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
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.
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:

\[ C_O = \frac{1}{A_r} \int I_r dA_r \]

- \( I_r \) is the averaged irradiance
- \( I_a \) is the insolation incident on the collector aperture
“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*
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 focusing lens and mirror to ignite fires.
Leonardo Da Vinci

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 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.
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 ft². 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.
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.
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.
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.

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.
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°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.
Parabolic Trough

- Cycle: steam turbine, CHP
- Status: commercial, 80 MW
- Projects ahead: 50 - 150 MW, Spain, India, Mexico, Egypt, Morocco, Crete, Jordan, USA, South Africa .......

Solar Electricity Generating System (SEGS)

- 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

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

helium (50 - 200 bar / 600 - 1200 °C)

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 GWhₑ/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 CO₂ / year

Source: Dr. Franz Trieb, German Aerospace Center (DLR)
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** 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
Figure 2. Integrated Solar Combined Cycle System [1].
Integrated Solar/Combined Cycle System
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.
A new SAIC faceted membrane heliostat is on test at the National Solar Thermal Test Facility.

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.
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
### Table 1. Experimental power towers.

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

Source: US DOE
**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, 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.

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

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

† S/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

Produced by the Center for Renewable Energy Resources May 1997

Model estimates of annual average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmosphere pressure and ozone resampled to a 0.04° resolution. See related documentation for more details including uncertainty analysis.

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