MODELLING OF PARABOLIC TROUGH COLLECTOR TYPE CONCENTRATIG SOLAR PLANT WITH THERMAL ENERGY STORAGE SYSTEM

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Abstract

The energy demand is on the rise with an urgent need to tap the abundant renewable energy sources in the region. This is essential for the future development of the Middle-East region as it reduces the dependency on fossil fuels and eliminates the problems associated with air pollution and greenhouse gases. Energy price of PV plant is less as compared to CSP plants. Whereas, CSP systems with thermal Energy storage capabilities can be effectively used to overcome intermittency issues of PV systems to balance demand with the supply of Electric power within safe levels of reliability by optimizing the Energy produced. The performance of the proposed CSP plant is further optimized by varying the solar multiple and full load hours of TES. The proposed parabolic trough based CSP plant with thermal energy storage is found to be feasible compare to solar PV system. The working of CSP plant and its components is described in this paper. Finally the modelling of CSP plant is carried out using Matlab Simulink.

I. INTRODUCTION

The time has come where the earth's energy situation can be defined as critical, which might be one of the reasons why many countries are becoming more conscious on subjects related to energy consume, energy efficiency, climate change, investment in renewable energies, dependence on fossil fuels…Therefore the uses of renewable energy sources are increased. The different kinds of renewable sources which are generally used in modern times are given as below:-

- Solar power plant
- Hydro power plant
- Geothermal energy
- Wind energy
- Biomass etc.

These different renewable energy sources have their own Advantages and disadvantages. But in the latest time use of solar energy is increased due to its feasibility, simple operation, etc. Compare to other sources. So, use of solar energy is popular in worldwide. "The solar rays come onto the earth surface is possible to convert into electrical energy then it provides electrical energy to world for 25 years." Concentrating Solar Power (CSP) plants use mirrors to concentrate sunlight onto a receiver, which collects and transfers the solar energy to a heat transfer fluid that can be used to supply heat for end-use applications or to generate electricity through conventional steam turbines. [5-6]

Concentrating Solar Power (CSP) plants use mirrors to concentrate sunlight onto a receiver, which collects and transfers the solar energy to a heat transfer fluid that can be used to supply heat for end-use applications or to generate electricity through conventional steam turbines. Large CSP plants can be equipped with a heat storage system to allow for heat supply or electricity generation at night duration and cloudy conditions also. There are four CSP plant variants, namely: - 1. Parabolic Trough, 2. Fresnel Reflector, 3. Solar Tower 4. Solar Dish, Which differ depending on the design, configuration of mirrors and receivers, heat transfer fluid used and whether or not heat storage is involved? The first three types are used mostly for power plants in centralised electricity generation, with the parabolic trough system being the most commercially mature technology. Solar dishes are more suitable for distributed generation. [5]

II. CONCENTRATING SOLAR POWER (CSP) PLANT

In concentrating solar power (CSP) technology sun's Direct Normal Irradiation (DNI) is concentrated to produce heat of temperature 400ºC to 1,000ºC [1]. This heat is used to produce electricity by conventional steam cycle, or combined cycle, or Stirling engine.

Figure-1: CSP Parabolic Trough Solar Collectors

PT is the most mature CSP technology, accounting for more than 90% of the currently installed CSP capacity. As illustrated in Figure 1, it is based on parabolic mirrors that concentrate the sun's rays on heat receivers (i.e. steel tubes) placed on the focal line. Receivers have a special coating to maximise energy absorption and minimise infrared re-irradiation and work in an evacuated glass envelope to avoid convection heat losses. The solar heat is removed by a heat transfer fluid (e.g. synthetic oil, molten salt) flowing in the receiver tube and transferred to a steam generator to produce the super-heated steam that runs the turbine. Mirrors and receivers (i.e. the solar collectors) track the sun's path along a single axis (usually East to West). An array of mirrors can be up to 100 metres long with a curved aperture of 5-6 metres. Most PT plants currently in operation have capacities between 14-80 MW e, efficiencies of around 14-16% (i.e. the ratio of solar irradiance power to net electric output) and maximum operating temperatures of 390'C, which is limited by the degradation of synthetic oil used for heat transfer. The use of molten salt at 550'C for either heat transfer or storage purposes is under demonstration. High temperature molten salt may increase both plant efficiency (e.g. 15%-17%) and thermal storage capacity. [6-7]

Parabolic Trough Collector Design

In a few short years, however, the situation has changed dramatically. As the trough project opportunities in Spain and the Southwest U.S. (in particular, in California) have increased, more companies are applying their expertise to develop commercial trough solar system designs.

At present, the list appears to be: (in random order)

- Flagsol (part of Solar Millennium)
- Solel Solar Systems
- Acciona Solar Power (was Solargenix)
- Sener / ACS Cobra
- Solucar R&D (part of Abengoa)
- IST Solucar (part of Abengoa)

Elements of a Parabolic Trough System:-

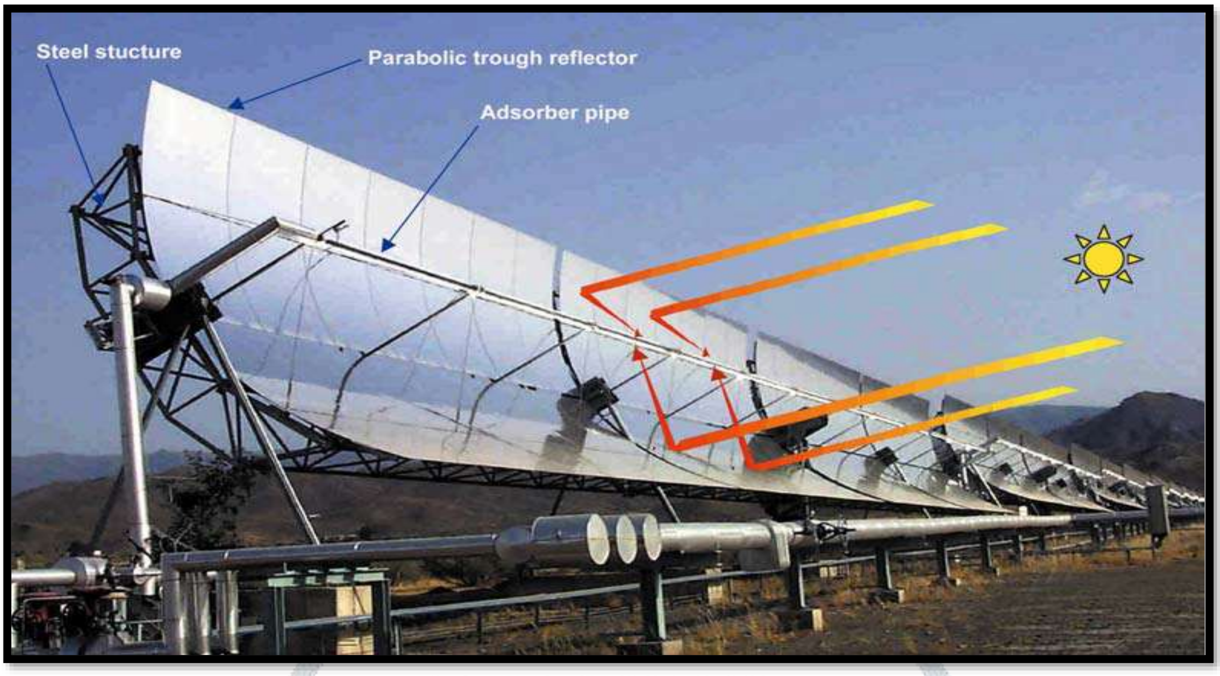

Figure-2 Parabolic Trough System design [8]

-Trough Collectors (single axis tracking)
- Heat-Collection Elements
- Reflectors
- Drives, controls, pylons
- Heat-transfer oil
- Oil-to-water Steam Generator
- Oil-to-salt Thermal Storage
- Conventional steam-Rankine cycle power block

Some Design Goals of a PT Collector to Achieve High Performance, Low Cost, Reliability and Durability:-

- High optical and tracking accuracy
- Low heat losses
- Manufacturing simplicity
- Reduced number of parts
- Corrosion resistance
- More compact transport methods
- Reduced field erection costs, w/o loss of optical accuracy
- Increased aperture area per SCA (reduced drive, control and power requirements per unit reflector area)

Types Reflectors:-

Figure-3 Flabeg Glass Mirrors

• Most current designs use Flabeg glass mirrors, and this is the only reflector used in the current commercial trough projects (SEGS/NS1/APS/AndaSol-1)
• 4mm glass mirrors have an initial hemispherical reflectivity of 93.5%
• Flabeg states that 98% of the reflected radiation falls on a 70mm diameter receiver
• Field durability of optical properties at SEGS plants
• Other glass/mirror manufacturers evaluating market

ReflecTech Silvered Film

Figure-4ReflecTech Silvered Film

- High Solar Reflectance
  - ~ 93.5% Hemispherical Reflectance
- Testing on Outdoor Weather ability
  - Ongoing NREL and Independent Lab Testing
- Low Production Costs
- Commercially-Available Materials
- No Capital Investment in New Equipment
- Roll Widths Sufficient for Large-Scale Solar
  - 60 inch wide rolls and smaller

Alanod Polished Aluminium

Figure-5 Alanod Polished Aluminium

- High Solar Reflectance
  - 91.5% Hemispherical Reflectance
- Testing on Outdoor Weather ability
  - Ongoing NREL testing; no change after 1 year
- Low Production Costs
  - Purchased industrial roll-coater for production

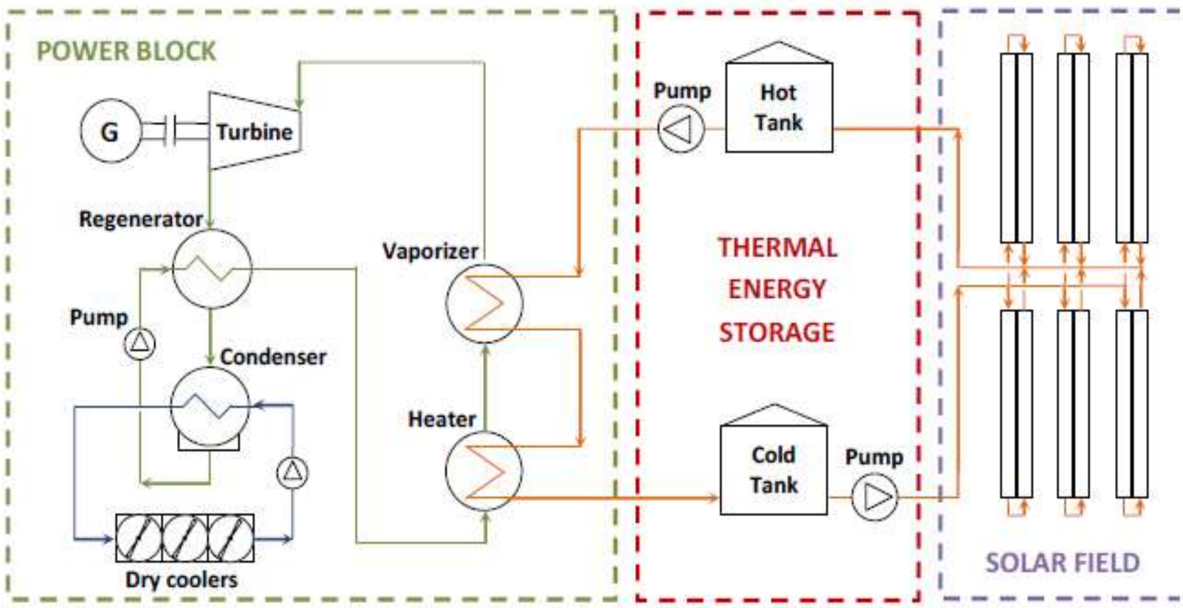

Figure-6 Process flow diagram of the CSP plant

For Electricity generation of 550 KWe the CSP Plant Parameters are:-

SOLAR FIELD		ORC UNIT	
Loops (200x9.0 m)	6	Thermal power input	3000 kW
Solar field collecting area	8400 m^2	Thermal oil temperatures (in/out)	260/150 °C
Solar field land area	10800 m^2	Thermal oil mass flow	11.1 kg/s
Solar field conversion efficiency	62.0 %	Gross conversion efficiency	20.0 %
Thermal oil mass flow	17.3 kg/s	Gross power output	600 kWe
Thermal power output	4690 kW	Condenser power output	2350 kW
THERMAL ENERGY STORAGE		OVERALL CSP PLANT	
Storage volume (each tank)	330 m^3	ORC internal consumption	20 kW
Thermal oil mass	195 t	Solar field internal consumption	30 kW
Thermal storage capacity	14.6 MWh	Net power output	550 kW

Table 1 Main design parameters of the CSP plant

Receivers:-

Figure 7- New Solel UVAC HCE New HCE

• **Improved Reliability**
• Improved external bellows and glass-to-metal seal shielding
• Added internal ring for glass-to-metal seal protection
• Very low failure on latest generation (<<1%)
• **Improved Vacuum Lifetime**
• Increased amount of getters for absorbing hydrogen
• Improved getter mounting to keep getters cool to increase hydrogen absorption capacity
• **Improved Selective Coating**
• New cermet coating that does not include Molybdenum (eliminates Fluorescent tube problem).
• Higher absorption
• Lower emittance

New Schott PTR HCE:-

Figure 8- New Schott bellow design

- **Improved Reliability**
- Improved match between glass and metal coefficients of thermal expansion
- 100% testing of glass-to-metal seal
- No glass-to-metal seal failures in field testing to date
- **Improved Performance**
- New bellows configuration that compresses when tube is hot (~2% benefit)
- Improved getter mounting to keep getters cool to increase hydrogen absorption capacity
- More durable anti-reflective coating on glass
- **Selective Coating**
- Similar to Luz

PARAMETER AFTER CALCULATION

Table 2 Solar Radiation Data

Latitude	28.11 N
Longitude	73.14 E
Mirror reflectivity efficiency	0.88
Solar Multiple	SM=2
Stow angle & Deploy angle	10 ˚& 170˚
Freeze protection temperature of HTF	260 deg (Hitec solar salt)
Irradiation at design	900-1000 W/m2
Collector type	Solargenix SGX-1
No. of modules per assembly	12
Angle between reflected sun rays and the vertical direction	$\lambda s = 61.64^{\circ}$

HTF pump efficiency	**0.85**

Collector Design Parameter

Table 3 Collector Design parameters

Structure	**Recycled aluminium or steel struts and geo hubs**
Wind load design basis	**~33 m/s**
Aperture width	**5.77m**
Focal length	**- -**
Length per collector module	**12m**
Length per SCA	**100-150m**
Geometric Concentration	**82**
Reflector	**Glass mirror**
SCAs/loop	**4**
Control system	**Acciona**
Aperture Area	**470 m2/SCA**
Weight/m2	**~ 22 kg/m2**
Peak optical η	**~77 %**

III. MODELLING OF CSP PLANT

Solar position:-

The solar position is very important because the sun is changing every hour during a day and every day during the year, so it's necessary to model the solar coordinate systems (horizontal and equatorial) during the year through solar angles. The horizontal coordinates are the solar altitude angle (αs) and the azimuth (φ), the latter being consisted by the solar azimuth angle (φs) and the surface azimuth angle (φsurf), as shown in **Figure 9**. The equatorial coordinates are the declination (δs) and the hour angle (hs). [8-9]

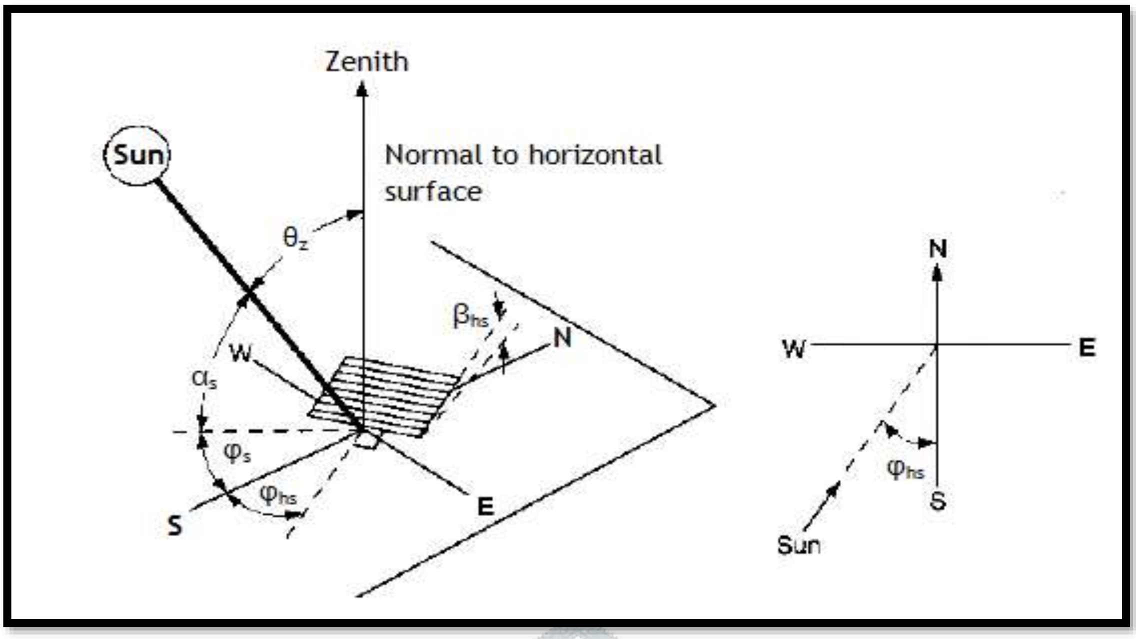

Figure9-Slope, surface azimuth angle, solar azimuth angle and zenith angle for a tilted parabolic surface

First of all, one has to calculate the solar declination (δs), the solar altitude angle (αs), the solar hour angle (hs), the solar azimuth angle (φs) and the solar zenith angle (θz), which their equations, are presented below.

The solar declination was calculated through the equation **(1)**,

$$\delta s = 23.45 * \sin[360 \div 365(284 + N)] \qquad (1)$$

Plotting the declination is obtained the solar declination angle over the year, as presented on **Figure 10**, which has its maximum value during the summer time and the lowest value on the winter time.

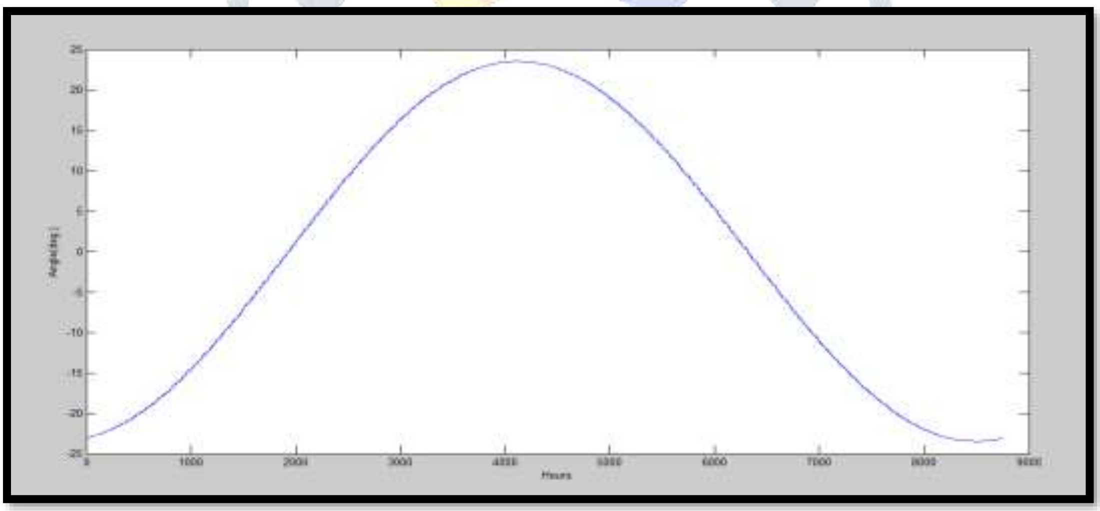

Figure 10-Solar declination angle for the year of 2015 and for the latitude and longitude proposed.

The solar hour angle (hs) is calculated using following equation **(2)**, where the solar hour, also known as solar time, is the apparent solar time of the day.

$$hs = (solar\ hour - 12) * 15° \qquad (2)$$

The solar altitude angle (αs) is computed with the next equation **(3)**

$$\alpha s = \sin^{-1}(\cosh hs * \cos\delta s * \cos\emptyset lat + \sin\delta s * \sin\emptyset lat \qquad (3)$$

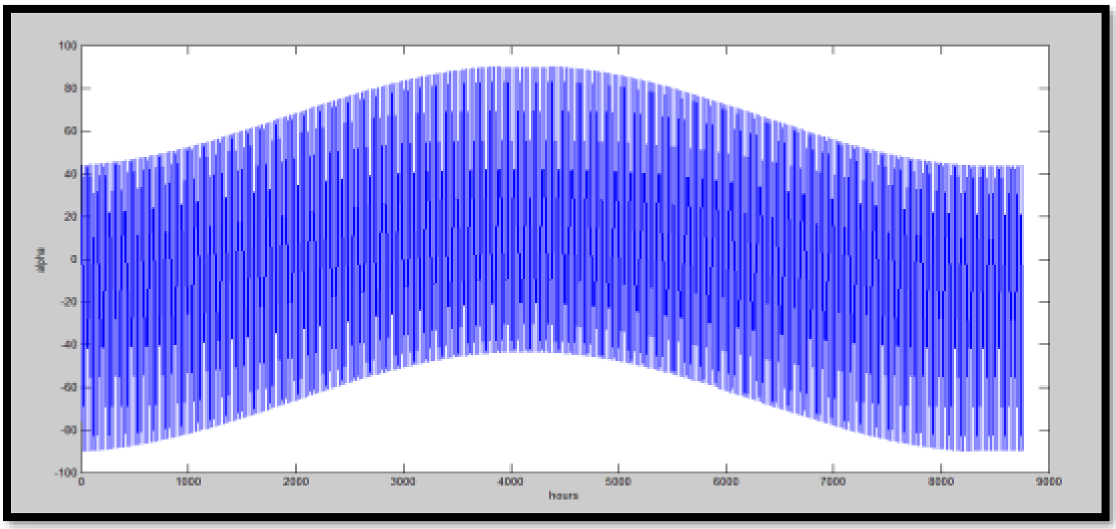

Figure 11-Plotting the solar altitude angle over the year

The solar zenith angle (θz) is obtained as a function of α subtracting 90º to this angle as presented in equation **(4)**:-

$$\theta z = 90° - \alpha s \quad (4)$$

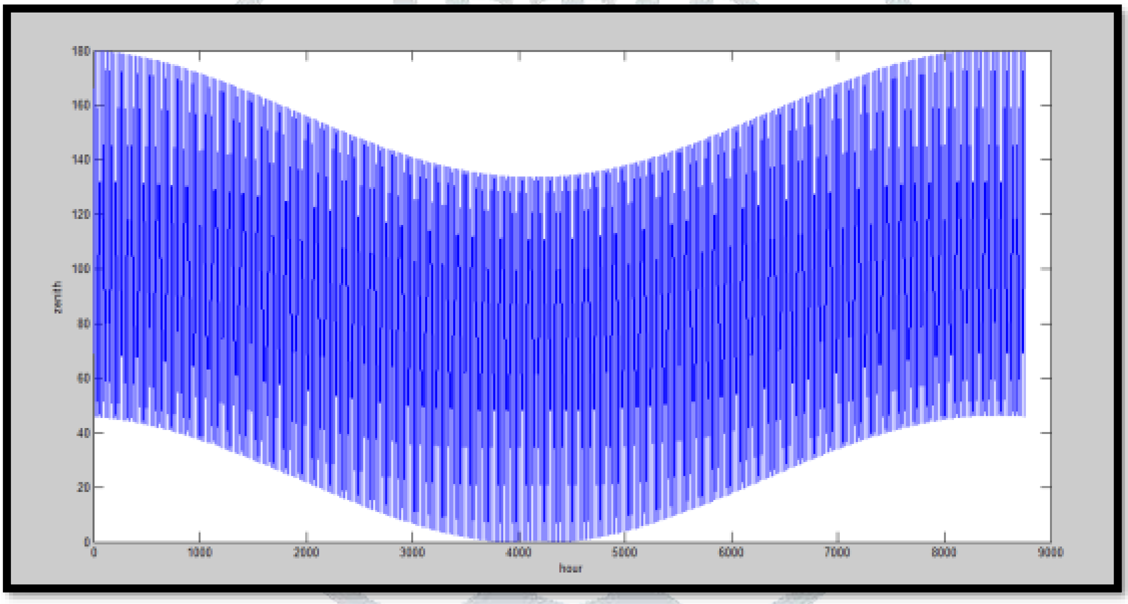

Figure 12-Plotting the solar zenith angle over the year

The solar azimuth angle (φs) was computed based in a literature work which considers a solar azimuth factor (φ') and the solar hour angle conditions, for getting such angle more accurately, as presented on the following equations **(5)**, **(6)** and **(7)**:-

$$\varphi' = \sin^{-1}(\cos \delta s * \sin hs \div \sin \theta z) \quad (5)$$

The solar hour angle conditions proposed are:-

$$If \cos hs \geq (\tan \delta s \div \tan \emptyset lat), then:$$

$$\varphi s = 180° - \varphi' \quad (6)$$

$$\text{If} \cos hs \leq (\tan \delta s \div \tan \emptyset lat), then:$$

$$\varphi s = 180° + \varphi' \quad (7)$$

The surface azimuth angle (φsurf) was obtained following the methodology proposed in the same work, which is conditioned by the positive or negative difference between the solar azimuth angle and the solar azimuth factor, as shown in equations **(8)** and **(9)**:-

$If\ \varphi s - \varphi' > 0$, then:-

$$\varphi surf = \varphi' + 90° \quad (8)$$

$If\ \varphi s - \varphi' < 0$, then:-

$$\varphi surf = \varphi' - 90° \quad (9)$$

The calculation of the previous angles is used for getting the solar incidence angle on each PTC (Parabolic Trough Collector) (θs), which depends also on the latitude (ϕlat), the solar declination (δs), the solar hour angle (hs) and the slope of each PTC along each hour of the day and each day of the year (βhs), as described in equation **(**10**)**.

$$\theta s = \cos^{-1}[(\sin \emptyset lat * \sin \delta s * \cos \beta hs) - (\cos \emptyset lat * \sin \delta s * \sin \beta hs * \cos \varphi surf) + (\cos \emptyset lat * \cos \delta s * \cos hs * \cos \beta hs) + (\sin \emptyset lat * \cos \delta s * \cos hs * \sin \beta hs * \cos \varphi surf) + (\cos \delta s * \sin hs * \sin \beta hs * \sin \varphi surf) \quad (10)$$

IV. SAM (SYSTEM ADVISOR MODEL) SOFTWARE RESULTS

The SAM model results of CSP plant is shown in fig below:

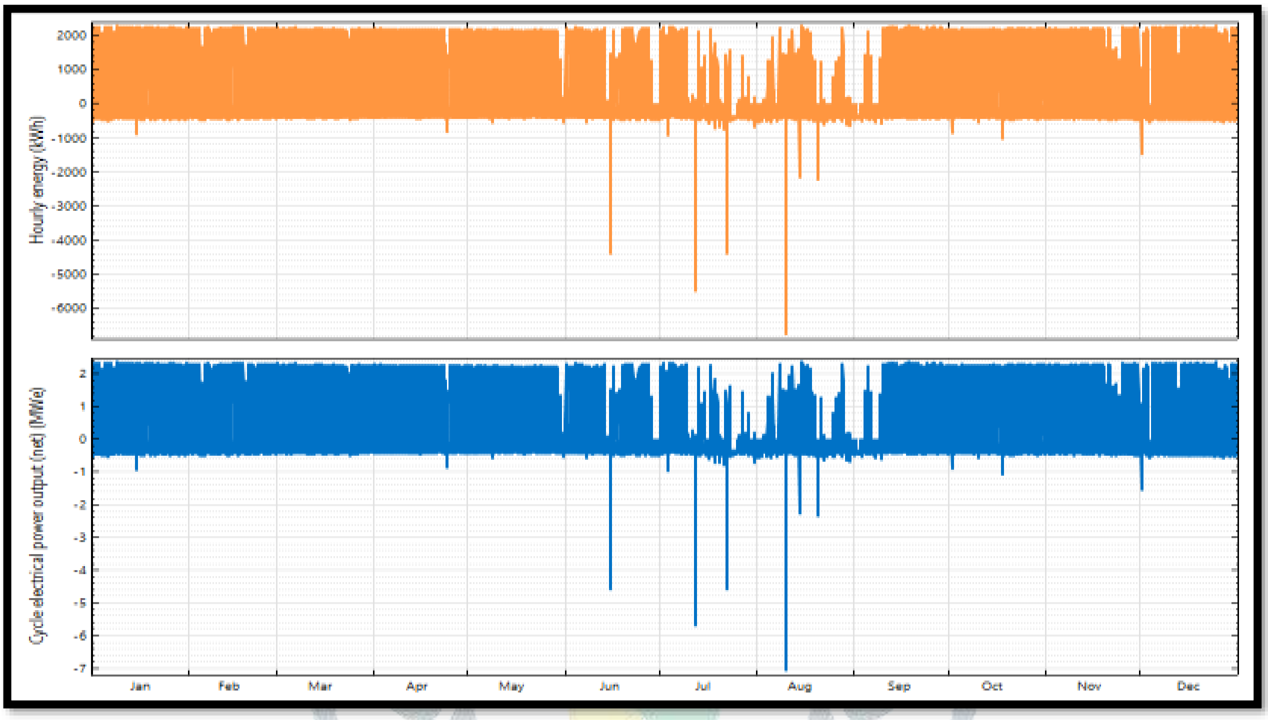

Fig. 13 Hourly energy and Inlet & cycle net electrical power

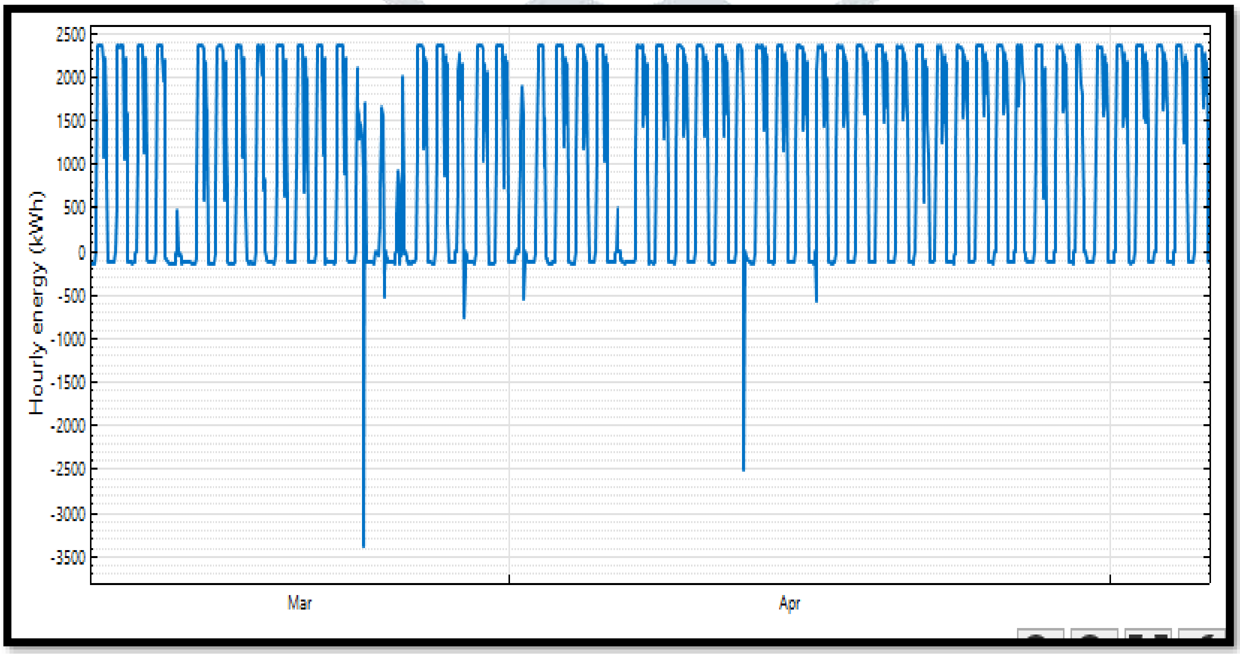

Fig. 14 Hourly Energy

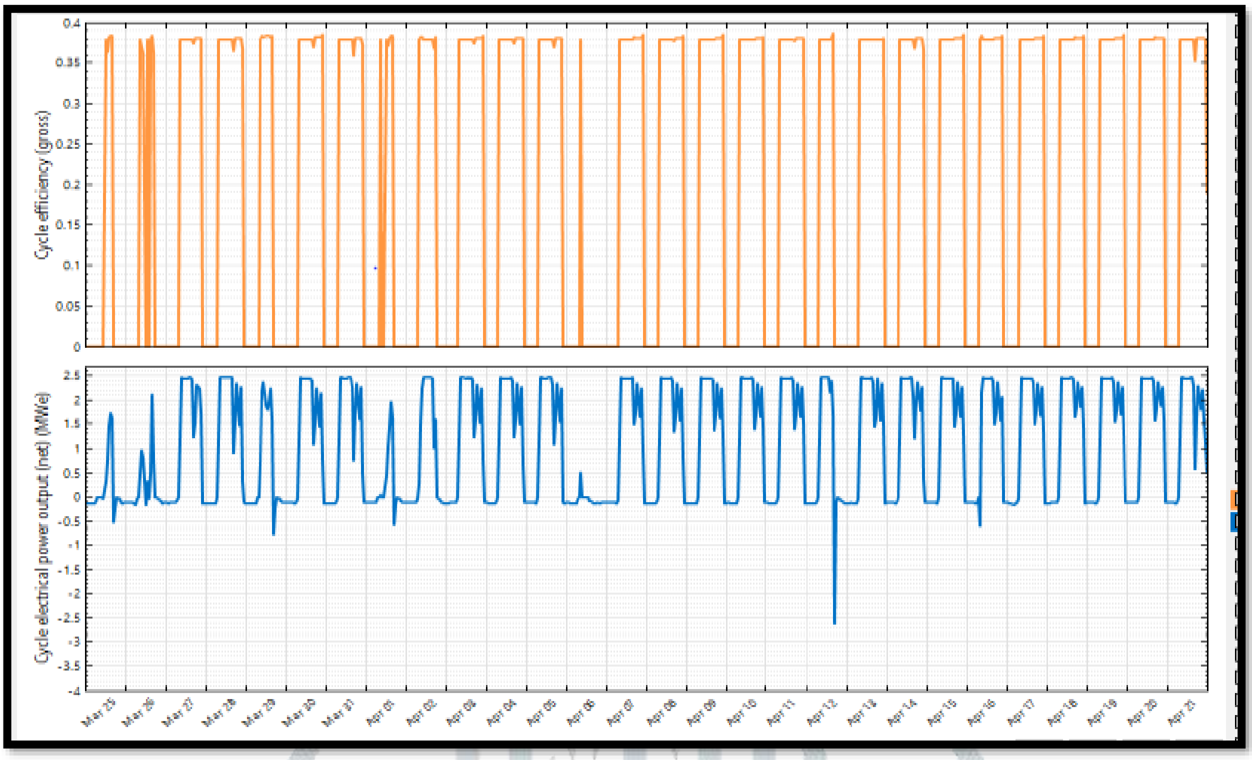

Fig. 15 Cycle Efficiency and Net Electrical power output

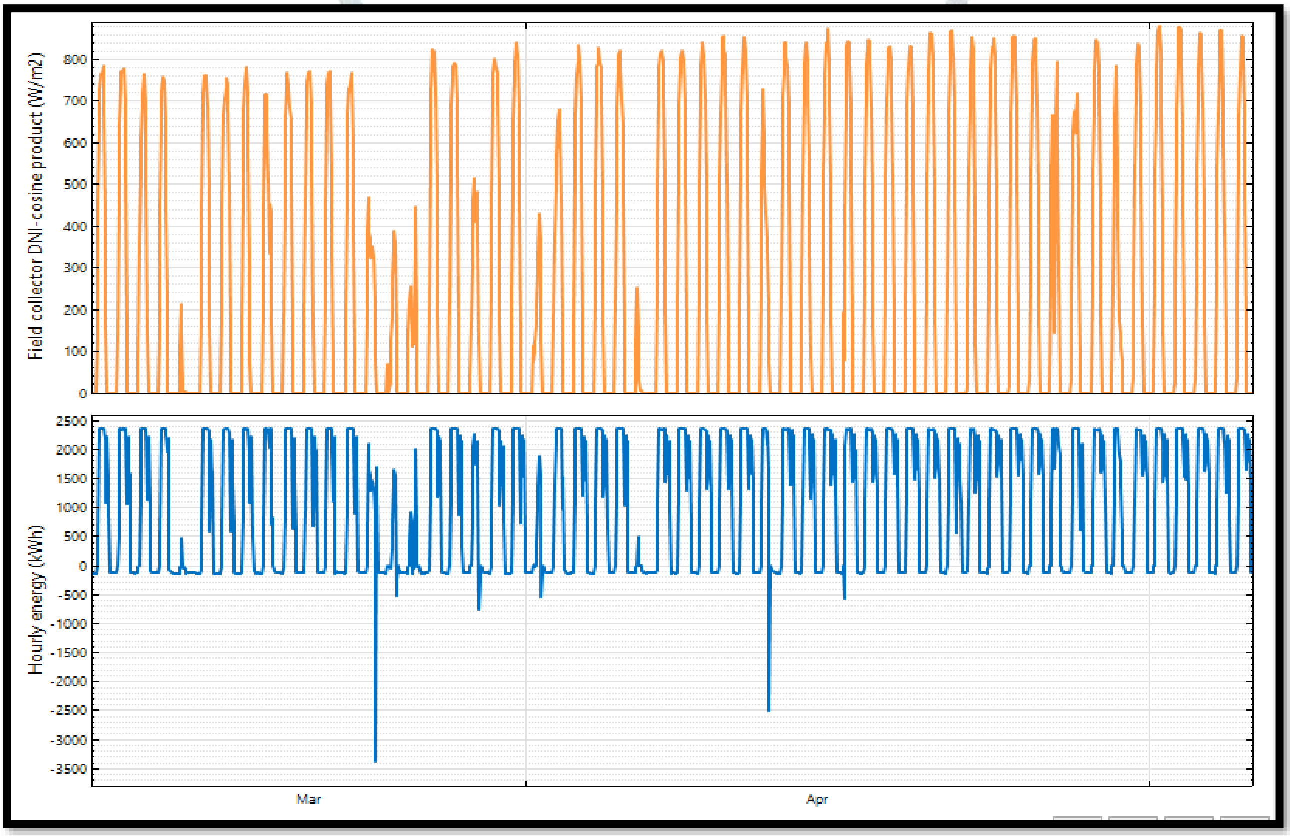

Fig 16 DNI and Hourly Energy

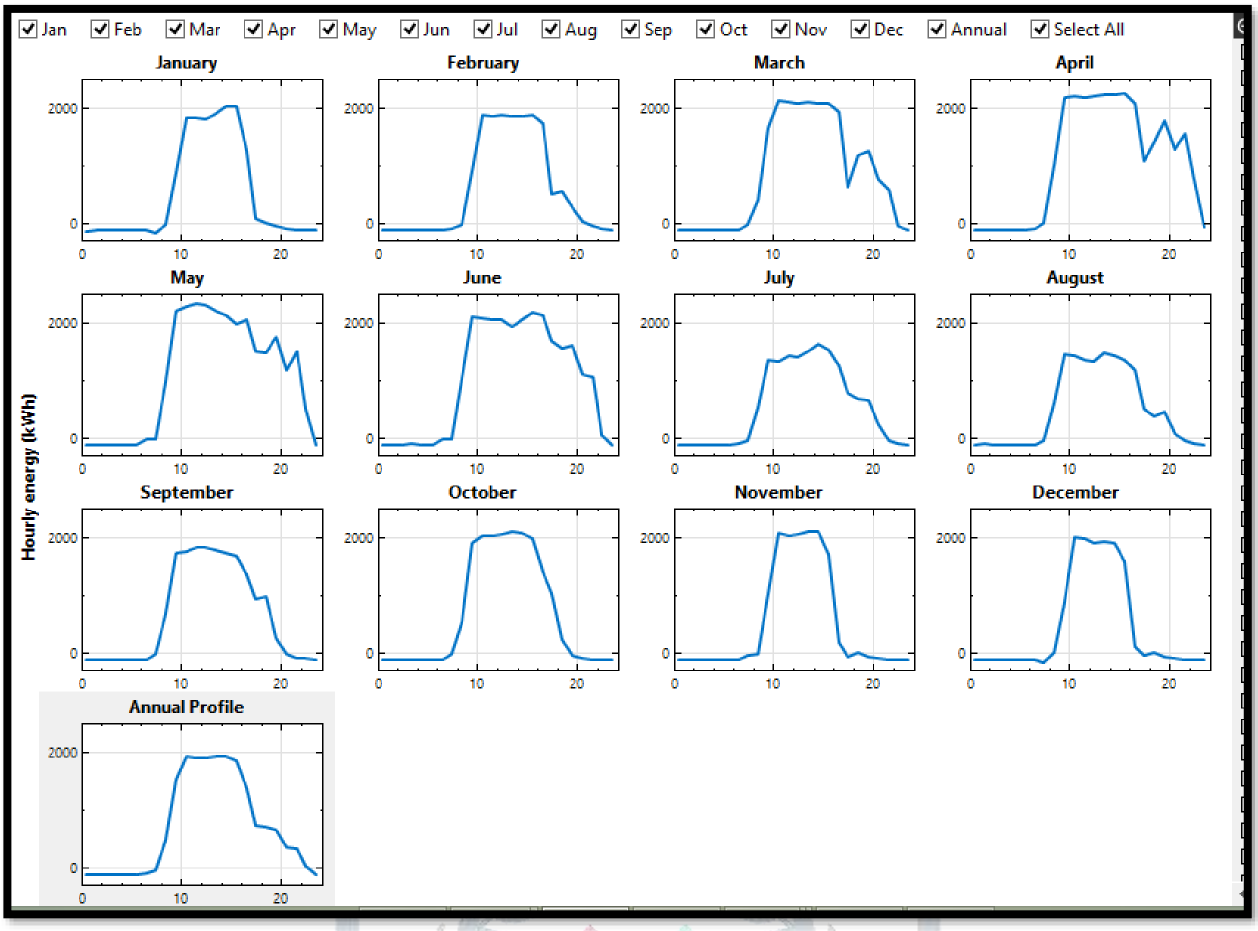

Fig. 17 every month energy

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