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## Solar thermal CSP technology

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### Abstract

Solar thermal concentrating solar power (CSP) plants, because of their capacity for large-scale generation of electricity and the possible integration of thermal storage devices and hybridization with backup fossil fuels, are meant to supply a significant part of the demand in countries of the solar belt. Nowadays, the market penetration of solar thermal electricity is steeply increasing, with commercial projects in Spain, USA, and other countries, being the most promising technology to follow the pathway of wind and photovoltaics to reach the goals for renewable energy implementation in 2020 and 2050. In the first commercial projects involving parabolic-trough technology, some improvements are being introduced like the use of large molten-salt heat storage systems able to provide high degrees of dispatchability to the operation of the plant, like the plants Andasol in Guadix, Spain, with 7.5 h of nominal storage, or the use of direct steam generation loops to replace thermal oil at the solar field. In the near future, the research and innovation being conducted within the field of linear Fresnel collectors may lead to high temperature systems able to operate up to 500°C and produce cost-effective superheated steam. Central receiver systems are opening the field to new thermal fluids like molten salts (Gemasolar tower plant in Seville, Spain) with more than 14 h of nominal storage and air, and new solar receivers like volumetric absorbers, allowing operation at temperatures above 1000°C. All these factors can lead to electricity generation cost reduction of CSP plants by 30–40% for the period 2010–2020, according to public roadmaps and cost analysis made by the International Energy Agency in 2010. *WIREs Energy Environ* 2014, 3:42–59. doi: 10.1002/wene.79

This article is categorized under:

- Concentrating Solar Power > Systems and Infrastructure

## Abstract



## INTRODUCTION

Solar thermal electricity or STE (also known as CSP or concentrating solar power) is expected to impact enormously on the world's bulk power supply by the middle of the century.<sup>1</sup> Nowadays, the high-temperature thermal conversion of concentrated solar energy is rapidly increasing, with many commercial projects taken up in Spain, USA, and other countries such as India, China, Israel, Australia, Algeria, and Italy. Spain with 2400 MW connected to the grid in 2013 is taking the lead on current commercial developments, together with USA where a target of 4500 MW for the same year has been fixed and other relevant programs like the 'Solar Mission' in India recently approved and going for 22 GW-solar, with a large fraction of thermal.<sup>2</sup> Only in Southern Europe, the technical potential of STE is more than 1000 GW and in Northern Africa it is immense.<sup>3</sup> Worldwide, the exploitation of less than 1% of the total solar thermal power plant potential would be enough to meet the recommendations of the United Nations' Intergovernmental Panel on Climate Change for long-term climate stabilization.<sup>4</sup>

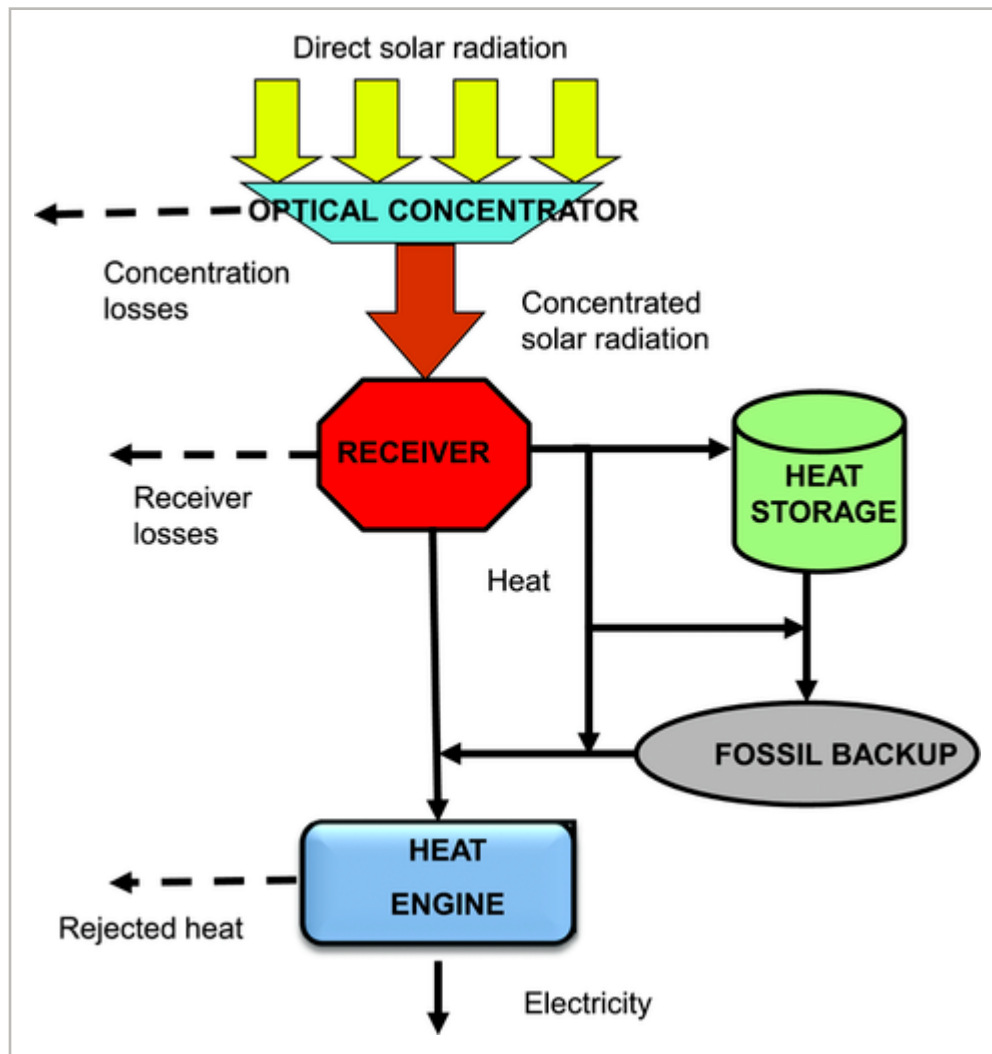
One megawatt installed concentrating solar thermal power avoids annually 688 tons of CO<sub>2</sub> compared with a combined cycle conventional plant, which uses natural gas and 1360 tons of CO<sub>2</sub> compared with a conventional coal/steam plant. A 1-m<sup>2</sup> mirror in the primary solar field produces 400 kWh of electricity per year, avoids 12 tons of CO<sub>2</sub> compared with a conventional

coal/steam plant and contributes to a saving of 2.5 tons of fossil fuels during its 25-year operation lifetime. The energy payback time for the materials of CSP systems is less than 1 year,<sup>5</sup> and most solar-field materials and structures can be recycled and used again for further plants.

But in terms of electric grid and quality of bulk power supply, it is the ability to provide dispatch on demand that makes STE stand out from other renewable energy technologies like photovoltaics or wind. Thermal energy storage systems store excess thermal heat collected by the solar field. Storage systems, alone or in combination with some fossil fuel backup, keep the plant running under full-load conditions. This capability of storing high-temperature thermal energy leads to economically competitive design options, as only the solar part has to be oversized. This STE plant feature is tremendously relevant, as penetration of solar energy into the bulk electricity market is possible only when substitution of intermediate-load power plants of about 4000–5000 h/year is achieved. The combination of energy on demand, grid stability, and high share of local content that lead to creation of local jobs provides a clear niche for STE within the renewable portfolio of technologies. A clear indicator of the globalization of such policies is that the International Energy Agency (IEA) is sensitive to STE within low-carbon future scenarios for the year 2050. At the IEA's Energy Technology Perspectives 2010,<sup>6</sup> STE is considered to play a significant role among the necessary mix of energy technologies needed to halving global energy-related CO<sub>2</sub> emissions by 2050, and this scenario would require capacity additions of about 14 GW/year (55 new solar thermal power plants of 250 MW each).

## CONCENTRATING SOLAR SYSTEMS

Even though solar radiation is a source of high temperature and exergy at origin, with a high radiosity of 63 MW/m<sup>2</sup>, sun-to-earth geometrical constraints lead to a dramatic dilution of flux and to irradiance available for terrestrial use, only slightly higher than 1 kW/m<sup>2</sup> with a consequent supply of low temperatures to the thermal fluid. It is therefore an essential requisite for solar thermal power plants and high-temperature solar chemistry applications to make use of optical concentration devices that enable the thermal conversion to be carried out at high solar fluxes and with relatively low heat losses.<sup>7, 8</sup> A simplified model of a STE plant is depicted in Figure 1.



**Figure 1**

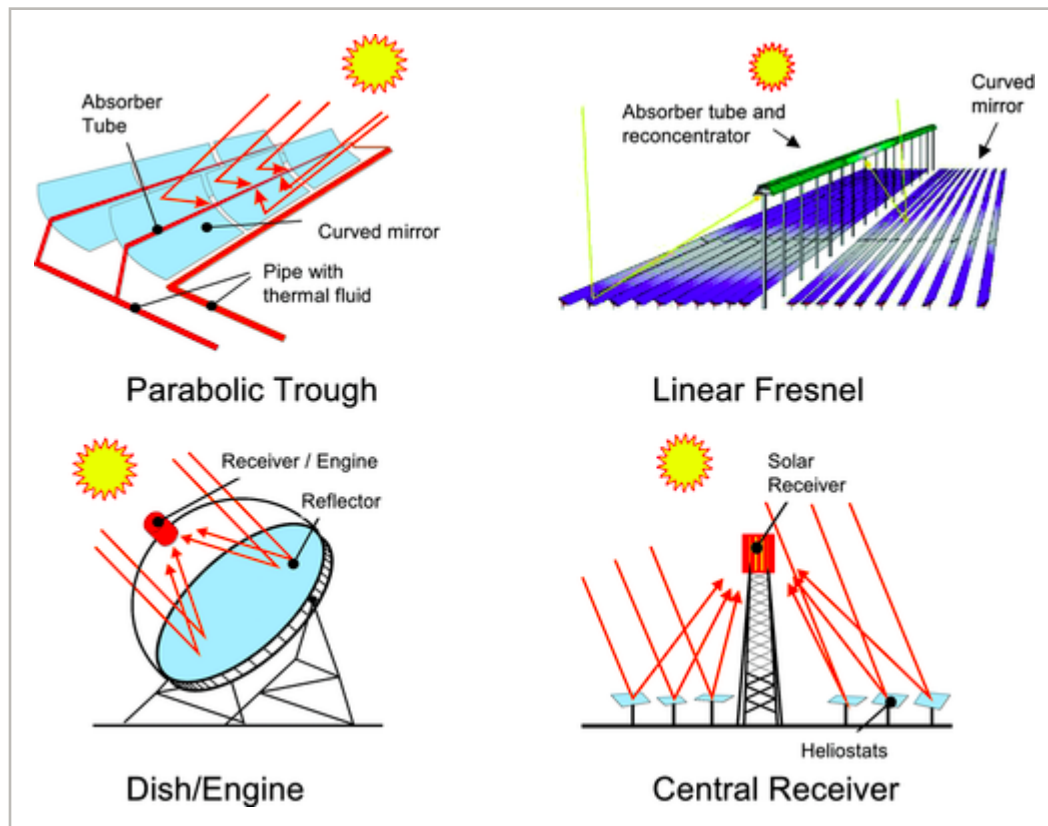
[Open in figure viewer](#) | [PowerPoint](#)

Flow diagram for a typical solar thermal power plant.

STE systems consist of a large reflective surface collecting the incoming solar radiation and concentrating it onto a solar receiver with a small aperture area.<sup>9</sup> The solar receiver is a high-absorptance radiative/convective heat exchanger that emulates as closely as possible the performance of a radiative black body. An ideal solar receiver would thus have negligible convection and conduction losses. In the case of a solar thermal power plant, the solar energy is transferred to a thermal fluid at an outlet temperature high enough to feed a heat engine or a turbine that produces electricity. The solar field is usually designed for a normal incident radiation of 800–900 W/m<sup>2</sup>. Annual normal incident radiation varies from 1600 to 2800 kWh/m<sup>2</sup>, allowing from 2000 to 3500 annual full-load operating hours with the solar element, depending on the available radiation at the particular site.<sup>10</sup>

Solar reflective concentrators follow the basic principles of Snell's Law of reflection.<sup>11</sup> In a specular surface, like the mirrors used in solar thermal power plants, the reflection angle equals the angle of incidence. The most practical and simplest primary geometrical concentrator typically used in STE systems is the parabola. Even though there are other concentrating devices like lenses or compound parabolic concentrators,<sup>12</sup> the reflective parabolic concentrators and their analogues are the systems with the greatest potential for scaling up at a reasonable cost.

Four CSP technologies are today represented at pilot and commercial scale<sup>13, 14</sup>: parabolic-trough collectors (PTCs), linear Fresnel reflector (LFR) systems, power towers or central receiver systems (CRS), and dish/engine systems (DE). All the existing plants mimic parabolic geometries with large mirror areas (Figure 2).



**Figure 2**

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Schematic diagrams of the four STE systems currently scaled up to pilot and demonstration sizes.

PTC and LFR are 2D concentrating systems in which the incoming solar radiation is concentrated onto a focal line by one-axis tracking mirrors. They are able to concentrate the



solar radiation flux 30–80 times, heating the thermal fluid up to 450°C, with power conversion unit sizes of 30–280 MW, and therefore, they are well suited for centralized power generation at dispatchable markets with a Rankine steam turbine/generator cycle. CRS optics is more complex, as the solar receiver is mounted on top of a tower and sunlight is concentrated by means of a large paraboloid that is discretized into a field of heliostats. This 3D concentrator is therefore off-axis and heliostats require two-axis tracking. Concentration factors are between 200 and 1000 and unit sizes are between 10 and 200 MW, and they are therefore well suited for dispatchable markets and integration into advanced thermodynamic cycles. A wide variety of thermal fluids, like saturated steam, superheated steam, molten salts, atmospheric air, or pressurized air, can be used, and temperatures vary between 300 and 1000°C. Finally, DE systems are small modular units with autonomous generation of electricity by Stirling engines or Brayton mini-turbines located at the focal point. Dishes are parabolic 3D concentrators with high concentration ratios (1000–3000) and unit sizes of 5–25 kW. Their current market niche is in both distributed on-grid and remote/off-grid power applications.[15-18](#)

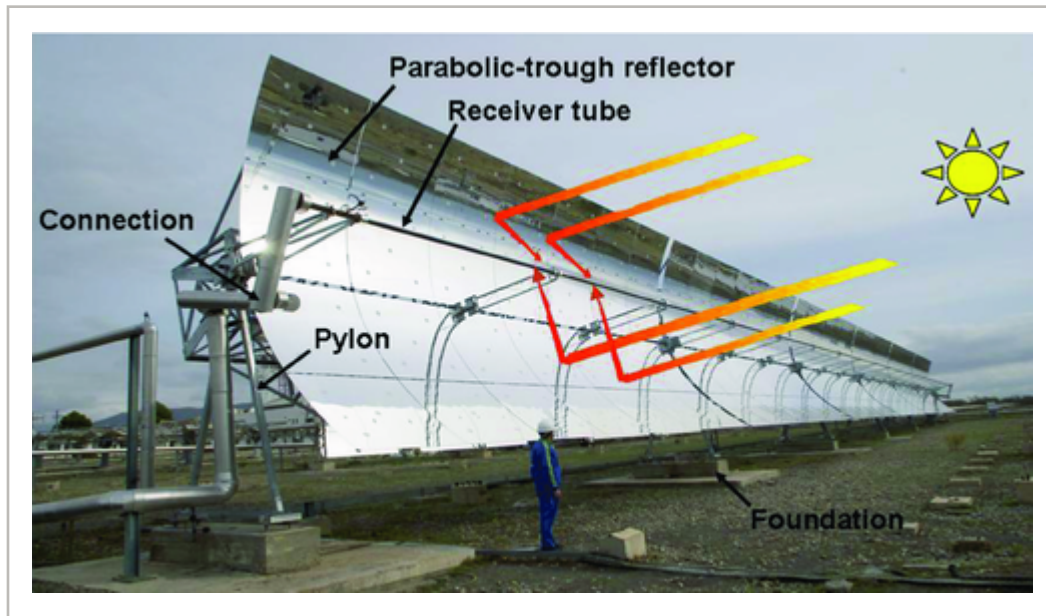
Typical nominal solar-to-electric conversion efficiencies may move between 20% for PTC and LFR systems, 23% for CRS, and 30% for DE. Annual capacity factors may be designed between values of about 20% for systems without thermal energy storage and more than 70% for systems making use of large storage units.[13](#) With current investment costs, all STE technologies are generally thought to require a public financial support strategy for market deployment. At present direct capital costs of STE and power generation costs are estimated to be two to three times those of fossil-fuel power plants, however, industry roadmaps advance 60% cost reduction before 2025.[10](#) In fact, governments at some countries like Spain are already accelerating the process of drastic tariff reduction with the goal of STE, PV, and wind energy becoming tariff equivalent in less than one decade.

Every square meter of STE field can produce up to 1200 kWh thermal energy per year or up to 400 kWh of electricity per year. That means a cumulative savings of up to 12 tons of carbon dioxide and 2.5 tons of fossil fuel per square meter of CSP system over its 25-year lifetime.[19](#)

## PARABOLIC TROUGHS

### The Parabolic-Trough Collector

PTCs are linear-focus concentrating solar devices suitable for working in the 150–400°C temperature range.[20](#) The current research with new thermal fluids intends to increase the operating temperature up to 500°C.[21](#) The concentrated radiation heats the fluid that circulates through the receiver tube, thus transforming the solar radiation into thermal energy in the form of the sensible heat of the fluid. Figure [3](#) shows a typical PTC and its components.



**Figure 3**

[Open in figure viewer](#) | [PowerPoint](#)

Typical parabolic-trough collector.

Collector rotation around its axis requires a drive unit. One drive unit is usually sufficient for several parabolic-trough modules connected in series and driven together as a single collector. Drive units composed of an electric motor and a gearbox combination are used for small collectors (aperture area  $<100 \text{ m}^2$ ), whereas powerful hydraulic drive units are required to rotate large collectors. A drive unit placed on the central pylon is commanded by a local control unit to track the sun. At present, all commercial PTC designs use a single-axis sun-tracking system.<sup>22</sup>

Thermal oils are commonly used as the working fluid in these collectors for temperatures above  $200^\circ\text{C}$  because at these operating temperatures, normal water would produce high pressures inside the receiver tubes and piping. This high pressure would require stronger joints and piping, and thus raise the price of the collectors and the entire solar field. However, the use of demineralized water for high temperatures/pressures is currently under investigation and the feasibility of direct steam generation at 100 bar/ $400^\circ\text{C}$  in the receiver tubes of PTCs has already been proven in an experimental stage.<sup>23</sup> For temperatures below  $200^\circ\text{C}$ , either a mixture of water/ethylene glycol or pressurized liquid water can be used as the working fluids because the pressure required in the liquid phase is moderate.

The oil most widely used in PTCs for temperatures up to  $395^\circ\text{C}$  is VP-1, which is a eutectic mixture of 73.5% diphenyl oxide/26.5% biphenyl. The main problem with this oil is its high solidification temperature ( $12^\circ\text{C}$ ), which requires an auxiliary heating system when oil lines run

the risk of cooling below this temperature. Because the boiling temperature at 1013 mbar is 257°C, the oil circuit must be pressurized with nitrogen, argon, or some other inert gas when oil is heated above this temperature. Although there are other suitable thermal oils for slightly higher working temperatures with lower solidification temperatures, they are too expensive for large solar plants.

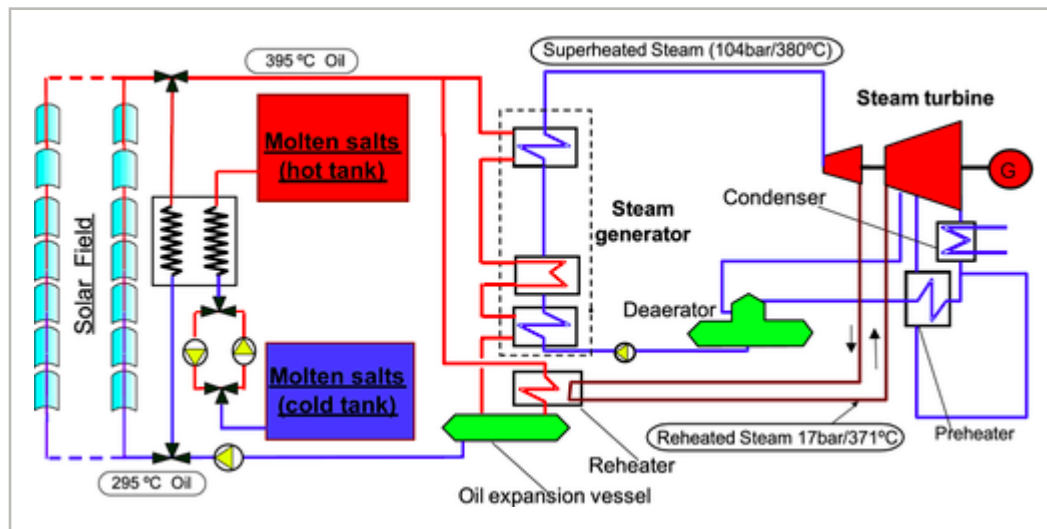
The typical PTC receiver tube is composed of an inner steel pipe surrounded by a glass tube to reduce convective heat losses from the hot steel pipe.<sup>9</sup> The steel pipe has a selective high-absorption (>90%), low-emission (<30% in the infrared) coating that reduces radiation thermal losses. Receiver tubes with glass vacuum tubes and glass pipes with an antireflective coating achieve higher PTC thermal efficiency and better annual performance, especially at higher operating temperatures. Receiver tubes with no vacuum are usually used for working temperatures below 250°C because thermal losses are not so critical at these temperatures. Because of the manufacturing constraints, the maximum length of a single receiver pipe is less than 6 m, so that the complete receiver tube of a PTC is composed of a number of single receiver pipes welded in series up to the total length of the PTC. The total length of a PTC is usually within 100–150 m.

Two PTC designs specially conceived for large solar thermal power plants are the LS-3 (owned by the Israeli company SOLEL Solar Systems) and EuroTrough (owned by the EuroTrough Consortium), both of which have a total length of 100 m and a width of 5.76 m, with back-silvered thick-glass mirrors and vacuum absorber pipes. American Solargenix design has an aluminum structure. However, other collector designs are recently becoming commercially available in the short-to-medium term like the ones developed by the companies Solargenix, Albiasa, or Sener.<sup>9, 21</sup> The main constraint when developing the mechanical design of a PTC is the maximum torsion at the collector ends because high torsion would lead to a smaller intercept factor and lower optical efficiency.

## Electricity Generation with PTCs

The suitable PTC temperature range and their good solar-to-thermal efficiency up to 400°C make it possible to integrate a parabolic-trough solar field in a Rankine water/steam power cycle to produce electricity. The simplified scheme of a typical solar thermal power plant using parabolic troughs integrated in a Rankine cycle is shown in Figure 4. The technology commercially available at present for parabolic-trough power plants is the heat transfer fluid (HTF) technology, which uses oil as the heat carrier between the solar field and the power block.





**Figure 4**

[Open in figure viewer](#) | [PowerPoint](#)

Parabolic-trough plant introducing a molten-salt circuit with two storage tanks to increment capacity factor.

Although parabolic-trough power plants usually have an auxiliary gas-fired heater to produce electricity when direct solar radiation is not available, the amount of electricity produced with natural gas is always limited to a reasonable level. This limit changes from one country to another: 25% in California (USA), 15% in Spain, and no limit in Algeria. Typical solar-to-electric efficiencies of a large solar thermal power plant (>30 MW<sub>e</sub>) with PTCs are between 15% and 22%, with an average value of about 17%. The yearly average efficiency of the solar field is about 50%.

The maturity of PTC systems is confirmed by the solar electricity generating systems (SEGS) plants. The plants SEGS II–IX, which use thermal oil as the working fluid (HTF technology), were designed and implemented by the LUZ International Limited company from 1985 to 1990. All the SEGS plants are located in the Mojave Desert, Northwest of Los Angeles (California). With their daily operation and over 2.2 million square meters of PTCs, SEGS plants are this technology's best example of commercial maturity and reliability. Their plant availability is over 98% and their solar-to-electric annual efficiency is in the range of 14–18%, with a peak efficiency of 22%.<sup>20</sup> Thanks to the continuous improvements in the SEGS plants, the total SEGS I cost of \$0.22/kWh<sub>e</sub> for electricity produced was reduced to \$0.16/kWh<sub>e</sub> in the SEGS II and down to \$0.09/kWh<sub>e</sub> in SEGS IX<sup>24</sup> by the year 1996.

With the revival of commercial STE projects since 2006 in US and Spain, a new generation of SEGS-type plants has come to the arena. This is the case of the Nevada Solar One (NSO) project of 75 MW<sub>e</sub> in the US, the Ibersol project in Puertollano, Spain, or the Shams One 100 MW<sub>e</sub> plant

in Abu Dhabi.<sup>25</sup> NSO started grid-connected operation in June 2007 and it is considered a milestone in the opening of the second market deployment of PTC technology in the world after SEGS experience. Since then, more than 40 PTC plants (about 50 MW<sub>e</sub> each) are being constructed and starting operation in Spain between the period 2007–2013 and more than 2 GW on track in the US.<sup>2</sup> Main characteristics of NSO plant are shown in Table 1.

**Table 1.** Main Characteristics of Nevada Solar One Plant

Solar Field		Power Block	
Solar collector assemblies	760	Turbine generator gross output	75 MW <sub>e</sub>
Aperture area (m)	5	Net output to utility	72 MW <sub>e</sub>
Aperture area (m <sup>2</sup> )	470	Solar steam inlet pressure	86.1 bar
Length (m)	100	Solar steam reheat pressure	19.5 bar
Concentration ratio	71	Solar steam inlet temperature	371°C
Optical efficiency	0.77		
Number of mirror segments	182,400		
Number of receiver tubes	18,240		
Field aperture (m <sup>2</sup> )	357,200		
Site area (km <sup>2</sup> )	1.62		
Field inlet temperature (°C)	300		
Field outlet temperature (°C)	390		

In spite of their environmental benefits, there are still some obstacles to the commercial use of this technology. The main barriers at present are the high investment cost (2500–5000 \$/kW, depending on plant size and thermal storage capacity) and the minimum size of the power block required for high thermodynamic efficiency. However, these barriers are shared by all the solar thermal power technologies currently available.<sup>26</sup>

One of the strategies to mitigate risk perception and increment the capacity factor of the power block is to integrate a parabolic-trough solar field in the bottoming cycle of a combined-cycle gas-fired power plant. This configuration is called the integrated solar combined cycle system

(ISCCS). Although the contribution of the solar system to the overall plant power output is small (approximately 10–15%) in the ISCCS configuration, it seems to be a good approach to market penetration in some developing countries, which is why the government of Algeria has promoted an ISCCS plant and the World Bank, through its Global Environment Facility (GEF), funded ISCCS plants in Morocco and Egypt.[27](#)

## Thermal Energy Storage and New Thermal Fluids

In many countries, the market penetration of STE systems is based on feed-in-tariffs or green certificates linked to significant restrictions or regulations regarding the use of hybrid concepts like ISCCS schemes. Because of that, the use of thermal energy storage systems with an oversized solar field is pursued to optimize economics and dispatchability of PTC plants.

For temperatures of up to 300°C, thermal mineral oil can be stored at ambient pressure, and is the most economical and practical solution. Synthetic and silicone oils, available for up to 410°C, have to be pressurized and are expensive. Then, molten salts can be used between 220 and 560°C at ambient pressure, but require parasitic energy to keep them liquid.

Two pioneer projects introducing thermal storage are the plants Andasol-I and Andasol-II.[28](#) This PTC plants installed in Guadix, Spain have a nominal power of 50 MW<sub>e</sub> each and an oversized solar field (510,120 m<sup>2</sup> mirrors surface area) with an integrated 1010 MW<sub>th</sub> molten-salt thermal storage system to extend the plant's full-load operation 7.5 h beyond daylight hours leading to a capacity factor of 41%. Figure [4](#) shows Andasol plant flow diagram and Figure [5](#) shows an aerial view of the tanks. As it can be observed, the introduction of a third circuit with molten salts adds more complexity with a number of new heat exchangers and heat tracing to avoid the salts thawing. It is still early to know the final result in terms of energy management and operational robustness. Early operational data demonstrate the capacity of the plant to supply electricity several hours after sunset. Other countries such as Italy are planning further steps with the use of molten salts both for thermal storage and solar field, like the 5-MW demonstration project Archimede.[29](#)



**Figure 5**

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Aerial view of power island and detail of molten-salt storage tanks and heat exchangers of Andasol plant in Guadix, Spain. This 50 MW plant stores thermal energy excess in 28,500 tons of nitrate molten salts able to provide up to 7.5 equivalent hours of operation at nominal capacity. Reproduced by permission of ACS/Cobra Energía (Spain).

Even though molten salts are nowadays the preferred option for demonstration and first commercial projects with storage in the US and Spain, there are other options under development and assessment like the use of concrete or other solid bed materials,<sup>30</sup> and the use of phase change media (PCM).<sup>31</sup> PCM provide a number of desirable features, for example, high volumetric storage capacities and heat availability at constant temperatures. Energy storage systems using the latent heat released on melting eutectic salts or metals have often been proposed, but never carried out on a large scale due to difficult and expensive internal heat exchange and cycling problems. Heat exchange between the HTF and the storage medium is seriously affected when the storage medium solidifies. Encapsulation of PCMs has been proposed to improve this. Combining the advantages of direct-contact heat exchange and latent heat, hybrid salt-ceramic phase change storage media have recently been proposed. The salt is retained within the submicron pores of a solid ceramic matrix such as magnesium oxide by surface tension and capillary force. Heat storage is then accomplished in two modes: by the latent heat of the salt and also the sensible heat of the salt and the ceramic matrix.<sup>32</sup>

PCM are extremely suitable for direct steam generation PTC plants. If the superheated steam required to feed the steam turbine in the power block were produced directly in the receiver tubes of the PTCs, the oil would be no longer necessary, and temperature limitation and environmental risks associated with the oil would be avoided. Simplification and cost reduction of overall plant configuration is then evident as only one fluid is used. This effect combined with the increment of efficiency after removing intermediate heat exchanger might lead to a reduction of 15% of the cost of the electricity produced. The disadvantages of this concept originate from the thermo-hydraulic problems associated with the two-phase flow existing in the evaporating section of the solar field. An additional disadvantage is the use of much heavier absorber tubes and interconnecting lines required for the high pressure steam. Nevertheless, experiments performed at in a 2-MW<sub>th</sub> loop at the Plataforma Solar de Almería (PSA) in Spain have proven the technical feasibility of direct steam generation with horizontal PTCs at 100 bar/400°C.<sup>33</sup> Two precommercial projects are under development in Spain to demonstrate the technical feasibility of direct steam generation combined with a power block.<sup>21</sup>

## LINEAR FRESNEL REFLECTORS

LFRs are composed by an array of linear (or slightly bent) mirror strips that independently move and collectively focus on absorber lines suspended from elevated towers. Reflective segments are close to the ground and can be assembled in a compact way up to 1 ha/MW. This technology aims at achieving the performance of parabolic troughs with lower costs. They are characterized by having a fix linear focus where the absorber is static.<sup>14</sup> However, optical efficiency is lower than that of parabolic troughs due to a higher impact of the incidence angle and the cosine factor. Consequently, operating temperature at the working fluid is usually lower, typically between 150 and 350°C. By this reason, linear Fresnel technology has been historically applied to generate saturated steam via direct in-tube steam generation, and use into ISCCS or in regenerative Rankine cycles, though current R&D is aiming at higher temperatures above 400°C.<sup>34</sup>

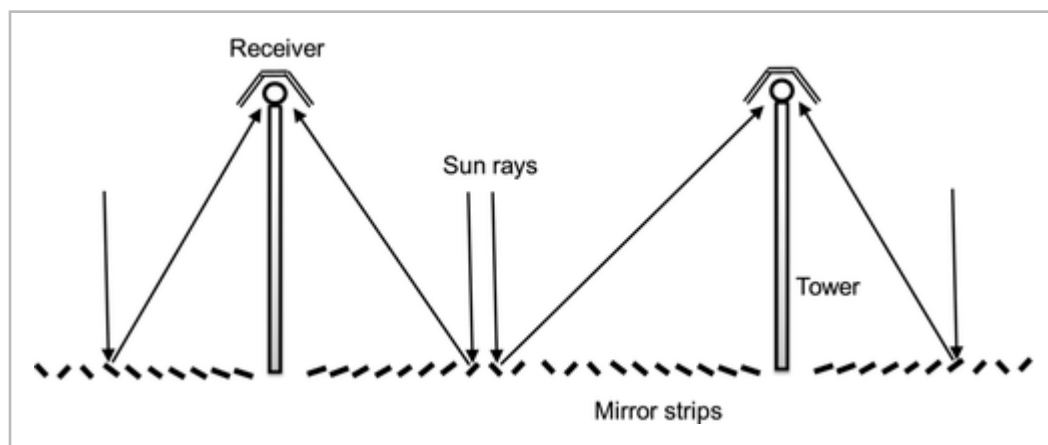
LFRs typically make use of lower cost nonvacuum thermal absorbers where the stagnant air cavity provides significant thermal insulation, light reflector support structures close to the ground, low cost flat float glass reflector, and low cost manual cleaning because the reflectors are at human height.<sup>35</sup> The LFRs also have much better ground utilization, typically using 60–70% of the ground area compared with about 33% for a trough system, and lower O&M costs because of more accessible reflectors.

### Historical evolution of LFR systems

After some pioneering experiences by Francia<sup>36</sup> and Di Canio et al.,<sup>37</sup> the first serious



development undertaken on the compact LFR system was proposed at the University of Sydney in 1993. The concept is composed by a single field of reflectors together with multiple linear receivers (see Figure 6). Each reflector is able to change their focal point from one receiver to another during the day to minimize shading and shadow losses in the dense reflector field. This system covers about 71% of the ground compared with 33% for parabolic-trough systems.<sup>38</sup> In 2000, the company Solarmundo built a 2400 m<sup>2</sup> LFR prototype collector field with such a technology at Liege, Belgium, but test results were not reported. Later the company moved to Germany and was renamed Solar Power Group (SPG). SPG signed an exclusivity cooperation agreement with DSD Industrieanlagen GmbH (renamed to MAN Ferrostaal Power Industry in 2005). A 800 kW linear Fresnel pilot operating at 450°C has already been tested in PSA, Spain.<sup>39, 40</sup>



**Figure 6**

[Open in figure viewer](#) | [PowerPoint](#)

Scheme of compact LFR system with a multitower array and dynamic aiming strategy of mirror strips.

Back in Australia, in early 2002, a new company, Solar Heat and Power Pty Ltd. (SHP), made extensive changes to the engineering design of the reflectors to lower cost and has become the first to commercialize LFR technology. SHP initiated in 2003 for Macquarie Generation, Australia's largest electricity generator, a demonstration project of 103 MW<sub>th</sub> (approximately 39 MW<sub>e</sub>) plant with the aim of supplying preheat to the coal fired Liddell power station. Phase 1 of the project, completed in 2004, resulted in a 1350 m<sup>2</sup> segment not connected to the coal fired plant, and was used to trial initial performance, and it first produced steam at 290°C in July 2004. The expansion to 9 MW<sub>th</sub> was completed by 2008. Activities of the company moved to the US and were continued by Ausra, Palo Alto. Ausra established a factory of components, tubular absorbers and mirrors in Las Vegas and built the Kimberlina 5-MW demonstration plant in Bakersfield at the end of 2008. In 2010, Ausra was purchased by AREVA that is

presently committed to the commercial deployment of this technology.

The third technology player after SPG/MAN and AREVA is the German company NOVATEC Solar, formerly NOVATEC Biosol. The technology of NOVATEC is based on its collector Nova-1 aimed to produce saturated steam at 270°C. They have developed a serial production factory for prefabricated components, a 1.4 MW small commercial plant, PE-1, in Puerto Errado, Murcia, Spain, which has been grid connected since March 2009, and a second 30 MW commercial plant, PE-2, (with a mirror surface of 302,000 m<sup>2</sup>) has been completed and is in operation since August 2012. NOVATEC is promoting 50 MW plants mixing PTC and LFR fields, where LFR provides preheating and evaporation and PTC field takes over superheating. The company claims that this hybridization results in 22% less land use and higher profitability. In March 2011, ABB acquired a 35% shareholding in Novatec Solar. In September 2011, Novatec Solar claimed that its technology has successfully generated superheated steam at temperatures above 500°C at its 1.4 MW demonstration plant in Murcia, Spain, by implementing a receiver containing vacuum absorber.[41](#)

In last few years, new companies have explored the application of Fresnel technologies for electricity generation. SkyFuel Inc., Albuquerque, New Mexico is developing the Linear Power Tower™, a Fresnel based-on concept designed to use a high-temperature molten-salt HTF and it incorporates thermal energy storage. In Europe, the French company CNIM is developing its own technology for the boiler part of the plant focusing on direct superheated steam generation and linear Fresnel principle. A first prototype (800 m<sup>2</sup>) has been built, commissioned, and pretested in 2010.[42](#)

## Future Technology Development and Performance Trends

Even though some solid commercial programmes are underway on LFR, still it is early to have consolidated performance data with respect to electricity production. The final optimization would integrate components development to increment temperature of operation and possible hybridization with other STE systems like parabolic troughs.

There are many possible types of receiver, including evacuated tube and PV modules, but the most cost-effective system seems to be an inverted cavity receiver. In the case of SHP technology, the absorber is a simple parallel array of steam pipes at the top of a linear cavity, with no additional redirection of the incoming light from the heliostats to minimize optical losses and the use of hot reflectors. In the case of SPG technology, the absorber is a single tube surmounted by a hot nonimaging reflector made of glass, which must be carefully manufactured to avoid thermal stress under heating, and exhibit some optical loss. Both systems can produce saturated steam or pressurized water. At present AREVA and NOVATEC

are looking for new absorbers able to work at temperatures above 450°C. By 2015, according to developers, linear Fresnel can be expected to be operating with superheated steam at 500°C yielding an efficiency improvement of up to 18.1% relative to current saturated steam operation at 270°C.[10](#)

For reflectors, automation is a key issue that has been demonstrated by NOVATEC. Additional effort should be given to the optimized demonstration of multitower arrays to maximize ground coverage ratios. However, it is the lack of reliable information regarding annual performance and daily evolution of steam production that should be targeted as a first priority. Still some concerns remain regarding the ability to control steam production because of the pronounced effect of cosine factor in this kind of plants. This dynamic performance would also affect the potential integration with other STE systems such as PTC or CRS. Until now, most comparative assessments vis-à-vis parabolic troughs are not economically conclusive, revealing the need to use much larger fields to compensate lower efficiencies. To achieve break even costs for electricity with current LFR technology, the cost target for the Fresnel solar power plants needs to be about 55% of the specific costs of parabolic-trough systems.[43](#)

## CENTRAL RECEIVER SYSTEMS

In power towers or CRSs, incident sunrays are tracked by large mirrored collectors (heliostats), which concentrate the energy flux onto radiative/convective heat exchangers called solar receivers, where energy is transferred to a thermal fluid, mounted on top of a tower (Figure [2](#)). Plant sizes of 10–200 MW are chosen because of economy of scale, even though advanced integration schemes are claiming the economics of smaller units as well.[44](#) The high solar flux incident on the receiver (averaging between 300 and 1000 kW/m<sup>2</sup>) enables operation at relatively high temperatures of up to 1000°C and integration of thermal energy into more efficient cycles in a step-by-step approach. CRS can be easily integrated in fossil plants for hybrid operation in a wide variety of options and has the potential for generating electricity with high annual capacity factors through the use of thermal storage. With storage, CRS plants are able to operate over 4500 h/year at nominal power.[45](#)

### Technology of Heliostats and Solar Receivers

The collector field consists of a large number of mirrors, called heliostats, with two-axis tracking and a local control system to continuously focus direct solar radiation onto the receiver aperture area. Heliostats fields are characterized by their off-axis optics. Because the solar receiver is located in a fixed position, the entire collector field must track the sun in such a way that each and every heliostat individually places its surface normal to the bisection of the angle subtended by sun and the solar receiver.

Heliostat field optical efficiency includes the cosine effect, shadowing, blocking, mirror

reflectivity, atmospheric attenuation, and receiver spillage.<sup>46</sup> Because of the large area of land required, complex optimization algorithms are used to optimize the annual energy produced by unit of land, and heliostats must be packed as close as possible so the receiver can be small and concentration high. Because the reflective surface of the heliostat is not normal to the incident rays, its effective area is reduced by the cosine of the angle of incidence; the annual average cosine varies from about 0.9 at two tower heights distance north of the tower to about 0.7 at two tower heights south of the tower. Of course, annual average cosine is highly dependent on site latitude. Consequently, in sites close to the Equator a surround field would be the best option to make best use of the land and reduce the tower height. North fields improve performance as latitude increases (South fields in the Southern hemisphere), in which case, all the heliostats are arranged on the North side of the tower.

The combination of all the above-mentioned factors influencing the performance of the heliostat field should be optimized to determine an efficient layout. There are many optimization approaches to establish the radial and azimuthal spacing of heliostats and rows.<sup>47</sup> One of the most classic, effective, and widespread procedures is the 'radial staggered' pattern, originally proposed by the University of Houston in the seventies.<sup>48</sup> Integral optimization of the heliostat field is decided by a tradeoff between cost and performance parameters. Heliostats, land and cabling network must be correlated with costs. Cost and performance also often have reverse trends, so that when heliostats are packed closer together, blocking and shadowing penalties increase, but related costs for land and wiring decrease. A classical code in use since the eighties for optimization of central receiver subsystems is DELSOL3.<sup>49</sup>

Mature low-cost heliostats consist of a reflecting surface, a support structure, a two-axis tracking mechanism, pedestal, foundation, and control system. The development of heliostats shows a clear trend from the early first generation prototypes, with a heavy, rigid structure, second-surface mirrors, and reflecting surfaces of around 40 m<sup>2</sup>,<sup>50</sup> to designs with large 100–120 m<sup>2</sup> reflecting surfaces, lighter structures, and lower-cost materials.<sup>51, 52</sup> Heliostats of 120 m<sup>2</sup> were finally adopted for the first commercial tower power plants PS10 and PS20 promoted by the company Abengoa Solar.<sup>53</sup> Since the first-generation units, heliostats have demonstrated beam qualities below 2.5 mrad (standard deviation of reflected rays including all heliostat errors but not including intrinsic errors due to the solar disk) that are good enough for practical applications in solar towers, so the main focus of development is directed at cost reduction. Estimated production costs of large area glass/metal heliostats for sustainable market scenarios are around \$130–200/m<sup>2</sup>. Large area glass/metal units make use of glass mirrors supported by metallic frame facets.

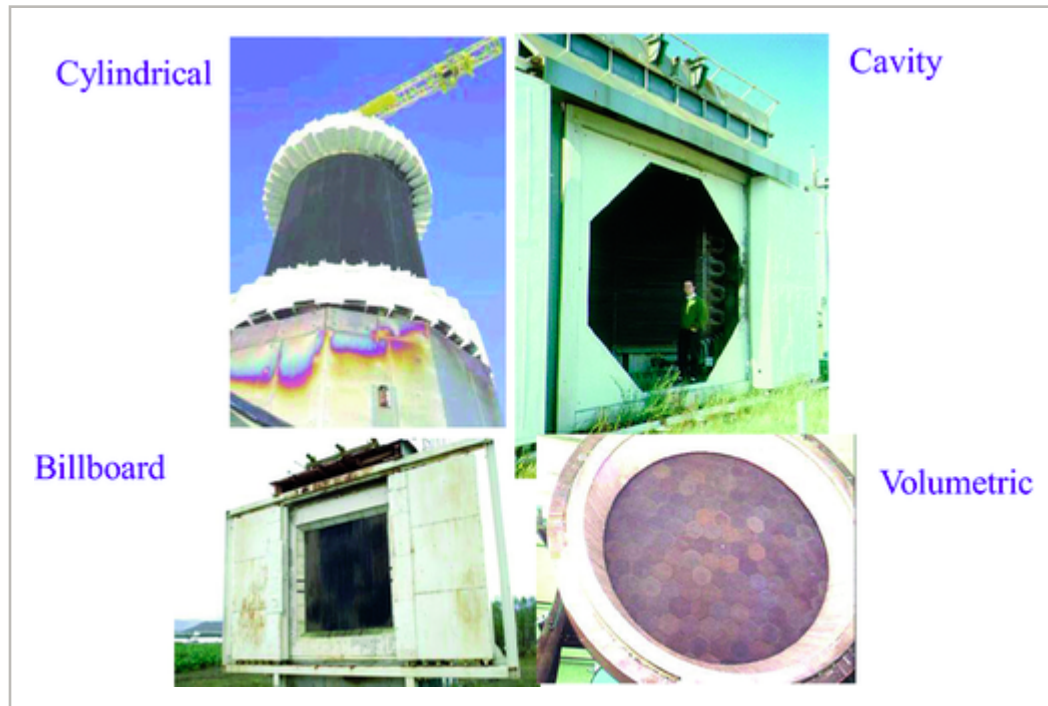
Recently, some developers are introducing substantial changes in the conception of heliostat design. A number of projects based on the paradigm of maximum modularity and mass

production of components are claiming small-size heliostats as a competitive low-cost option. Companies like Brightsource, eSolar, Aora, or Cloncurry are introducing heliostat units of only a few  $\text{m}^2$ . The small heliostats have better optical efficiency and the ones by eSolar can be flat mirrors compared with curved and canted facets in the large heliostats. This advantage and the easier transportation to the site with minimal installation works can lead to a further decrease in the heliostats costs. Brightsource with an ambitious program of large projects is making use of single-facet  $7.3\text{-m}^2$  heliostats<sup>54</sup> and the company eSolar with a multitower plant configuration presents a highly innovative field with ganged heliostats of extremely small size ( $1.14\text{ m}^2$  each) that implies the large number of 12,180 units for a single 2.5 MW tower.<sup>55</sup> If such small heliostats may reach installed costs below  $200\text{ \$/m}^2$ , it can only be understood under aggressive mass production plans and preassembly during manufacturing process by reducing on-site mounting works. Annual performance and availability of those highly populated fields are still under testing.

In a solar power tower plant, the receiver is the heat exchanger where the concentrated sunlight is intercepted and transformed into thermal energy useful in thermodynamic cycles. Radiant flux and temperature are substantially higher than in parabolic troughs, and therefore, high technology is involved in the design, and high-performance materials should be chosen. The solar receiver should mimic a black body by minimizing radiation losses. To do so cavities, black-painted tube panels or porous absorbers able to trap incident photons are used. In most designs, the solar receiver is a single unit that centralizes all the energy collected by the large mirror field, and therefore high availabilities and durability are a must. Just as cost reduction is the priority for further development in the collector field, in solar receivers, the priorities are thermal efficiency and durability. Typical receiver absorber operating temperatures are between  $500$  and  $1200^\circ\text{C}$  and incident flux covers a wide range between  $300$  and over  $1000\text{ kW/m}^2$ .<sup>9, 56</sup>

There are different solar receiver classifications criteria depending on the construction solution, the use of intermediate absorber materials, the kind of thermal fluid used or heat transfer mechanisms. According to the geometrical configuration, there are basically two design options, external and cavity-type receivers. In a cavity receiver, the radiation reflected from the heliostats passes through an aperture into a box-like structure before impinging on the heat transfer surface. Cavities are constrained angularly and subsequently used in North-field (or South-field) layouts. External receivers can be designed with a flat plate tubular panel or are cylindrically shaped. Cylindrical external receivers are the typical solution adopted for surround heliostat fields. Figure 7 shows examples of cylindrical external, billboard external and cavity receivers.





**Figure 7**

[Open in figure viewer](#) | [PowerPoint](#)

Different configurations of solar receivers. From left to right and top to bottom: (a) external tubular cylindrical, (b) cavity tubular, (c) billboard tubular, and (d) volumetric.

Receivers can be directly or indirectly irradiated depending on the absorber materials used to transfer the energy to the working fluid.<sup>57</sup> Directly irradiated receivers make use of fluids or particle streams able to efficiently absorb the concentrated flux. Particle receiver designs make use of falling curtains or fluidized beds. In many applications, and to avoid leaks to the atmosphere, direct receivers should have a transparent window. Windowed receivers are excellent solutions for chemical applications as well, but they are strongly limited by the size of a single window, and therefore clusters of receivers are necessary.

The key design element of indirectly heated receivers is the radiative/convective heat exchange surface or mechanism. Basically, two heat transfer options are used, tubular panels and volumetric surfaces. In tubular panels, the cooling thermal fluid flows inside the tube and removes the heat collected by the external black panel surface by convection. It is therefore operating as a recuperative heat exchanger. Depending on the HTF properties and incident solar flux, the tube might undergo thermo-mechanical stress. As heat transfer is through the tube surface, it is difficult to operate at an incident flux above  $600 \text{ kW/m}^2$  (peak). Table 2 shows how only with high thermal conductivity liquids like sodium it is possible to reach operating fluxes above  $1 \text{ MW/m}^2$ . Air-cooled receivers have difficulties working with tubular receivers because of the lower heat transfer coefficients. To improve the contact surface, a different

approach based on wire, foam or appropriately shaped materials within a volume are used. In volumetric receivers, highly porous structures operating as convective heat exchangers absorb the concentrated solar radiation.<sup>58</sup> The solar radiation is not absorbed on an outer surface, but inside the structure 'volume'. The heat transfer medium (mostly air) is forced through the porous structure and is heated by convective heat transfer.<sup>59</sup> Volumetric absorbers are usually made of thin heat-resistant wires (in knitted or layered grids) or either metal or ceramic (reticulated foams, etc.) open-cell matrix structures. Good volumetric absorbers are very porous, allowing the radiation to penetrate deeply into the structure. Thin substructures (wires, walls, or struts) ensure good convective heat transfer. A good volumetric absorber produces the so-called 'volumetric effect', which means that the irradiated side of the absorber is at a lower temperature than the medium leaving the absorber. Under specific operating conditions, volumetric absorbers tend to have an unstable mass flow distribution.<sup>60</sup> Receiver arrangements with mass flow adaptation elements (e.g., perforated plates) located behind the absorber can reduce this tendency, as well as appropriate selection of the operating conditions and the absorber material.<sup>61</sup> A number of initiatives have formulated air-cooled volumetric schemes for STE plants, both for atmospheric pressure,<sup>62, 63</sup> and for pressurized systems,<sup>56</sup> though still commercial plants with these technologies are missing. Although air-cooled open volumetric receivers are a promising way of producing superheated steam, the modest thermal efficiency at the receiver (74% nominal and 61.4% annual average) must still be improved.<sup>64</sup> At present, all the benefits from using higher outlet temperatures are sacrificed by radiation losses at the receiver, leading to low annual electricity production, so it is clear that volumetric receiver improvements must reduce losses.

**Table 2.** Operating Temperature and Flux Ranges of Solar Tower Receivers

Fluid	Water/Steam	Liquid Sodium	Molten Salt (nitrates)	Volumetric Air
Flux (MW/m <sup>2</sup> )				
Average	0.1–0.3	0.4–0.5	0.4–0.5	0.5–0.6
Peak	0.4–0.6	1.4–2.5	0.7–0.8	0.8–1.0
Fluid outlet temperature (°C)	490–525	540	540–565	(700–1,000)

Selection of a particular receiver technology is a complex task, as operating temperature, heat storage system, and thermodynamic cycle influence the design. In general, tubular technologies allow either high temperatures (up to 1000°C) or high pressures (up to 120 bar), but not both.<sup>65</sup> Directly irradiated or volumetric receivers allow even higher temperatures but

limit pressures to below 15 bar. In addition, for high solar concentrations and high temperatures, the use of secondary concentrators, that allow reducing thermal losses and improving the flux profile onto the aperture, is necessary in some cases. However, secondary concentrators lead to a limited view cone. This means that of all the possible heliostat positions around the tower, only those within the ellipse, resulting from the section boundary of the view cone with the ground plane, are usable.<sup>66</sup> Consequently, the use of receivers with secondary concentrators on the aperture is impacting on heliostat layout.

## Experience in CRSs

Although there have been a large number of STE tower projects, only a few have culminated in the construction of an entire experimental system.<sup>9, 46, 67</sup> The thermal fluids used in the receiver are saturated or superheated steam, nitrate-based molten salts and air. The most extensive precommercial experience has been collected by several European projects located in Spain at the premises of the PSA<sup>67</sup> and the 10 MW Solar One<sup>68</sup> and Solar Two plants<sup>69</sup> in the US. At present water/steam and molten salts are the HTFs being selected for the first generation of commercial plants.

### Water/Steam Plants: from PS10 and PS20 Projects to Superheated Steam

Production of superheated steam in the solar receiver has been demonstrated in several plants, such as Solar One, Eurelios, and CESA-1, but operating experience showed critical problems related to the control of zones with dissimilar heat transfer coefficients like boilers and superheaters.<sup>67</sup> Better results regarding absorber panel lifetime and controllability have been reported for saturated steam receivers. The good performance of saturated steam receivers was qualified at the 2-MW<sub>th</sub> Weizmann receiver that produced steam at 15 bar for 500 h in 1989.<sup>70</sup> Even though technical risks are reduced by saturated steam receivers, the outlet temperatures are significantly lower than those of superheated steam, making applications where heat storage is replaced by fossil fuel backup necessary.

PS10, the first commercial CRS plant in the world, adopted the conservative scheme of producing saturated steam to limit risk perception and avoid technology uncertainties. The 11 MW plant, located near Seville in South Spain, was designed to achieve an annual electricity production of 23 GWh at an investment cost of less than 3500€/kW. The project made use of available, well-proven technologies like the glass-metal heliostats and the saturated steam cavity receiver to produce steam at 40 bar and 250°C.<sup>53</sup> The plant is a solar-only system with saturated steam heat storage able to supply 50 min of plant operation at 50% load.<sup>9</sup> The system makes use of 624 heliostats of 121 m<sup>2</sup> each, distributed in a North-field configuration, a 100-m high tower, a 15 MWh heat storage system and a cavity receiver with four 4.8 × 12 m tubular panels. Although the system makes use of a saturated steam turbine working at low temperature, the nominal efficiency of the power block (30.7%) is relatively good. This

efficiency is the result of optimized management of waste heat in the thermodynamic cycle. The combination of optical, receiver, and power block efficiencies leads to a total nominal efficiency at design point of 21.7%. Total annual efficiency decreases to 15.4%, including operational losses and outages. PS10 is a milestone in the CRS deployment process, as it is the first solar power tower plant developed for commercial exploitation. Commercial operation started on June 21, 2007. Since then, the plant is performing as designed. The construction of PS20, a 20 MW<sub>e</sub> plant with the same technology as PS10, followed. PS20 started operation in May 2009. With 1255 heliostats (120 m<sup>2</sup> each) spread over 90 ha and with a tower of 165 m high, the plant is designed to produce 48.9 GWh/year.

Saturated steam plants are considered a temporary step to the more efficient superheated steam systems. Considering the problems found in the eighties with superheated steam receivers, the current trend is to develop dual receivers with independent absorbers, one of them for the preheating and evaporation and another one for the superheating step. The experience accumulated with heuristic algorithms in central control systems applied to aiming point strategies at heliostat fields allows achieving a flexible operation with multiaperture receivers. The company Abengoa Solar, developer of PS10 and PS20, is at present designing a superheated steam receiver for a new generation of water/steam plants.<sup>71</sup> But the most advanced strategy is the program announced by the BrightSource Industries (Israel) Ltd. (BSII) that it has already built a demonstration plant of 6 MW<sub>th</sub> located at the Negev desert in June 2008.<sup>54</sup> The final objective of BSII is to promote plants producing superheated steam at 160 bar and temperature of 565°C (named DPT550). With those characteristics, they expect up to 40% conversion efficiency at the power block for unit sizes between 100 and 200 MW. The receiver is cylindrical, dual, and with a drum. The first commercial project under development is Ivanpah Solar in California of 392 MW. The complex is comprised of three separate plants built in phases between 2010 and 2013. Planned conversion efficiency from solar to electricity is 20%.

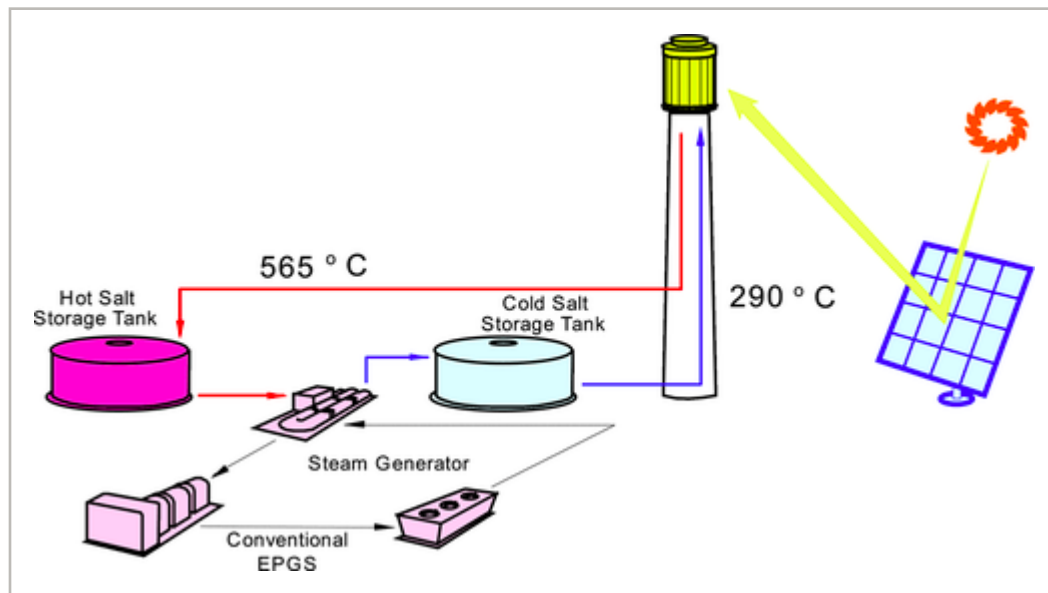
The combination of recent initiatives on small heliostats, compact modular multitower fields, and production of superheated steam may be clearly visualized in the development program of the company eSolar. This company proposes a high degree of modularity with power units of 46 MW covering 64 ha, consisting of 16 towers and their corresponding heliostat fields sharing a single central power block. With replication, modularity sizes up to 500 MW and upward may be obtained.<sup>72</sup> Within the development program of STE in the US, eSolar has four plants totalizing 334 MW.<sup>2</sup> Two modules of 2.5 MW each were installed in 2009 by eSolar in Lancaster, California, and are already in operation. Each receiver has two independent cavities and the heliostat layout consists of identical arrays to maximize replication and modularity. Each tower is associated with 12,180 flat heliostats of 1.14 m<sup>2</sup> each.<sup>55</sup> The receivers are dual-cavity, natural-circulation boilers. Inside the cavity, the feedwater is preheated with economizer

panels before entering the steam drum. A downcomer supplies water to evaporator panels where it is boiled. The saturated water/vapor mixture returns to the drum where the steam is separated, enters superheater panels, and reaches 440°C at 6.0 MPa. Each receiver absorbs a full-load power of 8.8 MW<sub>th</sub>. Overall plant efficiency expected by eSolar would be 23% solar to electricity.[72](#)

## Molten-Salt Systems: Solar Two and Gemasolar

For high annual capacity factors, solar-only power plants must have an integrated cost-effective thermal storage system. One such thermal storage system employs molten nitrate salt as the receiver HTF and thermal storage media. To be usable, the operating range of the molten nitrate salt, a mixture of 60% sodium nitrate and 40% potassium nitrate, must match the operating temperatures of modern Rankine cycle turbines. In a molten-salt power tower plant, cold salt at 290°C is pumped from a tank at ground level to the receiver mounted atop a tower where it is heated by concentrated sunlight to 565°C (Figure [8](#)). The salt flows back to ground level into another tank. To generate electricity, hot salt is pumped from the hot tank through a steam generator to make superheated steam. The superheated steam powers a Rankine-cycle turbine. The collector field can be sized to collect more power than is demanded by the steam generator system, and the excess salt is accumulated in the hot storage tank. With this type of storage system, solar power tower plants can be built with annual capacity factors up to 70%. As molten salt has a high energy storage capacity per volume (up to 500–700 kWh/m<sup>3</sup>), they are excellent candidates for solar thermal power plants with large capacity factors. Even though nitrate salt has a lower specific heat capacity per volume than carbonates, they still store 250 kWh/m<sup>3</sup>. The average heat conductivity of nitrates is 0.52 W/mK and their heat capacity is about 1.6 kJ/kg K. Nitrates are a cheap solution for large storage systems.





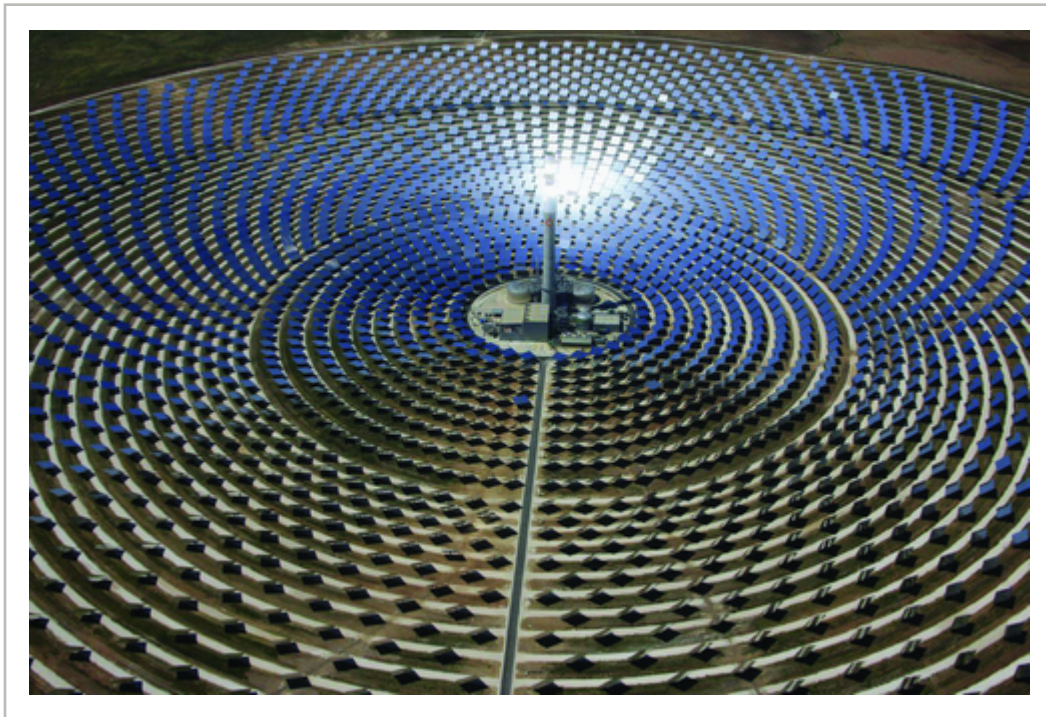
**Figure 8**

[Open in figure viewer](#) | [PowerPoint](#)

Schematic of a molten-salt central receiver system with cylindrical tubular receiver (EPGS: electric power generating system).

The largest demonstration of a molten-salt power tower was the Solar Two project, a 10 MW power tower located near Barstow, California. The purpose of the Solar Two project was to validate the technical characteristics of the molten-salt receiver, thermal storage, and steam generator technologies, improve the accuracy of economic projections for commercial projects by increasing the capital, operating, and maintenance cost database, and distribute information to utilities and the solar industry to foster a wider interest in the first commercial plants. A 110 MWh<sub>t</sub> two-tank molten-salt thermal storage system was installed, a 42 MW<sub>th</sub> receiver, a 35 MW<sub>th</sub> steam generator system (535°C, 100 bar).<sup>73</sup>

The plant began operating in June 1996. The project successfully demonstrated the potential of nitrate-salt technology. Some of the key results were: receiver efficiency was measured at 88%, the thermal storage system had a measured round-trip efficiency of over 97%, and the gross Rankine-turbine cycle efficiency was 34%, all of which matched performance projections. On one occasion, the plant operated around-the-clock for 154 h straight.<sup>74</sup> On April 8, 1999, testing and evaluation of this demonstration project was completed and subsequently was shut down. One attempt to prove scaled-up molten-salt technology is the Gemasolar project being promoted by Torresol Energy, a joint venture between the Spanish SENER and MASDAR initiative from Abu Dhabi.<sup>75</sup> Table 3 summarizes the main technical specifications of Gemasolar project and Figure 9 shows an aerial view of the plant.



**Figure 9**

[Open in figure viewer](#) | [PowerPoint](#)

Aerial view of Gemasolar plant, property of Torresol Energy© Torresol Energy, located in South Spain. At present, it is the largest commercial solar central receiver system with a circular-shape heliostat field.

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**Table 3.** Technical Specifications and Design Performance of the Gemasolar Project

Technical Specifications	
Heliostat field reflectant surface	304,750 m <sup>2</sup>
Number heliostats	2650
Land area of solar field	142 ha
Receiver thermal power	120 MW <sub>th</sub>
Tower height	145 m
Heat storage capacity	15 h

### Technical Specifications

Power at turbine	17 MW <sub>e</sub>
Power NG burner	16 MW <sub>th</sub>

### Operation

Annual electricity production	112 MW <sub>he</sub>
Production from fossil (annual)	15%
Capacity factor	74%

With only 17 MW<sub>e</sub>, the plant that connected to the grid in summer 2011 is designed to produce 112 GWh<sub>e</sub>/year. A large heliostat field of 304,750 m<sup>2</sup> (115 m<sup>2</sup> each heliostat) is oversized to supply 15-h equivalent heat storage capacity. The plant is designed to operate around-the-clock in summertime, leading to an annual capacity factor of 74%. Fossil backup corresponding to 15% of annual production will be added. The levelized energy costs are estimated to be approximately \$0.16/kWh. Gemasolar represents a breakthrough for solar technology in terms of time-dispatch management.[76](#)

## CONCLUSION AND OUTLOOK

From the seventies to the nineties, the development of STE technologies remained restricted to a few countries and only a few, though important, research institutions and industries were involved. The situation has dramatically changed since 2006 with the approval of specific feed-in-tariffs or power purchase agreements in Spain and the US. Both countries with more than 6 GW of projects under development and more than 2 GW in operation at the end of 2012 are undoubtedly leading the commercialization of STE.[77](#) Other countries such as India, China, Australia, and Italy adopted the STE process. Subsequently, a number and variety of engineering and construction companies, consultants, technologists, and developers committed to STE are rapidly growing. A clear indicator of the globalization of STE commercial deployment for the future energy scenario has been elaborated by the IEA. This considers STE to play a significant role among the necessary mix of energy technologies for halving global energy-related CO<sub>2</sub> emissions by 2050.[6](#) This scenario would require capacity addition of about 14 GW/year (55 new solar thermal power plants of 250 MW each). However, this new opportunity is introducing an important stress to the developers of STE. In a period of less than

5 years, in different parts of the world, these developers of STE are forced to move from strategies oriented to early commercialization markets based on special tariffs, to strategies oriented to a massive production of components and the development of large amounts of projects with less profitable tariffs. This situation is speeding up the implementation of second generation technologies, like direct steam generation or molten-salt systems, even though in some cases still some innovations are under assessment in early commercialization plants or demonstration projects.

Parabolic trough is the technology widely used nowadays in commercial projects, though other technologies like linear Fresnel collectors and CRSs are developing the first grid-connected projects and reveal promising impacts on cost reduction.<sup>13</sup> The reduction in electricity production costs should be a consequence, not only of mass production but also of scaling-up and R&D. A technology roadmap promoted by the European Industry Association ESTELA<sup>10</sup> states that by 2015, when most of the improvements currently under development are expected to be implemented in new plants, energy production boosts greater than 10% and cost decreases up to 20% are expected to be achieved. Furthermore, economies of scale resulting from plant size increase will also contribute to reduce plants' CAPEX per MW installed up to 30%. STE deployment in locations with very high solar radiation further contributes to the achievement of cost competitiveness of this technology by reducing costs of electricity up to 25%. All these factors can lead to electricity generation cost savings up to 30% by 2015 and up to 50% by 2025, reaching competitive levels with conventional sources (e.g., coal/gas with stabilized electricity costs <10€/kWh).

## ACKNOWLEDGEMENTS

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