Challenges in the Thermal Energy Storage for Solar Power Plants

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Abstract

The need for renewable and sustainable energy is clear. Concentrated Solar Power (CSP) is one means of power generation that is becoming economically viable to meet those needs. CSP however, does have limitations due to it's reliance on direct sunlight as a means of energy input. Thermal energy storage (TES) can overcome these limitations and can improve a plant's economic viability by allowing power production during peak demand periods that occur during non-daylight hours. The Solana project designed by Abener North America, near Gila Bend, AZ utilizes molten nitrate salt thermal energy storage to capture these benefits. Thermal energy storage has long been considered by the solar industry; and the Abengoa companies have endeavored to design and build the world's largest thermal energy storage system attached to a CSP plant. A variety of technical considerations must be made when designing a nitrate salt thermal energy storage system. Just a few of these design considerations include salt melting operations, the high temperature molten salt storage tank and tank foundation designs, TES heat exchangers, nitrogen blanketing, and the salt freeze protection design. The test facility designed and built by the Abengoa companies in 2009 in Sanlucar La Mayor Spain has provided much insight and experience necessary to answer many of these design issues. This paper will present in detail the technologies associated with, and the challenges in designing the world's largest nitrate salt thermal energy storage system by a world leader in renewable energy solutions.

Keywords: tes, thermal energy, molten salt, solar power, nitrogen blanket

Challenges in the Thermal Energy Storage for Solar Power Plants

Fossil fuels currently feed 85% of our energy demand. But, fossil fuels release carbon when burned, and carbon emissions are scientifically linked to the greenhouse gas effect and the growing concern of climate change.

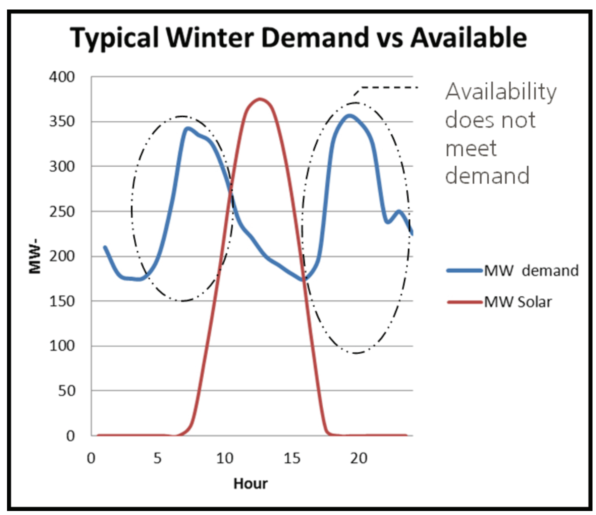
The administration has defined "clean energy" as nuclear power, natural gas and clean coal, as well as renewable sources such as wind and solar. The federal government and the industry are now looking even harder at natural gas, wind and solar for our clean energy needs due to clean coal costs and nuclear safety concerns. Solar energy production has the capability to transform our nation's energy system. Thermal energy storage has potential to level the power production to the overnight hours when the direct solar heat is not available.

The Solana project designed by Abener North America, near Gila Bend, AZ utilizes indirect molten nitrate salt thermal energy storage to capture these benefits.

1. Need for Thermal Storage Systems

Traditional CSP plants have their limitations due to their reliance on direct sunlight as a means of energy input, or direct normal incidence (DNI). It is intuitive that these DNI values are not available on a 24 hour basis even at the high incidence locations, nor are these DNI values constant during daylight hours during all months of the year.

It is apparent that the reliance of only sunlight for power production brings limitations for CSP plants for the full 24 hour period. These limitations can be compounded when this solar availability is overlapped with the electrical demand curves for the area. Figure 1.0 depicts a typical winter day demand curve with DNI values for the Phoenix, AZ area.



There is a significant amount of time where DNI availability does not meet the demand, particularly in the winter where electric resistant heaters are used in the morning and evening hours in the Phoenix area. The same can be said for late evening hours during the summer (for air conditioner usage).

Due to their size and corresponding metal mass and minimizing thermal stress, CSP plants are limited in power production due to the need to wait for the power block (SG and STG) to warm up before full DNI to power production can be realized. TES can be used in early morning hours before sunlight is available to warm up the Power Block such that the SG and STG are ready for the full DNI capacity as soon as it is available.

Extended power production periods beyond daylight hours, higher value energy production during peak demand periods, no loss of available DNI for morning warm-ups, and the opportunity for reaching nameplate production at low DNI help offset the capital costs of the TES system itself and the related increase in the size of the solar field.

A variety of technical considerations must be made when designing a nitrate salt thermal energy storage system. Just a few of these design considerations include salt melting operations, the high temperature molten salt storage tank and tank foundation designs, TES heat exchangers, nitrogen blanketing, and the salt freeze protection design.

2. Technical Consideration - Logistics of Salt Delivery

There is a great deal of logistics involved with the enormous quantity of salt necessary for the thermal energy system. There are over 126,000 metric tons of salt to be used on the Solana project; delivered to the site and melted. The quantity of salt required for TES is on the order of magnitude that stretches the limits of production for single vendors.

Considerations must be made as to manufacturer location, packaging of material, modes of transportation (ship, rail, truck), and secured storage areas (off-site and on-site). All of this can be affected by quantity of salt being purchased, technical grade, mixture ratio, and availability.

In addition, the potassium nitrate and sodium nitrate salts are designated by the Division of Homeland Security (DHS) as a security issue / theft risk for use as explosives / improvised explosive device precursors. The screening threshold quantity (STQ) is merely 400 pounds for each nitrate salt. As the quantity of nitrate salts onsite during commissioning for salt melting will far exceed these STQs, a Top-Screen should be prepared and submitted to the DHS. All designated storage and staging areas should be fenced, secured, and controlled with restricted access.

3. Technical Consideration - Salt Melting

Salt melting and preheating is one of the largest logistical challenges in the process of starting and commissioning a nitrate salt thermal energy storage system. This process involves bringing the storage tanks up to operating temperature prior to filling them with molten salt. The melting process includes receiving deliveries of salt, storing the salt, moving the salt from storage to preprocessing, preprocessing the salts prior to melting, melting and pumping the molten salt to the storage tanks.

The preheating system must be able to bring up the temperature of the storage tanks evenly as to not cause thermal stresses in the tank that would lead to a mechanical failure. It is necessary to instrument the tanks and the preheating system to detect temperature gradients. If extreme gradients are detected, the system should shut down to prevent damaging the storage tanks.

The preheating system also needs to be reliable and able to produce a large amount of high temperature air. There is a significant amount of heat required to bring the massive tank structures and foundations up to the operating temperatures required in a TES system. This process can take several days to weeks. Various systems have been investigated by Abener. Some preheating systems have been proven in previous TES installations and others may provide benefits over the proven systems but are yet untried.

4. Technical Consideration - N_2 Blanketing

Molten salt has a composition of 60:40 sodium nitrate and potassium nitrate ($NaNO_3$: KNO_3). However, there are also impurities in the salt, the amount of which varies depending upon the grade of salt purchased because they differ in the production process. Typical impurities include chlorides, sulfates, nitrites, and carbonates. If the salt were to be exposed to ambient air, which can contain significant amounts of water, there is a potential for corrosion of the tank, pipe, and heat exchanger.

To avoid this, the entire salt system is kept under slight pressure with a nitrogen blanket. This nitrogen blanket includes connections to the piping system to allow draining for maintenance and long term shutdowns.

Maintaining the nitrogen blanket itself is not a significant issue. What has been proven to be a design challenge is the inherent wicking effect of the salt through valving systems, even in the vapor space. Salt build up from salt wicking into colder vapor spaces can make PSV's, block valves, control valves, and small nitrogen lines effectively inoperable if the design does not incorporate proper safeguards.

5. Technical Consideration - Materials of Construction

Materials of construction are critical to creating an economical and successful indirect nitrate salt thermal energy storage system. There are many materials that are compatible with nitrate salts. Corrosion rates for materials in contact with nitrate salts have been documented in technical publications. Abener and Abengoa have done additional material testing in the Seville pilot plant to determine corrosion rates of various materials in nitrate salt service.

Besides chemical compatibility, another consideration in determining a material of construction for nitrate salt thermal energy storage is the high operating temperatures the material will see. Many materials will not operate reliably nor have published mechanical properties at the TES high operating / design temperatures. Some materials may be in the creep range which would not be acceptable for a TES structure.

Some materials would require post weld heat treatment if thicknesses go above design thresholds. This presents a large construction challenge that would be time consuming and costly, especially with the size of tank required for the Solana project (over 120 ft diameter). Post weld heat treatment of a tank shell as large as required on Solana TES would take many days and would require temporary insulation to be erected around the shell, significant instrumentation to be installed for monitoring, and a heat treatment burner system to be temporarily installed.

6. Technical Consideration - Tanks & Foundations

The tanks are outside of the normal boundaries of any one design standard or code. API-650 does not cover temperatures where the TES system operates. ASME does not provide design rules that are applicable for low pressure flat bottom storage tanks. Therefore, it is necessary to use good engineering judgment based on the available design standards and codes and to provide a thorough analysis of the storage tanks including finite element analysis (FEA) to completely evaluate the design of a TES tank. The FEA should incorporate the stresses due to the typical static and pressure loadings along with seismic and wind loading. Additional loadings for thermal stresses due to gradients in the tank should also be reviewed, especially when determining the allowable gradients in the tank for preheating.

There are various constraints that must be recognized when designing the tank. These constraints are then used to optimize the tank design so the system is as cost effective as possible. Some of these constraints are maximum tank height due to pump length, maximum plate thickness to avoid post weld heat treatment of the shell, minimizing tank heel to reduce installed cost while maximizing storage for a given tank size, and required storage capacity vs. number of batteries (one "Hot" tank and one "Cold" tank) units installed.

The tank foundations are also outside the normal design envelope for foundations. The foundation must be structurally sound at elevated temperatures, must provide sufficient anchorage to prevent tank uplift, and mostly, must be a good insulator. The foundation insulation factor is critical to optimize TES performance. It is necessary to minimize heat loss from the tank bottom preventing salt from freezing in the storage tank. Also minimizing heat loss to the sub foundation soil is critical as to not drive off excessive moisture in the soil causing large settlements of the tank and foundations. It is necessary to anchor the tank to prevent thermal walking. The tanks do not experience high thermal swings once in operation, however small thermal changes over time can cause the tank to move on its foundation.

Depending on the complexity of the foundation design it may be necessary to perform a thermal analysis via FEA. This analysis can accurately predict the heat losses that will occur through the foundation while the tanks are in operation. This step is important, as minimizing heat loss is critical to a successful and efficient TES system. Also the analysis can predict the temperatures that the surrounding soils will see. This temperature should be minimized as necessary for the site. Elevated temperatures can cause additional settlement that can and should be minimized by the foundation design.

7. Technical Consideration – TES Heat Exchanger

Heat exchangers are required for any indirect thermal energy storage system. As with any heat exchanger, several process parameters must be taken into consideration for its design. The expected working temperature of the hot salt is nearly as high as the HTF returning from the solar field and is a key indicator of the thermal efficiency of not only the heat exchanger during charging, but also the overall efficiency of the entire thermal energy storage system, as this hot salt temperature determines the amount of heat available for power generation during discharging. Therefore, when evaluating TES heat exchangers, both charging and discharging performance parameters (temperatures and flow rates) must be evaluated hand in hand.

The net amount of energy transfer, not just the hours of storage capacity, will determine the size of the heat exchanger, as it is rate dependent. While Solana has more than 6 hours of storage capacity, what is significant is that these 6 hours are at a rate of 235 MW-h. This requires an enormous heat exchange area. The number of shell and tube heat exchangers required to accommodate this was too excessive for consideration. Solana has been able to accommodate the heat exchange needs into just six plate and frame heat exchangers which reduces the required piping, footprint, and complexity of the control system.

Based on the area required for each of the six heat exchangers, as well as the pressure plates, the sheer mass of metal is enormous. Extreme care must be taken to avoid thermal shock/stress within the exchanger for both initial heat up and operation such that the temperature differences between the bundle and incoming fluid (HTF or salt) are minimized. Extensive temperature monitoring is required throughout the bundle (50 ft x 25 ft), pressure plates, header boxes, and tie rods.

Thermal efficiency of the heat exchanger is also dependent upon heat loss to atmosphere. With the above mentioned mass, heat loss can be a significant issue, not only through the heat exchanger itself but through the exchanger supports as well.

Due to the potential of salt pluggage and its detrimental effect on efficiency, the heat exchanger must be completely drainable. Additional care must be taken in regards to the salt piping system to/from the exchanger to facilitate this. Determining when to isolate the heat exchanger vs. drain the system is key to the piping design and operating controls.

Practically speaking, just the mere size of the heat exchangers offers challenges for fabrication, shipping, and placement on site.

8. Technical Consideration – Molten Salt Pumps

The main cold salt pumps move the cold salt from the cold salt tank through the HTF-to-salt heat exchanger to the hot salt tanks. The main hot salt pumps move the hot salt from the hot tank back through the HTF-to-salt heat exchanger to the cold tank.

Design considerations in the selection of the main pumps include:

- vertical turbine vs vertical centrifugal pumps
- materials of construction for all wetted parts
- sealing system types
- bearing cooling systems
- extremely high operating temperatures
- and warm up & cool down of the pumps

The pumps are extremely heavy and put a high static and dynamic load on the tank which has to be accounted for in the tank design and stress analysis. Additional considerations should be made for maintenance and servicing of the pumps. When the pumps are lifted out of the tank, consideration must be given to prevent the freezing of the salt still in the pumps. As well, consideration must also be given for reinstalling the pumps back into the high temperature service: the pumps must be heated to prevent thermal shock once the pumps are lowered back into the hot salt.

9. Technical Consideration – Heat Loss

As previously alluded to, heat loss to atmosphere is a significant issue to be considered for the TES heat exchangers. There a multitude of additional heat loss sources in the plant which will affect its overall power production. These include heat losses in the salt storage tanks through the walls and foundation, losses in TES area piping, and significant losses through solar field piping during overnight standby hours due to the miles of HTF solar field piping at relatively small sizes. Extreme care must be taken in regards to all salt piping as well as HTF piping in the solar field to avoid fluid freezing.

"Thermal Energy Storage" says it all when it comes to heat losses. The goal of the system is to store thermal energy. This means that heat loss should be minimized in order to maximize the efficiency of the TES system.

As with any heat loss problem, the answer to reducing heat loss is first to minimize or eliminate heat emitting fins on the tank, heat exchanger, and piping. Any attachment to the tank, heat exchanger or piping should be insulated and have a thermal break where the insulation terminates. Secondly, heat loss can be reduced by insulating sufficiently and properly. Heat losses can be a major problem if there is an inadequate amount of insulation. Even if the amount of insulation is sufficient, heat loss can still be a major issue if the installation is not correct. Insulation is one of the most important aspects of minimizing heat loss in the TES system.

10. Seville Test Facility

The test facility designed and built by the Abengoa companies in Sanlucar La Mayor, Spain has provided much insight and experience necessary to answer the design challenges surrounding TES. The test facility has been operating since March of 2009. The test facility includes hot and cold molten salt storage tanks, hot and cold molten salt pumps, a molten salt to HTF heat exchanger, and an HTF recirculation pump.

Overall, the plant continues to perform very well. There were many lessons learned in the startup and operations of the Seville test facility. Some of them were expected, some were not:

- Heat losses on the tank and heat exchanger were higher than expected – insulation installation quality is paramount
- Repeated failure of the HTF recirculation pump seals – this has been an ongoing design review and modifications with the pump manufacturer
- Wicking of the salt – it was foreseen the salt would wick, but now it is known the extent to which the salt will wick, even deeply into the nitrogen system (and valves)
- Stratification of the salt – despite the relatively small size of the tank, the salt temperatures in the tank were not homogeneous
- Blanket with nitrogen immediately at startup - slight corrosion on the CS salt tanks occurred from leaving the preheating system on too long (and exposing the ullage space to moist hot air) due to the higher than expected heat losses during preheating

The test facility designed and built by Abengoa has provided much insight and experience necessary to answer many of the technical consideration raised. This paper has described the technologies associated with, and the challenges in designing the world's largest nitrate salt thermal energy storage system by a world leader in renewable energy solutions.