MODELING AND SIMULATION OF THE NATIONAL SOLAR THERMAL RESEARCH DEMONSTRATION FACILITY IN GWALPAHARI

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Abstract

To facilitate research in the renewable energy field, the Government of India in cooperation with the Indian Institute of Technology Bombay established a research demonstration facility on the campus of National Institute of Solar Energy. This 1 MW_e concentrated solar power facility uses parabolic trough collectors and linear Fresnel reflectors to concentrate solar energy and produce thermal energy which is used in the power block for electricity production. The article describes a simulation model of the facility for a steady state condition with and without the Fresnel reflectors and an additional one for the calculation of the annual energy production as well as the corresponding simulation results.

Keywords: Concentrated Solar Power, Parabolic Trough Collector, Linear Fresnel Reflector, Simulation

1. Introduction

India, as a tropical country, possesses significant solar energy resources, which can be harnessed for electricity generation via concentrated solar thermal technologies. In recognition of this potential, the Government of India (GoI) has launched an ambitious program within the Jawaharlal Nehru National Solar Mission (JNNSM) aimed at generating 40 GW of solar powered electricity until 2022 (Nehru, 2021). This initiative necessitates the development of essential knowledge, workforce training, and the requisite infrastructure.

To promote awareness, foster research, develop a simulation software and establish a demonstration facility for solar thermal power, the Indian Institute of Technology Bombay (IIT B) initiated a project in 2008, with financing from the Ministry of New and Renewable Energy (MNRE) under the GoI.

The concentrated solar power (CSP) facility uses parabolic trough collectors (PTC) and linear Fresnel reflectors (LFR) to concentrate solar energy and produce thermal energy, which is used in the power block to produce electricity. The article describes simulation models of the CSP facility in steady state condition and an alternative model for calculating the annual energy production together the corresponding simulation results.

2. System Description

A 1 MW_e research and demonstration solar thermal power plant has been established within the campus of the National Institute of Solar Energy (NISE), under the purview of the Ministry of New and Renewable Energy (MNRE), Government of India (GoI), situated in Gwalpaharai, Haryana, India. The power plant harnesses two distinct technologies, namely the Parabolic Trough Collector (PTC) technology and the Linear Fresnel Reflector (LFR) technology. The PTC field boasts a thermal capacity of 3 MW_{th}, while the LFR field has a capacity of 2 MW_{th}, ultimately resulting in a 1 MW_e electric output. For the PTC field, the Heat Transfer Fluid

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(HTF) employed is Therminol VP 1 (Eastman Chemical Company, 2024) whereas the LFR field directly utilizes steam to facilitate the energy management process. A buffer thermal storage system is incorporated, allowing for a 30-minute storage period through a pressure vessel, designed for high temperature conditions (Nayak et. al., 2015). Figure 1 is a satellite image of the power plant at Gwalpahari.

Fig. 1: Satellite image of the power plant located at Gwalpahari (Google Maps, (2023))

The working fluid heated up by the PTC field, is stored in a high-temperature tank. Subsequently, it is conveyed to a heat exchanger, where it transfers its thermal energy to water, generating high-temperature steam. The cooled down HTF is then stored in a low-temperature vessel to maintain its circulation within the PTC solar field. The LFR field is responsible for producing saturated steam, which is extracted from the deaerator and released into the steam drum. These two loops interest over three heat exchangers. The high-temperature steam is directed into a steam turbine to generate mechanical power, which is then converted into electric power by an AC generator. The spent steam from the turbine is condensed through a condenser. A regeneration steam is also taken out of the turbine to optimize the overall efficiency.

3. Approach

Two different approaches were applied to model the performance of the facility. First model simulates the CSP facility for a steady state condition to investigate the peak performance of the system. For the second model, the annual production simulation is performed using SAM through various weather conditions of a typical year.

The steady state model was created in EBSILON® *Professional* by Iqony Soultions GmbH (STEAG, 2023), which is a specialized graphical software tool for the simulation and analysis of power plants. Components from the in-built library were used to conduct the steady state simulation. The model generated in EBSILON can be seen in Figure 2. The main components of this model are those of a simple Rankine cycle power plant, namely turbine, condenser, pump and generator as well as the CSP and LFR field as the heat source. Additional components such as heat exchangers, storage, deaerator and steam drum were also required which are shown in Figure 2.

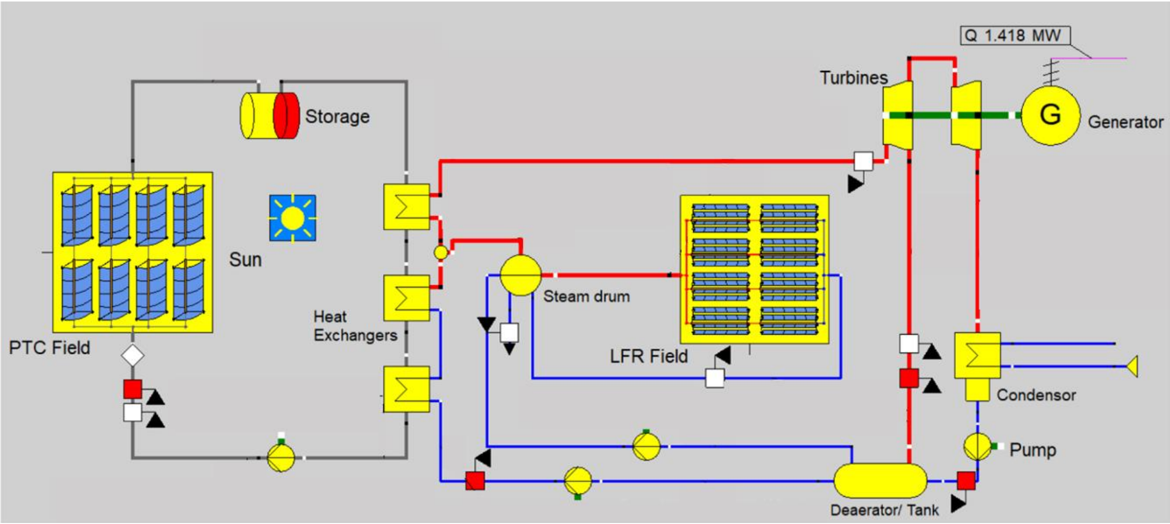

Fig. 2: Schematic diagram of the CSP demonstration facility in EBSILON® *Professional*

The plant utilizes two separate technologies for heat capture. The grey loop with the PTC field and storage on the left is utilizing Therminol VP1 as the HTF. The primary loop with the power block, condenser and deaerator and secondary loop with LFR field uses water/steam as the working medium. The steam flow from the LFR field is fed into the steam drum. While designing the simulation model, the loops were individually simulated and merged through the three cross flow heat exchangers, namely economizer, steam generator and the super heater. The saturated steam from the steam drum is merged with the primary loop before the superheater. There is also a regeneration stream bled into the deaerator at 2 bar and 0.15 kg·s^{-1}. The deaerator then splits the water stream with 0.84 kg·s^{-1} towards the LFR via the steam drum. The input parameters of the steady state simulation are shown in Table 1.

Tab. 1: Key parameters of the steady state simulation

Component	Parameter	Value
PTC Field	HTF	Therminol VP1
	Input Temperature	237 °C
	Number of collectors	12
	Input pressure	17.5 bar
LFR Field	HTF	Water / Steam
	Input Temperature	256 °C
	Number of collectors	16
	Input pressure	44 bar
Turbine	Isentropic Efficiency	75 %
	Inlet temperature	364.2 °C
Mass flow rate	Therminol VP 1	8.53 kg·s^{-1}
	Primary water steam loop	1.93 kg·s^{-1}
	Secondary water steam loop	2.22 kg·s^{-1}

As compared to the model of Nayak et. al. (2015) the deaerator has been substituted with a tank for simplification. The loop with the PTC field is installed with two storage tanks, a high temperature tank (393 °C) and a low temperature tank (232 °C), to provide approx. 30 minutes of thermal energy backup and to homogenize the fluid flow. For this simulation, only one tank is used as a simplification for the steady state analysis. Additionally, in the sun component constant DNI of 600 $W \cdot m^{-2}$ and an ambient temperature of 23 °C is used as the weather parameter for the chosen location.

To simulate the annual yield, System Advisory Model (SAM), which is developed by the National Renewable Energy Laboratory (NREL) (System Advisor Model, 2023), is used. SAM is a software package that incorporates various renewable energy models and graphical analysis tools. To develop the annual model, two separate models, namely one only dependent on PTC field and second one with LFR field, were generated. Both the models are generated as a non-financial model. These models were individually simulated and then combined in the software. For both the models the weather data was imported by NREL's National Solar Radiation Database (NSRDB). This database is a collection of international weather data. For this project, DNI from the model SUNY from the METEOSAT IODC is accessed (NSRDB, 2023). The PTC field has an area of 8,175 m^2 and a storage of 30 mins, whereas the LFR field has an area of 7,020 m^2 without any storage.

4. Results and Discussion

The solar power plant was modeled, simulated and the steady state results were compared to the expected design values given by Nayak et al. (2015) and are depicted in Table 2. It is to be noted that the LFR is determined to be only adding heat primarily for phase change as at the pressure of 44 bars the input water flow is at the boiling point and is released into the steam drum with a quality of 55 %. From the comparison, it can be seen that the deviations of the individual field loops of the simulation to the design point are relatively low. These deviations can be explained by the approximation of the input values. The power block efficiency of the simulation model is 7 % more than the design vale, which is due to the optimistic assumption of the isentropic efficiency of the expansion vessel, which was taken in accordance with the values taken by Bhukta et.al (2016). The higher power block efficiency results in 5 % deviation in the overall plant efficiency and the higher net heat capture and increased net electricity output. The values are listed in Table 3.

Tab. 2: Comparison of the results of the simulation to the design model presented in (Nayak et. al., 2015)

Component	Parameter	Simulation	Design model
PTC Field	Net heat capture	3.235 MW_{th}	3.000 MW_{th}
	Output Temperature	397.0 °C	393.0 °C
	Efficiency	66 %	61 %
LFR Field	Net heat capture	2.038 MW_{th}	2.000 MW_{th}
	Output Temperature	256.1 °C	256.1°C
	Efficiency	48 %	47 %
Power block	Efficiency	27 %	20 %
Overall plant	Efficiency	16 %	11 %

The presented simulation model has been used for further research, including sensitivity analysis, dependence of the LFR field and scale up possibilities. The sensitivity analysis and the scale-up model simulation results are presented in (Arora, 2023) and discussed in (Alexopoulos et al., 2024).

Along with the steady state simulation using both PTC and LFR systems, a further simulation was done only with the PTC field to compare the outputs of the power plant for both cases and analyze the dependency of the system output on the LFR field. Figure 3 illustrates the simulation model without the LFR field.

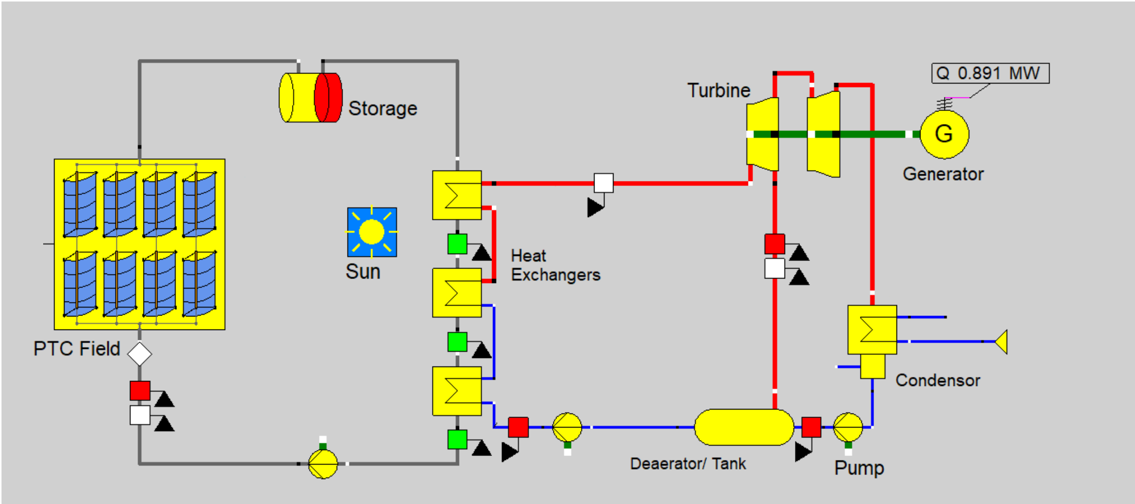

Fig. 3: Schematic diagram of the CSP demonstration facility without LFR module in EBSILON® *Professional*

To maintain the turbine input temperature of 350 °C from the design point, the flow rate of the water / steam cycle was decreased to 1.19 kg·s^{-1}. Due to a lower total heat capture by only the PTC field, 39 % decrease in the net electric output is observed. The results from the simulation models with and without the LFR field are summarized in Table 3.

Tab. 3: Comparison of the results from the simulation models with and without the LFR field

Model	Mass flow in the primary loop	Total net heat capture	Net plant capacity
Original combined model	1.93 kg·s^{-1}	5.273MW$_{th}$	1.418 MW$_{e}$
Only PTC Field	1.19 kg·s^{-1}	3.235 MW$_{th}$	0.891 MW$_{e}$

For the annual simulation conducted by SAM, the monthly electric output is depicted in Figure 4. In the months of March, April and May, the output is higher than in the monsoon season of India in the months of June to August. The results show that due to the increased cloud cover in monsoon and therefore lack of direct sunlight, the output of the plant drastically decreases. Furthermore, due to ambient temperatures in the November to January averaging below the Therminol VP1 freezing point of 12 °C (Eastman Chemical Company, 2024), additional heat was required to defrost the HTF for nominal usage and therefore showing an additional dip in the net output energy.

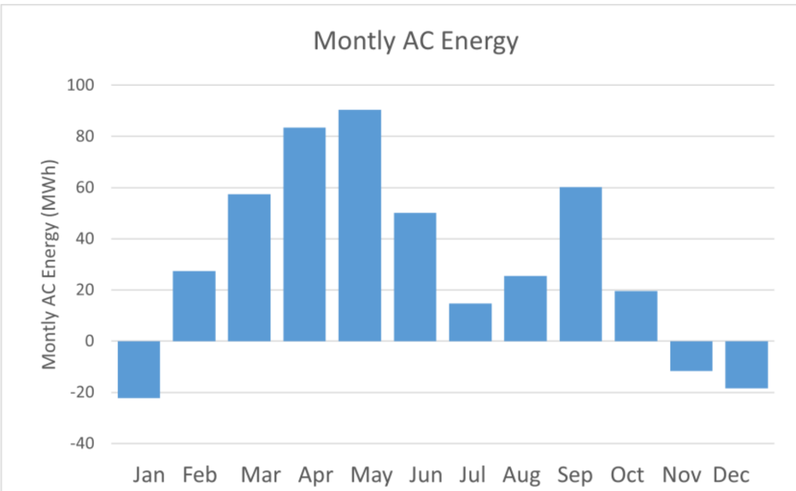

Fig. 4: Monthly electrical output of the power plant

5. Conclusion

The 1 MW_e power plant at the campus of NISE in Gwalpahari was simulated in EBSILON® *Professional* to conduct a steady state analysis and a comparison with the design point. This resulted in a minor deviation for the individual solar fields but 5 % deviation in the power block efficiency. These deviations resulted in a higher net output of the power plant than the design point. The steady state model was also simulated with only the PTC field to observe the dependance of the system on the LFR field. Due to a lower net heat capture, the output was 39 % lower than the combined model. An annual analysis was also done with SAM to check the output over the course of a year through various weather conditions. The annual simulation has shown that during the months with relatively higher DNI as compared to the monsoon months gave a comparable higher electric output. It was also to be noted that addition energy was required in winter to maintain the flow of Therminol VP1 as the ambient temperature was below its freezing point of 12 °C. A further DNI sensitivity analysis and also analysis of scale up possibilities are done in (Arora, 2023) and shown in (Alexopoulos et al, 2024).

6. Acknowledgments

This work was done in the framework of a thesis at Solar-Institut Jülich of the FH Aachen University of Applied Sciences.

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