Modeling and Simulation of a 100 MW Concentrated Solar Thermal Power Plant Using Parabolic Trough Collectors in Pakistan

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Abstract. The increasing energy demands of the modern era has created a critical situation. The world is now moving towards renewable and sustainable methods of producing energy, among them the most abundant renewable energy resource is solar energy. As the lifetime and efficiency of Concentrated Solar Power (CSP) is more as compared to photovoltaic (PV) and considering the solar potential of Pakistan, the design of a 100 MW Concentrated Solar thermal power plant using Parabolic Trough Collectors and a 6-hour thermal energy storage is proposed. The CSP plant is modeled and simulated using System Advisor Model (SAM). Based on certain parameters, a location receiving an annual Direct normal irradiance (DNI) of 1955 KWh/m²/year near Nawabshah is selected for the hypothetical solar thermal power plant. The plant consists of 189 solar collector loops with 8 parabolic trough collectors in each loop and HITEC solar salt as HTF. The simulation results show that the plant can generate 245,688,560 kWh (245.68 GWh) of electricity annually with a capacity factor of 28.1% and 93.8% gross to net conversion. The results of PTC Power plant encourage further investigation and development of CSP technologies for electricity generation in Pakistan.

Keywords: Simulation, solar, power plant, collectors

1. Introduction
The modern developing world’s energy requirements are growing rapidly. The use of fossil fuels to overcome these requirements has created a critical situation because the fossil fuels are causing serious environmental problems and in addition, the resources are in limited supply. To overcome this problem the focus is shifted towards the use of new sustainable electricity generation options, which take advantage of renewable energies and are economical. Solar Energy is one of the most promising renewable energy technology that can reduce the fossil fuel consumption and CO₂ Emissions.

Concentrated solar power (CSP) is the most promising way to convert solar energy into electricity. In contrast, Photovoltaic (PV) technology is less efficient and has a shorter life. In CSP technology, the sun rays coming from the sun are reflected a receiver by using collectors (mirror), the receiver carries fluid that absorbs the heat. There are different methods to concentrate the solar radiation depending upon the applications and desired temperatures. Parabolic trough collectors (PTC) as compared to flat plate solar collector requires less surface area decreasing concerns for high thermal losses. PTC shows least development risks and is the best one to achieve high temperature with commercially suitability, as compared to other concentrating technologies like Fresnel collector, solar tower, and dish sterling.
Pakistan is undergoing an unprecedented energy crisis since long time back. The demand and supply shortfall is around 5000MW in the country and an electrification rate of 73% (90% in urban areas and 68% in rural areas) [1]. Electricity generation in Pakistan is dominated by fossil fuels. Pakistan has limited fossil fuel resources and needs to import to fill this gap. Due to this energy shortfall, urban areas are facing 10–12-hour load shedding while in rural areas electricity remains unavailable for 16-18 hours[2]. There is a 2,900,000 MW solar energy potential due to Pakistan’s geographical location with more than 300 sunshine days, 26-28°C average annual temperature and 1900-2200 kWh/m² annual global irradiance [3]. The country receives on average global insolation of 19 megajoules per square meter of solar energy daily. These figures are ideal for a Concentrated Solar Thermal Power Plant. As stated in the Green Peace International report, the desert areas of the country are among the most suitable locations for CSP plants[4]. Hence solar thermal power generation is one of the ways to solve the energy crises of the country without harming the environment as well.

2. Site Selection
The primary phase of CSP power plant is site selection. Many parameters are considered while fulfilling the requirements of a CSP site. These factors are essential for the plant to generate electricity economically and to make it work best.
2.1. Site Requirements
The essential requirements for a CSP site are availability of Direct Normal Irradiation (DNI) > 1800 kWh/m²/year (5.2 kWh/m²/day) [5]. One axis sun tracking mechanism to maximize the incident solar radiation. Flatland area with an overall slope of less than 1 - 3% [6]. Lands with higher slope reduce the efficiency of a CSP plant, due to the reason that slope tends to give rise to self-shadowing and shading cast by nearby collectors. This can reduce the significant amount of radiation intercepted by the collector [7]. The wind speed of the location should be less than 15.64 m/s [8], higher wind speed can cause structural damage to the collector assembly. Other than these requirements some other required factors are convenient grid connection, water resources, Good transportation facilities and Back up fuel.

2.2. Site assessment for Power plant in Pakistan
Most of the area of Pakistan receives an average DNI of 4.5 to 6 kWh/m²/day. Values of just over 6.4 kWh/m²/day are reached in the southwestern region of Balochistan decreasing gradually towards the northeast of the country to 4.0 kWh/m²/day [1]. Figure 1 shows the annual DNI map of Pakistan.

![Annual DNI Map of Pakistan](image1.png)

**Figure 2. Geospatial Toolkit Results**

The site selection is carried out by using Solar radiation maps of Pakistan, Geospatial Toolkit by NREL (National Renewable Energy Laboratory) and Google earth. Initially, the primary criteria are considered. Figure 2 shows the results of Geospatial toolkit with parameters adjusted as, minimum DNI of 5.2 kWh/m²/day, the maximum land slope of 3% and the land is selected as barren or sparsely vegetated. The shortlisted sites from these results are given in table 1.

| Balochistan | Punjab       | Sindh        |
|-------------|--------------|--------------|
| Quetta      | D.G.Khan     | Nawabshah    |
| Qila Abdullah | Raheem Yar Khan | Sanghar     |
| Panjgur     | Bahawalpur   | Khairpur     |

Table 1. Shortlisted Sites [9]

Considering the remaining requirements Nara desert, a location near district Nawabshah located at latitude 26.55 °N and longitude 69.25 °E with annual DNI of 1955 kWh/m²/year, is the most optimum site for the plant [9]. The details specifications of the site are given in table 2.
Table 2. Selected site specifications [9]

| Requirement               | Availability                                      |
|---------------------------|---------------------------------------------------|
| Water Resources           | Nara Canal (8 km) Chotiari Dam (37 km)             |
| Grid Connection           | 132 kV Sanghar (~50km)                            |
| Wind Speed                | 0 - 5.4 m/s                                       |
| Transportation            | Nawabshah Railway station (62 km), Sanghar road (12 km) |
| Backup Fuel (Natural Gas) | Sawan gas field (60.82 km), Kadanwari gas field (77.18 km) |

3. Modeling and Simulation

The parabolic trough power plant works on the Rankine cycle. The heat is absorbed by the heat transfer fluid and is then transferred to water to generate steam. The integration of thermal storage helps to provide electricity during the period when solar radiation is not available. Figure 3 shows the schematics of a Parabolic Trough Power plant.

3.1. Heat Transfer Fluid (HTF)

Synthetic oils and molten salts are the most commonly used HTF for CSP power plants. Among them, Therminol VP-1 and Hitec solar salt are suitable options due to their higher specific heats, good heat carrying capacity and high density. Hitec Solar salt can achieve the highest temperature as compared to others and has a higher specific energy over Therminol VP-1. A detailed comparison of HTF properties is given in table 3.

Table 3. HTF properties [10]

| Name                  | Type                        | Min Operating Temp °C | Max Operating Temp °C | Freeze Point °C |
|-----------------------|-----------------------------|-----------------------|-----------------------|-----------------|
| Hitec Solar Salt      | Nitrate Salt                | 238                   | 593                   | 238             |
| Caloria HT 43         | Mineral Hydrocarbon         | -12                   | 315                   | -12 (pour point) |
| Therminol VP-1        | Mixture of Biphenyl and Diphenyl Oxide | 12                   | 400                   | 12 (crystallization point) |

3.2. Mathematical Modeling

Duffie and Beckman[11] presented a model to express useful heat gain $Q_u$ for a single concentrated collector given as:

$$Q_u = F_R A_d \left[ \frac{S - A_e}{A_u U_L (T_1 - T_u)} \right]$$  \hspace{1cm} (1)
Where $F_R$ is collector heat removal factor, $A_s$ is aperture area of the concentrator, $A_r$ is receiver area, $S$ is absorbed solar radiation, $U_L$ is heat loss coefficient, $T_i$ is fluid inlet temperature, $T_a$ is ambient temperature and output temperature of a collector is given by:

$$T_o = T_i + \frac{Q_s}{mC_p}$$

(2)

$T_o$ is outlet temperature, $m$ is the mass flow rate of HTF and $C_p$ is the specific heat capacity of HTF.

$$\text{No of loops required} = \frac{P_{AB}}{\text{No. of collectors per loop}}$$

(3)

3.2.1. Solar Field and Solar Multiple. The first factor for CSP plant is a solar field, an area where solar collectors are to be installed. The field aperture area expressed as a multiple of the aperture area required to operate the power cycle at its design capacity and is known as Solar Multiple (SM)\[10\].

$$SM = \frac{\text{Power Cycle Capacity}}{\text{Solar solar field Capacity}}$$

(4)

3.2.2. Design thermal output of Solar Field. Thermal energy obtained from the solar field under design condition at a given solar multiple, and is expressed as:

$$Q_{sf,des} = SM \left( \frac{W_{pb,des}}{\eta_{des}} \right)$$

(5)

Where $Q_{sf,des}$ is solar field design heat output, $W_{pb,des}$ design work out from power block and $\eta_{des}$ is design efficiency.

3.3. Solar Radiation Data and System Advisor Model (SAM)

SAM is a financial and performance model developed by the National Renewable Energy Laboratory (NREL) with the grants funded by U.S. Department of Energy, for the field of renewable energy. For annual performance prediction and cost estimation, it uses hourly solar radiation data of a typical year obtained from the concerned location. SAM uses the SAM CSV format for solar resource data, and can also read data from files in the TMY3, TMY2, and EPW formats. SAM comes with built-in radiation data for many locations including India and Bangladesh\[10\]. Unfortunately, it doesn’t include data for locations in Pakistan, thus for this work, the hourly radiation data of a year of the hypothetical plant location has been obtained from NREL National Solar Radiation Database (NSRDB) and is then integrated to SAM.

3.4. Plant Specifications and Configurations

The input parameters used in SAM for the simulation of the hypothetical plant are given in table 4.
Table 4: Plant Specifications and Configurations

| Parameter                  | Value                  | Parameter                  | Value                  |
|----------------------------|------------------------|----------------------------|------------------------|
| **Solar Field Parameters** |                        | **Parameter**              | **Value**              |
| Solar Multiple             | 2                      | Actual No. of loops        | 189                    |
| Design Irradiation        | 887 W/m²               | Single loop Aperture       | 5248 m²                |
| Design ambient Temp        | 150 °C                 | Total Aperture Reflective Area | 991872 m²             |
| Design wind Velocity       | 5 m/s                  | Field Thermal output       | 623.596 MWt            |
| No. of field subsections   | 2                      | Water usage Per wash       | 0.7                    |
| Row Spacing                | 15 m                   | Washes per year            | 63 L/m², Aper          |
| Stow Angle                 | 170°                   | Number of Assemblies per loop | 8                     |
| Deploy Angle               | 10°                    |                             |                        |
| HTF Pump Efficiency        | 0.85                   | Design Gross Output        | 111                    |
| **Heat Transfer Fluid**    |                        | **Parameter**              | **Value**              |
| Design Loop Inlet Temp     | 293                    | Estimated Gross to Net Conversion | 0.9                  |
| Design loop outlet Temp    | 525                    | Estimated net output at Design | 100                |
| Min Single loop flow rate  | 1 kg/sec               | Rated Cycle Conversion Efficiency | 0.356               |
| Max Single Loop Flow rate  | 12 kg/sec              | Design Inlet Temperature   | 525 °C                 |
| Min field velocity         | 0.153546 m/s           | Design Outlet Temperature  | 293 °C                 |
| Max Field Velocity         | 1.99737 m/s            | Boiler Operating Pressure  | 100 Bar                |
| Header design Min field velocity | 2 m/s                 | Cooling Condenser Type     | Evaporative            |
| Header design Max field velocity | 3 m/s                 |                             |                        |
| **Receiver**               |                        | **Parameter**              | **Value**              |
| Solen UVAC 3               |                        | Boiler Operating Pressure  | 100 Bar                |
| Absorber Tube Inner Diameter | 0.066               | Storage Volume             | 10482.8 m³            |
| Absorber Tube Outer Diameter | 0.07                |                             |                        |
| Total Receiver Losses      | 215.5 W/m              | Balance of Plant Parasitic [5] | 0.02467 MWe/Mwcap   |
| **Total Land Area**        | 858 Acres              | Auxiliary heater, Boiler Parasitic [5] | 0.02273 MWe/Mwcap |
| **Power Cycle**            |                        |                             |                        |
| HTF Pump Efficiency        | 0.85                   | Design Gross Output        | 111                    |
| **Heat Transfer Fluid**    |                        | Estimated Gross to Net Conversion | 0.9                  |
| Design Loop Inlet Temp     | 293                    | Estimated net output at Design | 100                |
| Design loop outlet Temp    | 525                    | Rated Cycle Conversion Efficiency | 0.356               |
| Min Single loop flow rate  | 1 kg/sec               | Design Inlet Temperature   | 525 °C                 |
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| Header design Min field velocity | 2 m/s                 |                             |                        |
| Header design Max field velocity | 3 m/s                 |                             |                        |
| **Parasitic**              |                        |                             |                        |
| Absorber Tube Inner Diameter | 0.066               |                             |                        |
| Absorber Tube Outer Diameter | 0.07                |                             |                        |
| Total Receiver Losses      | 215.5 W/m              |                             |                        |
| **Total Land Area**        | 858 Acres              |                             |                        |

4. Results and Performance Assessment

The simulation of the plant is carried out for one year i.e. 0 to 8760 Hours. The plant starts to generate electricity around 8 A.M on average. The highest amount of energy is generated during the month of May (26129.1 MWh) and the minimum electricity is generated during the month of December (12112.8 MWh). Figure 4 shows the monthly variation of the generated electricity. Maximum cycle electrical power output and maximum field thermal power incident were recorded as 124.586 MWe and 749.855 MWt respectively. The total thermal output of the field is recorded as 745534 MWht. The hypothetical plant is estimated to generate (245.68 GWh) of electricity annually. The gross to net conversion is estimated to be 93.8%. Furthermore, the plant operates with a capacity factor of 28.1% which is a promising value compared to the previously available value of 20.5% using Therminol VP-1[9].

![Figure 4. Monthly Electricity Generation](image-url)
4.1. Performance Comparison
The results obtained for the CSP plant are compared to similar work available in literature and the comparison is given in table 5. For this comparison, it shows that the CSP power plant using Parabolic Trough collectors in Nawabshah is technically viable and has the feasibility to work in this environment.

| Author           | Plant Capacity (MW) | Annual Energy Generation (GWh) | Capacity Factor |
|------------------|---------------------|--------------------------------|-----------------|
| This Work        | 100                 | 245                            | 28.1 %          |
| Bishoyi[13]      | 100                 | 285                            | 32.6 %          |
| Mohamed et al.[14]| 100                 | 237                            | 21.1 %          |

5. Conclusion
Based on the criteria of CSP power plant a location within Pakistan is selected and simulation of a 100MW Power plant using Parabolic Trough Collectors is performed. The results obtained provide the necessary data for designing a CSP power plant in Pakistan. The thermal performance of the plant showed good results and this work can be utilized for further investigation of CSP technologies in Pakistani Climate. The research also showed that Hitec Solar salt can increase the performance of the CSP Plant. However, further research and investigations are required to analyze and improve parameters such as Loop Configuration and Thermal Capacity. This work only investigates the thermal performance of the plant, in addition to this, financial models are also needed to be developed to check the economic viability of the technology. This technology has more life and efficiency than PV plants and can be utilized as a solution to energy concerns of Pakistan.

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