Comparison for Performance of Concentrated Parabolic Trough Power Plant in Egypt & Spain

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Abstract— The aim of this thesis is technical and financial simulation for the parameters affecting the performance of solar power plant operated by using concentrated parabolic trough system, also comparison between concentrated solar power plant in Aswan in South of Egypt, with Palma del rio II solar power plant in Spain was chosen as reference and comparison with proposed solar plant in Aswan with capacity of 50 Mwe by using the same input parameters like solar field area, trough type, absorber tube type, the only change is the heat transfer fluid from Biphenyl/Diphenyl oxide to molten salt. This simulation is done by physical modeling by using some assumption and the physical inputs such as: average solar incident irradiation, incident angles, trough type, factors affecting on efficiency, power and hourly energy & thermal losses calculated by heat transfer and thermodynamics equations implemented in System Advisory Model (SAM) program using TRNSYS software tool, Also comparison of the levelized cost of energy (LCOE) in the two plants where it is the most affecting economic parameter related to solar multiple and different power capacity and into comparison of Palma solar plant.

Keywords— CSP, Concentrated Solar Power, Parabolic Trough, Aswan

I. INTRODUCTION

Due to the limited fossil fuel resources, and expected that their price continues to rise as it did since oil was exploited. On the other hand climate change obliges the humanity to act accordingly to choose clean, cheap and renewable energy where concentration of CO2 has been increased to about 390 ppm CO2 at the end of 2010, 39% above the pre-industrial level. This lends to an average global temperature increase of 0.76 °C. In order not to exceed a global temperature increase of 2°C with a probability of 67%, CO2 concentration has to be limited at 450 ppm by 2050. This means that only 750 billion tons of Green House Gases can be emitted until 2050.

Taking into consideration historical reasonability as well as their Economic strength, developed countries must reduce their emissions by about 80% to 95% by 2050. Countries in transition and developing countries have more time to reduce their emissions.

However, taking into consideration the growth of population and the ongoing development in countries of transition and developing countries, a significant increase in energy consumption along with GHG emissions will be noticed. In 2011 the global energy consumption was around 510 EJ/year (Exajoule, 10^18) compared to 340 EJ/year in 1990. In parallel to this trend, the yearly amount of GHG emissions is increasing, reaching 30 ton of gases (Gt CO2) in 2010. If this trend is ongoing the limit of 750 Gt of GHG emissions will be reached before 2035 and it would cause the 2°C goal to not be met. Nevertheless all societies require energy services to meet basic human needs like lighting, cooking, mobility, communication, and to serve productive processes, but GHG emissions associated with the provision of energy services can be seen as the major cause of climate change [1]. Consequently, other ways of energy production have to be found.

This study is focused on one of the most important sources of power generation, its solar energy where energy from the sun is considered the main source of all renewable and sustainable kind of energy more than wind energy which is fluctuating and low efficiency in summer days also nuclear energy that requires large numbers of reactors to produce the same capacity of solar power plant beside its restrictions and potential dangers. This study focused on performance concentrated parabolic trough power plant in Egypt especially in Aswan. The objective of this study is technically and financially simulation the parameters affecting the performance of solar power plant operated by using concentrated parabolic trough system, also comparison between concentrated solar power plant in Aswan in South of Egypt and Palma del rio II in Spain as a reference. Egypt is taken in this study as it is located in the Sunbelt area which means that Egypt is endowed with high intensity of direct solar radiation ranging between 2000-3200 kwh/m2/year and sunshine duration that ranges from 9-11 hours with mostly clear days. Egypt’s primary locations are able to offer 500 more hours of solar operation each year compared to Spain and Greece, the most favorable European locations.
Especially the Upper Egypt region shows great potential for solar energy development, so Aswan in Egypt is chosen in this simulation. Other geographic parameters are taken into consideration like location, topography and climate, average level of solar radiation giving significant potential for utilizing this form of renewable energy: simple concentrated parabolic trough power plant was installed in Almaadi, Egypt in 1913 with capacity of 100 hp to generate electricity for irrigation pumps in cotton fields, now as this trend comes to high capacities and used as 24 hrs to generate electricity.

Egypt target share of 30% in year 2020 as it has now already 16% from hydro energy. Following this logic RE share in Egypt shall increase to about 55% in year 2050 with a yearly average growth of about 6%[15].Egypt is expected to increase its installed energy from now 17 GW to 50 GW in 2020 and with a smaller increase rate to 120 GW in year 2050. [3]

The study takes many steps in order to make the proposed comparison. In section 2, the calculation of sun position and average annual solar insolation are described as the input parameters to the CSP. Major aspects related to efficiency calculations are described as well. In section 3, solar insolation and solar power are calculated in the two cases. Efficiencies and output power, Thermal losses & hourly energy in the two locations are calculated by system advisory model and compared. In section 4, verification is investigated and the model analysis is conducted according to the new configuration. The life cycle cost and levelized cost is estimated. Results are compared and conclusions are drawn.

II. MODEL ANALYSIS DESCRIPTION

A set of different equations is needed to calculate the direct solar irradiation onto a surface, in this case a solar collector assembly, for a specific date, time and location on earth. The term solar time is used when calculating the angles that are needed to determine how much direct radiation will fall on a collector, and differs from the local time on earth.

The difference in minutes can be expressed as follows [8]:

\[
\text{Solttime-localtime} = 4(L_{\text{st}}-L_{\text{loc}})+E \tag{1}
\]

Where \(L_{\text{st}}\) is the standard meridian for the local time zone, \(L_{\text{loc}}\) is the longitude of the location in degrees west and \(E\) is the equation of time.

Equation of time is expressed as:

\[
E=229.2(0.00075+0.001868\cos B-0.032077\sin B) -0.0141615\cos 2B -0.04089\sin 2B \tag{2}
\]

Where:

\[
B=(n-1)360/365 \tag{3}
\]

& \(n=\text{day of year}\) [8].

The angle of incidence of direct solar radiation onto a north to south axis tracking collector can be calculated as follows [8]:

\[
\cos \theta=(\cos \theta_2^2+\sin \omega.\cos \theta^2)^{0.5} \tag{4}
\]

Where: \(\delta\) is the declination, the angular position of the sun at solar noon [8].

\[
\delta=23.45(\sin(360(284+n)/365)) \tag{5}
\]

\(\omega=\text{hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 per hour [14]}

\[
\omega=(t_{\text{sol}}-2)15 \tag{6}
\]

\(\theta_2\) is the zenith angle, the angle of incidence of beam radiation on a horizontal surface [8]

\[
\cos \theta_2=\cos(\delta)\cos(\phi)\cos(\omega)\sin(\delta)\sin(\phi) \tag{7}
\]

Where: \(\phi\) is the latitude.

Parabolic trough shaped mirror are simply used to concentrate sunlight on to thermally efficient receiver tube placed in trough focal line. As shown in Figure 1. In these tubes a heat transfer fluid is circulated. Heated by the concentrated sun rays, this HTF is then pumped through a series of heat exchangers to produce superheated steam. The steam is converted to electrical energy in a conventional steam turbine generator working on ideal Rankine cycle, which can either be part of a conventional steam cycle or integrated into a combined steam and gas turbine cycle.

Figure 1. Parabolic trough concentrator power plant.
This model is simplified where collector tilt angle and azimuth solar angle are assumed to be zero. The incidence angle $\theta$ is the angular difference between the normal to the aperture and the actual solar irradiation that can be seen in Figure 2.

$$\text{End loss} = 1 - (f \cdot \tan \theta / L_{SCA}) \tag{9}$$

Where:

- $f = $ focal length of the collectors (depend on collector type)
- $\theta = $ incident angle

Where shadowing between rows generally occurs at extreme solar positions (i.e. dusk or dawn) when the shadow cast by a collector closer to the sun obscures a portion of an adjacent collector and given by:

$$\text{Row shadow} = W_{\text{eff}} / W = L_{\text{spacing}} \cdot \cos(\theta) / W \cdot \cos(\theta) \tag{10}$$

Thus, collector tilt angle and arc can be determined by inserting weather data, with clear sky conditions, is done in the next problem. The incidence angle modifier (IAM) corrects for these additional reflection and absorption losses. The incidence angle modifier is given as an empirical fit to experimental data for a given collector type given by:

$$\text{IAM} = \frac{K}{\cos \theta} \tag{11}$$

This is different in value according to collector type.

The trough collector model captures optical efficiency with losses that area function of solar position and with fixed losses that are applied as constant multipliers. Fixed losses include tracking error, geometry defects, mirror soiling, mirror soiling, and general error not captured by the other items are given in the following table.

<table>
<thead>
<tr>
<th>Error description</th>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking error</td>
<td>$\eta_{\text{track}}$</td>
<td>(0.99)</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{track}}$</td>
<td>Inability of the collector to perfectly orient along the tracking angle; twisting of the collector about the lengthwise axis.</td>
</tr>
<tr>
<td>Geometry defects</td>
<td>$\eta_{\text{geo}}$</td>
<td>(0.98)</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{geo}}$</td>
<td>Poor alignment of the mirror modules; deviation in the position of the receiver tube from the optical focus; warping or discontinuities along the reflective surface.</td>
</tr>
<tr>
<td>Mirror reflectance</td>
<td>$\rho_m$</td>
<td>(0.935)</td>
</tr>
<tr>
<td></td>
<td>$\rho_m$</td>
<td>Specular reflectance within a cone angle defined by the collector and receiver geometry.</td>
</tr>
<tr>
<td>Mirror soiling</td>
<td>$\eta_{\text{soil}}$</td>
<td>(0.95)</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{soil}}$</td>
<td>Dirt or soiling on the reflective surface that prevents irradiation from reflecting to the receiver.</td>
</tr>
<tr>
<td>General error</td>
<td>$\eta_{\text{gen}}$</td>
<td>(0.99)</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{gen}}$</td>
<td>Any effect not captured within the previous categories.</td>
</tr>
</tbody>
</table>

The solar insolation is used as thermal input parameter to CSP in order to calculate the output power. The calculation of the total annual insolation, based on the hourly performance, with clear sky conditions, is done according to solar power prospectors supported by NREL. The key instruments for measuring solar radiation are EKO Instruments unique Solar Monitoring Station (SMS) or pyranometers and pyrheliometers. In general they are used to measure: Global, Diffuse and Direct radiation. The pyrheliometer (with a sun tracker) is used to measure direct radiation as used in Solar Thermal power plants. Clear sky beam and diffuse radiation are given by (Hottel, 22) or by BIRD model, also can be developed by insert weather data file to system advisory model to simulate solar radiation over the year hours or month.
The BIRD model mathematical equation (21) is:

\[ I_d = I_o (\cos \theta_z)(0.9662)T_R T_{UM} T_w T_A \] (12)
\[ I_s = I_o (\cos \theta_z)(0.79)T_s T_{UM} T_{AA}(0.5 (1-T_R)) + B_s(1-T_{AS})/|1 - M + (M)1.02 \] (13)
\[ I_f = (I_d + I_s)/(1 - r_g r_s) \] (14)

Where:

- \( B_s \): Ratio of the forward-scattered irradiance to the total scattered irradiance due to aerosols
- \( I_o \): Solar irradiance on a horizontal surface from atmospheric scattering (W/m²)
- \( I_d \): Direct solar irradiance on a horizontal surface (W/m²)
- \( I_s \): Extraterrestrial solar irradiance (1353 W/m²)
- \( I_f \): Total global solar irradiance on a horizontal surface (W/m²)
- \( M \): Air mass
- \( r_g \): Ground albedo
- \( r_s \): Sky, or atmospheric albedo
- \( S \): slant distance from solar field to receiver (kilometer)
- \( T_A \): Transmittance of aerosol absorptance and scattering
- \( T_{AA} \): Transmittance of aerosol absorptance
- \( T_{AS} \): Transmittance of dry air absorptance and scattering per Watt
- \( T_R \): Transmittance of ozone absorptance
- \( T_{UM} \): Transmittance of Rayleigh scattering
- \( T_w \): Transmittance of water vapor absorptance
- \( \theta_z \): Zenith angle

These equations included weather data file of specific location and simulated by system advisory model based on time series hourly or monthly. Also solar radiation can be measured experimentally in site or calculated by Hotell model [22,23]

\[ I_b = I_{b,0} \times \frac{r_g \times \cos \theta_z}{\cos \theta_z} \] (15)
\[ I_d = I_{d,0} \times \frac{r_d \times \cos \theta_z}{\cos \theta_z} \] (16)
\[ \tau_b = a_o \times b_o \times \exp(-K_s / \cos \theta_z) \] (17)
\[ \tau_d = 0.27a_o \times 0.2939 \times r_b \] (18)
\[ a_o = a_o^* \times r_o \] (19)
\[ a_1 = a_1^* \times r_1 \] (20)
\[ K_s = k_s \times r_s \] (21)

& to calculate constants for different altitudes, correction factors are used:

\[ a_o = 0.4237-0.00821(6-A)^2 \] (22)
\[ a_1 = 0.5055-0.00595(6.5-A)^2 \] (23)
\[ K_s = 0.2711-0.01858(2.5-A)^2 \] (24)

Where: \( A \) is altitude (m)
Correction factors as in the following table:

<table>
<thead>
<tr>
<th>Climate type</th>
<th>( r_0 )</th>
<th>( r_1 )</th>
<th>( r_{Ks} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>0.95</td>
<td>0.98</td>
<td>1.02</td>
</tr>
<tr>
<td>Mid latitude Summer</td>
<td>0.97</td>
<td>0.99</td>
<td>1.02</td>
</tr>
<tr>
<td>Subarctic Summer</td>
<td>0.99</td>
<td>0.99</td>
<td>1.01</td>
</tr>
<tr>
<td>Mid latitude Winter</td>
<td>1.03</td>
<td>1.01</td>
<td>1.00</td>
</tr>
</tbody>
</table>

III. OUTPUT POWER OF CSP

The amount of heat absorbed by the HTF in the receiver model considers the amount lost due to radiation and convection to the surroundings. The radiation and convection losses, either natural in case in no wind or forced in case of wind, are heat transferred from the outer glass envelope of the receiver.

\[ Q_{abs,env,i} = DNI \times \cos \theta \times \eta_{opt,i} \times \eta_{env} \times \eta_{abs} \] (25)

Absorbed energy by receiver:

\[ q_{abs,i} = q_{abs,env,i} \eta_{opt,i} \eta_{env} \] (26)

Absorbed energy by glass envelope:

\[ q_{abs,env,i} = q_{inc,i} \eta_{opt,i} \eta_{env} \] (27)

Where: \( q_{inc,i} \) is DNI. \( \alpha_{env} = 0.02 \) for glass envelope & absorptance of absorber is different according to selective coating of receiver tube from 0.92 to 0.97.

The total global solar irradiance on a horizontal surface \( IT (W/m^2) \) is calculated for the latitude of CSP in town of Palma in Spain \((39.55^\circ \) North Latitude and \(2.73^\circ \) East longitude). The same procedure is conducted for the Aswan city \((23.97^\circ \) North Latitude and \(32.78^\circ \) West longitude). (20) The results of global radiation incident upon a horizontal surface \((W/m^2)\) for the two locations are shown in figure 2.
Figure 3. Total solar irradiation for monthly maximum average for Palma del rio in Spain & Aswan in Egypt.

Figure 4. Optical efficiency for Palma in Spain & Aswan in Egypt.

Figure 5. DNI Cosine Product for Palma in Spain & Aswan in Egypt.

Figure 6. Hourly energy produced per month for plant of 50 Mwe in Palma, Spain & Aswan, Egypt.

Figure 7. Thermal power absorbed & dumped, Mwth for Palma, Spain & Aswan, Egypt.

Figure 8. Power into storage and power to cycle, Mwth for plant of 50 Mwe in Spain & Egypt.
Figure 9. Monthly net electric power for plant of 50 Mwe in Spain & Egypt.

Figure 10. Heat losses from storage tanks for plant of 50 Mwe in Spain & Egypt.

IV. VERIFICATION OF THE MODEL

To verify the system performance a comparison with the Palma del rio2 parabolic trough power plant is carried out with the same design parameters provided by the plant operator of solar field area 372,240 m² and collector type is SGNX-1, the only difference is using molten salt as heat transfer fluid in Aswan plant proposal. The goal is to match efficiencies from different parts of the system with them from the Palma power plant. The performance numbers given by Palma del rio are based on an average typical weather year. To match the incoming solar irradiation a median value of the yearly incoming solar irradiation for a typical meteorological year were used as input to the system model and the specific simulation day was set to day no. 197 (15th of July) as design day and the time from 4 AM till the end of day with thermal storage for 7.5 hrs as usual to be used at night operations. This represents a median value of the solar position. [20]

From these figures, total solar incident radiation is higher in Aswan than Palma plant in Spain, also optical efficiency is higher which means less end loss and shadow loss and incident angle modifier reaches to be one or less amount of scattered radiation due to cosine effect. But dumped power or wasted power by defocusing is higher in Aswan than of Spain due to large amount of solar incident radiation that increase defocusing in some sunny hours.

For simulation of hourly energy profile in the typical clear summer day, day no. 197. The incoming solar irradiation during the simulation is shown in Figure 1 & 3. The sudden drop in incoming solar irradiation is supposed to mimic a big cloud moving over the solar power plant which is clear in Spain. At first the system behaves as in the clear summer day case but when the sun is blocked by the cloud the thermal storage starts to discharge heat and the power plant can continue deliver power to the grid. For hourly profile, energy will be minimum as zero value from 6 pm till the end of day which means during night, and this require operation through hot storage tank loop while in Palma, it require more energy to back up the negative impact of hourly energy and this can be declared in figure 9 where thermal losses from storage tanks is higher in Spain than of Aswan.

V. CONCLUSIONS

According to the previous analysis, the following conclusions could be drawn:

1. The CSP power plant in Palma del rio - Spain is used as a demonstrative model in order to estimate the relative advantage of installing such kind of power plant in Aswan.

2. The calculated total direct solar insolation in Aswan is higher than in Palma del rio by 25% & by 67% for direct normal irradiation related to cosine effect or incident angle for maximum average daily values per month.

3. The optical efficiency of CSP power plant is higher than in Aswan by 1.125%, while the net output power in Aswan is 68 % higher than of Spain.

4. Finally, the feasibility study by system advisory model shows that the levelized cost of energy of the simulated plant in Aswan of 50 Mwₑ is 20.21 €/kwh and in Palma, Spain is 39.14 €/kwh which means cost of energy produced in Aswan is lower by 93.6 % than the CSP in Spain, Also the annual energy of CSP in Aswan is higher by 96 % than of Spain.
REFERENCES


