Exergoeconomic Comparison of Conventional Molten Salts versus Calcium Based Ternary Salt as Direct HTF-TES In CSP Parabolic Troughs Collectors

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Abstract

This paper presents an exergo-economic comparison of a Concentrated Solar Power (CSP) Parabolic Trough Collectors (PTC) loop using two alternative types of molten salts as direct Heat Transfer Fluid (HTF) and Thermal Energy Storage (TES) based on operational simulations. The plant size and configuration are inspired in the PTC loop with molten salts HTF and TES currently under deployment at University of Evora in Portugal while the molten salts assessed are conventional molten salt (Solar Salt) and a Calcium based ternary salt. The objective of this study is to establish a comparison of exergetic performance and cost contribution per component in the plant for the two types of HTF. The applied methodology allows to identify the suitability of use for the studied salts, to detect challenges in terms of cost and performance at component level and to identify the cost composition of the CSP electricity as final product, according to the exergetic efficiency, investment and operational cost per component for each case.

Keywords: Concentrated Solar Power, Exergo-economic, Molten salts,

1. Introduction

The usage of molten nitrate salts (60% $NaNO_3$ – 40% KNO_3) as HTF and TES medium in CSP-tower projects has been widely studied and commercialized to the point of being considered nowadays a mature CSP technology. However, no use for linear focusing system has been proven at a commercial scale while the potential advantages of reducing the melting temperature of the salts to operate as HTF in these linear systems have been broadly studied. Hereby a comparison between conventional molten salt and a calcium based ternary salt as direct HTF and TES in PTC is analyzed by means of an exergo economic study based on the predicted operation for a specific plant design operating with the two different salts.

2. Methodology

2.1. Layout definition and operational simulation

Plant components and streams as well as specific properties were modelled considering a layout case study for a molten salt PTC located in Evora, Portugal (38.567 N 7.911 W). The plant considered for this study is a solar field made of parabolic collectors where molten salt circulates through the receivers, with a total output of 1,8 MWth, a net aperture width of 6,78m, distance to focus of 2,17m and a concentration ratio of 76. The plant considers two molten salt tanks with a total storage capacity of 6 MWth. A power block was model considering a rankine cycle consistent of a steam generation stage, a turbine, a synchronous electrical generator and a wet cooling stage. The turbine presents a nominal electrical power of 0.35 MWe, an inlet and outlet temperature of 490°C and 150°C respectively, a mass flow and 1.7 kg/s. The solar multiple of the considered system is 1.8.

For the current investigation, a layout was considered that would enable a good balance between the different components (solar field, storage, steam generation, electricity production). The definition of components was done regarding the decomposition to be made to study the exergetic destruction and the cost composition of the process as in Table 1.

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Tab.1: PTC components and exergy streams

Component	Inputs streams	Output streams
Cold Tank (CT)	Cold molten salt (from PB) Electricity (from PB)	Cold molten salt (to HCE)
Parabolic Collector (PC)	DNI (from sun) Electricity (from PB)	Concentrated flux (to CF)
Receiver (HCE)	Cold molten salt (from CT) Electricity (from PB) Concentrated flux (from PC)	Hot molten salt (to HT and PB)
Hot tank (HT)	Hot molten salt (from HCE) Electricity (from PB)	Hot molten salt (to PB)
Power Block (PB)	Hot molten salt (from HCE and HT)	Electricity (to parasitics and final product)

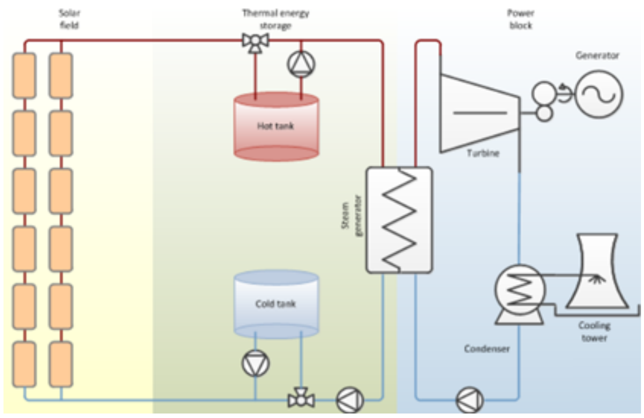

Fig 1. Schematics of the Plant Layout components considered (PC+HCE, CT, HT and PB)

2.2. Weather Data

A year of operation with hourly resolution was simulated using on ground measured DNI data for Evora, Portugal. The measured data has been recorded every 5 seconds and averaged every 10 minutes. DNI was measured with a Kipp&Zonen Pyrheliometer (model CHP1), a WMO First Class Pyrheliometer with an associated estimated uncertainty at daily scale of <1%. The pyrheliometer is calibrated every 2 years according to the standard ISO9059:1990.

Moreover, to evaluate the Plant output for a longer period of time, a cluster analysis for the same site in Evora has been performed in order to optimally select individual days able to represent the typical meteorological conditions at the site organized in clusters [1] (Guerreiro et al., 2016). This analysis had an error <1,1% when compared with the standard TMY approach, allowing a reduction of 90% in computing time.

3. Heat Transfer Fluid

Currently in Parabolic Concentrated Plants Thermal Oil is the most common HTF and Molten Salts the fluid chosen for heat storage media (HSM). Recent developments in molten salts technology are opening new application areas [1], and Molten salt is being used both as HTF and HSM in direct systems like Gemasolar in Spain (Tower Type) or in a first of a kind PTC Plant at Priolo Gargalo, Italy. In these case the so called "Solar Salt" binary mixture is being used.

In the current investigation, apart from "Solar Salt", a ternary nitrate mixture with Calcium, Potassium and Sodium was analyzed achieving both a lower fusion point and a higher temperature operation range. This is a double advantage in the sense that for the same storage capacity more energy can be stored and the investment costs for building the storage facility can also be reduced. A full characterization of the ternary mixture used was achieved in order to determine the viable operative range as well as important parameters like viscosity and heat capacity.

Tab 2. Maximum and minimum stable operating temperatures for two different molten salts [3]

Molten salt	Minimum temperature	Maximum temperature
Salt 1: 60% Na NO_3, 40% K NO_3 (Solar Salt)	221 ºC	600 ºC
Salt 2: CaNO3+ KNO3 + NaNO3 (Ternary)	134 ºC	525 ºC*

*Maximum Operating Temperature for a system mass loss of 1%

4. Exergoeconomic study

4.1 Operational Simulations

The energy performance of the PT-loop was simulated in a one year horizon with hourly resolution for both HTF-TES salts using the software SAM developed by NREL while the post-processing of data was carried out in MATLAB to solve the thermoeconomic system. The layout described above was kept the same for both salts and the only parameters changed were related to the activation of the freeze protection in tanks and piping due to the differences in the melting point between fluids. These temperatures imply also that the working temperature range is different between the fluids with 260ºC of range for the conventional solar salt from 290ºC to 550ºC as design temperatures and a range of 330ºC for the ternary salt from 160ºC to 490ºC. In these simulations, the power per stream in hourly resolution, as well as the mass flow, temperature and pressure were obtained for a year of operation in both cases.

4.2 Exergy Content per stream

The hourly exergy content budget per stream and the exergy efficiency per component was calculated considering the thermodynamic exergy and electricity only. The calculations were done on the base of the operational results obtained from SAM for power, mass flow, temperature and pressure. While for mass streams transporting exergy as sensitive heat the calculation of thermodynamic exergy content is a well-known procedure, done with respect to a reference state, based on the difference of enthalpy and entropy of the fluid with respect to their content in environmental conditions, for electromagnetic streams such as solar irradiation and concentrated flux, the equation of Petela was considered as indicated in equation (1):

$$Exergy\ of\ Solar\ Irradiation: \quad Ex_{DNI} = DN\,I \cdot \left(1 - \frac{4}{3}\frac{T_{env}}{T_{sun}} + \frac{1}{3}\left(\frac{T_{env}}{T_{sun}}\right)^4\right) \quad (1)$$

$$Exergy\ of\ HTF: \quad Ex_{HTF} = (H_{HTF} - H_{HTF_{env}}) - T_{env} \cdot (S_{HTF} - S_{HTF_{env}}) \quad (2)$$

$$Exergy\ of\ Electricity: \quad Ex_{electricity} = P_{AC} \cdot \Delta t \quad (3)$$

4.3 Economic assumptions

The investment cost per component was estimated considering an expected distribution of cost in a commercial PT plant with TES and on that basis, factors (as per cost breakdown used in SAM) were applied considering a total CAPEX (investment cost) of 6 MUSD/MWe which includes a storage cost of 65.USD/kWh (for a Solar Multiple of 1,8 and 7h storage).

Tab 3. Investment cost distribution per component

Component	Fraction of total cost
Collector and Site improvements	32%
Receiver and HTF	29%
Hot Tank and 50% TES salt	10%
Power Block	19%
Cold Tank and 50% TES salt	10%

Moreover, a classical project finance structure of 60/40 debt to equity with a final WACC of 6.7% in a 25-year horizon was considered.

4.4 Exergoeconomic Analysis

The specific exergoeconomic cost per stream, defined as the unit cost of exergy [US$/kJ], was calculated solving a cost balance equation system [4]. The equation system contains as many rows and columns as components (5) and streams (8) modeled in the system implying that is an underdetermined equation system as there are more streams than components. Therefore 3 auxiliary equations were used. Border conditions related to the free cost of solar irradiation, the equivalent cost of the streams coming from the receiver either into the Hot Tank or Power Block and a third the auxiliary equation was obtained by using the Extraction Method on the molten salt before and after entering the Power Block. Once the exergoeconomic system is solved for the plant operating with both salts, the relative added value factor and exergoeconomic factor are estimated for each case according to Bejan 1996.

The Relative Added Factor represents the relative increase in average cost per exergy unit between input (Ci) and output (Co) per component. Whenever there are components with more than one inlet or outlet, a weighted average cost is considered. Components with a high Relative added value factor are to be evaluated first in order to optimize the electricity cost.

$$R_{added\ value} = (c_{outlet} - c_{input})/c_{input} \tag{4}$$

The "Exergoeconomic factor" expresses as a ratio, the contribution of the non-exergy related cost to the total cost increase. A low value of the exergoeconomic factor calculated for a major component suggests that cost savings in the entire system might be achieved by improving the component efficiency even if the capital investment cost for this component (Zc) will increase. On the other hand, a high value of this factor suggests a decrease in the investment costs of this component at the expense of the component's efficiency.

$$EEF = \frac{\dot{Z}_c}{c_{waste} \cdot Ex_{waste} + \dot{Z}_c} \tag{5}$$

5. Results

5.1 Electricity Production

The results of the operational simulation show a major difference between both cases related to the capacity factor which is 9% higher for the ternary salt than for the conventional binary solar salt for the same layout. This result is obtained as a consequence of two main factors:

i. While the wider range of working temperature of the ternary allows to extract more power;

ii. The parasitic consumption of the tracing heaters in the field and the TES is much lower for the ternary case as the temperature difference between the cold salts and the ambient is lower. Other minor parasitic consumption such as the power consumption for the tracking system of the collector are equivalent in both cases.

The capacity factor, as well as the total electricity, the net electricity and the parasitic consumption are shown in table 4.

Table 4 Annual energy results.

HTF-TES	Total Output Electricity [GWh/year]	Parasitics [GWh/year]	Net Electricity [GWh/year]	Plant factor [%]
Solar Salt	1.08	0.47	0.61	19.8%
Ternary Salt	1.19	0.29	0.90	29.3%

5.2 Exergetic Performance

The components of the layout are connected one after the other and so the exergy output of one is the input of the following. Considering this, it is remarkable how the exergy output of each component is larger for the ternary salt case when compared to the conventional solar salt case. However, the exergy input of each component is equivalent in both cases. This is obtained because in the conventional solar salt case, the components are more intense in parasitic power consumption and so, the total exergy input is equivalent for both cases but the output is higher for the ternary. This implies that the exergy efficiency or second law efficiency is higher for the ternary (same input but higher output) and that the exergy destruction and exergetic waste is lower for each component when using ternary salts as shown in the following figure 1 and 2. This is a direct consequence of the wider range of temperature and the lower parasitic consumption of this case.

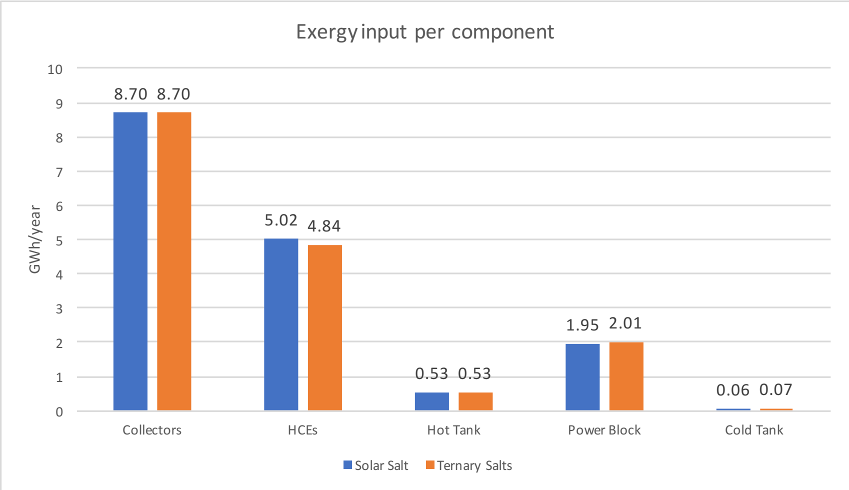

Figure 1 Exergy input and output per component

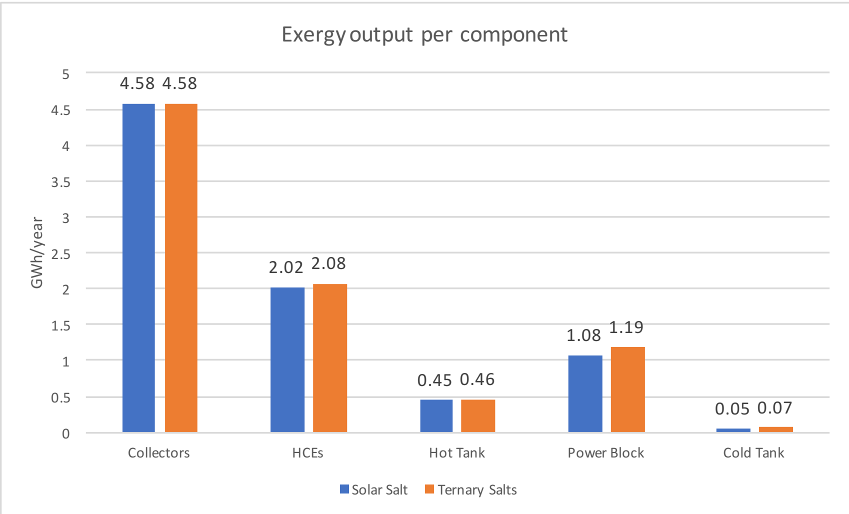

Figure 2 Exergy input and output per component

From the Exergy budget, it is also seen how the exergy is destroyed in each component reducing the exergy content of the consecutive streams in cascade as shown in figure 3. It is noticed that the exergy content per stream is always higher for the ternary salt case and in particular in the final electrical output as a consequence of both wider temperature range and lower parasitic consumption and the consequent higher efficiency of the components for that case.

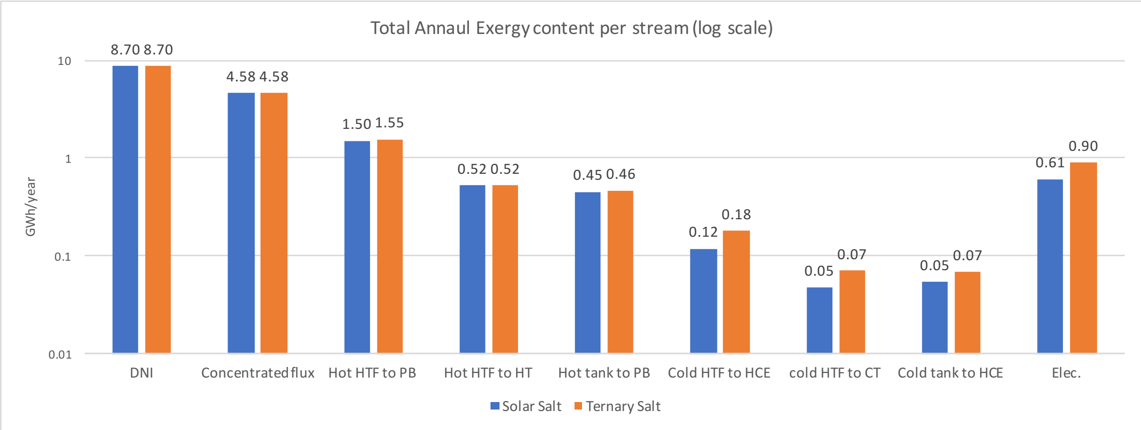

Figure 3 Total exergy content per stream

5.3 Exergoeconomic Performance

The thermoeconomic or exergoeconomic cost of the outlet exergy of a component is similar in terms of results to the well-known concept of LCOE but rather than the cost of energy of the whole plant, the thermoeconomic cost can be obtained for the exergy outputs of each component of the layout which all have their specific investment cost, exergy inlets and exergy efficiency. For the electricity coming out of the power block, this is the cost at which electricity must be sold but the thermoeconomic solution of a system also allows to see how the creation of cost being distributed in the operation of the plant and thus allows to understand which are the components that are responsible for increasing that cost. The obtained thermo-economical cost per stream as a result of solving the thermoeconomic system for both cases is shown in figure 4.

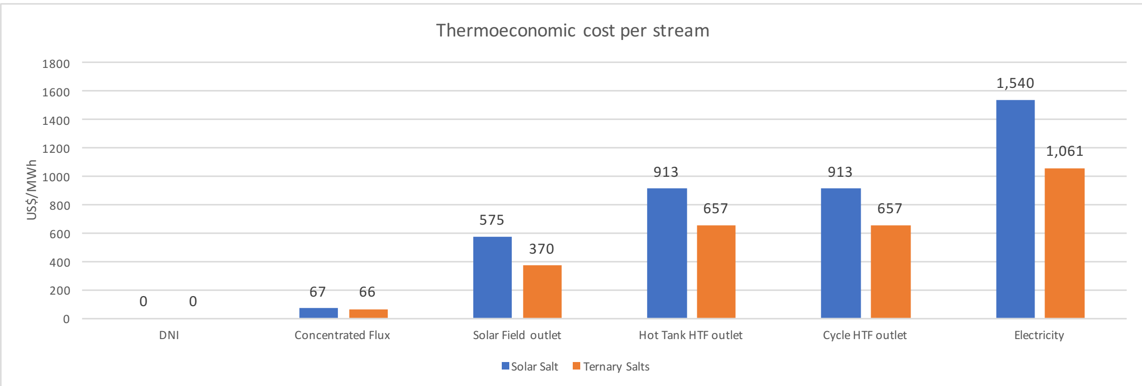

Figure 4. Thermoeconomic Cost per stream

It can be seen that the final cost of electricity seems unrealistically high. This is due to the high investment costs associated to a research pilot plant, however, a remarkable fact to observe is the proportional difference between the cost of electricity for the different salts, given the same plant layout where the ternary calcium based molten salts can reduced the price of electricity by one third when compared to conventional binary solar salt.

5.4 Relative Added value factor per component

This indicator is used to understand which component is the most important to optimize in order to reduce the final cost of the final product (electricity) but it does not give information if it would be preferable a cost reduction or a efficiency increase in the component. The results are shown in figure 5.

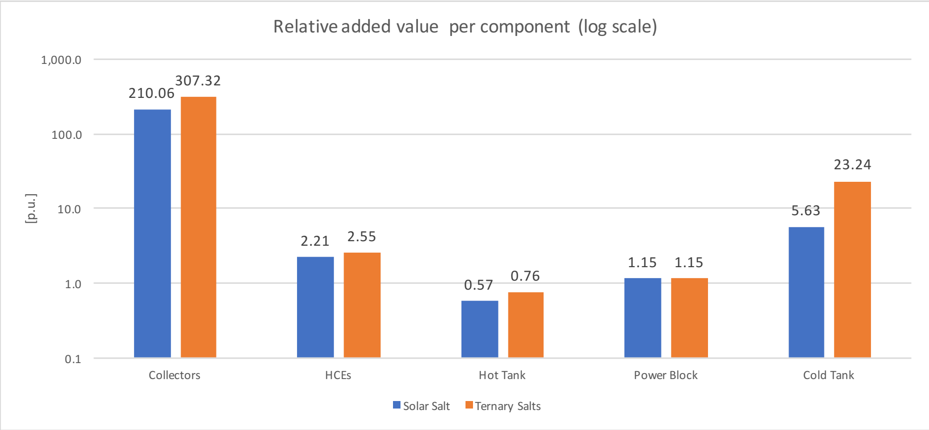

Figure 5 Relative added value

For both cases the higher relative added value is that of the parabolic collector (not including the HCE) as the cost of the inlet is mainly driven by free cost DNI followed by the cold tank. The relative added value keeps the same pattern in both cases, and a slight increment is observed in the ternary salt case. This means that for each component in the ternary case, the exergetic cost ratio is higher than for the conventional binary solar salt. This is obtained due to the lower calculated thermoeconomic cost for the ternary salt case when compared to the solar salt case implying that the difference between inlet and outlet represent a higher portion of the inlet cost for the ternary case. However, these factors are used to detected which components should be prioritized for optimization in order to reduce the final cost of electricity and it is important to notice that the order doesn't change between the cases.

5.5 Exergoeconomic factor per component

Once the relative added value factor is observed, the exergoeconomic factor can be assessed in order to understand if the component is exergoeconomic efficient. This factor is calculated as the cost of the component dover the cost of the component plus the exergy destructed in the component valorized at the cost of the stream. If this value is high or close to 1, means that the component is efficient, then it would be wiser to focus on cost reduction than efficiency improvement in order to reduce the cost of electricity and vice versa. This logic should be applied to those components with high relative added value. The exergoeconomic factor results are shown in figure 6.

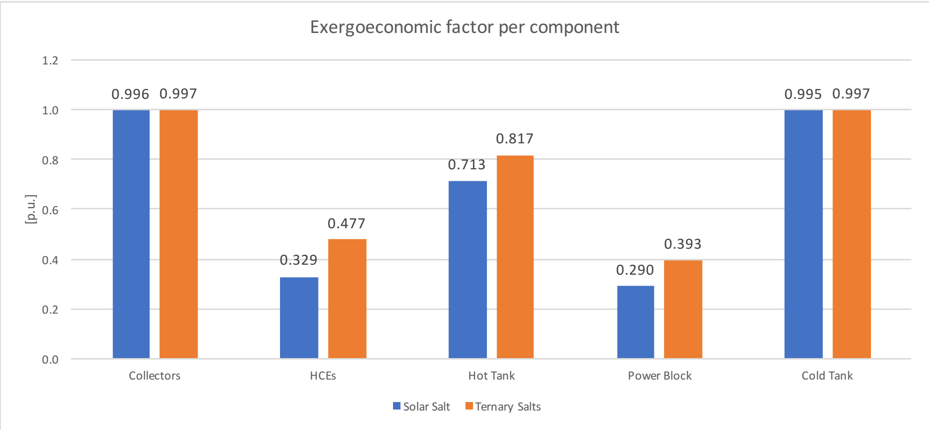

Figure 6 Exergoeconomic factor

In this study, it can be observed that the ternary salt case causes an increase in the exergoeconomic factor for all components, meaning an increase in the efficiency when taking into account the exergetic content per stream and their economic value. This is consequence of the reduction in the thermoeconomic cost per stream for the ternary case and also due to the increase in the efficiency and exergy outlet per component. This allows to infer that using ternary salts not only reduced the cost of the electricity and increase production but also makes the future challenges to be related to cost reduction per component, which is more linked to the consequences of market deployment, than increasing component efficiency which normally requires engineering and science. The high value of exergoeconomic factor for the collector component, which also present the highest relative added value, implies that the most efficient way to reduce the overall cost of the electricity in both cases is the reduction of the collector's cost followed by reductions in TES cost and finally the increase in receiver and power block efficiency.

6. Conclusions

The different energetic, exergetic and thermoeconomic performance of a PTC loop and TES operating with conventional solar salt and a calcium based ternary salt as HTF and TES were successfully investigated.

The ternary salt potentially allows to obtain higher capacity factors than conventional solar salts for a given loop and power block layout. This increase is given by the wider temperature operative range associated with a considerable lower melting point of the ternary salt compared to conventional molten salt and also due to the reduction in the parasitic consumption of the heat tracing system. The total net electricity obtained was 0,61 and 0,90 GWh/year respectively for the solar salt and ternary salt.

By using the ternary salt, an overall increase in the exergetic performance is achieved for each component of the layout due to the lower exergy destruction and waste associated to a higher operation range temperature. This causes a reduction of the thermoeconomic cost of electricity and HTF at each stage of the layout as well as an overall enhancement in the thermoeconomic indicators of "relative added value" factor and "exergoeconomic" factors.

As a summary, in order to reduce further the final cost of electricity, it is more interesting for future research to focus in a cost reduction per component rather than to pursue an efficiency increase. Concerning all components analyzed, the most effective electricity cost reduction would be obtained if the collectors' cost is reduced.

7. Acknowledgments

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