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Research paper

Modeling and performance simulation of 100 MW LFR based solar thermal power plant in Udaipur India ☆

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ABSTRACT

Solar energy is the most abundant source of energy on the earth and considered as an important alternative to fossil fuels. Solar energy can be converted into electric energy by using two different processes: photovoltaic conversion and the thermodynamic cycles. Lifetime and efficiency of PV power plant is lesser as compared to the CSP technology. CSP technology is viewed as one of the most promising alternative technology in the field of solar energy utilization. A 100 MW Linear Fresnel Reflector solar thermal power plant design with 6 hours of thermal energy storage has been evaluated for thermal performance using NREL SAM. A location receiving an annual DNI of 2248.17 kWh/m^2/year in Rajasthan is chosen for the technical feasibility of hypothetical CSP plant. The plant design consists of 16 numbers of solar collector modules in a loop. HITEC solar salt is chosen as an HTF due to its excellent thermodynamic properties. The designed plant can generate annual electricity of 263,973,360 kWh with the plant efficiency of 18.3 %. The capacity utilization of the proposed LFR plant is found to be 30.2%. The LFR solar thermal power plant performance results encourage further innovation and development of CSP plants in India.

1. Introduction

Power generation using solar energy is one of the most promising options in reduction of fossil fuel consumption and related CO_2 emissions. In India, Solar PV based power generation is given more importance so as to increase the share of electricity production from renewable energy quickly. It is envisaged by the government of India to generate 175 GW electricity from the renewable energy sources by 2022 under Jawaharlal Nehru National Solar Mission [1]. The proposed target is five times the current electricity production from the renewable energy sources. Out of 175 GW target, 100 GW of electricity is to be generated from solar energy alone, and the remaining will be from wind, biomass and small hydro. Solar PV based energy generation is land intensive as well as less efficient. Presently installed capacity of Solar PV based power plant is 8.7 GW [1]. In the current scenario, 97.6% of solar based energy is obtained from solar PV. The contribution of Concentrated Solar Power (CSP) is only 2.4% of the total solar based power generation [2]. In India, the population density (382 persons/km^2) is so high that land should be used judiciously. Since PV based power generation requires more land, there can be a shortage of the land, especially for housing and agriculture in the future. On the other hand, desert land (320,000 km^2) in the states of Rajasthan, Gujarat, and Haryana can be effectively used for solar-based technologies. Rajasthan has more desert area among Indian states. The desert areas are marked as barren lands as they are not suitable for living as well as agriculture. These regions are not preferred for solar PV applications because of high temperature and high DNI [3]. Also after 25 years of expected lifetime, the PV modules will be categorized as e-waste.

Concentrating solar power (CSP) technology is considered as one of the most alternative solutions of power generation from solar energy. In this technology, sunrays are focused onto a solar receiver with the help of mirrors. The energy captured by the receiver is converted to heat or electricity through a series of process. It can operate continuously for up to 100 years. For

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a CSP plant, higher DNI corresponds to higher electricity generation. As a rule of thumb, regions with low annual cloud shading and Direct Normal Incidence (DNI) exceeding 2000 kWh/m^2/year (5.5 kWh/m^2/day) can generate more units of electricity per area.

The linear Fresnel Reflector based CSP power plant is considered as one of the most promising technologies for arid and semi-arid regions. This technology is capable of producing power ranging from few kilowatts (remote power systems) to hundreds of megawatts (grid-connected power plants). Linear Fresnel reflector solar thermal power plants (LFRSTPP) mostly consist of a solar field and power blocks. TES (thermal energy storage) system can be used to enhance the system potential [4]. Presently installed capacity of CSP plant in India is about 503.5 MW [5].

Simplest application of LFR technology is for the direct steam generation eliminating the need of expensive thermo-oil and complex heat exchangers. The superheated steam can be generated directly in the absorber of the concentrating collector.

Mills and Morrison [6] presented the first results from the linear Fresnel solar concentrating collector installation of 1MWth at the Liddell power station. Direct steam generation with the solar array was achieved and optical performance met the design specifications.

Horn et al. presented an investment evaluation, determining the NPV and the LEC of an integrated solar combined-cycle system in Egypt [7].

Hosseini et al. performed a comparative study of different traditional and solar power plants using the levelized electricity cost as the reference metric [8].

A comparison in terms of the LEC between linear Fresnel and parabolic trough collector power plants was performed by Morin et al. [9].

Comparative analyses using the LEC among different renewable electricity generation technologies have been developed by Varun et al. [10] and by Giuliano et al. [3].

However, feasibility of large scale CSP Technology in Indian climatic condition has not been reported in the literature till date. This work is just an attempt to address the research gap existing in the field of large scale LFR CSP plants.

The main objectives of the research work are as follows:

1. Propose a suitable design of LFR CSP technology for renewable power generation in the identified sites of India.
2. Simulate the performance of a Linear Fresnel Reflective solar thermal power plant with the help of SAM (system advisor model) software and NREL weather data base.
3. Analyze the thermodynamic aspect and annual energy generation of the proposed Linear Fresnel Reflector solar thermal power plant technology.

2. Methodology

2.1. Thermodynamic cycle

Schematics of solar ORC are presented in Fig. 1. The organic Rankine cycle process is shown in T–S diagram in Fig. 2.

There are four processes in the Rankine cycle. These states are identified by numbers (in color) in the T-s diagram. Processes 1–2 and 3–4 would be represented by vertical lines on the T-s diagram.

- **Process 1–2**: The working fluid (HITEC Solar Salt) is pumped from low to high pressure.
- **Process 2–3**: The high-pressure liquid enters to the boiler, where it is heated at constant pressure by an external heat source to become a dry saturated vapor. The input energy required can be easily calculated using an enthalpy–entropy chart (h-s chart or Mollier diagram), or numerically, using steam tables.

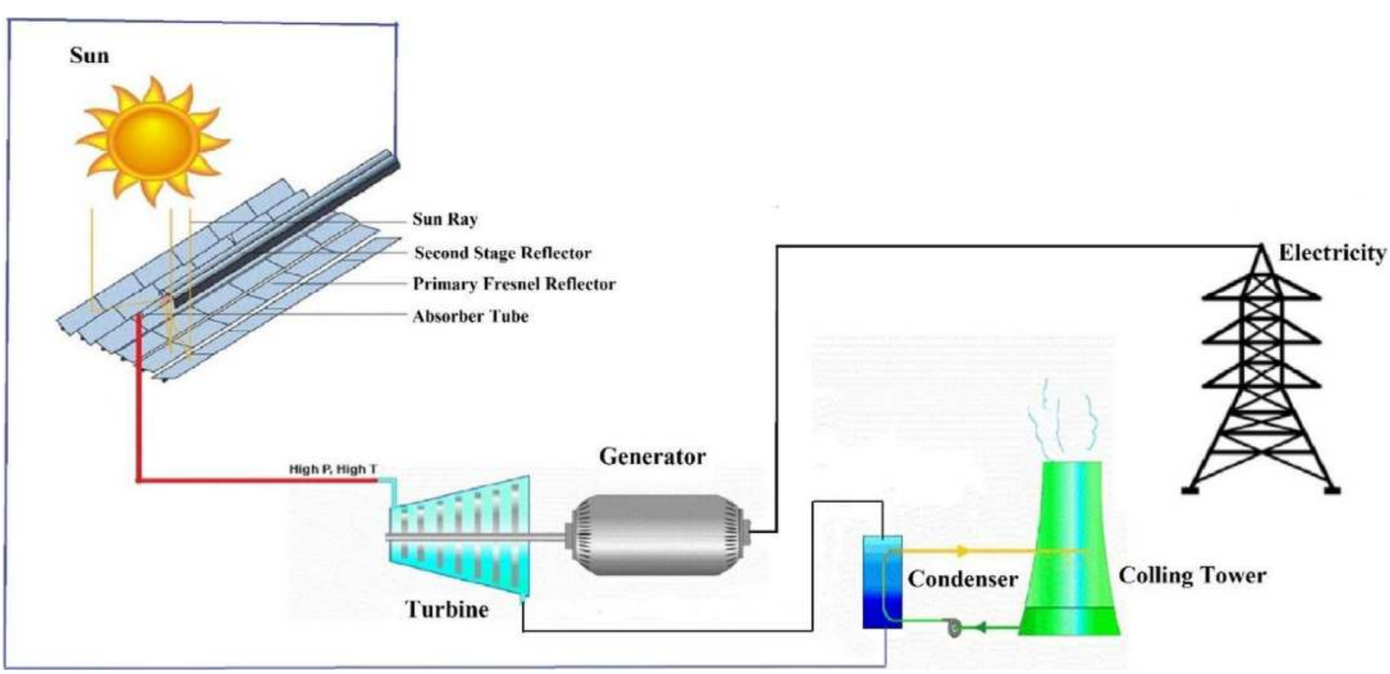

Fig. 1. Schematic diagram of Linear Fresnel Solar Thermal Power Plant.

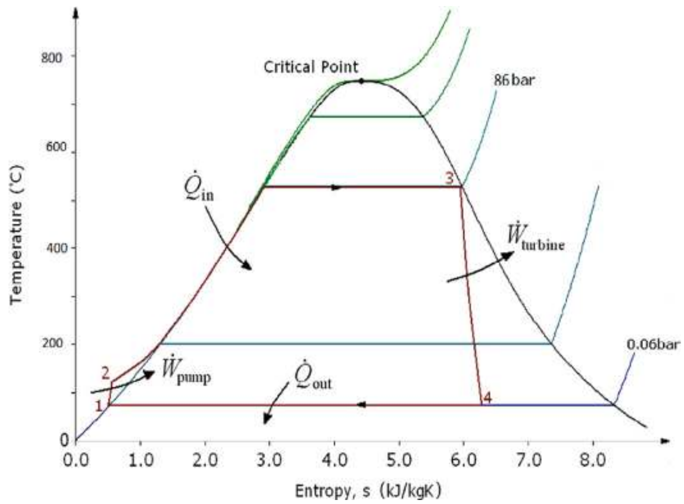

Fig. 2. T-S Diagram of a Rankine Cycle.

- **Process 3–4**: The dry saturated vapor expands through a turbine, generating electrical power. This process in the turbine decreases the temperature and pressure of the vapor, and some condensation may occur.
- **Process 4-1**: The wet vapor then enters to the condenser where it is condensed at a constant pressure to become a saturated liquid. The condenser is connected to the cooling tower for cooling the hot liquid HTF fluid.

Always in an ideal Rankine cycle, both the pump and turbine would be isentropic, i.e., the pump and turbine would generate no entropy and hence maximize the net work output. The Rankine cycle shown here prevents the vapor ending up in the superheat region after the expansion in the turbine, which reduces the energy removed by the condensers. The actual vapor power cycle differs from the ideal Rankine cycle because of irreversibilities.

$\dot{q}$ = Heat flow rate per unit time
$\dot{m}$ = Mass flow rate per unit time
$\dot{w}$ = Mechanical energy consumed per unit time
η_{thermo} = Thermodynamic efficiency of a power plant
h_1, h_2, h_3, h_4 = Specific enthalpies at indicated point on the T-S Diagram
p_1, p_2 = The pressure before and after the compression process

Efficiency of the CSP Plant

- At Turbine (3–4)

$$\dot{w}_t = h_3 - h_4$$

- At Condenser (1–4)

$$\dot{q}_{out} = h_1 - h_4$$

- At Pump (1–2)

$$\dot{w}_p = h_2 - h_1$$

- At Boiler (2–3)

$$\dot{q}_{in} = h_3 - h_2$$

$$\eta_{thermo} = \frac{\dot{w}_{net}}{\dot{q}_{in}} = \frac{w_t - w_p}{\dot{q}_{in}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

Table 1
List of heat transfer fluids [6].

Name	Type	Min optimal operating temp °C	Max optimal operating temp °C	Freeze point °C
Hitec Solar Salt	Nitrate salt	238	593	238
Hitec	Nitrate salt	142	538	142
Hitec XL	Nitrate salt	120	500	120
Caloria HT 43	Mineral hydrocarbon	−12	315	−12
Therminol VP-1	Mixture of biphenyl and diphenyl oxide	12	400	12
Therminol 59	Synthetic HTF	−45	315	−68
Therminol 66	n/a	0	345	−25
Dowtherm Q	Synthetic oil	−35	330	n/a
Dowtherm RP	Synthetic oil	n/a	330	n/a

2.2. HTF (heat transfer fluid)

Out of all the different types of HTF fluid, Therminaol VP-1 and HITEC solar salt provide better thermal performance than other fluid due to their high specific heat. It also has good heat carrying capacity. It is a high density and low viscosity fluid which can easily pass through the tube. Properties of various HTF are shown in Table 1 [11].

HITEC solar salt is extremely stable and free from contamination. It offers a few years of wonderful service at temperatures up to concerning 454 °C. Between 454 and 538 °C (the most suggested in operation temperature of HITEC), the salt, when utilized in a closed system, undergoes a slow thermal breakdown of the radical to nitrate, metal compound, and nitrogen:

$$5NaNo_2 \rightarrow 3NaNo_3 + Na_2 + N_2 \quad (1)$$

Nitrogen gas evolves slowly and gradually rises the freezing point of the salt mixture. Beyond 816°C, nitrogen evolves so rapidly that the molten salt seems to boil. Decomposition ceases as soon as the source of heat is removed, which indicates the decomposition reaction is endothermic. When HITEC Solar Salt is used in an open system, in touch with the air, and within the higher operating range between 350°C and 454–538°C, the nitrite is slowly oxidized by atmospheric oxygen:

$$2NaNo_2 + o_2 \rightarrow 2NaNo_3 \quad (2)$$

Other lesser reactions under these conditions which gradually alter the composition of the salt mixture are (1) the absorption of carbon dioxide to form carbonates which can precipitate and (2) the absorption of vapor to create alkaline metal hydroxides. These reactions that tend to raise the freezing point can be eliminated by blanketing the molten salt with nitrogen [12].

3. Modeling and simulation

3.1. System advisor model (SAM) software

SAM is developed by the National Renewable Energy Laboratory (NREL) with funds from the U.S. Department of Energy. SAM collaborates with Sandia National Laboratories for the PV models, and has collaborated with the University of Wisconsin's Solar Energy Laboratory for the concentrating solar power models. SAM is useful for performance and financial model to facilitate decision making and people involved in the renewable energy industry like:

- Project managers and engineers
- Policy analysts

Table 2
Shortlisted sites based on the high DNI [6].

Rajasthan	Gujarat	Madhya Pradesh	Karnataka	Tamil Nadu
Udaipur	Palanpur	Bhopal	Mysore	Madurai
Jaipur	Kutch	Indore	Tumakuru	Coimbatore
Bikaner	Mehsana	Rewa	Bengaluru	Chennai

Table 3
Based on DNI rank wise shortlisted site [6].

Rank	Site Location	Rank	Site location
1	Udaipur, Rajasthan	9	Tumakuru, Karnataka
2	Palanpur, Gujarat	10	Coimbatore, Tamil Nadu
3	Mehsana, Gujarat	11	Madurai, Tamil Nadu
4	Kutch, Gujarat	12	Bengaluru, Karnataka
5	Jaipur, Rajasthan	13	Bhopal, Madhya Pradesh
6	Indore, Madhya Pradesh	14	Rewa, Madhya Pradesh
7	Bikaner, Rajasthan	15	Chennai, Tamil Nadu
8	Mysore, Karnataka		

- Technology developers
- Researchers

SAM's user interface makes it possible for people with no experience in developing computer models to build a model of a renewable energy project, and to make cost and performance projections based on model results. To describe the renewable energy resource and weather conditions at a project location, SAM requires a weather data TMY file [6].

3.2. Site selection and solar resource assessment

India lies in a region with medium solar radiation. On average, 4.5–6.5 kWh/m^2/day of insolation exist in the country more than 85% of the area. Most part of the country receives 8 to 10 sunshine hours per day. Fig. 3 shows global horizontal irradiance map of India [6]. Shown in Fig. 4 is the DNI map of India along with appropriate site for constructing Linear Fresnel reflective solar thermal power plant (LFRSTPP). The primary phase of a CSP power plant is site selection. CSP based power plant can only be installed where the DNI ≥ 5.5 kWh/m^2/day (greater than 1800 kWh/m^2/year) [13]. For site selection, many factors are considered, i.e. water, land, etc. In the secondary phase, some extra parameters are required for installation of a solar thermal power plant; these are water supply, transportation, grid connection, soil structure, land cost, capital investment, environmental effect, etc. Indirectly, the global horizontal irradiance also depends upon the power generation.

Keeping in view the potential sites identified in Table 2 and the availability of climatological data, the sites with the highest value of annual DNI have been selected [14]. Based on the above site, selection criteria and availability of the solar radiation (Table 3), the following four potential sites are shortlisted for LFRSTPP (Table 4). Hourly DNI values in a standard format, mostly TMY2, (Typical Meteorological Year version 2) are required as an input data for simulation.

Out of all these locations Udaipur, Rajasthan is chosen for the feasibility study of the CSP plant because annual DNI of this location is very high as compared to other locations in India. Thus, this location fulfills all the site selection criteria for Installation of CSP based power plant. The required parameters are summarized in Table 5.

The site selected for the study is shown in Fig. 5.

Table 4
Annual DNI values for different potential sites [6].

Name of the Site	DNI kwh/m^2/year
Udaipur, Rajasthan	2248.17 kWh/m^2/year
Palanpur, Gujarat	2188.2 kWh/m^2/year
Mehsana, Gujarat	2141.71 kWh/m^2/year
Kutch, Gujarat	2076.74 kWh/m^2/year

Table 5
Summary of the required parameters near the selected site of Udaipur, Rajasthan.

Required Parameter	Availability
Water resources	* Upper lakes: Lake Badi, Chhota Madar & Bada Madar. * City Lakes: Lake Pichola, Fateh Sagar Lake, Swaroop Sagar, Rang Sagar, Kumharia Talab, Goverdhan Sagar. * Downstream Lake: Udaisagar Lake. * River: Ahar River.
Transportation	* Air way- Dabok airport, also known as Maharana Pratap Airport * Railway- Udaipur City and Rana Pratap Nagar railway station * Road way- NH 76 and NH 8

3.3. Mathematical modeling and simulation

3.3.1. Solar field

Solar field is the area where various solar radiation collecting devices such as collector, absorber. etc. have to be installed. It is initial and first deciding parameter for the design of any CSP plant.

3.3.2. Solar multiple

Solar multiple is defined as the field aperture area expressed as a multiple of the aperture area required to operate the power cycle at its design capacity. It is denoted as SM and mathematical formula is given below:

$$\mathrm{SM} = \frac{\text{power cycle capacity}}{\text{solar field capacity}} \tag{3}$$

3.3.3. Solar field design output

It is the thermal energy delivered by the solar field under design conditions at the given solar multiple. The value of solar field design output is calculated at the interface of receiver and power block as the function of the solar multiple.

The equation for the solar field design output is:

$$Q_{sf,des} = \frac{W_{pb,des}}{\eta_{des}} \times \mathrm{SM} \tag{4}$$

where, $Q_{sf,\ des}$ = solar field design heat output
$W_{pb,\ des}$ = design work out from power block
η_{des} = design efficiency
SM = Solar Multiple

3.3.4. Loop optical efficiency

The optical efficiency when incident radiation is normal to the aperture plane, not including end losses or cosine losses. This value does not include thermal losses from piping and the receivers.

Loop Optical Efficiency = Collector Optical Efficiency at Design × Receiver Optical Derate

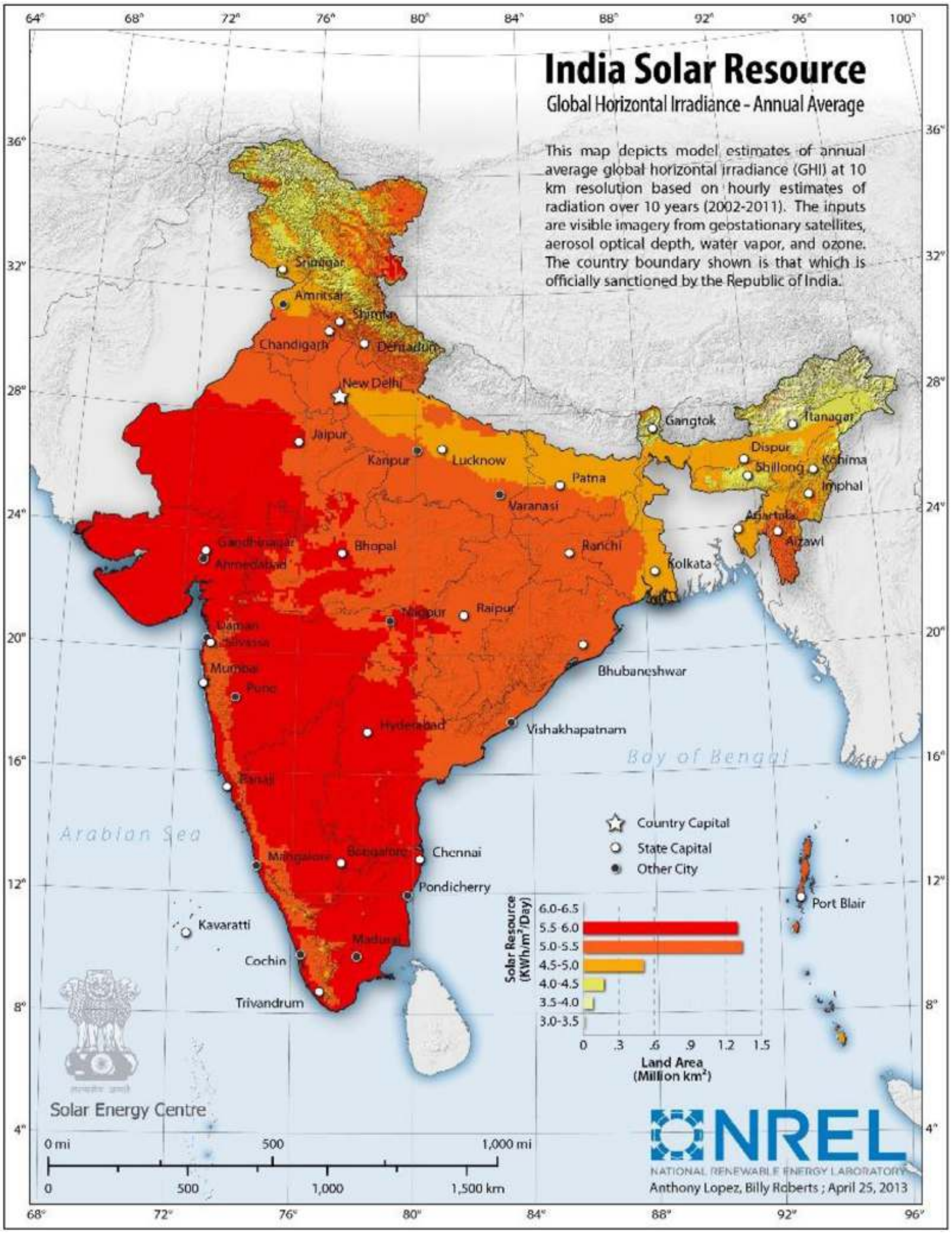

Fig. 3. Global Horizontal Irradiance
Source: (Source: NREL).

The optical efficiency is defined as follows:

$$\text{Optical Efficiency} = \text{Total Thermal Energy Absorbed by Receiver} \div (\text{Direct Normal Irradiance} \times \text{Actual Aperture Area}) \quad (5)$$

3.3.5. Collector and receiver

The collector and receiver of a linear Fresnel solar thermal power plant depend upon some parameters, i.e. longitudinal incidence angle, zenith angle, transversal incidence angle, etc. Fig. 6 .

3.3.5.1. Transverse incidence angle modifier ($\varnothing_T$). The incidence angle modifier polynomial for the transversal incidence angle to calculate the optical efficiency reduction associated with deviation of the irradiation incidence angle in the transversal plane is as follows:

$$\text{Incidence angle modifier}(\text{IAM}_\text{T}) = \text{C}_0 + \text{C}_1 * \varnothing_\text{T} + \text{C}_2 * \varnothing_\text{T}^2 + \text{C}_3 * \varnothing_\text{T}^3 + \text{C}_4 * \varnothing_\text{T}^2 \quad (6)$$

where $\varnothing_\text{T}$ is the transversal incidence angle.

3.3.5.2. Longitudinal incidence angle modifier ($\varnothing_L$). The incidence angle modifier polynomial for the longitudinal incidence angle to calculate the optical efficiency reduction associated with deviation of the irradiation incidence angle in the longitudinal plane is as

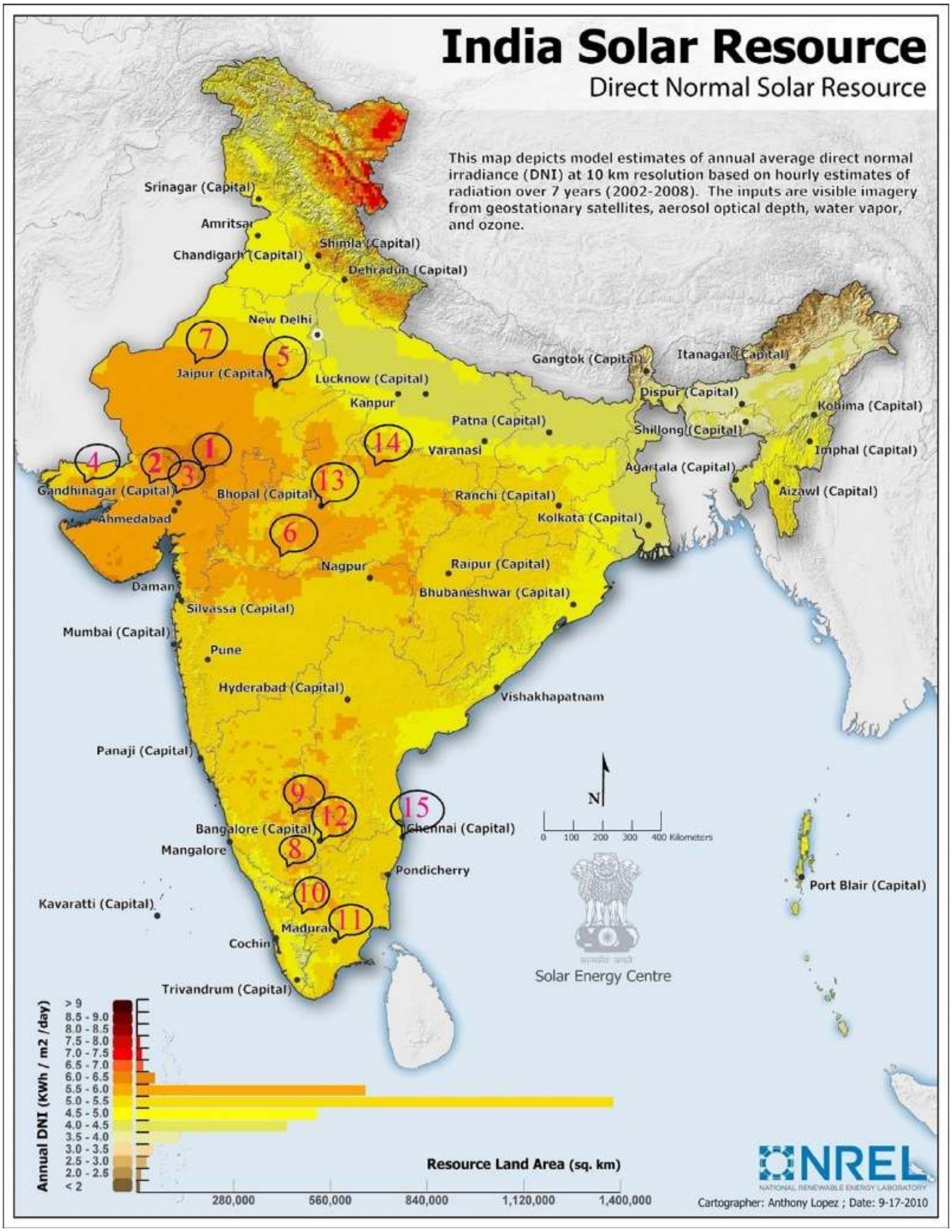

Fig. 4. Rank wise shortlisted all sites in DNI map of India.

follows:

$$\text{Incidence angle modifier}(IAM_L) = C_0 + C_1 * \varnothing_L + C_2 * \varnothing_L^2 + C_3 * \varnothing_L^3 + C_4 * \varnothing_L^4 \quad (7)$$

where $\varnothing_L$ is the longitudinal incidence angle.

3.3.5.3. Zenith angle ($\varnothing_Z$). The solar zenith angle is the angle between the zenith and the Centre of the sun's disc. The solar elevation angle is the altitude of the sun, the angle between the horizon and the Centre of the sun's disc.

3.3.6. Estimated net output at design (MWe)

The power cycles nominal capacity is calculated as the product of the design gross output and estimated gross to net conversion factor. This following relation is used for capacity-related calculations.

$$\begin{aligned}&\text{Estimated Net Output at Design}(\text{MWe})\\&= \text{Design Gross Output}(\text{MWe})\\&\times \text{Estimated Gross to Net Conversion Factor}\end{aligned} \quad (8)$$

3.4. Plant configuration/specification

Several input parameters are required for the evaluation of total electrical energy generation, plant efficiency; plant capacity factor and total input thermal energy of the concentrated solar power plant [6,12,15,16] which are listed in Table 6.

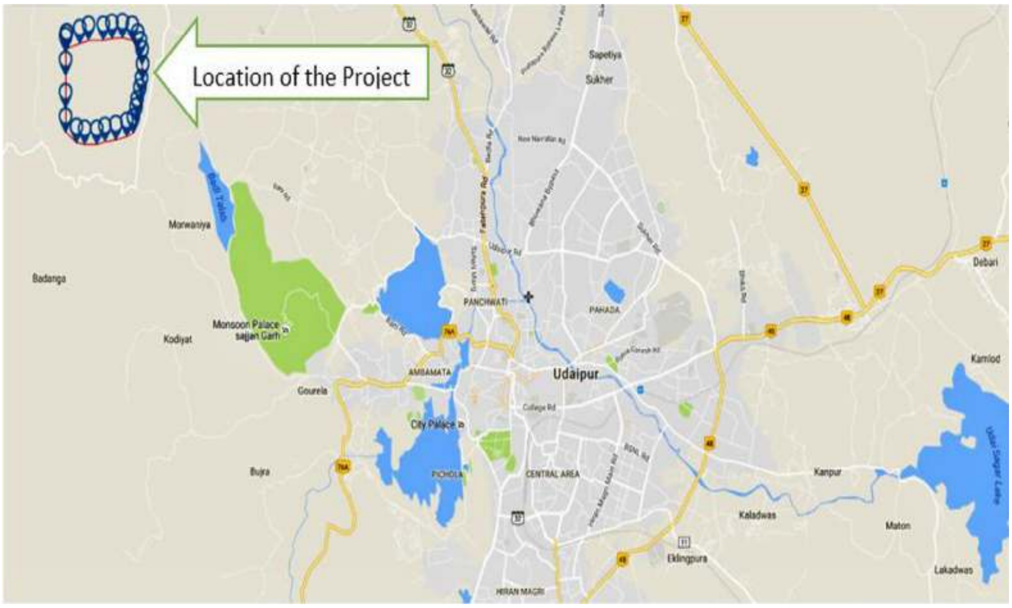

Fig. 5. Site of the proposed CSP power plant.

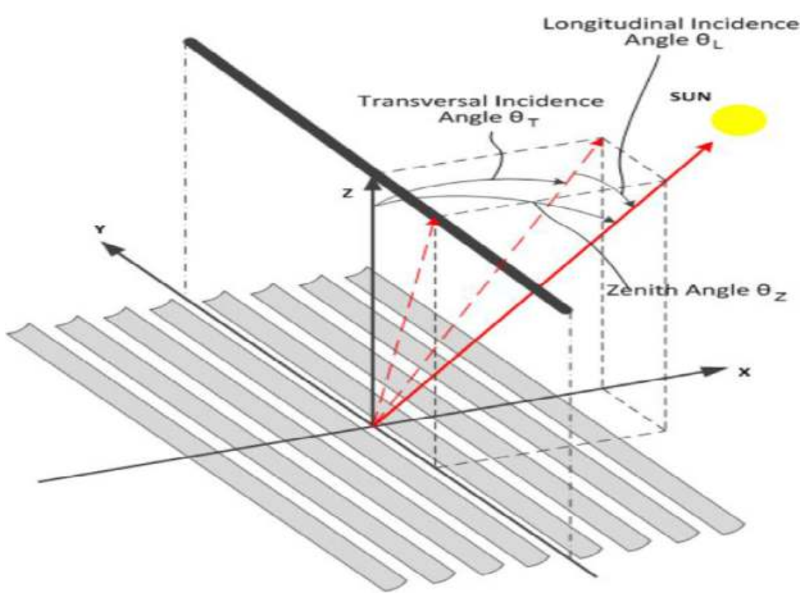

Fig. 6. Solar collector and receiver of Linear Fresnel Reflector solar thermal power plant.

4. Performance analysis of proposed LFR based solar thermal power plant

4.1. Solar potential assessment

For simulation of the hypothetical CSP power plant, any location with good DNI can be chosen provided its weather data are available. Udaipur, Rajasthan has been chosen in this analysis due to its favorable condition for CSP technology. The site selected for the study receives ample amount of solar radiation for 10–12 hrs/day throughout the year. A typical metrological year (TMY) data set of the selected site from NREL database has been used to evaluate the performance of Linear Fresnel Reflector solar thermal power plant. The climate data include hourly DNI, ambient temperature wind speed, atmospheric pressure, sun angle and solar azimuth angle for the complete year. An annual average of 2248.17 kWh/m^2/year DNI is received in Udaipur region. The plant is simulated for a period of one-year, i.e. 0 hours to 8760 hours. Maximum DNI received in the month of May was 237.1 kWh/m^2, and minimum DNI received in the month of August was 84.63 kWh/m^2. The monthly variation of average DNI at Udaipur is shown in Fig. 7 . The recorded maximum and minimum dry bulb temperature were 47.87°C and 6.40°C respectively. The recorded maximum and minimum wind speed were 6 m/s and 1.976m/s respectively. The variation of wind speed with dry bulb temperature is shown in Fig. 8 . Also, the heat map of the Beam Irradiance (w/m^2) for whole the year is shown in Fig. 9 .

Table 6
Linear fresnel reflector solar thermal power plant design parameters for simulation

Categories	Values	Reference & Assumption	Categories	Values	Reference and assumption
Location and resources			Design loop inlet temp.	293°c	NREL SAM
Location	Udaipur, India	Assume	Design loop outlet temp.	525°c	NREL SAM
Latitude and longitude	24.55 °N, 73.75 °E	NREL SAM	Min Single loop flow rate	3.01589 kg/s	NREL SAM
Solar field			Max Single Loop flow rate	14.4763 kg/s	NREL SAM
Solar multiple	2	NREL SAM	Header design min flow velocity	2 m/s	NREL SAM
Irradiation at design	887 w/m^2	NREL	Header design max flow velocity	3 m/s	NREL SAM
Design-point ambient temp.	50 °c	NREL	Design point		
Design-point wind Velocity	5 m/s	NREL	Actual no. of loops	140	NREL SAM
No. of field sub sections	2	NREL SAM	Single loop aperture	7524.8 m^2	NREL SAM
No. of collector modules in a loop	15	NREL SAM	Total aperture reflective area	524620 m^2	NREL SAM
Stow angle	170°	NREL SAM	Field thermal output	561.449 Mwt	NREL SAM
Deploy angle	10°	NREL SAM	Mirror washing		
HTF pump efficiency	0.85	Assume	Water usage per wash	0.02 L/m^2	NREL SAM
Heat transfer fluid			Wash per year	120	NREL SAM
Field HTF Fluid	Hitec Solar Salt	Assume	Land area		
Field HTF min operating temp.	238°c	NREL SAM	Solar field area	260.31 Acres	NREL SAM
Field HTF max operating temp.	593°c	NREL SAM	Total land area	416.51 Acres	NREL SAM

Categories	Values	Reference & Assumption	Categories	Values	Reference and assumption
Collector and receiver			Rated cycle conversion efficiency	0.397	NREL SAM
Receiver model type	Evacuated tube Model	Assume	Design inlet temp.	525 °c	NREL SAM
Absorber tube inner diameter	0.066 m	NREL SAM	Design outlet temp.	293 °c	NREL SAM
Absorber tube outer diameter	0.07 m	NREL SAM	Boiler operating pressure	71 bar	NREL SAM
Glass envelope inner diameter	0.115 m	NREL SAM	Cooling condenser type	Air- Cooled	Assumed
Glass envelope outer Diameter	0.12 m	NREL SAM	Thermal storage		
Average field temp. difference at design	367 °c	NREL SAM	Full load hour of TES	6 hr.	Assumed
Heat loss at design	166.25 w/m	NREL SAM	Storage volume	10482.8 m^3	NREL SAM
Power cycle			Parasitic		
Design gross output	111 MWe	Assume	Balance of plant parasitic	0.02467 MWe/MWcap	[16]
Estimated gross to net conversion Factor	0.9	NREL SAM	Auxiliary heater, boiler parasitic	0.02273 MWe/MWap	[15]
Estimated net output at design(nameplate)	100 MWe	NREL SAM	Piping thermal loss coefficient	0.45/m^2-k	Assume

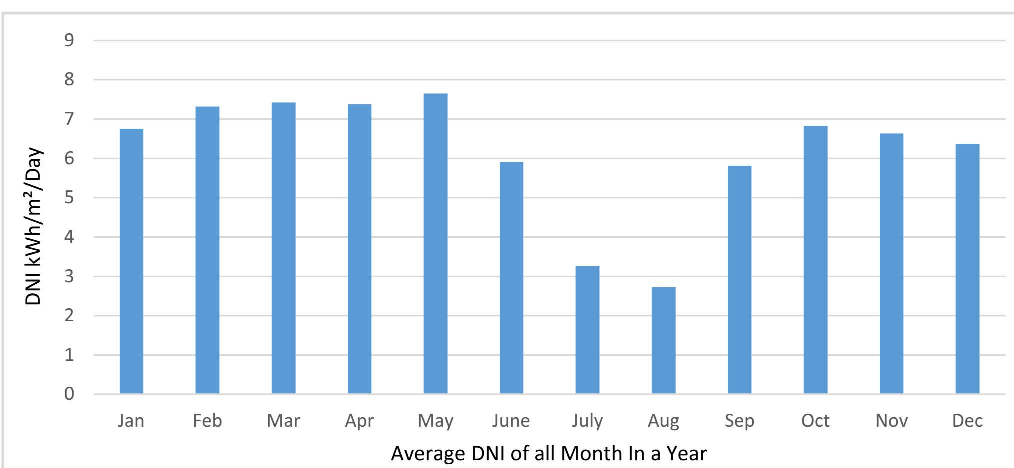

Fig. 7. Average DNI available at Udaipur/month.

4.2. System performance

The simulation is carried out using SAM software. Month wise energy generation from the hypothetical LFR solar thermal power plant is given in Fig. 10 . It is found that the maximum energy was generated during the month of May (32067.5 MWh), and minimum energy was generated during the month of July (11739.1 MWh). When the Heat Transfer Fluid (HTF) circulates from cold tank to the hot tank, minimum temperature of the cold header inlet reached a value of 263.041 °C. Similarly, the maximum temperature obtained at hot header outlet is 524.64 °C. The variation of hot outlet and cold header inlet temperature for a day (24 hours) is shown in Fig. 11 .

It is to be noted that the power generation starts only from 8.30 am, even though the sun rises at 6.30 am. At least 300 °C should be maintained in the hot tank for proper starting of the power plant. Otherwise, substitute fuel must be used to increase the tank temperature. The temperature loss from HTF fluid HITEC solar salt

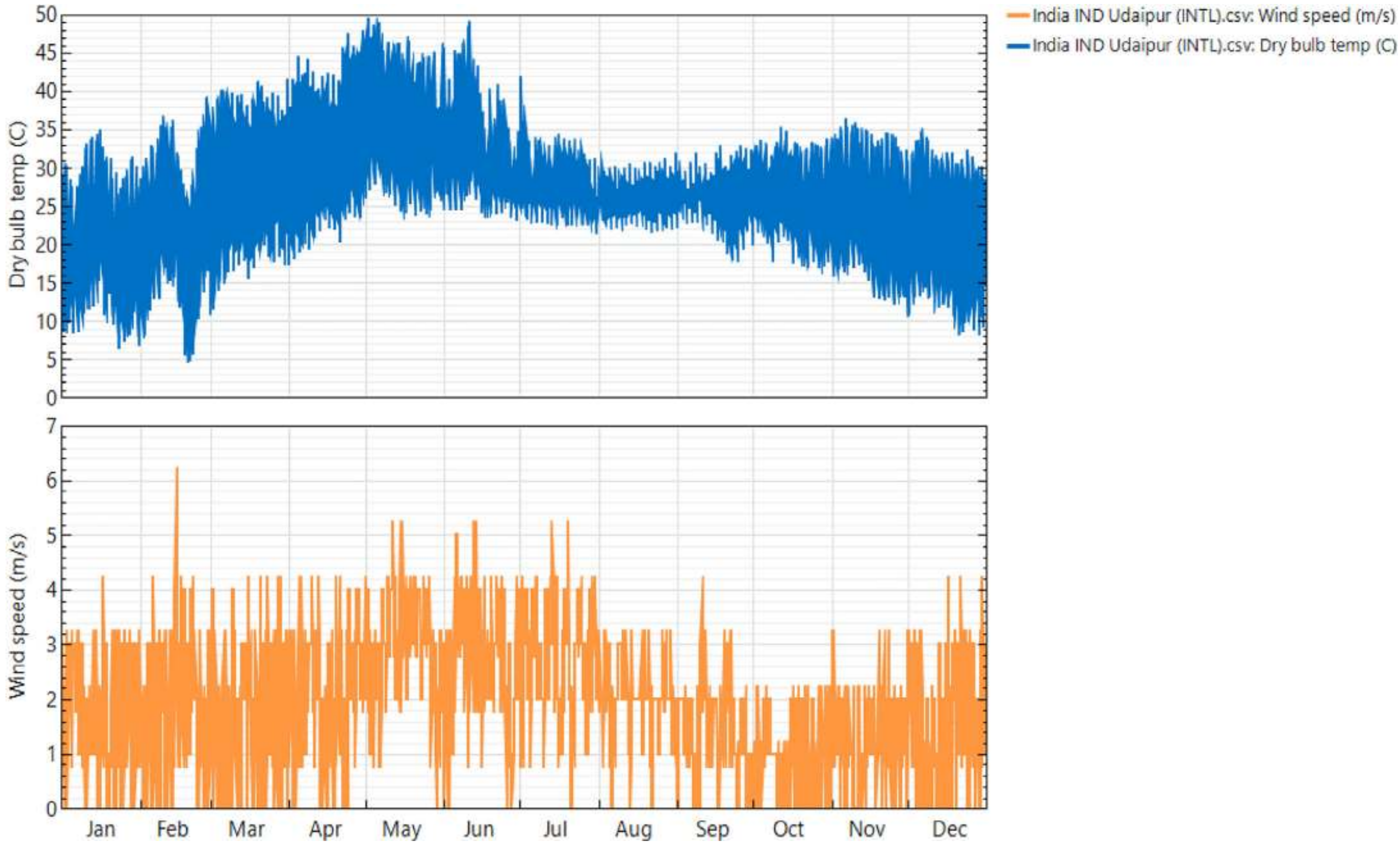

Fig. 8. Wind speed vs. dry bulb temp of the power plant location.

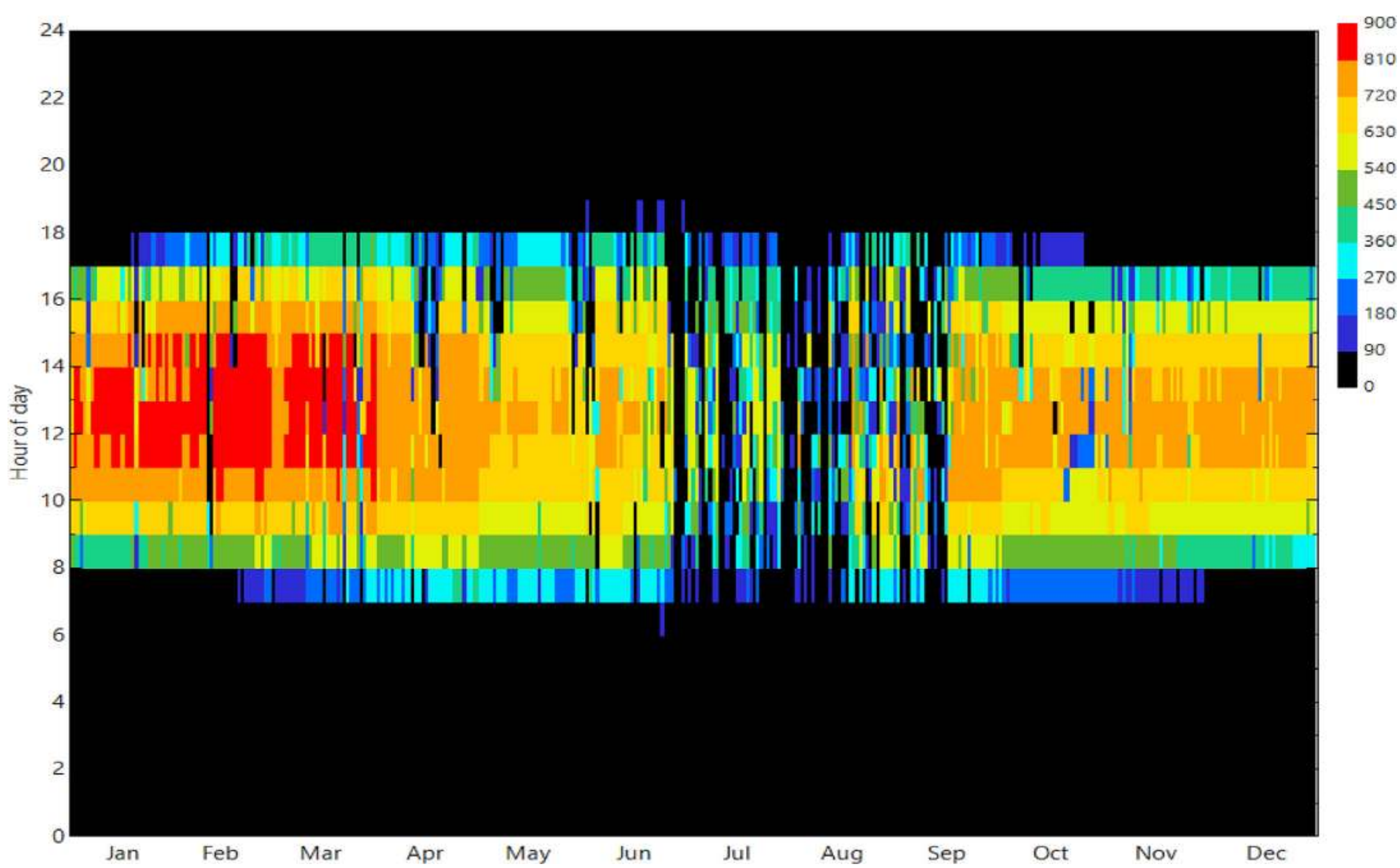

Fig. 9. Heat map of the beam irradiance (w/m^2) for one year.

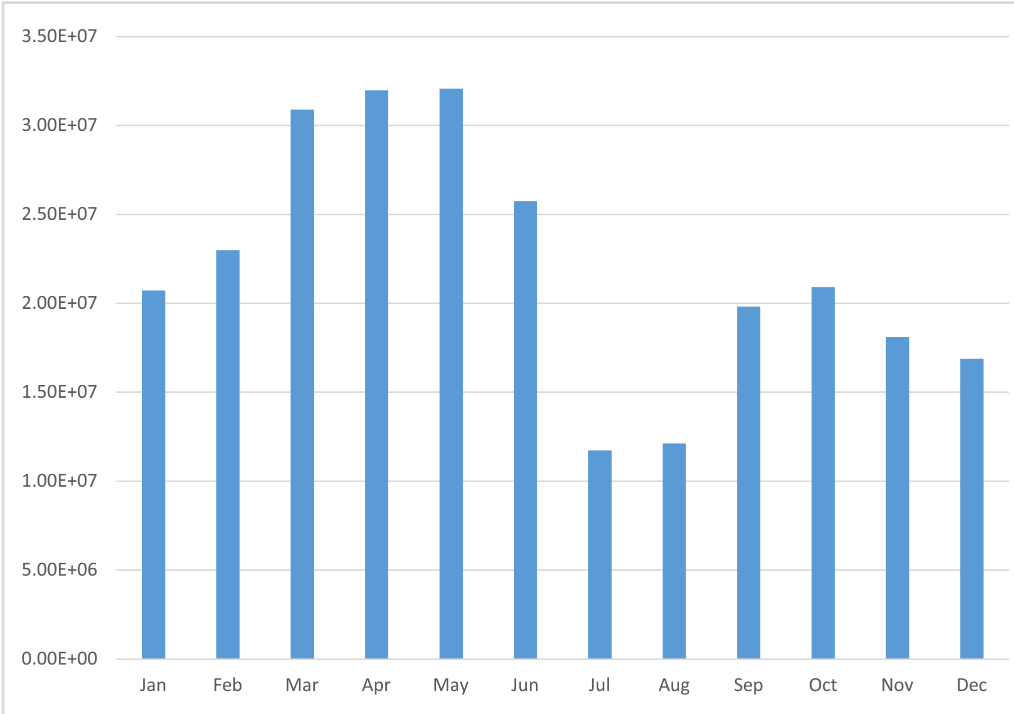

Fig. 10. Monthly energy generation.

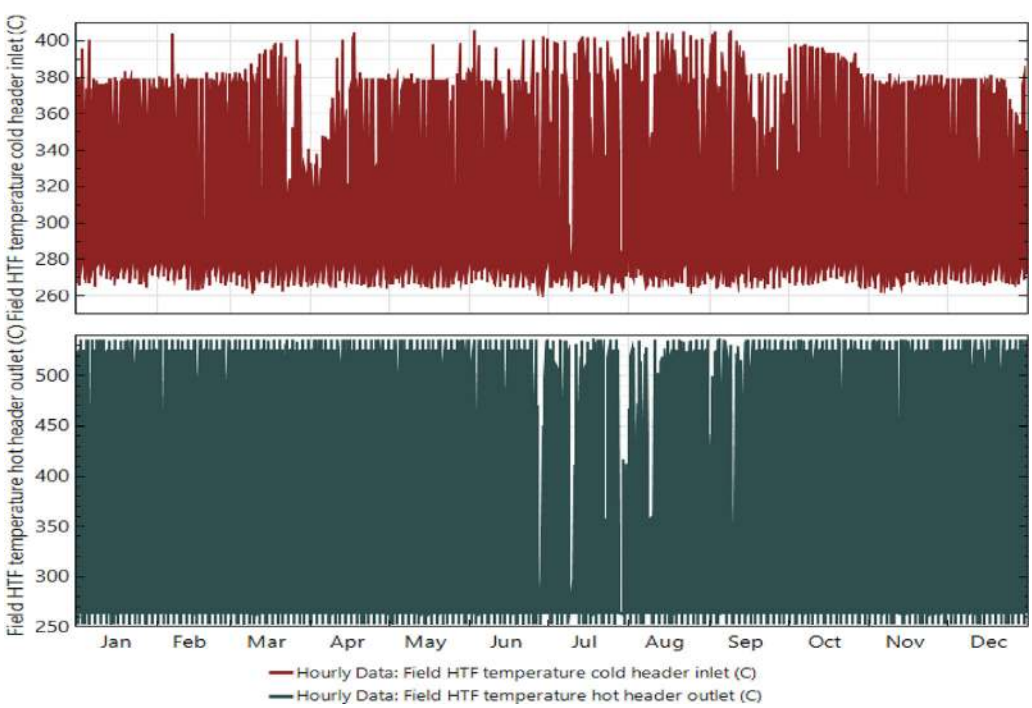

Fig. 11. Field temperature of cold header inlet and hot header outlet.

is around 7 °C/hr. This rate of decrease in temperature is seen to be reducing with respect to time. The maximum cycle efficiency obtained from the plant is 0.45913. The maximum cycle thermal power input was estimated at 293.577 MWt as well as maximum cycle electrical power output (net) was estimated at 120.328 MWe during the month of April. Similarly, maximum electrical power output (gross) was estimated at 125.166 MWe and maximum field thermal power incident was estimated at 911.253 MWt. TES a maximum thermal loss from the tank was estimated at 0.613466 MWt and TES thermal energy into storage was estimated at 152.51 MWt.

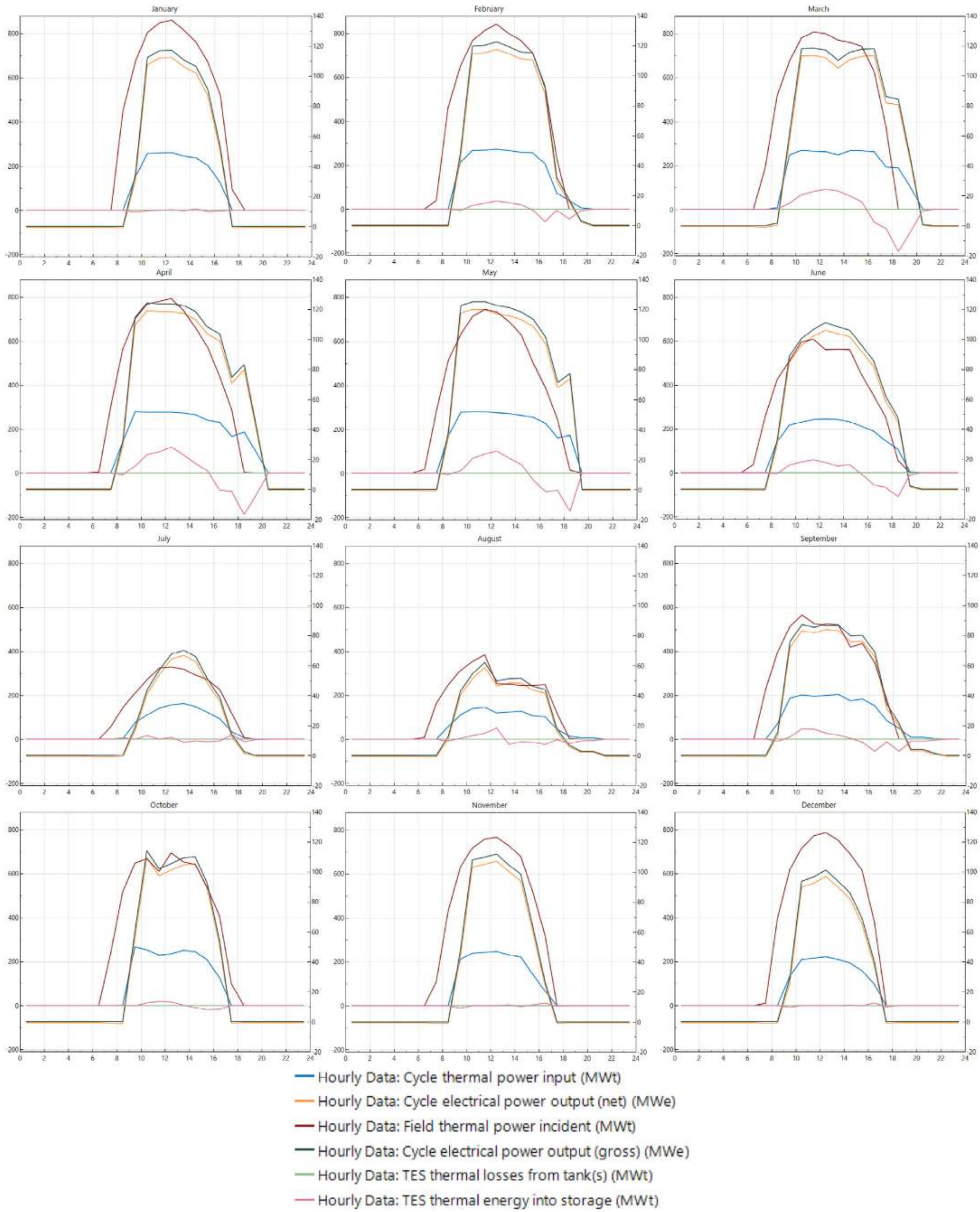

Fig. 12. Hourly data of cycle thermal power input, output (net) and output (gross) and field thermal power incident and TES thermal losses from tank and TES thermal energy into storage.

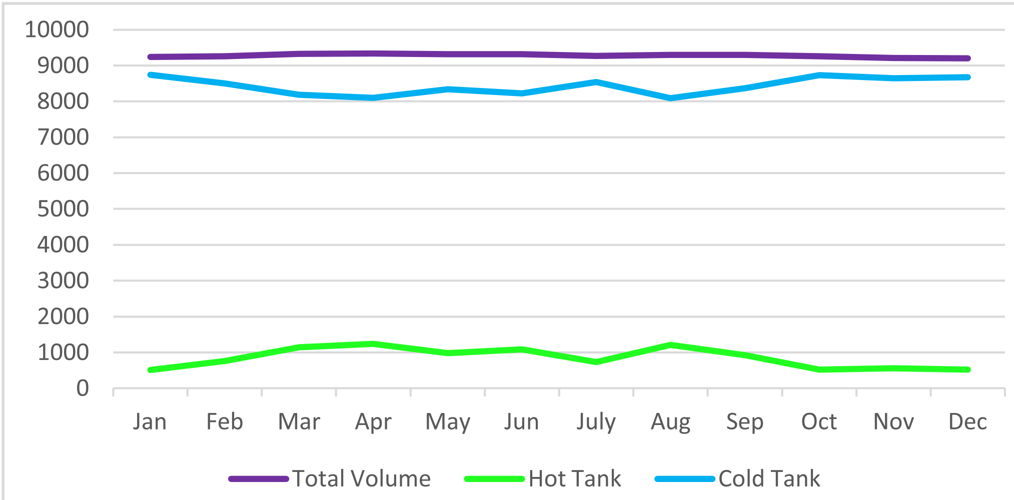

Fig. 13. TES HTF total volume, volume of hot tank, volume of cold tank.

Table 7
Net output energy of LFRSP Plant.

Metric	Value
Annual energy (year 1)	263,973,360 kWh
Capacity factor (year 1)	30.2%
Gross-to-net conversion	90.17%
Plant efficiency	18.3%
Annual water usage	677,863 m^3

The net electrical power generation depends on the field thermal power incident and the cycle thermal power input to the turbine, as shown in Fig. 12**.**

For generation of power after sunset, the HTF fluid should be stored in the storage tank for the 6 hr storage capacity. The maximum volume of total energy storage (TES) heat transfer fluid (HTF) tank is 9776.40 m^3, the maximum volume of TES HTF hot tank is 9273.13 m^3 and the maximum volume of TES HTF cold tank is 8819.03 m^3 as shown in Fig. 13.

The net energy generated annually from the hypothetical 100 MW CSP power plant is around 263,973,360 kWh (263.973 GWh). This plant is operating with a capacity utilization factor (CUF) of 30.2%**.** The 100 MW CSP Plant is having a gross to net conversion of 90.17% and overall plant efficiency is near to 18.3%. The results are shown in Table 7. Annually 677,863 m^3 of water is required for washing of Linear Fresnel Reflector that can be met from nearby lakes and rivers.

4.2.1. Discussion and future direction

This hypothetical simulation study is helpful in determining the technical feasibility of the LFRSP plant. The preliminary design of the LFRSP plant has been done and its performance is predicted. The thermal efficiency of the LFRSP for one of the fluids in this study can exceed 18.3 %. LFRSP plant-based technology produces lesser power compared to the other CSP technology. A relatively high combined heat and power efficiencies up to 74% are achievable with the use of the ORC technology [17,18].

LFRCSP is technically feasible, if the DNI of the location is greater than 5.5 kWh/m^2/day which is possible in Indian climatic conditions. The scope of the present work can be extended toward the study of most suitable designs of other CSP technology along with their economical analysis in Indian condition.

5. Conclusion

A 100 MW Linear Fresnel Reflector based solar thermal power plant is designed and simulated using SAM software. The simulated performance result of CSP plant in India has been successfully validated with the LFR solar thermal power plants operating across the world. There is a vast potential for successful operation of CSP plant in the country due to its high level of DNI and favorable characteristics. The proposed design showed reasonably good thermal performance and can be used for forecasting solar thermal power plant potential at any given location. The analysis provides the necessary data for the comparison of several aspects of the CSP technology. This is helpful in designing of Linear Fresnel Reflector solar thermal power plant in Indian climatic conditions. However, additional research investigations are required for analyzing the system design parameters such as collector loop, solar field configuration, heat transfer fluid, thermal capacity, and efficiency etc. Also, further research studies directed toward sensitivity analysis to determine the optimum condition for technical and economical viability of LFR solar thermal power plant is needed. Development of such utility-scale solar thermal power plant will be a major milestone in the renewable energy sector of India. It is indispensable for India with its abundant solar resource to exploit the different CSP technology based power generation including LFR solar thermal power plant.

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