Techno-Economical Assessment of Molten Salts Thermal Energy Storage Options in a Central Receiver Solar Plant in Southern Spain

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Abstract

Thermal Energy Storage is a key issue in concentrating solar power plants due to the need to tackle the conflict between dispatchability requirements of the utilities and the intermittent and unpredictable nature of solar radiation. In this context, molten salt tanks are the more widespread solution because of their effective trade-off between cost and functionality. This work presents a techno-economical assessment regarding the use of different salt mixtures as storage medium in a central receiver solar plant as well as the eventual improvement of its performance due to increasing the specific heat of the salts by the addition of nanoparticles. As case-study, an actual plant in southern Spain has been selected and System Advisor Model was adopted as performance estimation tool. After model validation, a sensitivity analysis involving plant indicators (E_{gen}, CF, V_{TES}, $LCOE$) and different storage scenarios was carried out. The results show no significant differences between commercial mixtures and an economical advantage of using nanoparticles.

Keywords: molten salts, central receiver solar plant.

1. Introduction

Thermal energy storage (TES) allows concentrating solar power plants (CSP) to continuously produce electricity despite the intermittent and unpredictable nature of the solar radiation. This advantage in regard to other renewable sources determines an intrinsic relation between the present rising of the global markets for CSP and the existence of certain TES solutions (Fernández et al., 2019) According to Libby (2009), three basic methods for storing energy at CSP facilities can be identified: sensible heat storage, latent heat storage and thermochemical storage. Another possible classification distinguishes among active and passive storage, taking into account the eventual circulation trough the plant systems of the storage medium (Kuravi et al., 2013).

The sensible heat storage is the more immediate and accepted option because the consolidated experience and reliability in other types of power plants and industrial facilities. It performs by charging/discharging of energy in liquid or solid materials after the raising/falling of their temperature, without a phase change. Liquid storage media systems can be combined with the collector field directly or indirectly, and relay normally either in a two-tank or a single-tank system. The most used liquids in solar thermal sensible energy storage systems are sodium, synthetic organic oils and molten nitrate salts. Two-tank active storage systems combined indirectly with the solar field are used typically in parabolic trough plants with thermal oil as heat transfer fluid (Ortega et al., 2008; Kelly and Kerney, 2004). In central receiver plants, molten salts are directly connected to the solar field (Figure 1). When molten solar salt is used as storage medium, the cold and hot tanks can operate at temperatures up to 290 °C and 565 °C, respectively. Control strategies of this kind of plants are determined mainly by the behavior of heat exchangers and tanks.
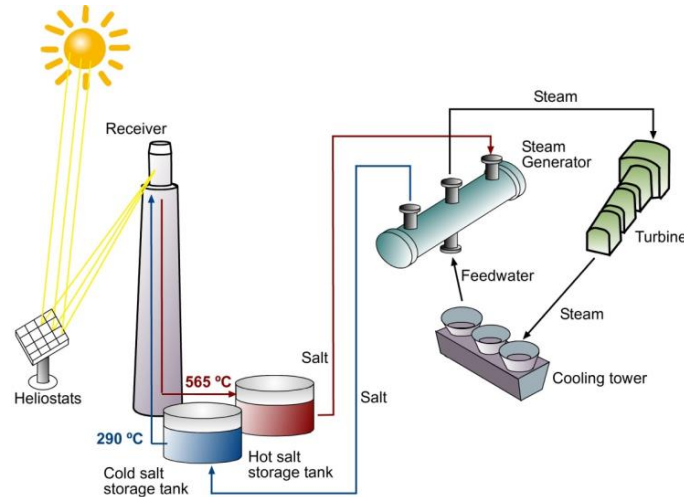
Fig. 1: Two-tank active storage system combined directly with the solar field

Some of these commercial CSP plants are located in the southern part of Spain and many actual specifications and performance data are available. This work presents the techno-economical assessment and the eventual performance improvement of a central receiver solar plant. In the study, the specific heat of the heat transfer fluid (HTF) is increased by the addition of nanoparticles. As reference-case, an actual plant located in Sevilla (Spain) has been considered. This plant is used in order to have a better representation of the basic facilities specifications and as model validation. The widely accepted tool System Advisor Model (SAM) has been used as plant performance estimation tool.

2. Material and Methods

This section presents the plant specifications and the properties of the different fluids used for the study. Details of the set of selected parameters describing the main characteristics of the plants can be found below. These parameters were selected in order to establish the most interesting plant configuration from the technological and economical points of view.

2.1. Plant specifications

In order to obtain realistic estimations, it has been used a model of plant based on an actual central receiver solar plant located Southern Spain (http://torresolenergy.com/en/gemasolar/), which will be used as reference. Plant systems have been selected and sized according to their similitude with the published specifications of the reference case. Table 1 contains used specifications.

2.2. Storage media

Different heat transfer fluids (HTF) have been evaluated as storage media: Solar Salt (60% $NaNO_3$, 40% KNO_3), Hitec salt (7% $NaNO_3$, 40% $NaNO_2$, 53% KNO_3), Hitec XL salt (48% $Ca(NO_3)_2$, 7% $NaNO_3$, 45% KNO_3) (Flamant, Benoit, 2014), and Sodium (Na). Table 2 shows their main characteristics.

Once the different HTF have been established, the next step is to study which of them leads to the best technical and economic results, making use of the different indicators studied in the following section.

The storage is based on the sensible energy variation experienced by the HTF during the charging or discharging processes:

$$Q = mc_p\Delta T, \qquad\qquad\qquad (eq. 1)$$

where:

- m is the mass of the storage material [kg],
- c_p is the specific heat in the operation temperature range [kJ kg^{-1} K^{-1}],
- ΔT is the temperature variation suffered by the HTF [K].

According to this formula, it is interesting to evaluate the impact on the results of increasing the specific heat of

the considered fluid. This increment can be achieved by adding nanometer-sized particles to the HTF with better performance, obtaining a colloidal suspension called nanofluid. By improving the specific heat of the salt, the storage capacity will be higher and hence, the storage volume could be reduced, not only in storage fluid, but also in tank size.

According to Mondragon et al., (2014) the use of nanoparticles of SiO_2 and Al_2O_3 with the solar salt can increase the specific heat up to a 50%. There are however other studies on the improvements of the c_p by using other materials as nanoparticles: Lasfargues et al. (2017) presented a study using CuO nanoparticles, in which a considerable increase of the specific heat when working at high temperature was achieved; and Muñoz-Sánchez et al. (2016) achieved an increase in c_p of up to 18% using nanoparticles called Bohemite.

How to achieve this improvement in thermal properties is still a topic of study today, although most of the accepted proposals are related to the formation of semi-solid layers around the nanoparticles.

Tab. 1: Model central receiver plant

Location	
Latitude	37° 33' 39.88" N
Longitude	5° 19' 53.56" W
Altitude	170 m
Climate	
DNI	4.86 kWh/m²/day
Diffuse radiation	1.75 kWh/m²/day
Temperature	18.4 ºC
Wind velocity	2.7 m/s
Heliostats field	
Dimensions	120 m² (10x12)
Type	Circular
Facets X axis	12
Facet Y axis	10
Reflectance area proportion	0.91
Reflector	0.99
Tower and Receiver	
Height	140m
Receiver	Cylinder
Dimensions	14.22 x 8.89 m
Panels	16
Inlet temperature	290ºC
Outlet temperature	565ºC
Thermal power	144.9 MWt

Tab. 2: Main properties of the studied storage fluids

Properties	Solar Salt	Hitec Salt	Hitec XL Salt	Sodium
Thermal conductivity [W/mK]	0.52	0.34	0.51	66.60
Heat capacity [kJ/kg K]	1.5	1.56	1.41	1.23
Fusion temperature [°C]	220-238	142	133	98
Degradation temperature [°C]	600	538	500	-
Storage cost [$/kWh]	5.8	10.7	15.2	21

2.3. Benchmarks

The following indexes have been selected for the performance estimations. These benchmarks can be used to establish a series of parameters that describe the main characteristics of the proposed configurations. Three of them are technical indicators: Annual energy generation (E_{gen}), Capacity factor (CF), and Required HTF volume (VTES); and the other three are economic indicators: Levelized cost of energy (LCOE), Net present value (NPV) and Internal rate of return (IRR):

Annual energy generation (E_{gen}): it is the sum of the energy generated per hour during a year. This indicator allows studying the production capacity in kWh for each plant configuration.

$$E_{gen} = \sum_{i=0}^{J} E_i, \qquad \text{(eq. 2)}$$

where:

- E_i is the energy generated in the hour *i*,
- *J* is the number of hours in a year.

Capacity factor (CF): defined as the energy generated by the facility during a period of time (one year) divided by the energy that would have been generated if the installation had worked at full load during that period of time.

$$CF = \frac{E_{gen}}{Pn*24*365}, \qquad \text{(eq. 3)}$$

where:

- E_{gen} is the energy generated during one year, in kWh,
- Pn is the nominal power in kW,

Required HTF volume (V_{TES}): refers to the amount of working fluid required for the production of 15h of storage.

LCOE: this indicator allows obtaining an economic valuation of the total cost of the project, including all the costs throughout its useful life: initial investment, operation and maintenance costs, costs for obtaining the capital, ... The *LCOE* is calculated as:

$$LCOE = \frac{\frac{I_0 + \sum_{i=0}^{N} C_i}{(1+r)^i}}{\sum_{i=0}^{N}\left[\frac{E_i}{(1+r)^i}\right]}, \qquad \text{(eq. 4)}$$

where:

- I_0 is the project initial investment cost,
- C_i is the cost generated in year *i*. It includes the variable and fixed costs associated to year i.
- E_i is the energy generated in year *i*.
- r is the real discount rate,
- N is the project life, in years.

NPV (Net Present Value): it is used to calculate the present value of a number of future cash flow generated by an investment. The NPV is calculated as:

$$NPV = \frac{\sum_{i=0}^{N} V_i}{(1+r)^i}, \qquad \text{(eq. 5)}$$

where:

- V_i represents the cash flow for each period *i*,

IRR: the internal rate of interest or economic return offered by an investment. In other words, it is the percentage of economic profit or loss that an investment will have. The IRR is calculated from the NPV as:

$$\text{NPV} = \frac{\sum_{i=0}^{N} V_i}{(1+r)^i} = \frac{V_1}{(1+IRR)^1} + \frac{V_2}{(1+IRR)^2} + \cdots + \frac{V_1}{(1+IRR)^N} = 0, \qquad \text{(eq. 6)}$$

where:

- *IRR* is the internal rate of return.

The previous techno-economical indicators list should be completed with the operation indicators, such as temperature or corrosion aspects, but these indicators are out of the scope of this work since there are not enough data for all studied materials.

3. Results and conclusions

System Advisor Model[1], SAM has been used as calculation tool. SAM package has been developed by the National Renewable Energy Laboratory and allows a detailed estimation of the hourly operation data and techno-economic benchmarks of the projects for renewable energy plants. For CSP plants, SAM allows to simulate the solar field, TES unit, and power block on an hourly basis as well as the corresponding integration to assess the plant annual performance. In this work, as overall operational data of the reference case (http://torresolenergy.com/en/gemasolar/) are published, the estimations regarding yearly yield and other plant operational data for model case has been validated. The simulated reference system is hence a 19.9 MW central receiver power plant, using solar salt as heat transfer fluid and with 15 equivalent hours of thermal storage. The operating temperature range of molten salt is 290- 565 °C, and the direct normal irradiance (DNI) is 950 W/m^2 with a solar multiple of 2.5.

Table 3 shows the results obtained with the different selected fluids for the modelled plant, and figure 2 summarizes graphically the results. The maximum difference obtained is a 13 % of the annual energy generation, being the differences of the rest of the benchmarks lower than 4%.

Tab. 3: Overall plant techno-economic indicators for different storage options (solar salt, validated case study)

| Indicator	HTF	Value	Deviation (%)
Generation	Solar salt	90.58 GWh	-
	Hitec salt	90.09 GWh	- 0.54
	Hitec XL	90.32 GWh	- 0.28
	Sodium	89.5 GWh	- 1.19
Capacity factor	Solar salt	56.5 GWh	-
	Hitec salt	56.2 %	- 0.53
	Hitec XL	56.3 %	- 0.35
	Sodium	55.8 %	- 1.24
TES Volume	Solar salt	3581 m^3	-
	Hitec salt	3544 m^3	- 1.03
	Hitec XL	3885 m^3	+ 8.49
	Sodium	9458 m^3	+ 164.12
LCOE	Solar salt	0.18 €/kWh	-
	Hitec salt	0.19 €/kWh	+ 5.55
	Hitec XL	0.19 €/kWh	+ 5.55
	Sodium	0.20 €/kWh	+ 11.11

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[1] https://sam.nrel.gov/
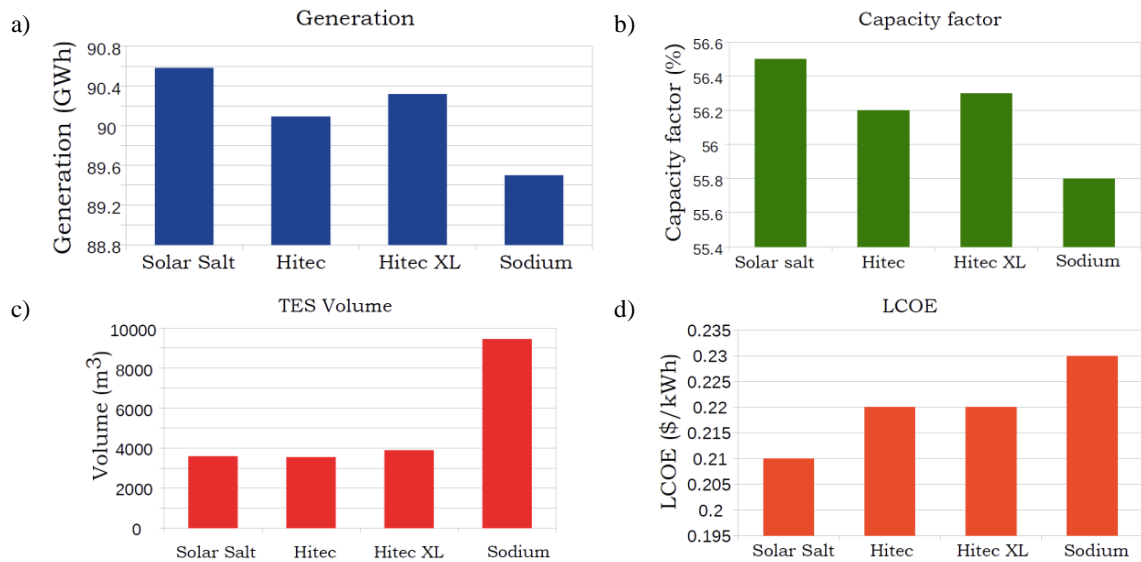
Fig. 2: Comparison of the techno-economic indicators for different storage options: a) Generation b) Capacity factor, c) HTF volume and d) LCOE

Based on the obtained results it can be concluded that, of the alternatives tested, the Solar Salt is the one that presents the best conditions for its use as HTF. However, the main factor for its use is the economic one, since the differences in most of the indicators are below 1%, due to the fact that the molten salts studied present very similar properties.

As far as storage is concerned, it has been demonstrated that using Hitec Salt can reduce the volume of salts required by 1%, offering conditions very similar to Solar Salt in the rest of the terms, although due to a higher cost, this volume reduction does not present an economic advantage, being more profitable to use Solar Salt.

Regarding the increment of c_p by addition of nanoparticles, solar salt has been considered as base case. Some sample scenarios have been considered according to the nanoparticles potential shown at laboratory level in the literature (Fernández *et al.*, 2019). The Table 4 summarizes these results.

Tab. 4: Impact on indicators of potential increasing the c_p of the HTF by adding nanoparticles

Δc_p (%)	E_{gen} (GWh)	ΔE_{gen} (%)	V_{TES} (m³)	ΔV_{TES} (%)
-	90.58	-	3581	-
25	90.97	0.47	2984	16.67
50	91.20	0.75	2487	30.55
75	91.35	0.94	2132	40.46

Although some c_p values have been simulated that still have not been achieved by adding nanoparticles, it has been demonstrated, however, that with the current progress (Δc_p = 50% achieved with SiO_2 y Al_2O_3), it is already possible to achieve great improvements in the storage, reducing the volume of salts by up to 30.55%.

4. Acknowledgments

5. References

Fernández A., Gomez-Vidal J., Oró E., Kruizenga A., Solé A., Cabeza L.F. (2019) Mainstreaming commercial CSP systems: A technology review, Renewable Energy, 140,152-176

Flamant, G., Benoit. H., 2014. Heat transfer fluid for concentrated solar systems. Solar Facilities for the european research area. Sfera II Summer School.

Kelly, B., Kearney, D., 2004. Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System, NREL.

Kuravi, S., Trahan, J., Goswami, Y., Rahman, M., Stefanakos, E., 2013. Thermal energy storage technologies and systems for concentrating solar power plants. Progress in Energy and Combustion Science 39, 285-319.

Lasfargues M, Stead G, Amjad M, Ding Y, Wen D. 2017. In Situ Production of Copper Oxide Nanoparticles in a Binary Molten Salt for Concentrated Solar Power Plant Applications. Materials, 10, 537.

Libby, C., 2009. Program on Technology Innovation: Evaluation of Concentrating Solar Thermal Energy Storage Systems. Electric Power Research Institute, Palo Alto, California.

Mondragon R., Andreu-Cabedo P., Hernandez L., Cabedo L., Martinez-Cuenca R., Torro S., Julia JE., 2014. Increment of specific heat of Solar Salt with SiO_2 and Al_2O_3 nanoparticles. Eurotherm Seminar 99. Advances in Thermal Energy Storage, 9, 582.

Muñoz-Sanchez B, Nieto-Maestre J, Iparraguirre-Torres I, Sanchez-Garcia JA, Julia JE, Garcia-Romero A. 2016. Preparation of nanofluids based on solar salt and boehmite nanoparticles: Characterization of starting materials. Conference Proceedings, 1734, 050031.

Ortega, J. I., Burgaleta, J. I., Téllez, F., 2008. Central Receiver System Solar Power Plant Using Molten Salt as Heat Transfer Fluid. Journal of Solar Energy Engineering, 130, 24501-1 - 24501-6.