

THERMAL ENERGY STORAGE WITH SOLAR POWER GENERATION

© M. Ragheb
2/9/2021

INTRODUCTION

The growth curve for solar energy systems is as fast as the one for wind energy, but with a 10-year time lag. The greatest promise lies in the Concentrated Solar Power, CSP thermal technology. Relatively small areas of the world's deserts could be used for electricity production to be transmitted to populated areas, as well as the production of desalted fresh water that these arid areas are much in need of.

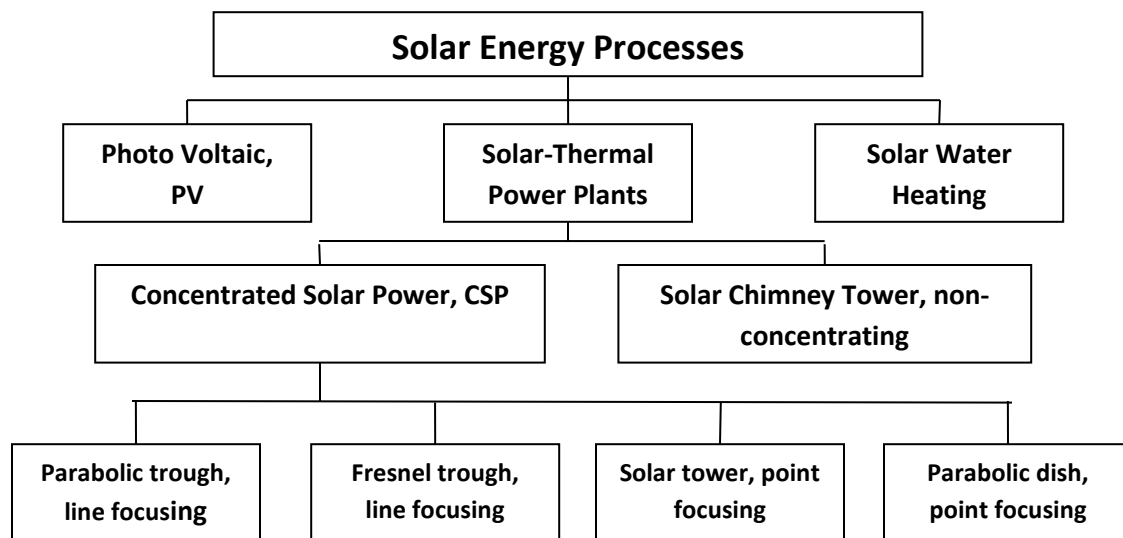


Figure 1. Solar energy processes.

In the USA, Concentrated Solar Power, CSP offers a similar potential in areas of the sun-belt and the American southwest as large offshore wind farms in Europe. However, by 2008 there was only 0.5 GWe of installed capacity worldwide, compared with the low and medium temperature solar water heating that has reached a capacity of 145 GWth.

The project pipeline has increased appreciably with 1 GWe planned for 2011. A growth rate of 35 percent / year is contemplated for the next few year. The installed capacity is forecast to reach 20 GWe by 2020. In comparison the installed wind power rated capacity in 2008 was 121 GW.

The CSP market is dominated by Spain and the USA. The drivers are declining production costs and a more favorable political environment including the use of feed-in tariffs.

A large project capacity is in the pipeline in the USA benefiting from a favorable regulatory framework including tax incentives. Under the Renewables Portfolio Standard, RPS, the electrical utilities are expected to produce a certain fraction of their electricity from renewable sources. The USA benefits from the existence of multiple favorable sites in the deserts of Arizona, California, Nevada, New Mexico and Texas.

ECONOMICAL ASPECTS

About 80 percent of the cost of CSP is due to construction and 20 percent is due to Operations and Maintenance, O&P. The fuel cost is free.

The cost of electricity from CSP is less than from Photo Voltaic, PV systems. Yet it is still high among the renewable sources.

With increased technology, mass production of components, economies of scale in plant sizes and increased market competition, rapid costs reductions are expected.

Minimal costs for projects at optimal sites in the USA are at about 15 ¢/kWhr. In the medium term these costs are expected to be reduced to the same level as conventional systems around 10 ¢/kWhr.

The largest plant is the 354 MW Solar Energy Generating Systems in the Mojave Desert, California, followed by the Solnova 150 MW plant and Andasol 100 MW, then Nevada Solar 1 at 64 MW. These use the parabolic trough concept. Plants that use the solar tower concept are PS20 (20 MW) and PS10 (11 MW) in Spain. About 13.9 GW are planned globally through 2014 with 5.6 GW in the USA.

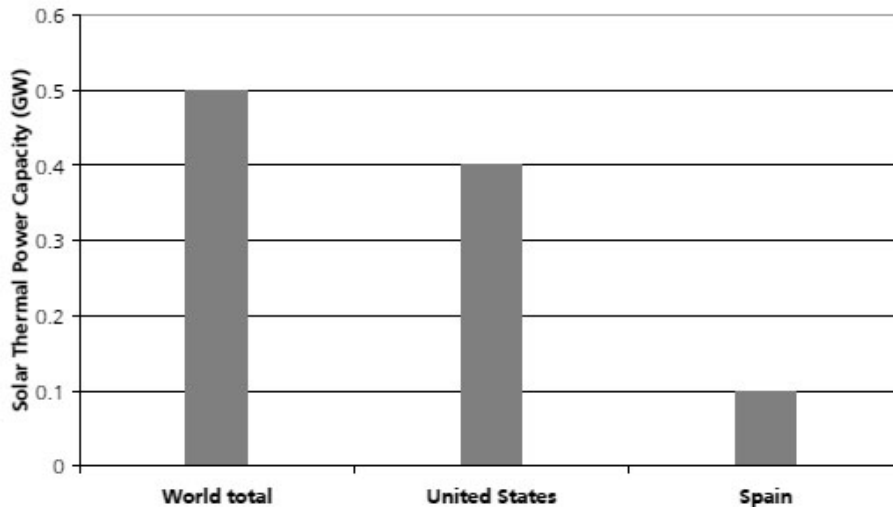


Figure 2. Installed Concentrated Solar Power, CSP, capacity in GWs, 2008.

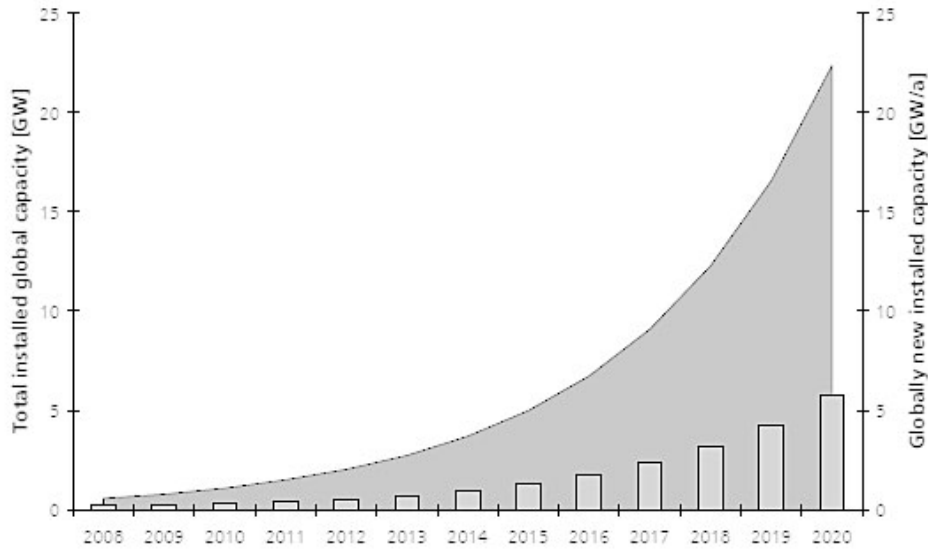


Figure 3. Growth of installed Concentrated Solar Power, CSP capacity.

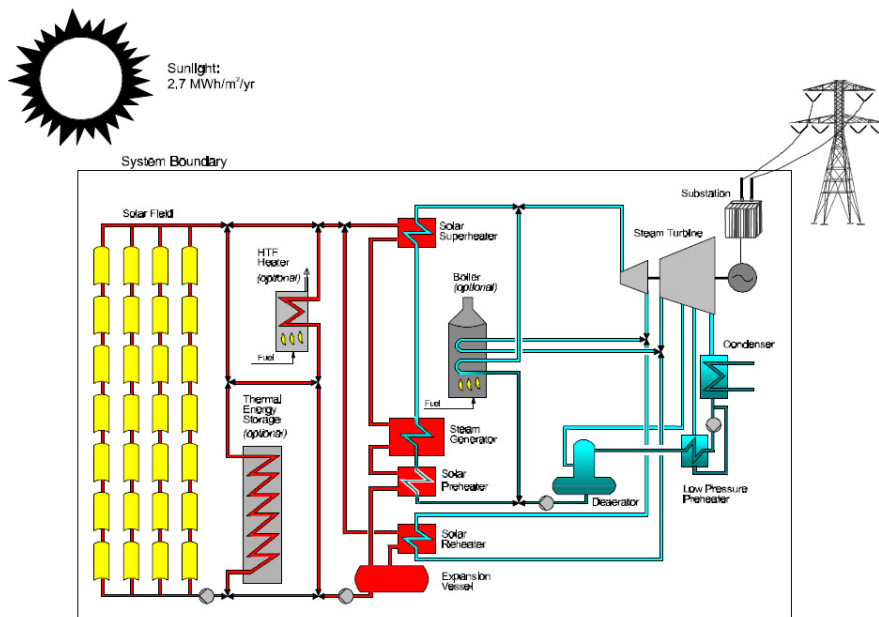


Figure 4. Conceptual plant design with energy storage as well as supplemental heating to enhance the capacity factor as well as avoid the thermal cycling problem encountered in solar-only plants.

A Direct Normal Radiation, DNR of 310 Watts/m² or 744 kW.hr/(m².day) for solar radiation is available at the Kramer Junction in California, USA..

The thermal energy generated by solar thermal energy can be stored for about 24 hours with little loss in a storage medium such as a molten salt. Dual fuel heaters using natural gas can be used when solar insolation is absent. The stored energy can later be released during the night or under cloudy skies. A solar thermal power plant, like fossil

fuel and nuclear power plants, can cover the base load or the minimum amount of power that needs to be produced to meet consumers' expected demands. This makes this mode of energy generation more valuable than wind energy which needs to cope with intermittency factor or capacity factor of the wind blowing up.

SELECTIVE SURFACES FOR SOLAR ENERGY APPLICATIONS

Table 1. Normal specular solar reflection of different materials for beam radiation [2].

Material	Reflectance
Electroplated silver	0.96
High purity Al	0.91
Sputtered Al optical reflector	0.89
Brytal processed Al	0.89
Back-silvered water white plate glass	0.88
Al with SiO coating	0.87
Al foil, 99.5 percent purity	0.86
Back aluminized 3M acrylic	0.86
Commercial Alzac process Al	0.85
Back aluminized 3M acrylic, 1 yr solar irradiation	0.85
Aluminized Type C Mylar from Mylar side	0.76

Table 2. Absorptance and emittance for long wave solar radiation. Flat plate solar collector temperature [2].

Material	Absorptance	Emittance, Long-wave radiation
Nickel Black, Oxides and sulfides of Ni and Zn on polished Ni.	0.91-0.94	0.11
Nickel Black, Oxides and sulfides of Ni and Zn on galvanized Fe.	0.89	0.12-0.18
Nickel Black, Oxides and sulfides of Ni and Zn on electroplated Ni on mild steel. After 6 hr immersion in boiling H ₂ O.	0.94	0.07
CuO on Ni, Electrode deposition of Cu followed by Cu oxidation	0.81	0.17
Co ₃ O ₄ on Ni, Deposition followed by oxidation.	0.90	0.27
CuO on Al, Sprayed dilute Cu(NO ₃) ₂ solution on hot Al Plate followed by baking,	0.93	0.11

Cu Black on Cu, Treatment of Cu by solution of NaOH and NaClO ₂ .	0.89	0.17
Ebanol Cu on Cu, Cu blackening treatment with CuO coatings.	0.90	0.16
CuO on anodized Al, Al treated with hot Cu(NO ₃) ₂ -KMnO ₄ solution followed by baking.	0.85	0.11
Al ₂ O ₃ -Mo-Al ₂ O ₃ -Mo-Al ₂ O ₃ -Mo-Al ₂ O ₃ , Interference layers on Mo.	0.91	0.085
PbS crystals on Al	0.89	0.20

HEAT TRANSFER FLUID (HTF) THERMAL FLUID HEATERS

The thermostat range of thermal fluid heaters makes use of a mineral oil known as Heat Transfer Fluid (HTF), which allows for operating temperatures up to 300°C at the heater outlet. This heated HTF, after circulation through the heater, is then indirectly used to heat the clients applications.

A single thermostat heat producer can often be used to satisfy many different heating applications for the same establishment, simultaneously and at different temperatures. As an example, a single HTF heater can indirectly produce hot air, steam, hot water etc, whilst being used for reactor vessel heating.

The HTF heaters are far superior to traditional hot water or steam boiler systems, mainly due to the temperatures attainable and lack of corrosion and stresses associated with pressure and water.

The HTF circuit is open to atmosphere in standard systems, and operates simply under normal pump discharge pressure. The HTF heaters operate without the need for chemical water treatment, pressure vessel inspection and certification and related requirements, and there is no corrosion inside the system.

The HTF heaters hence have a far longer life expectancy than a traditional water or steam boiler. The HTF heaters also produce much higher temperatures, up to 300°C on standard plants, and even up to 350°C on special request. If such temperatures were required using, as example, a steam boiler, unrealistic steam pressures of over 80 bar would be needed to achieve this temperature.

Existing units vary from 18 KW to 2.5 MW net heat output. Combinations of the standard sizes allows for total outputs anywhere over 2.5 MW. Systems can be manufactured to fire most fuels, such as diesel, paraffin, natural or LPG gas, or even heavy furnace fuels in some cases. All systems can also, as alternative, be manufactured in electrically heated format.

Standard systems come complete with their combustion and electrical controls as well as all safety equipment.

Table 3. Thermal Storage media used with parabolic trough solar power plants.

Storage medium	Operational Temperature		Density [kg/m ³]	Thermal heat conductivity [W/(m.K)]	Average heat capacity [kJ/(kg.K)]	Volumetric specific heat capacity [kW _{th} .hr/m ³]	Cost	
	Cold [°C]	Hot [°C]					[\$/kg]	[\$/kW _{th} .hr]

Phase change materials								
Sodium nitrate, Chile or Peru saltpeter, NaNO ₃	308		2.357	0.5	200	125	0.20	3.6
Potassium nitrate, Ordinary saltpeter, KNO ₃	333		2.110	0.5	267	156	0.30	4.1
Potassium hydroxide, Caustic potash, KOH	380		2.044	0.5	150	85	1.00	24.0
Salt-ceramics, Na ₂ CO ₃ (Sodium carbonate)-BaCO ₃ (Barium carbonate, witherite)/MgO(magnesium oxide, magnesia)	500-850		2.600	5.0	420	300	2.00	17.0
Sodium chloride, table salt, halite, NaCl	802		2.160	5.0	520	280	0.15	1.2
Sodium carbonate, soda ash, Na ₂ CO ₃	854		2.533	2.0	276	194	0.20	2.6
Potassium carbonate, potash, Na ₂ CO ₃	897		2.290	2.0	236	150	0.60	9.1
Liquid materials								
Mineral oil, liquid petroleum (alkanes, cyclic paraffins, petroleum jelly)	200	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil, polyalphaolefin, synthetic esters, hydrocracked/hydroisomerized base oils.	250	350	900	0.11	2.3	57	3.00	43.0
Silicone oil, polymerized siloxanes, ...Si-O-Si-O-Si...	300	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts, KNO ₂ , NaNO ₂	250	450	1,825	0.57	1.5	152	1.00	12.0
Nitrate salts, NaNO ₃ , KNO ₃	265	585	1,870	0.52	1.6	250	0.70	5.2
Carbonate salts, Na ₂ CO ₃	450	850	2,100	2.00	1.8	430	2.40	11.0
Liquid Na	270	530	850	71.00	1.3	80	2.00	21.0
Solid materials								
Sand-rock-mineral oil	200	300	1,700	1.0	1.30	60	0.15	4.2
Reinforced concrete	200	400	2,200	1.5	0.85	100	0.05	1.0
NaCl	200	500	2,160	7.0	0.85	150	0.15	1.5
Cast Fe	200	400	7,200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7,800	40.0	0.60	450	5.00	60.0
Silica fire bricks	200	700	1,820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1,200	3,000	5.0	1.15	600	2.00	6.0

CONCENTRATED SOLAR THERMAL POWER

The simplest implementation depends on technology that was developed in Egypt about 100 years ago where parabolic mirrors troughs concentrated solar radiation on water contained in tubes generating steam, which then drove turbines attached to pumps used for irrigation from the Nile River.

Plans exist for a Desertec project to provide Europe with 700 Tera Watts.hours (TW.hrs) of energy per year from solar electricity produced in North Africa's deserts and transmitted across the Mediterranean to Europe.

A solar east-west solar corridor is envisioned in the USA in conjunction with a wind energy north-south corridor.

Table 4. Parabolic Trough Solar Power Plants in the USA. Source: National Renewable Energy Laboratory (NREL).

	Location	First Year of Operation	Net Output [MW _e]	Solar Field Outlet [°C]	Solar Field Area [m ²]	Solar Turbine Efficiency [percent]	Power Cycle	Auxiliary equipment
Nevada Solar One	Boulder City, NV	2007	64	390	357,200	37.6	Reheat Steam Rankine Cycle 100 bar	None
Arizona Public Service (APS) Saguaro	Tucson, AZ	2006	1	300	10,340	20.7	Recuperated Organic Rankine Cycle (ORC) Pentane working fluid	None
SEGS* IX	Harper Lake, CA	1991	80	390	483,960	37.6	Solar steam and solar superheating 100 bar, reheat	Auxiliary natural gas Heat Transfer Fluid (HTF) heater as backup during low and non-solar hours
SEGS VIII	Harper Lake, CA	1990	80	390	464,340	37.6	100 bar, reheat	HTF heater augmentation during mid-peak hours and 12-6 pm summer peak
SEGS VI	Mojave Desert, Kramer Junction, CA	1989	30	390	188,000	37.5	100 bar, reheat	Auxiliary natural gas boiler
SEGS VII	Kramer Junction, CA	1989	30	390	194,280	37.5	100 bar, reheat	Auxiliary natural gas boiler
SEGS V	Kramer Junction, CA	1988	30	349	250,500	30.6	40 bar, steam	Auxiliary natural gas boiler

SEGS III	Kramer Junction, CA	1987	30	349	230,300	30.6	40 bar, steam	Auxiliary natural gas boiler
SEGS IV	Kramer Junction, CA	1987	30	349	230,300	30.6	40 bar, steam	Gas boiler
SEGS II	Daggett, CA	1986	30	316	190,338	29.4	40 bar, steam	Gas boiler
SEGS I	Daggett, CA	1985	13.8	307	82,960	31.5	Solar steam and natural gas superheating 40 bar, steam	3-hrs TES

*SEGS: Solar Electric Generating Station

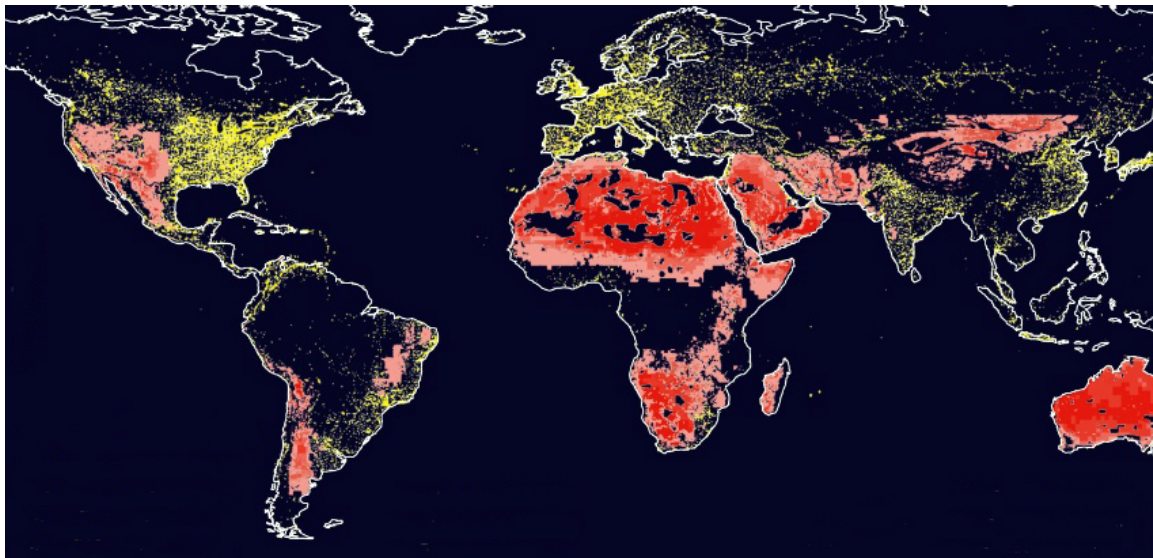


Figure 5. Desert regions with exploitable solar energy resources (red) and energy consumption regions (yellow). P3 Engineering Society. Desertec Foundation. Data from NASA and DLR (German Aerospace Center). Der Spiegel.

FOCUSING SYSTEMS CONFIGURATIONS

A variety of configurations are used to increase the flux of solar radiation on receivers. Cylindrical, hemispherical, conical or other curved geometries can be used.

Some configurations can focus diffuse radiation. The optical focusing configurations act only on beam radiation. Sun tracking becomes important for the focusing systems.

They can be classified as refractive lenses or reflectors, by the mounting and orientation system, by construction materials or by application.

An important parameter is the concentration ratio defined as:

$$\text{Concentration ratio} = \frac{\text{Area of concentrator aperture}}{\text{Receiver energy absorbing area}} \quad (1)$$
$$\text{CR} = \frac{A_c}{A_r}$$

The concentration ratios for surfaces of revolution can be much larger than their cylindrical counterparts.

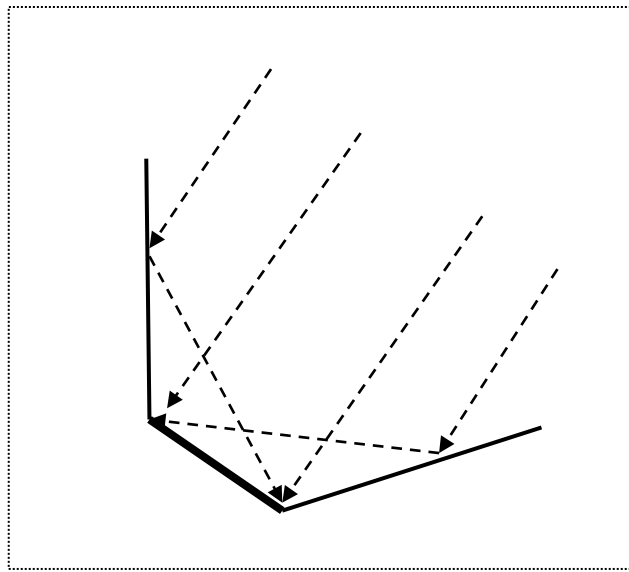


Figure 6. Plane reflector and plane receiver configuration. Low concentration factor, with a maximum value of less than 4.

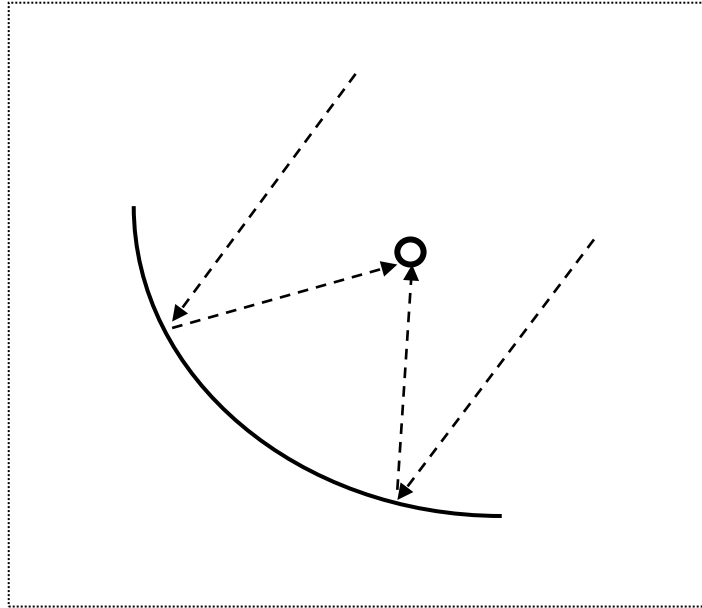


Figure 7. Paraboloid reflector, cylindrical receiver configuration. Leads to high concentration ratio for high temperature applications.

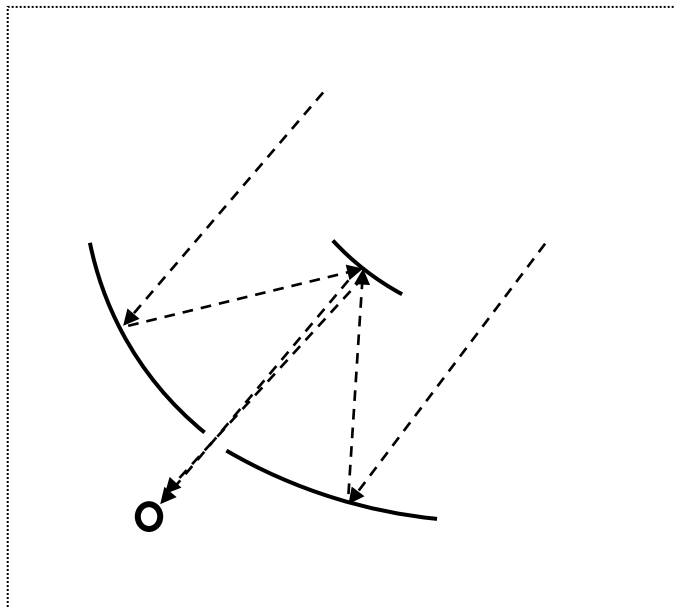


Figure 8. Paraboloid concentrator with a secondary reflector that reflects the radiation to a more convenient location than at the original focus.

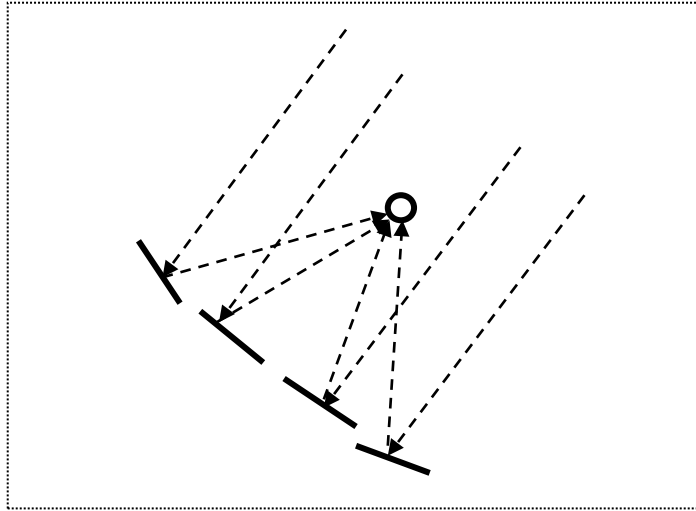


Figure 9. Reflecting Fresnel with flat reflectors configuration. Allows easy fabrication of components at the expense of a loss of the areas between the reflectors.

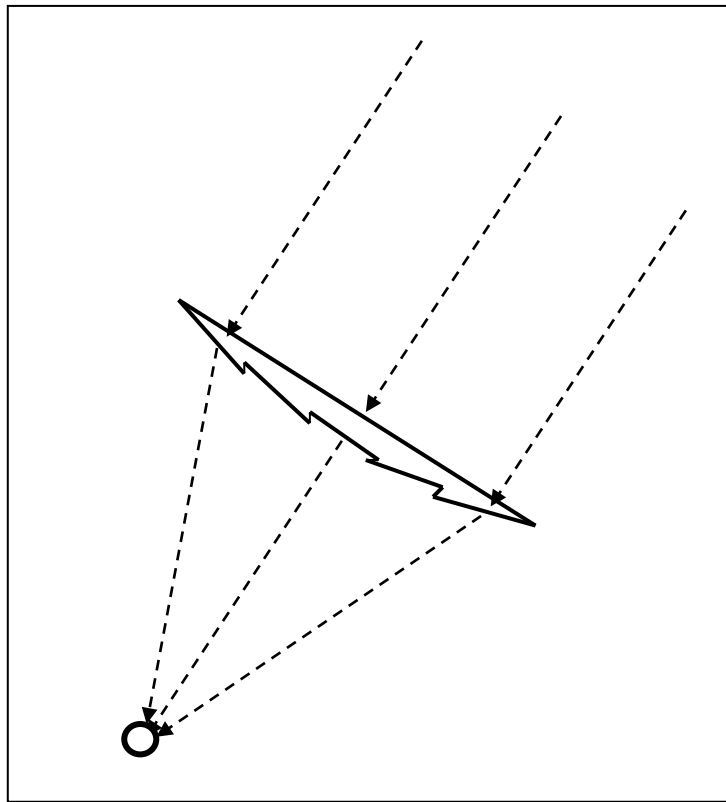


Figure 10. Fresnel refractor configuration.

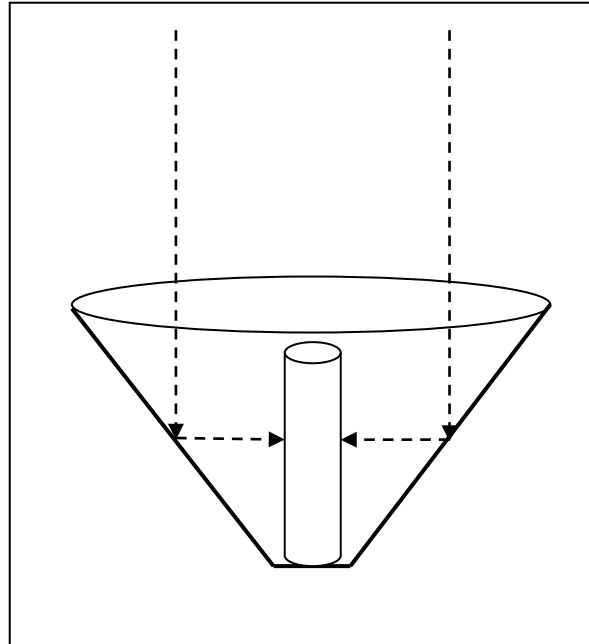


Figure 11. Conical reflector with cylindrical receiver configuration.

The configurations can use either:

1. Cylindrical reflectors or refractors with a receiver as a “line” focus.
2. Circular reflectors or refractors focusing the radiation at a “point” focus.

Cylindrical optical systems focus beam radiation to the receiver if the focal axis, the vertex line of the receiver and the sun lie in a plane. Hence, it is possible to rotate the optical plane around a single axis of rotation that could be: north-south, east-west, or inclined and parallel to the Earth’s axis with a rate of rotation of 15 degrees/hr.

TRACKING AND ORIENTATION

Solar reflectors that are in the form of surfaces of revolution must be oriented in such a way that the focus, the vertex and the sun are aligned in the same plane.

They must have the capability to adjust the position of the collector from its end-of-day to its beginning of day position.

They also must be capable of moving along two axes. These could be for instance, horizontal and vertical. One axis of rotation could be a polar axis that is inclined to be parallel to the Earth’s axis of rotation and the other perpendicular to it.

Several methods of the orientation of the collector are [1]:

- 1. Fixed:** The collector’s surface is perpendicular to the solar beam at noon at the time of the solar equinoxes.
- 2. Two perpendicular axes:** Rotation around the axes with continuous adjustments allowing the surface normal to continuously coincide with the solar beam.

3. Rotation around horizontal north-south axis: With continuous adjustment to obtain maximum energy incidence

4. Rotation around horizontal east-west axis:

a) Single daily adjustment needed so that the surface normal is perpendicular to the solar beam at noon every day of the year.

b) Continuous adjustment to obtain maximum energy incidence.

5. Rotation around axis parallel to the Earth's axis: With continuous adjustment to obtain maximum energy incidence.

Another classification is on the basis of:

1. Manual system: Depends on the operator's skill and his observations. It is adequate in areas of cheap labor. It is adequate when the concentration ratio is not too high.

2. Mechanized systems: Needed in an industrial context. These can again be classified as:

a) **Sun-seeking systems:** These use detectors to determine the system alignment and use control systems to make the necessary alignments.

b) **Programmed systems:** These cause the collector to move in a predetermined manner such as 15 degrees/hour about a polar axis. They may need occasional checking to assure that the system is adequately aligned.

c) **Hybrid programmed and sun-seeking systems:** Such combination would impose small corrections of a sun-seeking mechanism on a rough-positioning programmed system.

PARABOLIC TROUGH TECHNOLOGY

Four main types of CSP technologies are dominating the current industrial applications:

1. Parabolic trough: As of 2011, more than 90 percent of the installed and under construction capacity is of the parabolic trough type, as the most mature and proven technology. It uses trough-shaped mirrors to concentrate solar radiation on a receiver tube emplaced at the focal line of the trough where a thermal transfer fluid is circulated to absorb the thermal energy.

2. Fresnel trough / reflector: Is similar to the parabolic trough technology but uses the more convenient flat or less shaped mirrors to concentrate solar radiation on the receiver pipe.

3. Solar tower system: This is also referred to as a central receiver system. An array of heliostats or sun-tracking flat mirrors concentrate solar radiation on a focal surface containing a heat transfer fluid on top of a tower.

4. Parabolic dish: Those dishes with a Sterling engine receiver are relatively small units with a paraboloid dish similar to those used in satellite communications covered with small flat mirrors. An advantage of the Stirling engine is that it can be built without a water coolant and requires minimum maintenance. This makes it useful in arid areas of the world without water supplies.

Another less developed technology is the solar-wind hybrid chimney tower, where air is heated under a large collector roof where it rises through a chimney and powers horizontal wind turbines.

The temperatures reached in the Stirling cycle can reach 550-1,000 °C, and those in the solar tower system 400-500 °C.

DESERT SOLAR THERMAL PLANTS

Initially, critics of desert based solar thermal plants expressed the concern that shifting sand dunes would bury the solar mirrors and sand storms would scratch their surfaces, rendering them unusable.

These concerns are proven to be unfounded. Eighty percent of the deserts are free of dunes, and the migration routes of nomadic tribes could be easily avoided.

The optimal sites for solar thermal power plants are plateaus far from the coastal regions, where the sun delivers twenty percent more energy per hectare than in Spain.

It is hoped that the first Desertec pilot project could be built near the Moroccan city of Ouarzazate, on the southern edge of the Atlas Mountains. It would use cooling towers cooled with air instead of water, which would be of enormous benefit in the Sahara, but would increase costs by 5 to 10 percent.

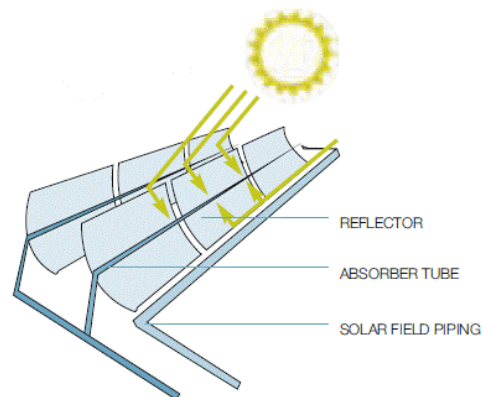


Figure 12. Andasol 1 solar plant in Grenada, Spain. The design follows the same principle of a solar plant built in Egypt 100 years ago; producing steam fed to a turbine running irrigation pumps for Nile River water. Source: DDP.

DESERTEC INDUSTRIAL INITIATIVE

The Desertec Industrial Initiative was launched in München, Germany on July 13, 2009. A consortium was formed including the Siemens Company, Munich Re, Deutsche Bank, RWE and E.on, among others.

SUSTAINABILITY CONSIDERATIONS

The energy payback period of CSP for the manufacturing and installation of equipment is similar to that of wind power systems at about 6 months.

Most of the materials used in CSP plants can be recycled. This includes glass, steel, and concrete.

The environmental impact of CSP plants is negligible.

The main concerns are that for some plant designs:

1. The water requirements must be taken into account. Only the Stirling cycle approach does not need appreciable amounts of water.
2. The land requirements are large. For a single 1 MW of installed capacity, 25,000-40,000 m² of land is needed. A 100 MW plant built in Spain requires 4 km² of land to deliver electricity to 400,000 people.

ENERGY STORAGE

Energy storage with solar thermal plants can be achieved with molten salts. The salt storage devices are giant tanks, with a diameter of up to 118 ft or 36 meters.

They contain liquid potassium and sodium nitrate as cheap mineral salts that are normally used in synthetic fertilizer production.

The control room operators can decide whether to conduct heat from the solar collectors directly to the turbine or into the salt tank. Once the salt tanks have been heated, the power plant can run at full capacity for seven hours using the stored heat from the tanks alone.

GRID TRANSMISSION USING HIGH VOLTAGE DC, HVDC

To bring the electricity from the desert regions to the population centers the grid system would use High Voltage Direct Current (HVDC) transmission lines. These can transmit electricity over a distance of 1,000 kilometers with losses of less than 3 percent.

The Norned cable as the longest underwater HVDC line came into operation in 2008. It transmits power from the Netherlands to Norway, or the other way around, depending on where the electricity happens to be cheaper at any given time. It recouped more than 10 percent of the initial investment within its first three months of operation.

Encased in plastic and protected by a metal shell, the cables consist of copper or aluminum wires with a thickness of 5 centimeters. They are unwound from special ships and buried on the sea floor by robots.

The 200 kilometer in length cable that is planned to connect the Bard offshore wind farm in the North Sea to the German grid will cost about €300 million. Some 80 to 100 of these cables would be needed to bring all the electricity to be generated in the Sahara Desert from North Africa to Europe.

Laying that cabling across the Mediterranean Sea may not be economically lucrative. A dispute between France and Spain that has been raging for years over the construction of a high performance cable in the Pyrénées Mountains is an example. Citizens' initiatives are constantly blocking or delaying new projects throughout Europe. Expanding a grid line in Germany takes 15 years, including all the expropriation proceedings.

On the other hand, locally in Morocco, which has almost no fossil fuel resources, Desertec has attracted a great deal of interest. In 2009 the Moroccans approved their

solar plan, under which the country, with support from the World Bank, will install 2,000 megawatts of solar power by 2020. It is hoped that Italy could reduce its environmental footprint with clean energy from Tunisia.

Electrical industrial giants like Siemens are involved in the business, but so are smaller, specialized companies. Cologne, Germany based Flagsol produces solar control devices. The Bavarian company Schott Solar makes heat receptors for the solar troughs, and Solar Millennium, based in Erlangen in southern Germany, provides project development services. German companies already control a third of the worldwide market for solar thermal energy.

The Wuppertal Institute for Climate, Environment and Energy calculated the projected revenues for German solar companies by the year 2050 under a best-case scenario at an astronomical figure: €2 trillion.

CONCENTRATED SOLAR THERMAL TOWER PRODUCTION



Figure 13. Tower concentrating plant, Andalusia, Spain.





Figure 14. The PS20 Solar Power Tower is the world's largest, Andalusia, Spain. Mirror array concentrates solar radiation on an absorber at the top of the tower with water and steam as working media. The tower supplies the energy need of 10,000 homes. Source: Der Spiegel.

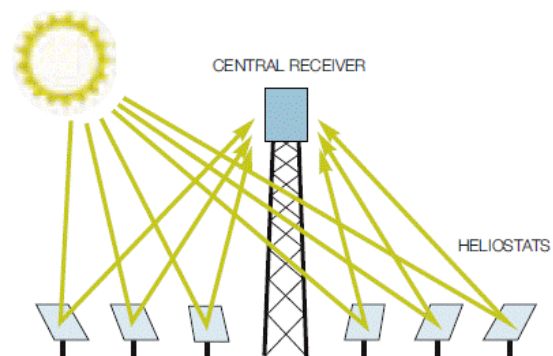


Figure 15. Solar Power Tower in the Mojave Desert, California. Source: Der Spiegel.



Figure 16. Solar Power Tower at Jülich, Germany. Source: Der Spiegel.



Figure 17. Solar Power Tower in the Negev Desert, Israel. Source: Der Spiegel.



Figure 18. Parabolic trough concentrator using oil as a working medium at 752 oF or 400 oC. Kramer Junction, California, USA. Source: Der Spiegel.



Figure 19. Nevada Solar One near Boulder City, Colorado, USA. Source: DDP, Siemens.



Figure 20. Plataforma solar research facility, Almeria, Spain. DPA.

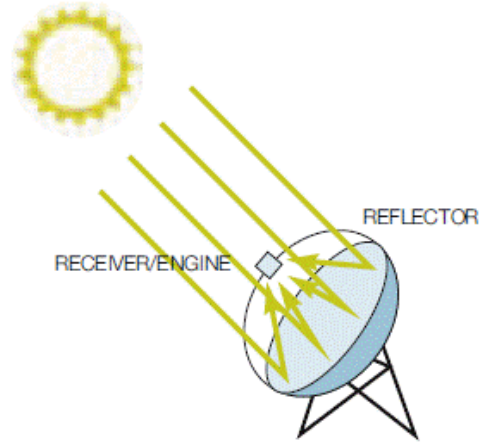


Figure 21. Solar dish concentrator, Plataforma Solar, Almeria, Spain. The concave mirror concentrator focuses solar radiation on a Stirling engine receiver using He as a working medium. Source: Der Spiegel.

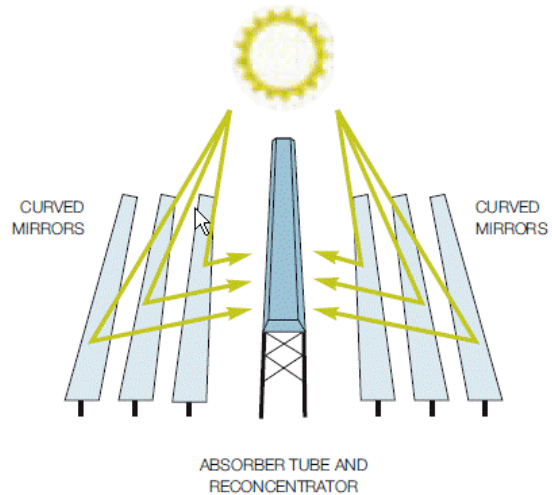


Figure 22. Fresnel lens mirror concentrator at Plataforma Solar, Almeria, Spain. Flat mirrors track solar radiation and focus it on a tube. The design is simpler and more economical than a trough concentrator but operates at a lower efficiency than a trough design. Source: Der Spiegel.

STORAGE STRATEGIES

With the use of storage and auxiliary systems, Concentrated Solar Energy (CSP) offers the possibility of producing electricity at 8 cents/Kw.hr. Current CSP plants are achieving costs of 12 cents/KW.hr.

In a hybrid storage and auxiliary system, a proportion of the energy during the day is sent to storage tanks to be later retrieved during the night period, in addition to the use of the auxiliary boilers.

Specialized solid and molten salts are favored because of their ability to receive and hold heat. Research is conducted into using specialized oils.

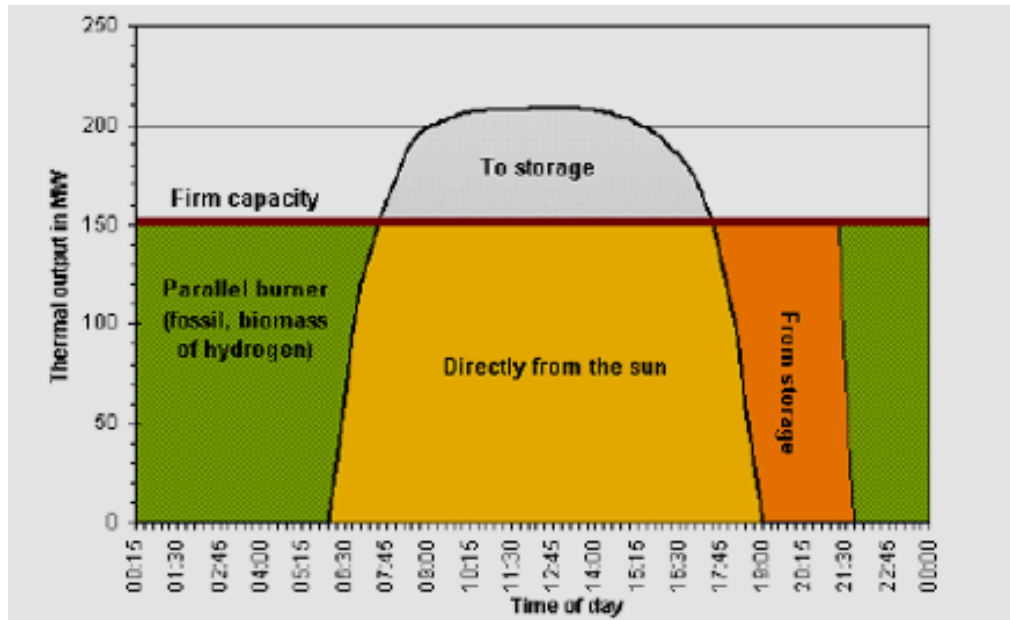


Figure 23. Daily period of energy storage in the Andasol 1 Project, Spain.





Figure 24. Evolution of experimental tanks to commercial storage tanks at the Andasol 1 and PS10 plants, Spain.

STIRLING CYCLE SYSTEMS

Stirling Energy Systems (SES) manufactures of the SunCatcher solar dish Stirling engine system.

The Stirling thermodynamic cycle stores energy in its recuperator.



Figure 25. Sterling engine dish receiver.

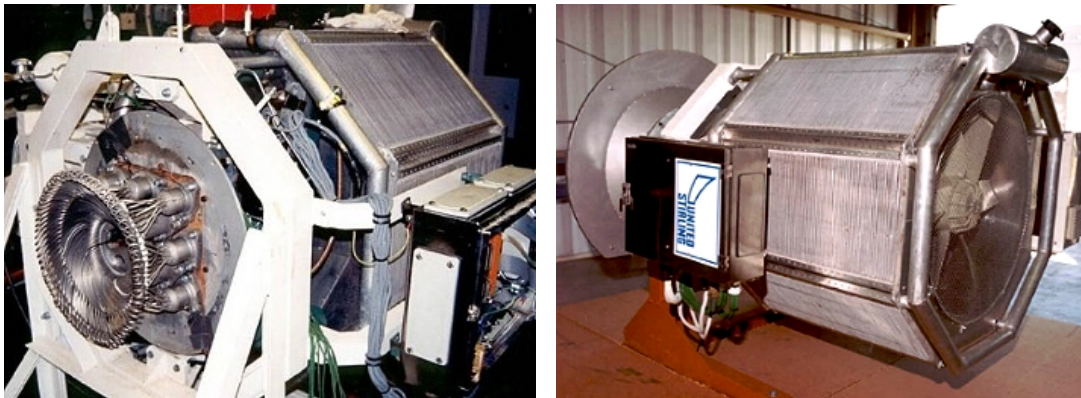


Figure 26. Stirling Cycle 25 kW Engine used with dish collector. Receiver end with spiral metal as pickup for the hot spot (left). Cooling fan to assist in cooling the condenser (right). The temperature difference between the hot and cold ends determines the efficiency of the unit. Source: Stirling Energy Systems.



Figure 27. Stirling Engine dish receiver in up and down positions. Source: SAIC.



Figure 28. SAIC 20 kW Stirling engine. Source: SAIC.



Figure 29. Concentrator array using Stirling engines.

COLLECTOR MATERIALS

Collectors are exposed to high temperatures, long term outdoor exposure, impact from hail, dust particles and need to be covered with glazing. The glazing materials should possess high light transmission at a reasonable cost. The desirable properties of the glazing materials are:

1. High visible light transmission,
2. Opacity to the long Infra Red (IR) radiation to reduce heat losses,
3. High temperature resistance,
4. Long life exposure to Ultra Violet (UV) radiation and temperature,
5. Acceptable impact resistance,
6. Light weight and good workability,
7. Economical.

Table 5. Some collector glazing materials choices.

Glazing Material	Properties
Glass	Low Fe, high transmission tempered glass is favored. Has long life, good transmittance high temperature resistance, low transmittance in long IR region. Glass is heavy, breakable and costly.
Polycarbonate	Used in roofs, greenhouses, porches, football helmets. General electric (GE) trade name: Lexan. Dynaglas. Has high transmittance, impact resistance, good temperature tolerance to 270 °F, low cost easy to handle, low transmission in long IR range. Low resistance to long time exposure to hot water vapor. Lower capability than glass. Needs UV protection coating.
Acrylic	Used if glazing is not exposed to high temperatures.
Fiber glass	Manufactured in rolls.

SHAMS 1 SOLAR POWER PLANT

A world competition is ongoing on plans for the world's largest solar thermal power plant. The United Arab Emirates (UAE) is joining the fray with a massive concentrated solar energy project called Shams 1 or Sun 1 in Arabic.

The Masdar Company is teaming up with French oil company Total and Spanish solar company Abengoa Solar to build a 100 MW solar plant outside of Abu Dhabi in the UAE. Compared with the monster Desertec project in Europe and North Africa, Shams 1 is a drop in the bucket, but will be up and running long before Desertec secures financing.

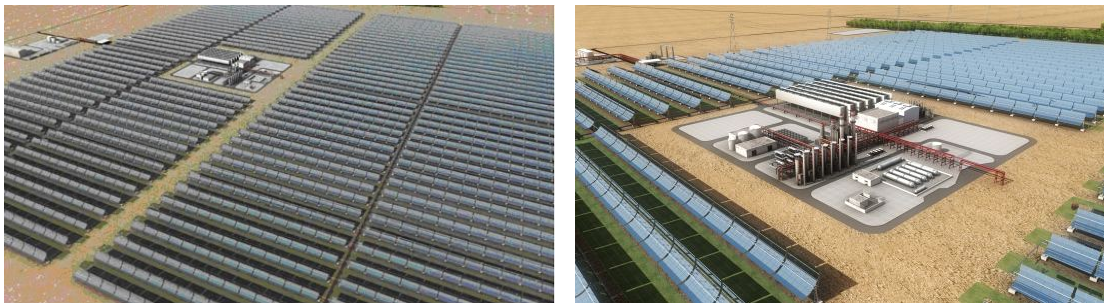
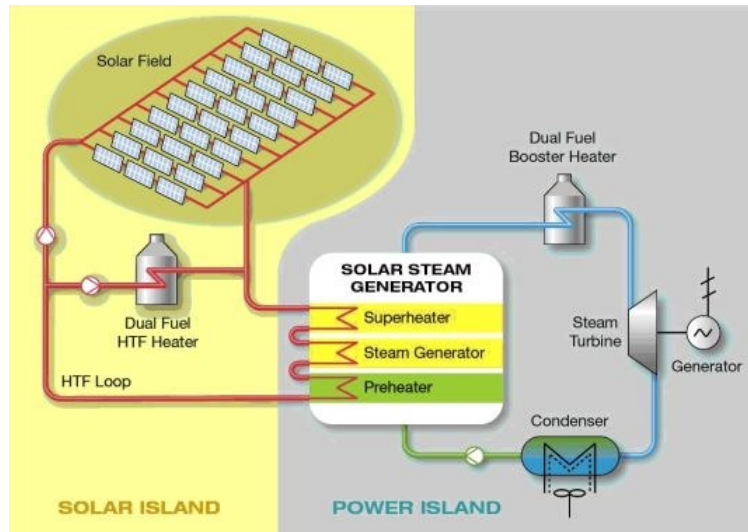


Figure 30. Shams-1 (Sun-1) solar power plant project, United Arab Emirates (UAE) is supplemented with a natural gas heater unit.

Shams-1 will be located 120 kilometers southwest of Abu Dhabi. The plant is comprised of a solar field consisting of 768 parabolic trough collectors supplied by Abengoa Solar, plus a backup natural gas boiler to supply power when the sun is not shining. The plant will displace approximately 175,000 tonnes of CO₂ per year and directly contribute to the UAE's goal of 7 percent renewable energy by 2020.

The new CSP plant will be jointly owned by Masdar (60 percent), Total (20 percent) and Abengoa Solar (20 percent). Construction is expected to commence in the fall of 2010 and should take approximately two years to complete.

The project is located about 75 miles southwest of UAE capital Abu Dhabi and estimated to cost between US\$500 and US\$700 million and is expected to generate around 100 megawatts of power, and will be the world's largest concentrating solar power plant (CSP) when completed by 2013.

Masdar currently operates a 10 MW Photo Voltaic (PV) power plant in Abu Dhabi. Unlike PV plants, which use solar panels that directly convert sunlight to electricity, CSPs reflect sunlight, usually with mirrors, heating liquids that produce steam to generate power.

The French Company, Total, which has stepped up its presence in solar energy sphere as competitors like Royal Shell and British Petroleum (BP), have turned their focus away from solar to second-generation biofuels, controls a 50 percent stake in both

PV cell maker Phototech and solar energy system producer and operator Tenesol. It is the biggest shareholder in organic solar product developer Konarka. For its part, Abengoa brings experience in building solar energy plants.

Desertec, the European Union project, which has ambitious goals of 1 GW of CSP is likely to not be completed for at least another 15 years.

AL-KURAYMAT CONCENTRATED SOLAR POWER (CSP) PLANT

Egypt inaugurated its first solar energy plant by the end of 2010. The plant is among four in the world with a 140 MW capacity.

The plant south of Cairo would be linked to the national grid as Egypt tries to meet a target of producing 20 percent of its energy needs from renewable sources by the end of 2020. The country's oil and gas reserves are projected to last for three more decades.

Concentrated solar power plants use mirrors to heat liquid which then heats water to power a steam generator that produces electricity.



Figure 31. Concentrated Solar Power (CSP) plant mirrors.

NEVADA 1 SOLAR PLANT

Built 35 miles south of Las Vegas at Boulder City, Nevada, the Concentrating Solar Power (CSP) plant covers 400 acres of land and has a capacity of 64 MW providing energy to 14,000 typical USA homes. It is the third largest of its kind in the world, built by the Acciona Company, and started operation in June 2007.

The plant consists of 760 parabolic concentrators with 182,000 mirrors that concentrate solar radiation on 18,240 receiver tubes.

It is operated by Solargenix Energy, Nevada Power Company and Sierra Pacific Resources.



Figure 32. Nevada Solar 1 power plant. Source: Acciona.

ALVARADO, SPAIN SOLAR THERMAL POWER PLANT

Spain has in July 2010 inaugurated the world's largest solar power raising the nation's total solar power production to the equivalent to the output of a nuclear power station.

Spain is a world leader in renewable energies and has long been a producer of hydroelectric power, only exceeded by China and the USA. It also has a highly developed wind power sector.

The new La Florida solar plant takes Spain's solar output to 432 MW, which compares with the USA output of 422 MW. The plant, at Alvarado, Badajoz, in the west of the country, is a parabolic trough. Sunlight is reflected off a parabolic mirror on to a fluid-filled tube. The heated liquid is then used to heat steam to run the turbines. The mirror rotates during the day to follow the sun's movement. The solar farm covers 550,000 square meters and produces 50 MW of power.



Figure 33. La Florida solar thermal power plant, Alvarado, Badajoz Spain. Photo: Reuters.

Protermosolar, the association that represents the solar energy sector, says that within a year another 600 MW will have come on-stream and projects that by 2013 solar capacity will have reached 2,500 MW.

The northern thinly populated region of Navarra is producing 75 percent of its energy from a range of renewables, including wind, solar, hydro and biomass. Spain's wind farms produce around 20,000 MW of electricity and on one day in November 2009 they accounted for 53 percent of demand. In 2009, solar energy met 2.8 percent of demand out a total of 12.9 percent for all renewable sources. In March 2010, the Spanish government announced a plan to increase the renewable share to 22.7 percent by 2020, slightly ahead of the EU targets.

With an average of 340 days of sunshine a year in Spain, solar is more reliable than wind energy. Spain is the fourth largest manufacturer of solar power technology in the world and both solar and wind power technology exports have become valuable earners in a country with a weak manufacturing.

SOLANA, ARIZONA SOLAR PLANT



Figure 34. Solana 280 MWe power plant, Arizona, USA. Source: Abengoa Solar.



Figure 35. Parabolic collectors at the Solana Plant, Arizona, USA. Source: Abengoa Solar.

The Solana solar plant near Phoenix, Arizona produces up 280 MWe of electricity. Construction of the Solana solar array, about 70 miles southwest of Phoenix, began in 2010 and had a final cost of \$2 billion. Arizona's largest public utility, Arizona Public Service (APS), will purchase all of the electricity produced by the solar plant for 30 years through a power purchase agreement with Abengoa Solar. The Solana solar array field covers 3 square miles with 3,200 mirrored parabolic trough collectors. Each collector is about 25 feet wide, 500 feet long, and 10 feet high [2].

The solar plant was financed in part by a Department of Energy (DOE) \$1.45 billion loan guarantee. It is the country's first large-scale solar plant with thermal energy storage system. Through the use of molten salt thermal energy storage the plant can continue to produce steam to drive the turbine and provide electricity for 6 hours without the concurrent use of the solar field.

The Solana solar plant will generate enough clean energy to power 70,000 households and will prevent about half a million tons of CO₂ from being emitted into the atmosphere per year. The construction of the plant created more than 2,000 jobs and a national supply chain that spans 165 companies in 29 states [2].

The Solana plant in 2013 stood as the world's largest parabolic trough plant. Being able to store the power in a molten salt allows the plant to continue distributing energy for 6 hours when the sun goes down or is blocked by poor weather. These six hours satisfy Arizona's peak electricity demands during the summer evenings and early night time hours. Dispatchability eliminates intermittency issues that other renewables, such as wind and photovoltaics, contend with, providing stability to the grid and thus increasing the value of the energy generated by the plant [2].

Abengoa Solar has two commercial solar power towers, 13 50MW trough plants, a solar-gas combined-cycle plant and five photo-voltaic plants in commercial operation worldwide. Abengoa has concentrated solar power plants under construction in the U.S., South Africa, Spain, and the United Arab Emirates, with a total capacity of 810 MWs [2].

CO₂ REFORMING INTO DIESEL FUEL

An alliance of industry, academic and government organizations, formed to commercialize technologies that will utilize concentrated solar energy to convert waste CO₂ into diesel fuel, was announced on June 1, 2010.

The team members include Sandia National Laboratories, Renewable Energy Institute International, Pacific Renewable Fuels, Pratt Whitney Rocketdyne (a United Technologies Division), Quanta Services, Desert Research Institute and Clean Energy Systems . Commercial partners have also signed on to advance work on the first round of commercial plants.

The solar reforming technology platform will be co-located next to industrial facilities that have waste CO₂ streams such as coal power plants, natural gas processing facilities, ethanol plants, cement production facilities and other stationary sources of CO₂.

A solar reforming system is currently being demonstrated in Sacramento, California, and demonstrations will continue both at Sandia's facilities in New Mexico and at a power plant project site in Bakersfield, California.

Planning for the first round of commercial plants is under way at several locations in the USA. The project team anticipates that deployment of the first commercial plants can begin in 2013. The project team has received a first phase of funding from the National Energy Technology Laboratory to demonstrate these technologies.

SOLAR THERMAL VALUE

The solar thermal value involves the following components:

1. Project development and financing,
2. Supply of engineering components,
3. Construction and operation.

The risks involved in solar projects involves:

1. Regulatory changes,
2. Withdrawal of political support,
3. Emergence of competing or disruptive technologies from other renewables,
4. Components and materials shortages caused by the fast growth expectations,
5. Geopolitical risks,
6. Financing risks and lack of capital.

DISCUSSION

The USA provides support for the domestic concentrating solar power industry through one and two-year tax incentives.

In Europe, where producers of solar, wind and other renewable energy are guaranteed high wholesale prices for up to 25 years through “feed-in tariffs.”

The more established future revenues that the feed-in tariffs make possible, helps the feasibility of new projects in Spain, despite the fact that Spain has much weaker sun resource than the American Southwest.

The latest USA plant: Nevada Solar 1 went on line in 2007. The largest solar energy generating facility in the world is designated as Solar Energy Generating Systems (SEGS) consists of 9 plants in the Mojave Desert in California, USA. The plants SEGS III to VII have a combined capacity of 150 MW and are located at Kramer Junction. The units SEGS VIII and IX with a capacity of 160 MW are located at Harper Lake. The units I and II (44 MW) are located at Daggett, California. The electrical output of all nine plants is 75 MWe with a capacity factor of 21 percent. Ninety percent of the electricity is generated from solar radiation and the rest from supplemental natural gas at night. The facilities cover 6.5 km² or 1,600 acres of desert land. They use 936,384 mirrors and the parabolic reflectors would extend over 370 kms or 229 miles.

REFERENCES

1. John A. Duffie and William A. Beckman, “Solar Energy Thermal Processes,” Wiley-Interscience, 1974.

2. Lucas Mearian, "U. S. Flips Switch on Massive Solar Power Array that also Stores Electricity," ComputerWorld, October 10, 2013.

EXERCISE

1. A Direct Normal Radiation, DNR of 310 Watts / m² or 7.44 kW.hr / (m².day) for solar radiation is available at the Kramer Junction in California, USA..

Estimate the land area needed for a 100 MWe plant, considering:

- a) The land coverage ratio of 80 percent,
- b) A plant thermal efficiency of 1/3,
- c) A capacity factor of 20 percent.