A Global Review of Concentrated Solar Power Storage

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ABSTRACT

Concentrating solar power (CSP) is already providing dispatchable solar power commercially in Spain, through the use of molten salt storage. This paper discusses four 50 MWe parabolic trough plants each with 7.5 hours of molten salt storage already operating in Spain, six in advanced stages of construction, and the 17 MWe Torresol Gemasolar power tower with 15 hours of molten salt storage – also under construction in Spain. This is followed by an overview of future CSP storage technologies such as advances in molten salt technologies, sensible heat storage in solids, phase change salts, and thermochemical storage cycles.

Keywords – Concentrating Solar Power, Energy Storage, Molten Salt.

INTRODUCTION

Concentrating solar power (CSP) can both generate and store renewable energy all in the one plant. Curved mirrors concentrate the sun’s energy to be stored as heat, for example in a mixture of hot molten salt, or in a chemical reaction. When required, this stored energy can be used to produce steam and drive a turbine. In this way, variable renewable energy sources such as wind and photovoltaics can be dispatched to the grid first, and the “back-up” provided by concentrating solar plants with storage.

CURRENT COMMERCIAL STORAGE TECHNOLOGY

Parabolic Trough plants with Molten Salt

Molten salt CSP storage has been commercially proven since the end of 2008, when the 50 MWe Andasol-1 plant began power production with 7.5 hours of molten salt storage, near Guadix in the province of Granada in Spain (Richter et al. 2009). The salt currently used commercially is a 60% to 40% mix of sodium and potassium nitrate. Andasol-1 uses parabolic trough mirrors to heat oil up to 393^{o}C with concentrated solar power, as illustrated in Figures 1, 2 and 3. Some of this oil is fed directly to the oil-to-steam heat exchanger to produce power straight away. The rest of the oil is passed through an oil-to-salt heat exchanger to heat molten salt for storage in an insulated tank at 386^{o}C. Power can then be produced on demand – the molten salt heats the oil, which in turn produces superheated steam to feed the turbine/generator set at 100 bar and 377^{o}C (SolarPACES Task Group I 2006).

Fig. 1: An aerial view of the Andasol-1 and Andasol-2 plants (Photo: Protermosolar). *Left inset:* Parabolic troughs tracking the sun at Andasol-1 (Photo: Author). *Right inset:* The hot and cold salt tanks and power block during construction (Photo: Protermosolar).

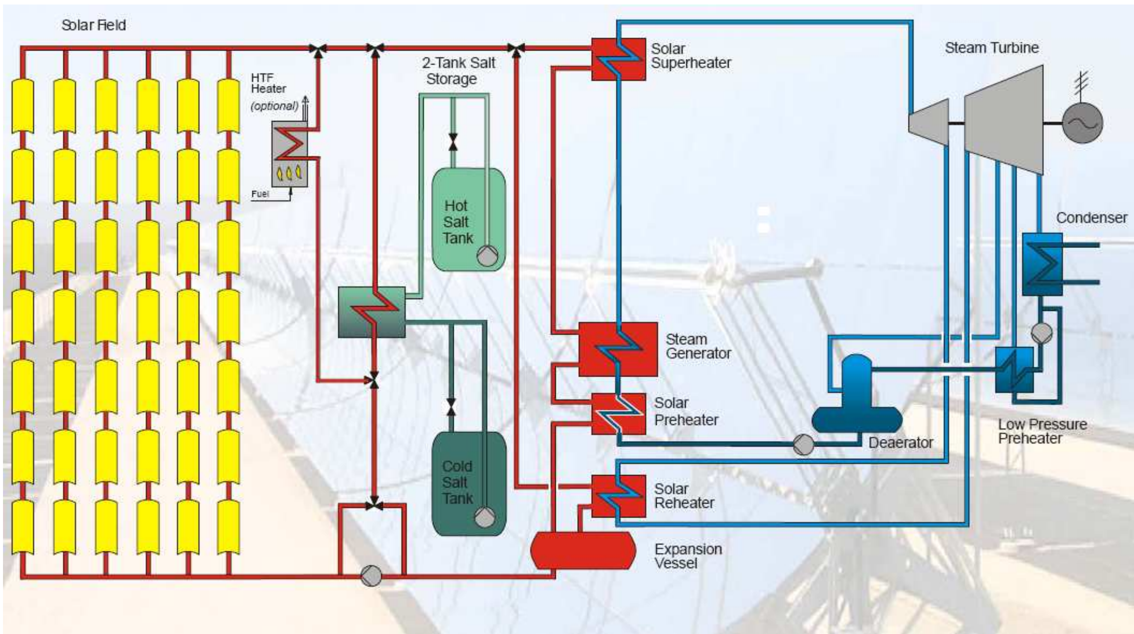

Fig. 2: A plant flow diagram for Andasol-1 and similar plants.

As at October 2010, three similar 50 MWe parabolic trough plants with 7.5 hours of molten salt storage have come online in Spain, bringing the total to four (Protermosolar 2010):

- **Andasol-1**;
- **Andasol-2**, located alongside Andasol-1;
- **Extresol-1** located near the city of Badajoz; and
- **La Florida**, also located near the city of Badajoz.

The engineering design of the molten salt storage systems for all four plants was performed by Spanish engineering firm SENER. The Spanish construction firm Cobra – subsidiary of ACS Cobra – was the major E.P.C. contractor for Andasol-1 (80%), with SENER holding 20% of the E.P.C. contract (NREL 2009). The engineering of the solar field and heat transfer fluid was subcontracted to Flagsol, a joint venture between German firms Solar Millennium and Ferrostaal (International Resource Journal 2010). ACS Cobra owns Andasol-1, Andasol-2 and Extresol-1, and is now constructing very similar plants, with Cobra as the sole E.P.C. contractor, including Manchasol-1 and Extresol-2. A third plant at the Andasol site is being constructed by Solar Millennium, Ferrostaal, Flagsol and the Spanish Duro Felguera (Solar Millennium 2010). Meanwhile the La Florida plant has been developed by Renovables SAMCA with various contractors.

As at October 2010, six parabolic trough plants with 50 MWe capacity and 7.5 hours of molten salt storage are currently in advanced stages of construction in Spain (Protermosolar 2010). These include the afore-mentioned:

- **Manchasol-1**, located near Alcázar de San Juan;
- **Extresol-2**, located alongside Extresol-1; and
- **Andasol-3**, located alongside Andasol-1 and 2.

Also under construction are:

- **La Dehesa,** located near the city of Badajoz;
- **Valle-1,** located near San José de Valle; and
- **Valle-2,** also located near San José de Valle.

Renovables SAMCA is developing the La Dehesa plant, while Valle-1 and Valle-2 are being developed by Torresol Energy. Several parabolic trough plants with molten salt storage have been proposed in the US, including Abengoa's 250 MWe Solana plant in Arizona, and the second phase of the Solar Trust of America's Blythe solar project. However, as at October 2010, no commercial projects with molten salt storage have begun construction in the US.

Molten Salt Power Towers

Power towers are another type of solar concentrator. Figure 3 compares the operating principles of parabolic trough concentrators and power tower, or "central receiver" concentrators. Parabolic troughs have a linear focus and low concentration ratio[1] (less than 100), while power towers have a point focus and high concentration ratio (greater

[1] The concentration ratio is the ratio of the area of the focus to the area of mirror surface.

than 1,000). Power towers can hence achieve higher temperatures more easily, and can thus be used to heat molten salt directly, as illustrated in Figure 4, rather than via heat transfer oil as in parabolic trough plants such as Andasol-1, and the other nine trough plants mentioned in this paper.

Parabolic Troughs   Power Towers

Fig. 3: Operating principles of parabolic troughs and power towers (Images: Siemens).

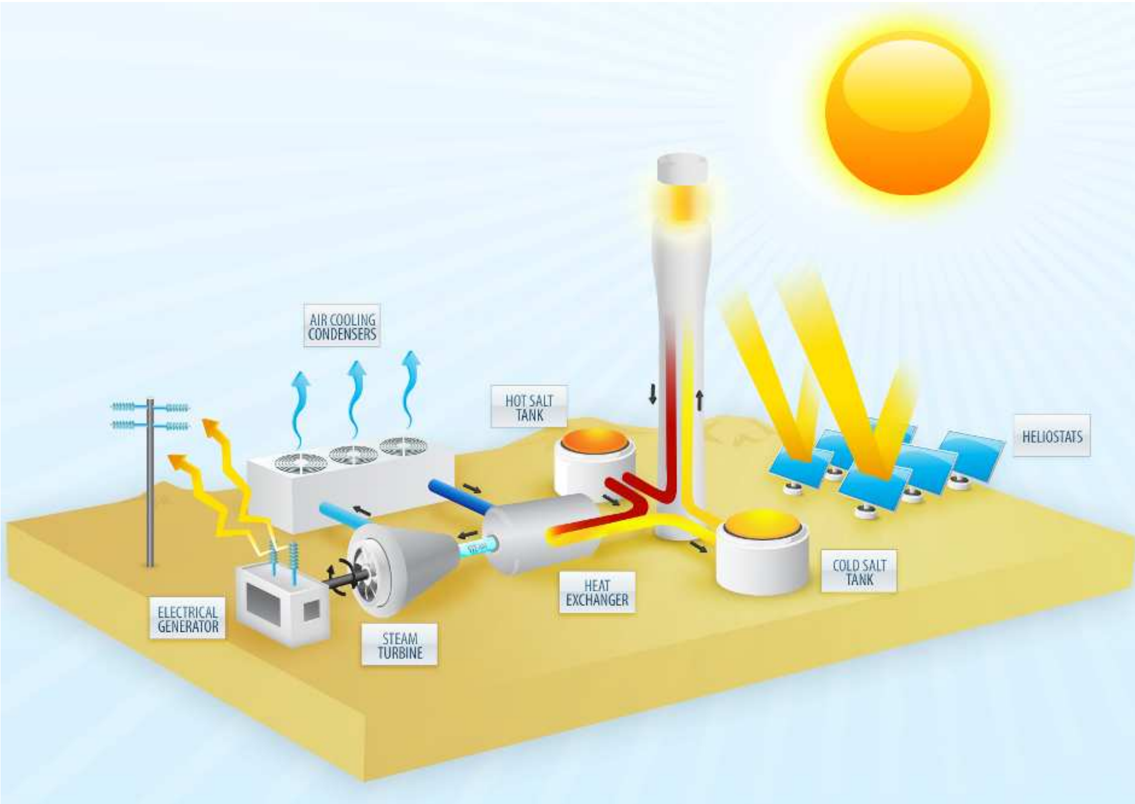

Fig. 4: The operating principle of a molten salt power tower (Image: Sharon Wong).

Figure 4 illustrates the operating principle of a molten salt power tower, which uses molten salt as both the heat transfer fluid and the storage medium:

1. "Cold" molten salt at 292^{o}C is pumped to the receiver at the top of the tower, where it is heated by concentrated solar radiation from the field of heliostat mirrors.
2. Hot salt at 565^{o}C travels back down the tower and is stored in the insulated hot salt tank (NREL 2009; Pacheco et al. 2002).

3. When power is required, hot salt from the storage tank is passed through the heat exchanger to create superheated steam – at 535°C and 100 bar in the case of Solar Two (Pacheco et al. 2002) – to turn the turbine and generate electricity.

Towers can achieve higher temperatures than the current trough technology which uses heat transfer oil. The hot molten salt is stored at 565°C for power towers, as opposed to 386°C for troughs. Hence, as the heat stored is proportional to the difference between hot and cold tank temperatures, a tower plant can store almost three times as much energy in the same amount of salt as a trough plant. The steam (Rankine) cycle efficiency is also related to the maximum steam temperature, so at 100 bar, the 535°C steam from the tower plant is much preferred to the 377°C from the trough plant. In addition, winter performance of power towers remains high, as the heliostat mirrors track the elevation of the sun in the sky, as well as movement from east to west. In contrast, troughs and other linear concentrators can have their energy output reduced to 25% of the summer output.

The first power towers to directly heat molten salt were the 2.5 MWe THEMIS tower in the French Pyrénées, and the 1 MWe Molten-Salt Electric Experiment (MSEE/Cat B) Project in the USA, both of which began operation in 1984. These were followed by the 10 MWe Solar Two power tower in Barstow, California, which featured 3 hours of molten salt storage, and operated from 1996 to 1999 (Reilly & Kolb 2001). The cost of the Solar Two project was shared between the US Department of Energy, and various industry partners, with technical support from Sandia National Laboratories and the National Renewable Energy Laboratory (NREL). A full list of project participants is given by Pacheco et al. (2002). Solar Two demonstrated molten salt power tower technology at a large scale, and resulted in practical recommendations for the commercialisation of the technology.

Molten salt power tower techology is now being commercially developed by Torresol Energy in Spain and SolarReserve in the USA. In March 2011, Torresol Energy will commission their flagship project – the 17 MWe Gemasolar power tower with 15h of molten salt storage, shown in Figures 5 and 6 (Lata et al. 2010). Gemasolar is located near Fuentes de Andalucía in the province of Seville, Spain. Torresol Energy is a joint venture between the Spanish engineering firm SENER (60%) and Abu Dhabi-based Masdar (40%), with plant construction being carried out by Cobra.

Fig. 5: Construction of the Torresol Gemasolar molten salt power tower (Photos: Torresol Energy). February 2010. *Inset:* May 2010.

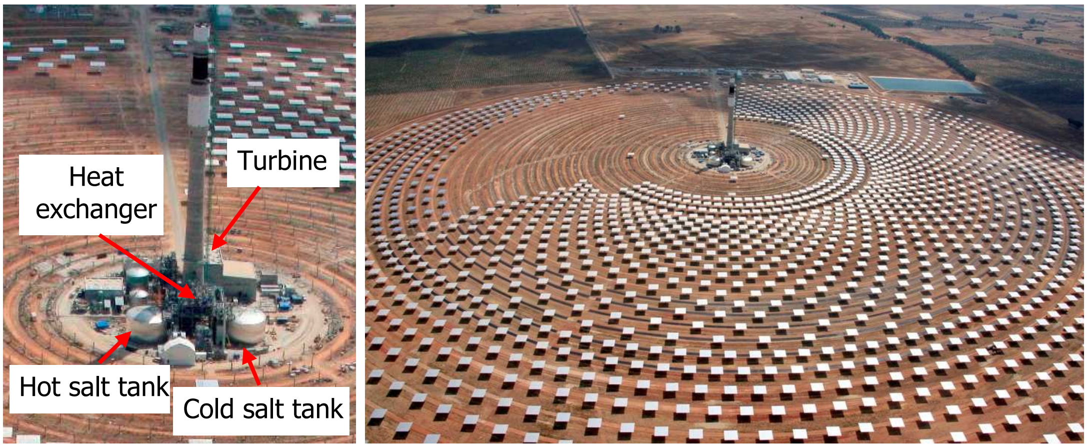

Fig. 6: Construction of the Torresol Gemasolar molten salt power tower (Photos: Torresol Energy). September 2010.

Meanwhile, SolarReserve's first project is set to be their 100 MWe Crescent Dunes Solar Energy Project near Tonopah in Nevada, USA, with 10 hours of molten salt storage. SolarReserve received approval for the project from the Public Utilities Commission of Nevada in July 2010, although as at October 2010, ground has not yet been broken on this project. In the meantime, the US Department of Energy has awarded around US$ 10 million each to Abengoa Solar, eSolar and Pratt & Whitney Rocketdyne to develop tower-based storage systems (Stekli 2010).

ADVANCES IN MOLTEN SALT STORAGE

Archimede Project – Parabolic Troughs with Direct Heating of Molten Salt

As mentioned in the preceding discussion, current commercial parabolic trough technology directly heats synthetic oil with the concentrated solar flux. However, in Priolo Gargallo, Sicily, the 5 MWe Archimede Project is aiming to prove that molten salt can be heated directly by troughs (Falchetta et al. 2010). This will by-pass the temperature limit imposed when using oil as the heat transfer fluid. Oils such as Dowtherm which are currently used in trough plants cannot be heated above around 393^{o}C (Relloso & Delgado 2009), as they are not thermally stable above this temperature. In contrast, by directly heating the molten salt, temperatures of up to 550^{o}C will be attained. This is due in part to the use of a new spectrally selective coating on the heat collector tubes (Falchetta et al. 2010). As at October 2010, the Archimede plant is in the final stages of commissioning. The plant was developed by Italian utility ENEL, with cooperation from the Italian Agency for Energy, Environment and New Technologies (ENEA), and is integrated with the steam cycle of an existing combined cycle power plant. Following commissioning, the plant will be run in two-year experimental phase, before handing over full management to the ENEL power station personnel.

Wizard Power – Indirect Molten Salt Storage with 500 m^2 Dishes

While molten salt storage has been integrated into trough and tower plants, it has not yet been used in conjunction with dish concentrators. This is the aim of Wizard Power's four-dish Whyalla Project in South Australia – to demonstrate an integrated dish and molten salt storage system (Coventry et al. 2010). Four 500 m^2 dish concentrators, originally developed at the Australian National University, will be used to produce superheated steam at 120 bar and 630^{o}C. This will heat 106 tonnes of salt to 565^{o}C which, in the second stage of the plant construction, will provide 4 hours of dispatchable power for a 560 kWe Siemens SST-060 turbine/generator set.

Advanced Salt Mixtures

As mentioned above, the salt currently used in molten salt plants is a 60% to 40% mix of sodium and potassium nitrate. However, to avoid the crystallisation point of this salt mix, the molten salt is operated between 292^{o}C and 630^{o}C (or 565^{o}C due to material limitations). Various research groups are investigating ternary and quaternary salt mixtures – which incorporate 3 or 4 different types of metal salts – with extended working temperature ranges. As the energy stored in a salt is proportional to the temperature difference, an extended temperature range means that more energy can be stored in the same amount of salt. For example, Bradshaw and Siegel (2009) investigated salt mixtures including salts of calcium and lithium to increase the liquid temperature range of the salts to 100^{o}C – 500^{o}C.

A different approach is being adopted by Glatzmaier et al. (2010). They are attempting to add small amounts of metallic nanoparticles to molten salt to increase the heat capacity of the salt. The energy stored in a salt is also proportional to the heat capacity, so if you double the heat capacity, twice the heat energy can be stored in the same amount of fluid with the same temperature limits.

Thermocline Salt Tanks

Current molten salt storage systems such as those used at Andasol-1, the other trough plants mentioned above, and the Gemasolar tower plant all use a two-tank system, as illustrated in Figures 2, 4 and 6. Cold salt at 292^{o}C is stored in one tank, and once heated by the solar field, hot salt is stored in a separate tank at 386^{o}C (trough plant) or 565^{o}C (tower plant). These salt storage tanks can be quite sizeable, especially at parabolic trough plants. For example, for 7.5 hours of storage at the 50 MWe Andasol-1 plant, both the hot tank and cold tank are sized to accommodate the total inventory of 28,500 tonnes of molten salt – leading to a tank diameter of 38.5 m and height of 14 m (Relloso & Delgado 2009). Therefore, one can imagine that building a single tank that contained both the cold salt and the hot salt at once – a thermocline tank – could produce substantial cost savings. This is not only because just one tank would need to be constructed, but also due to cost savings in the auxiliary piping and equipment. SENER in Spain, and Sandia National Laboratories in the US are both investigating such tanks (Lata & Blanco 2010; Kolb 2010). SENER is proposing a single tank with a floating barrier to separate the hot and cold salt, while Sandia Laboratories has investigated a system in which gravel filler is used to replace a certain volume of molten salt, and also prevent convection currents between hot and cold sections of the tank.

OTHER HEAT STORAGE METHODS

Sensible Heat Storage in Solids – Solid Particle Receiver

At Sandia National Laboratories in the US, a 2.5 MW_{th} solid particle receiver has been built in which spherical bauxite particles are dropped through the concentrated solar flux of a power tower (Siegel et al. 2010). In principle, the particles can be heated up to 900^{o}C – well past the thermal limits of molten nitrate salts, at around 630^{o}C. The particles can then be stored in a similar fashion to molten salt. Sandia Labs are now in the process of designing a larger-scale receiver, which they will use to determine whether the solid particle receiver will be technically and economically viable for electricity production.

Sensible Heat Storage in Solids – Ceramic Storage

DLR (the German Aerospace Centre) are investigating the use of ceramics as heat storage media for power towers with volumetric receivers and low pressure air as the working fluid (Zunft et al. 2009). This includes investigating checker bricks, honeycomb and packed bed designs. The 1.5 MWe experimental power tower in Jülich, Germany has one hour of honeycomb ceramic storage, and produces steam at 100 bar and 500^{o}C. It was developed by Kraftanlagen München, DLR, the Jülich Solar Institute, and Jülich Municipal Utilities.

Phase Change Storage

Another method of storing heat in CSP plants is to use the isothermal (constant temperature) heat transfer characteristics of phase change materials. DLR (the German Aerospace Centre) and German firm Ed Züblin are developing a three-part storage system that incorporates both sensible and phase change heat transfer, as shown in Figure 7 (Laing et al. 2010). In July 2010, the group completed commissioning of a 1,000 kWh test system producing superheated steam at 400^{o}C and 78 bar at the Endesa Litoral power plant in Carboneras, Spain. Concrete storage is used both to preheat water and superheat steam – both processes which involve sensible heat transfer. Meanwhile sodium nitrate is used as a phase change salt to transfer heat during the evaporation of water. Phase change storage systems are also the focus of current investigations funded by the US Department of Energy, with notable companies such as Acciona Energy partaking in the research (Stekli 2010).

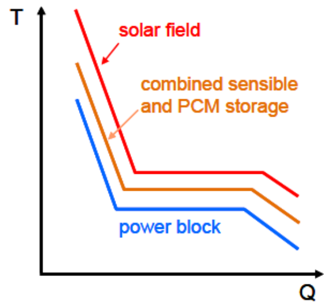

Fig. 7: Heat transfer in a three-part storage system

Thermochemical Storage

Thermochemical storage is one of the least-developed storage methods. Rather than storing heat by increasing the temperature of a substance or changing its physical state, as in the preceding discussions, thermochemical storage uses a reversible reaction to store energy in chemical bonds. Reactions involving ammonia, hydroxides, carbonates, hydrides and sulfates have been investigated in the past (Gil et al. 2010; Romero-Paredes et al. 2006). However, many of these storage systems involve storing gases at high pressure, as they are formed during the storage reaction, and need to be kept to perform the reverse reaction which releases heat. High pressure gas storage may not be an economical storage option in the medium term. Perhaps the most promising type of thermochemical storage involves redox reactions with metal oxides such as cobalt oxide, reaching temperatures of 900^{o}C (Wong et al. 2010). These redox reactions only require air as a reactant in the reverse reaction, so there is no need to store product gases.

SUMMARY

Molten salt storage is already available commercially for CSP plants, allowing solar power to be produced on demand. Four parabolic trough plants of 50 MWe capacity and with 7.5 hours of molten salt storage are already operating in Spain as at October 2010, with another six in advanced stages of construction. In addition, the 17 MWe Torresol Gemasolar power tower with 15 hours of molten salt storage will be commissioned in the first quarter of 2011.

Advances in molten salt technology include direct heating of the salts in parabolic trough plants, and application of molten salt storage to 500 m^2 dish concentrators. Other investigations include improving the thermal properties of molten salts and developing storage solutions in a single tank.

Storage methods that do not involve molten salt include sensible heat storage in solid particles and ceramics, a combination of sensible and phase change heat storage, and the use of reversible thermochemical reactions.

With these developments at hand, CSP will continue to provide dispatchable solar power, and replace coal and gas power stations in our electricity grids.

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