Integrated Thermoelectric Energy Storage in A Combined Cycle Solar Power Plant (tour)

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Abstract: Multi megawatt-thermoelectric energy storage based on thermodynamic cycles is an ambitious solution for the renewable energies conversion. The main advantage of this technology is the capacity of energy storage, However, ensuring the operation of TEES stations during unfavorable weather conditions is suspended. In this article, a specific thermoelectric energy storage system was studied «TEES», the TEES system converts electrical energy into sensible heat by means of an electric heater that uses the joule heating effect, the system TEES converts sensible heat into electrical energy by means of a hybrid power plant that operates on a combined cycle « Brayton and Rankine ». The hybrid power plant uses two thermal energy sources In order to secure the station in unfavorable weather conditions for the production of solar energy. The main idea is to using the gaz and the sensible heat stored as two thermal inputs in the gas turbine that uses a Brayton cycle, the thermal rejection from the gas turbine was recovered and used as a thermal input in the conventional steam turbine plant that uses a Rankine cycle. A thermodynamic analysis of the TEES system was performed in steady state, using the thermodynamic properties of the Coolprop database, a maximum thermal efficiency or Round trip electrical efficiency of 50% has been reached; when the heating temperature of the compressed air reaches 1100 ° C and When the isentropic efficiency of steam turbine is 90 percent.

Keywords: TEES, Coolprop, sensible heat, thermodynamics, thermoelectric, geothermal, Brayton, Rankine.

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1. Introduction

The increasing share of renewable energy sources in the electricity market poses new challenges in terms of reliability and control of electricity networks. Because of their unpredictable behaviour, wind or solar photovoltaic energy cannot always be converted into electricity, especially when most of the energy demand is covered by nuclear or coal-fired power plants. Alternatively, the generated electricity excess from renewable energy sources can be stored and used during peak periods, like in hydroelectric plants of the traditional pump [1]. As the available sites for the construction of such plants are running out, engineers are looking for alternatives for large-scale energy storage. Electricity storage technologies differ from each other. The others differ in terms of storage capacity and power. Although the maximum installed power capacities of some energy storage technologies reach tens of MW, only hydraulic pump and compressed air energy storage systems CAES can store and deliver this power for hours. The remaining technologies are mainly used to improve the stability of transmission systems and are therefore exploited for short periods [2,3]. Unlike the hydroelectric pump, the CAES is a developing technology and the subject of recent literature. The reader can refer to a review by Lund H. et al. on this subject [4]. The CAES can be improved with thermal storage, leading to Round trip efficiency of up to 70% [5]. A highly efficient and site-independent CAES system has recently been proposed by Kim Y.M. [6].

In this context, thermoelectric energy storage TEES [7-9] represents an interesting solution in the general context of the possibility of distributing energy systems based on renewable energies. A TEES system essentially consists of two sensitive accumulators of heat and cold, between which temperatures a heat engine works. The temperature levels are then recharged by a heat pump cycle. TEES cycles at several MW have been proposed often using a transcritical CO_2 cycle as a power cycle and each one of the cycles proposed has a Round trip efficiency that can reach 66 % [8-11]. Another variant of TEES is to use the Brayton cycle as a feed cycle with air [12], Argon or other rare gases [13,14] as working fluids. Studies have been conducted on optimizations for TEES. Peterson [15] and Henchoz et al. [16] noted the effectiveness of TEES at an ambient temperature. White et al. [12] have studied the thermodynamic aspects of a TEES system and have shown highly efficient compression and expansion processes that are clearly needed to achieve satisfactory cycle efficiency. In the literature, TEES systems are not widely studied, especially when considering the whole integration process of auxiliary thermal energy as heat input (in the charge or discharge cycle). Particularly in [17], a new TEES thermo-electric storage system with thermal integration was proposed. The main novelty was the introduction of an auxiliary heat source, which enhances the efficiency of the system. Thousands of mirrors reflect sunlight towards an absorber, which in turn converts that energy into heat, which is stored in molten salt. Having cheap solar heat as auxiliary energy with an electric heater is beneficial for efficiency. Incorporating thermoelectric storage into solar turbine plants raises the heat of salt to more than Thus, the gas became a reserve and not a permanent supplement to the solar heat). The usual heat pump used in the TEES installations during charge has been replaced by an electric heating element which acts as an intermediary for the direct conversion of electric energy into thermal energy.

2. Description and Method of Study

Figure .1 during the charge, electric energy generated by the wind and solar photovoltaic power plants was converted into sensible heat contained in the molten salt via an electric heater. Figure .1during discharge, sensible heat was converted into electric energy by a hybrid power plant uses combined cycle « Brayton and Rankine », combined cycle is interpreted as follows:

Brayton Cycle: the working fluid "air" is compressed by a compressor 1-2, the compressed air is heated by a 2-3 heater uses the sensible heat contained in liquid sodium, and then the compressed air is heated a second time through the combustion chamber 3-4 uses the gas, compressed air expands in turbine 4-5, producing mechanical energy to operate compressor 1-2 and the electricity generator.

Rankine cycle: 4-1, Saturated liquid are pumped to a high pressure 1-2, saturated steam is superheated by a recovery device that uses the thermal rejection from the gas turbine, The superheated steam expands in the 2-3 turbine, producing mechanical energy to operate the electric generator. The Steam condenses in condenser 3-4 which uses a cooling water circuit. Finally, the liquid discharges from the condenser is used to start a new cycle.

The impact of the parameter « steam Turbine isentropic efficiency, $\eta_{is,st}$ » on the TEES system operation was evaluated. In order to assess this impact, a thermodynamic calculation based on standard manufacturer conditions and the actual climatic conditions. The purpose of this thermodynamic calculation is to determine all the operating parameters from the TEES system, namely:

- Thermal efficiency..
- Total power.

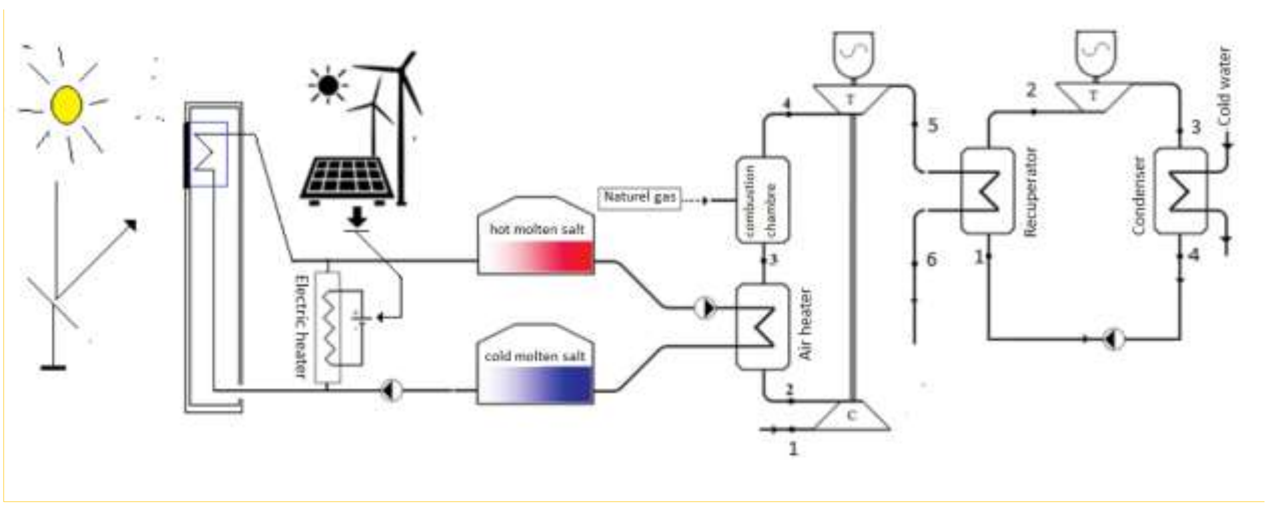

Figure .1: Schema of the TEES system.(Electric heater and receiver can be in series or in parallel)

3. Thermodynamic Analysis

3.1 Hypotheses

- The molten salt tanks are perfectly insulated.
- All transformation (Brayton Cycle: 2 to 4 and 5 to 6 | Rankine Cycle: 1 to 2 and 3 to 4) occurs at constant pressure.
- 100% of electrical energy is converted to sensible heat.
- Changes in thermodynamic properties and mass flow of air are considered negligible.

3.2 molten salt Cycle:

$$\dot{m}_{ms}.C_{ms}.T_{c,ms} - \dot{m}_{ms}.C_{ms}.T_{h,ms} + Q_e + Q_r = 0$$

$$\dot{m}_{ms}.C_{ms}.T_{h,ms} - \dot{m}_{ms}.C_{ms}.T_{c,ms} - Q_{2\text{-}3} = 0$$

$$Q_r + Q_e - Q_{2\text{-}3} = 0$$

3.3 Brayton Cycle :

$$\dot{m}_{ai}.h_1 + W_{(1\text{-}2)r} - \dot{m}_{ai}.h_2 = 0 \; ; \; W_{(1\text{-}2)r} = W_{(1\text{-}2)is} / \eta_{is,c}$$

$$\dot{m}_{ai}.h_2 + Q_{2-3} - \dot{m}_{ai}.h_3 = 0\ ;\ E_{a,h} = [T_3-T_2] / [T_{h,ms}-T_2]\ ,$$

$$C_{min}\,[T_3-T_2] = C_{max}\,[T_{h,ms}-T_{c,ms}]$$

$$C_{min} = \dot{m}_{ai}.[h_3-h_2]/[T_3-T_2],\ C_{max} = \dot{m}_{ms}.c_{ms}$$

$$\dot{m}_{ai}.h_3 + Q_{3-4} - \dot{m}_{ai}.h_4 = 0\ ;\ Q_{3-4} = \dot{m}_{gas}.LHV.\ \eta_{,cc}$$

$$\dot{m}_{ai}.h_4 - W_{GT(4-5)r} - \dot{m}_{ai}.h_5 = 0\ ;\ W_{GT(4-5)r} = W_{GT(4-5)is}\ .\ \eta_{is,t}$$

3.4 Rankine Cycle :

$$\dot{m}_{st}.h_4 + W_{p(4-1)r} - \dot{m}_{st}.h_1 = 0\ ;\ W_{p(4-1)r} = W_{p(4-1)is} / \eta_{is,p}$$

$$\dot{m}_{st}.h_1 + Q_{1-2} = \dot{m}_{st}.h_2\ ;\ E_r = [T_2-T_1] / [T_5-T_1],$$

$$C_{min}\,.[T_2-T_1] = C_{max}\,.[T_5-T_6]$$

$$C_{max}=\dot{m}_{ai}.[h_5-h_6]/[T_5-T_6]\ ,\ C_{min} = \dot{m}_{st}.[h_2-h_1] / [T_2-T_1]$$

$$\dot{m}_{st}.h_2 - W_{ST(2-3)r} - \dot{m}_{st}.h_3 = 0\ ;\ W_{ST(2-3)r} = W_{ST(2-3)is}\ .\ \eta_{is,st}$$

$$\dot{m}_{st}.h_3 - Q_{3-4} - \dot{m}_{st}.h_4 = 0;$$

3.5 Efficiencies:

$$\eta_{rte} = \eta_{th} = \left[\frac{(W_{GT(4-5)r} - W_{C(1-2)r} + W_{ST(4-5)r}).\eta_g - W_{p(4-1)r}/\eta_m}{(Q_{3-4} = 0) + Q_{2-3}}\right]$$

3.6 Input parameter:

Table.1: fluid storage property [18]

Property	($^7Li_2BeF_4$~Flibe!) Molten salt (ms)
Lower temperature limit , (°C)	459
Upper temperature limit ,(°C)	1400
Heat capacity C_{so} ,(KJ/ kg K)	2.34

Table.2: input operating parameters of the TEES system.

parameter	value
Electric heater power ; Q_e	50 MW
Hot molten salt tank temperature, $T_{h,ms}$	1183.93°C
Brayton Cycle	
Compressor pressure ratio , R_p	10
Compressed air temperature ,T_4	1100 °C
Compressor isentropic efficiency, $\eta_{is,c}$	85 %
Turbine isentropic efficiency, $\eta_{is,t}$	85 %
Air heater efficiency , $E_{a,h}$	90 %
Generator efficiency, η_g	98 %
Combustion chamber efficiency , $\eta_{,cc}$	95 %
Calorific value of gas (LHV)	50000 kJ/kg
Atmospheric condition ,	1 Bar
Atmospheric condition ,	25 °C
Rankine Cycle	
Condenser pinch point , T_1- $T_{c,o}$	5 °C
Cold water inlet temperature , $T_{c,i}$	25 °C
Saturated liquid temperature ,T_6	40 C
Recuperator efficiency , E_r	80 %
Turbine isentropic efficiency , $\eta_{is,t}$	90 %
Pompe isentropic efficiency , η_{isp}	85 %
Generator efficiency, η_g	98 %
Motors efficiency, η_m	98%

(E_r:80 % , NTU = 4 ,C_{min}/C_{max} = 1 [19]).($E_{a,h}$:90 %, NTU = 4.7 ,C_{min}/C_{max}=0.75 [19])

. E_r and $E_{s,h}$: counter-flow heat exchanger.

4. Results and Interpretation

Table.3: thermodynamic state for each point in cycles.

state	T °C	P Bar	H (KJ/Kg)	S(KJ/Kg-K)
		Brayton Cycle using air		
1	25	1	298.38	6.86
2	344.57	10	625.96	6.95
3	1100	10	1484.28	7.85
4	1100	10	1484.28	7.85
5	592.34	1	894.79	7.97
6	147.34	1	422	7.21
		Transcritical Rankine Cycle using methanol		
1	35	200	424852	-5.12
2	480	200	426697.96	-1.53
3	33	0.22	425993.78	-1.27
4	30	0.22	424822	-5.13

Table.3: output operating parameters of the TEES system.

parameter	value
Electric heater power ; Q_e	50 MW
Hot sodium tank temperature, $T_{h,so}$	885 °C
Cold sodium tank temperature, $T_{c,so}$	520.21 °C
Mass flow of sodium, $\dot{m}_{so}$	109.13 kg/s
Brayton Cycle using air	
Real work of the compressor , $W_{(1-2)r}$	30.284 MW
Real work of the turbine , $W_{GT(4-5)r}$	54.496 MW
Air heater power, Q_{2-3}	50 MW
receiver power, Q_{3-4}	29.34 MW
Mass flow of air , $\dot{m}_{ai}$	92.44 kg/s
Transcritical Rankine Cycle using methanol	
Recuperator power , Q_{1-2}	43.636 MW
Condenser power , Q_{3-4}	27.7 MW
Mass flow of steam, $\dot{m}_{st}$	23.63 kg/s
Real work of the turbine , $W_{ST(4-5)r}$	16.64 MW
Mass flow of cold water , $\dot{m}_{c,w}$	662.49 kg/s
Efficiencies	
Round trip electric efficiency ,η_{rte}	50.41 %
Thermal efficiency ,η_{th}	50.41 %
Total Power, P_t =($W_{GT(4-5)r}$ -$W_{C(1-2)r}$ + $W_{ST(4-5)r}$) .η_g - $W_{p(4-1)r}$ / η_m	40.04 MW

Table.4: output operating parameters of the TEES system.

$\eta_{is,t}$	70	75	80	85	90
Pt (mw)	35.666	36.602	37.508	38.409	39.326

Table.5: output operating parameters of the TEES system.

$\eta_{is,t}$	70	75	80	85	90
η_{ht} or η_{rte}	44.95%	46.13%	47.27%	48.41%	49.56%

Table.6: output operating parameters of the TEES system.

To calculate the cost of storing kilowatt-hours, we have 50 megawatts that enter as heat, and we recover 50 percent, or 25 megawatts, and the rest comes out in the form of lost heat, and by calculating the cost of producing this heat from a photovoltaic source, i.e. $5.875 million, if we consider $0.23-$0.24/ watt

The station operates 7 hours at night, which is equivalent to 7 sunny hours, and therefore the cost of storing kilowatt-hours is (($ kWh =5.875 million $ / (7 * 25 * 1000) = 33.57) and this number is low compared to US$379/usable kWh batteries[20][21]

5. Conclusion

Solar thermal energy is an inexhaustible resource that benefits the environment. Its integration in TEES systems is profitable especially on sites with More sun radiant. The study shows that the thermal efficiency of a hybrid thermal power plant using geothermal can reach 50 %, this means that the integration of electricity storage using sensible heat in proposed hybrid power plant is possible. The study shows that the integration of gas in the hybrid power plant can Ensures continuity of work of TEES system. The numerical application is based on an electrical input reach 50 MW, also The numerical application means that the proposed TEES system store electricity with a roundtrip electrical efficiency of 50%. The variance in performance of the TEES system was evaluated as a function of changes in isentropic efficiency of steam turbine. Consequently, in order to increase the Round trip electrical efficiency of the TEES, it is necessary to Choose a high efficiency turbine.

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