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FEASIBLE STUDY FOR THE CONCENTRATED SOLAR POWER PLANT INSTALLED IN ZAKHO

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ABSTRACT

Concentrated solar power (csp) plants offer a viable solution to the electricity issue and the environmental repercussions of traditional energy generating. This paper studies the technical and economic assessment of two concentrated solar power configurations parabolic trough collector systems and a solar power tower utilizing the system advisor model (sam) created by national renewable energy laboratory (nrel). The selected location is zakho city, which experiences an annual average direct normal irradiation (dni) surpassing 6.61 kwh/m²/day, rendering it very suitable for csp implementation. The analysis evaluates a 99.9 mw_e parabolic trough plant with a 101.66 mw_e solar power tower, focusing on monthly and annual energy outputs, system efficiencies, and levelized cost of energy (lcoe). The findings demonstrate that the parabolic trough attains a levelized cost of energy (lcoe) of 12.75 cents per kilowatt-hour and a capacity factor (cf) of 38.1%, but the solar power tower exhibits superior economic performance at 9.33 cents per kilowatt-hour and capacity factor 58.7%. Both technologies exhibit robust energy outputs and the capacity to substantially enhance the local energy composition. The findings indicate that csp projects in high-dni areas such as zakho can improve energy security, diminish greenhouse gas emissions, and promote sustainable development. Recommendations are offered for enhancing plant design, increasing cost efficiency, and incorporating csp into iraq's long-term renewable energy strategy.

KEYWORDS

Concentrating solar power , system advisor model , parabolic trough collector , solar power tower , direct normal irradiance.

1. INTRODUCTION

Non-renewable energy sources, such as fossil fuels, cause severe environmental deterioration by increasing CO_2 emissions. In contrast, statistical estimations show that petroleum-based resources and fossil fuel reserves are fast diminishing (Imam and Al-Turki, 2019),(Shafiee and Topal, 2009).

In addition to the environment, increased greenhouse gas emissions have an influence on public health. Researchers predict that by 2030, the direct costs of air pollution impact would exceed $4 billion worldwide (Shahsavari et al., 2019),(Organization, 2016).

Solar energy may be converted into thermal or electrical power, amongst other forms. Solar thermal technology transforms solar radiation into heat, which is then used for various applications. Solar thermal power is more ecologically sustainable, exhibiting little pollutant emissions in comparison to traditional energy generation methods. This method may be efficiently deployed in areas with significant direct sunshine exposure. The Middle Eastern regions are among the possible places globally that get direct, high-intensity solar radiation (Tsikalakis et al., 2011),(Jahangiri et al., 2016).

Concentrating solar power (CSP) is a highly promising technology that can facilitate the sustainable generation of electricity. A Concentrated Solar Power (CSP) system consists of a solar field, which includes a concentrator and a solar receiver, and a power block, comprising a heat engine and a generator. A solar receiver is a device that transforms focused solar energy into heat, which powers a heat engine. However, solar radiation is sporadic; so, thermal storage and supplementary heating are methods to improve the dispatchability of CSP-generated electricity. The solar-to-electric efficiency is a critical parameter for evaluating the operation of the CSP system (Madhlopa, 2022).

Concentrating solar power (CSP) is a method that use mirrors or lenses to direct sunlight to a focal point (or line), facilitating the accumulation of thermal energy in a material with high heat storage capacity. This focused thermal energy can be utilized to propel many thermal applications. Applications of CSP include power production, district heating systems, industrial process heating, and water desalination, among others (Modi et al., 2017),(Jouhara et al., 2020).

The principal importance of CPS lies in its status as a clean energy source, contributing minimally to greenhouse gas emissions over the lifecycle of the CSP plant, particularly in contrast to traditional fossil fuel energy sources (Achkari and El Fadar, 2020).

When evaluating the utilization of solar energy, four primary Concentrated Solar Power (CSP) technologies are employed: Parabolic trough collector, central solar tower , linear Fresnel reflector, and parabolic dish (Fernández et al., 2019);(Hayat et al., 2019).

Numerous studies conducted by professionals across the world have examined various aspects of the installation of concentrating solar power facilities.

Bayoumi et al. (Bayoumi et al., 2024) conducted an extensive analysis to assess the deployment of two concentrated solar power (CSP) technologies—solar tower and parabolic trough—across 28 specified sites in Egypt. The aim was to determine the ideal site-specific CSP configuration via a verified thermo-economic simulation through the SAM guidance model. Their investigation included environmental, technological, financial, and economic criteria to evaluate the thermal performance of each arrangement. Essential comparable metrics encompassed annual energy output, levelized cost of energy (LCOE), and water usage. The results indicated that while the solar tower system requires 25% more land and entails a 15% more capital expenditure compared to the parabolic trough, it delivers enhanced performance by lowering LCOE, augmenting yearly energy production, and improving water efficiency. Accordingly, Bayoumi et al. advocated adopting the solar tower configuration for implementation in Egypt's central and eastern areas, citing its superior efficiency and economic feasibility.

Liaqat et al. (Liaqat and Ordonez, 2023) investigated the design and efficiency of the CSP power plant for Pakistan. Leveraging economics, modelling, improvement, and site evaluation, the study assesses the advantages and drawbacks of many CSP systems in different places. Performing an analysis using the System Advisor Model. Several scenarios of 100-MW plants were modelled in Quetta and Nawabshah using central receiver systems, linear Fresnel reflectors, and parabolic trough collectors. The facilities enhanced storage capacity by integrating thermal energy storage with parametric analysis. A central receiver system for Quetta was the optimal choice, yielding the yearly energy output including 622 GWh at an expense of 7.44 cents per kWh.

Agyekum and Velkin (Agyekum and Velkin, 2020) Analyze the techno-economic performance of solar tower (ST) and parabolic trough (PT) technologies at two distinct locations in Ghana—Navrongo and Tamale—utilizing the System Advisor Model (SAM) software. A 100-MW power plant is modeled for each technology at Tamale and Navrongo, where solar insolation is elevated. The simulation results indicate that the solar tower is the optimal technology for both sites, yielding the highest annual power generation outputs of 424 GWh and 393 GWh, compared to 211 GWh and 190 GWh for the PTC at the Navrongo and Tamale sites, respectively.

Praveen et al. (RP et al., 2018) Worked a study on the design, performance evaluation, and optimization of a 100 MWe parabolic trough collector solar power plant coupled with thermal energy storage for use in Middle Eastern locations. The authors chose sample locations with an annual average direct normal irradiance (DNI) above 5.5 kWh/m²/day and evaluated the plant performance utilizing the System Advisor Model (SAM). Their research indicated that the suggested concentrated solar power (CSP) plant design could produce 333.15 GWh annually in Abu Dhabi and 369.26 GWh in Aswan, with capacity factors of 38.1% and 42.19%, respectively. The average efficiencies were documented as 14.35% for Abu Dhabi and 14.98% for Aswan. Furthermore, the optimization of the plant design was executed by adjusting factors such as the solar multiple and the full-load hours of thermal energy storage (TES). The study determined that a 100 MW parabolic trough concentrated solar power plant with thermal energy storage may significantly contribute to a sustainable energy future for the Middle East by diminishing reliance on fossil fuels.

Bashir et al. (Bashir and Özbey, 2022) Utilized the viability and design of an 80 MW parabolic trough concentrated solar power plant in Sudan using the System Advisor Model (SAM). Their findings indicate that at the levelized cost of electricity (LCOE) of USD 0.155 per kilowatt-hour, the planned plant was capable that generate 281.145 GWh of energy.

Boretti et al. (Boretti et al., 2020) performed a validation study of the System Advisor Model (SAM), a popular simulation program for renewable energy system modeling. They studied concentrated solar power (CSP) systems, including solar tower and parabolic trough systems, both with and without thermal energy storage. Four sizable plants in the southwestern United States were modeled in the study: Crescent Dunes (a 110 MW solar tower system) and Genesis, Mojave, and Solana (all 250 MW parabolic trough systems). The authors contrasted experimental data gathered since the beginning of each facility's operation with SAM's calculated monthly average capacity factors, which were based on data from typical weather years. According to their findings, SAM considerably underestimated the performance of solar tower systems while producing forecasts for parabolic trough systems that were somewhat accurate. Limitations in SAM's modeling of the solar field, receiver, and thermal energy storage components were the reason given for this disparity.

The aims of this study were to : (1) Comprehend the functioning of CSP plants via a literature review; (2) Evaluate the climatic conditions at the case study location for their appropriateness to accommodate a CSP facility; and (3) Model and simulate Solar Power Tower (SPT) Concentrated Solar Power (CSP) and Parabolic Trough Collector (PTC) CSP systems to evaluate their applicability based on performance and financial indicators.

2. MATHEMATICAL BACKGROUND

Concentrated Solar Power (CSP) plants are methods whereby a vast area of sunlight is focused onto a tiny receiver by means of mirrors or lenses. Heat generated from the focused energy then drives a thermodynamic cycle to create electricity. The following are the principal elements of a CSP plant, their purposes, and controlling equations:

Incident solar power on Receiver (Reddy et al., 2014):

$$Q_{incident} = G \cdot A_{field} \cdot \eta_{field} \quad (1)$$

Where $Q_{incident}$ is the incident solar power, G is the solar irradiance, A_{field} is area and η_{field} is the field efficiency.

Thermal Losses (Radiation): The thermal energy radiated from the glass envelope to the environment may be calculated using the formula that follows (Forristall, 2003).

$$Q_{rad,sky} = \sigma \pi \varepsilon_{gl} D_{gl,o} (T_{gl,o}^4 - T_{sky}^4) \quad (2)$$

Where $D_{gl,o}$ is glass cover outer diameter, $T_{gl,o}$ is glass cover outer surface temperature, T_{sky} is sky temperature, ε_{gl} is glass surface emissivity and σ is the Stefan-Boltzmann constant.

Power Block: The theoretical model for the Power cycle in a Rankine cycle (Naaim et al., 2024).

1- Energy balance of the turbine (work output):

$$\dot{W}_{Tur} = \dot{m} (h_{Tur,in} - h_{Tur,out}) \quad (3)$$

Where h_{in} and h_{out} are the specific enthalpies at the turbine inlet and outlet. The isentropic efficiency models turbine performance. The ratio of the turbine's actual work production to its ideal isentropic functioning is known as the isentropic efficiency

$$\eta_{Tur.,isen.} = \dot{W}_{Tur.} / \dot{W}_{Tur.,isen} = (h_{Tur.,in} - h_{Tur.,out}) / (h_{Tur.,in} - h_{Tur.,out,isen.}) \quad (4)$$

2- Work input of the pump

$$\dot{W}_{P} = \dot{m} (h_{Pump,out} - h_{Pump,in}) \quad (5)$$

$$\eta_{Pump,isen.} = \dot{W}_{pump,isen.} / \dot{W}_{pump} \quad (h_{Pump,out} - h_{Pump,in,isen.}) \; (h_{Pump,out} - h_{Pump,in}) \quad (6)$$

3- Energy balance of the boiler (heat input):

$$\dot{Q}_{Boi.} = \dot{m} (h_{Boi.,out} - h_{Boi.,in}) \quad (7)$$

4- Energy balance of the condenser (heat rejection):

$$\dot{Q}_{Cond.} = \dot{m} (h_{Cond.,out} - h_{Cond.,in}) \quad (8)$$

Removes excess heat from the power cycle to maintain efficiency.

Cooling can be water-based, air-based, or hybrid.

Heat Rejected by the Cooling System: $Q_{rejected=} \; W_{turbine+} \; Q_{condensed}$ (9)

5- The output of the net work: The output of the network of the Rankine cycle is determined by subtracting the work input to the pump from the work output of the turbine.

$$\dot{W_{net}} = \dot{W}_{Tur.-} \; \dot{W}_{Pump} \qquad (10)$$

Where W $_{net}$ is the net work output of the cycle

6- Thermal efficiency (η Ther.): The thermal efficiency of the Rankine cycle is defined as the ratio of net work production to heat intake.

$$\eta_{\,Ther.} = \dot{W_{net}} \,/\, \dot{Q}_{Boi.} \qquad (11)$$

Where h $_{Tur., out}$, h $_{Tur., in}$, h $_{Pump, out}$, h $_{Pump, in}$, h $_{Boi., out}$, h $_{Boi., in}$, h $_{Cond., out}$, and h $_{Cond., in}$ represent the enthalpies of the working fluid at the turbine outlet, turbine inlet, pump outlet, pump inlet, boiler outlet, boiler inlet, condenser outlet, and condenser inlet are specified, with ṁ representing the mass flow rate of the working fluid. These equations delineate the fundamental principles of energy conservation and efficiency for each element of a Rankine cycle. The precise formulation of these equations is contingent upon the thermodynamic features of the working fluid and the assumptions regarding the cycle design.

3. MATERIALS AND METHOD

The following tools, software, and technologies were employed in the study. For instance:
•Software: System Advisor Model (SAM) - used to simulate the performance of Concentrated Solar Power (CSP) installations.

• Examined technologies: Parabolic trough collector and solar power tower molten salt.

This delineates the methodology employed in the investigation. For instance:

1. Location Selection: Zakho City Was Selected Due To Its Solar Radiation Levels And The Area Energy Requirements.

2. Simulation Process:

• The System Advisor Model (SAM) was employed to simulate and evaluate CSP technology.

•The input data comprised sun irradiance, ambient temperature, wind speed, and site-specific characteristics.

3. Technology Comparison:

•The performance of two types of Concentrated Solar Power systems (Parabolic Trough and Solar Tower) was assessed.

• Simulations of each system were conducted with and without thermal energy storage.

4.Validation: Simulated outcomes were juxtaposed with existing experimental data or case studies for verification.

5. Evaluation Criteria: The feasibility of the project was evaluated using metrics such as energy output (kWh), system efficiency, capacity factor, and environmental impact.

This study used the System Advisor Model (SAM) created by National Renewable Energy Laboratory (NREL) to simulate and assess the performance of CSP systems in proximity to Zakho city. Both solar power tower and parabolic trough collector methods were simulated with thermal energy storage implementing molten salt. Site-specific environmental data, encompassing sun irradiance, temperature, and wind speed, were fed into SAM to provide precise performance models. The systems were evaluated according to energy output, thermal efficiency, and ecological advantages. Simulated outputs were corroborated by comparison with benchmark case studies. The objective was to identify the most viable CSP configuration for the region, proactively considering both technical and environmental factors.

All concentrating solar power (CSP) systems produce electricity by harnessing solar thermal energy from sunlight. Solar energy is focused by a field of mirrors onto a receiver, which absorbs the heat to generate steam that powers a turbine for electricity production.

3.1. System Description and Modeling of Parabolic Trough

In this work, the System Advisor Model (SAM) software (version 2023.12.17, modified to Revision 2, SSC 292) was used to conduct a thermal study of a proposed parabolic collector system (nrel.github.io/SAM). The adoption of the physical trough model stems from its relative simplicity and versatility (Wagner et al., 2010),(Wagner and Gilman, 2011). The solar field, power block, optional thermal energy storage, and fossil fuel backup systems are the fundamental parts of this system. The SAM's parabolic trough station is seen on Fig. 1.

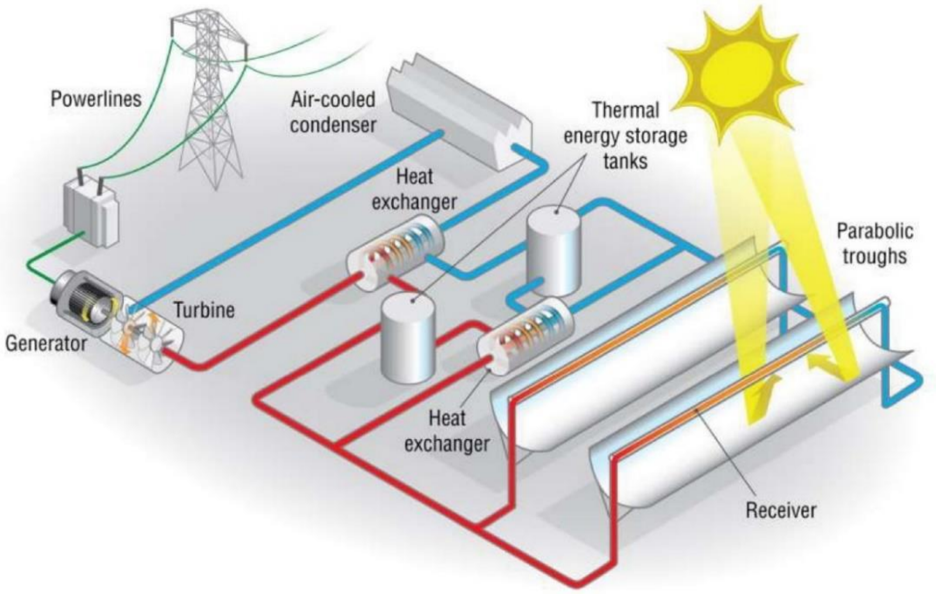


Fig. 1. Design of a parabolic trough facility using the System Advisor Model (SAM). Credit to NREL/SAM.

An instance is the physical parabolic trough model of a solar installation at Zakho, including a rated output of 99.9 MW and thermal energy storage for six hours. The model is evidently basic, employing simple equations and actual data to determine several components.

3.2. Solar Tower Molten Salt

Solar tower molten salt model is verified with SAM version 2023.12.17, revised to Revision 2, SSC 292. In this instance, we further consider the mean monthly outcomes of simulations and experiments over a standard year. In this case, only a single solar installation requires consideration. Fig. 2 presents a SAM depiction
regarding a solar power tower molten salt (nrel.github.io/SAM).

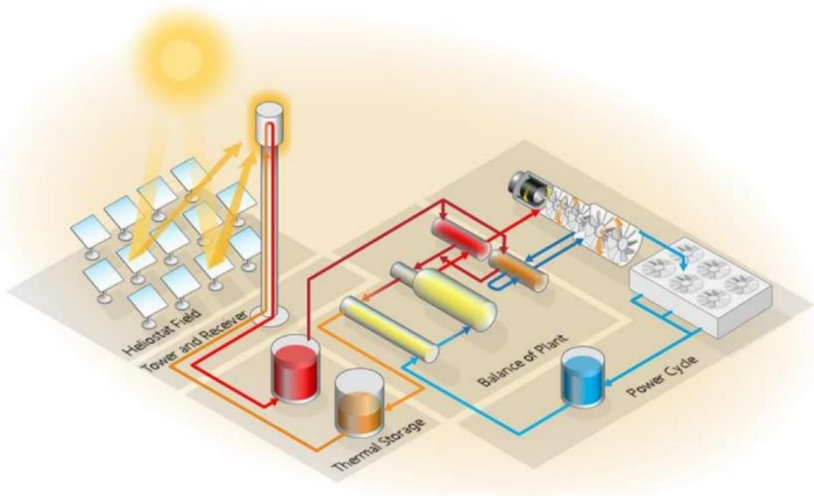


Fig. 2. Solar power tower molten salt factory SAM drawing. Credit NREL/SAM.

The solar field of heliostats, the power block, a receiver on top of a central tall tower, and optional thermal energy storage make up the central receiver system for concentrating solar power. There is also the possibility of using fossil fuels for backup and operating ramp-up. Many heliostats make up the solar field. Focusing solar Direct Normal Irradiance is directed onto the receiver atop the tall tower by flat, sun-tracking mirrors. By elevating the temperature of the heat transfer fluid in the receiver is directed to the power block, where thermal energy is collected.

A solar tower model for a plant with a rated capacity of 101.66 MW and ten hours for thermal energy storage situated at Zakho. This model is evidently rudimentary, delineating a great many components using straightforward equations and empirical data.

3.3. Attributes of the selected location

Identifying an appropriate site for a Concentrated Solar Power station is essential for leveraging to the power plant's advantages. Concentrated solar power plants are commercially viable in areas with a Direct Normal Irradiance (DNI) above 5.5 kWh/m². day (Sharif and Al-Hashmi, 2021). This research study, situated in Zakho, was chosen for investigation. Fig. 3 displays the hourly direct normal irradiance.

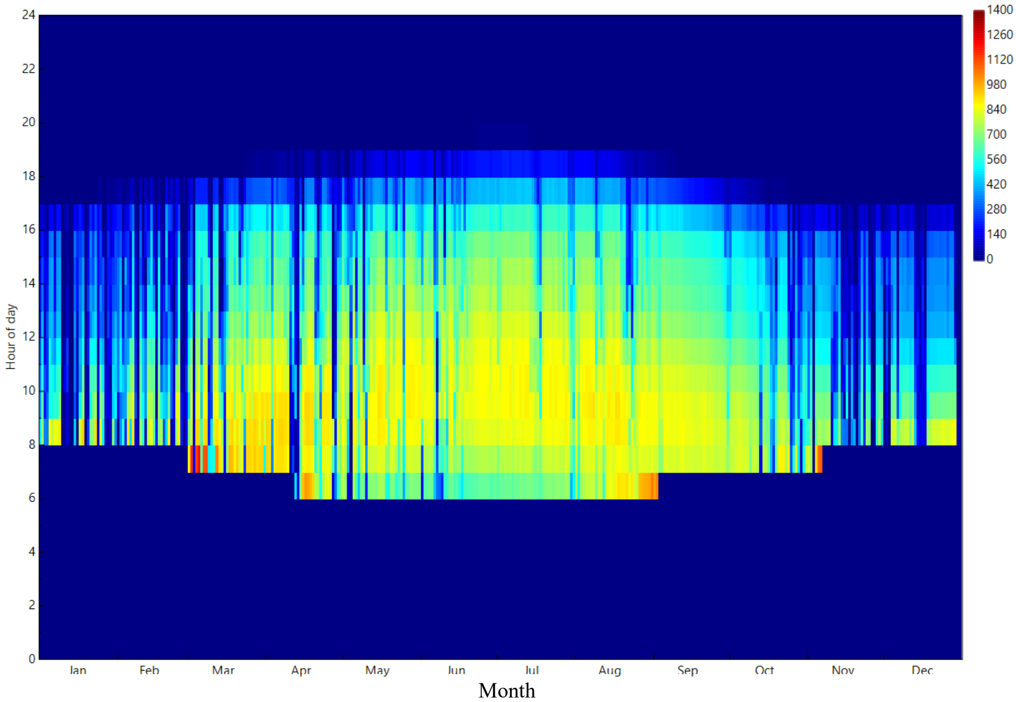


Fig. 3. Hourly of day DNI-Cosine Product Irradiance heat map (W/m^2) for Parabolic Trough Collector at Zakho city (nrel.github.io/SAM).

As proof of the heatmap, Fig. 3 shows the average DNI relative to hour of day (either for a single day or averaged over months). It demonstrates that the DNI irradiance peaks at just 1400 W/m^2 during the hours of the greatest direct sunshine. A parabolic trough solar field evolved within SAM using solar irradiance data for Zakho City.

Table 1 further delineates the attributes of the chosen installation site (nrel.github.io/SAM).

Table 1. characteristics of Zahko city

characteristics of Zakho City	
Latitude	37.144 degrees
Longitude	42.681 degrees
Elevation	431 m
Annual Direct Normal (beam)	6.61 kWh/m^2/day
Annual average temperature	17.8 °C
Annual average wind speed	1.7 m/s
Global horizontal	5.18 kWh/ m^2/day
Diffuse horizontal	1.33 kWh/ m^2/day
Data Source	ECMWF/ERA

3.4. Features of the planned parabolic trough CSP's design

In the first evaluation of this theoretical Parabolic Trough Collector founded solar thermal power plant design, a solar multiple was set at 2 to improve the factor of capacity and power generation under nocturnal and overcast situations. Heat transfer fluid must be preserved in a storage tank with a six-hour capacity to produce energy after sunset. Assume that the thermal energy storage necessitates 6 hours for full charging. Following the initial performance assessment of the plant, the solar energy of TES along with complete load hour measurements will be enhanced. Table 2 provides a summary of the design characteristics of the 99.9 MW Parabolic Trough Collector solar power facility.

Table 2. Design Characteristics of the 99.9 MW Parabolic Trough Under Consideration.

Collector Geometry (SCAs)	
Type	Sky Fuel SkyTrough
Reflective aperture area per SCA	656 m^2
Aperture width, total structure	6 m
Length of the collector assembly	115 m
Number of modules per assembly	8
Average surface to focus path length	2.15 m
Piping distance between assembly	1 m
Mirror reflectance	0.93
Dirt on mirror	0.97
Optical efficiency at design	0.848
Heat Transfer Fluid(HTF)	
Field Heat transfer fluid	Therminol VP-1
Field HTF min operating temp	12 °C
Field HTF max operating temp	400 °C
Freeze protection temp	150 °C
Min single loop flow rate	1 kg/s
Max single loop flow rate	12 kg/s
Min field flow velocity	0.3 m/s
Max field flow velocity	3.7 m/s
Receiver Geometry (HCEs)	
Type	Schott PTR80
Absorber tube inner diameter	0.076 m
Absorber tube outer diameter	0.08 m
Glass envelope inner diameter	0.115 m
Glass envelope outer diameter	0.12 m
Thermal Energy Storage	
Hours of storage at the design point	6.0 hours
Storage heat transfer fluid	Therminol VP-1
Storage tank volume	29,688.93 m^3
Storage tank heater efficiency	0.98
Tank diameter	56.13 m
Pumping power for HTF through storage	0.15 kJ/kg

3.5. Characteristics of the shortlisted location for Power Tower Molten Salt

Selecting an optimal site for a CSP station is essential for exploiting the power plant's advantages. concentrated solar power plants applying power tower technology. The site of Zakho was selected for analysis in this investigation. Fig. 4 illustrates the hourly direct normal irradiance.

The average DNI irradiance peaks at 1400 W/m2 during hours of maximum direct sunlight, as seen in Fig. 4 (either for a single day or average across months). Using sun irradiance data from Zakho city, a power tower molten salt solar field was constructed in SAM.

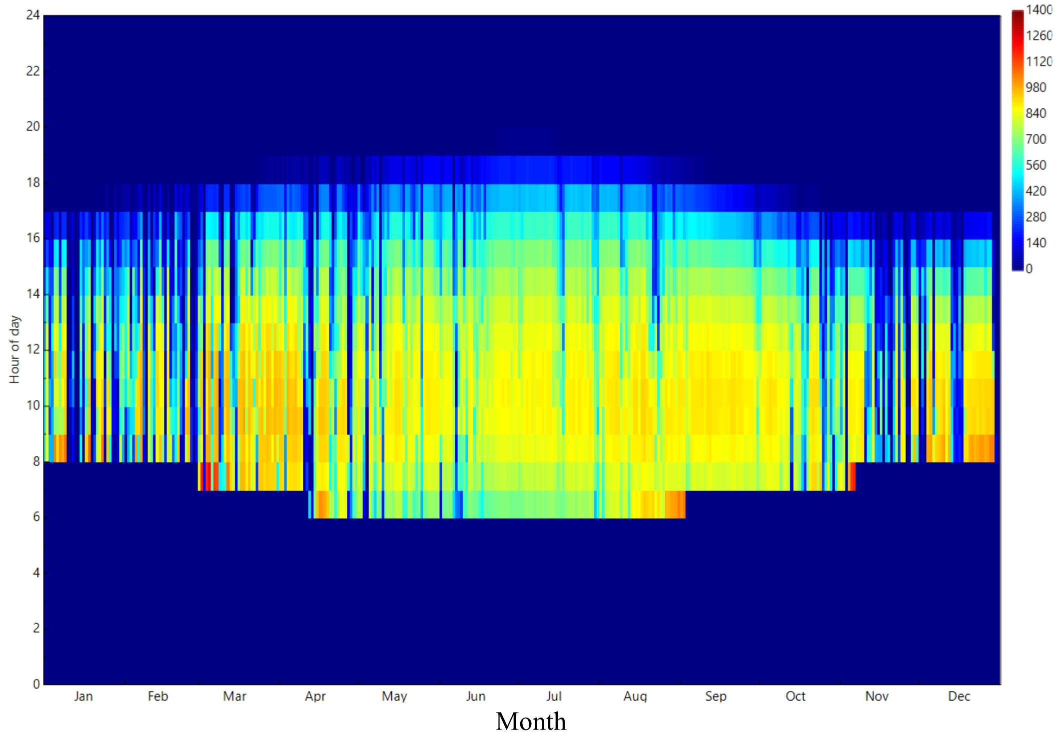


Fig. 4. Hourly of day DNI-Cosine Product Irradiance heat map (W/m^2) for power tower molten salt at Zakho city.

3.6. Features of the planned power tower CSP's design

To represent the hypothetical Power Tower-based solar thermal power plant architecture and enhance power production and capacity factors during the night and cloudy days, the solar multiple was established at 2. This was done for the preliminary investigation. After sunset, it is necessary to store heat transfer fluid (HTF) fluid in a storage canister that can keep energy for a period of ten hours. There is an assumption that the TES requires a minimum of 10 hours to fully install. The solar power and complete capacity hour prices for the plant will be modified by TES after the preliminary performance assessment. The 101.66 MW solar power tower solar design features are presented in Table 3.

Table 3. Design Characteristics of the 101.66 MW Solar power tower molten salt Under Consideration.

Receiver Geometry (HCEs)	
Type	Stainless AISI316
Tube wall thickness	1.25 mm
Tube outer diameter	40 mm
Coating emittance	0.88
Coating absorptance	0.94
Heat transfer fluid (HTF)	
HTF fluid type	Salt (60%NaNO3 40%KNO3)
HTF hot temperature	574.0 °C
HTF cold temperature	290.0 °C
Design receiver mass flow rate	1565.642 kg/s
Maximum single flow rate to receiver	1878.77 kg/s

Design HTF Velocity in receiver tube	5.940 m/s
Design total HFT pump power	8.489 MWe
Thermal energy storage (TES)	
Hours of storage at the design point	10 hours
TES thermal capacity	2791.3 MWt-hr
Available HFT volume	12986 m^3
Tank height	12 m
HFT density	1808 kg/m^3
Tank diameter	38.8 m
Pumping power for HTF through power block	0.55 kW/kg/s

4. RESULTS AND DISCUSSION

4.1. Performance evaluation of the Parabolic Trough CSP plant design.

The monthly energy output from the Parabolic Trough Collector, as calculated using SAM software, is illustrated in Fig. 5, where Zakho suggested a Concentrated Solar Power installation. The maximal monthly energy production from March to September ranging from 3.09548e+07 kWh to 3.63594e+07 kWh. Owing to the heightened DNI throughout in these months, the energy production in July was greatly elevated ranging from 4.75197e+07 kWh. The lowest energy output obtained by PTC plants from October to February ranging from 2.24307e+07 kWh to 8.79946e+06 kWh. This also makes sense because summertime, when solar irradiance is at its highest and the sky is clearest, is when CSP solar operates best. The main idea is that increased radiation, particularly during midday, results in increased consumption of energy, hence there is no need to preserve energy.

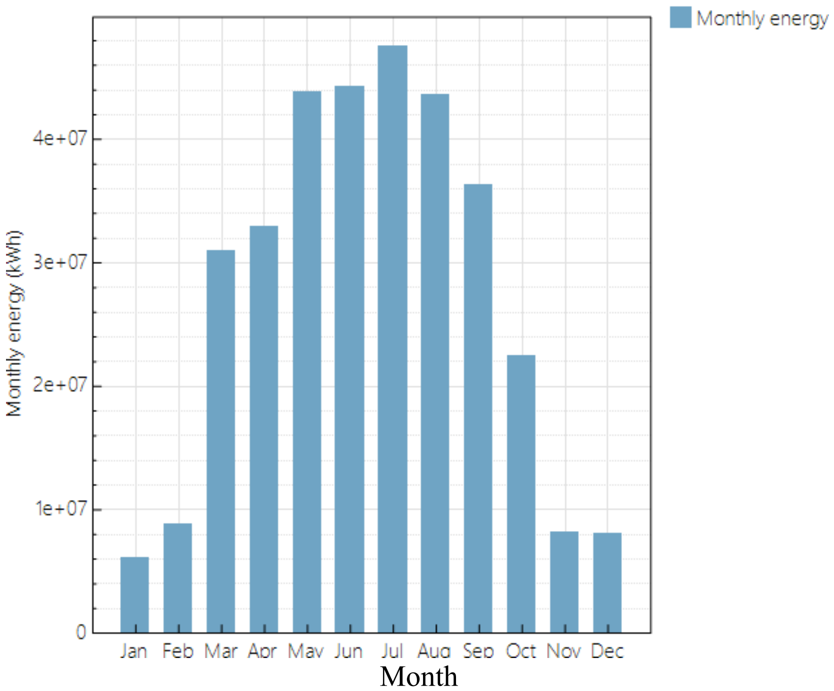
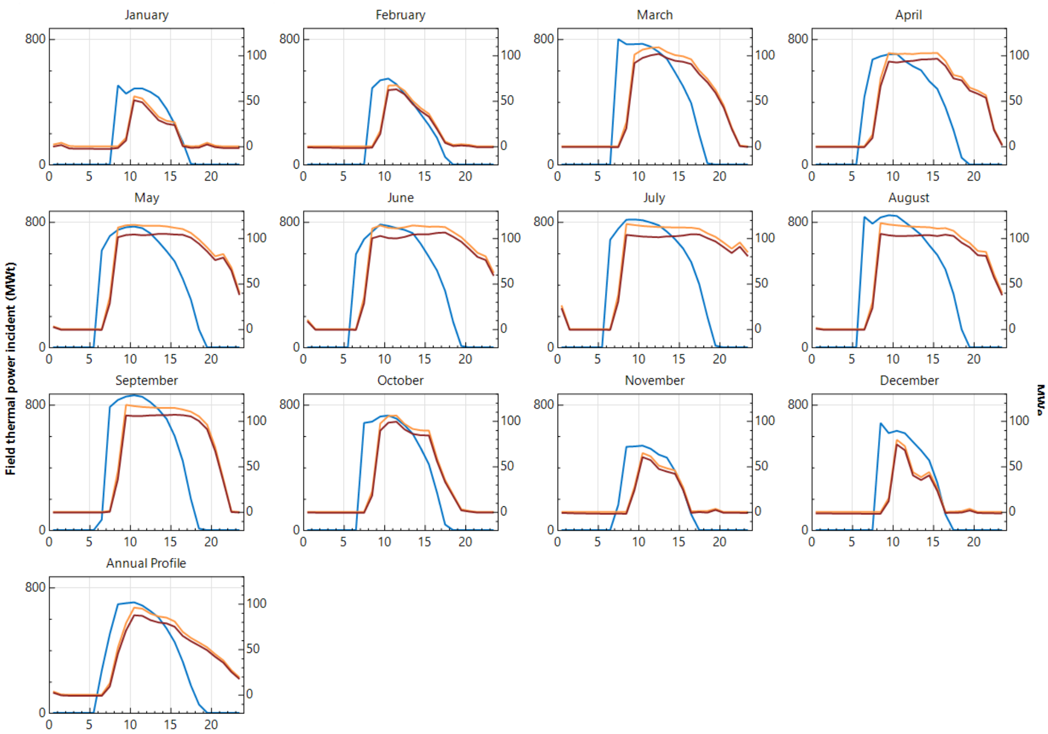


Fig. 5. Monthly energy production from the Parabolic Trough in Zakho.

Fig. 6 presents a hourly statistics for the anticipated power generation for on-site thermal power events for the Parabolic Trough Collector, encompassing full power generated and total power from the grid for PTC at Zahko.



Time of day (hours)

—— Hourly data: of field thermal power incident (MWt)

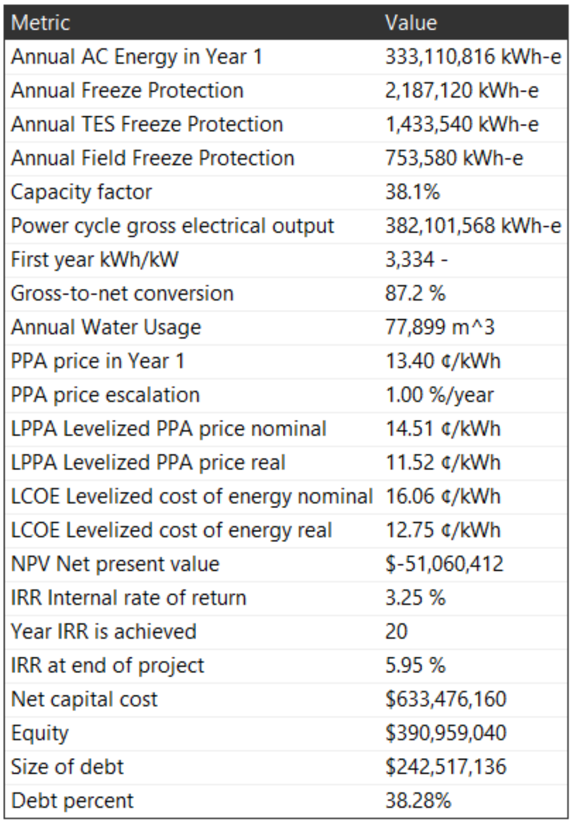
—— Hourly data: Electrical power output: gross (MWe)

—— Hourly data: Total electrical power to grid (MWe)

Fig. 6. Hourly statistics on Zahko's planned plant's gross electrical power generation, grid supply, and field thermal power incident for PTC.

The amount of solar energy at the chosen site for the suggested PTC plant determines the number of cycles it will experience. The image illustrates the anticipated scheduling capacity of a standard year, with an average day per month. The solar energy harvested at the solar farm will be adequate to operate the plant at full capacity during the height of summer months. Ample energy is retained to supply electricity at midnight between June to September. As a result, energy output decreases throughout the day, rendering stored energy inaccessible for nocturnal use. The solar energy obtained by a solar field during winter days will be inadequate for operating the plant at full capacity. Electricity generation is viable until about midnight in summer, as the surplus thermal energy accumulated throughout the day may be repurposed to the power cycle as the solar fields' output declines.

The plant's annual net electrical energy production was projected at approximately 333 GWh, with a capacity factor of 38.1%, indicating that the parabolic trough power plant may substantially aid in fulfilling Zakho's energy demands. A levelized cost of electricity of 12.75 ₵/kWh was determined for the power plant. Additionally, a negative net present value (NPV) of $-51,060,412 was calculated for the proposed project; Fig. 7 illustrates the comprehensive techno-economic performance indicators of the CSP plant.



Metric	Value
Annual AC Energy in Year 1	333,110,816 kWh-e
Annual Freeze Protection	2,187,120 kWh-e
Annual TES Freeze Protection	1,433,540 kWh-e
Annual Field Freeze Protection	753,580 kWh-e
Capacity factor	38.1%
Power cycle gross electrical output	382,101,568 kWh-e
First year kWh/kW	3,334 -
Gross-to-net conversion	87.2 %
Annual Water Usage	77,899 m^3
PPA price in Year 1	13.40 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	14.51 ¢/kWh
LPPA Levelized PPA price real	11.52 ¢/kWh
LCOE Levelized cost of energy nominal	16.06 ¢/kWh
LCOE Levelized cost of energy real	12.75 ¢/kWh
NPV Net present value	$-51,060,412
IRR Internal rate of return	3.25 %
Year IRR is achieved	20
IRR at end of project	5.95 %
Net capital cost	$633,476,160
Equity	$390,959,040
Size of debt	$242,517,136
Debt percent	38.28%

Fig. 7. Metrics for techno-economic success of the parabolic trough CSP plant.

Fig. 8 demonstrates the cycle efficiency of the projected Parabolic Trough Collector solar power facility in Zakho. The facility's average efficiency (gross) is 0.1635, with the maximum efficiency occurring at 0.3973.

increased DNI and reduced humidity during the summertime result in increased average cycle efficiency. The cleaning technique can be used to address further dust and dirt-related problems. The average cycle efficiency decreases in winter when radiation intensity is lower. The levelized cost of energy was 12.75 cents per kWh when the concept was initially developed.

4.2 performance evaluation of the CSP plant design for the solar tower

The monthly energy production from the power tower molten salt utilizing SAM software is displayed in Fig. 9 illustrates that the proposed CSP facility in Zakho can generate kWh monthly the maximal monthly energy production from March to September ranging from 4.79998e+07 kWh to 5.77816e+07 kWh. Owing to the heightened DNI throughout in these months, the energy production in July was greatly elevated ranging from 6.57951e+07 kWh. The lowest energy output obtained by PTC plants from October to February ranging from 4.09025e+07 kWh to 2.02034e+07 kWh. This is logical, as sun concentrating power (CSP) operates most effectively during summer, when solar irradiation is highest and atmospheric clarity is optimal. The crucial aspect is that energy conservation is unnecessary, as increased radiation, particularly around midday, leads to elevated energy consumption.

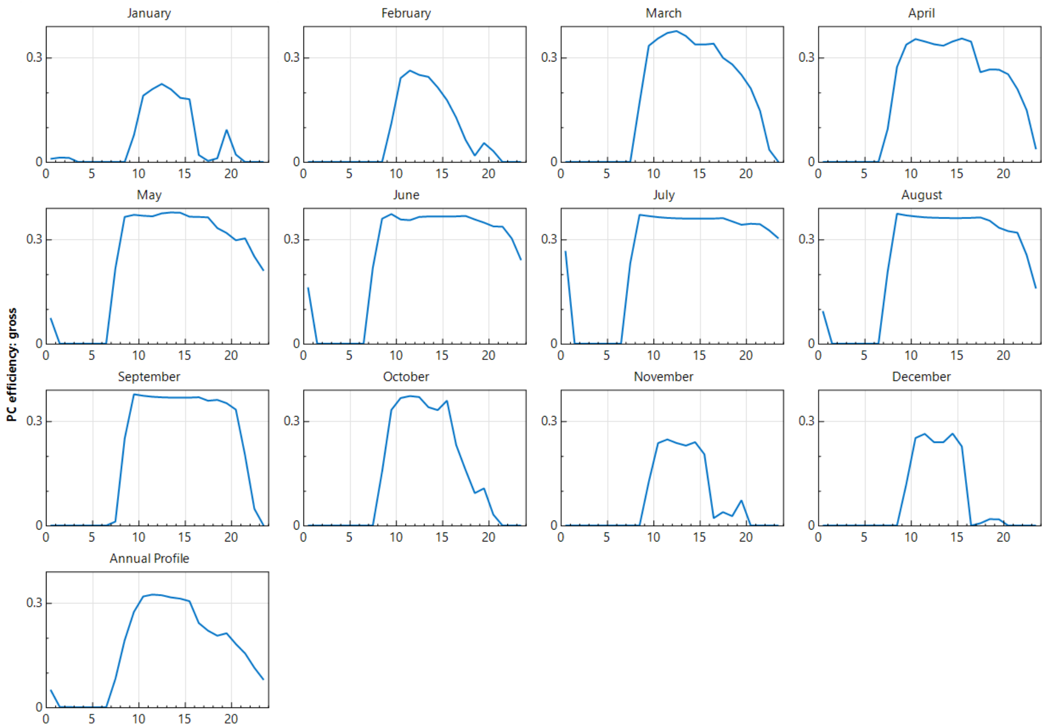


Fig. 8. Cycle Efficiency of the Proposed Zakho Facility for Parabolic Trough.

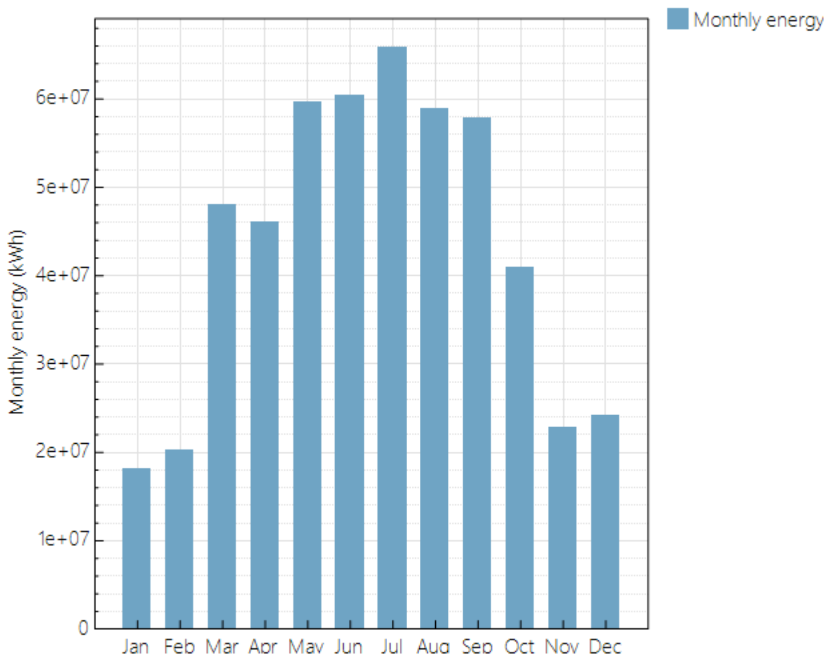
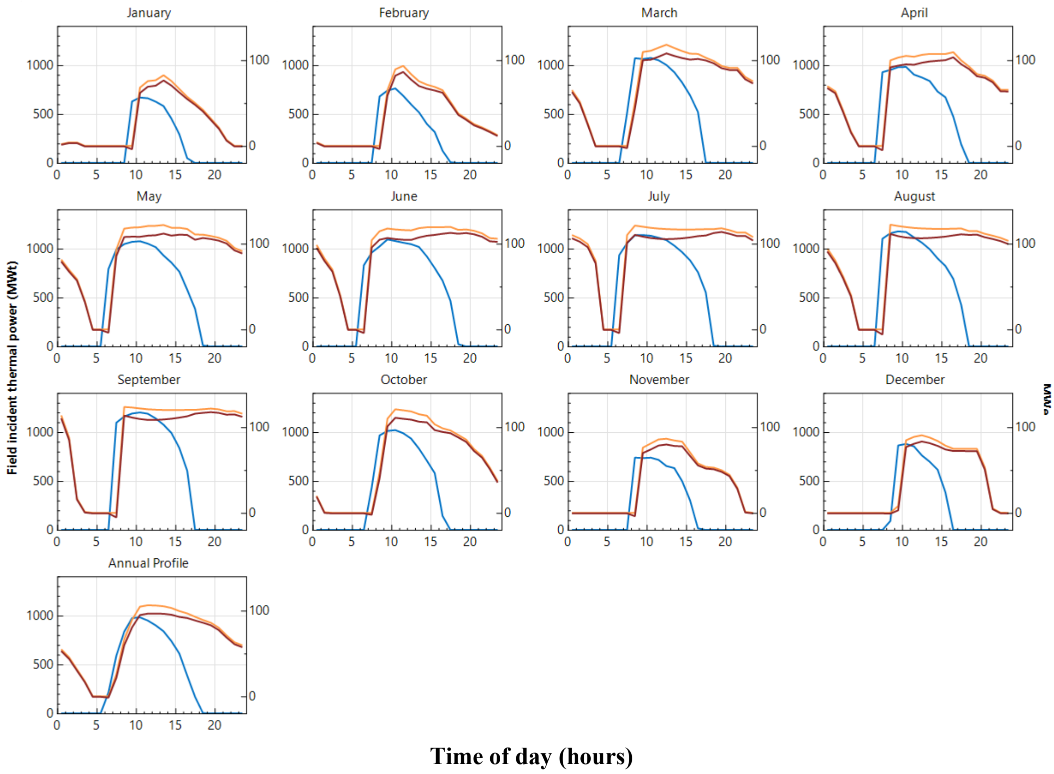


Fig. 9. Monthly energy production from power tower molten salt in Zakho.

Table 4. Monthly energy production for PTC and SPT.

Month	Monthly energy (kWh), PTC	Monthly energy (kWh), SPT
January	6.06343e+06	1.81079e+07
February	8.79946e+06	2.02034e+07
March	3.09548e+07	4.79998e+07
April	3.29225e+07	4.60273e+07
May	4.38392e+07	5.96081e+07
June	4.42901e+07	6.03762e+07
July	4.75197e+07	6.57951e+07
August	4.36113e+07	5.88773e+07
September	3.63594e+07	5.77816e+07
October	2.24307e+07	4.09025e+07
November	8.22627e+06	2.27995e+07
December	8.094e+06	2.41923e+07

Fig. 10 presents hourly data on total power generation, grid power, and on-site thermal power incidents for the proposed Solar Power Tower (SPT) facility in Zahko.



— Hourly data: of field thermal power incident (MWt)

— Hourly data: Electrical power output: gross (MWe)

— Hourly data: Total electrical power to grid (MWe)

Fig. 10. Hourly statistics on Zahko's planned plant's gross electrical power generation, grid supply, and field thermal power incident for SPT.

The project's annual net electrical energy output was calculated at approximately 522 GWh, with a capacity factor of 58.7%, indicating that the power tower plant may substantially assist in fulfilling Zakho's energy requirements. Additionally, a levelized cost of electricity of 9.33

₵/kWh was determined for the power plant. Additionally, a negative net present value (NPV) of $-75,242,784 was calculated for the proposed project; Fig. 11 illustrates the comprehensive techno-economic performance indicators of the CSP plant.

Fig. 11. Metrics for the techno-economic performance of the power tower CSP plant

Metric	Value
Annual AC energy (year 1)	522,671,072 kWh
Capacity factor (year 1)	58.7%
Annual Water Usage	96,742 m^3
PPA price in Year 1	9.50 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	10.29 ¢/kWh
LPPA Levelized PPA price real	8.17 ¢/kWh
LCOE Levelized cost of energy nominal	11.75 ¢/kWh
LCOE Levelized cost of energy real	9.33 ¢/kWh
NPV Net present value	$-75,242,784
IRR Internal rate of return	2.40 %
Year IRR is achieved	20
IRR at end of project	5.23 %
Net capital cost	$738,675,072
Equity	$467,855,264
Size of debt	$270,819,840
Debt percent	36.66%

Fig. 12 Showing Power cycle efficiency tower molten salt solar power plant in Zakho. The Tower Molten Salt plant has a mean efficiency (Gross) of 0.2447, with a maximum efficiency of 0.4451.

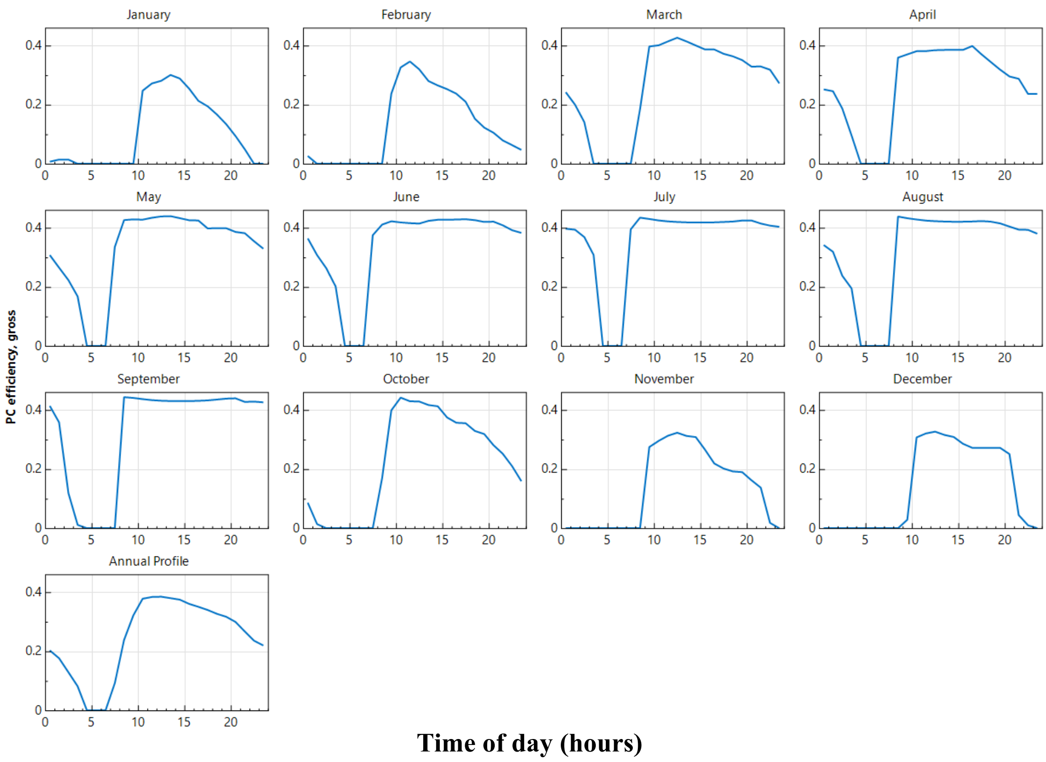


Fig. 12. Cycle Efficiency of the Proposed Zakho Facility for solar tower.

Cycle efficiency is greater in summer because of higher DNI and reduced humidity. The cleaning method can be employed to tackle further dust and dirt-related issues. The mean cycle efficiency diminishes during winter due to reduced radiation intensity. The levelized cost of energy was 9.33 cents per kWh at the time of the concept's initial development.

The results of this study correspond with prior work. Table 5 below presents a comparison of the hypothetical CSP plant with existing publications. demonstrating that the projected Levelized Cost of Energy (LCOE) for the proposed plant is inferior and more favorable in comparison to competing facilities.

Table 5. Comparison and verification of current CSP plant output with other literature.

Authors, Reference, Technology		**Nominal capacity (MWe)**	**Nets Annual Energy (GWh/year)**	**Capacity Factor (%)**	**Storage Capacity (hours)**	**LCOE (USD/ kWh)**
Bashir et al. (Bashir and Özbey, 2022), (PTC)		80	281.145	40.1	6	0.155
Sharif et al. (Sharif and Al-Hashmi, 2021), (PTC)		100	406.26	47.9	6	0.1348
Liaqat et al (Liaqat and Ordonez, 2023)	PTC	100	447.2	51	10	0.1171
	SPT	100	608	69.5	10	0.0903
This work	PTC	99.9	333.11	38.1	6	0.1275
	SPT	101.66	522.67	58.7	10	0.0933

5. CONCLUSIONS

The investigation of parabolic trough and solar power tower CSP configurations utilizing SAM version 2023.12.17 (Revision 2, SSC 292) for Zakho city substantiates the technical and economic feasibility of concentrated solar power given the local climatic circumstances, characterized by an annual average DNI of 6.61 kWh/m²/day. Both systems were designed with thermal energy storage, incorporating 6 hours for the parabolic trough and 10 hours for the solar power tower, thereby substantially improving their dependability and dispatchability.

Key findings encompass:

• Both CSP systems displayed significant performance potential and appropriateness for the selected area.

• The parabolic trough plant, equipped with 6 hours of thermal storage, attained a Levelized Cost of Energy (LCOE) of 12.75 cents per kilowatt-hour and a capacity factor of 38.1%.

• The solar power tower, equipped with 10 hours of thermal storage, demonstrated exceptional economic performance, attaining a levelized cost of electricity (LCOE) of 9.33 cents per kilowatt-hour and a capacity factor of 58.7%.
• The extended storage period of the power tower is indicative of its higher operating temperature, direct molten salt storage, and increased energy density, which provide enhanced dispatchability and consistent power supply.
• Both CSP systems demonstrated considerable promise for augmenting renewable energy integration in the regional power composition, hence bolstering energy security and reducing dependence on fossil fuels.
• The deployment of CSP in Zakho can significantly aid in reducing greenhouse gas emissions and promoting environmental sustainability by providing a cleaner and more dependable alternative to traditional energy generation.
• Further optimization of plant design, cost efficiency, and integration into Iraq's long-term renewable energy strategy will reinforce the role of CSP in sustainable development.

Future work should concentrate on enhancing thermal storage efficiency, optimizing plant design to further decrease the Levelized Cost of Energy (LCOE), and performing comprehensive site-specific analyses on grid integration, water utilization, and long-term reliability. Moreover, policy and financial assistance will be crucial to augment the economic competitiveness of CSP in Iraq.

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