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Performance Analysis of a Parabolic Trough Concentrated Solar Power Technology in Pakistan

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Abstract— Pakistan has been blessed with one of the highest direct solar radiation in the world. This provides great opportunity for harvesting clean energy. The rapid urbanization leads to higher energy demand per capita. This in conjunction with the global commitment to curb environmental impacts of conventional energy calls for investing and exploring the renewable energy resources. To study the concentrated solar power (CSP) based technology for Pakistan, a 20 MW of parabolic trough concentrated solar power plant with six hours thermal energy storage (TES) has been designed and simulated in this study. Quetta has been chosen for the technical feasibility of proposed power plant where annual direct normal irradiance (DNI) is 2206 kWh/m^2. The power plant consists of 33 numbers of loops each one has aperture area 5248 m^2 with a solar multiple of 2. VP-1 is chosen as heat transfer fluid (HTF) due to its high thermal stability and high melting point. The proposed CSP plant can generate annual electricity of 58.4 GWH with a capacity factor of 37.1 %. The simulation results indicate that proposed power plant can produced high amount of energy and such power plant can be installed to overcome the energy crisis of Pakistan.

Keywords— Parabolic trough, direct normal irradiance, thermal energy storage, heat transfer fluid, capacity factor.

I. INTRODUCTION

Energy resources play important role in world economy. Global energy demand increases, due to increase in world population and change in living standard of the people. Currently the world population is 7.2 billion which is predicted to reach 8.5 billion by 2025 [1]. Additionally the conventional energy resources are slated to run out soon, thus further accentuating the demand for green revolution in energy field. Extracting renewable energy supply in addition to the positive impact on environment also carries the economic argument. Approximately 1.8×10^{14} kW of energy from sun is reach at earth, about 60% of which it reach to the earth surface. Utilizing 1% of this potential can lead to significant reduction in global carbon emissions by offsetting the conventional fossil fuels for energy generation [2].

Solar energy can be used in two ways for energy generation i.e. by converting it to thermal energy and then electrical energy or by directly converting it to electrical energy through photovoltaic modules. Solar thermal energy is environmental friendly when it is compare to fossil fuel technology. CSP technology can be feasible for high irradiance and low clouding areas.

The average solar irradiance received by Pakistan is 5-6 kWh/m^2, which shows that Pakistan has large solar power generation potential. It has been reported by the alternative energy development board (AEDB) Pakistan that almost 28 solar projects are under progress with capacity of 956 MW power. The Quaid-e-Azam solar park is already adding a 100 MW of electricity to the national grid.

85 percent installed power plants are parabolic trough [3]. Table 1 shows the operational, under construction and development capacity of concentrated solar power plants.

TABLE 1. WORLD STATUS OF CONCENTRATED SOLAR POWER PLANTS [4]

Country	Operational (MW)	Under Construction (MW)	Development (MW)	Total (MW)
Mexico		14		14
Chile		110	1100	1210
South Africa	400	100	200	700
Australia	2.5		150	152.5
Morocco	380	150		530
MENA	140	120	1020	1280
India	205	295		500
Thailand	5			5
China	21	250	1089	1360
Europe	5	9	132	146
Spain	2304			2304
USA	1745			1745
Canada	1			1
Total (MW)	**5206**	**1048**	**3691**	**9945**

Deepak et al. [5] carried out a detailed analysis of 100 MW parabolic trough power plant in udaipur India. Rajistan is chosen for the proposed CSP plant where annual DNI is

2248.17 kWh/m^2 . Solar salt is used as a HTF. The Proposed power plant consists of 194 collector loops. Simulation results indicate that hypothetical power plant shows excellent thermal Performance.

A study by Montes et al. [6] analyzed the impact of solar multiple on annual energy output, natural gas usage and levelized cost of electricity (LOCE) for a parabolic trough solar thermal power plant with 50 MW capacity. The power plant comprises of energy storage as well as gas-fired steam boiler.

A study conducted in Cyprus on the technical specification, cost of power generated and land area required for a solar thermal power plant and concluded that parabolic trough is the most feasible technology because of the market maturity and other advantages [7]. Abbas et al. [8] carried out economic feasibility assessment of the solar parabolic trough based thermal power plant technology, analyzing 100 MW potential in four locations of Algeria. Kearney et al. [9] carried out a detailed analysis on molten salt for TES and heat transfer purpose. The study concluded that by using molten salt as a HTF, LOCE can be minimized.

Mohammad et al. [10] presented a feasibility study on 50 MWe parabolic trough power plant in Jordan. The study concluded that southern part of Jordan has huge potential for the installation of concentrated solar thermal power plants. R.Hosseini et al. [11] presented a technoeconomic analysis of the integrated solar combined cycle system (ISCCS) power plant in Iran. The study recommended that by adopting ISCCS technology can save fuel consumption cost and also reduce carbon dioxide emission.

From the above literature we concluded that globally concentrated solar power is a proven technology, but in Pakistan there is hardly any development in this field which is mostly due to the unavailability of in depth studies on its potential for power generation. Hence the objective of this study is to study the in depth feasibility of concentrated solar technology for Pakistan. The specific objectives are:

a. Study the detail behavior of CSP based technology for power generation in Pakistan.

b. Design and analysis of CSP based solar power plant in Pakistan.

II. SYSTEM DESCRIPTION

Parabolic troughs consist of single axis solar collectors with trackers which is shown in Figure 1. The solar field composed of several rows of collectors such that their long axes oriented north to south. They are commonly mounted on trackers enabling them to track solar radiations from east to west with sun movement. The solar trackers are armed with linear reflectors with parabola shape which concentrate the solar radiation on the receiver placed parallel to the reflector. Synthetic oil is pumped through a linear receiver which has high temperature operation capacity and ability to collect the heat. The common range of temperature during the operation is 300ºC and 400ºC. Subsequent to passage through receiver, the oil goes in to the heat exchanger which extracts the heat to make steam. The steam is subsequently used to run the turbine and generator to produce electricity. The temperature of steam at turbine intake may be somewhere between 370°C - 395°C at 100 bar. The steam rotates the turbine from where it reaches condenser and back to heat exchanger through pumps where the cycle starts once again. Typically condenser is cooled through mechanical draft wet cooling towers. Although dry cooling is also employed in some areas of water scarcity.

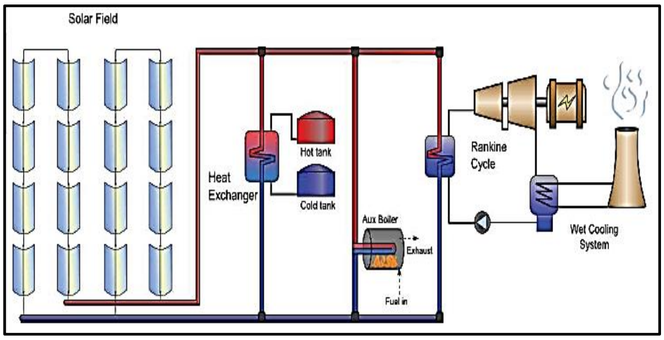


Figure 1. Parabolic trough power plant

III. SIMULATION STUDY

SAM is a computer modeling software which is used for performance elevation and cost analysis of renewable energy projects. It is commonly used by experts in renewable energy industry to assess the financial and performance analysis for well informed decision making. The users may include the following.

- Project lead engineers or project managers
- Policy experts
- Technology entrepreneurs
- Research scholars

The software caters to any range of projects like customers buying electricity at retail price or sale of electricity at bargained prices through PPA (Power Purchase Agreements). The easy to use interface allows even beginners or common users to develop models of their energy utilization systems or for installing renewable energy projects with cost analysis. SAM needs location weather data in form of typical meteorological year (TMY) file to give renewable energy potential available within the weather conditions.

A. Site Selection

Concentrated solar power (CSP) plant location holds great significance in acquiring the maximum benefits out of the available resources. Locations possessing DNI greater than 5.5 kWh/m^2/day are perfect contenders for CSP plant installation. Several other TMY data is important for estimating CSP plant output such as wind speed, atmospheric pressure, hourly DNI, and ambient temperature [2]. In this work weather data of eleven cities of Pakistan has been collected. It is found that Quetta has high irradiance and fulfills the technical selection criteria of CSP plants. Table 2 shows the weather data of different cities.

TABLE 2. METEOROLOGICAL CONDITIONS OF DIFFERENT CITIES

Province	Latitude	Longitude	DNI kWh/m^2/day	DNI KWh/m^2/year	Average temperature (°C)	Average Wind Speed (m/sec)	Source
Quetta	30.5	67.05	6.13	2206	19.1	2	NSRDB
Haripur	33.95	72.95	4.40	1584	23.3	1.3	NSRDB
Lahore	31.55	74.35	3.65	1314	27.2	1.4	NSRDB
Faisalabad	31.45	73.15	3.78	1360	28	1.3	NSRDB
Multan	30.15	71.55	4.01	1443	29.3	1.6	NSRDB
Karachi	25.05	67.25	4.51	1623	27.6	2.7	NSRDB
kalat	29.05	767.0	5.91	2127	24.7	2.2	NSRDB
zhob	31.35	69.45	5.56	2000	19.1	2.1	NSRDB
Mardan	34.15	72.05	4.38	1576	24.8	1.3	NSRDB
Ghotki	28.05	69.35	4.38	1576	30.5	1.8	NSRDB
Pak patans	30.35	73.35	3.89	1400	28.2	1.5	NSRDB

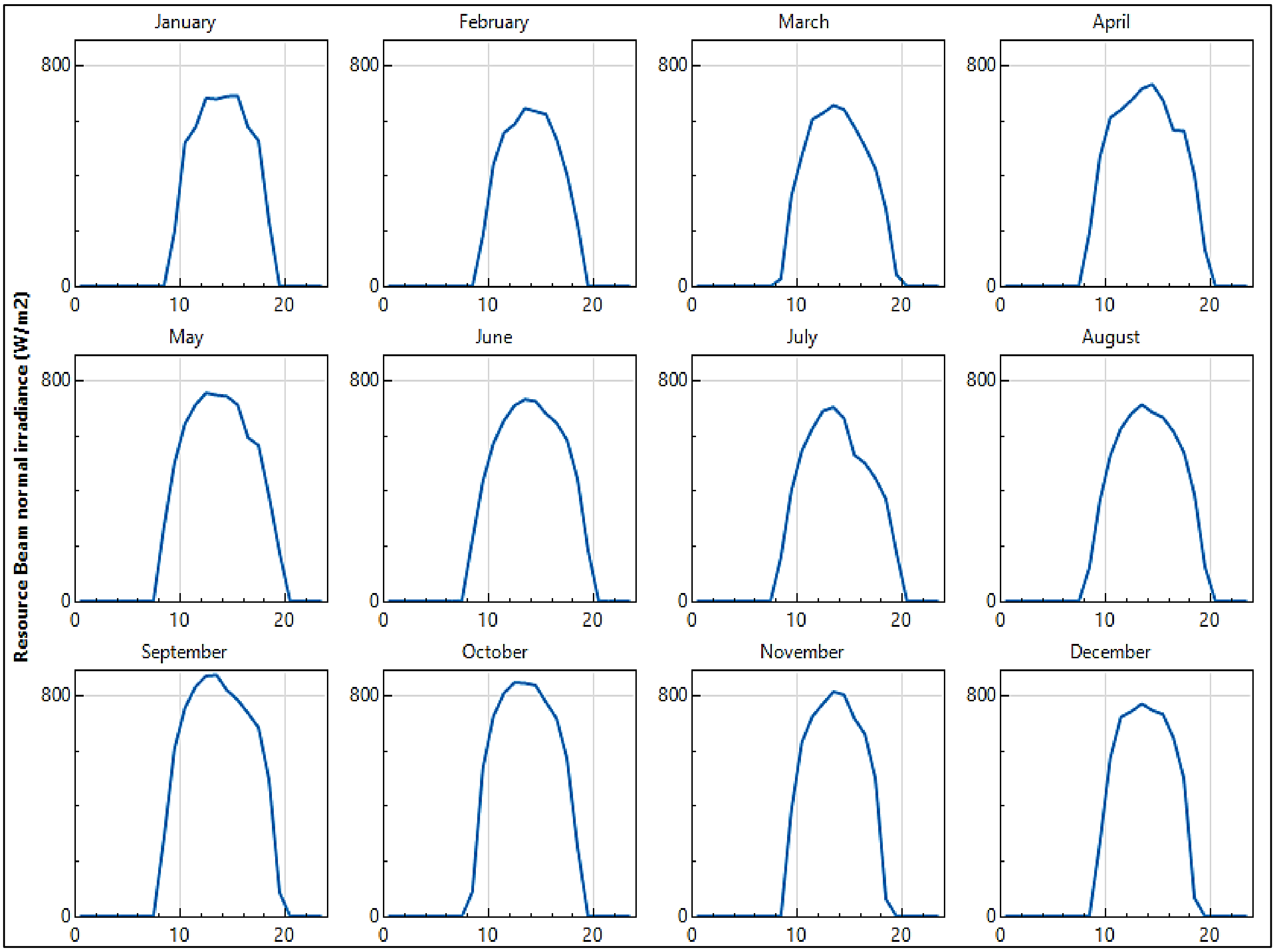


Figure 2. Direct normal irradiance (W/m^2)

Hourly TMY data available from national solar radiation database (NSRDB) helps assess the DNI patterns of any locations. Figure 2 encapsulates the variations in average DNI over a period of one year in Quetta. The high DNI of 5.5 kWh/m^2/day and greater barring the months of January and February makes this site suitable for CSP installation. The month of September is characterized by maximum DNI of 7.5 kWh/m^2/day while February marks the minimum DNI level of 5 kWh/m^2/day.

B. *Proposed power plant characteristics*

Parabolic trough technology is used all over the world. In this study we proposed 20 MW Power plant in which actual numbers of loops are 33, each one has aperture area 5248 m^2 with a solar multiple of 2. VP-1 is used as a HTF. VP-1 is a synthetic fluid which has high thermal stability and high melting point. The proposed power plant also ability to store thermal energy for six hours by utilizing solar salt. Table 3 shows the baseline parameters of proposed power plant.

TABLE 3. COLLECTOR CHARACTERISTICS

Parameter	**Value**
Area of Reflective Aperture	656 m^2
Focal Length	2.15 m
Collector Assembly Length	115 m
Modules per Assembly	8
Module Length	14.375 m
Aperture Width	6 m

C. *Specification and Configuration of the Parabolic Trough Power Plant*

To compute the performance indicators of the proposed plant i.e. gross electric output, capacity factor and water usage. The following input parameters are required for simulation which is shown in Table 4.

IV. RESULTS AND DISCUSSION

CSP plant operation depends on many parameters, prominent among which is DNI. Monthly electricity generation from the parabolic trough power plant is illustrated in Figure 3.

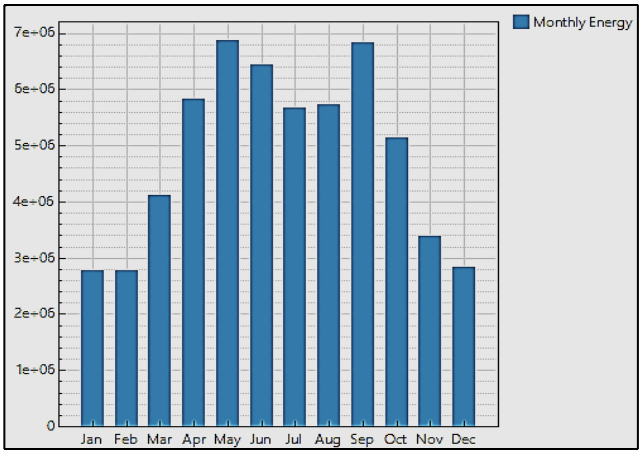


Figure 3. Monthly electrical output power

TABLE 4. DESIGN CHARACTERISTICS OF PARABOLIC TROUGH POWER PLANT

Characteristics	**Value**
Parameters of solar field	
Solar multiple (S.M)	2
DNI design value	949 W/m^2
Space between rows	15 m
Deployment angle	10 degree
Efficiency of HTF Pump	0.85
Heat transfer fluid	
Fluid type	VP-1
Mini Performing temperature of HTF	12 (°C)
Maxi Performing temperature of HTF	400 (°C)
HTF temp at entrance of the loop	293 (°C)
HTF temp at outlet of the loop	391 (°C)
Min single flow rate	1 kg/sec
Max single flow rate	12 kg/sec
Min flow velocity at design header	2 m/sec
Max flow velocity at design header	3 m/sec
Mini field flow velocity	0.2682 m/sec
Maxi field flow velocity	3.744 m/sec
Design point	
Loops number	33
Reflective aperture area	173184 m^2
Single loop aperture	5248 m^2
Field thermal output	112.36 MWt
Actual solar multiple	2
Optical efficiency of loop	0.72
Total loop conversion efficiency	0.69
Mirror washing	
Usage of water per wash	0.7 L/m^2.ap
Washes number (per year)	63
Land area	
Area of solar field	107 acre
Total land area	150 acres
Absorber tube	
Inner diameter	0.076 m
Outer diameter	0.08 m
Absorber material type	304L
Glass Envelope	
Inner diameter	0.115 m
Outer diameter	0.12 m
Power cycle	
Design electrical output (Gross)	20 MWe
Conversion factor	0.9
Nameplate output	18 MWe
Heat transfer fluid outlet temperature at design	293 °C
Heat transfer fluid inlet temperature at design	391 °C
Condenser type	Air cooled
Operating pressure of boiler	65 bar
Conversion efficiency of rated cycle	0.35
Thermal storage	
TES hour	6 hour
Storage volume	4559.35 m^3
Storage HTF type	Solar salt
Minimum fluid volume	227.968 m^3
Estimated tank heat loss	.16 MWt
Minimum operating temperature (Storage HTF)	238 °C
Maximum operating temperature (Storage HTF)	593 °C

From Figure 4 it is clear that proposed plant can generate high energy in May, June and September due to high irradiance, while minimum energy is generated in January and February due to low irradiance. When the process start, the HTF flow from cold reservoir to hot reservoir. As a result the Cold header minimum temperature reached to 166.79 °C while hot header maximum temperature reached to 391.96 °C which is illustrated in Figure 4.

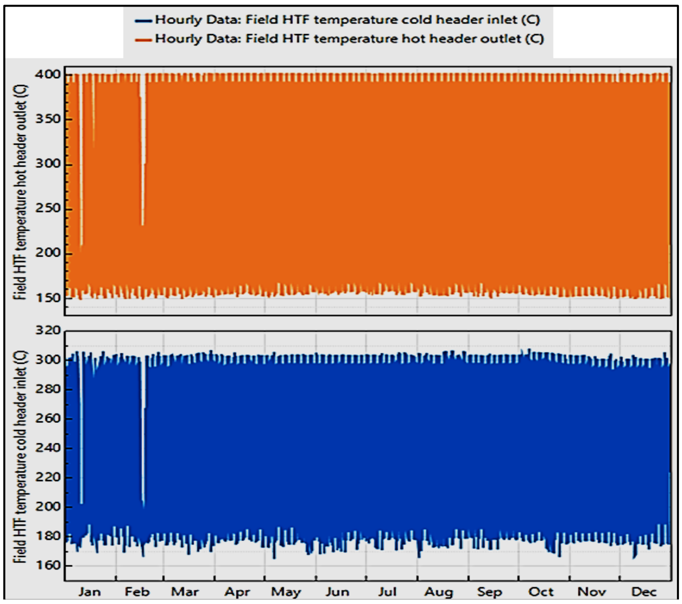


Figure 4. Temperature profile of cold header (inlet) and hot header (outlet)

Figure 5 shows the input power of cycle thermal power, incident thermal power and gross electric output of the proposed power plant hourly data. As we know that Gross electrical output depend on two parameters i.e. incident thermal power and cycle thermal Power. The Peak value of incident thermal power is recorded as 155 MWt. While maximum value of cycle thermal power is recorded as 55 MWt which is illustrated in Figure 5. The maximum cycle efficiency of parabolic power plant is achieved as 0.39 which is illustrated in Figure 6. The proposed plant also has storage capacity of 6 hour. The primary function of the storage tank is to store heat and generate the power after sun set. The maximum storage capacity of tank is 4559.35 m^3.

From Table 5 the total energy generated from 20MW power plant is 58432692 kWh (58.4 GWH) per year. Proposed plant is operated with the capacity factor of 37.1 % .Capacity factor is the number of hour per year that CSP can generate electricity. Annually 13613 m^3 amount of water is required for mirror washing.

TABLE 5. ANNUAL SIMULATED RESULTS OF PARABOLIC TROUGH CONCENTRATED SOLAR POWER PLANT

Simulation parameters	**Simulation result**
Gross Electric output (Year 1)	58432692 kWh
Gross Electric output (year 1)	58.4 GWh
Annual water usage (year 1)	13613 m^3
Capacity factor (year 1)	37.1 %

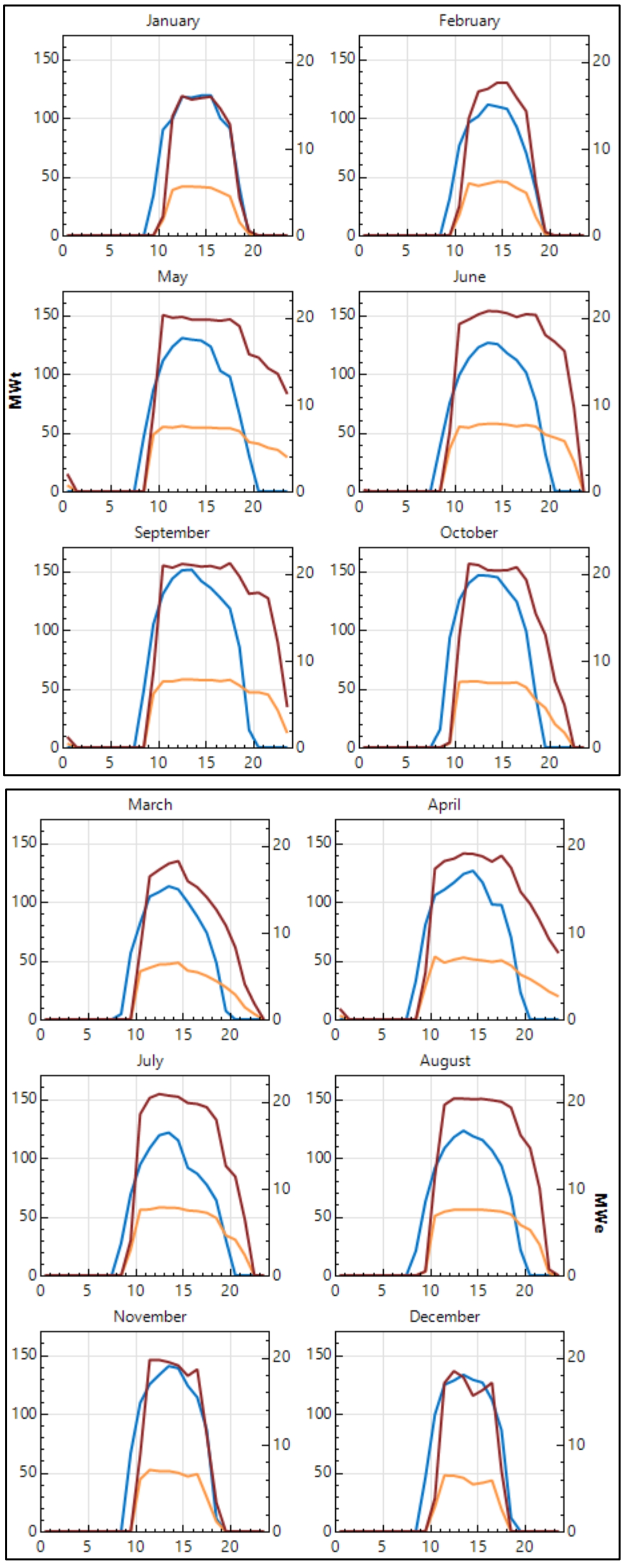
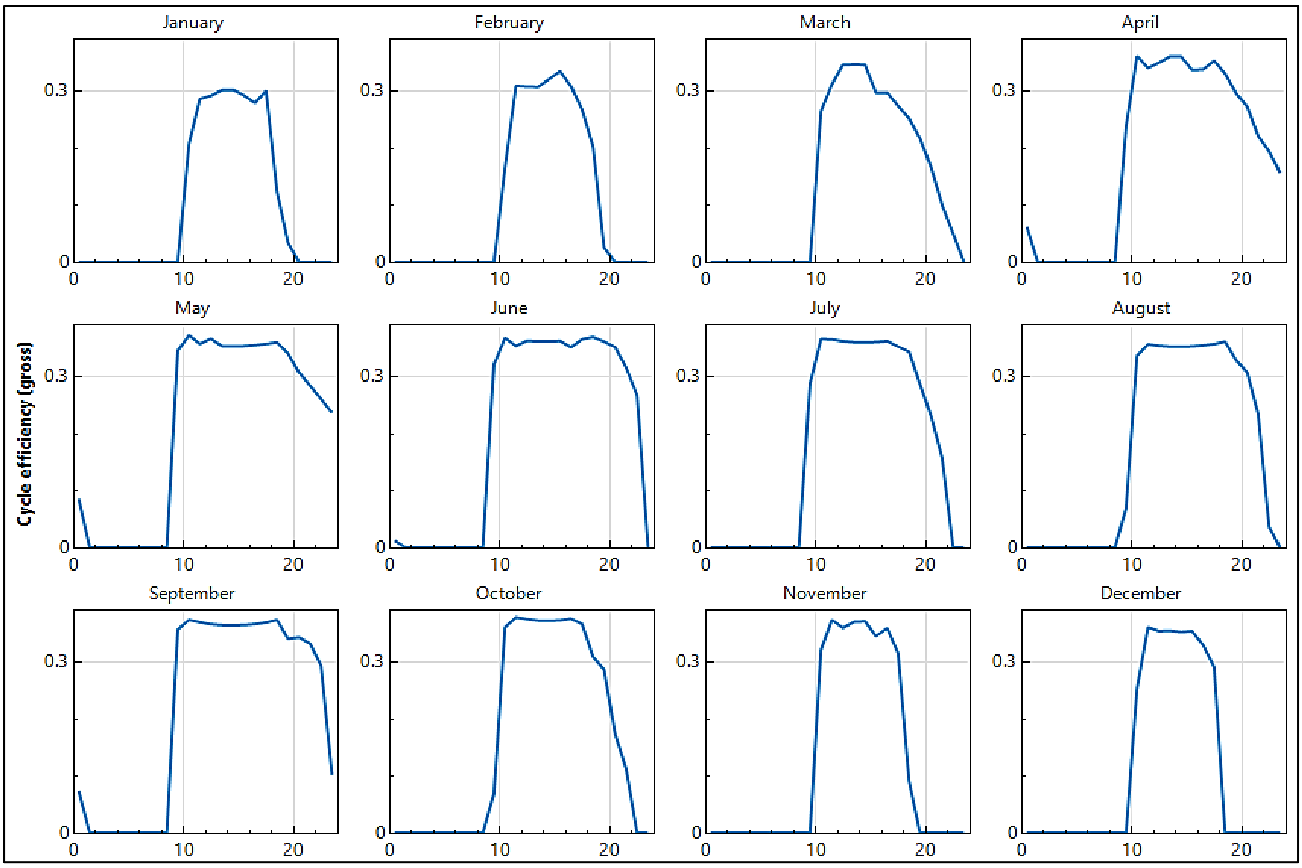


Figure 5. Hourly data of field thermal power incident, cycle electric power output and cycle thermal power input

Field thermal power incident (MWt)
Cycle electrical power output (Gross) (MWe)
Cycle Thermal power input (MWt)



Time of day (Hours)
Figure 6. Cycle efficiency of proposed power plant

Conclusions

- The proposed power plant can generate 58.4 GWH or 58432692 KWh with a capacity factor of 37.1 %.
- This analysis will provide a necessary path for the several aspects of the CSP technology which is necessary for design.
- Installation of large scale solar thermal power plant will pave the way for the utilization of the precious resource in Pakistan. Considering the abundant solar resource available in the country it is pertinent to explore various technology options available for tapping the resource most efficiently and most economically.
- This study only deals the performance analysis of the proposed power plant. Financial analysis is required to check the economic feasibility of parabolic trough power plant.

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