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Assessment of the Techno-economic Viability of the Optimal CSP Plant Technology in Egypt's Climate

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Photovoltaic (PV) and concentrated solar power (CSP) are the two main methods for capturing solar energy. Egypt has so far focused its energy investments on solar PV technology. However, considering Egypt's hot, dry weather throughout the year, centralized large-scale PV power generation would not be the best option for Egypt's energy needs. In light of the preceding, this study assesses the most suitable CSP technologies (parabolic trough collector, linear Fresnel reflector, and solar power tower (SPT)) for massively centralized power generation in Egypt. There are six potential sites for the construction of these power stations, all of which are close to cities and dispersed around Egypt. This is a result of the region's natural appropriateness for developing solar power facilities, its configuration, and its proximity to the Egyptian electrical system. The levelized cost of electricity (LCOE) and annual water consumption are two of the proposed power plant's key economic factors, which are examined. Additionally, a sensitivity analysis is used to verify the comparative technical analysis, which is based on electrical output and the capacity utilization factor. The results show that the Benban SPT site has both the highest produced energy and the lowest LCOE, with an annual production of 258,789.8 MWh and 11.71 ¢/kWh.

1. Introduction

Around 74 % of the world's energy consumption is provided by non-renewable sources, and that demand is frighteningly increasing (Ye et al., 2023). Emissions of carbon from energy sources based on fossil fuels pose a severe threat to the ongoing climate change conundrum (Lu et al., 2022). Energy usage has increased at an almost doubled average yearly growth rate since 2010. Since 2010, when the world economy began to recover from the financial crisis, the years 2017 and 2018 experienced the fastest increase. Global energy consumption grew in 2018, which resulted in a 1.7 % rise in carbon dioxide (CO_2) emissions. These alarming numbers show how swiftly greenhouse gas emissions are increasing. The Intergovernmental Panel on Climate Change issues a warning in light of this situation, stating that if the current trend persists, the global temperature may exceed 1.5 °C between 2030 and 2052 (Masson-Delmotte et al., 2018). Energy consumption tripled across the Middle East, North Africa, and Europe between 1980 and 2005, and it's expected to treble by 2050 (Pitz-Paal et al., 2012). The generation of electricity from renewable sources made up 26 % of the total up until 2018; 15.8 % of it came from hydropower, 5.5 % from wind, 2.4 % from solar photovoltaics, 2.2 % from biopower, and the remaining 0.4 % from geothermal, concentrated solar power (CSP), and ocean power. CSP is expected to generate 40 % of the electricity in the Middle East, Central Asia, Chile, China, India, Australia, and North Africa by the year 2050 (Azarpour et al., 2022). In light of this, Egypt may prove to be a fruitful location for the future production of CSP power according to Mohamed et al. (2022) and Elfeky et al. (2023). In order to lower the cost of installing CSP facilities, thermoclines are viewed as a promising solution for thermal power storage systems (Elfeky et al., 2022).

Many different technologies are employed by CSP systems, including the linear Fresnel reflector (LFR) system, the parabolic dish system (PDS), the solar power tower (SPT), and the parabolic trough collector (PTC) (Aboelmaaref et al. 2020). Currently, the CSP technologies with the highest installed capacity are PTC and SPT, which are also the most affordable (Yang et al., 2018). SPT technique is predicted to become the most economical CSP technology by 2025, surpassing other CSP technologies (Aseri et al., 2021), due to the fact

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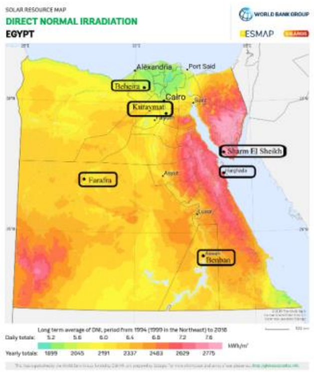
that it can operate at temperatures higher than the PTC system. The cost per kWh for building and running an energy-producing facility over its anticipated financial lifetime is known as the levelized cost of electricity (LCOE). The LCOE is anticipated to be lower in areas where solar radiation is higher than that of the baseline plant or where finance costs are lower than expected. The Dubai Electricity and Water Authority is constructing the 700 MW single-site CSP plant that will be the biggest in the United Arab Emirates. Egypt is situated in the sun belt, which offers an abundant supply of global horizontal irradiance (GHI) and direct normal irradiance (DNI).
The literature review demonstrates that the majority of research investigations are only concerned with Photovoltaic stations. However, there is not much research on the effectiveness of CSP technologies, especially in Sun Belt locations with a wide range of climatic conditions, like Egypt, where the western desert of the country is one of the most significant locations for utilizing solar energy for the generation of electricity. In order to cover the gap in the current literature, this research conducts a complete techno-economic assessment to determine the profitability of the CSP technique and the viability of its deployment in Egypt. The study's main contributions are as follows: The feasibility of CSP deployment in Egypt will be determined by (1) choosing the best places in Egypt for the development of CSP technology and (2) evaluating the technical and financial viability of the offered designs. Filling a knowledge gap regarding large-scale solar energy in Egypt, a detailed examination of the techno-economic viability of CSP will be notably helpful to the nation's power management enterprise. This study advances our understanding of the CSP technique's applicability in Egypt, which contributes to the body of information. It can also serve as a model for numerous other developing nations that wish to incorporate CSP technology into their array of energy sources.

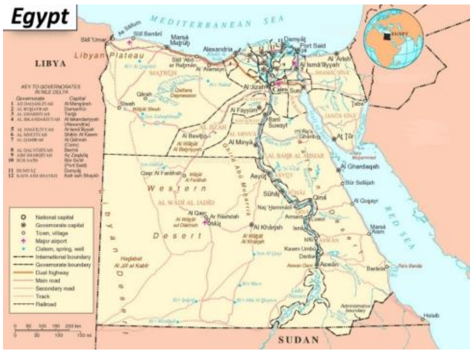
2. Technology for CSP plant

2.1 The CSP plant's proposed locations

The current analysis assumes that the DNI values must be more significant than or equal to 2,400 kWh/m^2/y (i.e., 6.5 kWh/m^2/day) for optimal CSP efficiency and a lower LCOE. In order to achieve this, the Global Solar Atlas 2.0 database of solar resource geographic information system (GIS) data for Egypt was used to produce a classed DNI solar map using ArcGIS. Six zones were consequently proposed as suitable locations for CSP plants after taking into consideration the additional evaluation criteria previously discussed, as indicated in Table 1. With a main grid resolution of roughly km, Figure 1a shows a satellite map of Egypt created by SolarGIS's Global Solar Atlas 2.0. Egypt has constructed a national highway network that covers about 18,000 km, as can be observed in Figure 1b; this infrastructure will greatly help Egypt to improve sustainability, especially the electricity and transportation networks.



(a) The typical scale of the DNI chart for Egypt



(b) An illustration of Egypt's main transportation systems

Figure 1: Egypt climate and logistics

Table 1 provides information on the candidate places' attributes and weather. SolarGIS was employed to gather meteorological data for specific zones, including the average daily DNI, two-meter wind speed, and ambient temperature (NASA, 2020)

2.2 Methodology and SAM software analysis

The potential of CSP technology in Egypt has yet to be thoroughly evaluated techno-economically; instead, solar photovoltaic systems are the main focus of previous research. This article's main objective is to inspire Egypt's government to pursue CSP technology and get beyond the barriers that stand in the way of it. In the study to generate energy in Egypt utilizing techno-economic evaluation, the most cutting-edge CSP technology, the SPT technique, was utilized. System Advisor Model (SAM, 2021), a tool created by the National Renewable

Energy Laboratory, was created with the goal of analyzing various renewable energy technologies, including PTC, LFR, and STP systems. Additionally, SAM offers a range of appropriate performance models. Using the financial assessment techniques that are also provided, the feasibility of a specific CSP proposal is also assessed.

Table 1: Features of the nominated sites (ONEBUILDING, 2023)

Location/ Attribute	Hurghada	Benban	Kuraymat	Sharm Sheikh	ElFarafra	Beheira
Latitude Longitude	&27°16'47.5"N 33°48'38.9"E	24° 5' 20.1768" N, 32° 53' 59.3880" E	29°16'36"N, 31°14'59"E	27°55'02"N, 33°58'51"E	27° 3'25.90"N, 27°58'32.80"E	30°31'38.50"N, 30°18'24.50"E
Elevation (m)	7	103	61	54	71	27
GHI (kWh/m2/day)	6.198	6.376	5.943	6.376	6.165	5.720
DNI (kWh/m2/day)	6.615	6.190	5.837	7.311	6.055	5.638
Latitude Longitude	&27°16'47.5"N 33°48'38.9"E	24° 5' 20.1768" N, 32° 53' 59.3880" E	29°16'36"N, 31°14'59"E	27°55'02"N, 33°58'51"E	27° 3'25.90"N, 27°58'32.80"E	30°31'38.50"N, 30°18'24.50"E
Elevation (m)	7	103	61	54	71	27

2.3 Technological and financial performance factors

To assess the technical and financial performance of the CSP, it is required to establish a variety of technical indicators. Several significant technical indicators that were employed in this investigation are listed below:
The difference between the overall power output (E_{gross}) and the power output from parasitic losses (E_{par}) is what the CSP plant refers to as the annual net electricity generated (AEG). The determination of the AEG is shown using the preceding equation (Awan et al., 2019).

$$AEG = \sum_{h=1}^{8760} \left(Q_{ST} A_{sf} \eta_{sh} \eta_{soil} \eta_{sto} \eta_{PB} \eta_{ta} - E_{par} \right) \tag{1}$$

where Q_{ST} symbolizes the thermal output on an hourly rate, the solar field area is denoted by A_{sf}, η_{sh} represents shade effectiveness, the soiling effect *is* indicated by η_{soil}, η_{sto} assesses the efficiency of thermal storage, power block effectiveness is described by η_{PB}, and η_{ta} denotes the efficiency of the turbine-alternator set.
A capacity factor (CF), which is represented by the following equation, is used to compare a power plant's actual generation capacity to its maximum potential generation capacity. The following formula presents the CF:

$$CF = \frac{AEG}{8760 \times \mathrm{E}_{gross}} \tag{2}$$

The yearly water consumption is the total amount of water used to cool the plant, produce steam, and clean the parts over the course of a year. Numerous economic factors must be taken into account when assessing the CSP plant's economic performance. The significant economic indicators considered in this analysis are described in the paragraphs that follow.
The LCOE is one of the most frequently used measures of the financial success of renewable energy development projects. The life-cycle cost of energy (LCOE) is determined by dividing the total costs incurred over the course of a project by the amount of energy produced during that time. A project with a lower LCOE will probably be more successful. In the SAM software, real and nominal LCOE are estimated. We include both the real and nominal LCOE in this analysis since the real LCOE is the set USD amount and accounts for the project's many years of inflation, while the nominal LCOE is the current USD amount and funds immediate activities. The LCOE of the CSP plant can be calculated using the formula below (Sultan et al., 2020):

$$LCOE = \frac{\sum_{t=1}^{n} \left[\frac{I_t + OM_t + F_t}{(1+d)^n} \right]}{\sum_{t=1}^{n} \left[\frac{E_t}{(1+d)^n} \right]} \tag{3}$$

where I_t represents the amount invested in year t, OM_t represents the cost of operations and upkeep in year t, F_t represents the fuel expense for year t, E_t represents the quantity of electricity actually produced in year t, d indicates the discount rate and the plant's lifespan represents by n.

3. Results and discussion

Findings from the 50 MW CSP plant that was evaluated are displayed in this section for the six locations that were picked: Hurghada, Benban, Kuraymat, Sharm El, Sheikh, Farafra, and Beheira. Important technical metrics, including the CF, AEG, and annual water usage, are monitored for the parameter's fluctuation analysis in order to analyze the operation of the plants.

3.1 Assessment of the six locations' performance

Figure 2 displays the power generated monthly by the six suggested locations for the proposed 50 MW CSP stations (Hurghada, Benban, Kuraymat, Sharm Elsheikh, Farafra, and Beheira). The Benban SPT project produces 258,789.8 MW of power overall each year. For the Benban location, the smallest quantity of power was produced-624.3 MW in December, while the most significant amount-801.7 MW, was produced in March. The Farafra SPT plant produces 254,352.7 MW of electricity annually, with June recording the highest electrical output at 810.136 MW and December having the lowest at 515.7 MW. With 212,380.2 MW for the SPT plant, the location at Beheira produced the least amount of power on an annual basis. It is clear that this SPT plant generates far more power than the other CSP technology, which is very advantageous for meeting the spike in demand for electricity during that season. The Sharm Elsheikh project, which is in third place after the Farafra location, produces 249,643.3 MW of electricity annually using SPT technology. In comparison to the PTC, the energy produced at the SPT plant's locations in Hurghada, Benban, Kuraymat, Sharm El-Sheikh, Farafra, and Beheira is greater by 14.99, 15, 19.03, 16.70, 17.72 and 19.91 %, while higher by 30, 30, 32.8, 31.43, 32.27 and 33.22 % than LFR system.

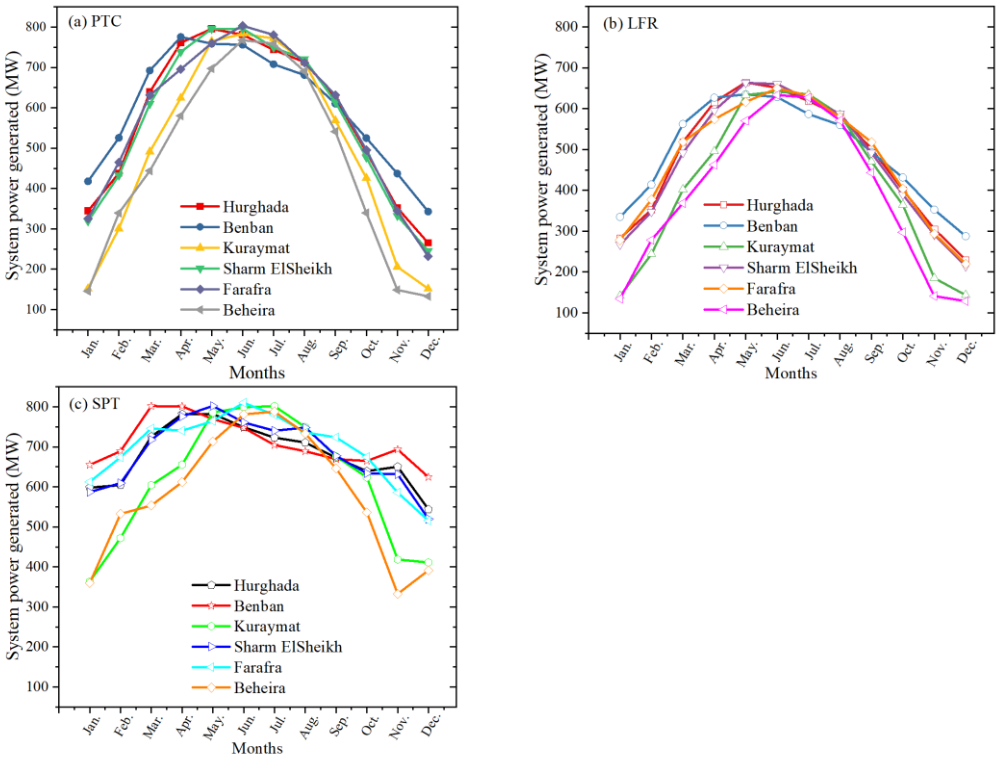


Figure 2: Indicates the average monthly system power generated by (a) PTC, (c) LFR, and (d) SPT technologies for the six sites

3.2 Techno-economic performance parameters

The financial results of the simulation for the three plants are shown at six different locations in Table 2. For the six locations examined, the LCOE real values for SPT were found at Hurghada, Benban, Kuraymat, Sharm Elsheikh, Farafra, and Beheira to be approximately 012.16, 11.71, 13.46, 12.13, 11.91, and 14.18 ¢/kWh, and for PTC plant to be approximately 13.18, 12.65, 15.27, 13.40, 13.31, and 16.24 ¢/kWh. These calculated LCOE figures are clearly less than the global weighted average LCOE for SPT facilities, which was estimated at 18.2 ¢/kWh (Timilsina, G.R. 2021).

Table 2: The financial results of the six locations

Location/ LCOE (¢/kWh)	Hurghada	Benban	Kuraymat	Sharm El Sheikh	Farafra	Beheira
PCT	13.18	12.65	15.27	13.40	13.31	16.24
LFR	15.17	14.71	17.47	15.44	15.34	18.52
SPT	12.16	11.71	13.46	12.13	11.91	14.18

The annual water use and change in CF for the modeled CSP plants are shown in Figure 3 in relation to the six potential locations. The projects at Hurghada, Farafra, Sharm Elsheikh, Kuraymat, and Beheira are in order to have the largest CF, according to Figure 3. The Beheira SPT site had the lowest CF at 53.9 %. In comparison, the Benban SPT location had the highest at 65.6 %. The yearly water use was equivalent to (42,370), (43,255), (40,542), (42,441), (42,685), and (39,708) m^3 for the SPT plant in Hurghada, Benban, Kuraymat, Sharm Elsheikh, Farafra, and Beheira. The Benban site used 43,255 m^3 of water annually, whereas Beheira used 39,708 m^3, which was the greatest and lowest. For the SPT plant, the locations with the lowest water usage levels are Beheira, Kuraymat, Farafra, Sharm El Sheikh, Hurghada, and Benban, in that order.

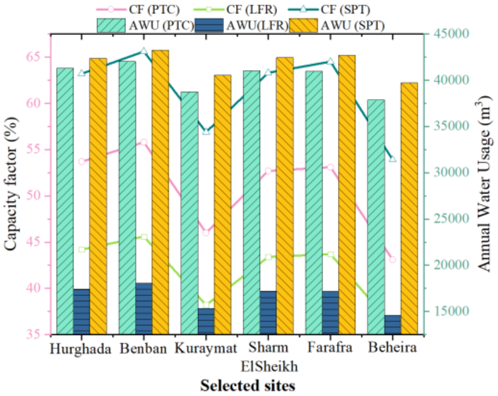


Figure 3: CF and yearly water use scenario analysis for site variance

4. Conclusions

The electricity sector is now being most seriously affected by Egypt's substantially increasing energy supply-demand gap. The population is growing steadily, and this degradation is mainly brought on by problems with hydropower and thermal power generation. Egypt hopes to solve its energy issues through the use of local renewable energy resources, implement its renewable energy roadmap, and achieve its objectives for sustained development and fulfillment in order to obtain a 100 % renewable energy share in 2050. In-depth coverage of the techno-economic performance of the CSP technology in Egypt was provided in this report. A 50 MW power plant was modeled for six different Egypt localities with access to a lot of solar resources. The significance of the study is due to the fact that research on CSP plant technology and how to use them most effectively in Egypt has yet to be done. The investigation's key findings will be thoroughly discussed as follows:

(1) With the highest amounts of energy produced and the lowest LCOE-258,789.8 MWh, 254,352.7 MWh, and 11.71 ¢/kWh and 11.91 ¢/kWh, Benban, and Farafra SPT plants show the best performance.

(2) The two plants with the lowest outputs, Kuraymat and Beheira LFR, have the highest LCOE and lowest generated energy, with respective values of 150,616.3 MWh, 141,812.1 MWh, and 17.47 ¢/kWh and 18.52 ¢/kWh.

(3) The Beheira SPT site had the lowest CF at 53.9 %, while the Benban SPT location had the highest at 65.6 %.

(4) The yearly water use was equivalent to 42,370, 43,255, 40,542, 42,441, 42,685, and 39,708 m^3 for the SPT plant in Hurghada, Benban, Kuraymat, Sharm Elsheikh, Farafra, and Beheira.

(5) Developing a sustainable development strategy, which calls for intentional policies to employ renewable energy in Upper Egypt for various development CSP projects, should be the Egyptian government's main goal.

Future implementations of this investigation will also be enhanced to evaluate the performance, economic, and environmental effects of CSP cooling technologies.

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