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Effect of Heat Transfer Fluids on the Techno-Economic Performance of Parabolic Trough based Solar Thermal Power Generation in India

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Abstract : The share of renewable energy based electricity generation in total energy mix in India is increasing day by day owing to climatic concerns and resource scarcity associated with fossil fuels. Solar thermal is a prominent option for renewable energy based power generation. The solar thermal technologies like parabolic trough, central tower receiver and linear Fresnel reflector are being used to generate electricity in the different part of the world. In the present study, the effect of heat transfer fluids(Solar salt, Hitec XL, Therminol VP-1, Hitec) on techno-economic performance of a 50MW parabolic trough based solar thermal power plant (without thermal energy storage) has been analyzed. The location of Jaisalmer in the state of Rajasthan, India has been considered for the analysis. Annual energy output has been obtained using System Advisor Model (SAM) simulation tool. Levelized cost of electricity (LCOE) has been computed. The results obtained reveals that Hitec–XL heat transfer fluid provides highest annual electricity output and correspondingly lowest LCOE in comparison to other heat transfer fluids considered in the study.

Keywords: Solar thermal power generation; parabolic trough; heat transfer fluid; levelized cost of electricity.

1. INTRODUCTION

High rate of GHG emissions and resource scarcity concerns associated with fossil fuel based electricity generation has renewed the interest of researchers to explore renewable energy sources for electricity generation (Pitz-Paal et al., 2003). Solar energy based power generation is one of the promising non-conventional energy source. Two routes are available to harness solar energy and convert into electrical energy. These are: Solar PV and solar thermal(IRENA and ETSAP, 2013; REN21, 2016). The concentrating solar power (CSP) can play a significant role in shifting carbon rich energy sector to green energy sector. Moreover, the option of incorporating relatively inexpensive thermal storage with solar thermal power plant is expected to improve it's dispatch ability (Sargent & Lundy, 2003). Several studies have analysed and assessed the effect of various design parameters such as collector field, design direct normal irradiance (DNI), solar multiple (SM), thermal energy storage (TES), type of heat transfer fluid (HFT) on techno-economic performance of solar thermal power plant(Sharma et al., 2015). Kumar and Reddy (Reddy and Kumar, 2012) have assessed feasibility of solar thermal power plant at 58 potential locations using synthetic oil and water as working fluids in solar parabolic trough field. The study observed that PTC based solar thermal power plants are economically viable in India. Feldhof et al. (Feldhoff et al., 2012, 2010) have carried out comparative studies for PTC based solar thermal power plant using water/steam and syntheticoil as HTF with and without TES system. As reported, using direct steam generation (DSG) could lead to reduction in cost of energy delivered by 11% without TES. Further, recent research is focused on enhancing thermodynamic performance of solar thermal power plant using different kind of heat transfer fluid using nano particles (Cingarapu et al., 2013; Fernández et al., 2014; Tiznobaik and Shin, 2013).

Though numerous studies have envisaged significant potential of solar thermal power generation in India (Purohit et al., 2013; Ramachandra et al., 2011; Sharma et al., 2014), very few studies have been reported that deals with study of effect of design parameters on the techno-economics of solar thermal power generation. In the present study, an attempt has been made to investigate the effect of heat transfer fluids (Solar salt, Hitec XL, Therminol VP-1, Hitec) on techno-economic performance of a 50MW parabolic trough based solar thermal power plant in India. The plant without thermal energy storage has been chosen for the study.

2. Site selection for the study

The analysis of the techno-economic performance of solar thermal power plantsin India is primarily based on available annual direct normal irradiance (DNI) in the region. As reported, the locations with annual DNI more than 1800 kWh/m^2 are technically and economically viable for deployment of solar thermal power plants (Purohit and Purohit, 2017). Figure 1 shows the distribution map of the daily average DNI for India. It is observed that most of the northern-western regionis having high DNI and hence significant potential for solar thermal power generation exist. . The site selected for the present analysis is falling in the same region. The geographic and environmental characteristics of the potential location i.e. Jaisalmer in the state of Rajasthan is summarized in Table 1. The monthly variation of ambient temperature and DNI for the location of Jaisalmer is presented in Figure 2.

3. PTC based solar power plant

Majority of operational solar thermal power plants across the globe are parabolic trough based as the technology is relatively more mature than central tower receiver and linear Fresnel reflector. Further most of the operational plants are of 50 MW nominal capacity. Hence, a 50 MW parabolic trough based solar thermal plant has been considered in the study. A schematic flow diagram of the 50MW Rankine cycle based solar thermal power plant is shown in Figure 3. In this cycle, the cold heat transfer fluid (HTF) gets heated in the solar collector field by incident solar radiation. This heated heat transfer fluid exchanges its heat and convert water into superheated steam in the steam generator. This high pressure (100 bar) and high temperature (375°C) steam is expanded in various stages of various turbines i.e. high pressure (H.P.), intermediate pressure (I.P.) and low pressure (L.P.) turbine. The outlet steam from the L.P. turbine is condensed back into

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water in the condenser and recycled to steam generator using feed water pumps and heaters.

In the present study, the technical data pertaining to one of the operational 50 MW PTC based solar thermal plant (Megha solar power plant located in Anantpur, Andhra Pradesh)has been taken for evaluation of electricity output and same are presented in Table 2.

4. Heat transfer fluids

The selection of optimum heat transfer fluid (HTF) is important aspect for overall techno-economic performance and efficiency of CSP plant over its entire useful life. Besides exchanging heat in steam generator, the HTF can also be used as thermal storage media to generate electricity in hours of no or intermittent sunshine. The selection of appropriate HTF depends on several desired physical characteristics including higher thermal stability at higher temperature, high thermal conductivity and boiling point, low viscosity and melting point, low corrosive nature and low cost (Batuecas et al., 2017). High heat capacity for storage is essential characteristic of HTF (González-Roubaud et al., 2017a). Based on material used, the heat transfer fluids can be : (a) water/steam, (b) thermal oils, (c) organic fluids, (d) molten salts, (e) liquid metals and (f) air/other gases (Vignarooban et al., 2015). In the present study, the performance CSP plant with commonly used thermal oil (Therminol VP-1) as HTF has been compared with three different molten salts. Table 3 presents characteristics of heat transfer fluids selected for the analysis.

5. Economic analysis

As mentioned earlier, the Megha Solar Plant has been chosen as reference plant and capital cost (US $2690/kW) of same has been considered for the analysis(SolarPACES, 2016). The capital cost used in the study is adjusted for the present year (i.e. 2017)(Decelerates and Flatten, 2017). The levelized cost of electricity (LCOE) has been estimated from the following expression (Kandpal and Garg, 2003):

$$\mathrm{LCOE} = \frac{(\text{Capital cost} \times \text{capital recovery factor}) + \text{annual O \& M cost}}{\text{Annual electricity output}} \quad (2)$$

Capital recovery factor (CRF) is given by:

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (3)$$

where d is discount rate and $n$is useful life of the plant. In the present study, a discount rate of 10%, useful life of 25 years has been assumed. Annual operation and maintenance (O&M) cost has been assumed as 2% of the capital cost.

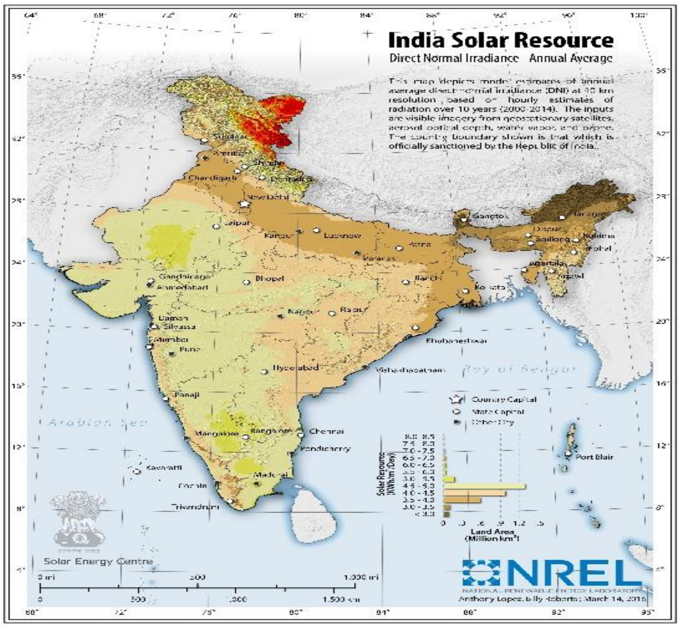

Figure 1: Daily average direct normal irradiance map for India

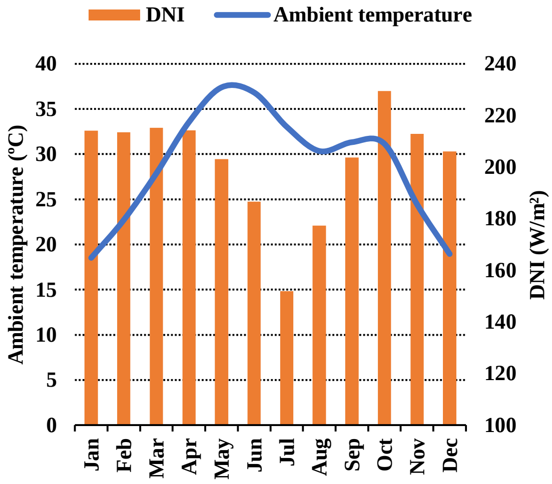

Figure 2: Monthly variation of ambient temperature and direct normal irradiance

Table 1
Details of location selected for the analysis

Latitude	°E	26.91
Longitude	°N	70.95
Wasteland	km²	16762
DNI	kWh/m²	1883
Dry bulb Temperature	(°C)	28.65
Wind speed	m/s	4.89
Rainfall	mm	181.2

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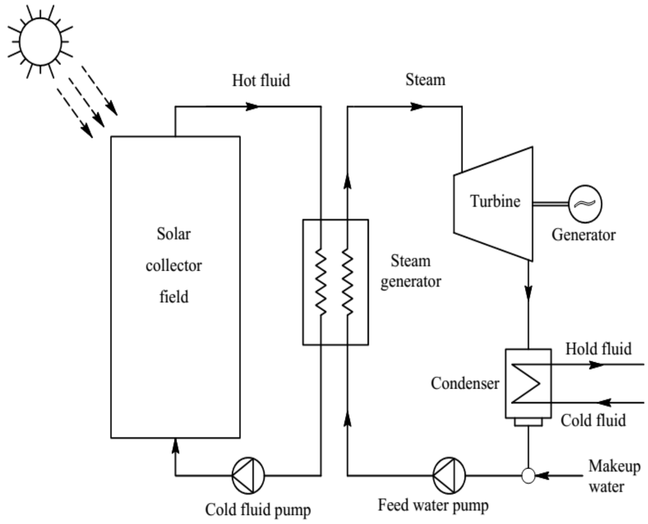

Figure3: Schematic of solar thermal power plant

Table 2
Design parameters used in simulation for 50MW PTC based solar thermal power plants(SolarPACES, 2016)

Parameter	Value
Collector	AlbiasaTrough AT150
Receiver	Siemens UVAC 2010
Heat Transfer fluid	Therminol VP-1
Irradiation at Design (W/m^2)	700
Solar multiple	1.20
Reflected area (m^2)	366,240
Land Area (km^2)	1.3
Year to year decline in output	Nil

Table 3
Characteristics of heat transfer fluids (González-Roubaud et al., 2017b; Jung et al., 2015)

Heat transfer fluid	Therminol VP-1	Solar salt	Hitec XL	Hitec
Composition (wt%)	$C_{12}H_{10}$ (73.5), $C_{12}H_{10}O$ (26.5)	$NaNO_3$ (60), KNO_3 (40)	$NaNO_3$ (7), KNO_3 (45), $Ca(NO_3)_2$ (48)	$NaNO_3$ (7), KNO_3 (53), $NaNO_2$ (40)
Minimum operating temperature (°C)	12	238	120	142
Maximum operating temperature (°C)	400	593	500	538
Density (kg/m^3)	764.3	1871.8	1956.5	1828.6
Specific heat (kJ/kgK)	2.457	1.502	1.432	1.56
Kinematic viscosity (at 300 °C) (Pa-s)	0.00059	0.00326	0.00637	0.00316

6. Results and discussion

The annual electricity output for the proposed solar thermal plants has been obtained using system advisor model (SAM). SAM is freeware renewable energy technology simulation tool and is developed by the National Renewable Energy Laboratory (NREL), USA (SAM, n.d.).The National Solar Radiation Database (NSRDB) source has been used for weather data (NREL - NSRDB, n.d.).The monthly energy output obtained for a 50MW PTC based solar thermal power plant using different heat transfer fluids is presented in Figure 4. It is observed that the variation in energy output follows the variation in monthly DNI values. Table 4 summarizes annual energy output, capacity utilization factor (CUF) and levelized cost of electricity (LCOE) for plant with different HTFs. As shown in the Table 4, the plant with Hitec – XLHTF generate relatively higher annual electricity output and hence minimum LCOE amongst the other HTF (Figure 5). The primary reason for the same can be attributed to relatively superior thermodynamics properties.

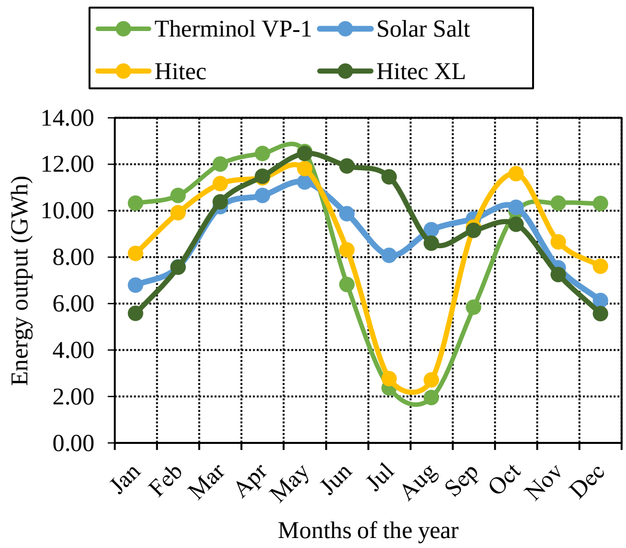

Figure 4 Monthly variation in energy output

Table 4

Annual energy output, capacity utilization and cost of energy delivered with different HTFs

Heat transfer fluid	Annual Electricity output (GWh)	CUF (%)	LCOE (₹ /kWh)
Therminol VP-1	105.5	24.1	10.8
Solar Salt	107.0	24.4	10.6
Hitec	103.3	23.6	11.0
Hitec XL	110.8	25.3	10.3

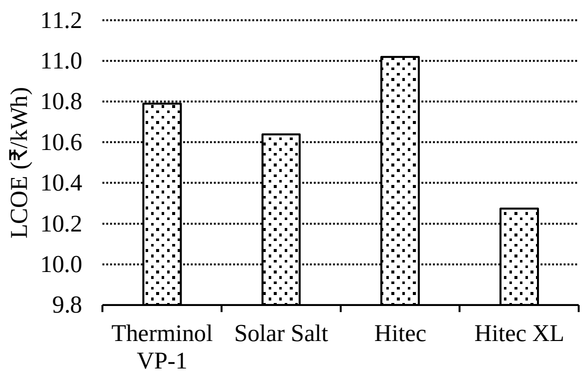

Figure 5 Variation in levelized cost of electricity for different HTFs

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7. Concluding remarks

An attempt has been made to analyze the effect of various heat transfer fluids on the techno-economics of a 50 MW solar thermal power plant in India. The location of Jaisalmer in Rajasthan has been selected for the same. Technical data pertaining to an operational plant in India has been used. Four different heat transfer fluids were used, and it was found that annual electricity output with the use of Hitec XL is maximum (Rs. 110.8 GWh) and LCOE is minimum (Rs. 10.3 per kWh). Further, annual electricity output with the use of Hitec heat transfer fluid is minimum (103.3 GWh) and LCOE is maximum (Rs. 11.0 per kWh). This reveals that among other parameters, the selection of proper heat transfer fluid has considerable impact on annual electricity output and cost of electricity delivery.

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