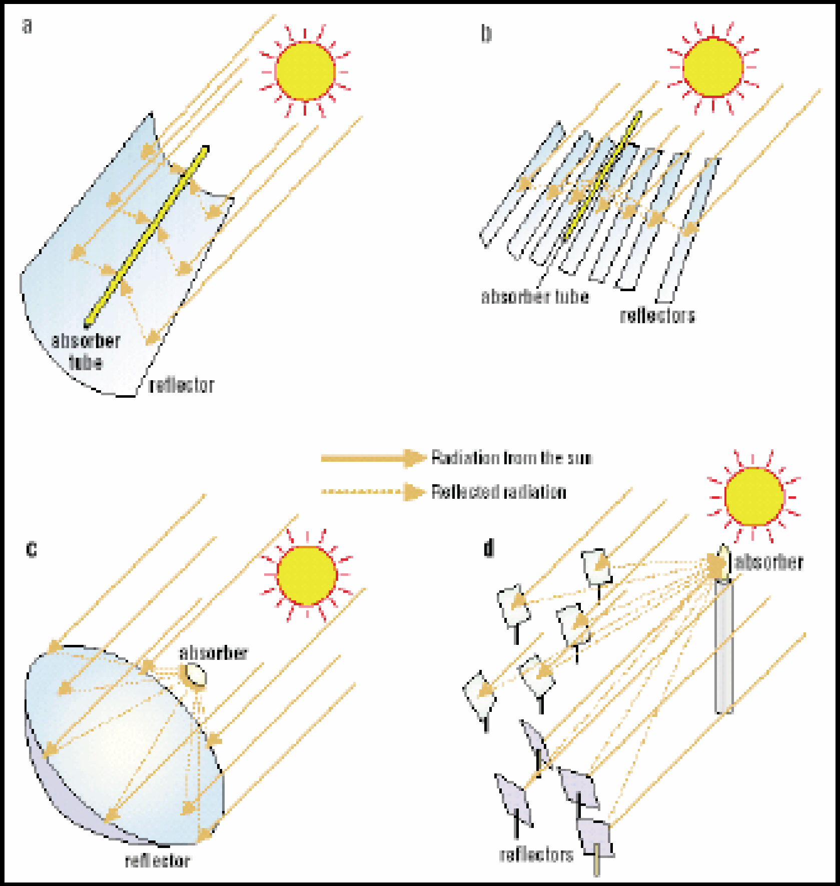
# Collector Configurations

Goal: Increasing the radiation flux on receivers




a) Tubular absorbers with diffusive back reflector; b) Tubular absorbers with specular cusp reflector; c) Plane receiver with plane reflector; d) parabolic concentrator; e) Fresnel reflector f) Array of heliostats with central receiver

# Sun Radiation Concentration



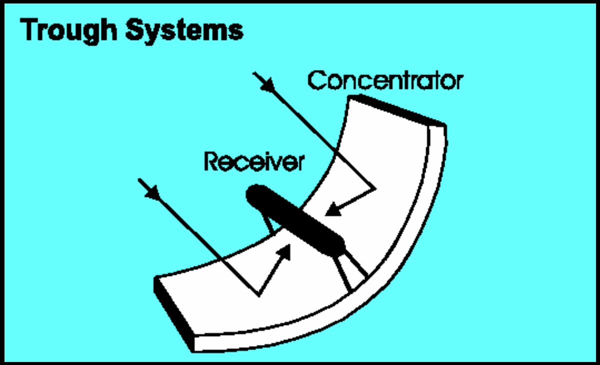

(a) parabolic trough collector

(b) linear Fresnel collector

(c) central receiver system with dish collector and

(d) central receiver system with distributed reflectors

# 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

# Parabolic-Trough Technology

## Solar Electric Generating Station (SEGS)

**Table 1. Parabolic-Trough Project Status** (as of December 1998)

| Country/State | Plant Configuration | Status |
|---|---|---|
| India | 135 MW$_e$ ISCCS | GEF approved, waiting for RFP** |
| Egypt | Open | GEF PDF*** B Grant approved |
| Morocco | Open | GEF government request |
| Mexico | ISCCS | GEF government request |
| Greece | 50 MW$_e$ SEGS* | IPP development, EU****Thermie Grant |
| Jordan | ISCCS or SEGS | On hold pending conventional IPP |
| Spain | 50 MW$_e$ SEGS | Waiting outcome of solar tariff |
| Arizona | 15–30 MW$_e$ ISCCS | Waiting outcome of solar portfolio standard |

*solar electric generating systems
**request for proposals
***project development funding
****European Union

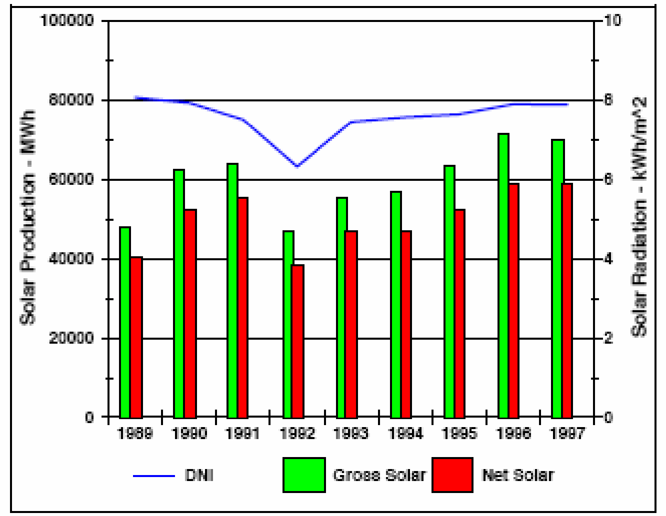
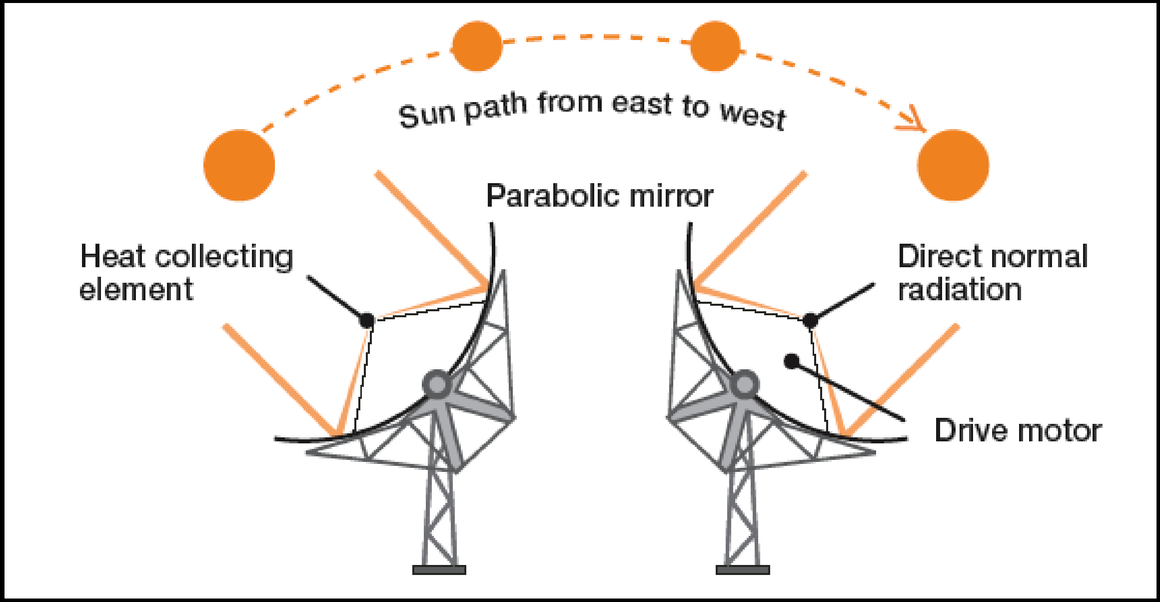



**Figure 3. SEGS VI historical performance**

Solar-electric efficiency : 10%

Levelized energy cost: $0.04-0.05/kWh

# Tracking Parabolic Trough Collector



# Parabolic-Trough System

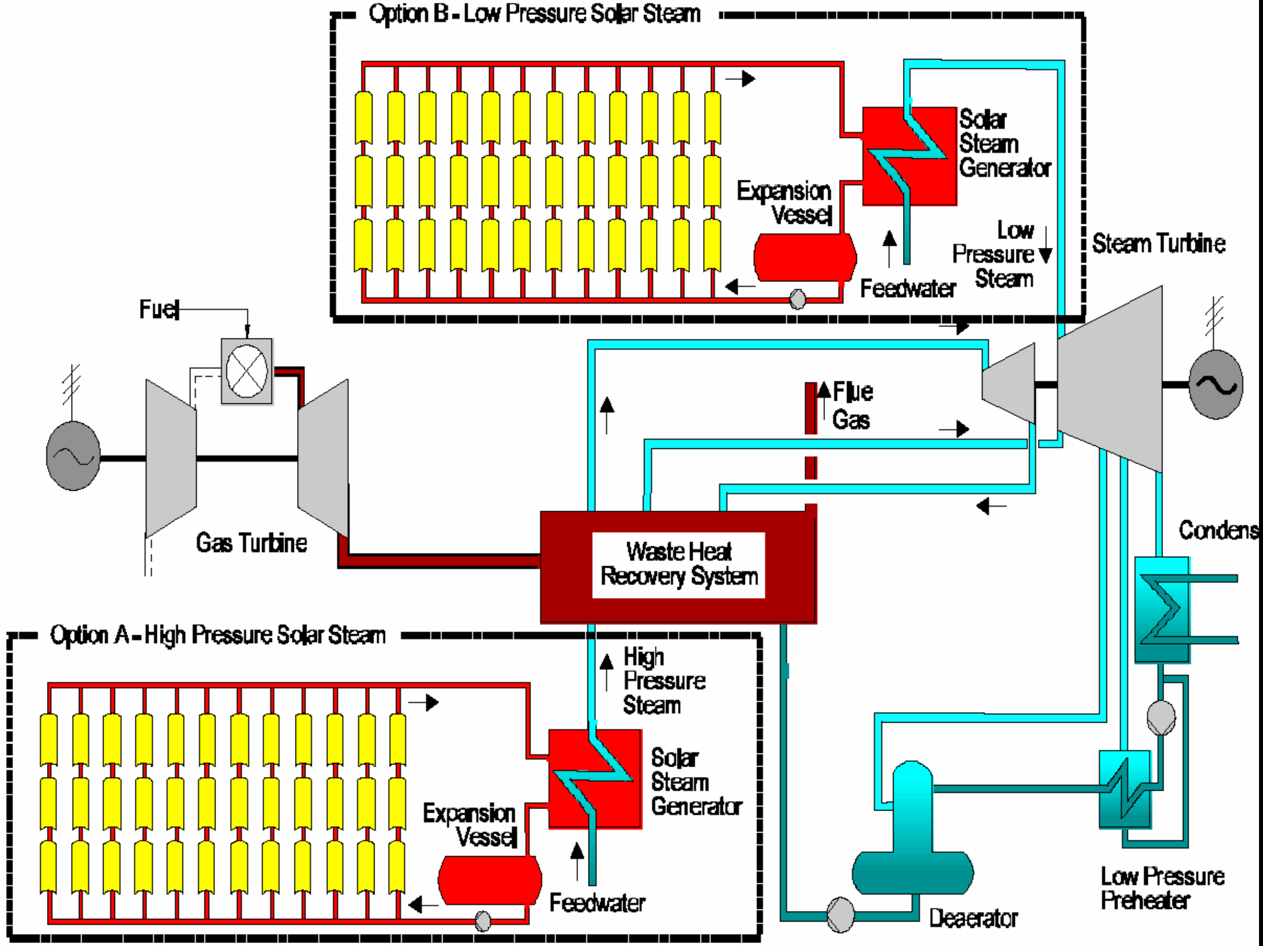
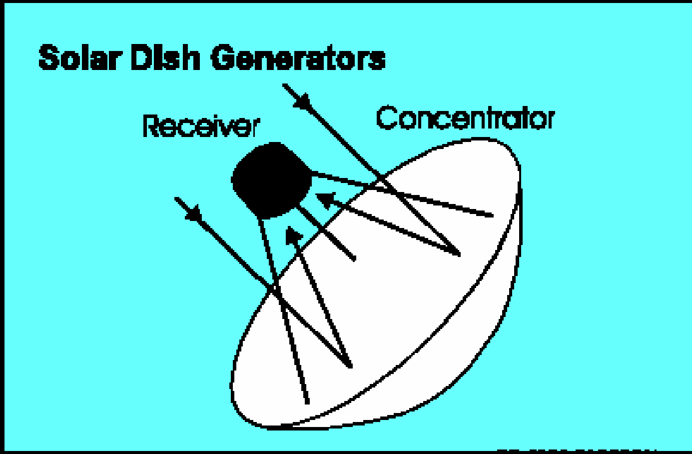
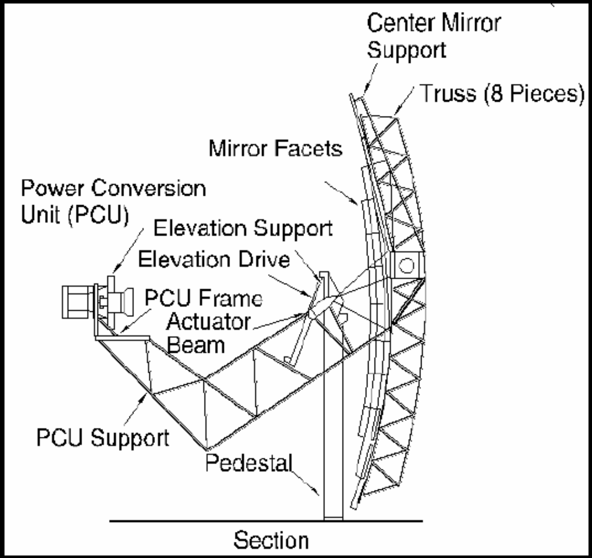



Figure 2. Integrated Solar Combined Cycle System [1].

Source: US DOE

# Solar Dish-engine

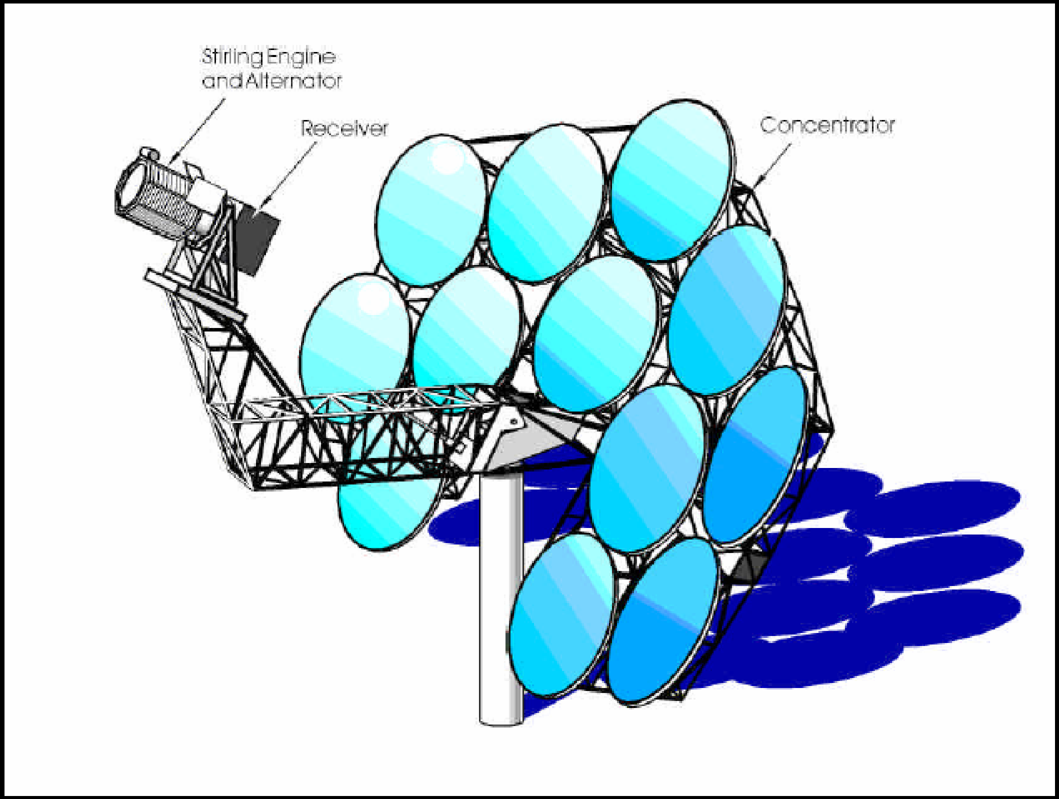


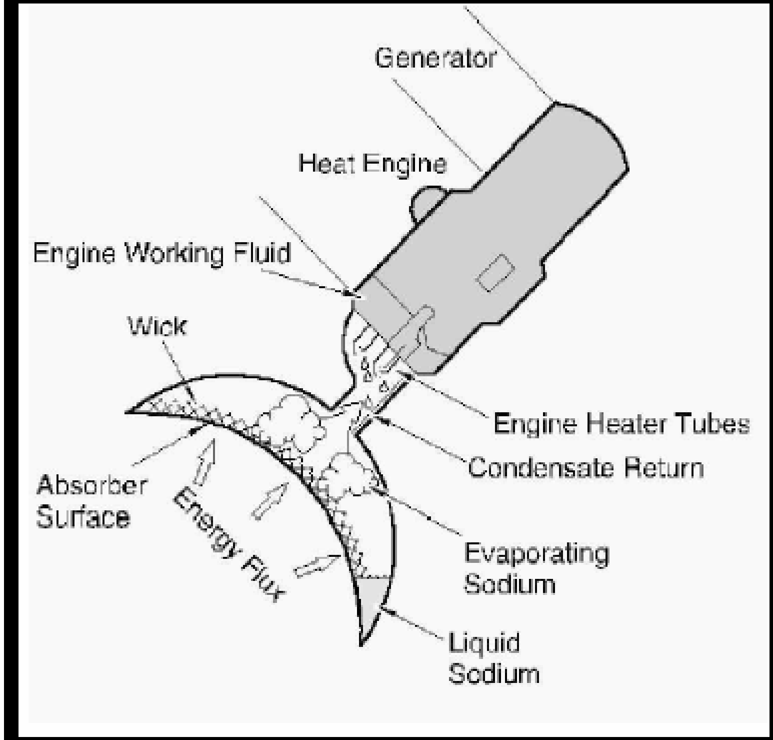




**Dish/Engine** systems use an array of parabolic dish-shaped mirrors (stretched membrane or flat glass facets) to focus solar energy onto a receiver located at the focal point of the dish (Figure 3). Fluid in the receiver is heated to 750°C (1,382°F) and used to generate electricity in a small engine 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.

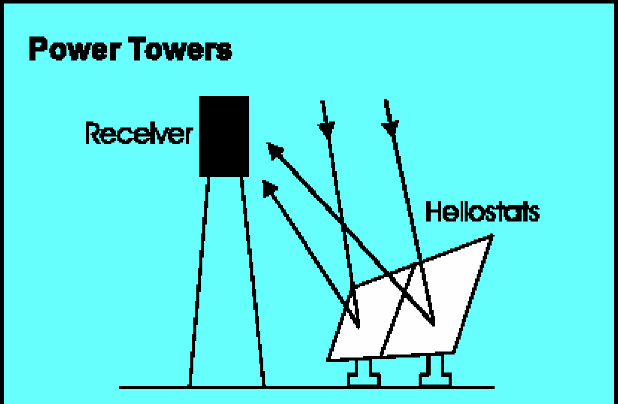
# Solar Dish-engine




Source: US DOE

# 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.

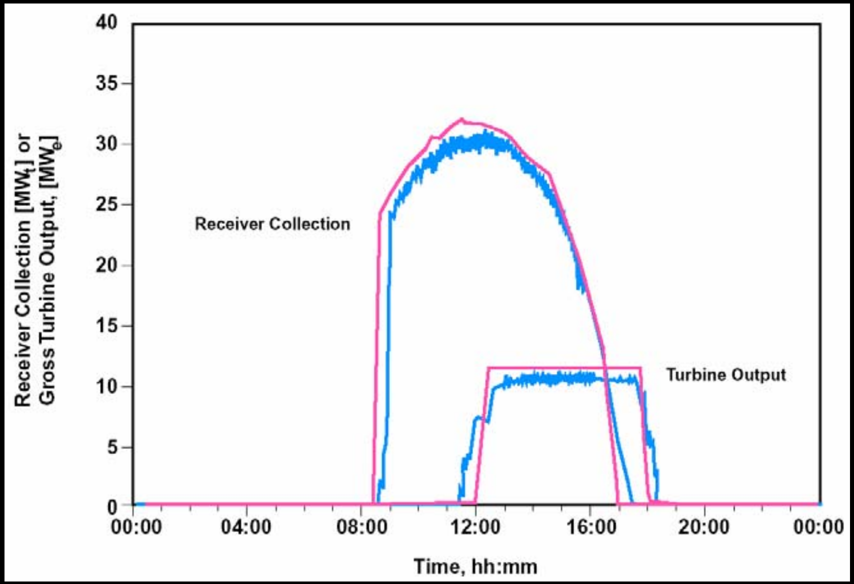
**Power Tower** systems use a circular field array of heliostats (large individually-tracking mirrors) to focus sunlight onto a central receiver mounted on top of a tower (Figure 2). The first power tower, Solar One, which was built in Southern California and operated in the mid-1980's, used a water/steam 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 two

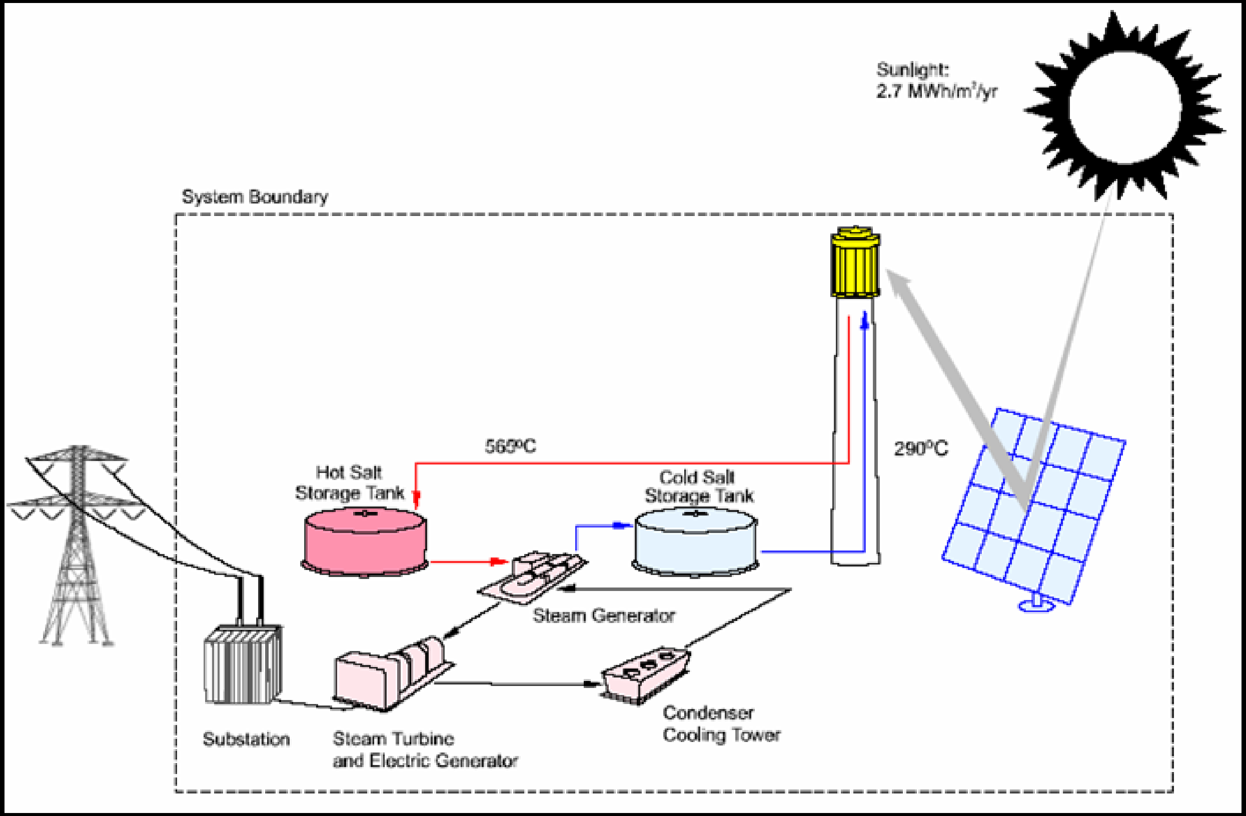
**Power Output:** Solar Two produced 1633 MWh over a 30-day period, exceeding its one-month performance measure of 1500 MWh of power production; the plant also produced a record turbine power output of 11.6 megawatts.




Source: US DOE

# Solar Power Tower

## Molten-salt power tower system




Electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger. Best suited for large scale applications: 30-400 MW

Liquid salt at 290ºC is pumped from a storage tank through the receiver where it is at 565ºC and then to a hot storage tank.

The hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine generator system.

Source: Sandia National Laboratories

# Solar Power Tower

## Electricity dispatchability

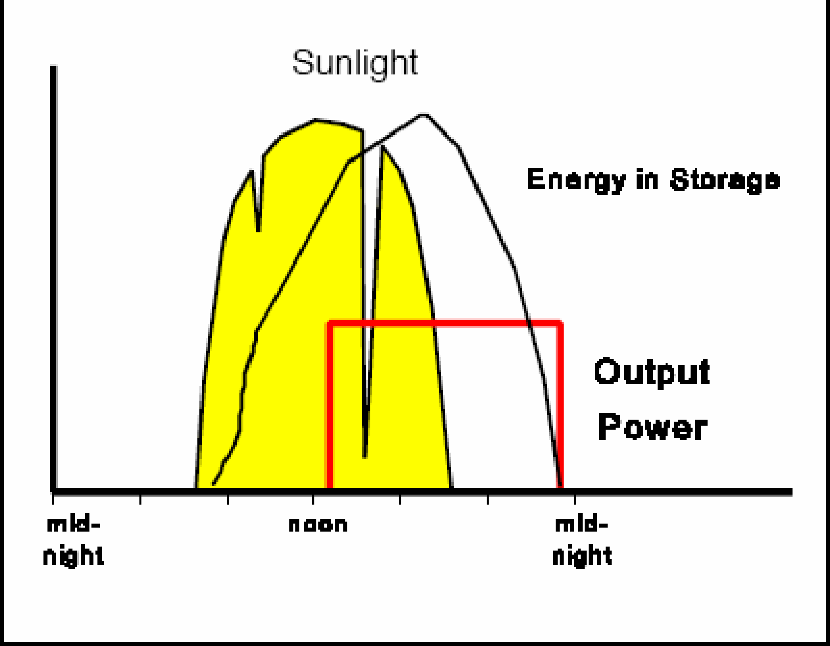



Table 1. Experimental power towers.

| 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 |

Table 2. Comparison of solar-energy storage systems.

| | Installed cost of energy storage for a 200 MW plant ($/kWhr$_e$) | Lifetime of storage system (years) | Round-trip storage efficiency (%) | Maximum operating temperature (°C/°F) |
|---|---|---|---|---|
| Molten-Salt Power Tower | 30 | 30 | 99 | 567/1,053 |
| Synthetic-Oil Parabolic Trough | 200 | 30 | 95 | 390/734 |
| Battery Storage Grid Connected | 500 to 800 | 5 to 10 | 76 | N/A |

# Thermal Storage

## Thermal Loss

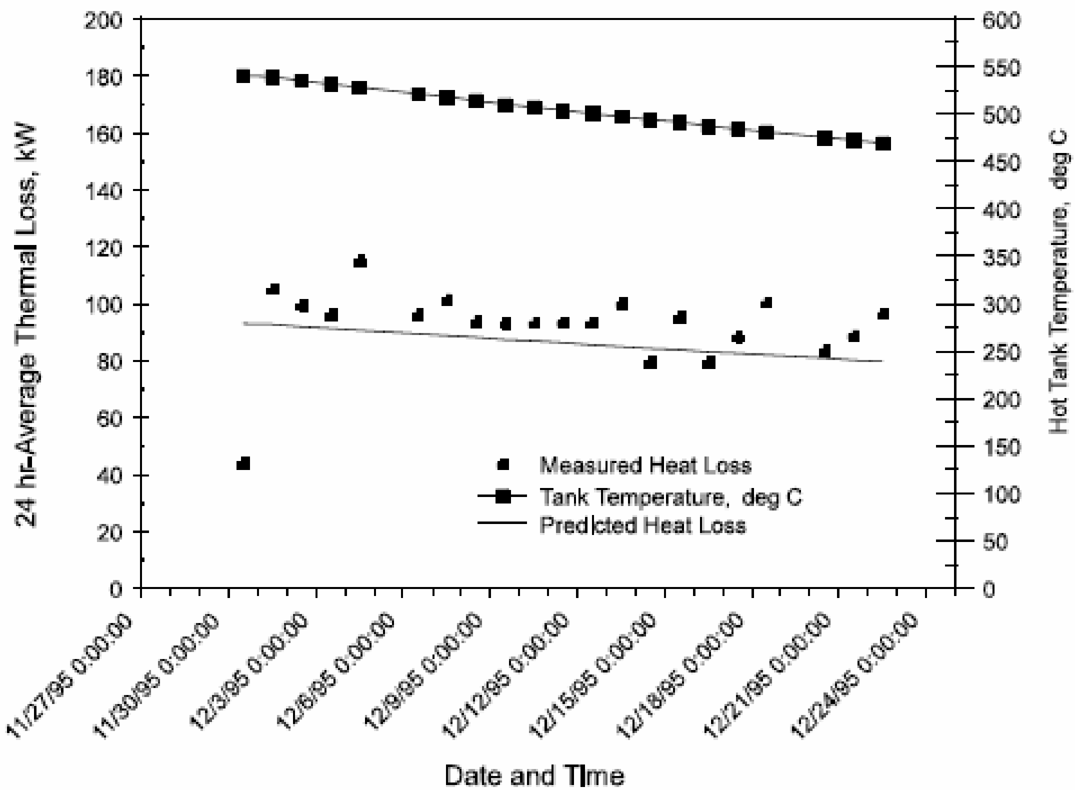
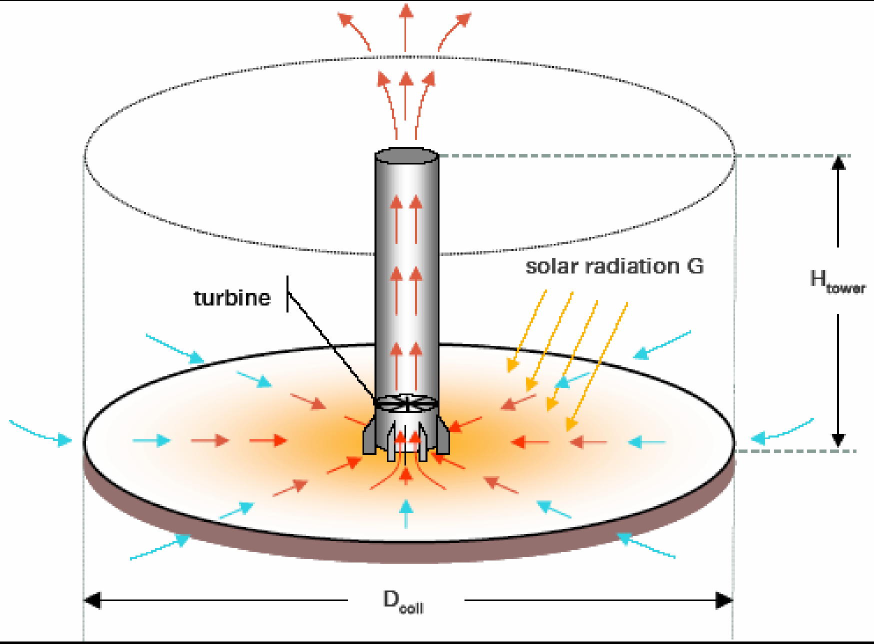



Figure 3. Cool down of hot storage tank at Solar Two.

# Solar Chimney/Tower




A solar chimney power plant has a high chimney (tower), with a height of up to 1000 m, and this is surrounded by a large collector roof, up to 130 m in diameter, that consists of glass or resistive plastic supported on a framework (see artist's impression). Towards its centre, the roof curves upwards to join the chimney, creating a funnel. The sun heats up the ground and the air underneath the collector roof, and the heated air follows the upward incline of the roof until it reaches the chimney. There, it flows at high speed through the chimney and drives wind generators at its bottom. The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2%, and depends mainly on the height of the tower, and so these power plants can only be constructed on land which is very cheap or free. Such areas are usually situated in desert regions. However, the whole power plant is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes. As with trough and tower plants, the minimum economical size of solar chimney power plants is also in the multi-megawatt range.

Source: www.sbp.de

**Design of Commercial Solar Updraft Tower Systems – Utilization of Solar Induced Convective Flows for Power Generation**

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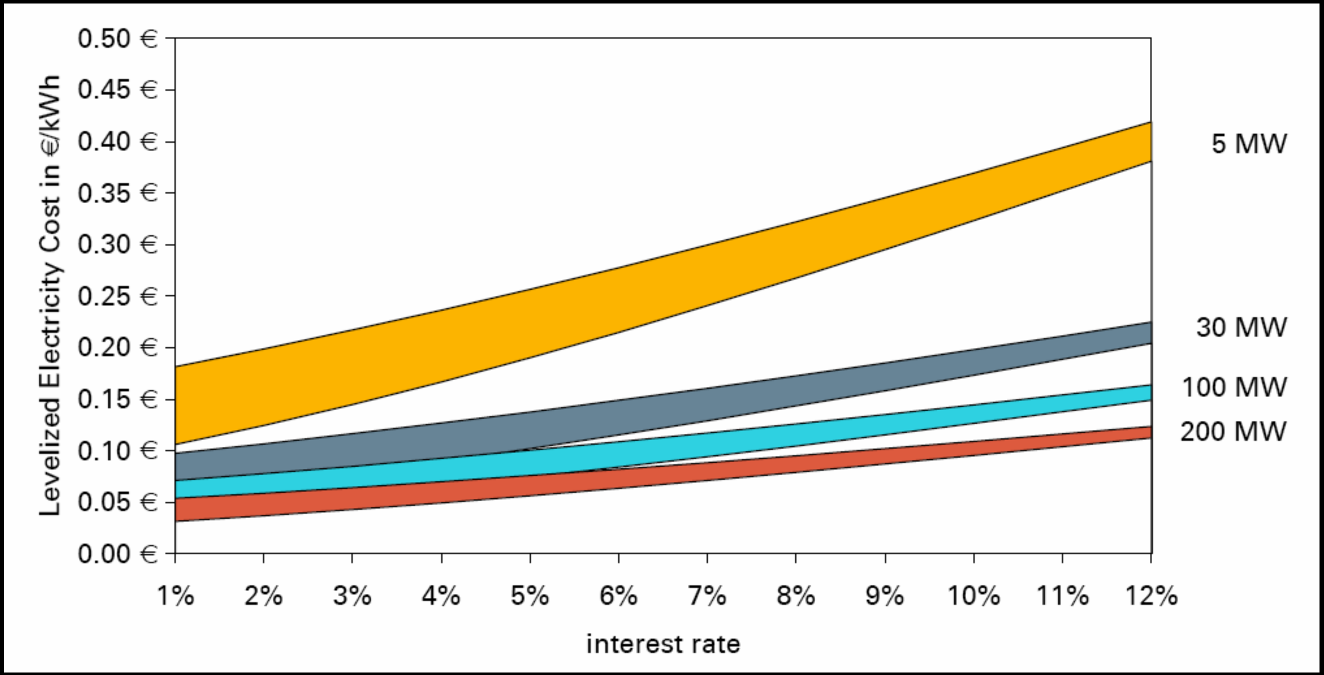
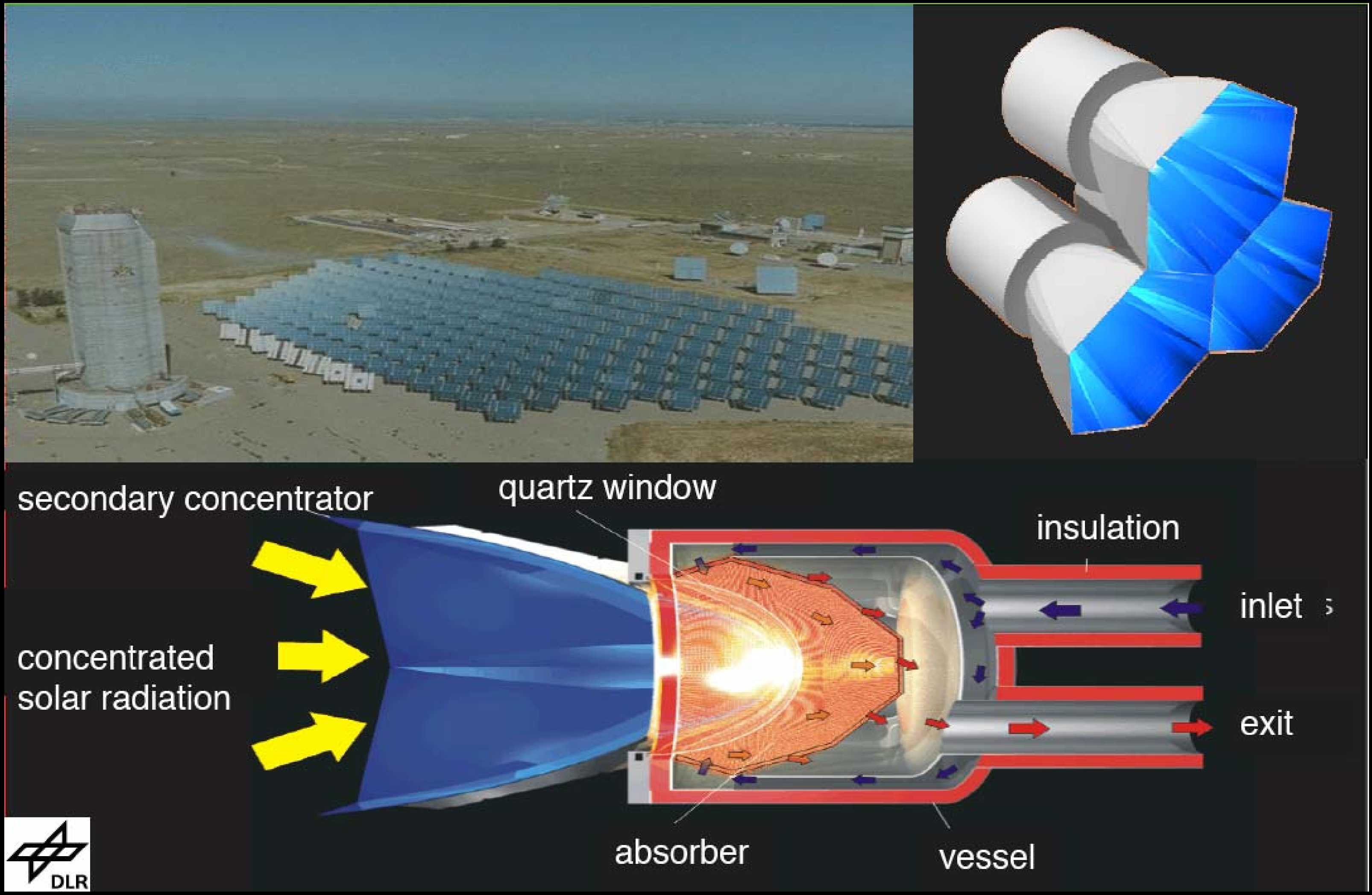
# Solar Chimney/Tower

| Capacity | MW | 5 | 30 | 100 | 200 |
|---|---|---|---|---|---|
| tower height | m | 550 | 750 | 1000 | 1000 |
| tower diameter | m | 45 | 70 | 110 | 120 |
| collector diameter | m | 1250 | 2900 | 4300 | 7000 |
| electricity output [A] | GWh/a | 14 | 99 | 320 | 680 |

[A] at a site with an annual global solar radiation of 2300 kWh/(m²a)

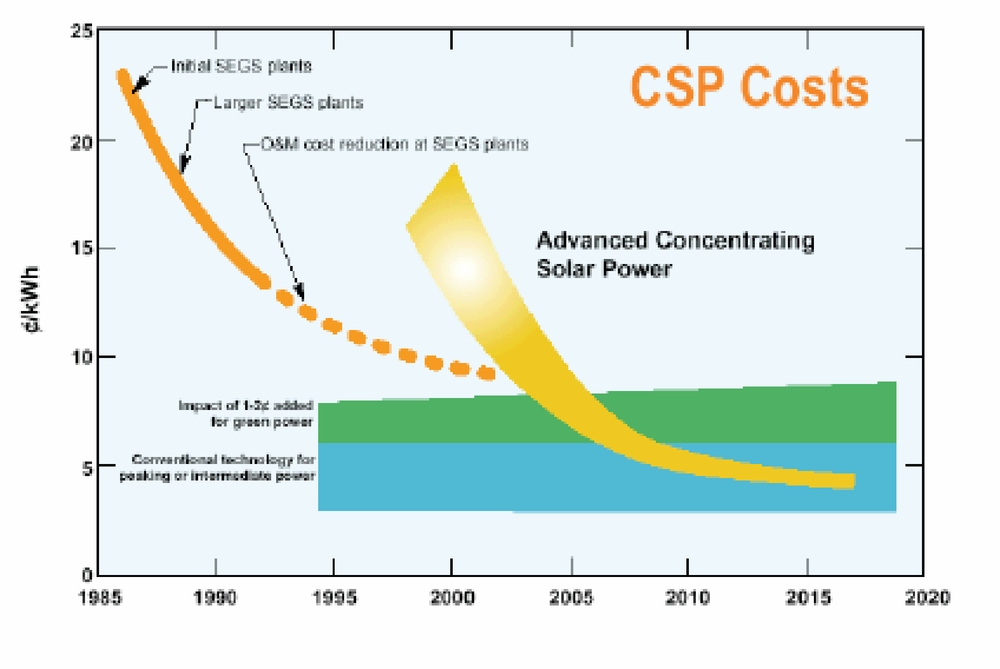


# Advanced Tower



# Commercial Solar Plant Costs

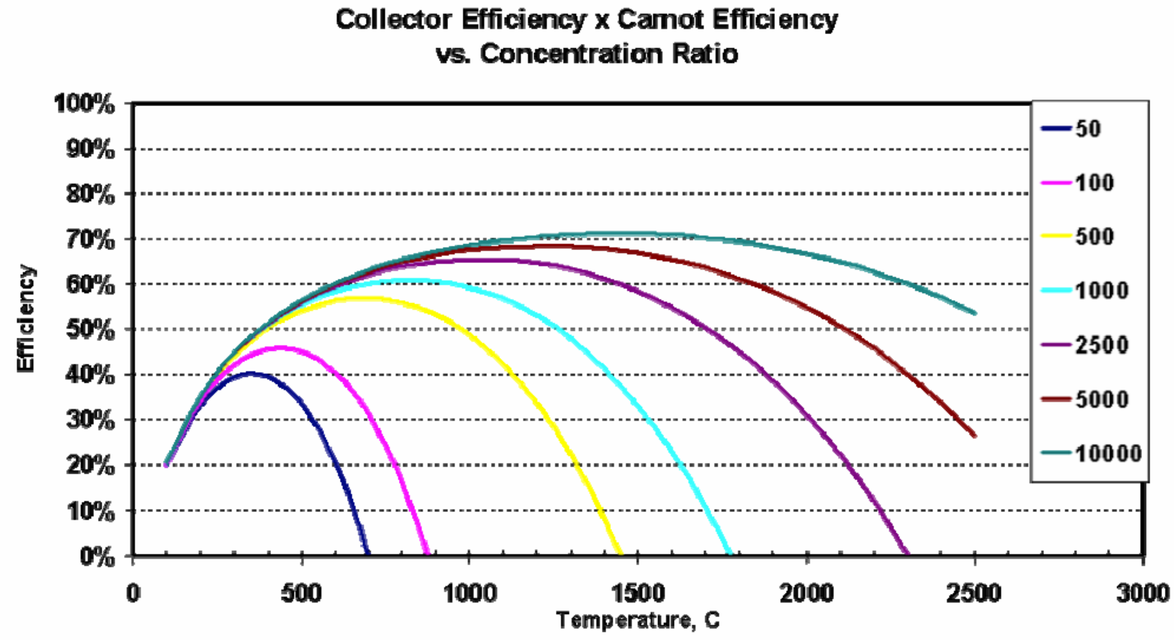
Solar Electric Generating Systems (SEGS)



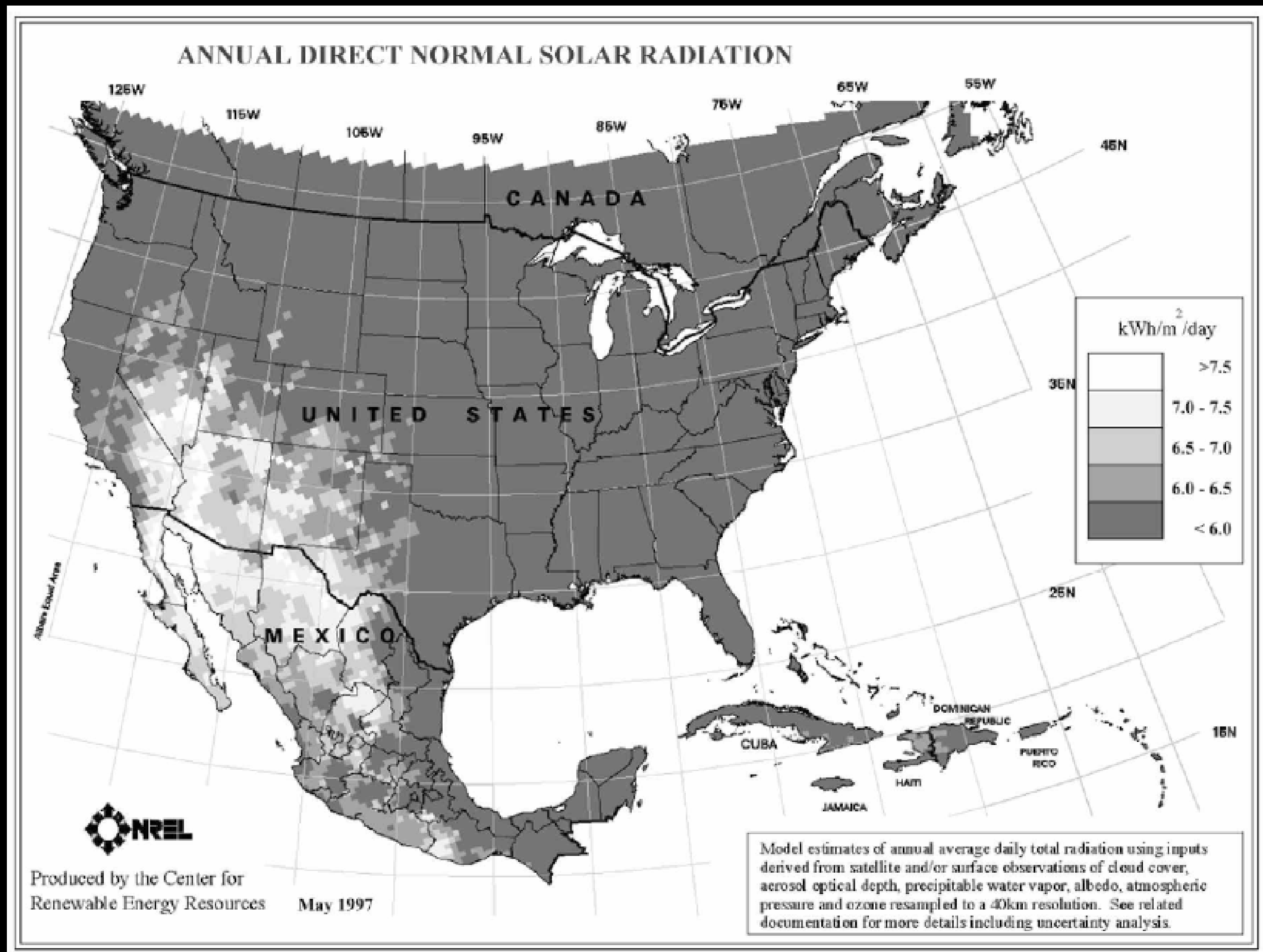

Levelized energy cost

# System Efficiency

$$\eta_{system} = \eta_{collector} * \eta_{process}$$

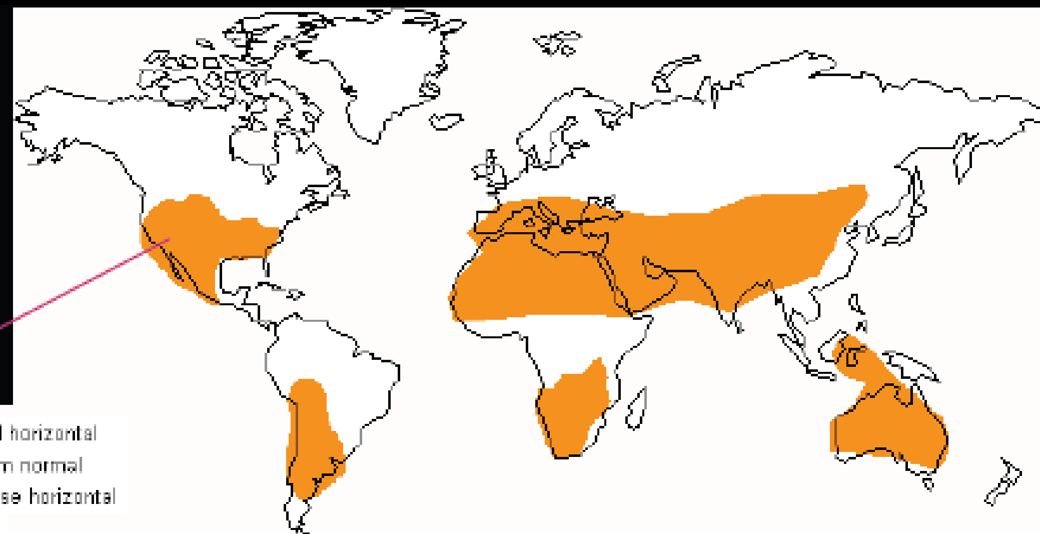


# US Solar Radiation Map

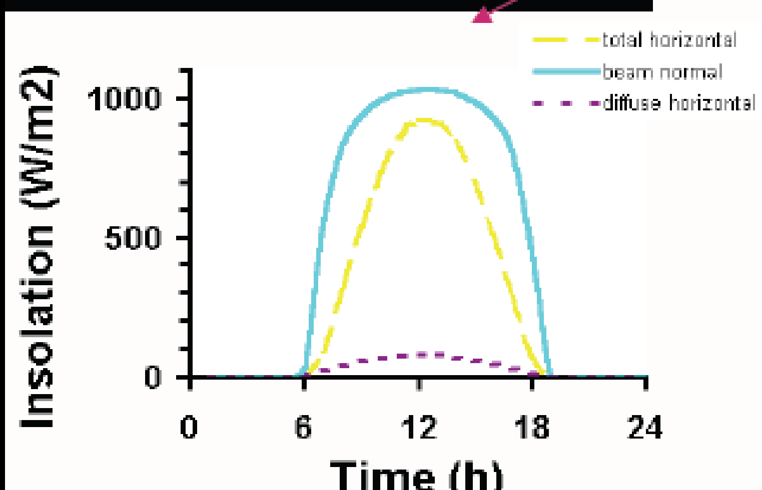



Source: US DOE

# The Solar Resource



Daggett, California




Peak radiation: 1030 $W/m^2$

Full Day: 10.6 $kWh/m^2$

# 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

# Flat Plate Collectors - Domestic Heating

# Flat-Plate Collectors

In the solar collector, the energy transfer is from source of radiant energy to a fluid.

The flux of incident radiation ~ 1000 $W/m^2$ ( it is variable)

The wavelength range: 0.3 - 3.0 $\mu$m

Energy delivery at moderate temperatures ~ 400K

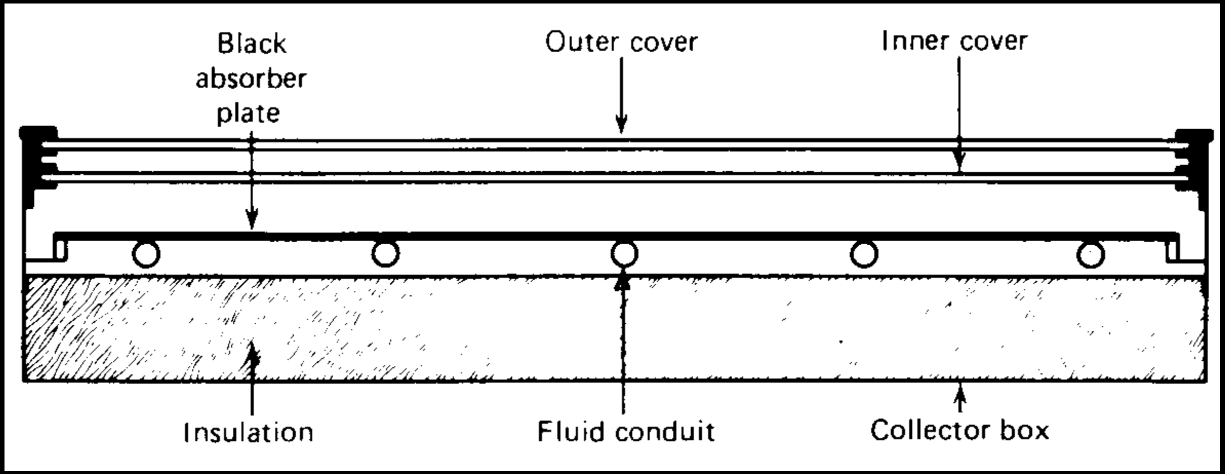
Use both beam and diffusive solar radiation - do not require tracking the Sun.

Major applications: solar water heating, building heating, air conditioning and industrial process heat.

Maximum temperature ~ 400K

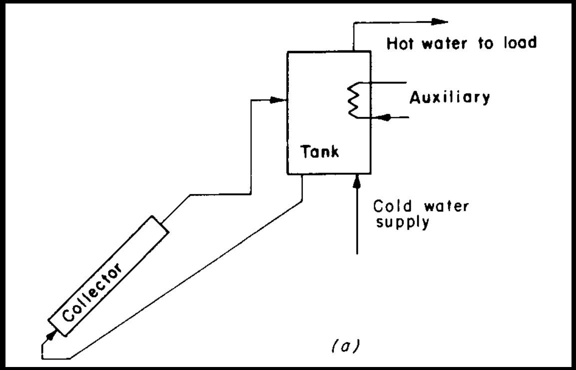
Source: Solar Engineering of Thermal processes by Duffie & Beckman, chapter 6.

# Basic Flat-Plate Collector

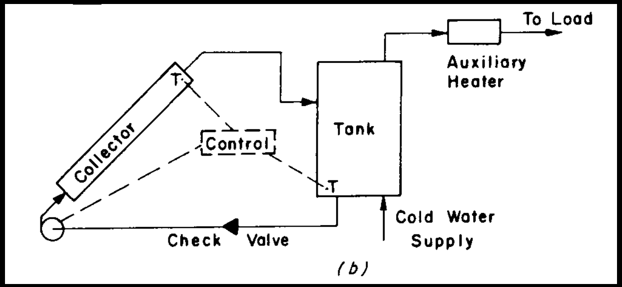


Sustainable Energy Science and Engineering Center

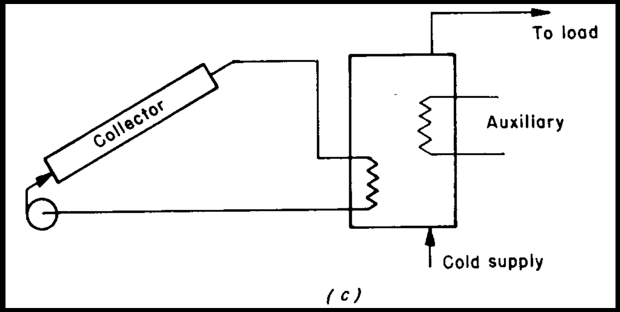
# Water Heater Configurations



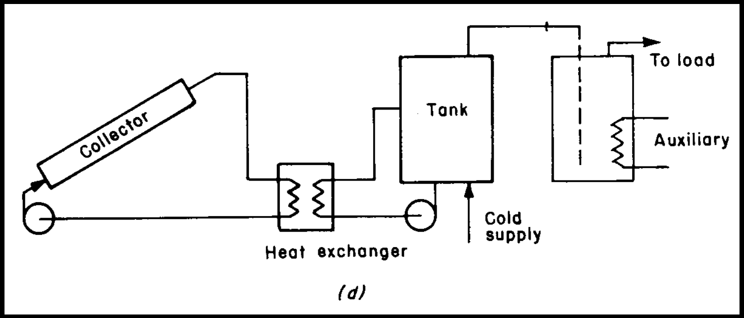

Natural circulation system




One tank forced circulation system

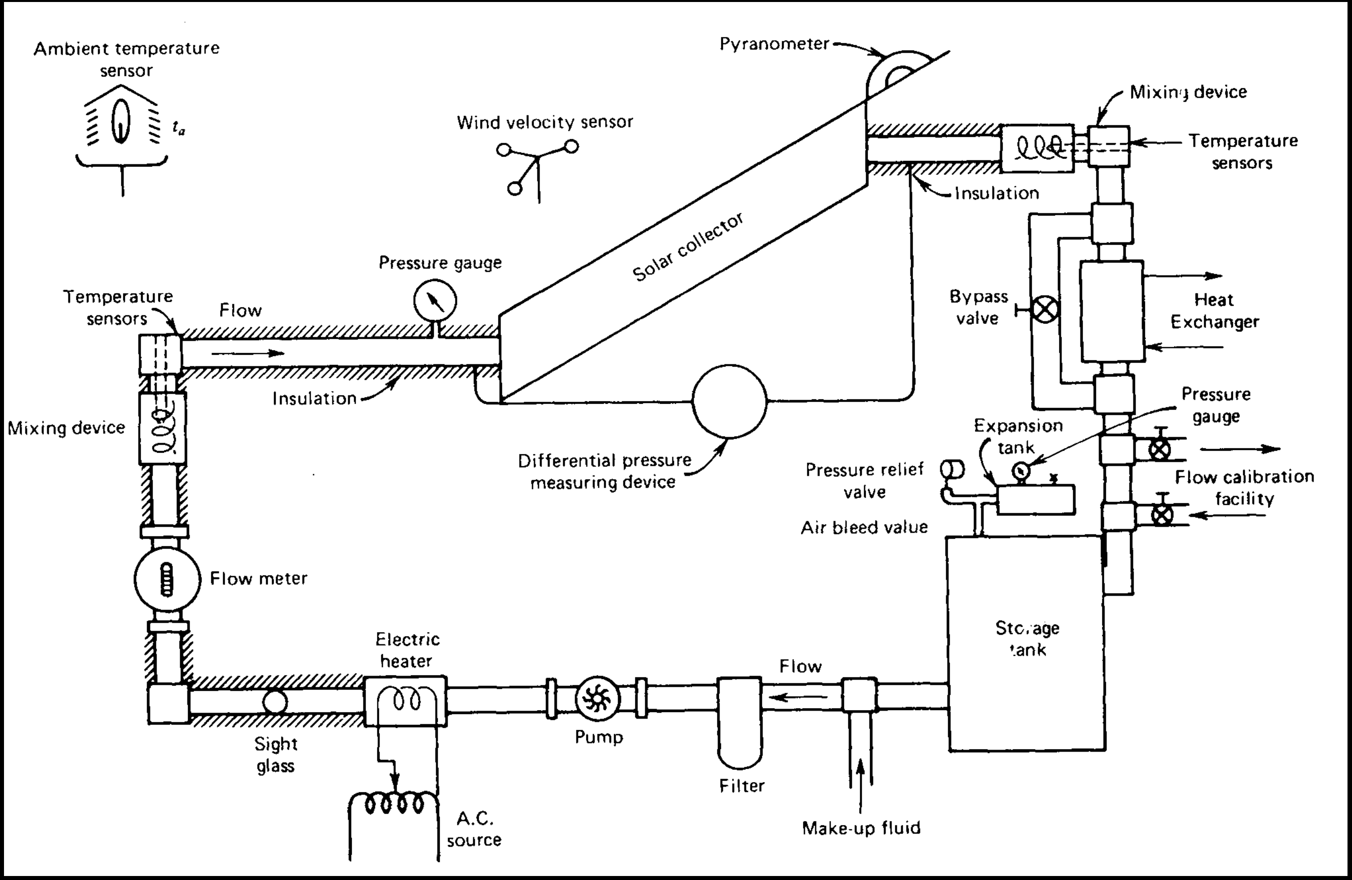



Antifreeze loop and internal heat exchanger




Antifreeze loop and external heat exchanger

# Liquid Heating Collector System



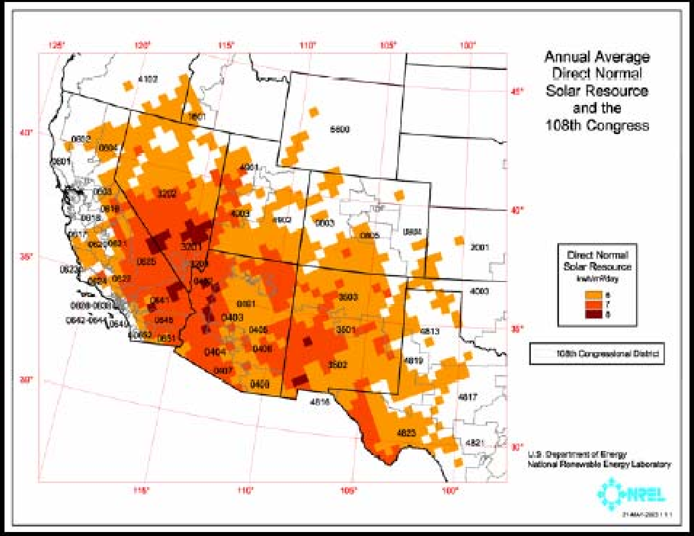
# Solar Thermal Conversion

| Technology | Temperature ($^{o}C$) | Concentration ratio | Tracking | Maximum conversion efficiency (Carnot) |
|---|---|---|---|---|
| Dish Concentrators | 50 - 1000 | 80 - 8000 | Two-axis | 80% |
| **Heliostat field + Central receiver** | 500-800 | 600-1000 | Two-axis | 73% |
| **Parabolic trough** | 260-400 | 8-90 | One-axis | 56% |
| **Flat plate collector** | 30-100 | 1 | | 21% |

# Southwest Strategy

## Resource Availability:

| State | Solar Capacity (MW) | Land Area (Sq Mi) |
| --- | --- | --- |
| AZ | 1,652,000 | 12,790 |
| CA | 742,305 | 5,750 |
| NV | 619,410 | 4,790 |
| NM | 1,119,000 | 9,157 |
| Total | 4,132,715 | 32,487 |




The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.

Solar Energy Resource ≥ 7.0 kWhr/m²/day (includes only excellent and premium resource)

**Current total generation in the four states is 83,500 MW.**

Source: Luc Moens. NREL; GCEP Workshop, October, 2004

# Solar Thermal Power Plant Potential

Comparably low power generation costs can be achieved wherever insolation reaches 1,900 kWh per square meter and year or more.