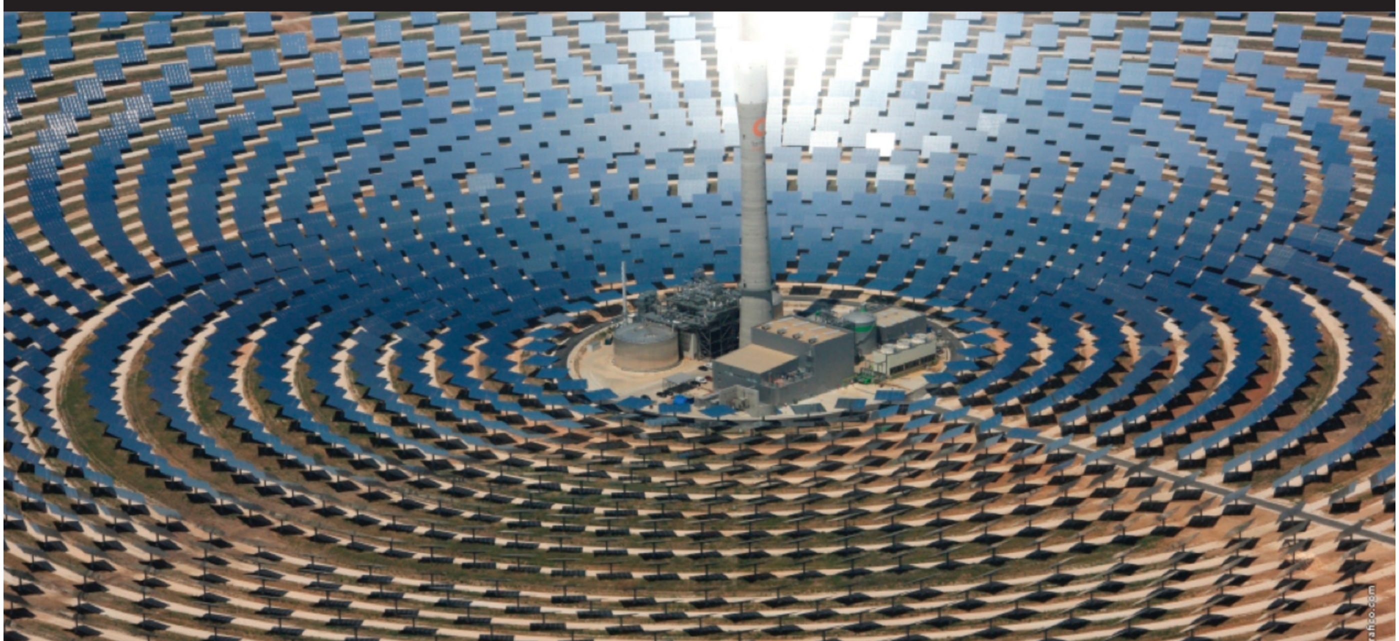
ELECTRIC POWER RESEARCH INSTITUTE

CASE STUDY ON THERMAL ENERGY STORAGE: GEMASOLAR



Source: SENER/Torresol Energy





October 2012

Introduction

Torresol Energy's Gemasolar plant is the first commercial[1] concentrating solar thermal power (CSP) plant to use a central receiver tower and two-tank molten salt thermal energy storage (TES) system. Formerly called "Solar Tres", Gemasolar was envisioned as a follow-on to the DOE's late-1990s Solar Two demonstration project. SENER, a premier CSP technology provider and system integrator[2], contributed engineering, technology and system integration expertise to the Gemasolar project, was the engineering, procurement, and construction (EPC) contractor, and also was responsible for the commissioning of the plant. Torresol Energy Investments S.A. is a joint venture of SENER (Spain) and Masdar (Abu Dhabi) that was given ownership responsibilities for the Gemasolar project. Torresol Energy Group is responsible for providing operating and maintenance support for Gemasolar.

The 19.9-MW (gross) Gemasolar project employs silvered glass heliostats and features a large molten-salt storage system that provides up to 15 hours of capacity, enabling expected net capacity factors near 75%, or approximately 110 GWh/year of generation. Gemasolar is the largest molten-salt central receiver project ever constructed and also the largest two-tank system to be operated at 565°C (1050°F). The estimated project investment was approximately 230 million Euros. Although it was financed over a 20-year project life, Torresol Energy expects it to operate much longer. In the company's view it is a long-term asset.

The Gemasolar plant is located in Fuentes de Andalucia, about 50 kilometers (30 miles) east of Seville, Spain. Compared to similar latitudes in the United States, Spain experiences more frequent cloud cover, with an annual equivalent of 32% cloud cover spread across the year, contrasted against an approximate cloud cover in the southwestern United States below 10%. As a result, the operation of solar thermal plants in Spain can be more complex than that of several thermal energy storage projects that operated in southern California in the 1980s and 1990s[3]. Plants without TES or fossil back up in Spain may experience several turbine start-ups on cloudy days due to cloud cover interrupting solar irradiance on the field. Use of TES can allow the plant to ride through these cloudy interruptions in addition to potentially creating dispatchable electricity.[4] Figure 1 shows the Gemasolar tower from a distance on a clear day.

[1] *The Solar Two central receiver CSP project in 1996 included a direct molten salt storage system, but was considered an R&D project*

[2] *SENER has participated in the design and construction of 26 solar thermal plants worldwide—one central receiver (Gemasolar) and 25 parabolic trough.*

[3] *Solar Two had a 110MWh two-tank molten-salt storage system and the SEGS I parabolic trough CSP plant had a 120 MWh two-tank thermal oil system.*

Figure 1: Gemasolar central receiver as seen from a distance (Source: T. Peterson)

Commissioned in May 2011 and first achieving 24 hours of uninterrupted electricity generation in June 2011, the Gemasolar plant has now operated for over a year, providing a prime case study for thermal energy storage. Information presented in this case study white paper was collected from a questionnaire completed by Torresol Energy and a number of published reports about the Gemasolar project.

Design

Project Design Specifications

The Gemasolar plant is nominally broken into three main systems: collection, storage and generation. The optimum relative sizing of the collector field, thermal storage system and turbine is unique to each project and depends on a number of factors, including solar

[4] *S. Relloso and J. Lata, "Molten Salt Thermal Storage: A Proven Solution to Increase Plant Dispatchability. Experience in Gemasolar Tower Plant", SolarPACES: 2011.*

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This white paper was prepared by Electric Power Research Institute (EPRI).

resource, storage system cost, market pricing, available financial incentives, etc. Gemasolar was designed to operate 24 hours a day in the summertime in order to minimize power block costs. It was determined that the total plant investment is lower for this strategy relative to other designs that produce the same amount of annual energy. See Figure 2 for overall system design characteristics. As the molten salt is circulated through the receiver, it is heated to 565°C (1050°F).

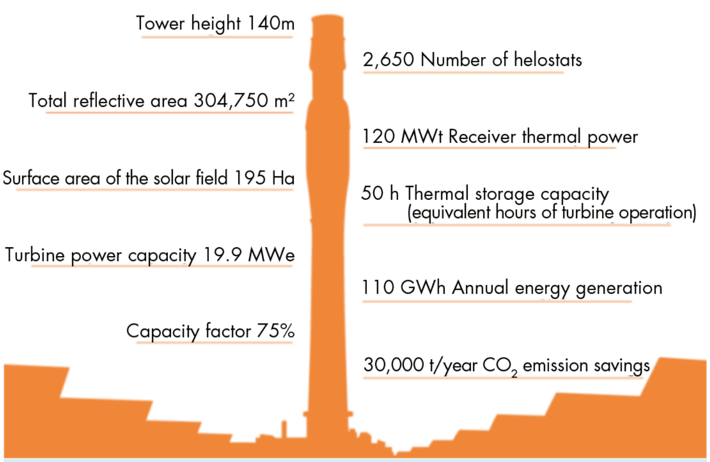

Figure 2: Gemasolar collector and overall system characteristics (Source: SENER/Torresol Energy)

In the collection system, the solar energy hits the solar field, where 2,650 heliostat units, each with a reflective area in the range of 120 square meters (approximately 10m x 11m), concentrate incident solar energy onto a 140-meter, 120-MW_t molten salt central receiver tower located in the center of the field. The flux concentration on the receiver can be up to 1000 suns. The heliostats are comprised of 35 mirrored facets, each 3mm thick. The facets are bonded with an adhesive to a galvanized stamped steel support.[5] Figure 3 shows the view of the central receiver from the base of the tower and the field of heliostats that reflect light onto the receiver.

Figure 3: Central receiver tower and heliostat field (Source: T. Peterson)

The storage system consists of a pair of large tanks—one hot and one cold—separated by a molten salt-to-steam heat exchanger. Hot molten salt from the receiver is stored inside the hot storage tank. The storage system capacity is approximately 770 MWh_t, which allows the plant to produce electricity at full load for up to 15 hours in the absence of solar radiation.

In the generation system, the molten salt flows from the hot storage tank through a steam generation heat exchanger to produce superheated steam, which is then expanded through the turbine/generator system, generating electricity that is delivered to the grid. The "cooled" molten salt (290°C or 514°F) is returned to the cold storage tank before it is pumped back through the receiver. The steam turbine is sized at 19.9 $MW_{e,gross}$. A salt heater powered by natural gas provides additional flexibility and dispatch capability, including morning startup support if sufficient storage capacity is unavailable. Figure 4 shows a schematic of a generic central receiver plant layout with direct two-tank molten salt storage.

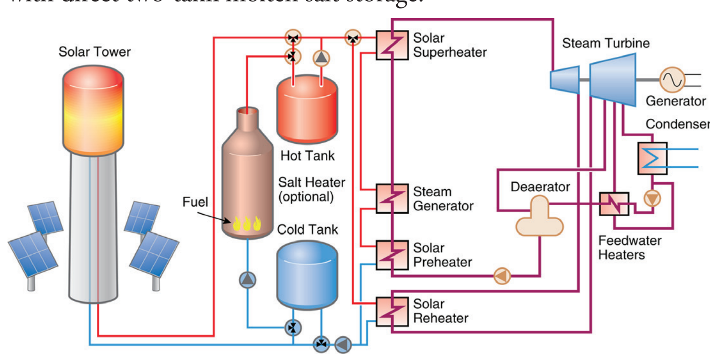

Figure 4: Gemasolar plant layout (Source: SENER/Torresol Energ)

[5] *J. Lata, S. Alcalde, D. Fernández, and X. Lekube, "First Surrounding Field of Heliostats in the World for Commercial Solar Power Plants – Gemasolar", SolarPACES: 2010 (FP_SOLARPACES-113).*

Thermal Energy Storage Tank Design Specifications

The energy storage system consists of two tanks: the hot tank is constructed of stainless steel to resist corrosion at higher temperatures, and the cold tank uses carbon steel. Each tank is over 10 meters (33 ft) tall and 20 meters (66 ft) in diameter (see Figure 5) and can hold up to 8,700 tonnes of molten salt.[6] Tank size dimensions were determined based on cost minimization calculations and are well below the maximum size possible for molten salt storage tanks. For example, storage tanks at Torresol Energy's Valle 1 and 2 parabolic trough plants are designed to hold up to 25,000 tonnes of molten salt, and an EPRI study[7] in 2011 estimated a maximum tank diameter of approximately 49 meters (160 ft) and maximum height of 15 meters (50 ft) for a maximum capacity of 3500 MWh_t would be feasible for a reference site in southern California. The foundations supporting the tanks, designed by SENER, include a cooling system.

Figure 5: Thermal energy storage tank shown with cars for scale (Source: SENER/Torresol Energy)

The tanks were designed to allow room for thermal expansion within the tank[8]; in addition, the piping system between the tanks and the rest of the plant was designed with no rigid connections to allow for thermal expansion within the system without causing structural damage. The hot and cold storage tanks are located on either side of the tower, with pipes running from the cold tank to the receiver and from the receiver to the hot tank.

Salt pumps are long-shafted, centrifugal pumps mounted above the tanks. The heat exchangers between the molten salt storage system and the steam cycle are located above the maximum level of molten salt in the storage tanks, so that all piping and equipment is self draining to the tanks. In the event of power loss all valves fail open, allowing the salt to drain. This is an important safety and risk mitigation feature.

Molten Salt

The molten salt used in the Gemasolar plant is a high purity mixture of sodium and potassium nitrates (60% $NaNO_3$ + 40% KNO_3)[9]. The use of molten salt as the heat transfer fluid has a number of benefits. Unlike synthetic oils that have operating temperatures below 400°C (750°F), molten salts can be operated at high temperatures above 550°C (1020°F), allowing for higher steam temperature and, therefore, increased steam cycle efficiency. The ability to use molten salt both as the primary heat transfer fluid circulating through the receiver and as the storage medium (known as a direct storage system) has two main benefits. It lowers capital costs through removal of a separate synthetic oil system and heat exchanger between the collection and storage systems, and it improves storage efficiency by reducing thermal losses incurred during heat transfer from the working fluid to the storage fluid. The higher temperature of the molten salt storage system, relative to what is achievable with conventional parabolic trough systems, also minimizes equipment size (see sidebar), which further reduces cost.

The molten salt nitrate mixture solidifies well above ambient temperature (238°C [460°F]), and considerable care must be taken to ensure that the salt does not freeze in the solar field or elsewhere in the storage system. This includes installing electric heat tracing on small diameter piping, valves and pumps that come in contact with the salt, and designing tanks with internal electrical heaters for use during plant commissioning and low-maintenance stops. While the high freeze temperature presents some challenges, one benefit is that in the case of any cracks or leaks the molten salt will not disperse. To reduce the likelihood of leaks, the system is designed to accommodate thermal expansion under a variety of scenarios. In addition, the nitrate salts are not considered hazardous materials; they are used extensively around the world to make fertilizer. Therefore, even in the case of a major failure, no environmental impacts related to molten salt usage would be expected.

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6 *J.I. Burgaleta, S. Arias, and D. Ramirez, "Gemasolar, the First Tower Thermosolar Commercial Plant with Molten Salt Storage", SolarPACES: 2011 (24831).*

7 Solar Thermocline Storage Systems: Preliminary Design Study. *EPRI, Palo Alto, CA: 2010. 1019581.*

8 *Cooling molten salt from 565°C to 290°C reduces the volume by approximately 10%.*

9 *S. Relloso and J. Lata, "Molten Salt Thermal Storage: A Proven Solution to Increase Plant Dispatchability. Experience in Gemasolar Tower Plant", SolarPACES: 2011 (39721).*

Storage volume is directly proportional to the difference between the charge and discharge temperatures. CSP technologies with a greater differential in the hot storage charging temperature and the cold return temperature will require a smaller volume to store the same amount of energy. It follows that parabolic trough storage operating at 400°C (752°F) requires roughly 2.5 times more storage volume than tower storage operating at a charging temperature of 560°C (1,040°F) with a nominal cold return temperature of 290°C (554°F) for both systems. EPRI's 2011 study[10] on two-tank and single-tank thermocline storage technologies compared the costs of thermal energy storage systems for direct central receiver and indirect parabolic trough plant designs. The results in Figure 6 show that for commercial scale systems, the storage system capital costs for the direct central receiver are roughly half the cost of the indirect parabolic trough for the same storage capacity.

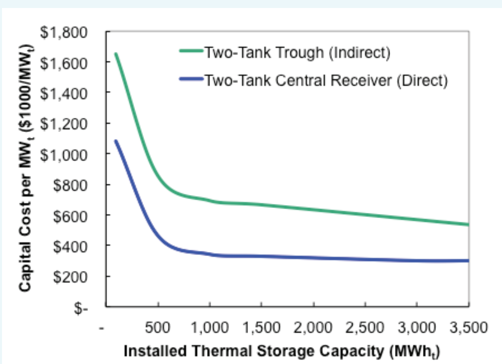

Figure 6: Molten Salt Thermal Energy Storage System Capital Cost Estimates as a Function of Installed Capacity, \$/kWh$_t$ (Jan. 2010 dollars)

Construction and Commissioning

Construction

While the full Gemasolar plant construction took approximately 29 months to complete, the storage tanks were constructed on-site in only 3 months. Hot and cold tanks were erected and molten salt pumps were manufactured and tested before the tanks were connected to the plant and before heat tracing was installed on the piping.[11]

[10] Solar Thermocline Storage Systems: Preliminary Design Study. *EPRI, Palo Alto, CA: 2010. 1019581.*

[11] *J.I. Burgaleta, S. Arias, and D. Ramirez, "Gemasolar, the First Tower Thermosolar Commercial Plant with Molten Salt Storage", SolarPACES: 2011 (24831).*

The 7,950 tonnes of molten salt used at the Gemasolar plant was stored in silos on-site in crystalline form as separate constituents, sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3). Prior to melting, the salt was crushed (to break up any lumps of coagulated salt) and delivered to a temporary natural gas burner in the desired proportions (60% $NaNO_3$, 40% KNO_3) using separate feed lines. Melting was done on a continuous basis, as opposed to batch melting, and it took two months to fully charge the system with melted molten salt.

Commissioning

Commissioning of the Gemasolar plant began in November 2010 and continued through April 2011 when commercial operation began. Because of the independence of the storage system and the generation system (i.e., the storage tanks can be charged while the turbine is idle, and power can be generated using stored energy when sunlight is not available), commissioning was able to take place in stages, facilitating the start up of the plant. The generation system start-up activities were able to take place regardless of weather conditions, while start up of the storage and collection systems, including the solar field and receiver, were delayed until Spring 2011 due to poor weather conditions.[12] Heliostat calibration took place in record time due to innovative dynamic tracking correction software and an automatic heliostat calibration system.[13] Figure 7 shows heliostats reflecting sunlight onto the receiver.

Figure 7: Heliostats focus sunlight on the receiver (Source: T. Peterson)

[12] *Ibid.*

[13] *J. Lata, S. Alcalde, D. Fernández, et al., "Commissioning and Operation of Commercial Heliostat Fields for Maximum but Safe Production", SolarPACES: 2011 (39417).*

The plant was synchronized with the grid at the end of April 2011, and has been providing electricity since early May 2011. At the end of June 2011, the plant successfully completed 24 hours of uninterrupted electricity production, setting a world record for a commercial solar plant. In a July 6, 2011 performance test, the plant was able to exceed the guaranteed performance during a 24 hour period, which was a condition of getting provisional plant acceptance. Figure 8 shows the continuous operation of the Gemasolar plant during a week in summer 2012.

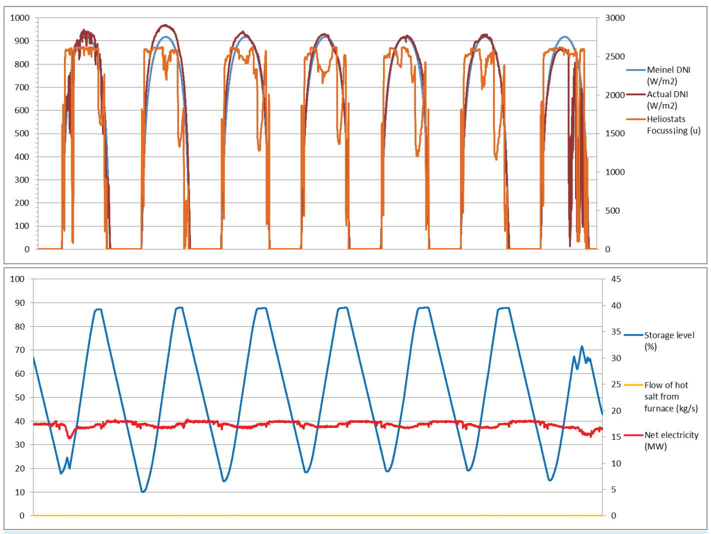

Figure 8: Example of Gemasolar Continuous Operation in Summer 2012[14] (Source: SENER/Torresol Energy)

Operational Strategies

Operating Modes

Charging thermal energy into the hot storage tank and discharging the hot salt to produce electricity can take place simultaneously and independently, except when a tank is empty or 100% full. The level of the tanks increases or decreases depending on the incoming energy and the demand of the turbine, but loading and unloading are completely independent. As a result, there is no time delay in "reversing" the charge/discharge process as is required with an indirect storage system. This unique feature allows the plant to modulate output to meet demand.

In general, the plant is run at full load during the day to produce power at maximum turbine efficiency. Any excess energy is used to charge the hot storage tank. At sundown, the available energy stored in the tank is calculated and the best way of using that energy is determined. Even if the storage capacity is not sufficient to run the plant at full load for the entire night, the plant can typically be run at part load to avoid shutdown. This reduces start-up warming and idle time in the morning and increases the life expectancy of the turbine.

In the summer the plant operates at full load the majority of the time. In winter the storage system is not fully charged at the end of the day, and plant operators must calculate the most profitable way of utilizing the stored energy. On most winter days the plant will operate at full load until the solar resource begins to drop, and then the output will be reduced to a level that avoids shutting down the turbine overnight. Below a certain minimum amount of stored energy that solution is not feasible, and the plant will be operated at full load until the stored energy is exhausted. Figure 9 shows typical summer and winter days.

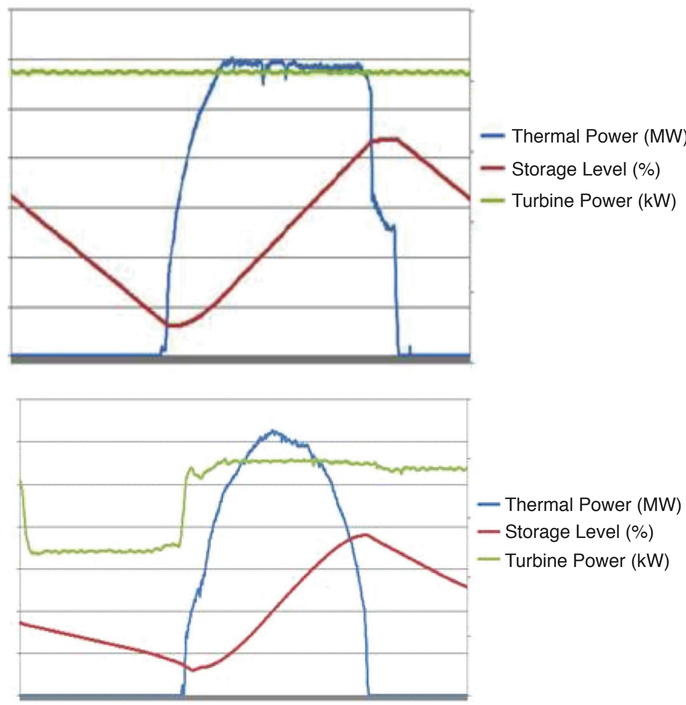

Figure 9: Typical daily operation profiles in summer and winter (Source: SENER/Torresol Energy)

[14] *S. Relloso and J. Lata, "Molten Salt Thermal Storage: A Proven Solution to Increase Plant Dispatchability. Experience in Gemasolar Tower Plant", SolarPACES: 2011 (39721).*

Dispatch Methodology

Based on weather estimations for the next day, a day-ahead hourly dispatch forecast is developed for the Gemasolar plant. The plant is then operated to match the forecast as best as possible, though there is the possibility to alter the forecast six times a day if necessary[15]. Dispatch decisions do not need to be made as an either-or decision between energy storage and electricity generation as the molten salt always enters the hot tank before entering the steam generator. The turbine can draw on the solar energy up to the maximum amount available and as soon as the energy captured in the solar field exceeds the turbine demand, the energy is stored.

Torresol Energy is in the process of developing software to maximize the profitability of plant operation by introducing a price factor equation. The goal is to increase plant profitability by allowing the plant output to be modulated to demand and, therefore, the price of electricity. For example, the plant may be run at part load during the morning when power prices are low, while operating at full load during the afternoon and evening peak periods. The software will consider hourly pricing, as well as weather forecasts and turbine start up costs, to optimize daily dispatch.

The Spanish legislation requires CSP plants to pass a set of dispatchability tests, consisting of unexpected orders to raise or decrease the output in less than half an hour. Torresol Energy has opted to conduct the testing in the winter months so as not to interrupt performance during the summer peak period. Having already successfully passed the tests in its two Valle parabolic trough plants the company is confident that Gemasolar will also pass.

Monitoring and Control

The storage system is monitored by several thermocouples located inside the tanks. In addition, there are controls for tank levels and flow rates. The steam turbine is a standard Siemens turbine that is controlled by software that limits the gradients of temperature changes to prevent failures, allowing it to operate in a wide range of operating conditions. The flow rate of the molten salt through the tower is controlled by variable speed pumps to maintain a fixed output temperature.

[15] *The opportunity to adjust the forecast is limited to eight hours ahead or longer.*

Reliability and Maintenance

To date, Gemasolar has not experienced any unplanned outages as a result of the storage system. It is anticipated that the plant will require one scheduled maintenance outage per year, but this is dictated by the turbine manufacturer, not by the solar design. That is, maintenance for the thermal storage system and collector field can be carried out during planned outages for turbine maintenance and is not expected to result in additional downtime. Spare parts are kept onsite as recommended or requested by equipment manufacturers.

The major maintenance requirements for the storage system will be regular maintenance of the pumps and valves. To date, pump wear at the plant has been low. Predictive maintenance has been used, measuring vibrations, temperatures, and operation time in order to anticipate needed maintenance. The staff at Gemasolar has undergone intensive training for general plant operation and maintenance. There are 39 staff responsible for plant O&M. An external contract is also in place for mechanical maintenance and repair tasks at the plant.

Torresol Energy does not expect a need to replace the molten salt as the nitrates are very stable. There are no impurities that need to be removed and, to date, no corrosion caused by molten salt has been observed. In general, Torresol Energy states that the operating and maintenance costs associated with the Gemasolar storage system are nominal.

Performance

Plant Capacity Factor and Performance Statistics

The Gemasolar plant has now been in operation for slightly over a year. In the first six months of plant operation, May 2011 through October 2011, the Gemasolar plant produced approximately 20 GWh of net electricity. Torresol Energy reports that, while this is lower than their long term expectations of a maximum of 110 GWh of net electricity production per year, they continue to progress along the learning curve and are improving operation day by day.

Torresol Energy also reports that the plant has achieved a maximum net exportation of 428 MWh in a single day and performance over 400 MWh/day for a period of several weeks in the summer months. Because the plant size has only been provided as the steam turbine's gross output of 19.9 MW_e and because the auxiliary load of the plant will vary based on full- versus part-load operation, the exact

net capacity factor cannot be calculated. However, it is believed that 428 MWh in a single day is close to full-load operation for an entire 24 hour period. In addition, Torresol Energy reports that the plant has run for complete weeks at full- or partial-load without any shutdowns.

Rankine cycle efficiencies at Gemasolar are comparable to conventional steam plants operating at similar temperatures. The only difference for the central receiver system is thermal loss due to accumulation while the stored salt sits in the tank, i.e., the storage system is charged during an eight hour period and discharged over the course of 24 hours. However, storage system efficiencies are expected to be quite high[16] and likely have little effect on steam cycle conditions. SENER has reported significant improvement in reducing plant auxiliary loads since the time that the plant was commissioned, but actual auxiliary loads have not been shared.

In its first year of operation, the Gemasolar plant has successfully matched power production within 6% deviation for hourly predictions versus hourly production, which is much better than other plants within the Spanish CSP sector with many more years of operating experience. As noted earlier, the direct storage system design allows the plant to produce power independently of the collection and storage systems and modulate power output without delays. This allows the Gemasolar plant to more easily adapt plant operation in response to changing weather and other factors.

Torresol Energy's long term expectations are that Gemasolar will operate for 6,400 equivalent hours per year of full-load operation for an annual capacity factor of nearly 75%. The company expects to achieve that milestone in 2012.

Thermal Energy Storage System Performance

When the hot storage tank is fully charged, the plant has demonstrated the ability to provide up to 15 hours of production at full load. Thermal losses from the hot tank are less than one degree Centigrade per day. In the summertime, the tank is often fully charged late in the afternoon and can operate the plant at full load throughout the night. In the wintertime, when the days are shorter and the amount of stored energy is lower, the plant has two options: to reduce the output of the plant to below full load to continue operation throughout the night, or to operate at full power output (i.e., maximum efficiency) until the storage tank is nearly exhausted and then stop for the remainder of the evening and restart the next morning. Figure 10 shows the view from the top of one of the storage tanks.

Figure 10: View of heliostat field from thermal energy storage tank

[16] Thermal energy storage is inherently efficient compared to electrical and mechanical forms of energy storage. The 10-MW Solar Two project with three hours of storage capacity demonstrated an effective efficiency of 99% (97% annual average) for its storage system between 1996-1999. The storage system capacity at Gemasolar is roughly fifteen times greater than the system at Solar Two. Because heat loss is proportional to the surface area of the tanks and stored energy capacity is a function of tank volume, the heat loss from the tanks at Gemasolar is expected to be lower. Torresol Energy estimates the round-trip efficiency will exceed 99%.

Discussion and Outlook

Solar thermal energy storage has the potential to significantly increase the operating flexibility of solar power. TES allows solar power plant operators to adjust electricity production to match system demand, enabling the sale of electricity during peak demand periods and boosting plant revenues. While at least a dozen parabolic trough plants with *indirect* molten salt storage systems have been built in the past four years, Gemasolar is the first *direct* molten salt storage system to be built since the US Department of Energy Solar Two project in the late 1990s. It represents a significant leap in scale and operational capabilities. Table 1 provides a summary of the Gemasolar plant specifications and achievements to date. Figure 11 shows the Gemasolar plant in the distance.

Figure 11: View from road leading to Gemasolar

Table 1 Gemasolar Central Receiver Plant Characteristics

Overall Plant	
Plant Size	19.9 MW_e (gross power), 120 MW_t (receiver capacity), 770 MWh_t (storage system capacity)
Location	Fuentes de Andalucia (50 km east of Seville, Spain)
Footprint	185 Hectare
Direct Normal Irradiation	2.172 $MWh/m^2/yr$
Solar Multiple	>2.5
Heliostat Statistics	2,650 @ roughly 120 m^2 (approximately 10m x 11m)
Tower Height	140 m
Expected Capacity Factor	About 75% (110 GWh/year)
Highest Daily Generation to Date	420 MWh (net)
Estimated Plant Lifetime	30 year book life
Construction Time	29 months
Thermal Energy Storage System	
Tank Dimensions	20 m (66 ft) diameter by 10 m (33 ft) high
Storage Tank Volume	7,950 tonnes each
Operating Temperature	565°C (1050°F)
Discharge Time at Maximum Generation	15 hours
Storage Capacity	770 MWh_t
Molten Salt Composition	60% $NaNO_3$ and 40% KNO_3
Thermal Energy Storage Efficiency	>99%

The initial operation of the Gemasolar central receiver plant with two-tank molten salt storage has demonstrated the feasibility of the technology to operate under commercial conditions at utility-scale, and verified continuous 24-hour operation. The high thermal storage capacity of the plant also allows the plant to operate at either full- or part-load throughout the night if desired, reducing plant stops and starts, which is expected to, in turn, reduce O&M expenditures and extend the life of the turbine. The storage capacity also makes the plant output dispatchable and improves the plant's capacity factor and profitability.

In comparing the Gemasolar technology with parabolic trough systems it is clear that high temperature molten salt allows for a more compact thermal storage system and eliminates the need for separate collection and storage systems, thereby improving efficiencies and reducing capital costs. Cycle efficiency is also improved because of the higher steam temperature. Operational and maintenance costs are reduced for a number of reasons, including avoidance of swivel joints, inclusion of self draining piping and the use of a single heat transfer fluid and thermal storage medium.

Torresol Energy views the molten salt storage system at Gemasolar as a promising technology for similar reasons: high thermal storage capacity, low operational costs, and high cycle efficiencies. Fifteen hours of stored capacity translates into greater operating flexibility, longer turbine lifetime, and maximization of the turbine investment through higher capacity factors. Operational costs are relatively low because there are few moving parts associated with the molten salt systems and the fluids are concentrated in a small area, keeping thermal losses and maintenance costs low. Using a single fluid for both collection and storage has design, cost and operational advantages. Finally, the high temperatures achievable with molten salt enable high thermodynamic efficiency[17].

Several developers have announced plans to scale up the direct molten salt central receiver technology at project sites in Spain, the U.S. and South Africa. Over 500 MW is planned over the next five years, and one or more plants are under construction as of this writing. The largest announced thermal energy storage system is designed with approximately 1200 MWh of storage capacity (eight hours at 110 MW), a 55% increase over the Gemasolar plant. While the cost of solar energy is still high compared to traditional generation options, Gemasolar is expected to reduce uncertainty in technology performance and potentially lower the cost to build future projects. The ideal amount of thermal energy storage will vary for different regions and specific projects, but as more plants are developed and costs continue to fall, thermal energy storage presents a unique opportunity to reduce the levelized cost of electricity while adding dispatchability. The operating flexibility and energy value of the direct molten salt central receiver with storage set it apart from other solar technology options.

[17] *EPRI estimates that commercial 100-MW scale molten salt central central plants will have net solar-to-electric efficiencies near 20% (*Renewable Energy Technology Guide*: 2010. EPRI, Palo Alto, CA: 2010. 1019760.)*

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