International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 9 Issue 8 Series I || August 2020 || PP 22-34

Design, Simulation and Performance Analysis of a 30 MWe Parabolic Trough Power Plant in Yola, Nigeria

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ABSTRACT ***:*** *Concentrated power technology have gained prominence all over the world as a result of the growing interests in green power and CO_2 reduction. As of today, there are several parabolic trough power plants operating in various parts of the world. Nigeria and sub-Saharan Africa are yet to partake in this technology despite the favorable weather available in the region for solar thermal power generation. This paper has designed, simulated and analyzed the performance of a 30 MW parabolic trough power plant in Yola, Nigeria. The design point has been set to 9 am of 23rd September which is autumnal equinox, a day with equal day and night length. The solar field was designed to maintain an economic optimum between a very large field, which will be economically unreasonable and small solar field, which causes the power plant to operate below capacity. Thermal storage was also included to compensate for non-insolation periods. The results show that the plant has a capacity factor of 46% and an average operating time of 12 hours daily. Hybridization will however be necessary to compensate for periods when the plant does not produce power.*

KEYWORDS -*Solar Energy, Parabolic Trough, Power Plant, Simulation, Hybridization,*

Date of Submission: 15-08-2020 Date of Acceptance: 01-09-2020

I. INTRODUCTION

The world's energy consumption is still dominated by hydrocarbon-based fossil fuels [1]. These fuels are responsible for greenhouse gases, which are the main cause of the increasing ecosystem, and climatic instabilities that has constituted several problems to humanity and also spells an impending doom if not checked. This has led to extensive research in renewable energy resources with solar energy taking the lead.

Solar energy is the most readily available and widely distributed alternative energy resource [2]. Concentrated Solar Power (CSP) technologies offer one of the best options to utilize these technologies. Concentrated Solar Power technologies have 3 design types; solar power towers, dish sterling and parabolic troughs among which parabolic troughs have the advantage of having a lower cost of development and has gained prominence as 70% of the total globally operational CSP plants use parabolic trough technologies [3]. These power plants use curved mirror troughs, which track the sun on a single axis concentrating sunlight onto a steel tube containing a heat transfer fluid running along a focal line of reflectors. The temperature of the fluid rises to about 400 ^{0}C and the fluid containing the heat energy is transported to a steam engine where about a third of the heat is converted to electricity [4].

Growing interests in green power and CO_2 reduction has helped increase interests in this technology around the world as the technology has been employed for power generation in various parts of the world. Notable is the SEGS, which has been in daily operation in in California Mojave Desert for up to 18 years. These plants provide solar electricity to meet the residential needs of a city with 350, 000 people [5]. Several other parabolic trough power plants are also under development in various parts of the world [6].

Over the years, simulation programs have been developed to project the performance of solar electric power plants. Programs such as SOLERGY and FLAGSOL were among the early programs developed [7;8]. More detailed models have been developed to account for full solar field conditions. Notable among them is TRNSYS and SAM. These programs have been efficient in simulating solar thermal power plants and have seen only slight deviation in the performance in the hypothetical and the real plant output [9]. A 30 MWe SEGS VI parabolic trough collector base power plant model was createdin TRNSYS to evaluate the behaviour of solar field and power cycle with 10% difference between model and plant data [10]. A study carried out by Rohani*et al.* (2017) to compare the results from software simulation with real plant data using the Andasol 3 power plant. A mean deviation of the 2.29% in the electrical output of the plant and a mean deviation of 0.52% for the solar field thermal energy. These programs are therefore reliable in simulating the solar thermal power plants [11].

Several studies have also been carried out to determine the performance of solar thermal power plants in various parts of the world. Bishoyi and Sudhaka (2017), designed and simulated a 100 MW parabolic trough-based CSP plant with 6 hours of thermal storage using the SAM (System Advisor Model) software in Udaipur, India. The result gotten showed the plant has a capacity factor of 32.6% and an annual efficiency of 21.3% [12].

Mohamed et al (2013) assessed the performance of a 100 MW parabolic trough power plant in Mediterranean and arid conditions in Algeria using the System Advisor Module software, results obtained showed a 13.8% efficiency and a 21.1% capacity factor [13]. Boukelia*et al.* (2015) modelled a 50 MW parabolic trough power plant integrated with thermal energy storage and fuel back up system. He obtained an efficiency of 21.8% and a capacity factor of 38.2% [14].

In Nigeria, the use of solar energy for electricity generation is limited to photovoltaic and despite its favorable disposition to solar radiation due to its geographic location; solar thermal technology is still at its infancy stage [15]. Electricity generation for Nigeria's grid is largely dominated by two sources - non-renewable thermal (natural gas and coal) and renewable water or hydro [16]. Coal and natural gas make up the largest portion of energy production in Nigeria, while energy generated from hydro is well below potential. Nigeria's installed electricity capacity is 12,522 MW, well below the current demand of 98,000 MW. The actual output is about 3,800 MW, resulting in a demand shortfall of 94,500 MW throughout the country. As a result of this wide gap between demand and output, only 45% of Nigeria's population have access to electricity. This power deficit has prompted users to seek alternative energy means, primarily through buying gas and diesel-powered generators. These alternatives are relatively expensive, and are major contributors to environmental pollution. [16]. While solar energy has been in use for power generation since 1987 in the hottest parts of the USA and has also been in operation in parts of the middle east and Europe, solar energy has not been harnessed for power generation in Nigeria.

Yola is located in northeast Nigeria, on latitude 9^0 12'N and longitude 12^0 29'E with an area of 831,000 km^2, it is reputed to be one of the hottest cities in Nigeria [17]. According to irradiation maps, the total amount of solar irradiation ranges from 21.20 MJ/m^2 to 29.51 MJ/m^2 monthly [18]. In fact, the intense heat from the sun in Yola Nigeria is been perceived more as a burden rather than a blessing as residents groan and curse nature under it during the hottest parts of the year. Hence, this work aimed at designing an economic model of a parabolic trough power plant and analyzing is performance to determine its viability. This will hopefully arouse interest and set Nigeria on the path to solar thermal power generation.

The model presented in this work is a power plant with a two-tank molten storage system operating without fossil fuel back up. The design point has been chosen among days with moderate solar radiation since thermal storage is available. This will enable extra received energy for sunny period to be stored for utilization during non-insolation periods. The design point conditions will be utilized and then the number of collectors per loop will be calculated after which thermal storage and power block will be integrated. The annual performance will be analyzed on a monthly basis in terms of the daily electric output, the monthly solar radiation received and the parasitic power consumed.

II. DESIGN AND SIMULATION

2.1 Design Point Conditions

The design point has been chosen among days with moderate solar radiation. September 23, which is autumnal equinox and therefore has equal day and night length has been chosen as the design day and 9 am has been selected as the design time. This time (9 am) was chosen to allow the power plant reach full load output in the morning and operate with the same throughout the day. The direct normal irradiance (DNI) for the design is calculated using the following steps [19].

$$I_{DN} = A_1 \times \exp\left(\frac{-P_L}{P_0} \times \frac{B}{\sin\alpha}\right) \quad (1)$$

where $\frac{P_L}{P_0}$ is the pressure ratio at the design location relative to the standard atmospheric pressure given as:

$$\frac{P_L}{P_0} = \exp(-0.0001184 \times H_{alt}) \quad (2)$$

where H_{alt} is the altitude in meters above sea level which has value of 184 m for Yola.

The values of extraterrestrial solar intensity A_1, the atmospheric extinction coefficient B, and the sky diffused factor C_1, have been estimated for any day of the month by the following equations [20]:

$$A_1 = 1158 \times \left[1 + 0.066 \times \cos\left(\frac{360n}{370}\right)\right] \quad (3)$$

$$B = 0.175[1 - 0.2 \times \cos(0.93n)] - 0.0045[1 - \cos(1.86n)] \quad (4)$$

$$C_1 = 0.0965\left[1 - 0.42\left(\frac{360n}{370}\right)\right] - 0.0075\left[1 - \cos(1.95n)\right] \quad (5)$$

n is the number of day in the year = 266
The sun altitude angle α and declination angle δ are given as [21],

$$\alpha = \sin^{-1}\left(\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi\right) \quad (6)$$

ω is the hour angle and ϕ is the latitude

$$\delta = 23.5\sin\left[360 \times \frac{(n-80)}{370}\right] \quad (7)$$

To find the hour angle, we find the solar time using the expression [21]

$$\omega = (t - 12) \times 15 \quad (8)$$

t is the solar time which is expressed as

$$t = LST + \frac{TC}{15} + \frac{E_t}{60} \quad (9)$$

LST is the local standard time which is 9 am and E_t is the equation of time which is expressed as

$$E_t = 9.2\left(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos(2B) - 0.04089\sin(2B)\right)$$

And $B = (n-1)\frac{360}{365}$

Time correction $TC = +15 - longitude$

In calculations for irradiation collected by a collector, only the beam irradiance is considered. It is calculated as [22]

$$I_b = I_{DN}\cos\theta \quad (10)$$

θ is the incident angle of solar radiation on the collectors. This can be calculated as [23]

$$\theta = \cos^{-1}\sqrt{1 - \left[\cos(\alpha - \theta_{col}) - \cos(\theta_{col})\cos(\alpha)(1 - \cos(\gamma_{sol} - \gamma_{col}))\right]^2} \quad (11)$$

α is the sun altitude angle and γ_{sol} is the solar azimuth and is calculated as

$$\gamma_{sol} = \omega\left|\cos^{-1}\left(\frac{\cos\theta_z\sin\phi - \sin\delta}{\sin\theta_z\cos\phi}\right)\right| \quad (12)$$

For horizontally placed collectors, the tilt angle for the collector $\theta_{col} = 0$. Since the collector has been placed to face the equator, the collector azimuth, $\gamma_{col} = 0$.

2.2 Solar Field Design

Solar Multiple

Since thermal storage is included in the design, the solar field has been enlarged so that the output power thermal at the design point exceeds the thermal power required by the power block and excess thermal power is stored for use at non insolation periods. The solar multiple (SM) i.e. the ratio of the thermal power of the solar field at design point to the required thermal power for the full-load operated power block, is selected so as to maintain an economic optimum between a large thermal field, which causes energy to be wasted at excellent radiation conditions and a small solar field which keeps the plant from reaching full capacity. By trial and error, a solar multiple of 1.7 has been selected. This simply means the solar field collects a 7^{th} more than the thermal power required to generate 30 MW electrical power at the design point.

Collectors and Receivers

The solar field consists of one or more loops of solar collector assemblies. A solar collector assembly (SCA) is an array of collectors with a common tracking unit [24]. The loop usually consists of a specific number of SCAs. A common header pipe provides each loop with a common heat transfer fluid (HTF) which is collected and returned back to the power block by a second header pipe. There are various kind of collectors and receivers available in the market today, for cost and efficiency, the Sky Trough parabolic trough collector and the Schott PTR80 receiver are being used in this model. Their properties are given in table 1.

We determine the number of collectors in a loop by using the differential equation for the temperature rise across a node [23].

$$T_{out,i} = \frac{\dot{q}_{abs,i}}{\dot{m}c_{pi}} + T_{in,i} + 2\left(\overline{T}_{0,i} - \frac{\dot{q}_{abs,i}}{2.\dot{m}c_{pi}} - T_{in,i}\right)\exp\left[\frac{-2\dot{m}c_{p,i}\Delta t}{m_i c_{p,i} mc_{i,bal,sca} L_i}\right] \quad (13)$$

We apply this equation to each node *i* in the loop where $T_{in,i}$ is the outlet temperature of the previous node in the loop. For *i =1*, the inlet temperature is the outlet temperature of the power block which is the inlet temperature of the entire solar field. The HTF mass of each node is calculated as a function of the receiver piping volume of the local HTF density.

$$m_i = \rho_i L_i A_{cs,i} \quad (14)$$

ρ is the density of the HTF = 773 kg/m^3
The absorbed heat is given as [25]

$$q_{abs} = (A_{sca} I_{bn}).\eta_{opt} \quad (15)$$

A_{sca} is the area of the solar collector assembly
η_{opt} is the optical efficiency
I_{bn} is the beam radiation at the design
The optical efficiency is

$$\eta_{opt} = SCA\ optical\ efficency\ at\ design\ \times HCE\ optical\ dearate \quad (16)$$

The HTF mass flow rate at the design $\dot{m}$ = 7 kg/s, average temperature is 342 ^{0}C and the heat capacity, c_p=2423 J/Kg.K. The HTF exits the sixth node at 390.7 ^{0}C. This implies that 6 SCAs are required per loop for the design.

Solar Field Layout

The collectors in the solar field has been oriented in the north-south direction tracking the sun from east to west. The solar field has two subsections to minimize pumping costs. The total thermal power required by the solar field is calculated as [26],

$$W_{th} = \frac{Gross\,rated\ electrical\ output}{cycle\ \text{cov}\,ersion\,efficiency} \times SM \quad (17)$$

The conventional thermal to electric conversion efficiency of parabolic trough Rankine cycle systems is 37%. Same has been assumed for this design. The required thermal output is therefore 153 MW$_t$. As calculated by System Advisor Module, 496 SCAs are required to produce this power. For our arrangement of 6 SCAs per loop, the plant consists of 83 loops of SCAs with 2 subsections. The spacing between the rows is 15m and the distance between SCAs in a row has been set to 1m.

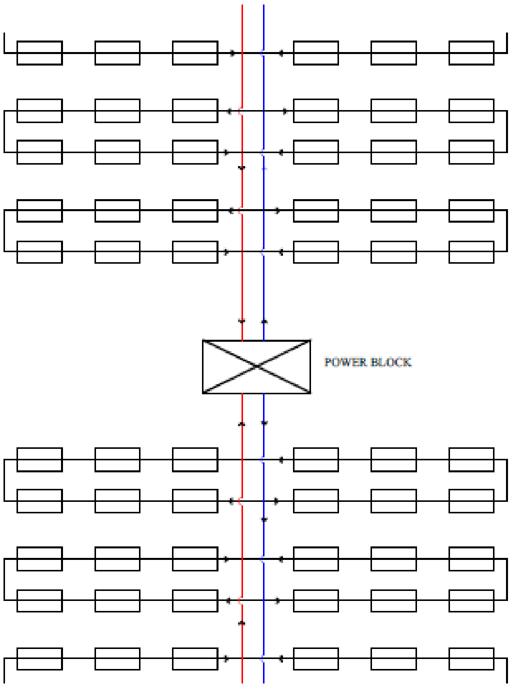


Fig. 1. Solar field configuration

Heat Transfer Fluid

The conventional heat transfer fluid used in parabolic trough power plants is *Therminol VP-1*. Itis a eutectic mixture of biphenyl/diphenyl oxide. It has a maximum operating temperature of 400 ^{0}C and a minimum operating temperature of 12 ^{0}C. With a conductivity of 0.18 W/m.K, and heat capacity of 2423 J/kg.K [24]. The HTF mass flow rate is a major determinant for the amount of heat gained in the loop. The solar field control algorithm therefore use user defined inputs to make operational decisions based on the design conditions. The mass flow rate is controlled to allow the outlet temperature to meet the design point value when possible. The minimum and maximum allowable mass flow rate for the loop is determined by [23]

$$\dot{m}_{\min} = v_{\min} \rho_c \pi \left(\frac{d_i}{2} \right)^2 \quad (18)$$

And the maximum mass flow rate is,

$$\dot{m}_{\max} = v_{\max} \rho_h \pi \left(\frac{d_i}{2} \right)^2 \quad (19)$$

Thermal Storage

Thermal storage has been included in the design to help bridge transient cloudiness and to compensate other weak radiation conditions in the sense that the power block is operated more frequently under full load conditions and less under part load conditions. The storage material selected for this design is Hitec solar salt. The model used in this design is the model for the SEGS power plant. It has the following characteristics as shown in table 1.

Table 1. Thermal Energy Storage Parameters [26]

Parameter	Value
Storage hours	6 hours
Maximum energy storage	550.57 MWht
Maximum power to storage	91.758 MWht
Maximum power from storage	92.969 MWht
Storage fluid minimum operating temperature	238^{0}C
Storage fluid maximum operating temperature	593^{0}C
Heat exchanger duty	1

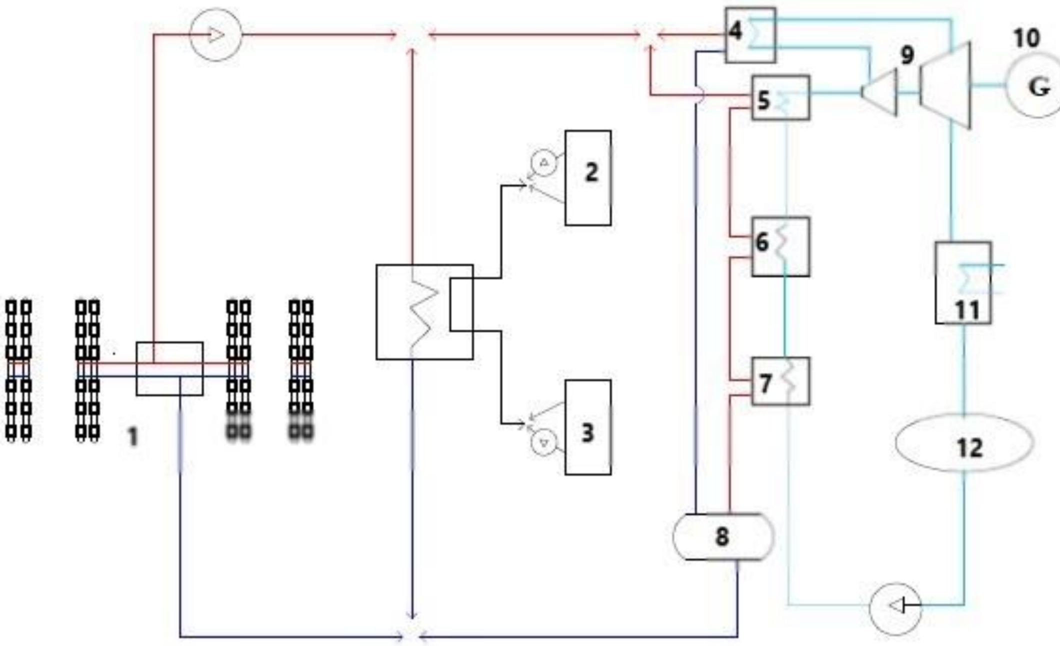
Since the power plant design point has been selected among days with moderate solar radiation, the storage system for this model has a capacity for 6 hours of thermal storage. This will hopefully allow storage for full operation of storage system in periods of higher solar radiation. System Advisor Module uses parameters such as the required hours of storage, the solar multiple, the rated output of the power plant and the cycle conversion efficiency all specified by the user to calculate the size of the thermal storage, heat exchangers and storage material volume required.

Power cycle

The power cycle used for this design is the regenerative Rankine cycle. This is the cycle commonly used in concentrated solar thermal power systems [27]. The SEGS 30 MW turbine has been used for this design. The power cycle parameters are given in table 2.

Table 2. Power Cycle Parameters [26]

Parameter	Values
Estimated net output at design	31 MWe
Design gross output	33.4 MWe
Design Cycle thermal input	89.09.3 MWht
Rated cycle conversion efficiency	0.3749
Max Turbine Over design Operation	1.15
Min Turbine Operation	0.15



1. Solar field 2. Warm storage 3. Cold storage 4. Re-heater 5. Super heater 6. Steam generator 7. Pre-heater 8. Expansion tank 9. Turbine 10. Generator 11. Condenser 12. Deaerator

Fig. 2. Schematic diagram of the power plant

III. SIMULATION OF THE POWER PLANT

The data calculated was used to run a simulation of the power plant using the System Advisor Module (SAM) software. Weather files for 3 years was collected from the Nigerian Environmental Climatic Observation Programme (NECOP) station situate in the Modibbo Adama University of Technology, Yola. SAM is a software developed by the US Department of Energy's National Renewable Energy Laboratory, (NREL) for modelling renewable energy projects [9]. The publicly available source code is written in FORTRAN, is, and runs off software called TRNSYS.

SAM requires input data to describe the performance characteristics of physical equipment in the system, and project costs and financial assumptions. The desktop application comes with default input values and tools for downloading some inputs from online data services. SAM also requires a weather data file as input to describe the renewable energy resource and weather conditions at a project location. SAM's performance models make time step-by-time step calculations of a power system's electric output, generating a set of time series data that represents the system's electricity production over a single year. The simulation time step depends on the temporal resolution of the data in the weather file, which can be hourly or sub hourly.

Table 1: Design parameters for simulation

Category	Values	Reference
Location and resource		
Location	Yola, Nigeria	
Longitude and Latitude	9.12 ^{0}N, 12.23 ^{0}E	
Elevation	189 m	
Solar field		
Solar multiple	1.7	
Number of SCAs per row	3	
Distance between SCA in a row	1 m	
Row spacing	15 m	
Deploy angle	10 m	
Stow angle	170 m	
Collector tilt	0^0	
Collector azimuth	0^0	
Non-solar field land area multiplier	1.4	
Design point		
Direct Normal Irradiance	683 W/m^2	
Ambient temperature	29.7 ^{0}C	
Wind velocity	5 m/s	
Heat Transfer Field		
HTF	Therminol VP-1	
Solar field inlet temp.	239 ^{0}C	

Solar field outlet temp.	371 ^{0}C
Solar field initial temp.	100 ^{0}C
Piping heat loss at design temp	10 W/m
Piping heat loss coefficient 1	0.001693
Piping heat loss coefficient 2	-1.683e-05
Piping heat loss coefficient 3	6.78e-08
Minimum temp.	50 ^{0}C
HTF gallon per area	0.614 gal/m^2
Collectors and Recievers	
Collectors (SCA)	Skyfuel SkyTrough
Collector Parameters	Use library values
Receiver 1	Schott PTR70 – vacuum
Receiver 2	Schott PTR70 – lost vacuum
Receiver 3	Schott PTR70 – broken glass
Receiver 4	Schott PTR70 - hydrogen
Receiver parameters	Use library values
Power Block	
Design gross output	33.4 MW
Estimated gross to net conversion factor	0.9
Power cycle	SEGS 30 MW turbine
Power cycle characteristics	Use library values
Boiler LHV efficiency	0.9
Thermal Storage	
Equivalent full load hours of thermal storage	6 hours
Turbine TES Adj. efficiency	0.985
Turbine TES Adj. gross output	0.998
Initial energy as fraction of maximum	0.2
Tank heat losses	0.97
Parasitic Power	SEGS VIII reference
Parasitic power characteristics	Use library values

3.1 Analysis of Performance

Output Performance

The hypothetical power plant has an annual thermal output of 384,981.436MWht and a gross electrical output of 143,250.487 MWe thereby having a net electrical annual output power 328,042.54 MWe. The capacity factor of the plant is 45.2 %. The plant occupies a total land area of 1.14 km^2. The annual parasitic power consumed by the plant is 19.2 MWe. The solar field energy absorption efficiency of the plant is 56.2%.

Solar Radiation Received

Figure 3 shows the thermal power incident on the solar fields, the solar thermal power absorbed by the field and the power transmitted by the field for power generation. Due to optical losses, which arise as a result of mutual shading of collectors, row end losses and geometrical inaccuracies of the solar field, only a fraction of the total power incident on the solar field is absorbed.

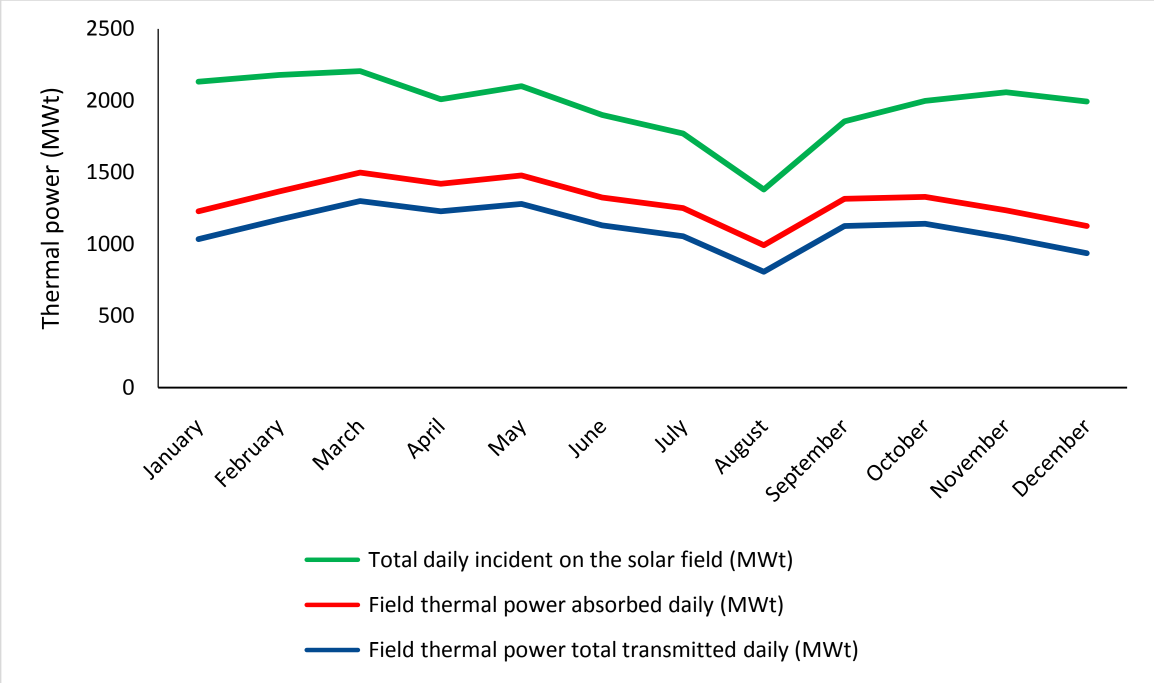


Fig. 3. Average daily thermal power received by the power plant

The highest amount of solar radiation incident on the solar field per day was in the month of March (2204 MW) which is followed by February and January. The month of August has the least incident thermal power on the solar field. The month of August however has the highest amount of power absorbed by the solar field. In this month, 71.7% of the incident power is absorbed.

The solar field absorbs up to 70% of the incident solar thermal power from the months of April to September. The absorbed power then decreases gradually until it reaches its lowest in the month of 56.5% absorption in December and slowly rises until it reaches 68% in March. This is because the collectors have been oriented in the North-South direction tracking the sun from East to West. For this kind of orientation, the solar field collects more energy in winter than it does in summer [28], hence, the energy collected increases as summer approaches and decreases thereafter.

Figure 3 also shows that at least 81% of the power collected by the solar field is transmitted for power generation. Thermal losses are responsible for this reduction. Thermal losses occur in pipes and joints. High ambient temperatures implies low thermal losses since the pipes are insulated by the surrounding air. It is therefore observed that less power is lost through thermal losses in the months of March April and May when the ambient temperatures are highest. The least conversion and hence, more losses (81.4%) occur in the month of August which has the highest rainfall in Yola [17]. On average, 84% of the total thermal power collected by the solar field is transmitted to the power block for electricity generation.

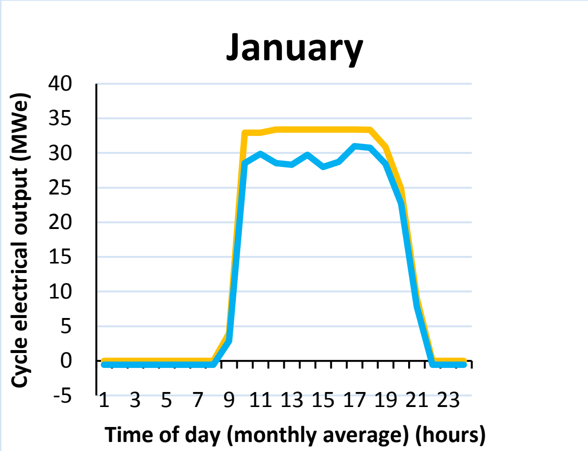
Electric Power Output

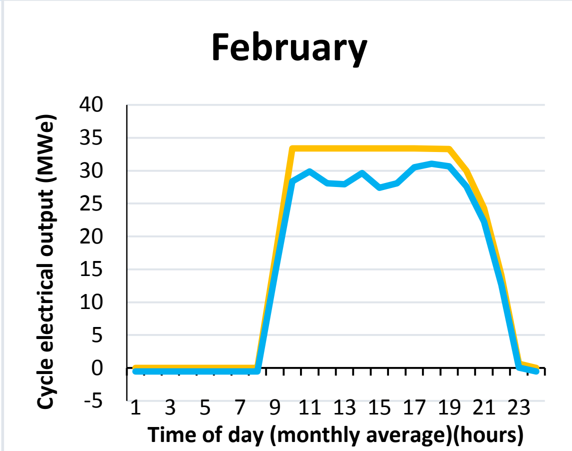
Figure 4 shows the monthly average of daily gross and net electrical power output of the power plant which has been designed to start production when the solar field produces 25% of the thermal power required.

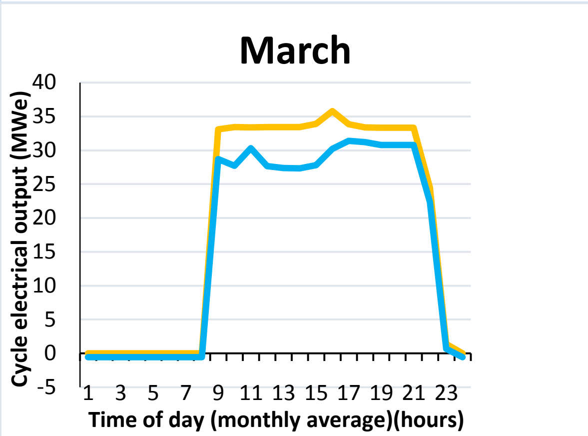
January and December are the coldest months in Yola. They are also the periods of shorter days. For these months, the power plant produces power for a total of 13 hours with 6 hours of full capacity (33.4 MW) and 7 hours near full load (over 26 MW). For the month of December, the plant begins power production with 10.2 MW power by 8:30 hours after which it reaches full capacity by 9:30 am and operates at full capacity 6 hours with 2 hours near full load after which the power produced drops gradually to 16.6 MW at 18:30 hours and then to 0.45 MW by 20:30 hours.

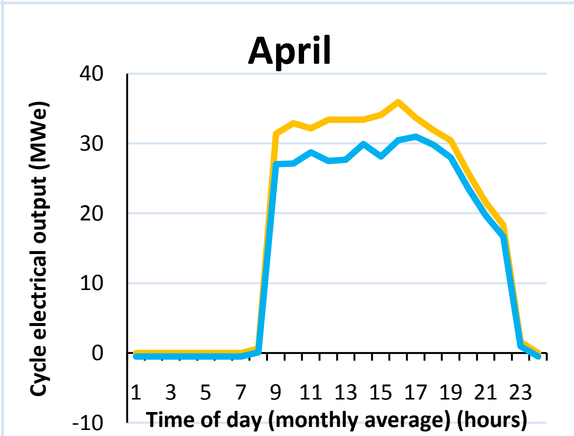
In the months of February, March, June and August, the plant typically begins production by 8:30 am and shuts down by 10:30 pm. In February, the plant begins production with 16.3 MW by 8:30 am after which it operates at full capacity for a duration of 9 hours then drops to 33.3 MW and operates near full capacity for 3 hours and then drops gradually to 0.6 MW after which it shuts down for the day. The month of March has the highest power output for the year. In this month, the plant typically reaches 33 MW by 8:30 am and maintains this amount of power until 20:30 hours (13 hours' duration) after which it operates in part load for an hour and then drops to 1.36 MW by 10:30 pm. In the month of June, the plant begins operation with an output of 21.8

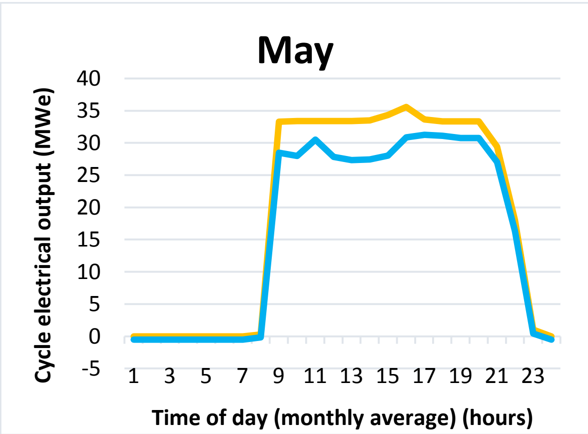
MW by 8:30 am and operates in full load for the next 8 hours after which it operates near full load near 3 hours and gradually drops to 1.3 MW by 10:30 pm which it shuts down for the day.

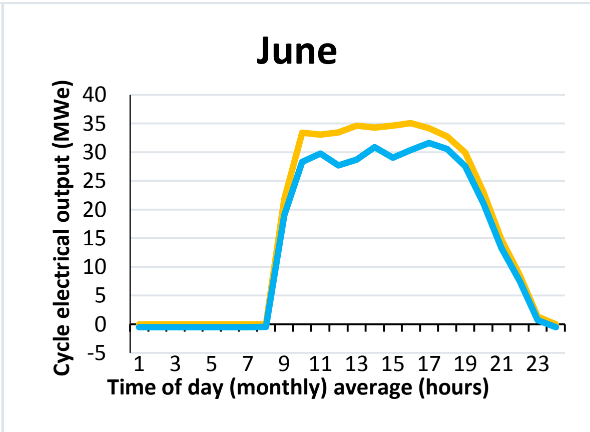












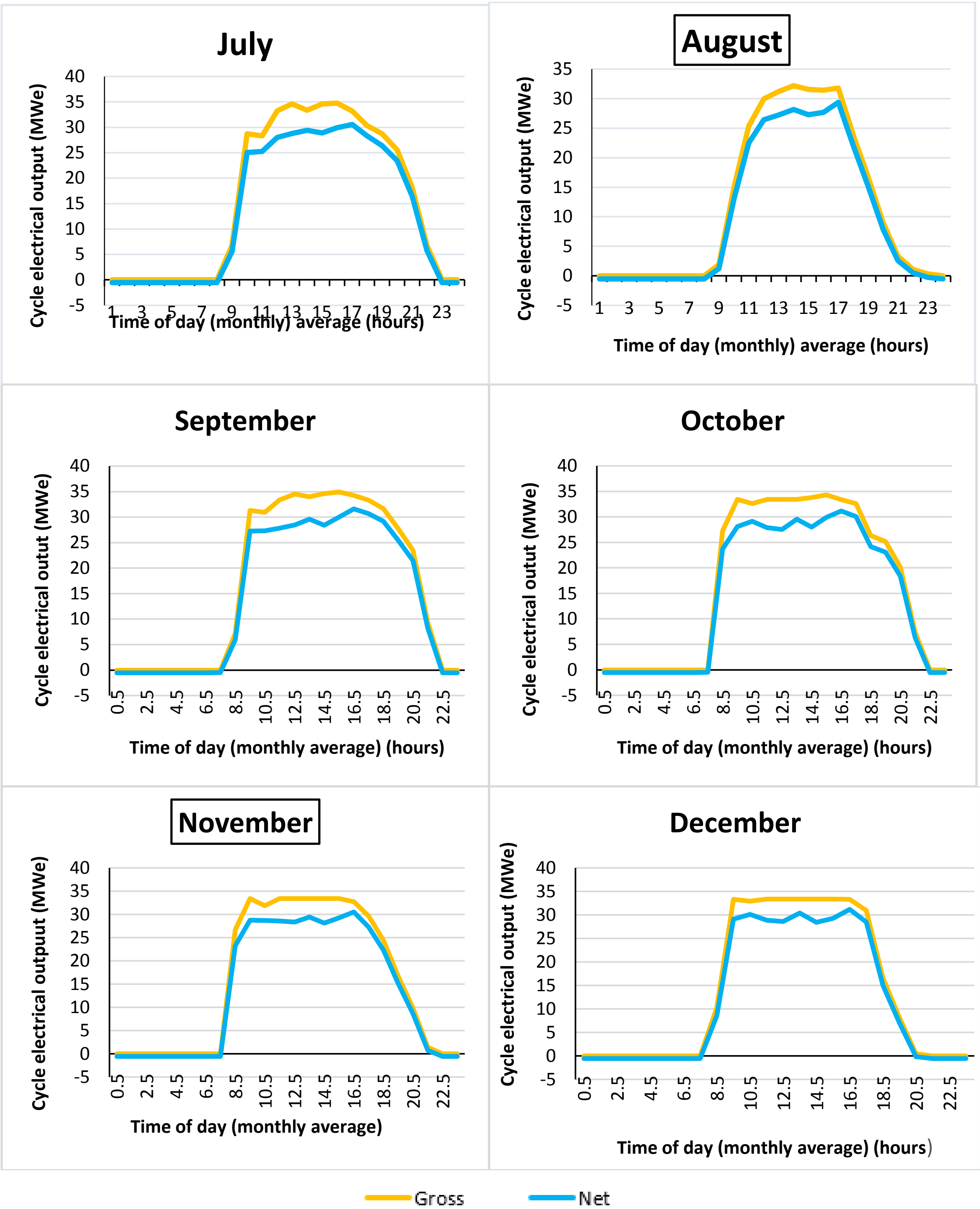


Fig. 4. Hourly data of cycle electrical output

The least power generated monthly by the plant is in the month of August. In this month, the plant operates for 13 hours average daily but never reaches full capacity. It produces up to 30 MW of electricity for 6 hours a day and up to 20 MW for 3 hours, above 10 MW for 2 hours, above 5 MW for an hour and less than 5 MW for 3 hours. The reason for the low output is possibly because August is the cloudiest month in the Yola and has the highest amount of rainfall as shown by weather files.

April and May are the only months in the year in which power is generated before 8 am. The power generated at this time is however negligible i.e. 0.6 MW for April and 0.3 MW for May. The plant in April produces up to 30 MW of electricity for 11 hours and reaches full capacity of 33.4 MW gross output for 6 hours and over 20 MW for 2 hours before dropping to 1.3 MW at 10:30 pm after which it shuts down for the day. May has 12 hours of over 30 MW generation with 8 hours of full capacity generation. It generates 29 MW for one more hour and then shuts down after 10:30 pm.

In the months of July, September, October and November, the plant begins generation by 8:30 and stops by 21:30. For each of these months, the plant delivers 6 hours of full load. October and November however have more power generated than the other months as the plant begins generation by 8:30 am with about 27 MW and produces over 30 MW for 8 hours.

The daily net electrical power output of the plant for each month is also shown in figure 4. This is the power available for transmission after deducting the parasitic power consumed by the plant. The net electrical power takes negative values when the gross power output by the plant is zero i.e. from 12 am to 7 am. This is because the power plant has some fixed loads which are in operation at all hours of the day, even at times when the plant is not generating any power.

It can also be seen from figure 3 that the net power produced does not reach full design value of 30 MW from 11 am to 2pm, except for some days in December, despite these hours being the hours of the day with the highest amount of insolation and the gross power being generated at full capacity. This is because the thermal energy storage pumps and HTF pumps are most active at these times and consume quite a lot of energy for their operations.

The month of March sees and average of 6 hours of full load generation daily. This is followed by the month of May which has an average of 5 hours daily. February, June and November each have an average of 3 hours of power generation at full capacity. January, April, and October each have 2 hours of full capacity generation daily while July and November each have one of full capacity net power output daily. The design net power output is almost never reached in August as this is the month with the least amount of sunshine for the year.

Parasitic Power

The electric power consumed by the plant for its operation which is termed parasitic losses, are given in the table 4.13.

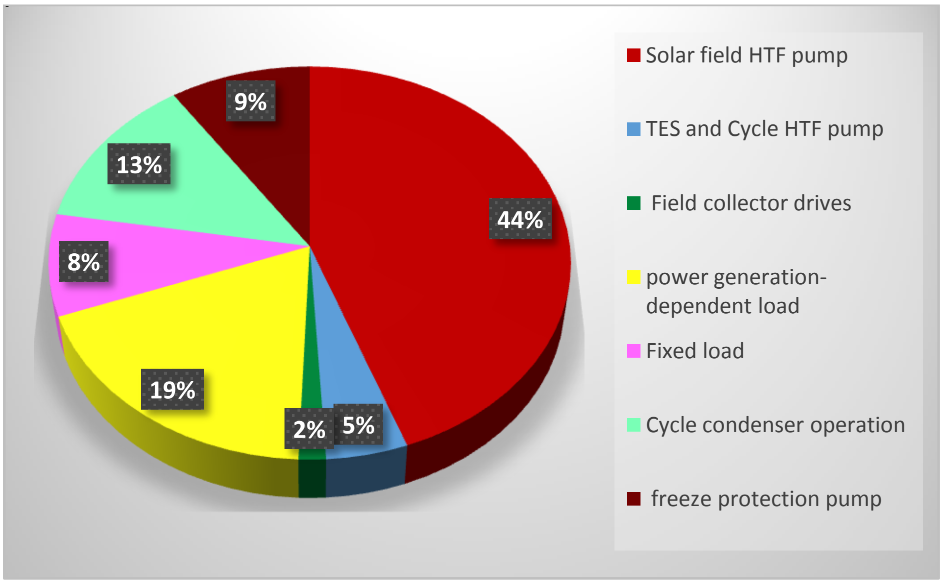


Fig. 5. Power consumed by various components of the power plant

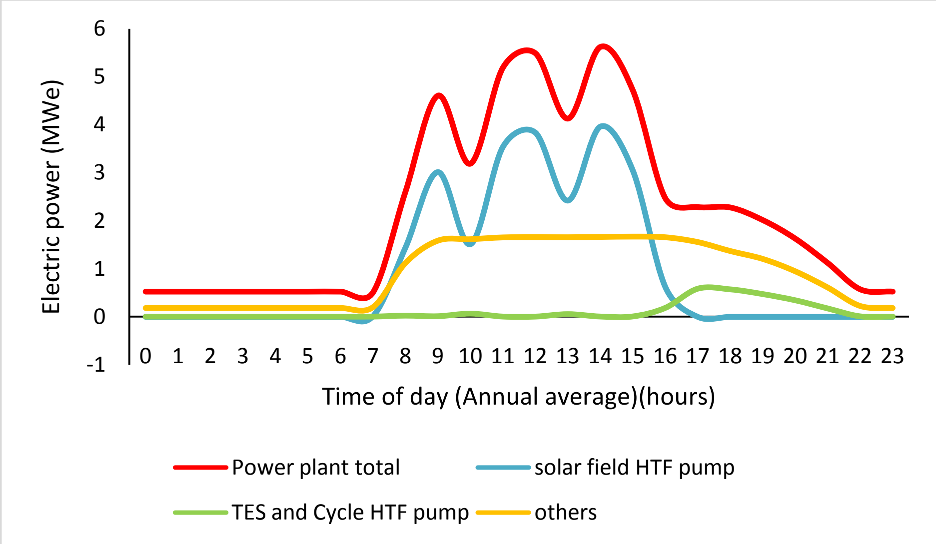


Fig. 6. Hourly parasitic power consumption of the power plant (annual average)

The plant consumes a maximum of 6 MW per hour and a minimum of 0.526 MW per hour as parasitic loads. These parasitic loads include the HTF pumps for the solar field, the TES and power cycle power cycle pumps, the field collector drives, power generation dependent load, fixed load, cycle condenser operations and the freeze protection pumps.

Figure 5 shows the percentage of power used by these various components. Most of the parasitic power consumed is utilized by the solar field HTF pumps. This is understandable considering the size of the solar field (322 m^2). This utilizes 44% of the total power consumed by the power plant. The power generation dependent load which includes the steam generators, heater and turbine operations take 19% of the total power consumed by the plant, the cycle condenser utilizes 13% of the parasitic power. Fixed loads account for 8% of the power consumed by the plant. These include equipment and appliances that are constantly in use in the plant even at times when the plant is not producing any power such as lightings, air conditioning and heating systems. The least power is consumed by the field collector drives which are responsible for tracking operations of the collectors. The account for only 2% of the parasitic power consumed.

Figure 6 shows the hourly parasitic power consumed by the plant. Most of the power consumption by parasitic load occur in the mid hours of the day. This is because the solar field HTF pumps which takes the highest share of the parasitic power consumed is most active at this time of the day. This is also same for the power generation dependent load. It can also be seen that the TES and cycle HTF pumps are mostly active in the early evenings (4 pm to 8 pm), the periods in which the power plant operates mostly form the energy stored in the thermal energy storage.

IV. CONCLUSION

This research designed a parabolic trough power plant which was simulated and the performance has been analyzed. The power plant was designed to reach full load operation from 9am and it has been equipped with a thermal energy storage to extend the time of operation. The average operating time of the plant is 12 hours daily leading to a capacity factor of 45.2%. Twelve hours of solar energy production can save the environment 2200 metric tons of CO_2 emissions [29]. The plant requires a total land area of 281 acres (1.14 km^2) which is about 228 football fields. This is however not an issue as Yola has surplus uninhabited land.

As compared to other major parabolic trough power plant all over the world, the model designed competes favorably. The SEGS solar plants in Mojave deserts in California, USA which occupies a total land area of 1600 acres have a combined rated power of 361 MW and a capacity factor of 21%, the Khata solar spark in South Africa occupies 1977 acres and has a rated net capacity of 100 MW with a capacity factor of 44.5%. The Andasol solar power plant has a rated output of 150 MW with a capacity factor of 37.7% and occupies 1500 acres of land [6].

Parasitic loses in the plant are high at times of high insolation when the solar field is most active as the power utilized by the solar field HTF pump is high. This ensures that the plant only nearly reaches the rated design net output of 30 MW at such times. The rated power can be increased to compensate for this loss, but an increase in the rated power also leads to an increase in the size of the solar field which means the parasitic power also increases proportionally. Results also show that the power plant modelled does not produce electricity from 11pm to 7am. Which gives rise to the need for hybridization with an alternative energy source to supplement the plant.

Result shows favourable conditions for the implementation of solar thermal power plants in Yola Nigeria. This design can also be replicated in other parts of the country. Further study is required to determine the economic returns of the plant as compared to other power sources available in the country.

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Alkasim, A, and Anyebe, D. "Design, Simulation and Performance Analysis of a 30 MWe Parabolic Trough Power Plant in Yola, Nigeria."*International Journal of Engineering Science Invention (IJESI)*, Vol. 09(07), 2020, PP 22-34. Journal DOI- 10.35629/6734