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Overview of Concentrated Solar Energy Technologies

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Primer on Concentrated Solar Energy

Credits: 6 PDH

Course Description

This course discusses several of the more proven concentrating solar power technologies presently on the market. Also discussed will be the basic units commonly found in most types of CSP facilities: solar reflectors (mirrors), solar receivers, and solar tracking devices, along with their ancillary components.

Discussed will be the primary application of using solar thermal heat for generating steam for turbine electrical power production. Other applications for concentrated solar are high thermal heat processes of a primary and secondary (or byproduct) nature, which are able to utilize the thermal output from these CSP systems.

Topics

- Overview of CSP Solar Thermal Plant Technology
- Solar Reflectors: Types of Mirrored or Reflective Solar Concentrators
- Solar Heat Absorbers (Receivers); Solar Tracking Devices
- Heat Transfer Fluids (HTF); Thermal Energy Storage Units (TES)
- Components of the Steam Rankine Power Block
- Supervisory Control and Data Acquisition (SCADA) in CSP Facilities
- Pros and Cons of CSP
- Secondary, or Byproduct Applications for CSP Thermal Heat Supply
- Finding the most Ideal Geographic Locations for CSP Facility Sites
- Summary of the Open and Enclosed Parabolic Trough System
- Utilizing CSP in the Petroleum Industry for EOR (Enhanced Oil Recovery) Efforts
- Utilizing CSP in Water Purification and Desalination Plants
- Niche Markets: the MicroCSP system
- Summary of LFR and CLFR systems
- Characteristics of Power Tower Facilities; and Solar Updraft Towers
- Alternative CSP Technologies and Systems
- Characteristics of (CPV) Concentrated Photovoltaic Systems
- Cutting Edge Tech: Luminescent Solar Concentrators
- Stirling Dish Engine System
- Thermodynamics: Power Cycles found in CSP applications



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Chapter One: Introduction

CSP Solar Thermal Plant Technology

Need for Solar

From the short period of time during the boom in solar energy technologies (following the OPEC oil embargo crisis of the 80's), solar thermal energy has been a technology which was proven to work on a utility scale.

Interest in this technology waned for several decades, as cheap fossil fuels were once again the main heat source in creating steam for turbine generators.

In recent years, however, there has been a renewed enthusiasm for using solar thermal heat systems (image below) to generate power for the global power grids, spurred on by governmental stimulus capital.

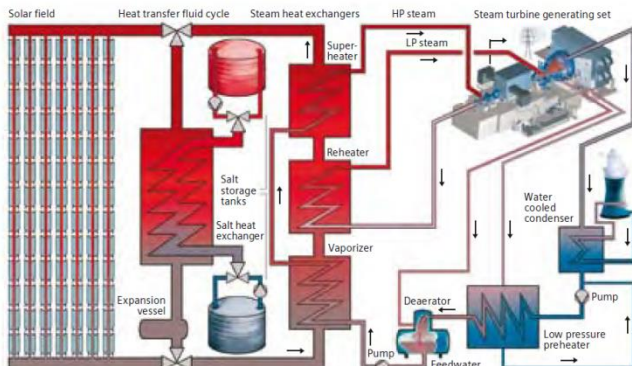


Diagram of a Typical Solar Power Plant Configuration

Image source: Siemens

The most time-proven form of concentrating solar power system is the parabolic trough solar collector system.

Other commonly implemented CSP technologies are the power tower or “central tower” plants, the linear Fresnel reflector plants, and variations of these three systems.

All three plant technologies have the same basic types of components and principles of operation, using:

- *Mirrors* – which focus and concentrate the direct solar radiation
- *Receivers* – which absorb or receive the heat from the reflected rays of sun
- *Sun Tracking Mechanisms* – that keep the mirrors or lenses oriented toward the sun's beam providing a steady and uninterrupted supply of direct, non-diffused sunlight.
- *Working Fluids or (HTF) Heat Transfer Fluids* - the solar radiation heats an HTF that is circulated to produce steam to drive a steam turbine, in turn producing electrical power. Similar in nature to a fossil fuel, nuclear, or natural gas power plant, CSP uses heat energy to create steam which causes rotation of the turbine to generate electrical power.
- *(TES) Thermal Energy Storage Systems* – TES systems such as molten salt tanks maintain the heat of the HTF, which later provides for continued power supply when unfavorable weather conditions occur or for the evening hours when the sun is down.
- *Power Block* – usually a steam-based Rankine, Stirling, or gas-based Brayton cycle, turbine generator for producing the electrical power output

CSP Mirrors (Concentrators)

Reflectors

There are various types of reflective surfaces and mirror frameworks used in a CSP facility, made from a variety of materials, with new products and configurations continually being developed.

Why Use Concentrating Collectors?

The primary reason for the interest in concentrating solar collectors for generating electricity, rather than the simpler, less expensive flat plate collectors, is the need for a temperature higher than that attainable with flat plate collectors for steam-cycle electricity generation.

Simpler, less expensive flat plate solar collectors work fine for solar space heating and solar water heating where the required temperature of the heated air is suitable; however the limited temperature to which they can heat a fluid prevents their practical use for solar generation of electricity.

Types of mirrors and support frameworks:

- *Parabolically curved troughs* - The parabolic through mirror frame (image) is a type of solar thermal concentrator that is straight in one axis and curved as a parabola in the other, and lined with a polished metal, curved mirrored glass, or other flexible reflective material such as the newer reflective films which are applied over aluminum underlays.



Parabolic Trough Mirrors
Image Source: Skyfuel.com

- *Plane-Surface Heliostats* – This type of concentrator (image) is usually a plane mirror frame, which uses a tracking system to maintain focus of the sunlight onto a solar receiver. These are typically used with power tower systems. These units tend to be as much as 50% of the total cost of developing a power tower facility, due to the high cost of heavy structural members with reinforced concrete foundations.

These frames tend to be plane surfaced, as curved surfaces would be problematic, as attempting to focus the center of the reflected beam onto the tower receiver at

such long distances would require a high level of precise adjustment, not to mention the added expense of the curved glass over flat glass.



Heliostat Mirror Unit
Image Source: en.wikipedia.org

- *Linear Reflective Fresnel Strip Mirrors* - LRF strip reflectors (image) use long, thin segments of mirror to focus the sun's rays onto an absorber, fixed at a common focal point of the reflectors. These mirrors are able to concentrate the sun's ray up to 30 times the normal intensity. This type of support system usually consists of a framework of uni-strut channels, which are near to the ground with a light support frame used for the absorbers.



Linear Fresnel Reflectors
Image Source: seia.org

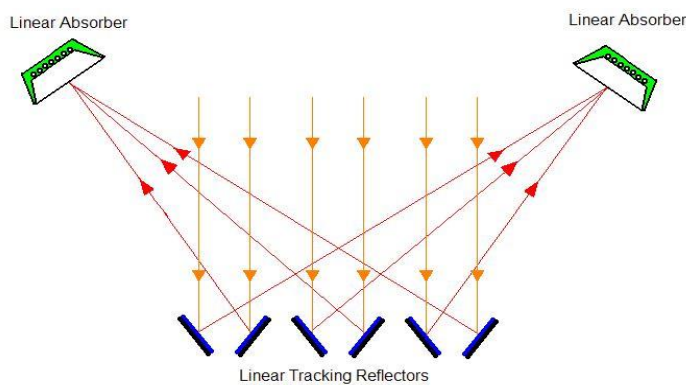
- *Compact LFR Mirrors* – Unlike traditional LFR's, the CLFR uses multiple absorbers above its mirrored strips. The additional absorbers allow the mirrors to alternate their inclination (image).

Advantage of the CLFR arrangement:

Less interference from adjacent strips - Alternating inclinations minimize the issue of reflectors blocking adjacent reflectors' access to sunlight, improving overall system efficiency.

More compact system - Multiple absorbers minimize the required ground space needed for installation, in turn reducing land cost.

Shortened absorber lines - The close proximity of the panels reduces the length of the absorber lines, thus reducing thermal losses via the absorber lines.



Compact Linear Fresnel Reflectors
Image Source: wikipedia.org

- *Parabolic Concave Dish Mirrors* – These mirrors (image) have a semi-parabolic cross section, and are manufactured in pie-shaped panels. They are affixed to a concave dish support frame. The unique shape of the mirrored panels makes these mirrors costly to install and replace.



Parabolic Concave Mirror
Image Source: volker-quaschnig.de

- *Flat Planed Reflector Dish Arrays* – These mirror frameworks (image below) generally consist of flat panes of reflector glass, affixed to a latticed support frame which creates a pseudo-concaved shape, focusing the mirror panes onto the focal point (receiver). By using an array of flat planed reflectors instead of curved glass, these units tend to be more cost-effective than the parabolically curved dishes.



Stirling Engine using the Dish Array Mirror Configuration
Image Source: Wikipedia.org

Other low-cost types of mirror materials:

- *Abrasion Resistant Polymer Reflector Film* – This is a low-cost alternative to expensive glass reflective surfaces. Whereas glass mirrors are heavy, fragile, expensive to manufacture and ship, this film (image) is lightweight, durable, and inexpensive to manufacture. The film is adhered to various underlay surfaces such as flat and curved aluminum sheets. Cost savings in using this film results from a decreased amount of structural support framework, manufacturing simplicity, low-cost shipping and transportation, and ease of field installation, and affordable replacement.



Parabolic Troughs using Polymer film
Image Source: Reflectech

- **Polished Stainless Steel** – Highly polished stainless steel (image) makes an exceptional reflective concentrator, is lightweight, and inexpensive to manufacture and ship.



Laser Polished Stainless Steel on a Wooden Slat Support Frame
Image Source: greenpowerscience.com

CSP Heat Absorbers (Receivers)

Solar Power Tower "Central" Receiver

These receiver towers (image) collect the focused sunlight from sun-tracking heliostat mirrors. Molten salts (40% potassium nitrate, 60% sodium nitrate) are used as the high heat capacity transfer fluid, which is circulated to superheat the water to drive the steam turbines.



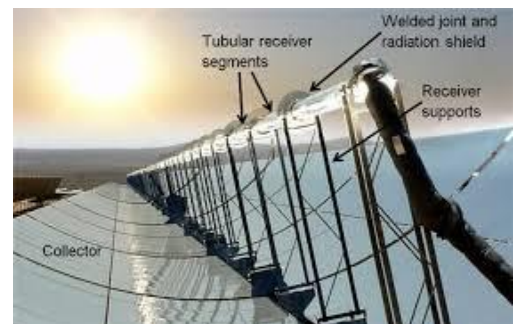
Solar Power Tower Receiver
Image Source: renewableenergyfocus.com

Parabolic Trough Receiver

This heat absorber (image) consists of a tube, which is usually a **Dewar tube*, which runs the length of the trough at its *focal line*.

***Dewar tubes** - are vacuum sealed tubes that have a gap between two glass container tubes, with the gap partially evacuated of air, creating a near-vacuum preventing heat transfer by conduction or convection. An example of a Dewar style flask container, which is based on the same design principles, is the common "thermos bottle".

The mirror is oriented so that sunlight is concentrated onto the tube, which contains the heat transfer fluid (commonly water, synthetic oils, or molten salt).



Parabolic Trough Receiver
Image Source: pre.ethz.ch

(CLFR) Compact Linear Fresnel Receiver

The Fresnel fixed heat absorber (image) receives focused sunlight from long, thin segments of mirror at roughly 30 times its normal intensity. This

concentrated energy is transferred through the absorber into the heat transfer fluid. As opposed to traditional LFR's, the CLFR utilizes multiple absorbers within the vicinity of the mirrors.



(LFR) Linear Fresnel Type Receiver
Image source: cspworld.org

Solar Dish Receiver and Generator (Stirling Engine)

The solar dish receiver unit (image) is mounted at the focal point of the parabolic dish or dish array. It generally consists of the receiver and generator assembly all in one package (image).

This allows for turnkey installations, where the power is readily available once the unit is put into place.



Dish Receiver and Engine
Image source: solarcentral.org



Receiver and Stirling Engine Assembly
Image source: mtholyoke.edu

Sun Tracking Systems

Tracking the Sun's Rays

Sunlight includes the direct beam, which carries about 90% of the solar energy, and the diffuse sunlight, that carries the remainder.

As the majority of the solar energy is in the direct beam, maximizing collection requires that the sun be exposed to the panels for the longest duration of time possible.

Tracking systems are required in a CSP system, as they allow for the maximum exposure to this direct portion of the sunbeam.

Direct beam solar radiation reaches the earth's surface in essentially a straight line, without being reflected, scattered or absorbed by particles or gases in the air.

Diffuse solar radiation, on the other hand, reaches the earth's surface after being scattered, reflected, or absorbed by gases or particles in the atmosphere.

Only direct beam solar radiation can be utilized and concentrated by concentrating collectors, so tracking systems are needed in a CSP system to keep the collectors aligned with the incoming direct beam solar radiation.

In tracking the sun, these concepts are of importance:

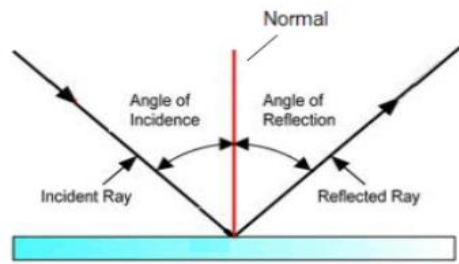
Angle of incidence and reflection

This is a measure of the deviation from "straight on" or 0° (the normal angle to the surface), as in the approach of a sun's ray to a reflective surface.

Trackers that have accuracies of $\pm 5^\circ$ deviance from normal, can deliver greater than 99.6% of the energy delivered by the direct beam plus 100% of the diffuse light.

The angle between the reflected ray and the normal is known as the *angle of reflection*. The law

of reflection states that when a ray of light reflects off a surface, the angle of incidence equals the angle of reflection.



Angle of Incidence and Angle of Reflection

Direct Normal Irradiance (DNI)

DNI is the amount of solar beam radiation received per unit area of reflective surface, which is normal to the rays that come in a straight line from the direction of the sun.

Albedo

This is the amount of solar radiation that is reflected; defined as the fraction of solar radiation that is reflected from the ground, ground cover, and bodies of water on the surface of the earth.

Trackers can be:

- *Single-axis* – these tracking systems move and track along a single line of motion, such as east to west. The single axis trackers are used with the parabolic trough systems.
- *Dual-axis* - these tracking systems can adjust throughout the day from east to west, and also from south to north simultaneously. They are required for the heliostat mirror units, and the dish units.

Single Axis Trackers

- *Horizontal (HSAT)* - The axis of rotation for horizontal single axis trackers are horizontal with respect to the ground.
- *Vertical (VSAT)* - The axis of rotation for vertical single axis trackers are vertical with respect to the ground.
- *Tilted (TSAT)* - All trackers with axes of rotation between horizontal and vertical are considered tilted single axis trackers.
- *Polar (PSAT)* - The tilted single axis is aligned to the polar star (which is a visible star, that

is approximately aligned with the Earth's axis of rotation).

Dual Axis Trackers

- *Tip-Tilt (TTDAT)* – This is a dual axis tracker which is so-named because the panel array is mounted on top of a pole. Normally the east–west movement is driven by rotating the array around the top of the pole.
- *Azimuth-Altitude (AADAT)* - An azimuth-altitude dual axis tracker has its primary axis (the azimuth axis) vertical to the ground. The secondary axis, often called elevation axis, is then typically normal to the primary axis.

Drive Types

- *Active tracker* - Active trackers use motors and gear trains to direct the tracker as directed by a controller responding to the solar direction. Light-sensing trackers typically have two photosensors, such as photodiodes, configured differentially so that they output a null when receiving the same light flux.
- *Passive tracker* – One type of passive tracker uses compressed gas fluid with a low boiling point, that is driven to one side or the other (by solar heat generated gas pressure) to cause the tracker to move in response to an imbalance.
- *Chronological tracker* - A chronological tracker counteracts the Earth's rotation by turning at an equal rate as the earth, but in the opposite direction. The rates aren't exactly equaled, as when the earth circles the sun, the position of the sun changes with respect to the earth by 360° every year or 365.24 days. A chronological tracker is a simple yet accurate solar tracker specifically for use with a polar mount.

Light-sensing Trackers (Photon detecting control devices)

These typically have two photosensors (photo conductors), configured differentially so that they output a null when receiving the same light flux.

These types of trackers tend to operate erratically on cloudy days.

Two types of photoconductors:

- *Photodiodes* - are semiconductor devices that can convert light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The PV solar cell used to generate electric solar power is a large area photodiode. Photodiodes are unidirectional and can operate in “off and on” photoconductive output only.
- *Light Dependent Resistors (LDR)* - or a photocell is a light-controlled variable resistor. The varied resistance of the photoresistor decreases with increasing incident light intensity (conduction varies with light intensity), meaning it exhibits *photoconductivity*. LDR's are bidirectional and can provide variable degrees of photoconductive output. They are low cost and well suited for rugged environments.

Fixed Mount vs Floating Mounts

Solar trackers can be built using a “floating” foundation, which sits on the ground without requiring concrete foundations. These floating trackers are placed on a gravel pan which is weighted with materials such as sand or gravel, to prevent overturning by wind forces.

Floating trackers can typically sustain similar wind loads as traditional fixed-mounted trackers. The use of floating trackers increases the number of potential sites, as they can be placed in locations with soil conditions which are unsuitable for bearing the loads of concrete foundations.

Types of Heat Transfer Fluids

Molten Nitrate Salt

This is an excellent thermal storage medium to use on CSP systems, but it can also be problematic due to its relatively high freezing point (220C/428F).

To maintain the salt in a molten state, a complex heat trace system must be used, which is composed of electric wires attached to the outside surface of the piping network.

Liquid salts used for heat transfer in power plants are called molten salts because normally they are solids at standard temperature and pressure.

Conventional mixtures of sodium nitrates and potassium nitrates are already proven as energy storage media in trough and tower configurations. The new concept is to use those nitrate salts as the HTF as well as for storage, which can lead to a more efficient trough plant design.

Salts are cheaper, denser, and can retain more energy per volume than oil-based HTFs. They can be directly stored and accessed at near-ambient pressure, not at oil-based fluid's considerably higher vapor pressure.

A larger tank can be used for both expansion and short-term storage when the fluid is hot, minimizing the need for additional tanks and heat exchangers, and making it easier to incorporate heat storage.

Where leaking synthetic oil HTFs pose spill and fire hazards, leaking molten salt will solidify and can be cleaned by scooping with a shovel. Salts do not degrade over time, do not need to be replaced, and do not exhibit the hydrogen permeation problem that oil-based HTFs exhibited.

Salt Freeze Problems

Salt based trough plants are designed to continuously circulate HTF through loops, even at night, but if molten salt ceases to circulate and cools below its melting point for a few days or

weeks due to various reasons, the salts can freeze and contract.

Contraction itself is not the problem, but when the salts re-melt, they will expand. If a pipe containing frozen salt is filled solid, it may rupture upon re-melting. This will require a re-melting process to occur slowly, over the course of several days or weeks.

Absorber or receiver tubes could also be permanently damaged if they were completely filled with salt when frozen. Trough salt plants contain electric heat tracing to maintain the circulating system in a warm state during cold nights, and reduce the potential for freezing.

Research is focused on finding compatible salts with lower melting points to solve this dilemma. Additives such as lithium nitrate may be able to reduce melting points to as low as 80 °C by creating more complex salt blends.

This is still above ambient temperatures, but far below the melting point of conventional nitrate sodium mixtures of 220 °C. Even so, lithium nitrate is an expensive additive, especially when dealing with thousands of gallons of HTF mixture.

Synthetic Oils

Most trough plants with synthetic or organic oil heat transfer fluids (HTFs) are limited to less than 400 °C. While using synthetic oil as a HTF is well suited for lower temperature heat transfer, problems can arise with using this as a transfer medium. During spill situations, hazmat cleanup efforts are required.

They are a flammable substance as well, creating potential fire hazards at the plant. As was illustrated in the SEGS TES accident in 1999, when an incident occurred with hundreds of thousands of gallons of flammable HTF; it can develop into a major disaster situation, quickly.

Direct Steam

Another option to consider is using high pressure direct steam heated in the absorbers, for powering

the turbine generator. This eliminates the need for heat exchangers (to transfer the heat from the HTF to the steam Rankine loop).

In systems using highly-insulated types of absorbers such as the Dewar tube, heat losses during solar field circulation can be kept to a minimum.

Other Components of a CSP System

Auxiliary Components

In addition to the main components of a CSP, there are a number of auxiliary components involved which make up a CSP facility.

(TES) Thermal Energy Storage

One challenge facing the use of CSP is the limitations of energy production when the sun sets or is blocked by clouds.

(TES) Thermal energy storage (image) provides a workable solution to this challenge.

When the HTF is either oil or molten salt, then the thermal energy can be stored for later use. A number of thermal energy storage technologies have been tested and implemented over the years.

Two-Tank Direct System

In this TES system the HTF and the storage fluid are the same, with thermal energy being stored in two tanks, one at high temperature, and the other at low temperature.

Fluid from the low-temperature tank flows through the solar absorber or receiver, where solar energy heats it to a high temperature and it then flows to the high-temperature tank for storage.

Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production. The fluid exits the heat exchanger at a low temperature and returns to the low-temperature tank.



Two Tank Direct Molten Salt TES at the Solar Two Power Tower Plant
Image source: NREL

Two-tank direct storage was used in early parabolic trough power plants (such as at the SEGS I) and at the Solar Two power tower (image) in California. The SEGS trough plants used mineral oil as the HTF and storage fluid, while Solar Two used molten salt.

Two-Tank Indirect System

Two-tank indirect systems function in the same way as two-tank direct systems, except different fluids are used as the HTF and storage fluids. This system is used in plants in which the HTF is costly or not well suited for use as the storage fluid.

The storage fluid from the low-temperature tank flows through an extra heat exchanger, where it is heated by the high-temperature HTF. The high-temperature storage fluid then flows back to the high-temperature storage tank.

The fluid exits this heat exchanger at a low temperature and returns to the solar absorber or receiver, where it is heated back to a high temperature.

Storage fluid from the high-temperature tank is used to generate steam in the same manner as the two-tank direct system. The expense of the additional heat exchanger adds to the system's overall cost.

This system will be used in many of the proposed parabolic power plants being developed in Spain (image) and has also been proposed for several U.S. parabolic trough plants. The plants will use

organic oil as the HTF and molten salt as the storage fluid.



Two-Tank Indirect TES at Andasol1 in Spain
Image source: greenthoughts.us

Single-Tank Thermocline System

Single-tank thermocline systems (image) store the thermal energy in a solid medium, generally silica sand, which is located in a single tank.

At any given time during the plant's operations, a portion of the silica is at high temperature, and a portion is at low temperature.

The stratified thermal regions are separated by a temperature gradient (thermocline). High-temperature HTF flows into the top of the thermocline and exits the bottom at low temperature.

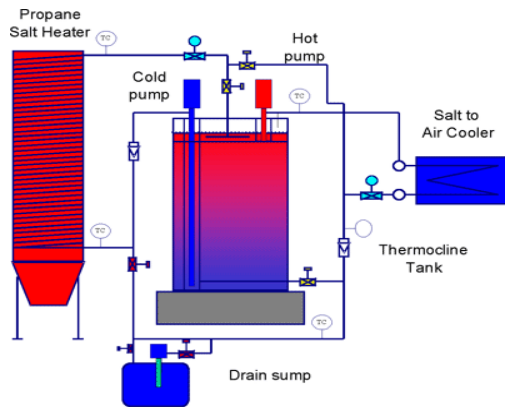
This process adjusts the thermocline downward and adds thermal energy to the system for storage.

Reversing the flow moves the thermocline upward, removing thermal energy from the system to generate steam and electricity.

Buoyant effects create thermal stratification of the fluid within the tank, which stabilize and maintain the thermocline.

Using a solid storage medium and only needing one tank reduces the cost of this system relative to two-tank systems.

This system was demonstrated at the Solar One power tower, where steam was used as the HTF and mineral oil was used as the storage fluid.



Thermocline TES Process

Image source: NREL

Concrete (Experimental Solid TES)

The German Aerospace Center (DLR) is experimenting with the viability of using solid, TES media such as high-temperature concrete, or castable ceramic materials in parabolic trough TES units.

This system uses the standard HTF in the solar field, which passes through an array of pipes imbedded in the solid medium to transfer the thermal energy to and from the solid media during plant operation.

This approach is due to the low cost of the solid media, however issues include maintaining reliable thermal transfer between the concrete and piping, and the heat transfer rates into and out of the solid medium.

Phase-Change Materials (such as graphite)

These allow large amounts of energy to be stored in small volumes, resulting in lower storage media costs. Initially phase-change materials were a consideration for use in parabolic trough plants that used Therminol in the solar field.

Later, an approach that used a cascading set of phase-change materials to transfer heat from the HTF was considered. In this approach, thermal energy transfers to a series of heat exchangers containing phase-change material that melt at slightly different temperatures. To discharge the storage, the heat transfer fluid flow is reversed.

This results in reheating of the heat transfer fluid. Although testing proved the technical feasibility of this system, further development of the concept was hindered because of the complexity of the system, the thermodynamic penalty of going from sensible heat to latent heat and back to sensible heat, and the uncertainty over the lifetime of phase-change materials.

Steam Rankine Power Cycle

The power cycle typically utilized in Trough, Power Tower and LFR systems is the Rankine steam cycle (standard, organic, or modified).

The standard cycle is typically used in high heat application, while the organic is used for lower heat applications such as with waste heat.

Steam Turbine

A steam turbine (image) is a heat engine which extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft.

Because the turbine generates rotary motion, it is well suited to be used to drive an AC electrical generator. The majority of all electrical generation in the US is by use of steam turbines.

There are two basic steam turbine types, *impulse* (which has fixed nozzles that orient the steam flow into high speed jets.) turbines and *reaction* (the rotor blades themselves are arranged to form convergent nozzles) turbines, whose blades are designed control the speed, direction and pressure of the steam as it passes through the turbine.



Steam Turbine Generator for Solar Plant Application

Image Source: Siemens

Electrical energy generation using steam turbines involves three energy conversions, using thermal energy to create steam, converting the thermal energy of the steam into kinetic energy in the turbine, and then using a rotary generator to convert the turbine's mechanical energy into electrical energy.

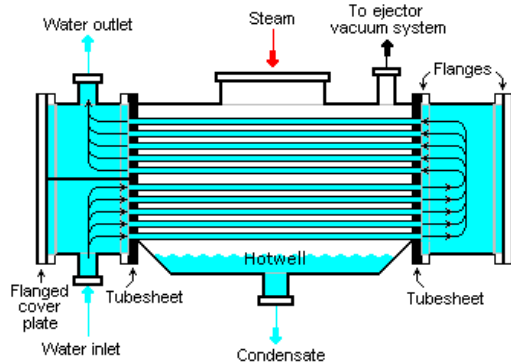
The turbine generator used in solar plants, are the same types used within the various fossil fuel plants.

Steam turbines installed in CSP plants have certain requirements:

- The daily cycling (startup and shutdown) and temperature variations of a CSP system require that a CSP steam turbine have fast daily startup capabilities, as the generator will not be run all 24 hours in the day
- The turbine needs to be matched to the specific MW power output of the plant
- It needs to be highly efficient, and optimized to handle a wide steam flow range, as the solar energy thermal intensity and the cycling conditions can vary according to the weather and time of day
- It can be operated in non-reheat, single reheat, and double reheat cycles
- It must be matched to the air-cooled or water-cooled plant specifications

Condenser

A steam condenser (image) is a type of heat exchanger which returns the post-turbine steam to a liquid state.



Steam Generator Condenser

Image source: Alibaba

De-aerators

A deaerator is a device used for the removal of oxygen and other dissolved gases (such as CO₂) from the feedwater to steam-generating boilers.

(Dissolved oxygen in boiler feedwater will cause serious corrosion damage in steam systems by attaching to the walls of metal piping and other metallic equipment and forming rust.)

Preheaters

A feedwater heater is a power plant component used to pre-heat water delivered to a steam generating boiler. Preheating the feedwater reduces the irreversible losses involved in steam generation and therefore improves the thermodynamic efficiency of the system.

This reduces operating costs and helps to eliminate thermal shock to the boiler metal when the feedwater is introduced back into the steam cycle.

In a steam power plant's modified Rankine cycle, feedwater heaters allow the feedwater to be brought up to the saturation temperature gradually minimizing the irreversible losses associated with heat transfer to the working fluid (water).

Superheaters

A steam superheater is used in steam generators and heat-recovery steam generators (HRSGs). Their purpose is to raise steam temperature from saturation conditions to the desired final temperature, which can be as high as 1,000°F.

When used in steam turbines, superheated steam decreases the steam heat rate of the turbine and thus improves the turbine and overall plant power output and efficiency.

Typical System Pumps

Most of the pumps used in the CSP need to be designed to handle high thermal processes or conditions.

High temperature conditions such as:

- Condenser to Receiver
- Low Pressure Preheater to Condenser

- Solar Preheater to De-aerator
- (HTF Pump) Solar Field to TES
- TES recirculation

Boiler Feedwater

This is the working fluid part of the steam closed (never open to the atmosphere loop) system or Rankine cycle.

Control Systems - SCADA for Solar

SCADA (supervisory control and data acquisition) is a large scale control system for managing automated processes.

SCADA generally refers to a centralized system which monitors and controls an entire set of complex systems.

Utility scale SCADA systems include the following :

- *Data Acquisition* – collection of data from field devices such as PV Inverters, meters, sensors. These devices communicate to PLCs or PC for data and status reports via communication interfaces. Data is then compiled and formatted in a way that a workstation operator using the HMI can make supervisory decisions to adjust or override normal controls.
- *(HMI) Human-Machine Interface* - As data is acquired and compiled, it is then converted and displayed graphically, so that an administrations operator at the HMI interface (image) can quickly and easily view the status of the various solar systems. Mobile touchscreen devices are quickly becoming the HMI of choice, as the graphical interfaces can easily be designed using the endless variety of mobile app software programs. Android, Apple, Blackberry and others, can all function as core SCADA operating platforms.



HMI display for a Microgrid control system

Image source: etap.com

- *Event and Alarm Management* - SCADA systems also have the functionality to alert system administrators as to any alarms and system malfunctions which might occur at a solar power plant. Maintenance scheduling reminders, etc. can also be automatically sent to the appropriate personnel through the SCADA control network.
- *Remote Monitoring* – Solar plant system administrators will usually have the ability to remotely check on the various sensory devices of a solar plant. Many SCADA systems include web functionality which allows monitoring via mobile HMI devices. Once an event occurs, the operator can check it remotely and usually resolve the event from practically any location accessible by phone or web.
- *Archiving* – The SCADA system can store and back up the data acquired from the site concerning: production, maintenance, status, scheduling, reports, etc. for future analysis.
- *Database* – All of the SCADA information can be exported to a database (ex. - SQL Server DB) for querying and analysis of the data. The database can be setup remotely in a cloud server, or set up in a local database server.

Benefits and Drawbacks to CSP Technology

Benefits of CSP Technology:

- *Zero carbon emissions* - Clean non-polluting energy with a minimal carbon footprint
- *Eliminates foreign dependency on fossil fuels* - Puts money in the pockets of local,

domestic energy suppliers, not foreign entities

- *Potential for Uninterrupted Power* - Non-intermittent power delivery when integrated with thermal storage systems, or when hybridized with natural gas or fossil fuels
- *Steam Turbine Power* - Uses the same steam turbine power generators as conventional plants
- *Easily Integrated into Grid* - Easily integrated into the power grid as a (DG) distributed generation component
- *Economic Benefits* - Boosts the national economy by creating many new solar companies and jobs
- *Not subject to fluctuating pricing* - Is not subject to global price fluctuations, and manipulations, as are fossil fuels

Drawbacks to CSP Tech:

Potential Harm to Wildlife: In Particular, Avian (Bird) Mortalities

It may appear to be a trivial issue, but one potential roadblock to CSP development is the issue of migratory bird flight within the CSP solar facilities.

In 2013, as part of a federal investigation, officials with the National Fish and Wildlife Forensics Lab recovered over 233 deceased birds from the sites of three Californian desert solar power plants.

They concluded that many of the birds had been killed by the intensity of the beam, generated in the CSP solar facilities (image).



Singed Bird Mortality
Image source: mirror.co.uk

Various witnesses driving through the California deserts have seen birds with their feathers ignited mid-air, after flying through the concentrated beam of the desert CSP systems.

Lake Effect

The birds are drawn to facilities to feed on insects attracted by facility lighting, or by the “lake effect” of the numerous mirrors.

The “lake effect,” is an illusion in which birds and their insect prey can mistake a reflective solar facility for a body of water, or they spot water ponds at the site, and fly through the concentrated beam.

Endangered Species Mortality

One of the birds found among the dead birds was a Yuma clapper rail, of which fewer than 1,000 are thought to still be in existence.

The discovery of this endangered bird among the other dead was a strong catalyst provoking an ensuing legal action which challenges at least a half dozen additional solar plants planned in California and Arizona desert regions.

Now, as CSP facilities are at long last, being planned and built in increasing numbers, solar energy developers are facing outcry and opposition for the harm that their clean energy facilities may potentially cause to wildlife.

If the issue of a wildlife impact continues to remain unresolved, the growth of the promising CSP industry could be hampered by lawsuits and public opposition from conservational activist groups.

Activist working to shut down the Soda Mountain Solar Project

This project is a proposed industrial-scale renewable energy development that would be constructed less than one mile from the boundary of the Mojave National Preserve.

Activists have been fighting this project due to concerns over the following issues:

- *Desert tortoise* - the proposed project is located in a key habitat linkage for the desert tortoise.
- *Desert bighorn sheep* - Biologists specializing in desert bighorn sheep are working to delineate and re-establish key migration corridors for these desert bighorn. Routes which link different bighorn populations ensure that bighorn populations do not become genetically isolated. (Bighorn sheep that become genetically isolated are less healthy and have a greater chance of eventually becoming eradicated). One of the more promising route locations to re-establish inter-population breeding is *across a major freeway* which is between the North and South Soda Mountains (where this proposed energy project would be located).
- *Groundwater* - Groundwater pumping for the operation of the proposed project could threaten the water resources at Mohave Chub Spring in the Mojave National Preserve. This spring supports a population of the federally endangered Mohave Tui Chub, a rare desert fish. The concern is that pumping of naturally limited groundwater to support the project *may* adversely impact water quantity and quality at Mohave Chub Spring and thus the federally endangered fish.

- Enhanced Oil Recovery
- Desalination - Reverse Osmosis
- Desalination - Thermal Distillation
- Wastewater Purification
- Food Industry Processes: Roasting, Broiling, Dehydration, Boiling, Steaming
- Sterilization, Pasteurization, and Distillation
- Climate Control: Cooling – to heat an AC Chiller Boiler
- Climate Control: Heating
- Water Heating for Swimming Pools

Oil Exploration - (EOR) Enhanced Oil Recovery

In the oil exploration industry, solar-generated steam can be injected into tapped-out oil wells to make heavy oils viscous enough to be recovered, in a process called (EOR), or Enhanced Oil Recovery.

Saltwater Desalination – (RO) Reverse Osmosis

Standard osmosis involves a solvent (such as water) moving from a region of low solute concentration, through a membrane, to a region of high solute concentration.

The movement of a pure solvent equalizes solute concentrations on each side of the membrane, generating *osmotic pressure*.

Applying an external pressure to reverse the natural flow of solvent is called **reverse osmosis** (image) to create clean water using this process, seawater or brackish water is pressurized against one surface of the membrane, causing salt-depleted water to move across the membrane, releasing clean water from the low-pressure side.

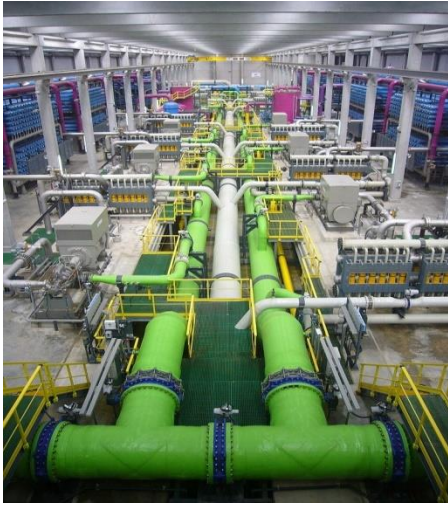
Other Uses for the CSP Thermal Heat Supply rather than Electrical Power Generation

Heat Process Applications

Driving steam-powered electrical generators to produce electrical power output is just one of the many applications of the high thermal output of a CSP system.

CSP systems can be used in a wide variety of commercial, industrial, and home use heat process applications.

Other heat processes which could utilize CSP thermal output are:



Reverse Osmosis Desalination Plant in Spain
Image Source: James Grellier

Reverse osmosis systems typically use less energy than thermal distillation systems, which has led to a reduction in overall desalination costs over the past decade.

Nevertheless, desalination remains an expensive and energy intensive process, which is why CSP technology shows such promise for being at the forefront of future drought relief efforts.

Saltwater Desalination – Thermal Distillation

Thermal desalination mimics the natural process of the water cycle – evaporation, accumulation, condensation, and collection.

Since heat is a vital part of thermal desalination, the process is often linked to power plants and refineries in using their waste heat.

There are three main types of thermal desalination – vapor compression (VC), multi-effect distillation (MED) and multi-stage flash distillation (MSF).

Wastewater Purification

The same processes used for desalinating water, can be applied to purify contaminated or wastewater sources. In addition, a byproduct of wastewater treatment, methane gas, can be tapped and used as a cogenerating heat source.

Food Industry

In industrial applications they can be used for any heat processes such as sterilization, distillation, dehydration, roasting, cooking, etc.

Climate Control AC Chiller Boilers

Some small scale CSP systems have been adapted for use in climate control cooling processes. The heat process from the CSP thermal loop is integrated into the boiler system of the AC chiller.

Climate Control Hydronic Heaters

Some systems have even been adapted for use in hydronic heating. CSP is well suited for use in hydronic, radiant heat applications.

Solar heating is usually supplemental rather than primary, in order to maintain thermostatically control temperatures within the required narrow temperature ranges of about 3 degrees F.

There are various types of hydronic (circulating liquid) radiant heat systems:

- In-floor wet applications (in solid mass - ex. concrete slab)
- In-floor dry applications (in air voids - ex. inter-joint or suspended ceiling installations)
- Radiant panels (in-wall or ceiling installations)
- Radiator-based
- Baseboard heaters

Solar Sterilization

Sterilizing medical instruments in solar powered autoclaves is a potential use for the smaller scale CSP units.

Also solar powered water sterilization can be accomplished using (UV) solar ultraviolet, (Electricity) solar generated electrical fields, and (Heat) solar thermal processes.

This could be of a tremendous benefit in many third world regions, to make biologically-contaminated (with bacteria, viruses, protozoa and worms) water safe to drink.

Solar Pasteurization

This is a process that kills bacteria in liquid food. This process achieves this by eliminating pathogenic microbes and lowering microbial numbers to prolong the quality of the food.

Pasteurization is not intended to kill all micro-organisms but rather reduce the number of viable pathogens so they are unlikely to cause disease. Water heated to temperatures below 100 °C is generally referred to as “pasteurized water”.

Swimming Pool Heating

Though most residential solar pool heating is accomplished by circulating the pool water through a solar manifold, CSP can generate much higher temperatures, heating a much larger pool such as one found in a resort, or municipal setting.

Geographical Limitations for CSP Implementation

The success and widespread implementation of CSP technology is limited by the percentage of cloud cover a particular region experiences throughout the year.

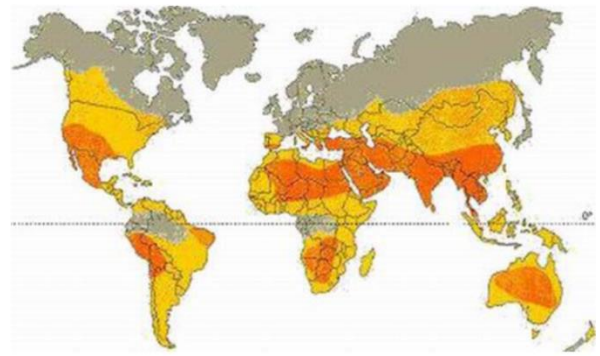
Some regions such as the UK might see a limited return on investment when investing largely in present day CSP technology.

However, other countries (image) with arid climates and limited annual cloud coverage could benefit enormously such as:

- central and western Australia
- the Arabic peninsula
- Northern and Southern Africa
- the high plateaus of the Andes states
- large areas of India
- northeast Brazil
- northern Mexico
- the Southwest of the United States

Potential sites in Europe are located in:

- Spain
- Italy
- Greece
- Some of the Mediterranean islands



Areas of Highest Potential for CSP Use (High DNI)
Image Source: FSU

The Urgent Need for CSP development in Third World Regions

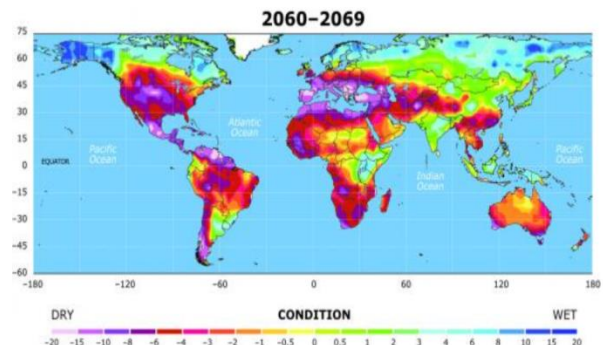
Drought relief

In future drought stricken, desertificated regions of the world (image), and this technology holds great potential for cheap water production from saline or other polluted water sources.

Presently, around 1% of the world's population depends on desalinated water to meet their daily needs, but by 2025, the United Nations expect 14% of the world's population to be encountering water scarcity.

The largest percentage of desalinated water consumption of any country is in Israel, which now produces an estimated 40% of its domestic water use from seawater desalination.

Without drastic water conservation measures, the desalination industry has a very promising future, without a doubt.



Future Estimated Global Drought Conditions
Image Source: National Center for Atmospheric Research

Water purification and food preservation

CSP would be able to sterilize and pasteurize water and food supplies, reducing mortalities from waterborne diseases and spoiled food supplies.

Electrical power for severely isolated regions

Small scale CSP power plants could provide power to small third world villages, which presently rely on diesel fueled generators for basic electrical needs, and fire for cooking and light.

Chapter Two: Trough Style Systems

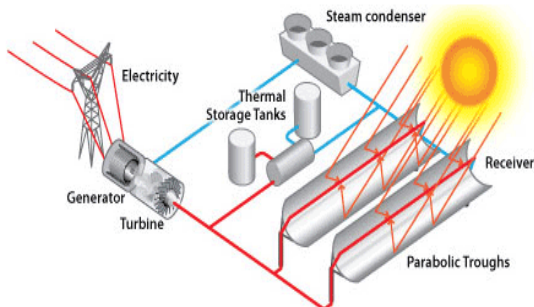
Parabolic Trough Systems

Systems Description

The oldest and most well-established CSP technology is the parabolic trough system (image). In California and Nevada, within the Mojave Desert, exist nine trough-based solar power plants, known as Solar Electric Generating Station I (SEGS I) through 9 (SEGS9), which have been operating reliably since the 80's.

The combined electric generating capacity of these plants is 354MW (megawatts).

These systems use a series of parabolically-curved, mirrored troughs which reflect and focus the direct sunlight onto the fluid-filled tube or receiver. This tube runs the full length of the trough, centered at the focal point of the curved mirrored reflector panels.



Parabolic Trough System

Image Source: Dept. of Energy

Utility-scale parabolic trough facilities consist of many such troughs, laid out in parallel over a large area of land. Other CSP designs lack the long track record of these trough systems, making the trough design the most thoroughly proven CSP technology.

Parabolic trough technology is currently making a comeback, with several new plants in development. The use of Organic Rankine Cycle generators allows solar trough plants as small as 1

MW to be built (such as the new Saguaro plant north of Tucson, AZ).

Trough Sun-Tracking

To track the daily position of the sun perpendicular to the trough's receiver, the trough slowly tilts from east to west (single-axis), so that the direct sunlight remains focused upon the receiver for the longest duration possible.

The southerly to northerly seasonal changes in the angle of the sun, do not create a need for realignment of the mirrors, as the light is simply concentrated onto another portion the receiver. This eliminates the need for dual axis tracking, as the focal area is linear, not centered.

Heat Transfer Fluids

Molten salt is one transfer fluid which is typically used as a heat transfer medium in a parabolic trough receiver. Other commonly used fluids are synthetic oil, water, and super-heated (above boiling point) steam.

These fluids are used in a heat engine (the steam turbine generator), where about a third of the heat is converted to electricity, (depending upon the efficiency of the total system).

Storage of Thermal Energy

Parabolic trough technology allows energy to be stored as heat, which is less expensive than electrical storage allowing the energy from these plants to be available at times of peak demand.

The SEGS Plants in the Mojave Desert

The SEGS parabolic trough facility (image) in the Mojave Desert was once the world's largest solar power plant, both thermal and non-thermal, for many years, prior to the recent commissioning of the Ivanpah tower facility in 2014.



Parabolic Trough Collectors at SEGS III to VII –
Kramer Junction, CA

Image Source: Dept. of Energy

It consists of:

- SEGS I–II (44 MW) - installed at Daggett
- SEGS III–VII (150 MW) - installed at Kramer Junction
- SEGS VIII–IX (160 MW) - installed at Harper Lake
- SEGS X through SEGS XII had been planned but were scrapped, due to insufficient development capital

The Kramer Junction DNI

averages 340 days of sun/year, and receives an average (DNI) direct normal irradiation of 7.4 kWh/m²/day (310 W/m²), one of the best in the US.

Thermal Storage Accident at SEGS

In 1999, a thermal storage tank exploded at the SEGS II (Daggett) solar power plant, sending flames and smoke into the sky.

Firefighters at the scene commented that “it was like putting out a house fire with a garden hose”. The 900,000-gallon tank was holding an oil-based HTF called therminol. The accident had the potential to spread to two adjacent containers holding sulfuric acid and caustic soda, both toxic substances.

Due to the potential for toxic fume migration, the employees and local residents required evacuation.

Heat Transfer System of SEGS

The heat transfer fluid used at the SEGS plants is synthetic oil (Therminol), which is capable of

heating up to over 400 °C (750 °F). The light focused on the absorber tube is roughly 75 times the intensity of ordinary sunlight.

The synthetic oil transfers its heat to water, which boils and drives a Rankine cycle steam turbine, which in turn generates the electrical power.

Synthetic oil is used to transfer the heat (in lieu of water) keeping the pressure within manageable parameters.

Natural Gas supplemental heat source

The SEGS plants supplement steam production using natural gas in times of poor sunlight. As the plants are located in the desert, this only requires about 10% of the steam power to come from natural gas. The remaining 90% of the plant’s steam is produced by the solar thermal process.

Other Large-Scale Trough-Style Facilities:

Four out of five of the world’s largest solar energy facilities are located in the USA:

- **Solar Energy Generating Systems (354 MW)(SEGS)** Mojave Desert, California
- **Mojave Solar Project (280 MW)** Barstow, California
- **Solana Generating Station (280 MW)** Gila Bend, Arizona
- **Genesis Solar Energy Project (250 MW)** Blythe, California

Mojave Solar Park (proposed 553 MW) (canceled)

Another Mojave Desert project, the Mojave Solar Park was in development with a completion date set for 2011.

This proposed plant was to cover nine square miles of desert and generate 553 MW of solar thermal power, far out-powering even the SEGS facility. The capacity of 553 MW would have been capable of powering 400,000 homes. However, the Mojave Solar Park was canceled in 2011.

Enclosed Parabolic Trough

Enclosed Systems

An enclosed trough facility (image) is similar to the conventional trough system, except that it is enclosed within a standard greenhouse type of glassed housing.

The glasshouse shields the components of the system from the wind, rain, corrosive elements, and dust, all of which have a negative impact on the system's reliability and efficiency.

The greatest source of mirror breakage is wind, with thousands of mirrors replaced annually within the nine Mojave SEGS plants.

Automated glass washing systems operate routinely, to aid in maintaining a clean, transparent facility shell.



Enclosed Parabolic Trough CSP Facility
Image Source: Greentechmedia.com

As water is pumped through the network of stationary tubes, centered at the focal point of the parabolic panels, it is brought to the boiling point, in order to generate steam for process heating (turbines or other intended purposes).

By sheltering the mirrors from the cooling effects of the wind, higher temperatures required for heating the HTF may be achieved.

Suspended Trough Design

In the enclosed system, there is the added option of suspending the lighter weight, mirrored panels from the ceiling of the glasshouse.

As the trough system only requires a single-axis tracking system, the mirrors can easily be rotated on the suspension wires to retrieve the optimal amount of sunlight.

The Proposed 1.021-Gigawatt "Miraah" Enclosed Trough Project

Petroleum Development Oman (PDO), the largest producer of oil and gas in Oman, and a venture-capital funded group, GlassPoint, are together developing what will be, the world's largest solar facility.

The 1,021-megawatt "Miraah" project is a turnkey enclosed trough system capable of generating 6,000 tons of steam per day for the purpose of raising heavy oil within depleted wells, from the Amal oil field in Oman.

The system's "once-through" design is nearly identical in operation to conventional (OTSGs) oilfield once-through steam generators, using the same feedwater and delivering steam to the field's main injection header.

The greenhouse-style facility is comprised of enclosed parabolic solar troughs, which use mirrors to focus sun onto a water-filled tube, thus yielding high-pressure steam. However, instead of using the steam to power turbines, the steam will be injected into the earth to heat the residual heavy oil left in the oil reservoir.

The glass enclosure (image) will shield the mirrors from the desert elements, and an automated washing system will keep the glass enclosure free of dust and dirt, as the oil fields of Oman lie in a region with about 15 times higher dust or "soiling rate" than locations where CSP is typically deployed.

This CSP system is enclosed in a wind-shielding greenhouse, which allows for less structural steel, smaller concrete foundations, and thinner mirrors, allowing for considerable savings in construction costs.



Rendering of Miraah Glass Enclosed Trough System
Image source: Glasspoint

Automated Roof Washer

In many parts of the Middle East, condensation occurs overnight on the dusty surfaces, resulting in sandy grime that requires washing.

The enclosed structure is fitted with an automated roof washing system capable of cleaning the entire roof surface nightly, while solar collectors are offline. Most of the wash water is retrieved by a gutter system and can be re-used.

Air Filtration

Dust infiltration is minimized by positive pressure from an air-handling unit, which provides filtered, dried air at slight overpressure within the structure in all conditions.

This is designed to cope with intense dust storms of long duration. These measures have proven effective in delivering consistent energy output in oilfield conditions.

Radiation Transmission Losses from the Enclosure

The minimal amount of DNI loss due to the roof glass and structural shading is more than compensated for, by the reduction in dust scour and daily dust collection on the mirrors. Also the enclosure insulates the receivers from the wind, reducing heat losses.

Solar Radiation Availability

The measure of the solar radiation used by a CSP is direct normal irradiance (DNI). The Oman deserts receive a DNI of over 2,000 KWh/yr. in most locations, with higher altitudes reaching over 2,500 KWh/yr.

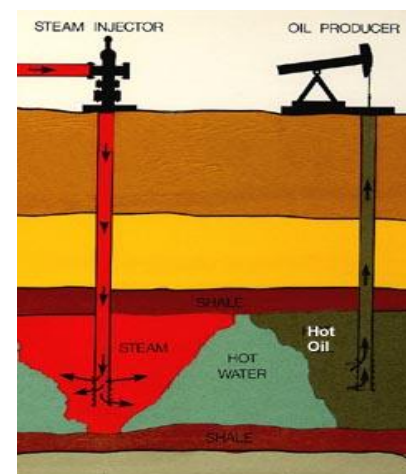
The Amal location receives 2,057 KWh/yr. Due to Oman's low latitude, the DNI does not have large seasonal fluctuations.

CSP for Thermal Enhanced Oil Recovery (EOR)

Thermal EOR (Enhanced Oil Recovery) (image) is a real-world application in which CSP could effectively replace natural gas as a means for creating the steam used in the heavy oil recovery process.

Oil field operations presently use large amounts of natural gas to generate the steam used to draw residual heavy oil from depleted wells through thermal EOR.

This technique has been used for several decades, accounting for more than 40 percent of the domestic EOR production.



Steam-based Enhance Oil Recovery Process
Image source: en.wikipedia.org

The oil industry is now required to use a good bit of their own petroleum products, in order to harvest the heavy oil left behind by past conventional oil drilling processes. It takes a quarter of a barrel of oil to produce a barrel of heavy oil.

In Oman, 23 percent of its own natural gas is used primarily for thermal EOR.

It's estimated that as much as 14 percent of all natural gas burned in California is burned in thermal EOR operations, with the country of

Kuwait consuming more gas for EOR than for power production. Both locations are geographically ideal for these types of CSP facilities.

Previous Solar EOR Projects

Applying solar energy to steam generation for EOR is not a new concept:

- In 1983, ARCO Solar constructed a 1-MW, thermal, solar steam generation pilot project in Taft, Calif.
- In February 2011, GlassPoint Solar delivered the world's first commercial, solar EOR installation for Berry Petroleum in California.
- Later, in 2011, Chevron and Bright Source Energy opened a 29-MW solar-to-steam facility at Coalinga field in California.

Even so, there are challenges that remain, such as project costs and the practical aspects of applying CSP to thermal EOR in an oilfield environment.

MicroCSP (Registered TM of Sopogy, Inc.)

MicroCSP systems

These systems (image) are small, modular process heating plants, fashioned after the larger-scaled parabolic troughs, which can be used for small power projects and rooftop installations.

The technology operates at lower temperatures and pressures than a full scale system, so it's affordable to install and run. MicroCSP power plants typically incorporate sun tracking systems and thermal storage units, or small scale TES.



a MicroCSP parabolic trough system with single-axis tracking unit

Image Source: Solarpowerworld.com

The cost is comparable to PV, but is capable of generating more electrical output and provides less intermittent service due to the tracker/storage combination.

For maintaining cost-effectiveness and efficiency, an optimal plant size is in the range of 5MW to 25MW, with some of their systems reaching 50MW.

Their plants generate heat and steam in a range of 100 to 250 °C, which is at much lower temperatures than full scale CSP plants for generating electricity, however, the middle range is an ideal temperature for heat processes.

Sopogy's CSP collectors are based on the designs used in the traditional CSP systems found in the Mojave Desert (at the SEGS facilities), but are smaller in collector size, lighter weight, and operate at lower thermal temperatures (usually below 600 °F).

MicroCSP systems have already been implemented in the following "process heat" applications:

- community-sized power plants (1 MW to 50 MW)
- Industrial heating and AC
- Agricultural
- Manufacturing
- Remote desalination

MicroCSP systems have been used to heat large water supplies, such as:

- resort swimming pools
- water parks
- large laundry facilities
- sterilization facilities
- distillation facilities

Storage Units of a MicroCSP System

Incorporating thermal storage is a vital step, when dealing with the unpredictability of sunlight and cloud cover. Without storage, intermittent clouds make constant solar energy production totally

unreliable. Electrical power production is intermittent, AC absorption chillers lose efficiency, and industrial heat processing becomes inconsistent.

The MicroCSP storage units stabilize production, even offering the capability for load shifting, (or moving energy production from daytime to night).

By using stored thermal fluids in the morning, the collector field can be flooded with warm transfer fluid, exploiting morning hot spots in a large solar field, and increasing daily energy output by several hours.

Benefits of Thermal Storage Units

- Add vital flexibility to a MicroCSP system
- Multiple units can be installed
- stabilizes energy production, balancing out the brightest and darkest times of the 24-hour period
- kick-starts or accelerates plant start-up

Limited potential for electrical and solar thermal markets

Due to the dropping prices of PV (Photovoltaic) equipment, and with the large amount of capital being invested in further developing those technologies, the MicroCSP will likely remain only a niche application for the foreseeable future.

Applications for Industrial Air Conditioning

MicroCSP systems can directly heat an AC system's absorption chillers (image) with solar heated transfer fluid, as absorption chillers do not use electricity.

These chillers run off of boilers which burn diesel, oil, or natural gas. MicroCSP collectors replace these fossil fuels with clean, free, renewable energy.

Solar thermal fuel and absorption chillers eliminate the need to generate electricity, resulting in a sustainable solar air conditioning process.



Rooftop mounted AC Chiller System

Image source: dmcainc.com

How the Solar Thermal Heat can Produce Cooling

In the absorption chiller, the hot transfer fluid from the collector heats a solution of water (refrigerant) and lithium bromide (absorbent) in a low pressure vacuum.

The low pressure and low temperature cause a phase change from water to vapor. This phase change from a liquid to a vapor creates a chilling effect. Fans then distribute the cool air throughout the facility.

The water vapor is then turned back into a liquid by the condenser unit, and is re-combined with the lithium bromide in the absorber.

Some Sopogy AC Projects:

- In 2010, a hybrid electricity and H2O system was completed at Eckerd College in St. Petersburg Florida
- Masdar City in Abu Dhabi successfully activated a 50-ton AC system driven by MicroCSP collectors
- Kalaeloa Solar One and the State of Hawaii Department of Hawaiian Homelands announced a 5MW electrical project using Sopogy Solar technologies
- In December 2010, Yu Hao Long announced the intent to purchase 200MW of Sopogy's solar technology for the development of a Concentrating Solar Power project with the Chinese National Grid
- In 2011, the Fort Bliss Air Force Base in Texas installed a 40-ton MicroCSP air conditioning system.

Micro-CSP Feasibility

Micro-CSP has a variety of other special niche applications, as well:

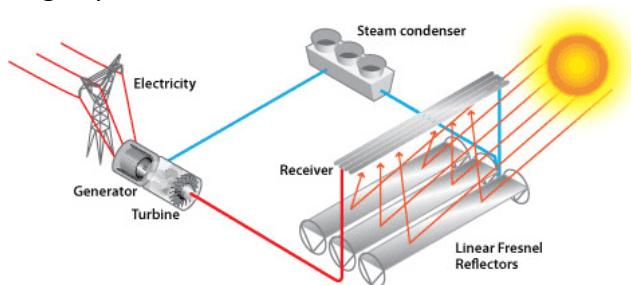
- Remote small-scale distributed energy generation facilities
- Industrial process heat
- Air Conditioning and Heating
- Enhanced oil recovery in the oil industry
- Emulsion processes
- Desalination to create drinking water

Though the success of the MicroCSP system is limited by the affordability of PV technologies, there will likely be many special applications for this unique product, in the coming future.

Chapter 3: Linear Fresnel Reflector (LFR)

LFR Systems

A variation on the Parabolic Trough design is the LFR system, which uses flat paned Fresnel-lensed mirror strips in lieu of the curved glass approach of trough systems.



Linear Fresnel System

Image Source: Dept. of Energy

System Description

The LFR (image) uses a multitude of thin mirror strips instead of parabolic troughs to concentrate the sunlight from a field of mirrors onto tubes of working fluid (HTF).

The advantage of this system is that flat mirrors are much cheaper to produce than parabolic mirrors, and allow for a greater density of reflectors in the array, allowing more of the sunlight to be used.



Linear Fresnel Strip Mirrors and Receiver

Image Source: evwind.com

These mirrors are able to focus the sun's energy to approximately 30 times its normal intensity. This concentrated energy is transferred through the absorber into the HTF (which can be oil, steam, or molten salt). The fluid then goes through a heat exchanger to power a steam generator. (When

steam is used as the HTF, there is no need for an expensive heat exchanger unit in the loop).

A linear Fresnel reflector power plant focuses light onto one or more linear receivers which are positioned above the mirrors.

Located above the receivers, is a small, parabolic, downward-angled trough mirror that can be attached for further focusing of the sunlight onto the absorber tubes. This has the added benefit of shielding the absorber tube from the cooling effects of air currents.

These systems provide a lower total cost, by sharing a receiver between several mirrors (as compared with trough and dish designs), while still using the simple linear-focused geometry with a single tracking axis.

The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not support the receiver, so the framework is structurally a lighter weight.

When mirrors are aimed at different receivers at different times of day, this can allow for a denser packing of mirrors, allowing for less land use for the system.

In addition to the differences in the shape of the mirrors, the LFR differs from that of the parabolic trough in that the absorber is mounted above the mirror field.

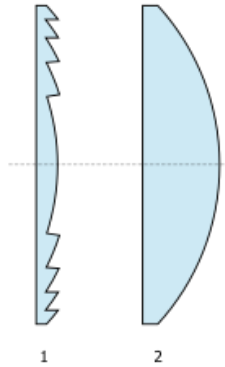
Also, the reflector is constructed of many low row segments, which focus collectively on an elevated long tower receiver running parallel to the reflector rotational axis.

Fresnel Lenses

A Fresnel lens (image) is a type of compact lens. The Fresnel lens reduces the amount of material required compared to a conventional lens by dividing the lens into a set of concentric annular sections.

An ideal Fresnel lens would have infinitely many such sections. In each section, the overall thickness is decreased compared to an equivalent simple lens.

This effectively divides the continuous surface of a standard lens into a set of surfaces of the same curvature, with stepwise discontinuities between them.



(1) Fresnel Lens, (2) Traditional Curved Lens

Image source: wikipedia

The design allows the construction of lenses of large aperture and short focal length without the mass and volume of material that would be required by a lens of conventional design.

A Fresnel lens can be made much thinner than a comparable conventional lens, in some cases taking the form of a flat sheet. A Fresnel lens can capture more oblique light (light from a lower point of origin, such as evening sun), thus allowing the light from a lighthouse equipped with one to be visible over greater distances.

Fresnel lenses are able to create collimated light (light whose rays are parallel, and therefore will spread minimally as it propagates.) Fresnel lens design allows a substantial reduction in thickness (and thus mass and volume of material), at the expense of reducing the imaging quality of the lens

Use of Fresnel lenses in CPV

When used with photovoltaic technology, these Fresnel lens can concentrate sunlight (with a ratio of almost 500:1) onto solar cells, allowing the active solar-cell surface to be reduced to a fraction compared to conventional solar modules. This

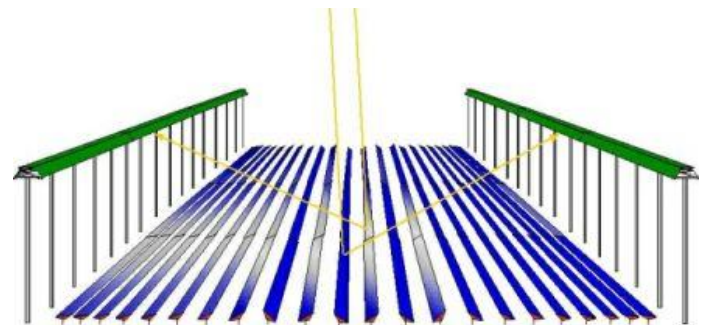
offers a considerable cost-saving potential by low material consumption, and allows the use of more efficient cells that would otherwise be too expensive.

Concentrating LFR (CLFR) Systems

A concentrating linear Fresnel reflector system (or a Compact Linear Fresnel Reflector), is a variation of the Linear Fresnel Reflector (LFR) technology.

While LFR's use a single fixed absorber located at the common focal point to the reflectors, the CLFR (image) utilizes multiple absorbers within the vicinity of the mirrors.

CLFR solar systems (image) alternate the inclination of their mirrors to focus solar energy on the multiple absorbers, improving system efficiency and reducing overall cost.



CLFR system

Image Source: physics.usyd.edu.au

Benefits of the CLFR multi-absorber system (image):

- Alternating inclinations reduce the effect of reflectors blocking adjacent reflectors' access to sunlight, improving system efficiency.
- Multiple absorbers minimize the amount of land use required for installation, reducing land acquisition costs.
- Having the mirror panels consolidated reduces the length of absorber lines, therefore reducing heat losses by the absorber lines.



Multiple Absorbers in a CLFR system

Image Source: ABB.com

The Puerto Errado 2 (PE2) LFR Solar Thermal Facility in Murcia, Spain

Became the world's first linear Fresnel solar energy facility to generate power on a large utility-scale basis.

This Spanish facility produces 30 MW of solar energy for the power grid - enough to power 15,000 homes and avoid some 16,000 metric tons of CO₂ emissions annually.

PE2 is the third commercial installation based on this technology.

- A 1.4 MW plant has been delivering power to Spain's electrical grid since 2009
- In May 2012, a 9.3 MW plant was completed at the 2,000 MW Liddell coal-fired power plant in New South Wales, Australia – integrating CSP technology with conventional coal-fired power generation for the first time ever

The plant uses direct steam generation and does not require heat exchangers and oil-filled absorber tube networks for heat transfer. Instead this highly economical and proven concept utilizes compact almost flat glass mirrors.

The uniquely efficient solar boiler produces superheated steam directly at a temperature of up to 500 degrees Celsius and a pressure of 100 bar.

By using standard materials such as sheet plates and glass mirrors the cost of building and operating the plants is exceptionally low. This is because the

automated mass production of key components can be made in locally erected production facilities and quickly and accurately assembled. The plant is efficient in its use of land and uses a robotic mirror cleaning system that uses very little water.

This LFR plant's design is an ideal model for use in a wide range of applications such as solar augmentation of fossil fuel power plants, enhanced oil recovery, solar desalination, solar cooling, and to provide process steam or heat for mining and other industries.

Chapter Four: Power Tower Systems

Power Tower Systems

Systems Description

With power tower CSP systems (image), large fields of flat, sun-tracking mirrors (heliostats) are utilized, focusing the sun's rays onto a receiver tower.

The HTF (typically molten salt) is heated in the receiver tower and used to transfer heat to the steam generator. Solar power tower systems are also known as "Central Tower Systems" or "Heliostat Systems".



Receiver Tower with a surrounding field of Heliostat Structures

Image source: Sandia Labs

Advantages of a solar power tower:

- the concentration of light onto one single receiver (the tower) yields higher temperatures
- The mirrors in a solar power tower system receive sunlight by tracking the sun at two axes. This is more advantageous as it can receive sunshine even when the sun is low in the sky as is the case during winter months or even at dawn and twilight
- Solar power towers are environmentally safe systems. No hazardous gases or liquid emissions are released. If a salt spill occurs,

the salt will freeze before significant contamination (soil salination) occurs. It can then be picked up with a shovel and can be cleaned and recycled.

Disadvantages of a solar power tower:

- Requires a significant amount of land use (the Ivanpah plant encompasses 3,500 acres)
- The efficiency is less than that of Stirling systems
- Rigid support structures with reinforced concrete foundations are needed for each of the heliostats; heliostats account for roughly $\frac{1}{2}$ of the total cost of the entire plant (the proposed Supcon plant in Qinghai, China will use 217,440 heliostats in its design)
- Wind causes problems with the mirrors which can affect efficiency; the flat planed heliostats are heavily influenced by winds due to their non-aerodynamic shape

Receiver Tower

Power tower systems use a central receiver system, which allows for higher operating temperatures and thus greater efficiencies.

Computer-controlled flat mirrors (called heliostats) track the sun along two axes and focus solar energy on a receiver at the top of a high tower. The focused energy is used to heat the HTF of choice, to produce steam and run a central power generator.

Use Solar Storage Receivers (SSR's)

The 3 MW power tower plant located in Lake Cargelligo, New South Wales is using a novel approach to thermal energy storage. This plant uses CSP focused into graphite (SSR) Solar Storage Receivers, arranged in a multi tower array.

The project consists of eight SSR's each mounted on its own tower. The graphite receiver acts as receiver, boiler and storage system, with each tower connecting to a central steam manifold. The

plant has 620 heliostats, a 500C receiver outlet temp, and uses water/steam as the HTF.

Ivanpah Solar Electric Generating Station (World's Largest)

The Ivanpah SEGS is presently the world's largest power tower facility in the world with a 392 MW gross turbine capacity.

This plant has a combine *aperture area of 2,600,000 square meters, using a total of 173,500 heliostat structures; spread over 3,500 acres of desert land.

**Note: Aperture area is the part of the collector through which light enters, passes, or is reflected (such as the aperture on a camera which is the area of the shutter opening which exposes the film).*

List of power tower based CSP plants worldwide, with specifications:

- **ACME Solar Tower** – This is an operational 2.5 MW plant in India which uses a Rankine steam cycle, with wet cooling towers. It has a receiver outlet temp of 440C, with a series of 14,280 heliostat concentrators, and uses water/steam as the HTF.
- **Ashalim Plot B (Megalim)** - This is an in-development 121 MW plant in Israel which will use a Rankine steam cycle with wet cooling towers. It will have a receiver tower height of 240 meters, with a series of 50,000 heliostat concentrators, and use water/steam as the HTF.
- **Atacama-1** - This is an in-development 110 MW plant in Chile which will use a Rankine steam cycle, and a 2-tank direct TES. It will have a receiver outlet temp of 550C, with a series of 10,600 heliostat concentrators, and use molten salt as the HTF.
- **Copiapó** - This is an in-development 260 MW plant in Chile which will use a Rankine steam cycle, with dry cooling. It will have a 2-tank direct TES, with 14 hours of storage capacity, and uses molten salt as the HTF.
- **Crescent Dunes Solar Energy Project (World's tallest tower structure)** - This is an operational 110 MW plant in Nevada which uses a Rankine steam cycle. It has a receiver outlet temp of 1050F, with a series of 10,347 heliostat concentrators, and uses molten salt as the HTF. TES is achieved by raising the salt temperature from 550 to 1050 F, with a projected thermal storage efficiency is 99%. The receiver panel height alone is 100 ft. high.
- **Dahan Power Plant** – This is an operational 1 MW plant in Beijing, China which uses 100 heliostats. It is wet-cooled, and uses a Rankine steam cycle for power generation. The TES is saturated steam/oil; with a receiver outlet temp is 440C. The fossil backup is an oil-fired boiler system.
- **Gemasolar Thermosolar Plant (Gemasolar)** - This is an operational 19.9 MW plant in Spain, which consists of 2,650 heliostats, a receiver outlet temp of 565C, uses wet cooling, and uses a 15% fossil backup of natural gas. The TES is a 2-tank direct system with a cold salt tank (290C) from where salts are pumped to the tower receiver and heated to 565C, to be stored in the hot salt tank (565°C). This plant had the first high-temperature solar receiver with molten salt (potassium and sodium nitrates), which provides 15 hours of TES and an annual capacity factor of about 75%.
- **Greenway CSP Mersin Tower Plant** – This is a demonstrational 1.4 MW plant in Turkey, which consists of a water/steam HTF, and a steam Rankine cycle. The TES is a molten salt, single 3-phase tank with natural circulation, and a super steam junction design.
- **Ivanpah Solar Electric Generating System (ISEGS)** – Ivanpah, located in California, consists of a total of three separate plant locations, Ivanpah 1 has a total capacity of 126 MW and Ivanpah 2 and 3 are both 133 MW each. With a total of 173,500 heliostats, Ivanpah is the largest solar thermal power tower system in the world. The gross turbine capacity is 392 MW, is dry-cooled, and utilizes water/steam as the

HTF, with a receiver outlet temp of 1050F. The fossil fuel backup is natural gas. The three sites comprise a total land use of 3,500 acres.

- **Jemalong Solar Thermal Station** – This 1.1 MW plant is under construction in New South Wales, Australia. It will have 3,500 heliostats, dry cooling, a receiver outlet temp of 560C, a steam Rankine cycle, air cooled condensation, and a 2 tank direct TES, with liquid sodium HTF.
- **Jülich Solar Tower** - This 1.5 MW plant is a demonstrational facility in Rhineland, Germany. It has 2,153 heliostats, dry cooling, a receiver outlet temp of 680C, steam Rankine cycle, and a ceramic heat sink TES system with 1.5 hours of storage capacity.
- **Khi Solar One** – This is a 50 MW facility in Northern Cape, South Africa. It has 4,120 heliostats, water/steam HTF, dry cooling, and saturated steam TES.
- **Lake Cargelligo** – This Australian 3 MW plant uses CSP focused into a graphite (SSR) Solar Storage Receiver, arranged in a multi tower solar array. The project consists of eight SSR's each mounted on its own tower. The graphite receiver acts as receiver, boiler and storage system. The plant has 620 heliostats, a 500C receiver outlet temp, and uses water/steam as the HTF.
- **NOOR III** – This 150 MW plant located in Morocco is presently under construction. It will have molten salt as the HTF, with a 2-tank TES that can provide 8 hours of storage capacity.
- **Palen Solar Electric Generating System** – This is an under development 500MW facility with dual 250 MW turbine units. It will be dry cooled with air-cooled condensation.
- **Planta Solar 10 (PS10)** – This 11 MW facility located in Spain, is a wet cooled, system consisting of 624 heliostats, and natural gas fossil backup.
- **Planta Solar 20 (PS20)** – This 20 MW facility is also a wet cooled system with 1,255 heliostats and natural gas backup.
- **Qinghai Delingha Solar Thermal Generation Project** – This is a 270 MW facility under development in the Qinghai region of China. It will have a 2-tank TES capable of 3 hours of molten salt storage capacity.
- **Redstone Solar Thermal Power Plant** – This is an in-development 100 MW plant located in South Africa, with an HTF consisting of molten salt. It will have dry cooling, a receiver outlet temp of 566C, and a 2-tank molten salt TES with a 12 hour capacity.
- **Rice Solar Energy Project (RSEP)** – This facility is under development in the Mojave Desert region of California. It will have a turbine gross capacity of 150 MW, 17,170 heliostats, dry cooling, and a 540ft. tower. The TES is achieved by raising salt temperature from 550 to 1050 F. Thermal storage efficiency is 99%
- **Sierra SunTower (Sierra)** – This facility consists of 24,360 heliostats, yet only has a gross turbine capacity of 5 MW. It has wet cooling towers, and has been producing power since 2009.
- **Supcon Solar Project** – This Chinese plant is partially completed, with a planned capacity of 50 MW, consisting of 217,440 heliostat structures. The HTF will be molten salt, as well as the 2 tank TES. The first 10 MW phase of the project was connected to the Chinese grid in July 2013. The second phase is currently under development.

Chapter 4: Alternate Systems

Other Types of CSP Solar Systems

Hybrid Systems

This is a thermal heat system that does not rely on one source of thermal heat. It usually consists of a primary fuel source which is supplemented by a backup source.

(An example may be: a Solar CSP system using natural gas as a backup system to maintain the heat balance during periods of cloud cover, or shortened winter sun exposure; or when a system may need to achieve more constant or elevated temperatures, fossil fuels can be used to balance and raise the heat of the steam entering the turbine accordingly).



Hybrid Plants utilize Two Separate Fuel Sources

Image source: jbsnews.com

Examples of common hybrid combinations are:

- Renewables and Fossil Fuels (solar plus natural gas backup is most common)
- Renewables and Biomass Fuels
- Coal and Natural Gas

Cogeneration Plants

Hybrid plants are typically confused with cogeneration plants. In a hybrid plant, there are two different sources of thermal heat sources (such as biomass and solar, or solar and fossil) which are used for electrical power generation.

In a cogeneration plant, a given fuel source is used to create the heat for the steam for the electrical power generation, while the waste heat from that

primary steam cycle is reclaimed for use in a secondary heat process.

(SUT) Solar Updraft Towers

Solar chimney power plants (image) consist of a high chimney (tower), with a height of up to 3000 ft.

This is surrounded by a large collector roof, up to 400 ft. in diameter that consists of glass or resistive plastic supported on a framework. Towards its center, the roof curves upwards to join the chimney, creating a form of 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.



Prototype Solar Updraft Tower in Spain
Image Source: widakora.wikipedia.org



MJ solar cells with concentrating Dish Lenses
Image source: pyrosolar.nl

Concentrator Photovoltaics (CPV)

Though often confused with one another, CPV and CSP are totally different technologies:

- CPV - uses the photovoltaic effect to directly generate electrical output from sunlight
- CSP – takes heat from the sun's radiation, to create steam, to drive a turbine, that turns a generator, that then produces electricity

Different from conventional photovoltaic systems, CPV units use lenses (image) and curved mirrors (image) to focus sunlight onto small, but highly efficient, multi-junction (MJ) solar cells.

Additionally, CPV systems often use solar trackers and sometimes a cooling system to further increase their efficiency.



Tracking MJ Cells with Concentrating Fresnel lenses
Image source: ibnalnafees.ae

CPV may presently be economical for niche markets which have the following application characteristics:

- regions with high solar (DNI) direct normal incidence
- minimal area available for placing of a solar collector array
- constant demand for low-temperature (85–90 °C) waste heat
- high cost of grid electricity
- limited access to grid electricity
- access to backup sources of power or cost-efficient storage (electrical and thermal)

The CPV Unit of Measure – “Suns”

CPV systems are categorized based on the amount of their solar concentration. The unit of measure for solar concentration is "suns", which is the square of the magnification.

Two instruments which are commonly used to measure a CPV unit's rating are the pyranometer and the Pyrheliometer.

Pyranometer

(see image) This is a type of actinometer (instruments used to measure the heating power of radiation) used to measure broadband solar irradiance on a planar surface and is a sensor that is designed to measure the solar radiation flux density. These meters are used extensively in solar energy studies.



Pyranometer

Image source: wikipedia.org

Pyrheliometer

(see image) This is an instrument for measurement of direct beam solar irradiance. Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded.



Pyrheliometer

Image source: pvresources.com

(LCPV) Low Concentration PV

Low concentration PV systems are rated with a solar concentration of between 2 to 100 suns. For economic reasons, conventional or modified silicon solar cells are typically used in low concentration PV systems.

At concentrations of 2 to 100 suns, the heat flux is low enough that the cells do not require an active cooling system.

The laws of optics dictate that a solar collector with a low concentration ratio can have a high acceptance angle (the maximum angle at which incoming sunlight can be captured by a solar

concentrator) and thus not require active solar tracking.

(MCPV) Medium Concentration PV

- These cells have concentrations of 100 to 300 suns
- require single or dual axis tracking
- require passive or active cooling

(HCPV) High Concentration PV

R&D efforts are quickly improving CPV competitiveness in the utility-scale segment of the market and in regions of high exposure to sunlight.

Systems using high concentrator photovoltaics (HCPV) have the most potential for becoming competitive with CSP, in the upcoming future. They possess the highest efficiency of all existing PV technologies, and a smaller photovoltaic array.

Commercial HCPV systems have reached efficiencies of up to 42% with concentration levels above 400, with the potential to increase the efficiency of this technology to 50% by the mid-2020s.

As of December 2014, best lab cell efficiency for concentrator MJ-cells reached 46% (four or more junctions). Most CPV installations are located in China, the United States, South Africa, Italy and Spain.

HCPV directly competes with concentrated solar power (CSP) as both technologies are suited best for areas with high (DNI) direct normal irradiance, such as the Sun Belt region in the United States and the Golden Banana in Southern Europe.

HCPV systems use concentrating optics, consisting of dish reflectors or Fresnel lenses that concentrate sunlight to intensities of 1,000 suns or more.

HCPV cells require high-capacity heat sinks to prevent heat damage and to manage temperature related electrical performance issues and a drastic decline in life expectancy of the units.

Additionally, the heat sinks must operate passively, as the power needed for active cooling would reduce the overall conversion efficiency and economy.

MJ vs SJ cells

(MJ) Multi-junction cells are currently preferable over (SJ) single junction cells, as they offer more efficiency and have a lower temperature coefficient (less efficiency loss per temperature increase).

The efficiency of both cell types increases with higher concentration, (with MJ efficiency rising faster).

Concentrated Photovoltaics and Thermal

Concentrator photovoltaics and thermal (CPVT), also sometimes called combined heat and power solar (CHAPS) or hybrid thermal CPV, produces usable heat and electricity within the same system.

CPVT at high concentrations (image) of over 100 suns (HCPVT) utilize similar components (dual-axis tracking and multi-junction photovoltaic cells) as HCPV.

A fluid actively cools the integrated thermal-photovoltaic receiver, and simultaneously transports the collected waste heat.



HCPVT Systems
Image source: geek.com

Typically, one or more receivers and a heat exchanger operate within a closed thermal loop. To maintain efficient overall operation and avoid thermal damage, the demand for heat from the

secondary side of the heat exchanger must remain consistently high.

Under optimal operating conditions, collection efficiencies of 70% are anticipated. Net operating efficiencies depend greatly on how well a system is engineered to match the demands of the particular thermal application.

The maximum temperature of CPVT systems is typically too low to power a boiler for additional steam-based cogeneration of electrical power.

These systems may be economical to power lower temperature applications having a constant high heat demand.

The waste heat may be employed in:

- district heating
- water heating
- air conditioning
- desalination
- process heat

(LSC) Luminescent Solar Concentrators

A new emerging type of solar concentrator which is being developed is the luminescent solar concentrator (image) which is composed of luminescent plates.

They absorb solar light which is converted to fluorescence directed to plate edges where it shines in a concentrated form.

The edges of the plate are where the solar cells would be attached, to absorb the light concentration.



Luminescent Solar Concentrator Plate
Image Source: pi-lab.co.uk

The concentration factor is directly proportional to the plate surface and inversely proportional to the plate edges.

This arrangement allows use of small amounts of solar cells as a result of concentration of the fluorescent light.

The excitement around these concentrators lies with the fact that they are able to also concentrate diffuse light which is especially important for use in regions of lower DNI, plus they do not require solar tracking.

Chapter 5: Dish Stirling Engine Systems and Power Cycles

Dish Stirling Engine Systems

Dish Stirling Engine Systems

Dish Stirling engines are a breed apart from the other CSP technologies. They offer many potential advantages over the other forms of CSP.

Modularity is one of the biggest selling points of a Dish system as each unit is a turnkey power plant, with concentrator, receiver, and AC generator all in one.

Unlike the steam turbine based systems, the dish systems can be implemented in multiple phases, which helps to supplement financing of the project along the way, by immediately being able to supply the grid with bankable power through net metering.

As the output is already in the form of grid-ready AC power, these are basically plug-n-play appliances.

Demonstrational Dish Engine Plant – Maricopa Solar (The SunCatcher™ Dish Design)

Started in 2010 in Maricopa County, Arizona, this 1.5 MW demonstrational plant consisted of (60) SunCatcher Stirling Energy Systems (SES). The SunCatcher is a 25KW solar-to-grid quality electrical generating technology.

The SunCatcher system is a 38ft wide parabolic dish with precision mirrors that automatically tracks and captures the sun to concentrate the solar energy onto the Power Conversion Unit (PCU) converting this energy to grid-quality electricity. This particular design can be scaled from 1.5MW to nearly 1 GW, to meet the future power needs.

The plant design allows for commissioning by 9MW groups, leading to lower commissioning risk and therefore project completion risks. This modularity allows power plants to scale to customer size requirements and available land use.

These units did not use water for electricity generation or cooling cycles, and a minimal amount of water was used for site operations and washing of mirrors. It was not built to be fully operational and had no TES.

The gross annual solar-to-electricity efficiency was around 26%. By producing AC power directly, and not requiring DC to AC power conversion, boosts the efficiency of these units.

This plant was decommissioned in September 2011, after being used for a short period to demonstrate system potentials.

Following the period around 2010, interest in Dish plants waned considerably, as these plants lack the potential for TES integration. Without storage, dish Stirling essentially delivers power in the same manner as PV.

PV is a more established and reliable technology, and has experienced a drastic price drop, recently. Also, structurally there are engineering challenges in supporting the dishes and providing accurate and consistent tracking.

As with the MicroCSP units, there will likely be niche markets for this type of CSP, but as far as utility scale mass production of Dish Engines, it's possible that that ship has sailed.



Maricopa Solar SunCatcher units
Image source: Tessera Solar

Standard Rankine Cycle

The Rankine cycle (image) is an idealized thermodynamic cycle of a heat engine (such as a steam turbine generator) that converts heat into mechanical work output.

The heat (from the HTF) is supplied externally to a closed loop, which usually uses water as the working fluid.

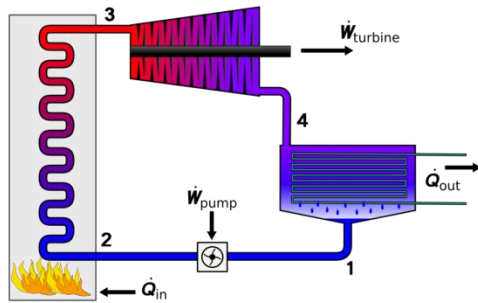


Diagram of the Rankine Cycle

Basic layout of the Rankine cycle:

- Fluid is pumped to high pressure going from state 1 to 2.
- Heat is added in the boiler by the burning of fuel (although heat can be added by any method) boiling the fluid to state 3.
- The vapor expands through the turbine dropping significantly in pressure and temperature to state 4.
- The vapor is condensed back to a liquid and fed back in the pump, to renew the cycle.

(ORC) Organic Rankine Cycle Generator (for use with waste heat)

The Organic Rankine cycle (ORC) is named for its use of an organic working fluid with a boiling point (liquid to vapor phase change), which occurs at a lower temperature than the water-steam phase change. The fluid allows Rankine cycle heat recovery from lower temperature sources such as waste heat.

The low-temperature heat is converted into useful work that can itself be converted into electricity.

The ORC can be used in the solar parabolic trough technology in place of the usual steam Rankine cycle allowing power generation at lower capacities and with a lower collector temperature.

This makes it more possible to implement low-cost, small scale decentralized CSP units. Using Organic Rankine Cycle (ORC) power may compete with

photovoltaics (PV) and diesel generators on a levelized cost of electricity (LCOE) basis for off-grid duty. In remote areas where there is no source of cheaper “grid” energy, small CSP plants using ORC power cycles may be an option.

The Organic Rankine Cycle's principle is based on a turbo-generator working as a normal steam turbine to transform thermal energy into mechanical energy and finally into electric energy through an electric generator.

Instead of the water steam, the ORC system vaporizes an organic fluid, characterized by a molecular mass higher than water, which leads to a slower rotation of the turbine and lower pressure and erosion of the metallic parts and blades.

How the Process Works

The process is based on the following thermodynamic cycle:

- A heat source heats a working fluid (thermal oil) to a high temperature, within a closed circuit
- The hot thermal oil is drawn into and away from the ORC module (XXXX) in closed circuit
- In the ORC it evaporates the organic working fluid of the ORC in a heat exchanger system (pre-heater and evaporator)
- Organic vapor expands in the turbine, producing the mechanical energy, further transformed into electric energy through a generator
- The vapor is then cooled by a fluid in a closed circuit and condensed. The water warms up at about 80 - 90°C and it is used for different applications requiring heat
- The condensed organic fluid is pumped back into the regenerator to close the circuit and restart the cycle.

Efficiency of the ORC

The ORC cycle has a high overall energy efficiency: 98% of incoming thermal power in the thermal oil is transformed into electric energy (around 20%)

and heat (78%), with extremely limited thermal leaks, only 2 % due to thermal isolation, radiance and losses in the generator; the electric efficiency obtained in non cogenerative cases is much higher (around 24% and more).

Use of ORC with Waste Heat Recovery Processes

This is one of the most advantageous uses for the organic Rankine cycle (ORC) is in converting waste heat into electrical power generation or for use with other heat processing applications. It can be applied to any number of heat processes which will function using low temperature waste heat.

Stirling Power Cycle

Stirling cycle engines used in solar dish/Stirling systems are high-temperature, high-pressure, externally heated engines that use hydrogen or helium as the HTF (working gas).

Characteristics of a Stirling cycle:

- Working gas temperatures of over 700C (1292°F) and pressures as high as 20 MPa are used in modern high-performance Stirling engines.
- In the Stirling cycle, the working gas is heated and cooled alternately, by constant-temperature and constant-volume processes.
- Stirling engines usually incorporate an efficiency-enhancing regenerator that captures heat during constant-volume cooling and replaces it when the gas is heated at constant volume. There are a number of mechanical configurations that implement these constant-temperature and constant-volume processes; most involving the use of a piston-in-cylinder configuration.
- The best of the Stirling engines achieve thermal-to-electric conversion efficiencies of about 40%.
- Stirling engines are an ideal choice for dish/engine systems, as they are highly efficiency, and their external heating makes them adaptable to concentrated solar flux.

Brayton Cycle

The Brayton engine, (jet engine, combustion turbine, or gas turbine), is an internal combustion engine which produces power by the controlled burning of fuel.

In a Dish/Brayton system, solar heat replaces or supplements the fuel. The resultant hot gas rapidly expands to produce power. In a gas turbine, the burning is continuous and the expanding gas is used to turn a turbine and alternator.

As in the Stirling engine, reclaiming the waste heat is vital to high efficiency, thus waste heat exhausted from the turbine is used to preheat the air from the compressor.

The recuperating gas turbine engines that are suited for solar thermal heat uses have pressure ratios of approximately 2.5, and turbine inlet temperatures in the neighborhood of 850C (1,562°F). Possible thermal-to-electric efficiencies of Brayton engines for Dish/Brayton applications exceed 30%.

A hybrid open solar Brayton cycle was operated for the first time consistently and effectively at a demonstration facility in Seville, Spain. The air was heated from 570 K to over 1000 K in the combustor chamber.

Further hybridization was achieved by running a hybridized Brayton cycle with solar energy and Biodiesel only. This technology was scaled up to 4.6 MW within the project where it is currently demonstrated at pre-commercial scale.

The thermodynamic open cycle process (Brayton cycle) at the Seville solar hybrid plant:

- Air is compressed, raising its pressure and temperature
- Compressed air is heated in the solar receiver using concentrated solar energy
- Compressed air is heated in the combustion chamber using Natural gas

- Hot air expands and drives the turbine; turbine drives generator, producing electrical power output
- Heat energy of exhaust gases from the turbine is recovered with a bottoming steam cycle or a recuperator, then used to preheat the working fluid

The Future of CSP

The solar landscape is presently very fluid, with new innovations being developed on what seem as though, a weekly basis. As technology constantly changes with CSP, the core infrastructure of solar thermal plants will likely remain constant.

The basis of a CSP system: the solar concentrators, the support framework, the tracking systems, the HTF circulatory network, and the thermal storage; these will all remain usable for whatever technology is developed.

If high efficiency CPV becomes the technology of choice, then those cells could easily replace the HTF receivers presently in place.

Billions of dollars have been invested into these facilities, and billions more will continue to flow into this essential infrastructure.

Fossil fuels and all other consumable fuel sources will one day go away forever, regardless of the opinions of some. Our future generations will have as much a need for a fully energized electrical grid, as the present generations do.

This technology has basically sat on the shelf for the past 30 years waiting to be fully recognized.