Techno-Economics of Central Tower Receiver Power Plants in India: Effect of Heat Transfer Fluids/Thermal Storage Media

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Abstract

Results of a preliminary attempt to study the effect of different fluids as heat transfer fluid (HTF) as well as thermal energy storage (TES) medium on the techno-economics of a 100 MW nominal capacity CTR based plant with the provision of 12.0 hours of thermal energy storage are presented. For this purpose, solar salt, KCl-$MgCl_2$, $NaCl$-KCl-$MgCl_2$ and liquid sodium have been considered.

From the results obtained, it is observed that merely attaining higher temperatures for a heat transfer fluid or thermal storage media is not going to significantly affect the techno-economics of the CSP plant. The thermo-physical properties and cost of heat transfer/ thermal storage fluids have considerable effect on cost of thermal energy storage sub-system, parasitic requirements, as well as operational and maintenance requirements.

Keywords: CSP plant, techno-economics, heat transfer fluid, thermal energy storage, levelized cost of electricity

1. Introduction

Amongst the concentrating technologies for solar thermal power generation, parabolic trough solar collector (PTSC) and central tower receiver (CTR) have attained significant commercial maturity for large scale dissemination. CTR technology has been considered as a potential candidate for third generation CSP plants primarily due to achievable higher operating temperatures (>600˚C) resulting in higher power cycle efficiency (Neises and Turchi, 2019). It is also noted that the choice of material(s) for heat transfer fluid (HTF) and thermal energy storage (TES) medium is likely to affect the cycle efficiency, net annual electricity output, maintenance requirements and consequently cost of electricity delivery (Liu et al., 2016).

As shown in Fig. 1, the CSP plants typically consist of a solar energy collection system, a thermal energy storage/transfer system and a power generation system. In the case of a CTR based solar thermal power plant, the reflected solar radiation from the heliostat field gets absorbed at the receiver located at the top of the central tower to heat the heat transfer fluid. The hot fluid can be used directly to generate steam or can be stored in hot tanks (Palacios et al., 2020).

Presently, almost 75% of the total installed capacity (6.55GW) in the different parts of the world is based on PTSC while about 20% plants are based on CTR technology (SolarPACES, 2021). Several studies have been reported in the literature on the use of molten salt as heat transfer as well as thermal energy storage media in CTR based plants due to its favorable thermo-physical-economic properties (Aseri et al., 2021; Ortega et al., 2008; Parrado et al., 2016; Turchi and Heath, 2013). Since the installation of 11 MW nominal capacity commercial CTR based CSP plant (PS10) at Spain with one hour of thermal energy storage during 2005-2007, use of different thermal energy storage media has been considered. The operating restrictions associated with state-of-the-art solar salt, $NaNO_3$-KNO_3 has necessitated development of a new mixture of salts or consideration of alternative options such as direct steam generation and air heating. In view of this, González-Roubaud et al. (2017) have compared the performance of CTR based plants with direct steam generation and storage against the molten salt based TES system. The study observed that direct molten salt based TES delivers electricity at a lower cost due to less number of components involved. Analyzing the effect of nitrate, chloride, fluoride, carbonate based salts as heat transfer fluids on techno-economics for CTR based plants in China, the authors suggested that the integration of nitrate ($NaNO_3$-KNO_3) mixed solar salt based TES system can generate electricity at a lower cost than the other salts (Zhuang et al., 2019). In view of continued interest in solar thermal power generation in India, a preliminary attempt has been made in the present study to analyze the effect of different HTF/TES media based on binary or ternary mixtures of nitrate salts, chloride salts, and liquid metals on the techno-economics of CTR based CSP plants in India.

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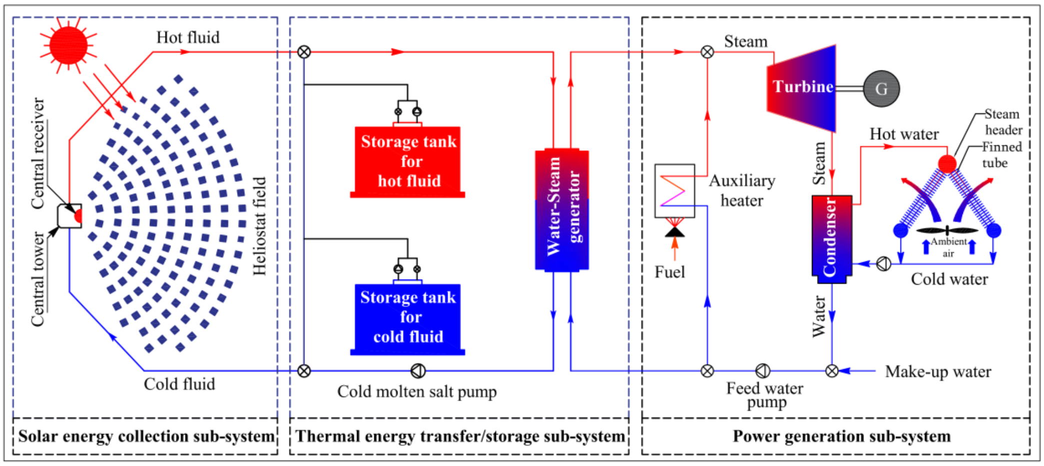


Fig. 1 Schematic of a dry-cooled CTR based CSP plant with two-tank direct thermal energy storage

2. Methodology

The outline of the methodology adopted to assess the techno-economic performance is presented in Figure 2 and the same is briefly described in the following paragraphs.

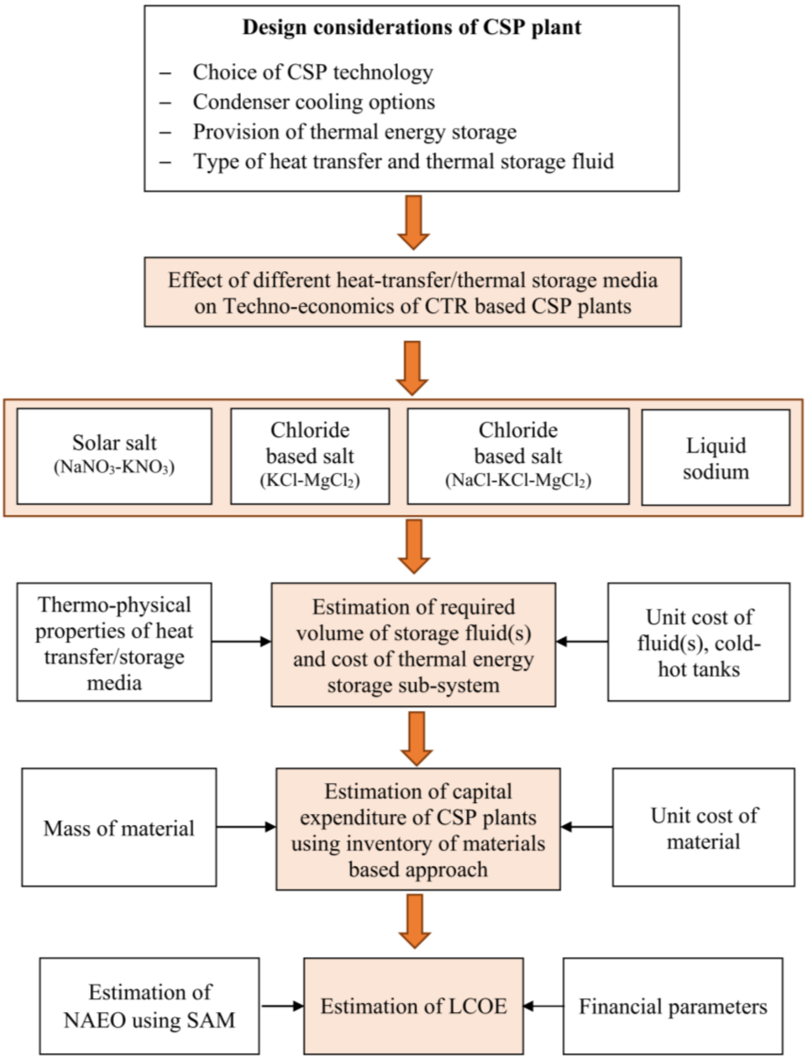


Fig. 2 A schematic representation of methodology adopted to assess the effect of HTF/TES medium on techno-economic performance of CTR based CSP Plant

Considering a threshold annual value (2000 kWh/m^2) of direct normal irradiance (DNI) at wastelands, Sharma et al. (2015) have identified 95 locations with potential for deployment of CSP plants in India, excluding potential wastelands suitable for solar PV and onshore wind power plants. Further, out of these locations, Aseri et al., (2020a) have found that at 67 potential locations (with high annual DNI), the wet cooled condenser technology is not feasible due to the unavailability of adequate amount of water for condenser cooling. Considering this, the district of Jaisalmer in the state of Rajasthan is selected as a potential location for deploying 100 MW nominal capacity dry-cooled CTR based CSP plant with a provision of 12.0 hours of direct thermal energy storage.

In the CTR based plants, the heat transfer fluid can also be stored directly in thermal energy storage system to operate the plant during off sunshine hours. Hence, in the present study, a single fluid is considered as heat transfer and storage fluid. In order to investigate the effect of the choice of heat transfer (as well as thermal storage) fluids on the techno-economics of CSP plants, four different fluids (i.e., a nitrate based salt, two chloride based salts and a liquid metal) have been considered. For these HTFs, the variation of thermo-physical properties with temperature is shown in Fig. 3. The thermo-physical properties along with unit cost (US$/kg) of various HTFs at 700°C temperature (500ºC for solar salt) are presented in Tab. 1.

With the use of hourly values of weather data (obtained from the National Solar Radiation Data Base, NREL, USA) and System Advisor Model (SAM), the technical performance parameters such as net annual electricity output (NAEO), capacity utilization factor, water requirements have been obtained (NSRDB, 2018; SAM, 2021). The design parameters and specifications used in the analysis pertaining to the heliostat field, receiver, tower, thermal energy storage and power block of CTR based CSP plants are presented in Tab. 2.

The increase in operating cycle temperature and change in heat transfer/thermal storage media affects the system design in terms of number of heliostats, height of central tower, size of central receiver, number of tanks and their sizes, etc. In the present study, these design parameters are estimated using SAM (2021) and the same are presented in Tab. 3.

In order to estimate the cost of thermal energy storage sub-system based on different fluids used as HTF and storage media the required volume of the thermal fluid (V_{tes}) to operate the power cycle for 12.0 hours at full load capacity is estimated from the following expression (SAM, 2021).

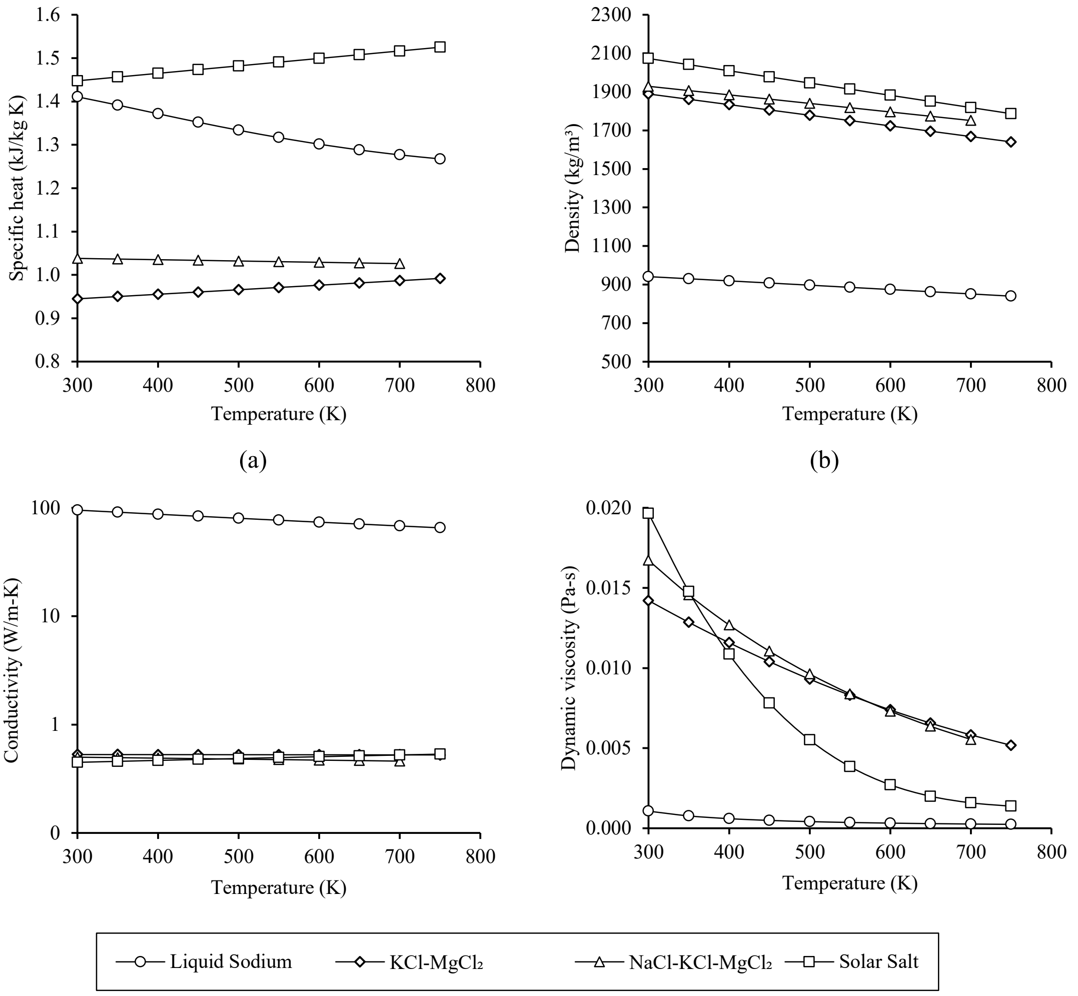
$$V_{tes}(m^3) = \frac{\frac{W_{gross}}{\eta_{pb}} H_{tes}}{\rho\, c_p\, \epsilon_{hex}\left[\left(T_{sf,out} - T_{hex,hot}\right) - \left(T_{sf,in} - T_{hex,cold}\right)\right]} \times (3.6 \times 10^6) \qquad \text{(Eq. 1)}$$

where W_{gross} represents the gross power output from the plant (MW), η_{pb} the efficiency of the power cycle, H_{tes} hours of thermal energy storage (hours), ρ the density of HTF (kg/m^3), Cp specific heat of salt (J/kg°C), ε_{hex} effectiveness of salt-to-steam generator, $T_{sf,in}$ and $T_{sf,out}$ inlet and outlet temperature at solar field (°C), and $T_{hex,hot}$ and $T_{hex,cold}$ hot and cold temperatures respectively at salt-to-steam generator (°C).

Following the inventory of materials approach developed and used by the authors (Aseri et al., 2020b), the capital expenditure (CAPEX) has been estimated for the CSP plant considered in the study with all fluids as HTF and TES media. The CAPEX estimated with solar salt as heat transfer and thermal energy storage fluid is considered as the base value of the CAPEX. It is worth mentioning that with a change in HTF, the required size of hot and cold tanks also changes due to change in thermo-physical properties of HTF, consequently affecting the CAPEX of CSP plants. The levelized cost of electricity (LCOE) which is essentially the breakeven value of the cost of electricity is estimated as

$$LCOE = \frac{\left(CAPEX \times \frac{d(1+d)^n}{(1+d)^n - 1}\right) + Annual\ operation\ and\ maintenance\ cost}{Net\ annual\ electricity\ output} \qquad \text{(Eq. 2)}$$

where *d* represents the discount rate (weighted average cost of capital) and *n* the useful life of the plant. In the present study, a discount rate of 10%, useful life of 30 years and annual operation and maintenance (O&M) cost of 2% of the CAPEX has been assumed.



(a) (b)

(c) (d)

Fig. 3 Variation of thermo-physical properties of different heat transfer fluids with temperature

Tab. 1. Thermo-physical properties and unit cost of heat transfer cum thermal energy storage media (Manzolini et al., 2021)

Thermal fluid	**Chemical and composition (fraction)**	**Melting temperature (°C)**	**Maximum operating temperature (°C)**	**Density (kg/m^3)**	**Specific heat (J/kg-K)**	**Viscosity (Pa-s)**	**Thermal conductivity (W/m-K)**	**Cost (US$/kg)**
Solar Salts	$NaNO_3$-KNO_3 (0.6-0.4)	223	600	1740	1538	0.0012	0.547	0.80
Chloride based salt	KCl-$MgCl_2$ (0.68-0.32)	445	>700	1556	1150	0.0015	0.4347	0.35
	NaCl-KCl-$MgCl_2$ (0.245-0.205-0.55)	383	>700	1631	1018	0.0021	0.4380	0.29
Liquid metal	Liquid Sodium (Na)	142	>800	787	1252	0.0002	55.31	2.0

Properties are estimated at a temperature of 700ºC except for solar salt (500ºC)

Tab. 2 Design parameters and specifications used in the analysis

Sub-System	Parameter	Unit	Value
Heliostat field	Solar collector used	-	Heliostat
	Width of heliostat	m	12.2
	Height of heliostat	m	12.2
	No. of facets in a heliostat	-	16.0
	Aperture area of a heliostat	m^2	144.4
	Heliostat reflectance	%	90.0
	Maximum heliostat distance to tower height ratio	-	9.5
	Minimum heliostat distance to tower height ratio	-	0.75
	Water requirement per wash	L/m^2	0.7
	Washes per year	-	63.0
Rankine cycle based power block	Turbine inlet temperature	°C	565, 600, 650
	Gross to net conversion factor	-	0.9
	Boiler operating pressure	bar	100
	Rated power block efficiency at 565°C	%	41.2
	Rated power block efficiency at 600°C	%	42.7#
	Rated power block efficiency at 650°C	%	43.5#
	Turbine over design operation	-	1.05
	Blowdown fraction	%	2.0
	Condenser cooling technology	-	Dry
	Condenser pressure	mm Hg	50.8
	Annual decline in output	%	Nil
	Availability of plant	%	96

Sub-System	Parameter	Unit	Value
Tower and Receiver	Receiver type	-	External
	Tube inner/outer diameter	m	0.0375/0.040
	Material of receiver tubes	-	SS AISI316
	Emittance of coating	-	0.88
	Absorptance of coating	-	0.94
	Design value of heat loss	kW$_{th}$/m^2	30.0
	Efficiency of HTF pump	-	0.85
	Design inlet temperature of HTF	°C	290
	Design outlet temperature of solar salt	°C	574
	Design outlet temperature of KCl-MgCl$_2$	°C	610
	Design outlet temperature of NaCl-KCl-MgCl$_2$, liquid sodium	°C	670
Thermal energy storage	Thermal energy storage media	-	Same as HTF
	Height of storage tank	m	12.0
	Minimum design temperature of solar salt	°C	290
	Minimum design temperature of KCl-MgCl$_2$	°C	260
	Minimum design temperature of NaCl-KCl-MgCl$_2$	°C	430
	Minimum design temperature of liquid sodium	°C	280

Efficiency is estimated considering isentropic expansion in the turbine and isentropic compression in the pump

Tab. 3 Design parameters considered for CSP plants based on different HTF cum TES medium (SAM, 2021)

Parameter	Unit	HTF / TES media used			
		Solar Salt	**KCl-$MgCl_2$**	**NaCl- KCl-$MgCl_2$**	**Liquid Sodium**
Thermal energy required from solar field	MW_{th}	755	728	715	715
Number of heliostats	-	16948	16334	16006	15991
Height of the central tower	m	254.53	247.95	247.36	247.8
Diameter of central receiver	m	23.30	23.07	23.60	23.05
Height of central receiver	m	25.47	24.56	24.29	24.40
Number of pairs of hot-cold tanks	-	6	7	10	10
Height of hot/cold tanks	m	12	12	12	12
Diameter of hot/cold tanks	m	17.3	18.2	18.3	18.0
Land area	km^2	14.9	14.5	14.2	14.1

3. Results and Discussion

Using the thermo-physical properties (Tab. 1) and Eq. (1), the required volume (or mass) of fluid used as HTF and TES medium and also the cost of 12.0 hours TES sub-system based on different heat transfer/storage fluids have been estimated and the same are presented in Tab. 4. The estimate for the cost of chloride salts based TES sub-system (US $26.4-35.9 million) is found close to that of the system based on nitrate salts (US $33.6 million) due to relatively small variation in thermo-physical properties. However, with the use of liquid sodium as HTF/storage medium the investment requirement is expected to increase by 94% in comparison to that for solar salt based TES sub-system. The lower density and higher cost (US $2.0/kg) of liquid sodium lead to higher cost of the TES sub-system.

Tab. 4 Estimates for the volume, mass and cost of 12.0 hours of TES sub-system based on different fluids

Storage fluid	Thermal energy in storage tanks	Volume of storage fluid	Mass of storage fluid	Unit cost of storage fluid	Cost of storage fluid	Cost of hot-cold tanks	CAPEX of TES sub-system
	(MWh_{th})	**(m^3)**	**($\times 10^6$ kg)**	**(US$/kg)**	**Million US$**		
Solar Salt	3236.2	15530	27.02	0.8	21.6	12.0	33.6
KCl-$MgCl_2$	3119.6	20084	31.25	0.4	10.9	15.5	26.4
NaCl-KCl-$MgCl_2$	3065.1	28835	47.01	0.3	13.6	22.3	35.9
Liquid sodium	3065.1	27856	21.92	2.0	43.8	21.5	65.3

The CAPEX of 100 MW CTR based CSP plants with 12.0 hours of TES are estimated based on the inventory of materials based approach and detailed break-up of the same is presented in Tab. 5. From the estimates, it is observed that the CAPEX varies in the range of US$438.5 to US$490.9 million for 100 MW nominal capacity CSP plant considering nitrate, chlorides and liquid sodium as heat transfer fluids/storage media.

The parasitic power required by different components involved in HTF and TES sub-systems depends on the thermo-physical properties of HTF and TES medium used. The required annual parasitic power by different components/sub-systems of 100 MW CTR based CSP plants with 12.0 hours of TES is presented in Fig. 4. From the results it may be observed that highest parasitic power (33-66%) is required in the receiver and tower sub-system followed by condenser (10-22%). The annual parasitic requirement in receiver and tower sub-systems for plants based on solar salt, liquid sodium, KCl-$MgCl_2$ and NaCl-KCl-$MgCl_2$ has been estimated at 27.5 GWh, 42.0 GWh, 43.2 GWh and 100.2 GWh respectively. The increase in parasitic power in receiver and tower sub-system for NaCl- KCl-$MgCl_2$ based plant can be attributed to the fact that due to relatively lower heat capacity ($\rho \times C_p$), higher volume (28835 m^3) of salt is required to be pumped in different sub-systems.

Tab. 5 Estimates of capital expenditure for CTR based CSP plants with the provision of 12.0 hours of thermal energy storage with different HTF/TES media

System of CSP plant	**Estimates of CAPEX (million US$) of CSP plant**			
	Solar Salt	**KCl-MgCl$_2$**	**NaCl- KCl-MgCl$_2$**	**Liquid Sodium**
Direct cost				
Site improvement	67.1	65.1	56.2	58.6
Heliostat field	121.8	116.7	107.6	107.6
Tower/Receiver	18.4	17.6	16.3	16.3
Power block	31.7	31.1	30.1	30.1
Thermal energy storage	33.6	26.4	35.9	65.4
Sub-total	**272.5**	**256.9**	**246.1**	**278.0**
Contingency	19.1	18.0	17.2	19.5
Gross-total	**291.6**	**274.9**	**263.3**	**297.4**
Indirect cost				
Engineering, procurement & construction	29.2	27.5	26.3	29.7
Owner's cost	14.6	13.7	13.2	14.9
Soft cost	20.4	19.2	18.4	20.8
Land cost	74.8	72.6	62.7	65.4
Taxation	60.4	56.9	54.5	61.6
Sub-total	**199.3**	**190.0**	**175.1**	**192.4**
Total installation cost	**490.9**	**464.9**	**438.5**	**489.8**
Specific capital cost (US$/kW)	4909	4649	4385	4898

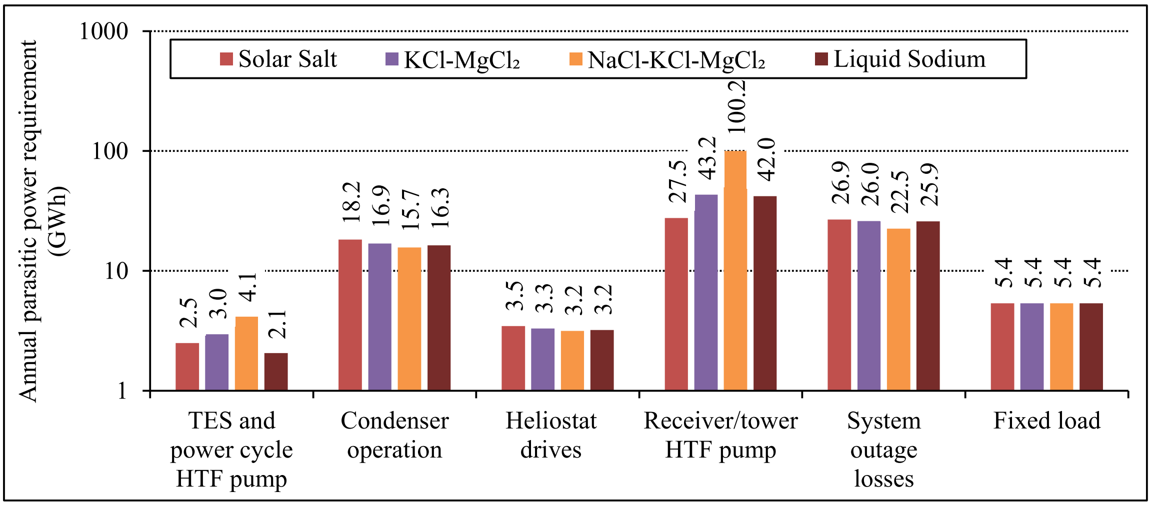
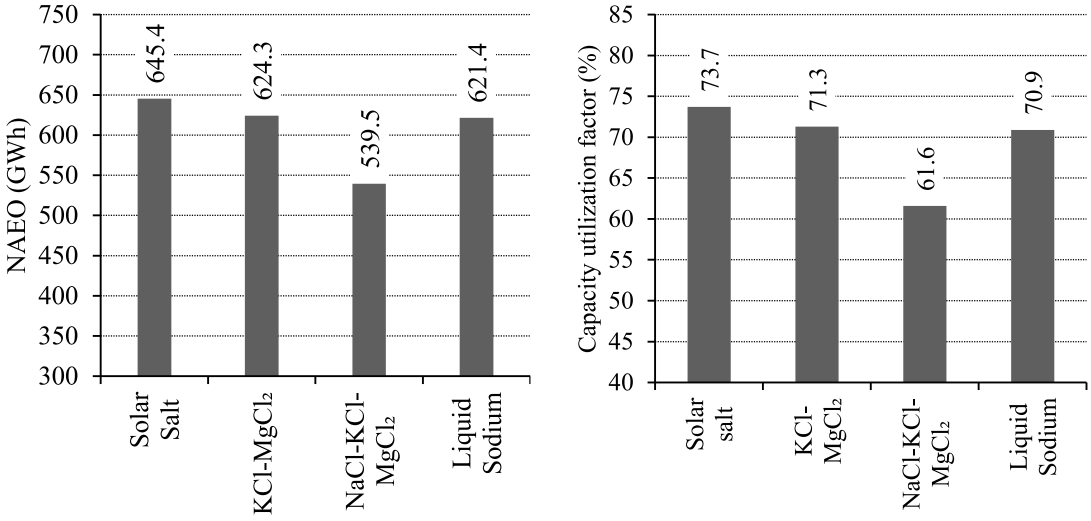


Fig. 4 Parasitic power requirement in different components of CTR based CSP plants

Fig. 5(a) shows net annual electricity output (NAEO) estimated for CSP plants based on different HTFs. From the results, it may be observed that CTR plant based on solar salt delivers highest NAEO (645.4 GWh) followed by plants with KCl-MgCl$_2$ (624.3 GWh), liquid sodium (621.4 GWh) and NaCl-KCl-MgCl$_2$ (539.5 GWh) as HTF /TES medium. A similar pattern is also observed in the estimates of capacity utilization of the CTR plants (Fig. 5(b)).

The estimated values of LCOE are presented in Fig. 6. As per the results obtained, the lowest LCOE can be achieved for KCl-MgCl$_2$ based plants (US $93.9/MWh), followed by plants using solar salt (US $95.9/MWh), liquid sodium (US $99.4/MWh) and NaCl-KCl-MgCl$_2$ (US $102.5/MWh) as HTF/TES media.

From the above mentioned results, it is worth mentioning that though the variation in LCOE for all the plants considered is not significant, the HTFs that has the highest achievable temperature shall definitely have an advantage for third generation CSP plants that are essentially based on supercritical CO$_2$ power cycle. The reason for the same is relatively lower volume of HTFs required and significantly lower cost of supercritical CO$_2$ power block as compared to power block based on Rankine cycle. The metallurgical issues associated with chloride based salts leading to corrosive attacks give the liquid sodium based plant an edge over other HTF based plants (Ding and Bauer, 2021; Sarvghad et al., 2022).



(a) **(b)**

Fig. 5. Results of technical and economic performance (a) NAEO, (b) capacity utilization factor

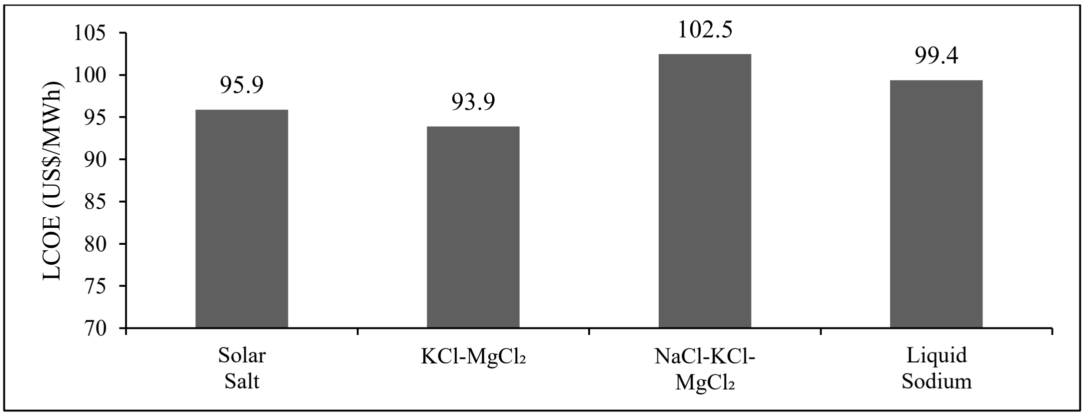


Fig. 6 Estimates of levelized cost of electricity for 100 MW CTR based plants with 12.0 h of TES

4. Concluding remarks

In the present study, an attempt has been made towards analyzing the effect of heat transfer fluid as well as thermal energy storage media on the techno-economics of a 100 MW dry-cooled CTR based CSP plant with the provision of 12.0 hours of thermal energy storage. Based on the availability of suitable wastelands and DNI, Jaisalmer (Rajasthan) in India has been selected as a potential site for deployment. In the present study, four different heat transfer fluids as well as thermal energy storage medium have been considered.

From the results obtained, it may be observed that the thermo-physical properties and cost of heat transfer (or thermal energy storage) fluids can affect techno-economic performance of CSP plants significantly. The parasitic requirement by the various components sub-systems depends on the HTF used thus affecting the net annual electricity output of the plants. Moreover, the cost and thermo-physical properties of the fluid used also affect the cost of thermal energy storage sub-systems and consequently the overall cost of the plant.

From the results of this preliminary study, it is observed that the value of LCOE is lowest with $KCl\text{-}MgCl_2$ (US$93.9/MWh) used as heat transfer and storage medium though the values of LCOE with other three HTF/storage media is marginally different - US$95.9/MWh for solar salt, US$99.4/MWh for liquid sodium, and US$102.5/MWh for $NaCl\text{-}KCl\text{-}MgCl_2$.

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References

Aseri, T.K., Sharma, C., Kandpal, T.C., 2021. Estimation of Capital Costs and Techno-Economic Appraisal of Parabolic Trough Solar Collector and Solar Power Tower based CSP Plants in India for Different Condenser Cooling Options. Renew. Energy 178, 344–362. https://doi.org/10.1016/j.renene.2021.05.166

Aseri, T.K., Sharma, C., Kandpal, T.C., 2020a. Assessment of water availability for wet cooling at potential locations for solar thermal power generation in India. Int. J. Ambient Energy 41, 1126–1141. https://doi.org/10.1080/01430750.2018.1507926

Aseri, T.K., Sharma, C., Kandpal, T.C., 2020b. Estimating capital cost of parabolic trough collector based concentrating solar power plants for financial appraisal: Approaches and a case study for India. Renew. Energy 156, 1117–1131. https://doi.org/10.1016/j.renene.2020.04.138

Ding, W., Bauer, T., 2021. Progress in Research and Development of Molten Chloride Salt Technology for Next Generation Concentrated Solar Power Plants. Engineering 7, 334–347. https://doi.org/10.1016/j.eng.2020.06.027

González-Roubaud, E., Pérez-Osorio, D., Prieto, C., 2017. Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. Renew. Sustain. Energy Rev. 80, 133–148. https://doi.org/10.1016/j.rser.2017.05.084

Liu, M., Steven Tay, N.H., Bell, S., Belusko, M., Jacob, R., Will, G., Saman, W., Bruno, F., 2016. Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. Renew. Sustain. Energy Rev. 53, 1411–1432. https://doi.org/10.1016/j.rser.2015.09.026

Manzolini, G., Lucca, G., Binotti, M., Lozza, G., 2021. A two-step procedure for the selection of innovative high temperature heat transfer fluids in solar tower power plants. Renew. Energy 177, 807–822. https://doi.org/10.1016/j.renene.2021.05.153

Neises, T., Turchi, C., 2019. Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650 °C. Sol. Energy 181, 27–36. https://doi.org/10.1016/j.solener.2019.01.078

NSRDB, 2018. The National Solar Radiation Database (NSRDB). Natl. Renew. Energy Lab. USA. https:/nsrdb.nrel.gov/ (accessed 4.3.18).

Ortega, J.I., Burgaleta, J.I., Téllez, F.M., 2008. Central Receiver System Solar Power Plant Using Molten Salt as Heat Transfer Fluid. J. Sol. Energy Eng. 130, 024501. https://doi.org/10.1115/1.2807210

Palacios, A., Barreneche, C., Navarro, M.E., Ding, Y., 2020. Thermal energy storage technologies for concentrated solar power – A review from a materials perspective. Renew. Energy 156, 1244–1265. https://doi.org/10.1016/j.renene.2019.10.127

Parrado, C., Marzo, A., Fuentealba, E., Fernández, A.G., 2016. 2050 LCOE improvement using new molten salts for thermal energy storage in CSP plants. Renew. Sustain. Energy Rev. 57, 505–514. https://doi.org/10.1016/j.rser.2015.12.148

SAM, 2021. System Advisor Model, Version 2021.12.02 Revision 1, SSC 238. National Renewable Energy Laboratory, Alliance for Sustainable Energy, LLC for Department of Energy, USA. https://sam.nrel.gov/ (accessed 3.3.22).

Sarvghad, M., Ong, T.C., Bell, S., Rumman, R., Delkasar, S., Woodcock, J.W., Will, G., Andersson, G., Lewis, D.A., Steinberg, A., 2022. On the compatibility of liquid sodium as heat transfer fluid for advanced concentrated solar thermal energy systems. Sol. Energy Mater. Sol. Cells 246, 111897. https://doi.org/10.1016/j.solmat.2022.111897

Sharma, C., Sharma, A.K., Mullick, S.C., Kandpal, T.C., 2015. Assessment of solar thermal power generation potential in India. Renew. Sustain. Energy Rev. 42, 902–912. https://doi.org/10.1016/j.rser.2014.10.059

SolarPACES, 2021. Concentrating Solar Power Projects. Natl. Renew. Energy Lab. USA. https://solarpaces.nrel.gov/ (accessed 3.12.22).

Turchi, C.S., Heath, G.A., 2013. Molten Salt Power Tower Cost Model for the System Advisor Model (SAM). Technical Report: NREL/TP-5500-57625, National Renewable Energy Laboratory, USA.

Zhuang, X., Xu, X., Liu, W., Xu, W., 2019. LCOE Analysis of Tower Concentrating Solar Power Plants Using Different Molten-Salts for Thermal Energy Storage in China. Energies 12, 1–17. https://doi.org/10.3390/en12071394