# A Novel Methodology for Comparing Thermal Energy Storage to Chemical and Mechanical Energy Storage Technologies of Electricity

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## Abstract

This paper presents a novel methodology for comparing thermal energy storage to electrochemical, chemical, and mechanical energy storage technologies. The emphasis of this paper is placed on the development of a round trip efficiency formulation for molten salt thermal energy storage systems. The charging and discharging processes of compressed air energy storage, flywheel energy storage, fuel cells, and batteries are well understood and defined from a physics standpoint in the context of comparing these systems. However, the challenge lays in comparing the charging process of these systems with the charging process of thermal energy storage systems for concentrating solar power plants (CSP). The source of energy for all these systems is electrical energy except for the CSP plant where the input is thermal energy. In essence, the round trip efficiency for all these systems should be in the form of the ratio of electrical output to electrical input. This paper also presents the thermodynamic modelling equations including the estimation of losses for a CSP plant specifically in terms of the receiver, heat exchanger, storage system, and power block. The round trip efficiency and the levelized cost of energy (LCOE) are the metrics used for comparison purposes. The thermal energy storage system is specifically compared to vanadium redox, sodium sulphur, and compressed air energy storage (CAES) systems from a large scale storage perspective of 100's of MWh. The estimated round trip efficiency and LCOE of the molten salt storage system using Andasol 3 data was about 86% and 216 $/MWh respectively. The LCOE of molten salt storage system was significantly lower than that of vanadium redox, sodium sulphur, and CAES. The preliminary results of this modelling will serve as a platform for the future generation of a thermal energy storage roadmap integrated in a comprehensive energy storage roadmap from a system of systems perspective.

**Keywords:** round trip efficiency, thermal energy storage, energy storage roadmap, levelized cost of energy, exergy analysis, molten salt losses, mechanical storage, chemical storage

## NOMENCLATURE

| | |
|---|---|
| $\eta$ | Roundtrip efficiency [%] |
| $\eta_{th}$ | Cycle efficiency |
| $\eta_{hx}$ | Thermal efficiency of the heat exchanger [%] |
| $A_{ref}$ | Reference area [$m^2$] |
| $C_p$ | Specific heat capacity [J/kgK] |
| $E_{out,ws}$ | CSP output energy with storage [J] |
| $E_{out,ns}$ | CSP output energy without storage [J] |
| $FCR$ | Fixed charge rate |
| $\Delta G_d$ | Exergy destruction during discharge [J/kg] |
| $\Delta G_c$ | Exergy consumption during charge [J/kg] |
| $h$ | Enthalpy [J/kg] |
| $\Delta H$ | Change in enthalpy [J/kg] |
| $HXL$ | Heat exchanger losses [J] |
| $IC$ | Investment cost [US Dollars] |
| $L$ | Height of the tank [m] |
| $m_{salt}$ | Mass of molten salt [kg] |
| $m_{HTF}$ | Mass of HTF [kg] |
| $m_{dotf}$ | Mass flow rate of the HTF |
| $p$ | Perimeter of the round tank [m] |
| $Q_{loss,top}$ | Heat lost through the top of the cylinder [J] |
| $Q_{loss,cond}$ | Heat lost through the foundation [J] |
| $Q_{loss,env}$ | Heat lost through the sides [J] |
| $Q_{in}$ | Input energy [J] |
| $Q_{out}$ | Output energy [J] |
| $Qdot$ | Rate of heat lost [W] |
| $SSL$ | Storage system losses [K] |
| $\Delta S$ | Change in entropy [J/kg] |
| $T_{out,st}$ | Temperature of the hot tank [K] |
| $T_{in,st}$ | Temperature of the cold tank [K] |
| $T_{out,HTF}$ | HTF outlet temperature [K] |
| $T_{in,HTF}$ | HTF inlet temperature [K] |
| $T_H$ | Maximum temperature reached during charging [K] |
| $T_{hot}$ | Temperature of the hot tank [K] |
| $T_{cold}$ | Temperature of the cold tank [K] |
| $T_m$ | Temperature of the tank [K] |
| $T_{ref}$ | Reference Temperature [K] |
| $T_{amb}$ | Ambient temperature [K] |
| $T_{tank}(x)$ | Temperature variation along the height of the tank [K] |
| $T_{env}$ | Temperature outside the tank [K] |

| | |
|---|---|
| $U_{overall}$ | Overall heat transfer coefficient [W/m$^2$K] |
| $U(T)$ | Sensible energy storage expression [J] |
| $W_T$ | Turbine work [J] |
| $W_P$ | Pump work [J] |

## 1. Introduction

Energy storage is an integral component of the smart grid concept in the context of energy storage modelling and integration of renewables into the grid. The ability to generate thermal energy and/or electricity from a stock of energy storage technologies, effectively and on demand, will determine their respective values as stored energy. The advantages of energy storage include but are not limited to power quality, load levelling, reduction in transmission line capacity, and having cost efficient power systems [20]. Round trip efficiency is an important parameter for assessing performance of all storage systems in general and it's simply defined in this context as the ratio of energy output to energy input. Round trip efficiencies for different energy storage systems are specified [20].

The ability to provide electricity at night during peak hours effectively and in a cost efficient manner sets the stage for concentrating solar power (CSP) with thermal energy storage through the elimination of large scale photovoltaic systems with battery storage. CSP with thermal energy storage is an economic incubator for independent power producers (IPP's) in the context of the time of day tariff, whereby a higher tariff is given to the IPP's for generating power during peak hours. In the context of South Africa, the time of day tariff was increased to 270% of the base rate when providing power between the hours of 16:30 to 21:30 [22].

The inherent need to develop and substantiate a novel methodology for comparing thermal energy storage (TES) to other electrical storage technologies is envisaged for laying the groundwork for a comprehensive thermal energy storage roadmap from a performance perspective. Round trip efficiency is the currently used performance metric in all storage systems including thermal energy storage systems. There are three formulations of round trip efficiency currently used in TES systems namely the first law efficiency, second law efficiency, and storage effectiveness [1]. The Achilles heel of performance evaluations of TES is encapsulated in the definitions of these efficiencies, which are in the form of the ratio of thermal energy output to thermal energy input. This formulation methodology makes it difficult to compare TES to electrical storage technologies, whereby the formulation takes the form of the ratio of electrical energy output to electrical energy input. The analysis done in this paper presents an ingenious methodology of formulating the round trip efficiency of a molten salt storage system, such that it can be compared to electrical storage technologies from an electrical energy perspective. The comparison is specifically made to vanadium redox batteries, sodium sulphur batteries, and compressed air energy storage, as these systems have large scale storage capabilities of 100's of MWh. Modelling and simulation of TES integration in a CSP plant is essential in analysing the performance of TES systems. Storage sizing methodologies that don't incorporate performance are not robust in depicting the losses and usability [1]. The integration of TES and its design considerations are discussed [2].

TES system integration in a CSP plant effectively provides power on demand during night hours and economic benefit to CSP power producers by incorporating the time of day tariff. The performance metric of round trip efficiency and the cost metric of levelized cost of energy (LCOE) are essential parameters for comparing TES systems to electrical storage systems through the development of a comprehensive thermal energy storage roadmap that would entail performance, cost, technological readiness levels, economic, and policy framework for TES technologies. A fleet of TES technologies are investigated for performance and cost efficiency [3-7]. The need to develop cost efficient TES systems complimented with low melting point and high temperature materials research for TES systems is envisioned for the future.

## 2. Methodology

The charging and discharging processes of batteries and fuel cells, compressed air energy storage, flywheel energy storage, and TES are compared in Figures 1 to 4 in order to derive the round trip efficiency formulation. Efficiency is simply defined as the ratio of electrical energy output to electrical energy input, as shown in Figures 1 to 3. It is important to note that the input energy is equivalent to the energy of a system without storage in Figures 1 to 3. The input source of energy is electrical energy in Figures 1 to 3 except for Figure 4, where the input is thermal energy. The very same stipulation holds for TES and is demonstrated by taking the energy ratio of a CSP system with storage divided by a CSP system without storage, as shown in Figure 4. The ratio obtained equals the thermal storage efficiency.

The block diagrams of Figures 1 to 3 shows the representative values of round trip efficiency for these systems garnered through literature. Figure 1 shows a simplified charging and discharging cycle of a battery and fuel cell. Figure 2 shows electrical energy fed into a compressor which drives the air into a cavern/vessel, which is later discharged due to peak demand. Figure 3 shows electrical energy driving a motor/generator system that spins a flywheel, which later drives the generator due to the inertia of the flywheel during the discharge cycle. Figures 4 and 5 illustrate the mechanism of a parabolic trough CSP plant with storage. The efficiency of the storage system is expressed as follows in Figures 1 to 4:

$$\eta = \frac{Eout,ws}{Eout,ns} \qquad (1)$$

This performance metric expression provides a compact way to compare TES to electrical storage technologies from an electrical energy perspective.

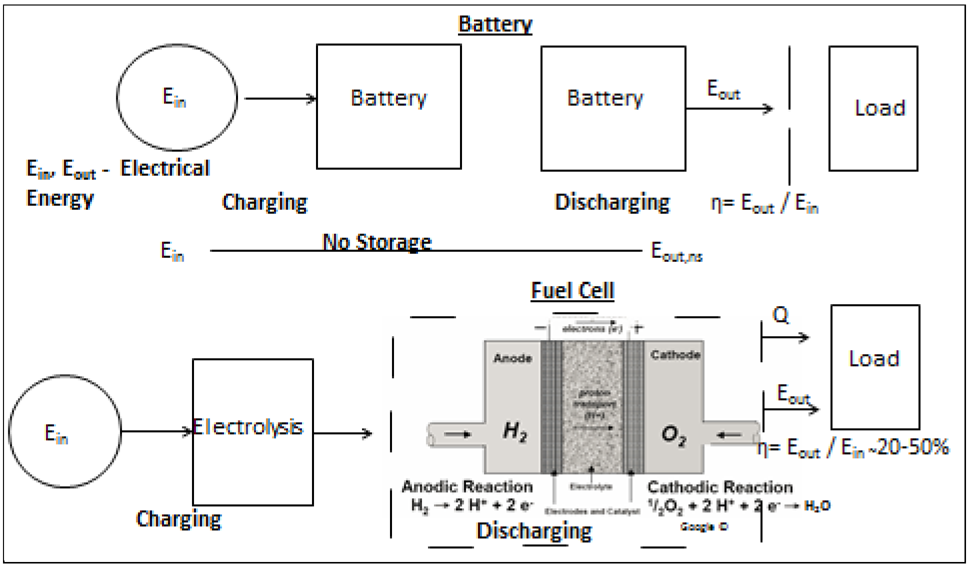


**Figure 1** Charging and discharging processes of batteries and fuel cells.

The round trip efficiencies of batteries are shown in Table 1.

**Table 1** Round trip efficiencies of batteries [20].

| Battery | Round trip efficiency |
|---|---|
| Vanadium redox | 75-85% |
| Lead acid | 70-90% |
| Sodium sulphur | 80-90% |
| Lithium ion | 85-90% |
| Nickel cadmium | 60-65% |

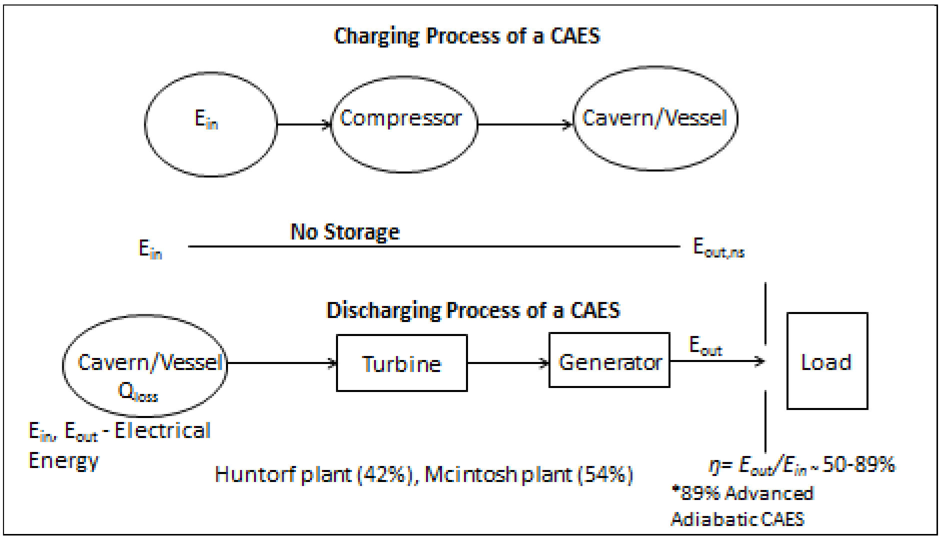


**Figure 2** Charging and discharging processes of CAES.

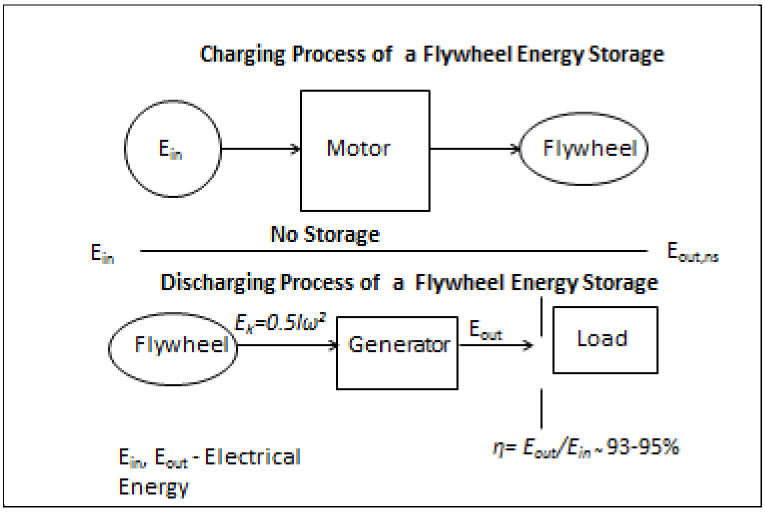


**Figure 3** Charging and discharging processes of flywheel energy storage.

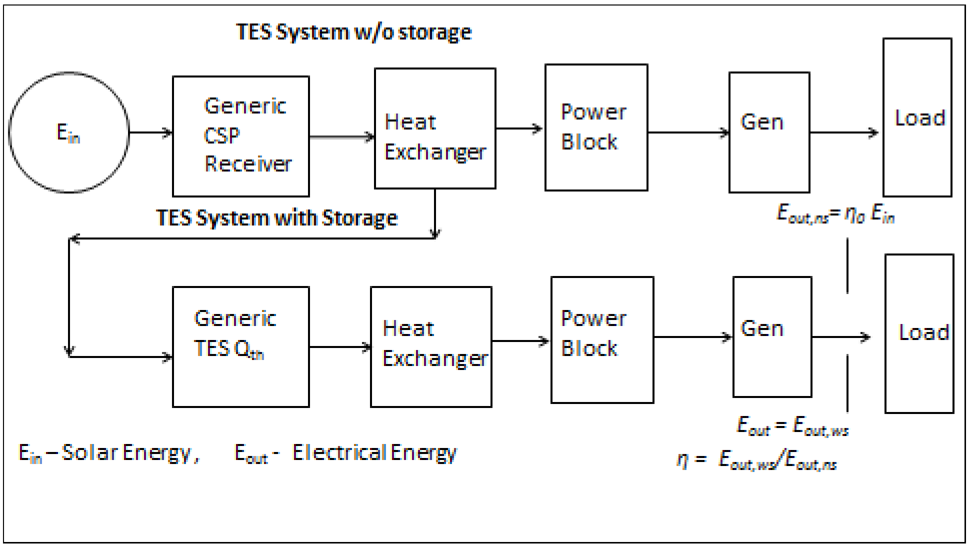


**Figure 4** Charging and discharging processes of a CSP plant with and without storage.

**Figure 5** Andasol-1 & 2 CSP plant layouts [21].

## 2.1 Energy Analysis and LCOE Formulation

The thermodynamic model comprises of the governing equations of heat transfer between heat transfer fluid (HTF) and molten salt storage; heat exchanger losses; and molten salt storage tank losses.

The expression relating the temperatures of the HTF and molten salt is shown below (2).

$$T_{out,st} = T_{in,st} + \eta_{hx} (T_{out,HTF} - T_{in,HTF}) \quad (2)$$

The sensible expression for molten salt storage is expressed as follows:

$$U(T) = m_{salt} C_{p,salt} (T_{out,st} - T_{in,st}) \quad (3)$$

The heat transfer relationship between HTF and TES is expressed as follows:

$$m_{HTF} C_{p,HTF} (T_{out,HTF} - T_{in,HTF}) = U(T) - SSL - HXL \quad (4)$$

A simple Rankine cycle power block is shown in Figure 6.

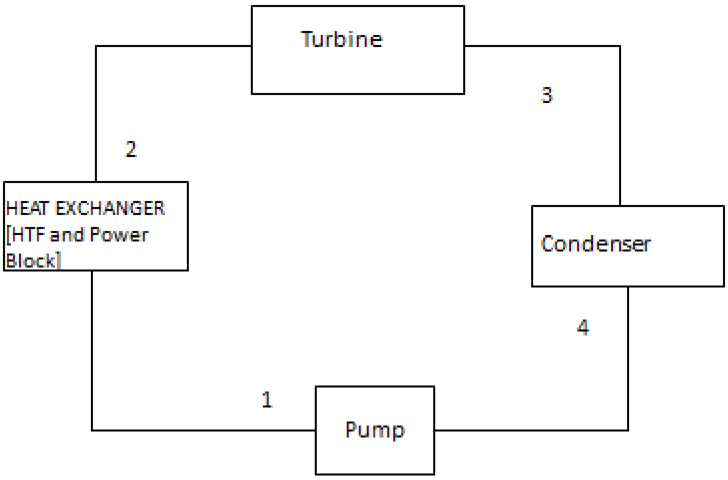


**Figure 6** Power Block.

By performing component analysis through the application of the first law of thermodynamics yields the expressions as follows:

$$\text{Heat Exchanger: } Q_{in} = h_2 - h_1 \quad (5)$$

$$\text{Turbine: } W_T = h_2 - h_3 \quad (6)$$

$$\text{Condenser: } Q_{out} = h_4 - h_3 \quad (7)$$

$$\text{Pump: } W_P = h_1 - h_4 \quad (8)$$

$$\eta_{th} = [W_T + W_P] / Q_{in} \quad (9)$$

The expressions for the energy with and without storage are expressed as follows:

$$E_{out,ws} = [U(T) - SSL - HXL]\ \eta_{th} \quad (10)$$

$$E_{out,ns} = [U_{HTF}(T) - HXL]\eta_{th} \quad (11)$$

where by:

$$U_{HTF}(T) = m_{HTF}\, C_{p,HTF}\, (T_{out,\,HTF} - T_{in,HTF}) \quad (12)$$

In essence, the output energy is the product of thermal energy and plant efficiency. It is important to note that the plant efficiency is the same in the cases with and without storage. The round trip efficiency is expressed as follows:

$$\eta = E_{out,ws} / E_{out,ns} = [U(T) - SSL - HXL] / [U_{HTF}(T) - HXL] \quad (13)$$

Molten salt storage system losses estimation methods are discussed in the literature [8-10].

The tank losses are expressed as follows:

$$Qdot_{cond,loss} + Qdot_{top,loss} + \int_0^L ph\,(T_{tank}(x) - T_{env})dx = U_{overall}A_{ref}(T_m - T_{amb}) \quad (14)$$

The round trip efficiency can be expressed as follows:

$$\eta = \frac{m_{salt}C_{p,salt}\,(T_{out,st} - T_{in,st})\{2(1-\eta_{hx})\} - \int_{to}^{tf} Qdotloss\,dt}{m_{HTF}\,C_{p,HTF}\,(T_{out,HTF} - T_{in,HTF})(1-\eta_{hx})} \quad (15)$$

The round trip efficiency expressed in (15) provides a direct comparison to electrical storage technologies given the ratio is based on electrical energy, as opposed to TES performance efficiencies defined in literature and expressed in (16) and (17).

$$\eta_{TES,I} = T_{hot} - T_{cold} / T_H - T_{cold} \quad (16)$$

$$\eta_{TES,II} = |\Delta G_d / \Delta G_c| \quad (17)$$

The other metric that is important for comparing TES to other electrical energy storage technologies is the LCOE and is expressed in (18).

$$LCOE\ [\$/MWh_e] = \frac{IC*FCR + Fuel\ cost + O\&M\ cost}{Net\ electric\ output} \quad (18)$$

## 2.2 Exergy Analysis

The fundamentals of exergy analysis are discussed [12-19]. The exergy change of the storage is expressed in (19). The exergy analysis was carried out in order to take into account the loss of available work due to temperature loss of the storage medium. The reference temperature is taken to be the ambient temperature in this analysis. The change in enthalpy and the change in entropy equations (24-27) during charging and discharging are derived using a linear form of the specific heat capacity where c and d are constants.

$$\Delta G = \Delta H - T_{amb}\,\Delta S \quad (19)$$

where by:

$$\Delta H_c = \int_{T_{ref}}^{T_{hot}} C_p(T)\, dT \quad (20)$$

$$\Delta H_d = \int_{T_{ref}}^{T_{cold}} C_p(T)\, dT \quad (21)$$

$$\Delta S_c = \int_{T_{ref}}^{T_{hot}} \frac{C_p(T)}{T}\, dT \quad (22)$$

$$\Delta S_d = \int_{T_{ref}}^{T_c} \frac{C_p(T)}{T}\, dT \quad (23)$$

$$\Delta H_c = c\left(T_{hot} - T_{ref}\right) + \frac{d}{2}\left(T_{hot}{}^2 - T_{ref}{}^2\right) \quad (24)$$

$$\Delta S_c = c\, ln\frac{T_{hot}}{T_{ref}} + d\left(T_{hot} - T_{ref}\right) \quad (25)$$

$$\Delta H_d = c\left(T_{cold} - T_{ref}\right) + \frac{d}{2}\left(T_{cold}{}^2 - T_{ref}{}^2\right) \quad (26)$$

$$\Delta S_d = c\, ln\frac{T_{cold}}{T_{ref}} + d\left(T_{cold} - T_{ref}\right) \quad (27)$$

The specific heat capacities of the HTF and molten salt were assumed to be linear and are expressed in (28) and (29) respectively.

$$C_{p,HTF}(T) = 0.002414\ T(^0C) + 1.498 \ \ (kJ/kgK) \quad (28)$$

$$C_p(T) = 1443 + 0.172\ T(^0C) \ \ (J/kgK) \quad (29)$$

The heat exchanger exergy loss is expressed in (30).

$$EX_{Loss,HX} = \int_{to}^{t} m_{dotf}\left[\int_{Ti}^{To} C_p(T)dT - T_{amb}\int_{Ti}^{To}\frac{C_p(T)}{T}\, dT\right] dt \quad (30)$$

## 3. Results and Discussion

The round trip efficiency and LCOE of the Andasol 3 plant were estimated with expressions (15) and (18) using Andasol 3 data and are tabulated in Table 2. Andasol 3 is a $50MW_e$ parabolic trough plant with 7.5 hours of molten salt storage in Spain. Parabolic trough CSP plants with molten salt storage have the least LCOE compared to vanadium redox batteries, sodium sulphur batteries, and compressed air energy storage, as shown in

Tables 2, 4, and 5. The estimated round trip efficiency of molten salt storage in Table 2 compares well with the round trip efficiencies of compressed air energy storage, vanadium redox, and sodium sulphur batteries.

**Table 2** Andasol 3 data used for estimation of round trip efficiency and LCOE.

| | |
|---|---|
| **Molten salt tank losses** | 2.5% |
| **Heat exchanger losses** | 10% |
| **Temperature hot tank** | 386$^0$C |
| **Temperature cold tank** | 296$^0$C |
| **HTF inlet temperature** | 293$^0$C |
| **HTF outlet temperature** | 393$^0$C |
| **Molten salt energy** | 125 MW |
| **HTF energy** | 125 MW |
| **Energy output with storage** | 97 MW |
| **Energy output without storage** | 112.5 MW |
| **Round trip efficiency** | 86% |
| **Total project cost** | 400 million Dollars |
| **Annual O&M cost** | 1.6 million Dollars |
| **Net electric output per annum** | 200 GWh |
| **LCOE** | 216 $/MWh$_e$ |

The cost of electricity output for a molten salt storage system for a CSP plant equals the total cost of the stored electricity as shown in Table 2. The cost of generating electricity is added to the total cost of the stored electricity for the other technologies lised in Table 4 in order to compare it with the LCOE of the molten salt storage system. The cost of generating electricity based on conventional and renewable sources are 77 $/MWh$_e$ and 97 $/MWh$_e$ respectively [25]. The exergy analysis results using Andasol 3 data are shown in Table 3.

**Table 3** Exergy analysis results.

| | |
|---|---|
| $\Delta G_c$ | 70 137 J/kg |
| $\Delta G_d$ | -1473 J/kg |
| **Exergy destruction/loss** | 2.1% |
| **Exergy efficiency** | 98% |
| **Heat exchanger exergy loss** | 11% |

Exergy destruction is the lost available work, which is proportional to entropy generation, and as seen in Table 3, the storage exergy destruction is relatively small. This result is indicative of the fact that exergy destruction in a CSP plant with storage materializes in the power block, where it lowers the cycle efficiency. Therefore, the round trip efficiency of molten salt storage systems can be formulated using energy analysis only.

The estimated LCOE and cost breakdown of 50 MW vanadium redox and sodium sulphur batteries with 6 hours of storage are shown in Table 4.

**Table 4** LCOE cost breakdown of vanadium redox and sodium sulphur batteries [23].

| **Technology** | **Energy Discharged per Year (MWh)** | **Investment Cost ($)** | **Fixed O&M Cost ($/kW-yr)** | **Variable O&M Cost ($/kWh)** | **Battery Replacement. Cost ($/kW)** | **Total O&M Cost ($10^6$$)** | **LCOE ($/MWh)** |
|---|---|---|---|---|---|---|---|
| Vanadium redox | 109 500 | 186 703 160 | 4.5 | 0.0005 | 746 | 37.4 | 519 |
| Sodium sulphur | 109 500 | 153 530 750 | 4.5 | 0.0005 | 450 | 22.6 | 351 |

**Table 5** LCOE of other storage technologies – 50 MW, 300 MWh [24].

| **Technology** | **LCOE [$/MWh$_e$] (cost of stored electricity)** | **LCOE [$/MWh$_e$] based on conventional source** | **LCOE [$/MWh$_e$] based on renewable source** |
|---|---|---|---|
| CAES | 275 | 352 | 372 |
| Sodium sulphur | 350 | 427 | 447 |
| Advanced lead acid T1 | 625 | 702 | 722 |
| Advanced lead acid T2 | 325 | 402 | 422 |
| Zinc bromine | 288 | 365 | 385 |
| Vanadium redox | 525 | 602 | 622 |

The estimated LCOE values of vanadium redox and sodium sulphur batteries in Table 5 are in close agreement with the corresponding values in Table 4. In essence, the usage of molten salt both as a heat transfer fluid (HTF) and storage in parabolic trough CSP plants yields lower LCOE and higher efficiency, which makes it cost competitive to solar tower systems.

## 4. Conclusion

The estimated round trip efficiency of 86% of molten salt storage systems compares well with the first law efficiency measure of TES which ranges from 93-99%. The estimated LCOE of parabolic troughs with thermal energy storage is the lowest compared to compressed air energy storage, vanadium redox, and sodium sulphur batteries. The use of molten salt both as an HTF and storage in parabolic trough plants will lower the LCOE to a point of making it cost competitive with solar towers. Hence, this sets the stage for CSP plants with thermal energy storage in the context of the smart grid concept.

The exergy destruction of molten salt storage was estimated to be about 2.1%, which justifies that molten salt storage systems have both high energy and exergy efficiency. The storage exergy efficiency was estimated to be about 98% using the second law efficiency formulation.

According to the International Energy Workshop (IEW) held in 2013, TES roadmap requires the need to determine the maturity of thermal energy storage technologies in terms of the push and pull of each technology; legal and technological framework readiness; breakthrough technologies in high temperature thermal energy storage; favourable electricity tariffs; envision needs for future energy systems complimented with a rolling-plan vision for the year 2050 deployment. This study is in conjunction with the vision of the IEW from a performance and cost comparison of TES with other electrical storage technologies.

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