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Assessment of a Solar Parabolic Trough Power Plant with Grid Integration in Egypt

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Abstract

Concentrating Solar Power (CSP) is a promising technology for generating efficient renewable solar energy in countries with high Direct Normal Irradiance (DNI). Egypt as one of those countries could harness the sun's energy for the generation of power, which could have an appreciable impact on the future Egypt's energy plan. Nevertheless, the current and planned CSP projects do not match with the Egyptian solar energy potential. In reviewing the literature, many studies have been conducted on the application of CSP technology in the Middle East but usually for the technical and economic aspects. In contrast, there are few studies that extend to the next step of grid integration and the associated load flow studies. Accordingly, this study examined both the technological and economic aspects for a potential 100 MW CSP plant in Egypt in addition to investigating the grid integration performance by conducting a load flow analysis.

1. Introduction

CSP technology has the potential to be built on a larger scale in the future, and many countries have adopted this type of plant for generating energy, especially countries with high DNI that are suitable for this kind of installation. Spain, for instance, has total of 50 projects installed and under construction; also, the USA has 24 projects both installed and planned. China also has large advances in a short time with total of 23 installed and planned projects (NREL n.d.).

Ironically, the first parabolic trough systems were installed in Egypt in 1912 to provide power for an irrigation system, the capacity of this facility was 500 kW (Al-soud and Hrayshat 2009). Yet it was not until 2011 at the Kuraymat ISCC Plant, with parabolic trough concentrators and an overall capacity of 140 MW (120 MW combined cycle and 20 MW depending on solar energy), that Egypt began to again harness CSP technology.

That said, in recent times there have been a number of studies conducted in the Middle East regarding CSP technologies in general inluding detailed analysis of both the technological and economic aspects of a specific technology or a specific site. Mihoub et al. (2016) proposed a methodology for determining the best set of parameters that will ensure the optimum design of future CSP plants with minimum levelised cost of energy (LCOE) and maximal yearly power generation. The term LCOE measures the lifetime costs divided by the energy produced by a system, i.e. the total cost of installing and operating a project expressed in dollars per kilowatt hour (kWh) of electricity generated by the system over its life (Short et al. 1995). Another study was conducted by Abbas et al. (2013) in which they discussed the potential for installing a parabolic trough plant of 100 MW at four sites with different climates. The study confirmed the idea that the arid regions are the most suitable for installing CSP plants with highest level of annual generated power and lowest cost, while Mediterranean climate regions are the least suitable for CSP technology.

In Egypt, Shouman and Khattab (2015) presented a road map strategy for introducing CSP into the Egyptian market after investigating the main barriers to financing such a project. In addition, the study included the peak load and medium load segment of the power supply in Egypt. Furthermore, the study focused on analysing several data sources to compare CSP technologies and LCOE with conventional sources of electricity. The study included the calculation of the cost of generating power from conventional sources and its development in the future, followed by the determination of the cost of CSP with its development in the future based on the economies of scale after its expected expansion. The results showed that Egypt's CSP potential exceeds 73 000 TWh/year which is one of the highest in the region. These findings confirmed that Egypt is one of the most suitable countries for this technology.

However, these previous studies only considered the technical or economic sides of CSP technology. There are not many studies on CSP when connected to the grid, with the study conducted by Patel et al. (Patel et al. 2015), that included both modelling and simulation of CSP plants with grid integration being a notable exception. Hence, the aim of this study was to examine the technical and economic aspects of a potential 100 MW CSP plant in Egypt in addition to investigating the grid integration performance.

2. CSP Model Design in SAM and Simulation

2.1. Site Identification

Prior to undertaking any analysis of a CSP plant in Egypt it was necessary to identify an appropriate site. As CSP technology relies on DNI, this is the first factor that affects the siting selection process. However, in reality a CSP plant cannot be installed in middle of the desert where there is no supporting infrastructure. Consequently, other factors should be considered, for instance, infrastructure including road networks and electrical grid. As a result, an initial site assessment was performed considering: irradiation data, land resource and investigating the land availability and topography and other factors that are related to geographical features of the selected areas and infrastructure for the national grid and proximity to transmission lines or substations, water resources and access roads. This preliminary evaluation identified several sites, which was then refined using a multi-criteria quantitative design matrix process to deliver three potential sites (28.06 N, 33.25 E; 27.27 N, 33.66 E and 29.61 N, 32.75 E)

Having identified these potential locations for the proposed CSP plant, it was decided to use the System Advisor Model (SAM) to simulate the performance of the CSP plant at the selected locations. For designing the simulation model, some parameters need to be set according to technical details related to the technology used. Consequently, the CSP parabolic trough (physical model) was selected as a performance model while LCOE was selected as a financial model.

2.2. Design Parameters in SAM

After selecting the performance model to be employed in the simulation process, the technical parameters for the system itself need to be set accordingly, starting from location and resource to power cycle and thermal storage. The proposed CSP plant size was 100 MW with 8 h full load hours' thermal storage. It had a solar multiple of 2.5 and solar field area of 2.87 km^2 and total land area of 4 km^2. In addition, LUZ LS-3 collectors and Siemens UVAC 2010 receivers were selected in SAM model. While Therminol VP-1 was selected as the heat transfer fluid and also used as a thermal storage medium. Table 1 shows the technical parameters that were used in SAM.

Table 1. The technical parameters used in SAM.

Technical parameters	Value
Solar multiple (actual)	2.5
Solar field area (km²)	2.877
Field aperture (km²)	1.1
Total land area (km²)	4
Row spacing (m)	15
Field subsection	6
Number of loops	253
Collector	Luz LS-3
Receiver	Siemens UVAC 2010
HTF	Therminol VP-1
Thermal storage (TES)	Therminol VP-1
Full load hours of TES	8

2.3. Financial Parameters in SAM

After finalising the technical parameters, the second part of this simulation study involved setting the values of the financial parameters. These values need to be set according to the current status of the Egyptian energy market. For instance, an average value of the inflation rate over the past 25 years was assumed representative of inflation over the term of this analysis. Additional parameters were based on a study conducted by Hussein et al. (2015) that discussed the current and the possible future costs for renewable energy technologies in the Egyptian energy market, which included a parabolic trough power plant of 100 MW with and without thermal storage. The values from Hussein et al.' study for the parabolic trough plant with 8 hours' thermal storage, as shown in Table 2, were used in this research to provide a realistic benchmark.

Moreover, in performing the financial analysis, SAM calculates the LCOE by using the fixed charge rate method. The LCOE can be calculated through equation (1) (Short et al. 1995):

$$\boldsymbol{LCOE = \frac{FCR \times CC}{Q} + \frac{FOC}{Q} + VOC} \quad \textbf{(1)}$$

where CC is the capital cost, FOC is the fixed operating cost, VOC is the variable operating cost, and Q is the annual energy generated by the plant.

Table 2. The financial parameters used in SAM

Financial parameters	Value
Capital cost ($/kW)	5225
Fixed operating cost (annual) ($/kW)	22
Variable Operating cost ($/kWh)	0.02
Analysis period (years)	25
Inflation rate (%)	8.6
Internal rate of return (nominal) (%)	18
Project term debt (%)	70
Nominal debt interest rate (%)	9.5
Effective tax rate (%)	22.5
Depreciation schedule (%)	4
Nominal construction interest rate (%)	9

3. SAM Results and Discussion

In examining the results of the SAM study, the effect of the thermal storage can be seen in Figure 1. In this, the energy output is shifted from daytime to the evening hours as the peak load pattern for Egypt was followed. In saying this, the annual thermal energy delivered to the power block and the annual thermal energy generated by the field for the three sites had the same order of value of generated energy. The largest annual generation of thermal energy was the first site (28.06 N, 33.25 E), delivering around 1400 GWh. As for the monthly electrical energy output from the three sites, shown in

Figure **2**, in the summer months the values are nearly equal, and during winter the energy produced in each month in both sites (1) and (2) are quite close, whereas the third site had a noticeably lower output.

The SAM analysis showed that the first selected site (28.06 N, 33.25 E) had the lowest LCOE at 10.07 US₵/kWh and it had the highest value of produced annual energy at 464.68 GWh and had the highest capacity factor at 53.1%. At the second selected site (27.27 N, 33.66 E), the LCOE was slightly higher at 10.4 US ₵/kWh.

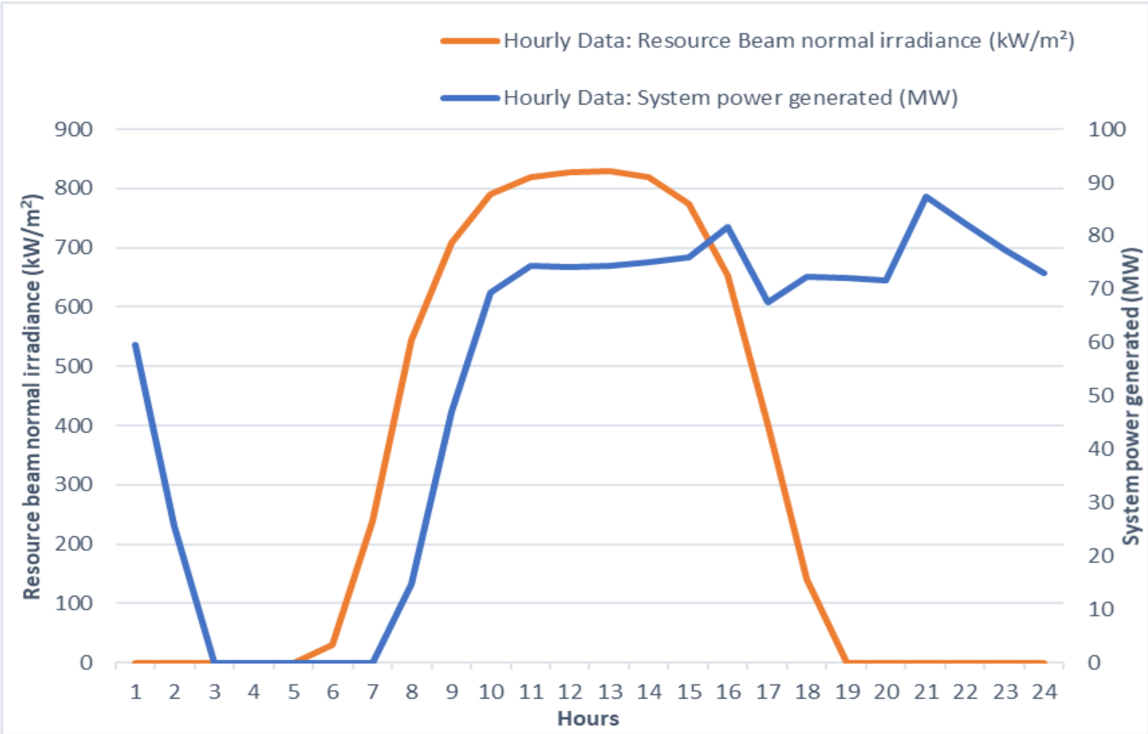

Figure 1.The hourly profile of the electrical energy output compared to the received DNI at the first site.

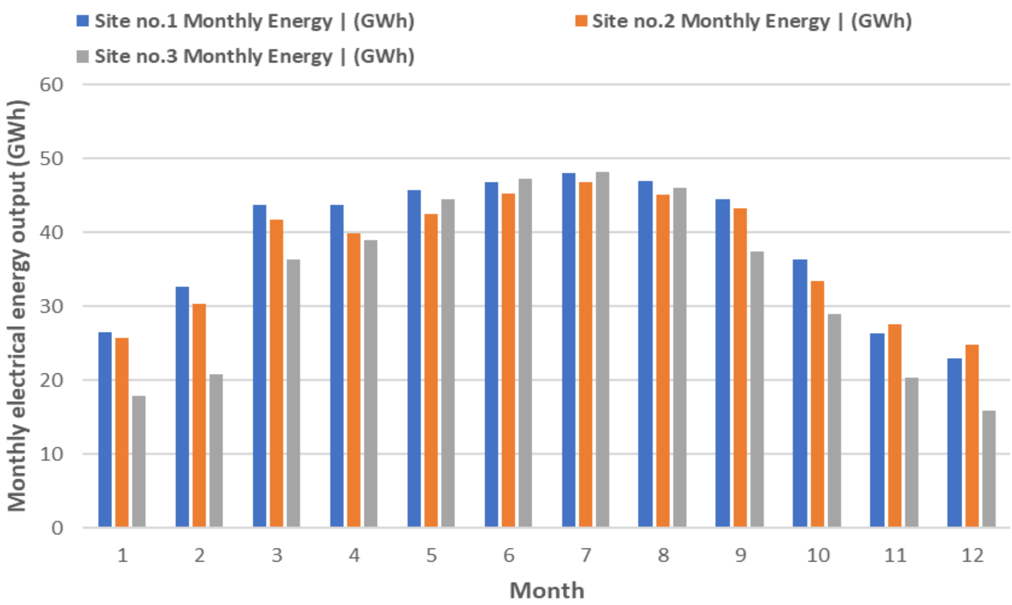

Figure 2. Monthly electrical energy output for the three selected sites

This site also delivered less annual energy, about 446.7 GWh, and had a lower capacity factor at 51.04 %. Finally, the third site (29.61 N, 32.75 E) had the highest LCOE 11.3 US ₵/kWh, the lowest energy production 403.14 GWh, and capacity factor 46.1 %. A summary of the results for the three sites is shown in

Table 3. The results confirmed that all the selected sites are suitable for this type of technology with the first site being preferred to be used in the next stage of this study, as it offers the best potential for a CSP plant of the sites identified.

Site	**Site (1) 28.06 N, 33.25 E**	**Site (2) 27.27 N, 33.66 E**	**Site (3) 29.61 N, 32.75 E**
Annual energy (GWh)	464.7	446.7	403.1
Capacity factor (%)	53.1	51.04	46.07
Gross to Net Conversion Factor (%)	90.5	90.6	90.7
Electrical source - Power cycle gross output (GWh)	535.2	513.8	463.2
Thermal energy to the power block (GWh)	1445.2	1395.3	1255.9
Thermal power produced by the field (GWh)	1569	1474	1314
LCOE(¢/kWh)	10.07	10.4	11.30

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Table 3. Summary of the outputs of each site.

4. Power System Model

Having selected the best site for the proposed CSP plant, a power system model was designed using Simulink to perform a load flow analysis of the system when integrated into the Egyptian national grid. The first selected site is located at 28.06 N, 33.25 E, which is near to both the 220 kV transmission lines and a large load centre (Ras Shukeir). Based on the location, the proposed CSP plant is considered an additional power system to be integrated to an existing grid network. The proposed power system model is shown in **Error! Reference source not found.**

Figure 3. This model includes generation, transmission and load stages.

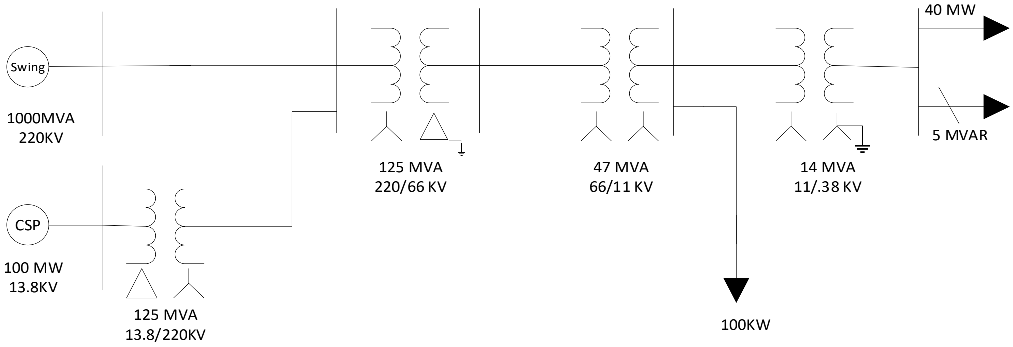

Figure 3. Single line diagram for the proposed power system model

Undertaking power flow studies is important to assure the performance of the proposed CSP plant in three ways. Firstly, it is important for estimating the losses of the proposed system. Secondly, it is important to determine the real and reactive power limits of the generation unit. Thirdly, it is important to ensure that the transmission lines and transformers are not overloaded or underloaded, and to calculate the bus voltage magnitudes and angles (Glover et al. 2017; Murty 2017).

The first step in power flow calculations is to obtain the input data which include: bus data, transmission line data, and transformer data. Each bus is associated with four variables: voltage magnitude, phase angle, net real power, and reactive power supplied to the bus. At each bus, two of these variables are known, and the other two must be computed by power flow calculations, whether manually or via suitable software (Glover et al. 2017).

Bus Classification

Before the load flow calculation is conducted, the types of the buses in power systems need to be clarified. A bus is a node at a line or many lines where one or many loads and generators are connected in a power network. In general buses are classified as follows:

- Load bus: A bus at which no generation exists, and only load is connected. The two known quantities for this bus are active load demand P_d and reactive load demand Q_d, hence it is usually defined as a P-Q bus (Glover et al. 2017; Murty 2017).
- Voltage controlled bus: Also, called a generator bus or P-V bus. At this bus, the voltage magnitude can be controlled. The real power in this case is generated by a synchronous generator which can be varied by changing the mechanical input;

accordingly, the rotor axis position will change with respect to reference axis or reference bus, which means the phase angle of the rotor δ is directly related to the real power generated by the machine (Murty 2017). The real power generation P_g and voltage magnitude $|V_g|$ are known values, while the reactive power Q_g and phase angle δg is unknown and need to be computed (Murty 2017).

- Slack bus: In any power network, the power flows from the generators to loads through transmission lines. Consequently, power losses occur in power conductors, which leads to the power balance equations (2) and (3) (Murty 2017):

$$P_g - P_d - P_L = 0 \tag{2}$$

$$Q_g - Q_d - Q_L = 0 \tag{3}$$

  P_g and Q_g are the total real and reactive generations, P_d and Q_d are the total real and reactive power demands, and P_L and Q_L are the total power losses in transmission network (Murty 2017). The values of P_g, Q_g, P_d and Q_d are known or estimated, and the power losses P_L and Q_L are unknown and need to be calculated after the analysis of the power flow in the network (Murty 2017). Yet these losses have to be supplied by the generators of the system. For this reason, one of the generators or generating buses is identified as the slack bus or swing bus; at this bus both P_g and Q_g are not specified (Murty 2017). In addition, the voltage phase angle has a fixed value which is usually 0°, hence, all the voltage phase angles values are measured with respect to this bus which makes it the only reference bus in the system. All system losses are supplied by the generation at this bus (Murty 2017).

In performing the load flow analysis, the CSP system was modelled as a synchronous generator with a time varying output (based on the SAM generated output). The salient pole type PU fundamental synchronous machine was used in the Simulink model. In addition, in the proposed model, one step-up transformer and three step-down transformers and a grounding transformer were included. The MVA ratings that were used in the power system model were decided based on the power transformers that have been used in the Egyptian grid network, which were supplied by a local company manufacturing transformers. As for power transmission, as the distance between the proposed plant and the nearest transmission line is 1 km only, while the distance from the transmission line to the load centre was considered to be 5 km, as at the first selected site. Consequently, this distance was used in the model as a part of the transmission line transporting from the 220 kV transmission line to the step-down transformer of 220/66 kV as the 1 km distance was neglected between the station and the 220 kV network.

Thus, in this power system model a three-phase series resistance, inductance, conductance (RLC) branch was used as a representation of a three-phase transmission line. The conductance is always neglected in short transmission line (Glover et al. 2017), as for the values of resistance and inductance, both were determined based on technical specification of the conductors' material that are usually used in the Egyptian grid network (Alsuraih 2014). For the three phase loads included in the model, as information regarding the load demand in the selected locations was not available, instead, in this model, the load was set according the power output generated by the proposed CSP plant in SAM.

For the load flow solution in Simulink, as stated, the system is not isolated, and it is considered an addition to an existing grid network, for this reason, a swing bus was added to the model to provide the losses of the transmission network. This swing bus was set at 1000 MVA with a base voltage of 220 kV that matched with the transmission network voltage; its voltage phase angle was 0° as this bus was the reference for all the buses in the model. Simulink provides load flow buses that can be used in this model as bus identification for each stage of transmission. Six of them were added to the model, one at 13.8 kV generation after the synchronous generator, also one by the swing bus with 220 kV and after the 220 kV transmission stage, in addition buses were added at 66 kV, 11 kV and 0.38 kV loads.

5. Load Flow Analysis Results and Discussion

After conducting the load flow simulation for every hour of generation during the day, the total generation, total losses, p.u voltage values and voltage angels were calculated for each hour of the 24-hour generation profile. A selection of the results of the load flow solution is shown in Table 4.

As stated before in relation to the importance of a swing bus in load flow calculations, it was clear that it was responsible for providing system losses, especially as the reactive power is always needed for transmitting the power with all the losses included. Also, due to the short distance to load centres, the power losses were less. In addition, when the CSP was not generating the required power, the swing bus provided this power as the loads are constant, they will always need to be met. Also, it was noticed that all the buses followed the reference bus, which in this case is the swing bus.

Hours	**Total Generation**	**Total PQ load**	**Total losses**	**Swing bus P & Q**	**CSP P &Q**	**Voltage (p.u.) and angle (deg)**			**No. of itera-tions**
						Bus 13.8	**Bus11 (load)**	**Bus 380 (load)**	
1	41.66 MW/ 27.69 Mvar	40.20 MW/ 5.00 Mvar	0.67 MW/ 21.93 Mvar	-17.88 MW/ 26.79 Mvar	59.54 MW/ 0.90 Mvar	1/ -25.65 °	0.911/ -41.40°	0.870/ -51.73°	3
2	41.57 MW/ 24.02 Mvar	40.20 MW/ 5.00 Mvar	0.58 MW/ 18.25 Mvar	15.85 MW/ 24.02 Mvar	25.72 MW/ 0 Mvar	1/ -28.13 °	0.911/ -41.40°	0.870/ -51.73°	5

21	41.79 MW/ 32.94 Mvar	40.20 MW/ 5.00 Mvar	0.80 MW/ 27.18 Mvar	-45.68 MW/ 30.11 Mvar	87.48 MW/ 2.83 Mvar	1/ - 23.59 °	0.911/ -41.40°	0.870/ - 51.73°	3
24	41.72 MW/ 29.99 Mvar	40.20 MW/ 5.00 Mvar	0.73 MW/ 24.23 Mvar	-31.41 MW/ 28.28 Mvar	73.13 MW/ 1.71 Mvar	1/ - 24.65 °	0.911/ -41.40°	0.870/ - 51.73°	3

Table 4. Selection of the results obtained from the load flow solution in Simulink.

Consequently, the p.u. voltage values and phase angles in the 66 kV, 11 kV and 0.38 kV buses were not changed during the whole day of simulation, which confirmed the system reliability. As for the 13.8 KV bus, the phase angle changed through the day, according to the changing field voltage and mechanical power input each time in the synchronous generator.

6. Conclusion

This study assessed both technical and economic aspects to achieve the lowest LCOE with highest generation performance of the proposed CSP plant. The study also succeeded in presenting a different perspective in combining both SAM modelling and grid integration Simulink modelling, and performing power flow studies and giving a clearer image of the predicted performance of the proposed CSP plant when connected to the grid. Furthermore, the load flow solution results showed the values of the expected voltage and voltage angles for each bus for a 24-hour period were acceptable when connected to the grid. Consequently, based on these case studies and results, installing CSP plants in Egypt can be seriously considered in the future on a bigger scale.

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