Modelling, simulation and analysis of 5 MWe Linear Fresnel Collector based solar thermal energy conversion cycle with energy storage

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Abstract

Solar thermal energy conversion cycle is a preferable option for process industries both for steam generation and electricity generation. Linear Fresnel Reflector (LFR) Technology is becoming equally competitive to Parabolic Trough Technology for the past five years. It is cost effective, easy to install and requires relatively less land area. In this paper, a solar thermal energy conversion cycle with energy storage is designed based on LFR technology for a 5 MW electricity generation. Process heat generating industries in India can utilize the solar energy and power their equipment during solar and non-solar hours. Solar field based on LFR collectors is designed to heat the heat transfer fluid (HTF) flowing through the absorber tube. Solar salt in molten state is used as both the HTF and thermal energy storage (TES) material. Solar resource assessment data for a few Indian cities is mapped from National Solar Radiation Database (NSRDB) database. Length of the solar field along with different TES materials is designed for each location. The variation of mass flow rate of HTF against the plant operating hours is also analysed. The solar field area is an optimum choice between the plant equipment cost and the monthly electrical units generated. Out of ten locations analysed in this work, Ananthapuramu happens to be the best place for harnessing solar energy to generate electricity through thermal energy conversion cycle. At this place, annual energy yield of a 5 MWe Linear Fresnel solar thermal power plant is 12,500 MWH with 6 hours of storage.

Keywords: Solar thermal, Linear Fresnel Reflectors, Thermal Energy Storage, Annual Energy Yield, Molten Salt, Ananthapuramu.

1. INTRODUCTION

India is a country that has a locational advantage to capture sun energy with respect to equatorial plane. For most of the sites in India, average annual solar global radiation value is 5.75 kWh/m^2-day [1]. Solar thermal energy conversion is useful for industries for both process steam and electrical power generation. Ministry of New and Renewable Energy Sources has been trying to encourage solar thermal power for a decade in India. National Institute of Solar energy (NISE) at Gurugram has a test setup of 1 MW solar thermal power plant based on Parabolic Trough Collector (PTC) and Linear Fresnel Reflector (LFR) Technology [2]. Private developers have established these PTC based power generation units in megawatt sizes at Rajasthan and in Andhra Pradesh in during 2013-2014 [3,4]. World's largest Linear Fresnel Power plant is commissioned in India in 2014 and generates 280GWh of electrical energy per year [5]. LFR technology has crossed the demonstration stage but still not matured as PTC in terms of using it for process industries ranging from 500 kW to 5 MW in India. Telangana, Andhra Pradesh and other states have the solar thermal energy potential of 229 GW with a threshold Direct Normal Irradiance (DNI) of 1800 kWh/m^2/year and 36 GW with a threshold DNI of 1800 kWh/m^2/year [6]. There are a few important industrially popular sites in India with interesting values of DNI (with averages above 500 kW/m^2) that are favourable for LFR implementation. Such sites have been invariably chosen to perform simulations in this work. Existing Process industries require steam for processes such as laundry, water and milk pasteurisation, automobile washing, agricultural drying, sterilization, fermentation and chemical synthesis. During the non-production times, the same plant can also feed electrical power to the grid as well or can operate on a hybrid scheme. Solar thermal projects for process heat and electricity power generation requirements can utilize the thermal energy storage (TES) to achieve a thermal backup for a discharge duration of 4 hours to 18 hours. Mount Abu, India has a solar thermal power plant with TES based on Scheffler dish that generates steam for daily cooking purposes. This plant was funded by UN Development Programme (UNDP), Global Environment Facility and Ministry of Renewable Energy Sources (MNRE), Government of India and uses a Cast Iron TES block at 450^0C to supply steam. Cast Iron and Molten Salt have only been tried in India till date as TES, where in usage of other storage materials made of Phase Change Materials (PCM) is yet to reach the commercial usage.

LFR concentrated solar thermal technology is most promising for electric energy production and process steam generation with a remarkable potential to reduce construction and maintenance costs [6]. In India, commercial LFR based solar thermal power plants cost Rs. 12 Crore per MW with an additional capital cost of Rs. 2 Crore per hour of TES [17].

Table 1 presents the list of relevant global research works on LFR performance simulation and couple of Indian commercial solar thermal power plants.

S.No	Details of the LFR plants in Literature	Techno-Commercial Performance Parameters reported
1	K.S. Reddy et al. (2012) Solar thermal power plant 100 MW Modelling & Simulation [8]	Net Energy Efficiency of 1 MWe - 16% Net Energy Efficiency of 50 MWe – 27.21% Levelized Cost of Energy (LCOE) – Rs. 10.19/ kWh Software used – Cycle Tempo
2	Deepak and Sudhakar (2017) [9]	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%. Software Used – SAM (NREL)
3	Mokhtar Ghodbane et al.(2019) [16]	thermal efficiency of the solar reflector has reached 37.5%; absorbed tube temperature, it ranged between 264.78 and 347.78 _C; superheated steam temperature, it ranged between 233.38 and 263.73C Software Used – Numerical Analysis in FEM coded in MATLAB
4	A. Buscemi, et al. Concrete thermal energy storage for linear Fresnel collectors for a Pasta making Factory in Italy (2020) [10]	Plant area including Solar field and storage area 11000 m^2 Electricity units generated 4.3152 GWH Overall Solar field efficiency 39% with 48% of solar energy contributing to Storage. Software Used: TRNSYS
5	Reliance Solar thermal power plant 125 MW, Rajasthan, India (2014) [17]	280 GWh of electricity every year and can offset over 2.1 million tonnes of carbon dioxide for 10 years. Software used: Not Applicable.
6	LFR Solar thermal power plant Dadri Uttara Pradesh, India (2015) [19]	14MW plant developed by Thermax Ltd and Frenell GmbH, 30000 m^2 and Annual Energy Yield 14 GWh. Software used: Not Applicable.

7	Danish et al. Innovative Greenhouse-LFR concept (2021) [11]	greenhouse-LFR, the maximum thermal efficiency was 73.2% whereas for conventional-LFR it was 37.2% Modelled by SolTrace software
8	Present work	5 MWe solar thermal LFR and TES plant simulation modelling software used is SAM, NREL [18]

Table 1. Literature survey on LFR solar thermal power plants and their simulation studies

2. SOLAR THERMAL POWER PLANT MODELING

LFR technology requires improvements in terms of achieving higher optical efficiencies but has better competitive edge when compared for overall cost vs. efficiency. LFR achieves higher values of land use efficiency and wind loads can be neglected to design their low-profile structure [7]. It becomes essential to model a solar thermal energy conversion plant of LFR technology with TES for various sites in India for evaluating the feasibility of a 5 MWe sizing plant. This research work performs simulations of LFR based solar thermal plant for ten locations (cities) in India. The work is aimed at achieving following objectives:

1. Estimating the Annual Energy Yield at new potential locations in India with a 5 MW_e LFR Solar thermal power plant
2. Analysing the thermal and electrical outputs of the plant for 4 hours of thermal energy storage.

2.1. Solar resource estimation at identified sites for LFR plants:

The potential for Concentrated Solar thermal Power (CSP) in India is estimated to be 2800 GW. But for CSP projects, estimation of Direct Normal Irradiance is most important. Any deviations in the measurement of DNI leads to increase in the number of Fresnel mirrors after the commissioning of the power plant. The uncertainty in DNI values coming from Satellite data needs to be corrected with operating power plants data or through theoretical modelling. Out of the ten Indian cities (that are industrially popular and have many process industries present in and around) where data is collected from NSRDB database of NREL laboratory, basic solar radiation assessment exercise is performed so as to analyse the availability of solar radiation as per the declination angle and sun rise time. Solar declination is the angle between the earth-sun line and the equatorial plane.

Declination of any given location is given by the equation $\delta = 23.45\,Sin\left[\frac{360}{365}(284+n)\right]$ ---(1).

Where *n* is the number of day and India, which is in Northern hemisphere, $\delta > 0$, during spring and summer (May 21st to September 21st) there is no much tracking is required as optimum tilt for an Indian location is zero for three months from May to July. And for those months where $\delta < 0$ (September 21st to March 21st) the optimum tilt angle required for the collector is ranging in between 24.290 to 560 [13]. Hence, studying the effect of declination angle with respect to sunrise time, so as to determine the tracking start time and program their values for SCADA systems is much vital for a tracking system design. There are many models to estimate the DNI values [14] and System Advisor Modelling (SAM) [18] developed by NREL, USA uses the National Solar Radiation Database (NSRDB) that has the data pertaining to various sites in India NSRDB data contains DNI, Direct Horizontal Irradiance (DHI), Dry-bulb Temperature, Dry bulb temperature (°C), Dew point temperature (°C), Relative humidity (%), Atmospheric pressure (mbar), Wind speed (only 2 metres above the ground value) (m/s), Wind direction (°E of N) and Albedo pertaining to the chosen location. . For designing the solar thermal collectors, only DNI data is significant.

2.2. Solar Thermal Power plant design

LFR based Linearly focussing systems are popular for both process steam generation and electricity power requirements due to their less construction, installation and integration costs. The reasons are - they do not have much moving joints, wind loads are lower due to near to ground mounting, least shading problems, tightly packed area with mirrors and simple-to-clean systems. Main disadvantage of LFR systems is they have optical losses. Concentrated ratios of LFR systems are 10 to 40, where as those of the Parabolic Trough systems are in between 30 to 100 [6]. Power plant for electricity generation using LFR technology has four major blocks – Linear Fresnel solar field, Storage Block, Heat exchanger block and Power block (traditional Rankine cycle block without a boiler). In this work, The solar thermal power plant is designed and modelling is performed using SAM tool [18].

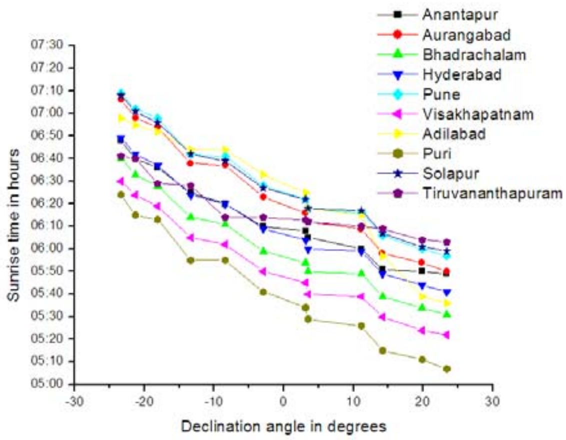

Fig 1. Variation of Sun rise time in Hours with declination angle at various locations in India

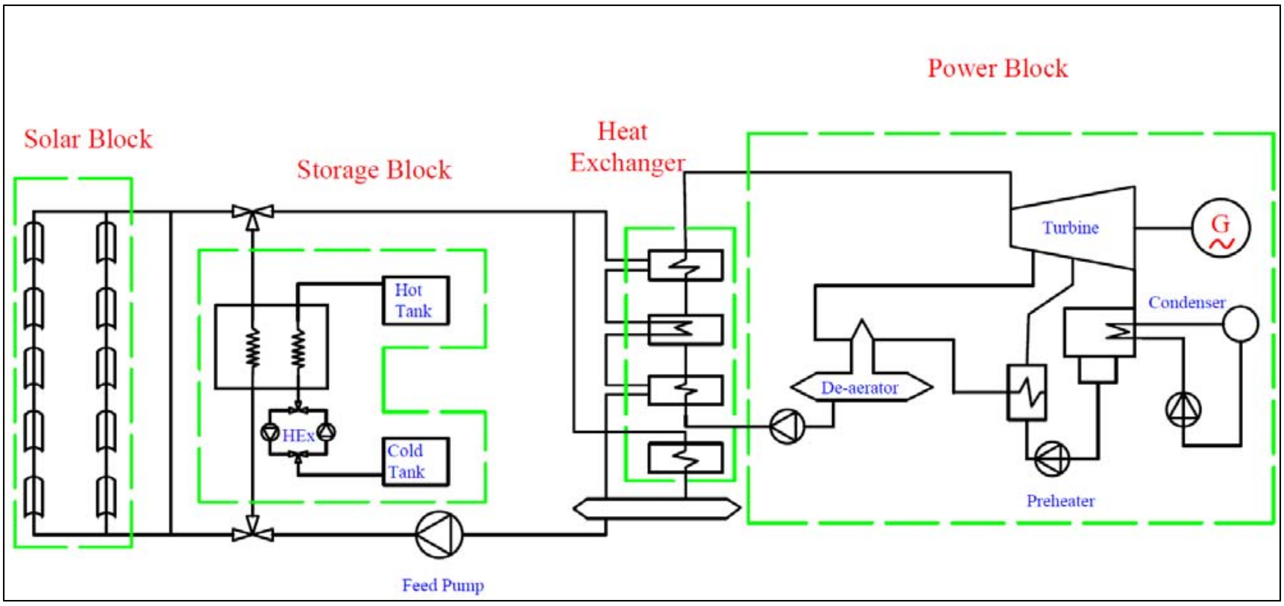

Fig 2. Block diagram of Solar Thermal Power plant with LFR and TES simulation

2.2.1. LFR Solar field array design

Linear Fresnel Reflectors are made of multiple narrow segments of mirrors concentrating the sunlight on an absorber tube above them. The absorber tube in LFR, is placed at the focal line of the Parabolic Trough. The principal advantage of LFR is they are placed near to ground, leading to minimal wind loads and less heavy structure. The basic module used in this work to design the LFR field array consists of 11 primary reflector units amounting to a total reflector surface of 22m^2 and a receiver unit [15]. The basic module is represented in the figure 2. Package density of the LFR module is defined as the ratio of aperture area to ground area. Mirror reflectivity is 95% with Scott PTR 70 receiver with direct solar absorptance 0.95 and optical efficiency of 0.635 at zenith angle. Maximum operating temperature of the absorber is 400^{0}C with a thermal loss coefficient of 0.000043W/m^2/K^2. Thermal output of the LFR module shown in the figure 3, is given by 12.3 kW/m^2 with a total installation surface area of 377 W/m^2. Single loop aperture area is 7524.8 m^2 and there are 7 such loops in the solar field. The characteristics of LFR system are defined as a function of overall efficiency of the

LFR system with respect to the temperature differential between the Heat Transfer Fluid (HTF) and the ambient temperature. It can be observed that for ambient temperatures in India, the system performance is near to its rated design efficiency value. The total collector area of 5 MW LFR power plant is 85000 m^2. Field are is 13 acres multiplied by non-solar field multiplier of 1.6.

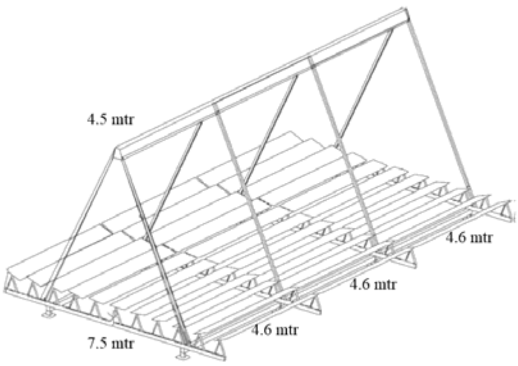

Fig.3. Drawing of the Fresnel solar collector module

Simulation block	Elements of interest	Remarks
Solar Resource Assessment	I_{bn}	Direct Normal Irradiance (data available from NSDRB data base directly) in kWh/m^2
Solar Field	Solar Collector Assembly (SCA)	Area of SCA (7.5 m X 4.6 m) = 22 m^2 Thermal output 12.3 kW per module [LF 11] 377 W/m^2 as per total installation surface area
	Conversion efficiency of the collector loop	Maximum efficiency 66.3%
	Total area of the solar field	52673.47 m^2 with Solar Multiple Value = 2.3
	Thermal energy output from solar field	30 MW_{th}
	Net-Effective land area required by the plant	85000 m^2
Heat transfer fluid (HTF)	Full load storage hours considered	4 Hours
TES	Storage volume	282.289 m^3
	Storage Tank diameter	4.23 m
	Minimum Fluid Volume	14.1144 m^3
	Thermal capacity of TES	50.38 MW_{th}
	Estimated Heat Loss	0.0436 MW_{th}
	HTF outlet temperature	525^0C
	Design inlet temperature of HTF Cycle	293^0C
	HTF mass flow rate	35.9 kg/sec
Power Block		
	Rated cycle conversion efficiency	39.7%
	Net electrical output of the plant at Nameplate	4.5 MW_e

Table. 2. Simulation parameters of Thermal Energy conversion cycle parameters of 5 MW_e.

2.2.2. HTF and TES flow arrangement:

HTF fluid selected for this simulation and modelling is molten salt and is flowing through the solar field array with 10 kg/hour that gets settled in hot and cold tanks. Hot and cold tanks are big cylindrical structures of the size of 4.23 diameter. The variation of HTF mass flow rate vs. the solar time is presented in the figure 4. It can be understood that outlet temperature of the HTF is almost directly proportional to the mass flow rate and is maximum during the noon. Field HTF is maintained at a minimum operating temperature of 238^0C and a maximum operating temperature of 593^0C. TES hot tank temperature is varying with solar time and reaches a maximum of 475^0C and at 2 PM, it starts decreasing till 465^0C up to 10 PM. The simulation tool has provision to use variety of Molten salts known as Hi-Tec Solar Salt, Therminol VP-1 and Dowtherm RP. Out of three HTFs, Hitec salt is found to be superior in performance. Hitech Salt (Solar Salt) used in solar plants consists of potassium nitrate (53% by weight), sodium nitrite $NaNO_2$ (40% by weight), and sodium nitrate (7% by weight) with a liquid temperature range of 149°C - 538°C. TES is also Hitec salt here, whose minimum storage temperature is 238^0C in the simulation cycle. For 4-hours storage, Total tank volume is 313 m^3 for a thermal capacity of 56 MW_{th}. TES fluid density is 1829.33 kg/m^3. Cold tank set point is 263^0C. The power plant design parameters are presented in table 1. The variation of mass flow rate and hourly variation of outlet temperature of HTF flowing in the receiver tubes of the solar field along with solar time is represented in the graph for Ananthapuramu Location at a mean day of the year. In between 8AM to 6PM the temperature and mass flow rate of the designed plant are around 500^0C and 160 Tonnes per hour respectively. Hourly variation of mass flow rate and HTF outlet temperature during a solar day is represented in Fig 4.

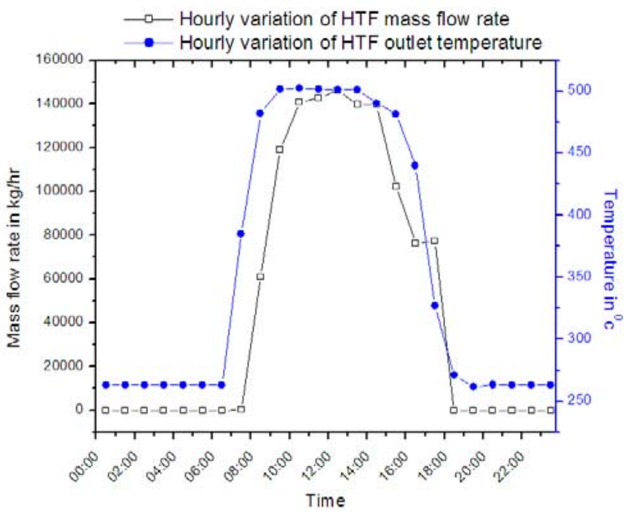

Fig. 4. Variation of Mass Flow rate of HTF during a solar day in the field

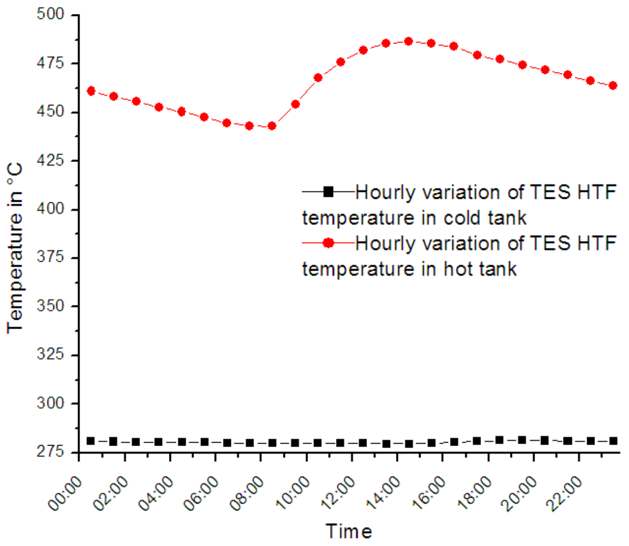

Fig. 5. Hourly variation of TES tanks temperature

Fig 5 shows the variation of TES material Molten Salt in the cold tank vs. hot tank during the solar hours or plant operation hours. It becomes crucial for the plant operation to maintain the temperatures of hot and cold tanks at a minimum of 475^{0}C so as to avoid the problems of HTF becoming frozen during cold climates.

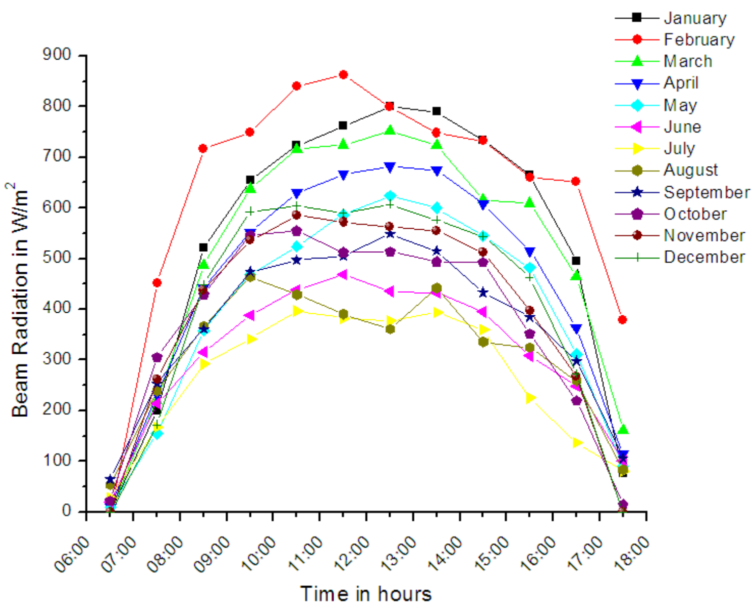

Fig 6. Distribution of Solar beam radiation in Ananthapuramu (Anantapur), India Long. Latt.

Fig 6, depicts the daily solar radiation spectrum around the year in Ananthapuramu location which happens to be highest of all the sites considered in this work. This place is the most favourable location for installing the solar thermal power plants in India.

Fig 7, displays the mean monthly net energy generation by a LFR solar thermal plant of 5 MWe capacity. The total number of electrical units generated Ananthapuramu in kWh has been found to be the highest.

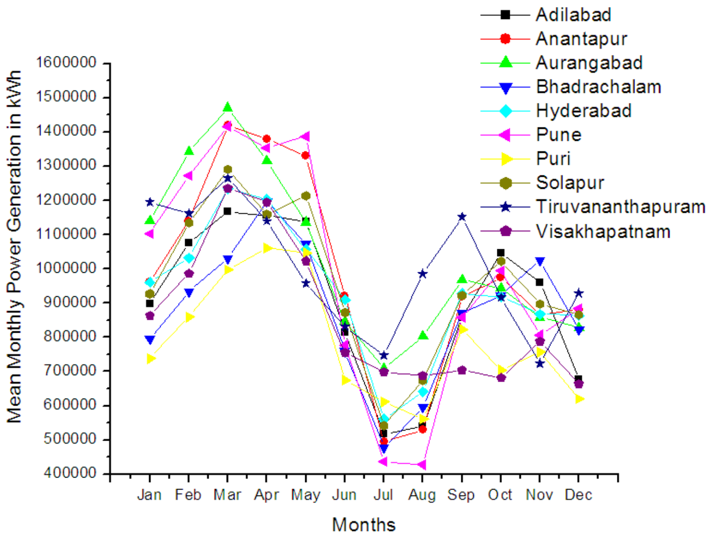

Fig 7. Mean monthly net energy generation units at various sites

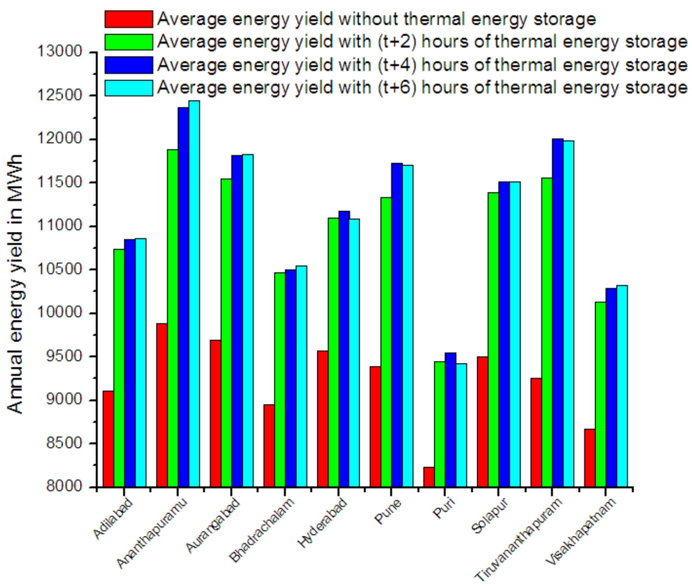

Fig.8. Annual Energy yield in kWh at various locations in India

Graph 8, compares the annual energy yield with and without storage at each location with Ananthapuramu being the location with the highest AEY.

Fig 9 and 10 show the variation of thermal and electrical power output from a 5 MW LFR plant installed at Ananthapuramu with its input Solar radiation i.e DNI. This annual average value is the point of interest to the power plant developer in preparing their detailed project report to be submitted for bankability.

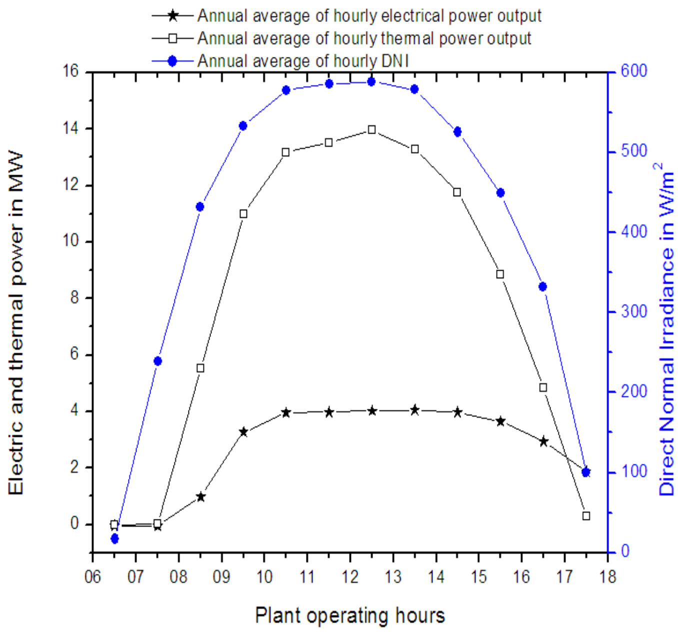

Fig.9. Electrical energy output of 5 Mwe LFR plant at Ananthapuramu location

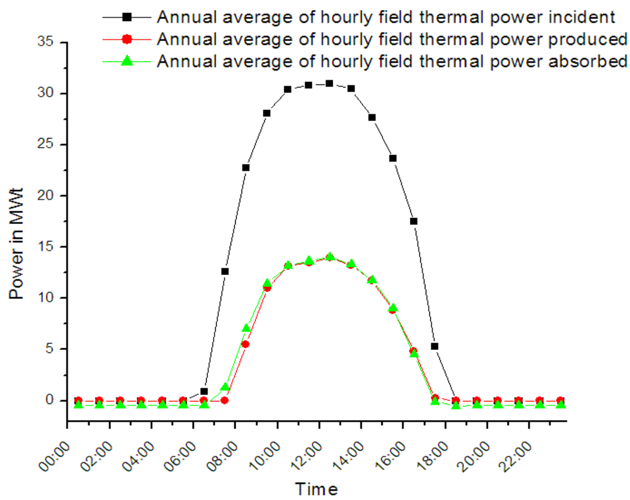

Fig. 10. Daily avaerage thermal energy output of LFR plant at Ananthapuramu

3. CONCLUSIONS

Solar thermal power plants are a preferable option to electricity where transportation of fuel is expensive such as deserts and dry arid land areas. Linear Fresnel Reflector (LFR) based solar thermal is a reliable, cost-effective technology for power generation in India. Ten industrially significant locations have been taken for analysis in this study and simulations have been performed to predict the Annual Energy Yield (in MWH_e per year) of a 5 MW_e LFR solar thermal power plant with TES, across all these locations. Out of all these locations, Ananthapuramu, Andhra Pradesh has been identified as a potential site for a 5 MW LFR plant. Ananthapuramu with the longitude and latitude values of 14.36 and 77.65N is a popular solar site with the high values of measured DNI. LFR technology has the advantage of cost vs. performance over the other concentrated solar thermal technologies. A 5 MW LFR solar thermal plant can generate 12500 MWH of Annual Energy Units at Ananthapuramu with energy storage being considered. The modelling & simulation performed in this work will be useful for analysing the daily and monthly performance of the plant with TES. This work highlights the usage of SAP modelling software for the simulation of concentrated solar thermal plants. With such analysis, power plant designers and developers can get an initial estimate on performance and can analyse the techno-commercial feasibility of the power plant in the location of interest. Currently CSP Projects in India, have been suffering with lack of policy upgradation & proper DNI assessment. Increased infrastructure costs, high maintenance costs and lack of indigenously manufactured LFR mirrors are the major hurdles for the growth of solar thermal power plants in India. More practical and industry-grade installations would ensure stabilised growth both in kW and MW scale in India. This research work is an attempt to help designing the solar thermal power plants for process industries having few acres of barren lands.

4. REFERENCES

1. Jamil, B., Siddiqui, A. T., & Akhtar, N. (2016). Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India. Engineering Science and Technology, an International Journal, 19(4), 1826-1835.11
2. Sharma, C., Sharma, A. K., Mullick, S. C., & Kandpal, T. C. (2015). Assessment of solar thermal power generation potential in India. Renewable and Sustainable Energy Reviews, 42, 902-912.
3. Desai, N. B., Bandyopadhyay, S., Nayak, J. K., Banerjee, R., & Kedare, S. B. (2014). Simulation of 1MWe solar thermal power plant. Energy Procedia, 57, 507-516.
4. Desai, N. B., & Bandyopadhyay, S. (2017). Line-focusing concentrating solar collector-based power plants: a review. Clean Technologies and Environmental Policy, 19(1), 9-35.
5. https://cleantechnica.com/2014/11/14/worlds-largest-linear-fresnel-csp-project-commissioned-india/

6. Karathanasis, S. (2019). Linear Fresnel Reflector Systems for Solar Radiation Concentration. Springer International Publishing.
7. Sun, J., Zhang, Z., Wang, L., Zhang, Z., & Wei, J. (2020). Comprehensive Review of Line-Focus Concentrating Solar Thermal Technologies: Parabolic Trough Collector (PTC) vs Linear Fresnel Reflector (LFR). Journal of Thermal Science, 1-28.
8. Reddy, K. S., Ravi Kumar, K., & Devaraj, V. A. (2012). Feasibility analysis of megawatt scale solar thermal power plants. Journal of Renewable and Sustainable Energy, 4(6), 063111.
9. Bishoyi, D., & Sudhakar, K. (2017). Modeling and performance simulation of 100 MW LFR based solar thermal power plant in Udaipur India. Resource-Efficient Technologies, 3(4), 365-377.
10. A. Buscemi, D. Panno, G. Ciulla, M. Beccali, V. Lo Brano, Concrete thermal energy storage for linear Fresnel collectors: Exploiting the South Mediterranean's solar potential for agri-food processes, Energy Conversion and Management,Volume 166,2018,Pages 719-734, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.04.075.
11. Danish, S. N., Almutairi, Z., El-Leathy, A., Al-Ansary, H., Jardan, Y., & Alaqel, S. (2021). Modeling and Performance Simulation of an Innovative Concept of Linear Fresnel Reflector based CSP System. Journal of Thermal Science, 1-11.
12. Baba, Y. F., Ajdad, H., Al Mers, A., Bouatem, A., Idrissi, B. B., & El Alj, S. (2020). Preliminary cost-effectiveness assessment of a Linear Fresnel Concentrator: Case studies. Case Studies in Thermal Engineering, 22, 100730.
13. Jamil, B., Siddiqui, A. T., & Akhtar, N. (2016). Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India. Engineering Science and Technology, an International Journal, 19(4), 1826-1835.
14. Mousavi Maleki, S. A., Hizam, H., & Gomes, C. (2017). Estimation of hourly, daily and monthly global solar radiation on inclined surfaces: Models re-visited. Energies, 10(1), 134.
15. Compact Linear Fresnel Reflector Technical Data sheet by Industrial Solar GmbH (www.industrial-solar.de)
16. Ghodbane, M., Boumeddane, B., Said, Z., & Bellos, E. (2019). A numerical simulation of a linear Fresnel solar reflector directed to produce steam for the power plant. Journal of cleaner production, 231, 494-508.
17. https://helioscsp.com/india-reliance-powers-dhursar-concentrated-solar-power-csp-project-nears-completion/

18. System advisor model (SAM) general description (Version 2020.11. 29). National Renewable Energy Laboratory Technical Report.
19. https://solarpaces.nrel.gov/project/dadri-iscc-plant