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An Analysis of the Effect of Molten Salt Thermal Storage on Parabolic Trough Concentrated Solar Power Plant Efficiency

***Christopher Hickin* [1]*, Henry Li* [2] *and Sharnan Kemp* [3]**

Faculty of Science, University of Technology Sydney, P.O. Box 123, Australia

[1] E-Mail: Christopher.J.Hickin@student.uts.edu.au

[2] E-Mail: Henry.Li-1@student.uts.edu.au

[3] E-Mail: Sharnan.Kemp@student.uts.edu.au

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Abstract: In the development of renewable energy sources, there has been a trend toward increasing and stabilising the power output of Concentrated Solar Power Plants (CSPPs) during times of reduced solar resource through the use of Thermal Energy Storage Devices (TESDs). This study investigates whether the use of a molten salt TESD decreases the efficiency of a parabolic trough CSPP due to additional system energy losses despite prolonging the operational time of the CSPP. A theoretical analysis of a simplified CSPP was made to determine if a TESD would impact the efficiency of the CSPP. This was followed up by a survey of currently active parabolic trough CSPPs both with and without molten salt TESDs. The theoretical analysis illustrated that a TESD would have no effect on the efficiency of a CSPP. However, the survey revealed that the use of a TESD improved the efficiency of a CSPP. The results of the study don't support

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the theoretical analysis or the hypothesis suggesting that a property has been overlooked. This property is most likely to be that generators tend to operate best within a certain temperature range, and in a CSPP the optimum temperature range cannot be maintained. This results in a generator being selected capable of operating for the longest period with the lowest amount of excess solar energy. When a TESD is implemented, the excess solar energy is stored for later use, prolonging the generator's running time and increasing the useable energy. The realisation of the ability of a TESD to increase the efficiency of a CSPP as well as extending its operating time shows a promising area of development in CSPP technology and increasing its application in electricity generation.

Keywords: Concentrated Solar Power; Thermal Energy Storage; Molten Salt; Parabolic Trough; Efficiency

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1. Introduction

Throughout the last century, fossil fuels have been a major part of the world energy market. However, as the world’s energy demand has increased [1], so too has its burden on the Earth, leading to a need to implement renewable and environmentally friendly forms of power generation. Concentrated Solar Power (CSP) is one such power generation method being utilised and developed. Power is generated through the reflection of sunlight onto a receiver, the heat from this is then transferred to steam to power a turbine. While these setups may be attractive from an environmental point of view, there are key detractors from using this as a primary source of power generation, two of the larger being power generation during times of low light, and low efficiency. A method of combating the former utilises Thermal Energy Storage Devices (TESD) to store energy for these downtimes. This study seeks to investigate the impact of TESDs on the efficiency of the Concentrated Solar Power Plants (CSPPs) they are attached to.

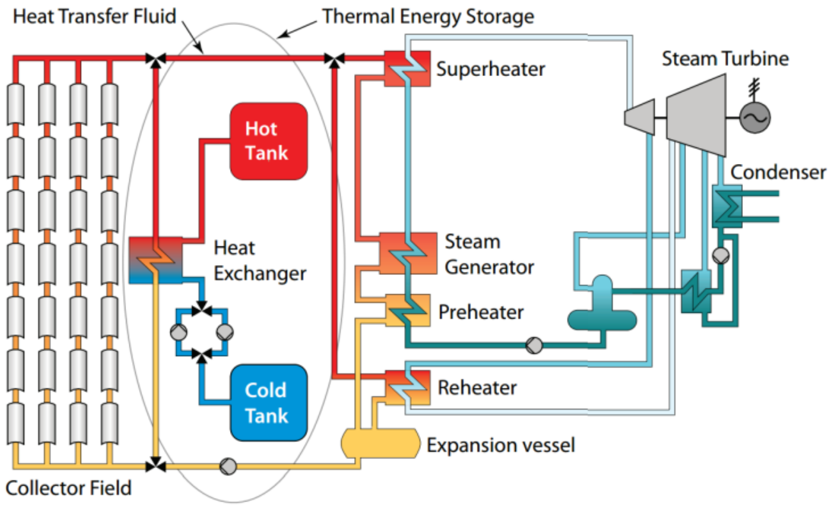
Figure 1. Example of a Parabolic Trough CSPP Setup [2]

CSP technology, having been first put into practice in the 70s, has flourished recently, with dozens of new CSP projects coming to completion in the new millennium [3]. Many improvements in design have occurred since the first plant was constructed. These include better solar tracking, usage of better materials in construction, new materials to act as better thermal transfer fluids, and the focus of this study, TESDs [4]. These upgrades make the technology more viable through a variety of means; reducing both the initial and ongoing costs of the plant, increasing the efficiency of the electricity generation, and partially overcoming the major hurdle stopping CSP from being a major energy provided: low light power generation.

There are four main types of CSP plants that are currently in use. These are Parabolic Troughs, Linear Fresnel Reflectors, Sterling Dish, and Power Tower systems. While these all have different setups, their primary mechanism is the same; reflection of sunlight onto a central receiver. Of these systems, the Sterling dish is the most efficient, reaching an efficiency of 27% [5]. The Linear Fresnel Reflector, parabolic trough, and tower system all have efficiencies of close to 13% [6]. It is worth noting photovoltaics in this comparison, as despite being a different technology and having a different mechanism of action, they also generate power from sunlight. While having reached peaks of 45% efficiency in laboratory testing environments, it is more likely to see an efficiency of 18% when used commercially [7]. While these results may fall short of electricity generation technologies such as coal and nuclear, they show that a viable and clean alternative energy source for electricity production is available.

The CSP technologies this study will be focusing on are the parabolic trough and the molten salt TESD. The parabolic trough is the most prevalent of the CSPPs as it was the first design. It consists of a series of curved, rectangular reflectors that reflect the light onto a central line containing the transfer fluid that is suspended above the trough. This variation of CSP runs at between 200 and 300 degrees. Once the heat is collected, it is either transferred to a TESD or used to generate steam for the turbine. Though there are varying setups for the TESD, they all consist of a hot and cold reservoir, heat exchanger, and a pump. When heat from an external system is available, the molten salt is pumped from the cold reservoir through the heat exchanger and stored in the hot reservoir. When the external system requires heat the process may be reversed, pumping the heated salt back through the heat exchanger and stored back in the cold reservoir [8].

Figure 2. Schematic diagram of a CSPP with a TESD [9]



Major components of a parabolic trough power plant are shown. Heat transfer fluid from the collector field may generate electricity directly or be sent to thermal energy storage for later electricity generation.

The hypothesis of this paper proposes that by looking at the efficiency of a CSP plant with a molten salt TESD attached, it would be expected that if the theoretical net daily heat of a thermal storage device is zero, then the annual efficiency of a CSP plant without a TESD would be greater than one that does due to energy losses associated with the efficiency of thermal storage devices and heat exchangers. It would follow that if the CSP plants with Thermal Storage (TS) have a lower efficiency than their TS lacking counterparts, that it would be more efficient to store energy electrically than thermally. Knowing this can allow manufacturers of CSP plants to more accurately decide on the benefits of either having more efficiency in their plant compared to having longer uptime with solar-based power generation.

2. Methods

In order to test the validity of the proposed hypothesis a meta-study was performed, analysing the efficiency of CSPPs that utilised a TESD against CSPPs that did not, and a theoretical analysis of the two systems was undertaken. The theoretical analysis was performed by applying the first law of thermodynamics with the assumptions that:

- The generator system remains the same
- There is no energy stored in the solar receiver thermal circuit
- No work is done by the solar receiver thermal circuit
- There are no energy losses in the system

In order to limit variables and minimise error, the study was restricted to parabolic trough CSPPs that are currently operational that use a steam Rankine cycle to generate power. When gathering data for the TESD equipped CSPPs the TESD was confined to a two-tank molten salt system. The required data for the analysis was collected from the National Renewable Energy Laboratory databases.

The analysis also included gathering data from currently active parabolic trough CSPPs using molten salt TESD (as seen in Table 3 and 4). The main accumulation of data included:

- Annual solar resource [SR] (kWh/m²/year)
- Aperture area [A] (m²)
- Annual Electricity generation [G] (MWh/year)

By applying the accumulated data, the annual solar resource captured by the CSPPs was calculated. This was done by multiplying the annual solar resource by the aperture area, and the annual efficiency (η) of each CSPP was also calculated. This was done by:

$$\eta = \frac{G}{SR \times A} \tag{1}$$

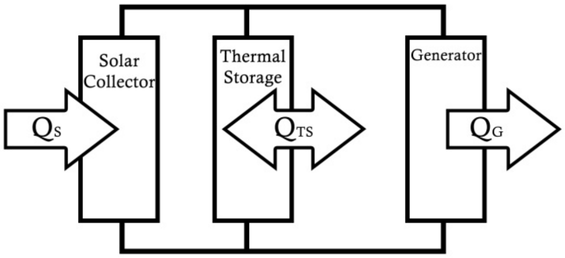
This process was repeated for operational parabolic trough CSPPs that does not utilize a TESD. Calculations for all CSPPs efficiencies were then averaged. A comparison was made between the averaged efficiencies from each category to determine if a TESD would affect the annual efficiency of a CSPP.

3. Results and Discussion

3.1. Theoretical Analysis

In order to simplify the analysis a CSPP can be separated into three closed systems; the solar receiver (SR), generator (steam Rankine cycle) and TESD. For this analysis, we shall assume that the energy losses are negligible, the steam Rankine cycle of the generator remains the same for both setups, and the internal energy of the solar receiver remains constant.

Figure 3. Simplified Schematic of the Solar Receiver Thermal Circuit



The key system to focus on is the solar receiver, and specifically the heat transferred to the generator as this is what will determine the output energy. An expansion of the following derivation of the following equations can be found in the appendix. Applying the first law of thermodynamics to this system gives us the equation:

$$\Delta Q = Q_{SR} \pm Q_{TS} + Q_G = 0 \tag{3}$$

This equation states that the heat from the solar resource being added to the system is equal to the heat leaving the system into the thermal storage and the generator. It is important to note that the heat from the TEDS can be either negative or positive depending on whether it is charging from the system or discharging into the system. When the TESD is discharging into the system the equation becomes:

$$Q_{SR,1} = Q_{TS,1} + Q_{G,1} \tag{4}$$

During the period of time when the TESD is recharging and removing heat from the system the equation is written as:

$$Q_{SR,2} = Q_{TS,2} + Q_{G,2} \tag{5}$$

For this analysis, it will also be assumed that the TESD undergoes a full recharge-discharge cycle in a day in order to prolong the effective operation time of the CSPP as would be done in an actual plant. This assumption then gives the daily net TESD heat as zero, which in turn yields an annual heat as zero. This result is equivalent to that of a CSPP which does not use a TESD.

$$Q_{SR,3} = Q_{G,3} \tag{6}$$

With the assumption that the steam Rankine cycle remains the same in each scenario, the annual efficiency of each of the CSPPs would be equal. In a real world situation, it is likely that the efficiency of a TESD CSPP would be lower than its non-TESD counterpart. This lower efficiency may be due to the energy losses associated with storing and transferring the thermal energy with the additional processes introduced by the addition of a TESD.

3.1. CSPP Data

Table 1. Parabolic Trough CSPPs Efficiency using a Molten Salt.

Plant	Aperture Area (m^2)	Solar Resource (kWh/m^2 Yr)	Available Power (MWh/Yr)	Electricity Generation (MWh/yr)	Efficiency (%)
Andasol-1 (AS-1)	510120	2136	1089616.32	158000	14.50
Andasol-2 (AS-2)	510120	2136	1089616.32	158000	14.50
Andasol-3 (AS-3)	510120	2200	1122264.00	175000	15.59
Archimede	31860	1936	61680.96	9200	14.92
Arcosol 50	510120	2097	1069721.64	175000	16.36
ASE Demo Plant	3398	1527	5188.75	275	5.30
Aste 1A	510120	2019	1029932.28	170000	16.51
Aster 1B	510120	2019	1029932.28	170000	16.51
Astexol II	510120	2052	1046766.24	170000	16.24
Extresol-1	510120	2168	1105940.16	158000	14.29
Extresol-2	510120	2168	1105940.16	158000	14.29
Extresol-3	510120	2168	1105940.16	158000	14.29
La Africana	550000	1950	1072500.00	170000	15.85
Manchasol-1	510120	2208	1126344.96	158000	14.03
Manchasol-2	510120	2208	1126344.96	158000	14.03
Termesol 50	510120	2097	1069721.64	175000	16.36
				Average	14.60

Table 2. Parabolic Trough CSPPs Efficiency without a TESD.

Plant	Aperture Area (m^2)	Solar Resource (kWh/m^2 Yr)	Available Power (MWh/Yr)	Electricity Generation (MWh/yr)	Efficiency (%)
Helios 1	300000	2217	665100.00	97000	14.58
Helios II	300000	2217	665100.00	97000	14.58
Ibersol Ciudad Real (Puertollano)	287760	2061	593073.36	103000	17.37
ISCC Kuraymat	130800	2431	317974.80	34000	10.69
La Risca	352854	2174	767104.60	105200	13.71
Lebirja 1	412020	1993	821155.86	120000	14.61
Majadas 1	372240	2142	797338.08	104500	13.11
Palma del Río I	372240	2291	852801.84	114500	13.43
Palma del Río II	372240	2291	852801.84	114500	13.43
Saguaro Power Plant	100000	2636	263600.00	2000	0.76
Shams 1	627840	1934	1214242.56	210000	17.29
				Average	13.05

Figure 4. CSPP without TESD Efficiency Distribution with Normal Distribution Curve Overlay

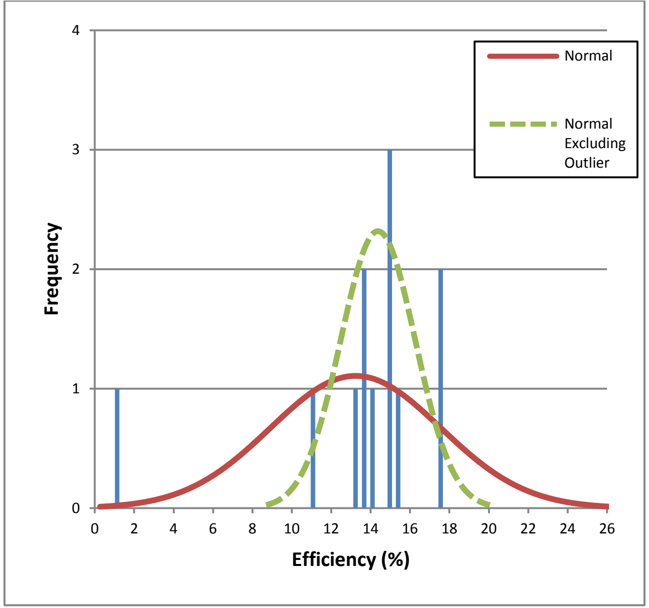
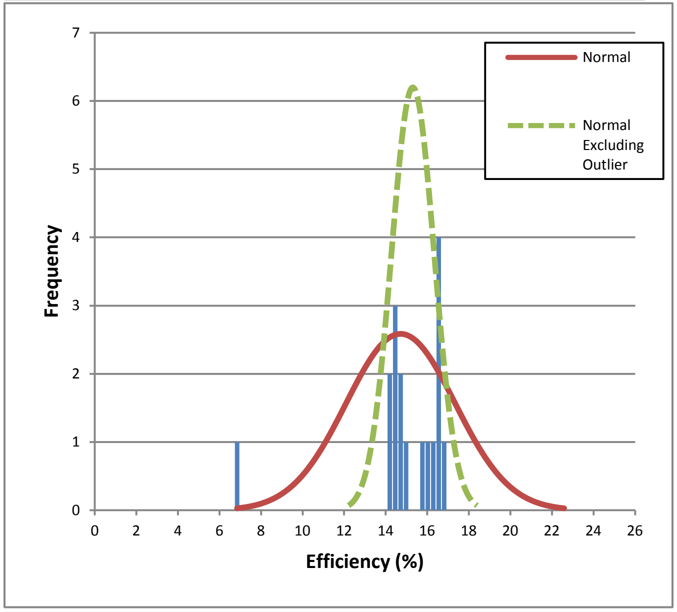


Figure 5. CSPP with TESD Efficiency Distribution with Normal Distribution Curve Overlay



4. Conclusions

The distribution of the CSPPs with the TESD presents a possible bimodal distribution. This type of distribution is usually an outcome when the results of two different processes are combined in the same set of data. When comparing the distribution of the systems using TESDs with the expected normal distribution excluding the outlier, the potential for a bimodal distribution becomes more distinct. However as the available data set is limited this cannot be confirmed. Both distribution graphs also highlight a low-end outlier by a significant amount. This again suggests that there are different processes being used though the data gathered remains insufficient to support this. When the outliers are excluded from the normal distribution curve it more closely matches the accumulated results.

The hypothesis that the efficiency of a CSPP with a TESD would be less than one without it is proven to be false from the gathered results. We found that, when compared, the average efficiency of the CSPPs with a TESD was greater than those without one. These findings would infer that the addition of a TESD in a CSPP can use more of the available solar resource. This ability may be due to the specifications of the turbine in the steam Rankine cycle used to convert the thermal energy to electrical energy.

In a CSPP, the heat transferred to the working fluid varies. This variation does not allow the turbine to operate at its maximum capacity resulting in a loss of power output. Because of this a turbine needs to be selected that is capable of working for the longest period with the lowest amount of excess solar energy. In a CSPP that uses a TESD, the excess solar energy can be stored for later use. By doing this, the generator can run at its maximum capacity for longer, and the amount of useable energy is increased.

As the difference in the efficiencies is relatively small more data must be obtained to solidify this result. To do this, a wider variety of CSPP configurations may be sampled as well as the specifications of the power block used. The calculated averages may also be misrepresentative of the actual efficiency difference due to the limited sample size available for analysis.

Following from this analysis other varieties of CSPP should be analysed along with the effects of differing power blocks and TESDs. This wider range of data should provide more conclusive results in order to distinguish more clearly the reason behind and future use of TESDs in CSPPs.

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Appendix - Theoretical Calculations

Symbol Definitions

ΔU	Total System Internal Energy
ΔQ	Total System Heat
ΔW	Total System Work
Q_{SR}	Solar Receiver Heat
Q_{TS}	TESD Heat
Q_G	Generator Heat

Looking only at the solar receiver system
The first law of thermodynamics:

$$\Delta U = \Delta Q + \Delta W \tag{2}$$

Expanding the first law to the solar receiver and assuming no energy is stored in the system, and no work is done by or to the system gives:

$$\Delta Q = Q_{SR} \pm Q_{TS} + Q_G = 0 \tag{3}$$

Having state one as the period of time when the TESD is discharging into the system the equation can then be written as:

$$Q_{SR,1} + Q_{TS,1} = Q_{G,1} \tag{4}$$

State 2 is the period when the TESD is charging which yields:

$$Q_{SR,2} = Q_{TS,2} + Q_{G,2} \tag{5}$$

If state 3 is taken over the period of a day and it is assumed that the TESD goes through a recharge-discharge cycle in a day then $Q_{TS,3} = 0$. With this assumption the equation then becomes:

$$Q_{SR,3} = Q_{G,3} \tag{6}$$

This equation is the same as that which would model a CSPP without a TESD, and when the period is extended to a year the equation and relationship still applies.