SASEC2015
Third Southern African Solar Energy Conference
11 – 13 May 2015
Kruger National Park, South Africa

A THERMODYNAMIC MODEL FOR COMPARING THERMAL ENERGY STORAGE SYSTEM TO ELECTROCHEMICAL, CHEMICAL, AND MECHANICAL ENERGY STORAGE TECHNOLOGIES

Hameer S.* and Van Niekerk J.L.
*Author for correspondence
Centre for Renewable and Sustainable Energy Studies,
University of Stellenbosch,
Stellenbosch, 7600,
South Africa,
E-mail: hameer@sun.ac.za

ABSTRACT
This paper presents a novel methodology for comparing thermal energy storage to electrochemical, chemical, and mechanical energy storage technologies. The machination of this model is hinged on the development of a round trip efficiency formulation for these 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 results from the modelling are compared with solar power plants in operation and literature. The crux of this modelling can be regarded as a platform for the generation of a thermal energy storage roadmap cocooned in a comprehensive energy storage roadmap from a system of systems perspective.

INTRODUCTION
The quest to develop a novel methodology for comparing thermal energy storage (TES) to other electrical storage technologies is envisaged for laying the groundwork for jettisoning the thermal energy storage roadmap. Round trip efficiency is the currently used performance metric in 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. 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 plethora of TES technologies are investigated for performance and cost efficiency [3-7]. The quest to develop cost efficient TES systems complimented with low melting point and high temperature materials research for TES systems is envisioned for the future.

NOMENCLATURE

η	Roundtrip efficiency [%]
η_{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
ΔG_d	Exergy destruction during discharge [J/kg]
ΔG_c	Exergy consumption during charge [J/kg]
h	Enthalpy [J/kg]
IC	Investment cost [US Dollars]
L	Height of the tank [m]
msalt	Mass of molten salt [kg]
m_{HTF}	Mass of HTF [kg]
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]
Qdot	Rate of heat lost [W]
$T_{out,st}$	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_m	Temperature of the tank [K]
T_{amb}	Ambient temperature [K]
Ttank(x)	Temperature variation along the height of the tank [K]
T_{env}	Temperature outside the tank [K]
Uoverall	Overall heat transfer coefficient [W/m^{2}K]
U(T)	Sensible storage expression [J]

METHODOLOGY

The charging and discharging processes of batteries and fuel cells, compressed air energy storage (CAES), 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 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 underpinnings of a parabolic trough CSP plant with and without storage. Round trip efficiency 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.

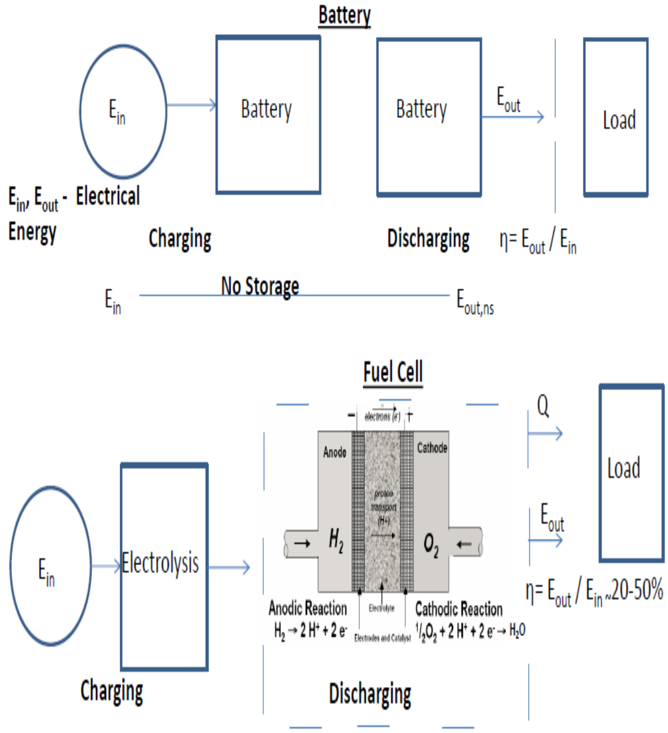

Figure 1 Charging and discharging processes of batteries and fuel cells.

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

Table 1 Round trip efficiencies of batteries.

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

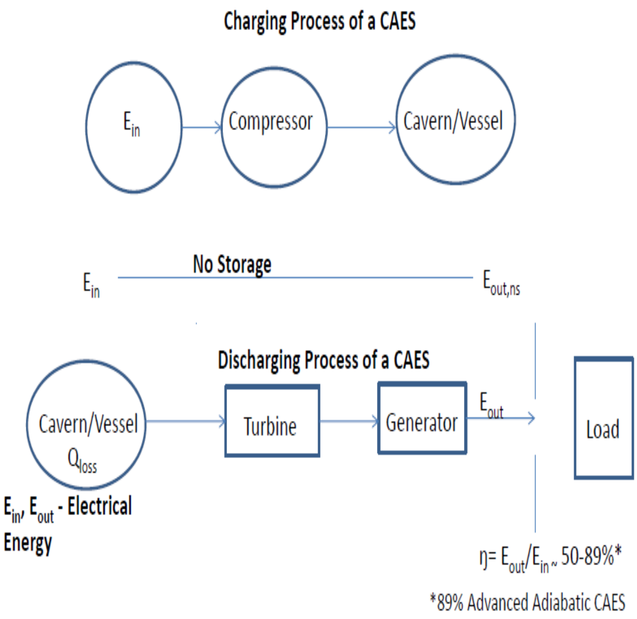

Figure 2 Charging and discharging processes of CAES.

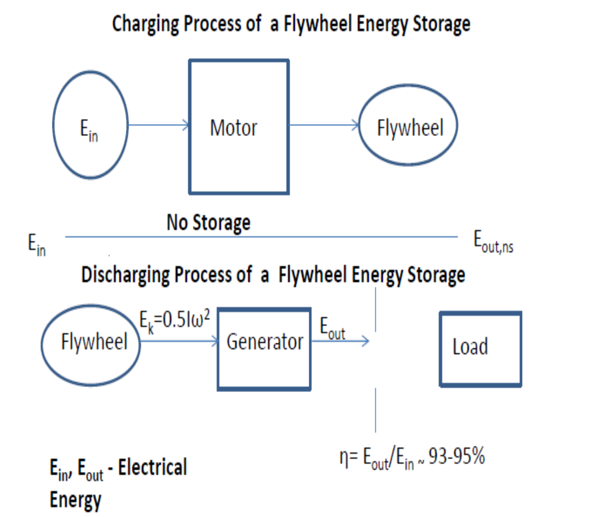

Figure 3 Charging and discharging processes of flywheel energy storage.

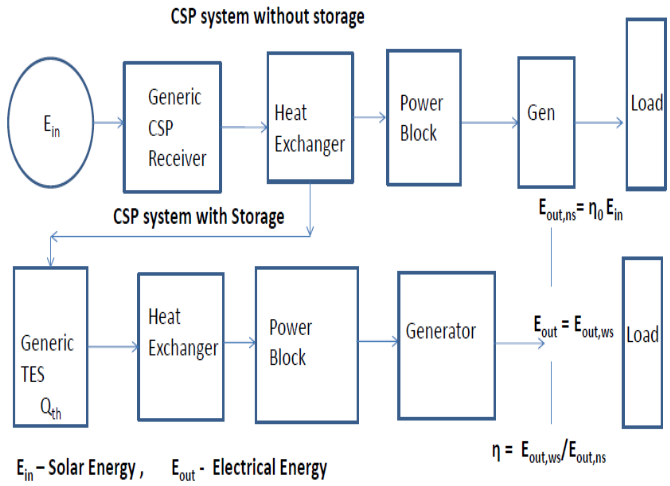

Figure 4 Charging and discharging processes of a CSP plant with and without storage.

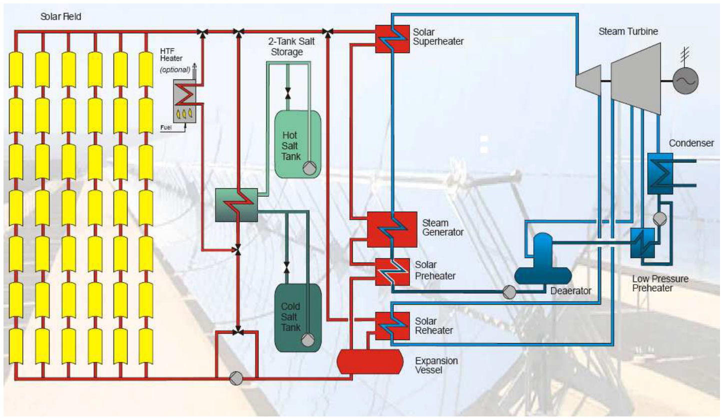

Figure 5 Andasol 1 CSP plant.

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 oil to salt heat exchanger is shown in Figure 6.

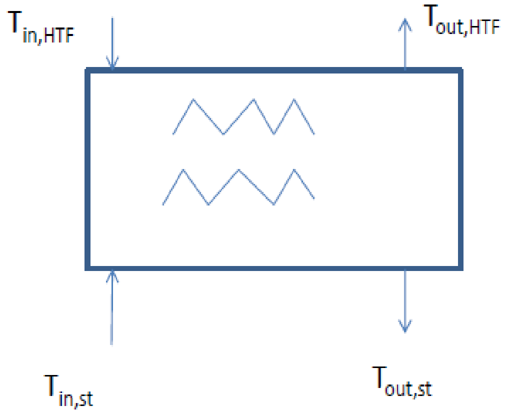

Figure 6 Oil to salt heat exchanger.

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

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

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

$U(T) = msaltCp_{,salt} (T_{out,st} - T_{in,st})$ (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) - Storage System Losses - Heat Exchanger Energy Losses (4)

A simple Rankine cycle power block is shown in Figure 7.

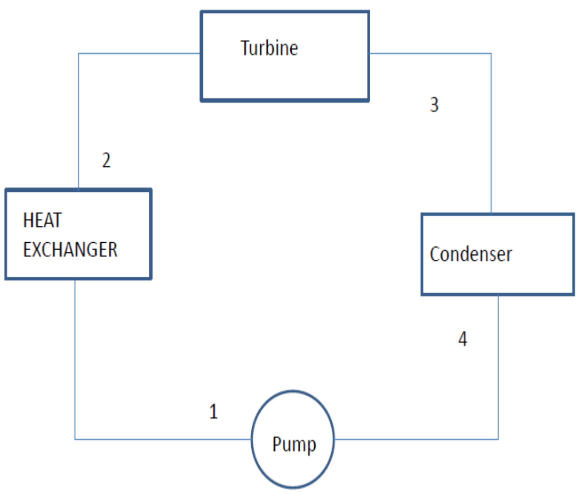

Figure 7 Power Block.

By performing component analysis through the application of the first law of thermodynamics and using the classical Cengel sign convention yields the expressions as follows:

Heat Exchanger: $Q_{in} = h_2 - h_1$ (5)
Turbine: $W_T = h_2 - h_3$ (6)
Condenser: $Q_{out} = h_4 - h_3$ (7)
Pump: $W_P = h_1 - h_4$ (8)
$\eta_{th} = [W_T + W_P] / Q_{in}$ (9)

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

$E_{out,ws}$ = [U(T) - Storage System Losses - Heat Exchanger Energy Losses] η_{th} (10)

$E_{out,ns}$ = [$U_{HTF}(T)$ - Heat Exchanger Energy Losses]η_{th} (11)

Where by:

$U_{HTF}(T) = m_{HTF} C_{p,HTF} (T_{out,\ HTF} - T_{in,HTF})$ (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) - Storage System Losses - Heat Exchanger Energy Losses] / [$U_{HTF}(T)$ - Heat Exchanger Energy Losses] (13)

Molten salt storage system losses estimation methods are discussed in the literature [8-10]. The losses in a molten salt tank are depicted in Figure 8 [1].

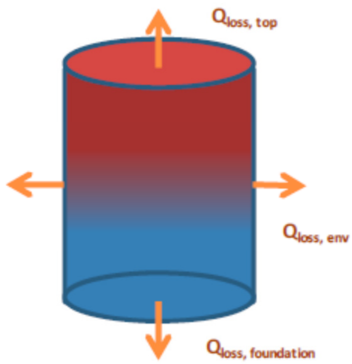

Figure 8 Molten salt tank losses [1].

The tank losses are expressed as follows:

$$Qdot_{cond,loss} + Qdot_{top,loss} + \int_0^L ph\,(Ttank(x) - Tenv)dx = UoverallAref(Tm - Tamb) \quad (14)$$

The round trip efficiency can be expressed as follows:

$$\eta = \frac{msaltCp,salt\,(Tout,st - Tin,st)\{2(1-\eta hx)\} - \int_{to}^{tf} Qdotloss\,dt}{mHTF\ Cp,HTF\,(Tout,\ HTF - Tin,HTF)(1-\eta hx)} \quad (15)$$

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).

$\eta_{TES,I} = T_{hot} - T_{cold} / T_H - T_{cold}$ (16)
$\eta_{TES,II} = |\Delta G_d / \Delta G_c|$ (17)

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

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

RESULTS

The round trip efficiency and LCOE 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.

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	386^0C
Temperature cold tank	296^0C
HTF inlet temperature	293^0C
HTF outlet temperature	393^0C
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 LCOE of other storage technologies are shown in Table 3.

Table 3 LCOE of other storage technologies – 50MW (EPRI, 2011).

Technology	**LCOE[$\$/MWh_e$]**
Compressed air energy storage (CAES)	275
Sodium sulphur	350
Advanced lead acid T1	625
Advanced lead acid T2	325
Zinc bromine	288
Vanadium redox	525
Pumped hydro (280 MW)	250

The estimated current and future costs of parabolic trough systems are shown in Table 4 [11].

Table 4 Current and future costs of parabolic trough systems [11].

	2010	2010	2015	2015	2020
Design Inputs:					
Turbine MWe (gross/net)	111/100	110/100	280/250	110/100	280/250
HTF	Syn. Oil	Syn. Oil	Syn. Oil	Salt	Salt
Solar Field Temperature (°C)	391	391	391	450	500
Solar Multiple	1.3	2.0	2.0	2.0	2.8
Thermal Storage Hours	0	6	6	6	12
Cost & Performance Inputs:					
System Availability	94%	94%	96%	96%	96%
Turbine efficiency (cooling method)	0.377 (wet)	0.377 (wet)	0.356 (dry)	0.379 (dry)	0.397 (dry)
Collector Reflectance	0.935	0.935	0.95	0.95	0.95
Solar Field ($/m2)	295	295	245	245	190
HTF System ($/m2)	90	90	90	50	50
Thermal Storage ($/kWh-t)	-	80	80	50	25
Power Block ($/kWe - gross)	940	940	875	1140	875
O&M ($/kW-yr)	70	70	60	60	45
Cost & Performance outputs:					
Capacity Factor	26%	41%	43%	43%	60%
Installed Cost ($/W)	4.6	8.0	7.9	6.6	6.5
LCOE (cents/kWh, real)	17.3	17.9	16.5	14.2	9.9

The estimated current and future costs of tower systems are shown in Table 5 [11].

Table 5 Current and future costs of tower systems [11].

	2015	2020	2025
Design Inputs:			
Turbine MW_e (gross/net)	111/100	111/100	220/200
Solar Field Temperature (°C)	565	565	650
Solar Multiple	1.8	2.6	2.8
Thermal Storage Hours	6	12	12
Cost & Performance Inputs:			
System Availability	91%	94%	96%
Turbine efficiency (dry cooled)	0.416	0.416	0.47
Collector Reflectance	0.95	0.95	0.95
Solar Field ($/m2)	200	143	120
Tower/Receiver ($/$kW_t$)	200	200	170
Thermal Storage ($/$kWh_t$)	30	20	20
Power Block, ($/$kW_e$ - gross)	1140	1140	975
O&M ($/kW-yr)	65	50	50
Cost & Performance outputs:			
Capacity Factor	43%	60%	65%
Installed Cost ($/W)	6.3	7.3	5.9
LCOE (cents/kWh, real)	13.7	10.9	9.4

Tables 4 and 5 shows the cost trajectories of parabolic trough systems and solar tower systems respectively. 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.

CONCLUSION

The estimated round trip efficiency of 86% 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 pumped hydro storage, compressed air energy storage, and 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 back drop 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 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.

REFERENCES

[1] Ma Z, Glatzmaier G, Turchi C, Wagner M. Thermal energy storage performance metrics and use in thermal energy storage design. Colorado: ASES World Renewable Energy Forum Denver; 2012.

[2] Kuravi, S., Trahan, J., Goswami, D., 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.

[3] D. Bharathan and G. Glatzmaier, “Progress in Thermal Energy Storage Modeling”, Proceedings of the ASME 2009 3rd International Conference of Energy Sustainability, ES2008, San Francisco, CA, 2008

[4] D. Bharathan, “Thermal Storage Modeling”, NREL Milestone Report, 2010.

[5] J. T. Van Lew, P. Li,C. L. Chan, W. Karaki, and J. Stephens, “Analysis of Heat Storage and Delivery of a Thermocline Tank Having Solid Filler Material”, Journal of Solar Energy Engineering, ASME, MAY 2011, Vol. 133.

[6] J. E. Pacheco, S. K. Showalter, and W. J. Kolb, “Development of a molten-salt thermocline thermal storage system for parabolic trough plants”, J. Solar Energy Engineering, v124, pp153-159, 2002.

[7] R. Muren, D. Arias, D. Chapman, L. Erickson, A. Gavilan, “Coupled transient system analysis: a new method of passive thermal energy storage modeling for high temperature concentrated solar power systems”, Proceedings of ESFuelCell2011, ASME Energy Sustainability Fuel Cell 2011, August, 2011, Washington DC, USA.

[8] Spelling, J., Jocker, M., Martin, A., 2012. Annual performance improvement for solar steam turbines through the use of temperature maintaining modifications. Solar Energy, 496–504.

[9] Rovira, A., Montes, M.J., Valdes, M., Martinez-Val, J.M., 2011. Energy management in solar thermal power plants with double thermal storage system and subdivided solar field. Applied Energy, 4055–4066.

[10] Zaversky, F., Garcia-Barberena, J., Sanchez, M., Astrain, D., 2013. Transient molten salt two-tank thermal storage modelling for CSP performance simulations. Solar Energy 93, 294-311.

[11] Turchi, C., Mehos, M., Ho, C., Kolb, G. Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market. SolarPACES 2010, September, 2010, France.