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A multi-criteria performance assessment of concentrated solar power plants for site and technology selection in Egypt

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Abstract
The objective of this research is to investigate the implementation of two concentrated solar power (CSP) technologies in the 28 devoted locations in Egypt, in order to select the optimum site-specific CSP technology. This may be achieved by a validated thermo-economic simulation of power plants using the Sam advisory model and an investigation of the two proposed CSP technologies' configurations to fulfill the power plant's thermal demand. Simulations take into consideration the environmental, technical, financial, and economic aspects of the projects. Among many simulated parameters, three are considered to compare the two proposed technologies' configurations in the 28 locations utilizing geographic information system aid. Those parameters are the annual power production, the levelized cost of energy, and water consumption. A comparative analysis indicated that the solar tower requires 25% more land than the parabolic trough. The additional collecting area raised the net capital cost of the solar tower system by 15% over the parabolic trough model. As a result, the solar tower arrangement reduces the levelized cost of energy while increasing the yearly power generated and water required by the power plant. Simulation results favored the proposed solar tower configuration over the parabolic trough and recommended the implementation of such concentrated solar power projects in the central and eastern locations of Egypt.

Keywords Multi-criteria decision analysis · Sustainability · Concentrated solar power · Parabolic trough · Solar tower · Geographic information system

List of symbols

A	Area, m^2
G	Solar irradiance, W/m^2
N	Number
P	Pressure, bar
Q	Thermal power, W
T	Temperature, °C
W	Width, m

Abbreviations

CSP	Concentrated solar power
CST	Central solar tower
DNI	Direct normal irradiation
EFLSH	Equivalent full load storage hours
EPC	Engineering, procurement, and construction
GHG	Greenhouse gas
GHI	Global horizontal irradiance
GIS	Geographic information system
HTF	Heat transfer fluid
IRR	Internal rate of return
LCOE	Levelized cost of energy
LEC	Levelized energy cost
LFR	Linear Fresnel reflector
MACRS	Modified accelerated cost recovery system
MENA	Middle East and North Africa
NREA	New and renewable energy authority
PTC	Parabolic trough collector
SAM	Sam advisory model
SM	Solar multiple

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Subscripts

amb	Ambient
att	Atmospheric attenuation factor
cav	Cavity
col	Collector
cos	Cosine factor
e	Electricity
env	Glass envelope
hyd	Hydraulic
i	Inlet
m	Module
o	Outlet
refl	Mirror reflectivity factor
sh&bl	Shadowing and blocking factor
t	Thermal
t_{loss}	Total loss

Greek symbols

η	Efficiency, %
ε	Effectiveness

Introduction

One of the world's most pressing concerns is satisfying the rising energy demands in an eco-friendly and sustainable manner (Dincer and Acar 2015), especially in progressively developing countries with booming populations like Egypt. In this respect, the provision of renewable energy options is a must. Egypt's Vision 2030 focuses on sustainable development in the country and considers energy to be the second most important pillar of the ten pillars of sustainable development (https://mped.gov.eg/EgyptVision?lang=en). The vision report emphasizes the optimum and domestic usage of energy resources as well as the diversification of the energy supply mix to incorporate renewable energy to produce electricity. Moreover, the report emphasizes mitigation of carbon dioxide emissions from the energy sector. Consequently, a presidential decree was issued in 2016 for devoting 28 locations (http://nrea.gov.eg/test/en/Home), which are categorized into 6 major zones, to be developed through renewable energy projects by the New and Renewable Energy Authority (NREA) and Ministry of Electricity and Renewable Energy, as shown in Fig. 1 (Moharram et al. 2022).

The most abundant renewable energy resource in Egypt is solar energy (Aliyu et al. 2018). Much of the emphasis on renewable energy is therefore targeted at the optimal and site-specific solar energy technologies to be implemented. There is a potential to reduce greenhouse gas (GHG) emissions in Egypt by 80–95% by following the Middle East and North Africa (MENA) Energy Policy Plan, which seeks to reduce climate change by capping the global temperature rise to no more than 2 °C (Menichetti et al. 2018; Elshafey et al. 2018). The integration of concentrated solar power (CSP) technologies with already existing thermal (fossil) power plants presents one of the low carbon energy technology solutions that may be adopted (Cioccolanti et al. 2019). Although CSP has a relatively large number of independent elements, making it a complex technology, this limitation
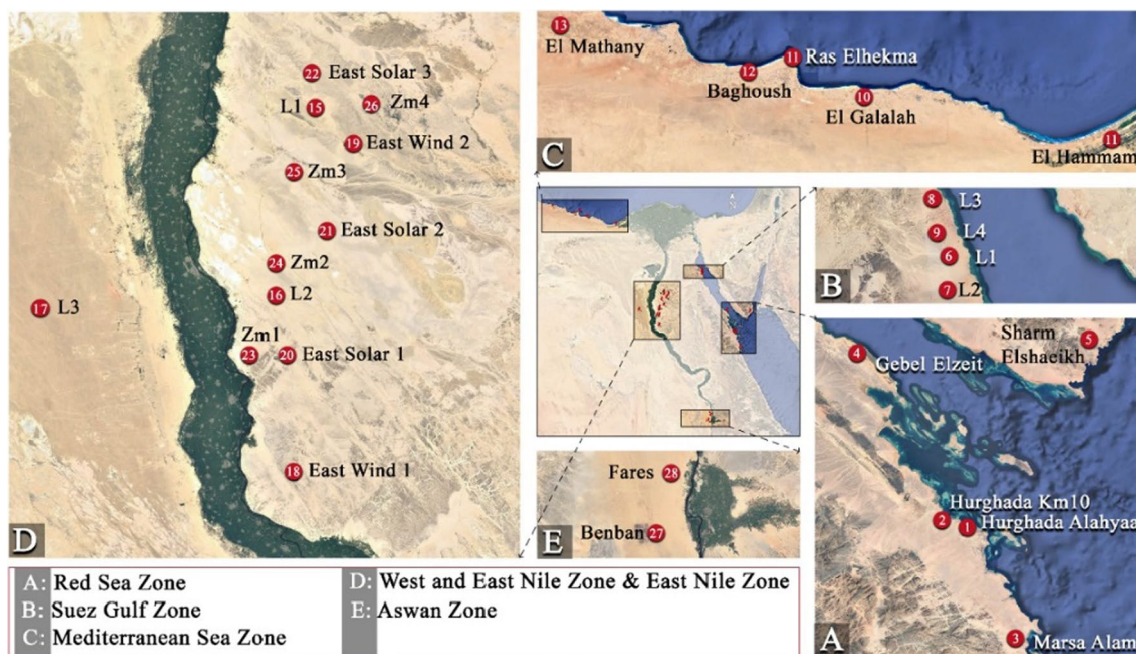

Fig. 1 Lands devoted for development by the NREA in Egypt

is counterweighted by the fact that the technology provides application flexibility to suit demand. The conversion to thermal energy distinguishes CSP from the other main renewable energy technologies, such as hydropower, wind power, and photovoltaic cells (PV). Additionally, CSP is particularly appealing due to its advantages in terms of high efficiency, low operating costs, and good scale-up potential (Zhang et al. 2013). The selection of the site for the construction of a CSP power plant is subject to certain important conditions that must be met in order to ensure the economic output of electricity. The NREA has considered these criteria during the selection of the 28 locations and verified the feasibility of implementing CSP technologies. General site requirements are as follows:

- Annual Direct Normal Irradiation (DNI) should be greater than 1900 kWh/m^2 (Zhao et al. 2009).
- Flat land area with an overall slope of less than 1–3% (Yang et al. 2010), as the intensity of solar radiation is essentially controlled by the ground slope at a certain location (Allen et al. 2006). Due to various parameters such as self-shadowing and shading cast by surrounding terrain, the amount of radiation intercepted by the collectors is significantly reduced. As a result, land with a steeper slope has an impact on solar plant productivity.
- The wind speed should be less than 15.64 m/s in order to decrease the stresses applied to the support structure of the solar collector assembly (Shahrukh Saleem and ul Asar 2021).
- Availability of accessible grid connections if the CSP project is not designed to fulfill a specific local (site) demand for industrial applications.
- Availability of water resources, as the large amount of water consumed in the cooling towers is one of the disadvantages of CSP for power generation.
- The availability of good transportation facilities is a socio-economic aspect that should be considered in developing remote areas where CSP projects are usually built.
- Consideration of protected areas, wildlife traffic, and agriculture.
- Availability of a backup fuel supply.

Concentrated solar power (CSP) technologies

When considering harnessing solar energy, there are four main CSP technologies used: a Parabolic Trough Collector (PTC), a Central Solar Tower (CST), a Linear Fresnel Reflector (LFR) and a parabolic dish (Fernández et al. 2019; Hayat et al. 2019). Concentrated solar power plants are gaining increasing interest, mostly by using the parabolic trough collector system (PTC), although solar power towers are progressively occupying a significant market position due to their advantages in terms of higher efficiency, lower operating costs, and good scale-up potential.

A PTC plant consists of a group of reflectors that are curved in one dimension in a parabolic shape to focus direct solar radiation along an absorber tube that is mounted in the focal line of the parabola. In order to prevent heat loss to the ambient air, the absorber tube is enveloped by an evacuated glass tube. The reflectors and the absorber tubes move in tandem with the sun using a linear axis tracking mechanism from sunrise to sunset (Zhang et al. 2013). On the other hand, CST systems utilize a large field of mirrors implemented with a solar tracking mechanism on two axes, referred to as heliostats. The sunlight is focused at the top of the tower into the cavity of the central receiver (Gadalla and Saghafifar 2018), where the concentrated solar energy is absorbed by the circulating working fluid, converting the solar energy into thermal energy (Shatnawi et al. 2019).

Several recent studies have been conducted discussing the main features, operating principles, advantages, and challenges associated with PTC and CST systems, as evident in Table 1. Although CST plants are undeniably less widespread than PTC plants, there is an open debate in the literature about which CSP technology may have the best blooming prospects (Boretti et al. 2019). Taking into account the degree of maturity, the ease of implementation, and the literature reviews performed by researchers, PTCs represent a competitive technology supplying an adequate amount of heat to run conventional steam power plants in Egypt (Moharram et al. 2021a).

Contributions of previous research on concentrated solar power systems.

Multi-criteria decision making for optimum site and technology selection

When contemplating CSP deployment, it is worth noting that very few of the previously conducted studies have integrated location and technology selections in order to attain a decision-making strategy for the optimum selection, as shown in Table 2.

Contributions of previous research on simulation techniques for optimum site and technology selection.

Table 1 Contributions of previous research on concentrated solar power systems

References	Approach	Key findings
Baig et al. (2015)	A contrastive study between different solar collectors	PTCs have the highest reliability and maturity among CSP technologies
Purohit and Purohit (2010)	Theoretical examination of electricity generation in India using distinct CSP technologies	PTCs have the highest maturity level, leading to greater power output and lower unit electrical costs
Morin et al. (2012)	Examination of the cost and efficiency objectives of PTC and LFR power plants	PTCs are superior to LFR in all respects, except that LFR requires two-thirds less area
Desai and Bandyopadhyay (2015), Zhu (2013)	Demonstration of LFR with direct steam production as a cheaper solution using flat mirrors and simple design	LFR has lower optical efficiency compared to PTC technology
Franchini et al. (2013)	A comparative study between PTC and CST technologies integrated into the Rankine solar cycle	CST plants have higher overall efficiency compared to PTC when integrated with the Rankine cycle for power generation
Jorgenson et al. (2013)	Testimony on seasonal and daily fluctuations in solar irradiance causing variation in power production using PTC and CST	PTC has a strong seasonal dependence due to the seasonal "cosine" effect, which is more evident for single-axis tracking parabolic trough collectors than for two-axis tracking heliostats used in tower configurations
Hayat et al. (2019)	Comprehensive review of different concentrated solar power technologies utilized in electricity generation	CST plants are the most promising technology due to their low storage costs, achievable high capacity factor, and greater efficiency of the steam cycle

Table 2 Contributions of previous research on simulation techniques for optimum site and technology selection

References	Simulation technique	Key findings	Limitations
Wu et al. (2019)	Fuzzy PROMETHEE II technique integrated with fuzzy operator	Social and environmental aspects are the focus when pursuing a sustainable perspective in the site selection procedure	The study focuses solely on sustainability, overlooking the levelized cost of energy
Aly et al. (2017)	GIS-based analysis and Multicriteria Decision-Making (MCDM) techniques	Identifying the optimum locations for CSP plants implementation in Tanzania	The proposed solar power facility's contribution to the electricity grid was not taken into consideration
Division of Energy Systems Analysis at the Royal Institute of Technology for IRENA (Hermann et al. 2014)	GIS-based analysis	Determined the technological potential for utility-scale solar, wind, and biomass technologies based on the geographic potential of the African continent	Critical variables that greatly impact the economic viability of implementing the suggested renewable energy technology were excluded

Few studies investigated CSP technology, which relied mostly on parabolic trough collectors, while the others concentrated only on PV technology. Based on the objectives of each assessment and the selected strategy for addressing the problem, it may be argued that various investigations employed distinct methodologies and assumptions based on the governmental objectives in each location. There does not appear to be a comprehensive study in the literature that combines the levelized cost of energy, power productivity, and environmental impact for two distinct CSP technologies (PTC and CST) in a decision-making approach that takes into account the distinct local resources and geographical characteristics of different sites.

The novelty of this study is the development of a prediction tool using SAM software to anticipate the performance of concentrated solar power plants in Egypt. The two most mature CSP technologies (PTC and CST) are examined to determine the ideal choice to implement in several locations with favorable weather conditions, taking into consideration minimal environmental impact, cost efficiency, and high power productivity. Consequently, this signifies the feasibility and reliability of employing CSP plants to operate in Egypt, replacing conventional steam power plants, taking into account the site meteorological data, component benchmarks, and local financing and taxing regulations. Moreover, the proposed model is developed to aid the government's strategic plans targeting sustainable development in Egypt.

Materials and methods

From the previous review, more attention has been focused on the implementation of solar thermal power plants in Egypt, utilizing various CSP technologies at different locations. Illustrated in Fig. 2 are the schematic diagrams of the two proposed configurations under investigation in this study, employing parabolic trough collectors and central solar tower technologies, respectively (Csp Models and System Advisor Model 2021). The proposed plant can be disassembled into three main components. Firstly, the solar field acts as the heat source for the plant, whether by utilizing PTC or CST. Secondly, thermal energy storage tanks are mandatory in order to meet the plant's thermal demand during low solar irradiance periods and at night. The third component is the steam Rankine cycle, consisting of the heat exchanger, steam turbine, generator, and condenser.

The output forecasts and financial projections for CSP plants can now be made using a variety of free tools designed for fast measurements, such as "Greenius," developed by the Institute of Solar Research, or System Advisor Model (SAM), developed by NREL and distributed as a free software platform for forecasting the hourly and sub-hourly energy output of various renewable energy sources (Polo et al. 2017; Blair et al. 2014). As a consequence of SAM's versatility and capacities, it is becoming a basic method for the performance evaluation of CSP and PV plants in many studies (Avila-Marin et al. 2013; Vasallo and Bravo 2016; Bishoyi and Sudhakar 2017). In the research reported herein, two SAM simulations of a 115 MW CSP plant have been performed in the areas under investigation, utilizing parabolic trough and solar tower technologies individually. The input parameters will be presented in this section and may be classified as environmental, financial, and economic data.

Environmental data

Solar radiation data availability is essential, along with other data, for the simulation of any CSP project. Hourly DNI and
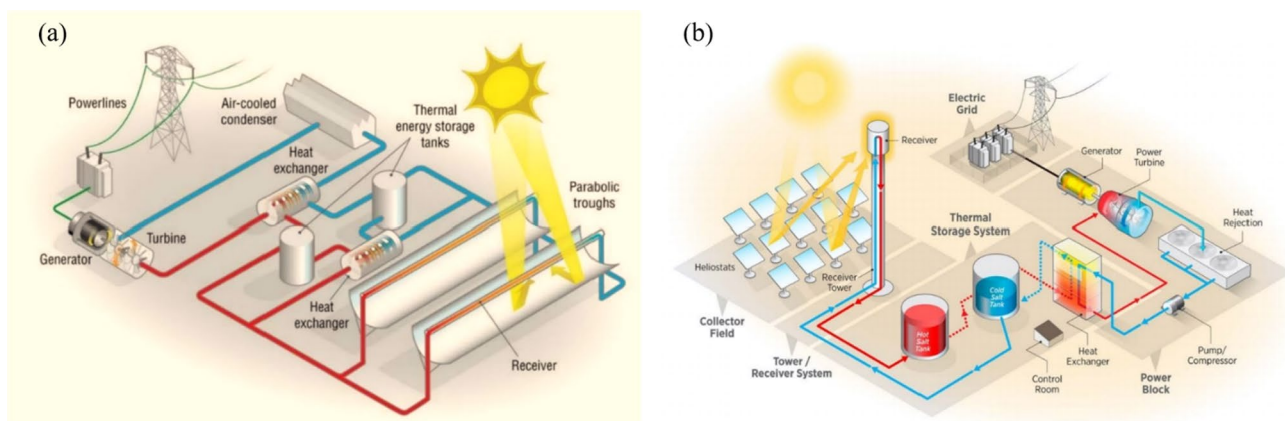

Fig. 2 Proposed plant configurations **a** PTC power plant, **b** CST power plant

Table 3 Environmental data sources

Source	Data type	Coverage	URLs
Solar GIS	Satellite data	Region between 60 North and 50 South latitude angles; from 1994, 1999 or 2006 to date depending on the region	https://solargis.com/about-us
SoDa Helioclim	Satellite data	Europe, Africa, Middle East from 2004 to date	http://www.soda-pro.com/web-services/radiation/helioclim-3-real-time-and-forecast
Meteonorm	Ground data	Global from 1981 to 2010	https://meteonorm.com/en/meteonorm-parameter
PVGIS	Mix	Global from 1981 to 2011	https://re.jrc.ec.europa.eu/pvg_tools/en/#TMY
NASA-SSE	Satellite data	Global from 1997 to date	https://ceres.larc.nasa.gov/

GHI values for a specific location in a standard format, most commonly TMY3 (Typical Meteorological Year version 3), are necessary to be used for any software (Cebecauer and Suri 2015). Some of the sources of the datasets are presented in Table 3. Mandatory solar, wind, and ambient (meteorological) data over a time period of two decades have been

Table 4 Parabolic trough and central solar tower plants design input parameters

Parabolic trough		Solar tower	
Solar field details			
Solar multiple	2	Solar multiple	2.4
Single loop aperture (m^2)	5248	Single heliostat area (m^2)	144.4
Number of loops	210	Number of heliostats	8790
Number of solar collectors per loop	8	Mirror reflectance	0.9
Field thermal output (MW$_t$)	623.6	Field thermal output (MW$_t$)	669.9
Solar field area (km^2)	2.376	Solar field area (km^2)	4.442
Total land area (km^2)	3.326	Total land area (km^2)	5.076
Collector area (km^2)	0.950	Total heliostat reflective area (km^2)	1.265
Collector Length (m)	99.5	Tower height (m)	193.5
Collector Width (m)	5.77	Receiver height (m)	21.60
Absorber tube outer diameter (m)	0.08	Receiver diameter (m)	17.65
Glass envelope outer diameter (m)	0.12	HTF type	Salt (60% $NaNO_3$ + 40% KNO_3)
HTF type	Therminol VP-1		
HTF hot temperature (°C)	391	HTF hot temperature (°C)	574
HTF cold temperature (°C)	293	HTF cold temperature (°C)	290
Thermal storage			
Storage fluid	Hitec solar salt	Storage fluid	Hitec solar salt
Full load hours (h)	10	Full load hours (h)	10
Storage volume (m^3)	25,325	Storage volume (m^3)	25,325
Storage capacity (MW$_t$)	3858	Storage capacity (MW$_t$)	3858
Loss coefficient (W/m^{2}K)	0.4	Loss coefficient (W/m^{2}K)	0.4
Tank height (m)	20	Tank height (m)	20
Tank diameter (m)	37.7	Tank diameter (m)	37.7
Power cycle			
Net output (MW$_e$)	102.3	Net output (MW$_e$)	103.5
Thermal efficiency (%)	35.6	Thermal efficiency (%)	41.2
Boiler pressure (bar)	100	Boiler pressure (bar)	100
Condenser type	Cooling tower	Condenser type	Cooling tower

collected from the Meteonorm database (https://meteonorm.com/en/meteonorm-parameter).

Technical data

The terminologies solar multiple (SM) and Equivalent Full Load Storage Hours (EFLSH), which are widely used to express the basic configuration of CSP plants, are applied. The SM is the proportion of the solar field's yield at design conditions to the nominal turbine power, while the EFLSH represents the ratio between design storage capacity and nominal turbine capacity. The proposed parabolic trough collector and solar tower power plants' input design parameters are presented in Table 4. The primary designs

Table 5 Financial input parameters (https://www.cbe.org.eg/en/Pages/default.aspx)

Parameter	Value
Fiscal data	
IRR target (%)	8
IRR target year	20
Analysis period (year)	25
Inflation rate (%/year)	2.5
Real discount rate (%/year)	3
Income tax rate (%/year)	22.5
Sales tax (% of total direct cost)	5
Insurance rate (% of installed cost)	0.5
Property tax rate (%/year)	0
Net salvage value (% of installed cost)	0
Project term debt	
Debt tenor (years)	18
Annual interest rate (%)	3
Up-front fee (% of total debt)	2.75
Construction finance	
Up-front fee (% of principal)	1
Months prior to operation	24
Annual interest rate (%)	4
Reserve accounts	
Interest on reserves (%/year)	1.75
Working capital reserve (months of operating costs)	6
Debt service reserve account (months of principal and interest payments)	6
Depreciation	
Allocations (%)	90
Period	5 years

were based on SAM default data, then modifications were applied, such as the selection of collectors, receiver tubes, power plants and other parameters aiming to lower LCOE and water consumption.

Financial data

The main financial input parameters are summarized in Table 5. A common interest rate of 3.0%/year has been selected (soft loan). Moreover, the debt period and operational plant life are assumed to be 18 and 25 years, respectively.

Economic data

In order to determine whether the proposed plant is practical and cost-effective, an economic evaluation is essential to assess the plant in comparison with conventional alternatives. An overview of parabolic trough and solar tower investment and operational costs is presented in Table 6 based on SAM default values, collected data from similar recent projects, and local benchmarks.

Model validation

The System Advisor Model (SAM) software has been extensively validated against experimental data for concentrated solar power energy facilities by Boretti et al. (2020). Their validation was based on data from the 250 MW parabolic trough facilities of Genesis, Mojave, and Solana, and the 110 MW solar tower facility of Crescent Dunes in the USA, concluding that SAM can be considered a reliable tool to model CSP technologies. Moreover, both solar fields (PTC and CST) presented in this paper have been validated against the following basic mathematical models.

Parabolic trough collector mathematical model

The following mathematical model presented by Moharram et al. (2021b) for modeling parabolic trough collectors has been utilized to validate the results obtained from the solar field in the proposed model.

The instantaneous efficiency of parabolic trough collectors can be calculated from its characteristic curve for the Euro-trough model using Eq. 1. Consequently, the amount of heat gained can be deducted as shown in Eq. 2.

Table 6 Economic input parameters (https://sam.nrel.gov/sites/sam.nrel.gov/files/content/case_studies/sam_case_csp_physical_trough_andasol-1_2013-1-15.pdf)

Parabolic trough			Solar tower		
Parameter	Unit	Unit Cost	Parameter	Unit	Unit Cost
Direct capital cost					
Site improvements	950,000m^2	25 USD/m^2	Site improvements	1,269,000 m^2	16 USD/m^2
Solar field	950,000 m^2	150 USD/m^2	Heliostat field	1,269,000 m^2	145 USD/m^2
HTF system	950,000 m^2	60 USD/m^2	Tower & Receiver	1	110.5 Million USD
Storage	3858 MW$_t$	65,000 USD/MW$_t$	Storage	3858 MW$_t$	24,000 USD/MW$_t$
Power plant	115 MW$_e$	850,000 USD/MW$_e$	Power plant	115 MWe	850,000 USD/MW$_e$
Balance of plant	115 MW$_e$	105,000 USD/MW$_e$	Balance of plant	115 MWe	340,000 USD/MW$_e$
Contingency		7%	Contingency		7%
Indirect capital cost					
EPC cost		5%	EPC cost		5%
Total land cost	Presidential Decree	nil	Total land cost	Presidential Decree	nil
Sales tax		5%	Sales tax		5%
Installed cost					
Total installed cost per net capacity	115 MW$_e$	5,263,000 USD/MW$_e$	Total installed cost per net capacity	115 MW$_e$	5,845,000 USD/MW$_e$
O&M costs					
Fixed cost	115 MW$_e$	66,000 USD/MW$_e$`	Fixed cost	115 MW$_e$	66,000 USD/MW$_e$
Variable cost	115 MW$_e$	3000 USD/MW$_e$	Variable cost	115 MW$_e$	3,500 USD/MW$_e$

$$\eta_{\text{PTC}} = 0.75 - 4.5 \times 10^{-5}\left(T_{\text{col}} - T_{\text{amb}}\right)$$
$$- 0.039\left(\frac{T_{\text{col}} - T_{\text{amb}}}{G}\right) - 3 \times 10^{-4}$$
$$\times G\left(\frac{T_{\text{col}} - T_{\text{amb}}}{G}\right)^2 \tag{1}$$

$$Q = A_{\text{field}} \times \eta_{\text{PTC}} \times G \tag{2}$$

The parabolic trough area can be deduced using Eq. 3 by means of the benchmark standards for collector width and glass envelope diameter.

$$A_{\text{PTC}} = L_{\text{PTC}} \times \left(W_{\text{col}} - D_{\text{env}}\right) \tag{3}$$

Moreover, by assigning the collector mass flow rate and the hydraulic mass flow rate as input parameters, the number of loops, loop area, loop width, and the number of parabolic trough collectors are then calculated using Eqs. 4–7, respectively.

$$N_{\text{loop}} = \frac{\dot{m}_{\text{col}}}{\dot{m}_{\text{hyd}}} \tag{4}$$

$$A_{\text{loop}} = \frac{A_{\text{PTC}}}{N_{\text{loop}}} \tag{5}$$

$$W_{\text{loop}} = \frac{A_{\text{loop}}}{L_{\text{m}}} \tag{6}$$

$$N_{\text{PTCs}} = \frac{A_{\text{PTC}}}{L_{\text{m}} \times \left(W_{\text{col}} - D_{\text{env}}\right)} \tag{7}$$

The total pressure losses are subsequently calculated based on major and minor losses along the field length. The general loss equation is presented in Eq. 8.

$$P_{t_{\text{loss}}} = N_{\text{loop}} \times \Delta P_{\text{loop}} \tag{8}$$

Central solar tower mathematical model

The mathematical model for CST presented in the following section was used to anticipate the basic output performance parameters required to validate the data obtained using SAM software. The heliostat field is the costliest component when considering the implementation of CSTs; therefore,

the heliostats should be carefully allocated in the field to obtain the maximum efficiency. Thus, solar field efficiency is deduced using Eq. 9 (Moukhtar et al. 2021). Consequently, the amount of thermal energy available can be obtained using Eq. 10 (Reddy et al. 2014).

$$\eta_{field} = \eta_{refl} \times \eta_{att} \times \eta_{cos} \times \eta_{sh\&bl} \tag{9}$$

$$Q = A_{field} \times \eta_{field} \times G \tag{10}$$

The cavity top temperature is calculated based on the cavity effectiveness relation between receiver temperature and inlet and outlet temperatures as expressed in Eq. 11.

$$T_{rec} = \left(\frac{T_o - T_i}{\varepsilon_{cav}} \right) + T_i \tag{11}$$

Validation results

The validation procedure was conducted by using variable solar intensities in order to measure the output thermal energy available from both CSP technologies. Similar input parameters and climatic data were processed using SAM software and compared to the results obtained using MATLAB software to solve the mathematical model of each solar field. Preliminary results considering output thermal energy were computed using both models, yielding a standard error of 2.38% and 3.62% for the PTC model and CST model, respectively. Moreover, SAM validation was performed on two CSP reference plants in Spain: Andasol-1 as a parabolic trough and Gemasolar as a solar molten-salt tower plant. For Andasol-1 and Gemasolar, the annual production uncertainty was 2.6% and 2.4%, respectively (https://sam.nrel.gov/sites/sam.nrel.gov/files/content/case_studies/sam_case_csp_physical_trough_andasol-1_2013-1-15.pdf).

Results and discussion

A comparative study was conducted for the two proposed configurations previously described, yielding a performance assessment for the 28 different locations of implementation. Taking into consideration the conversion efficiency of both collectors, together with the effective operating hours governing the thermal storage capacity for both technologies, the calculated land area required

for the solar tower is higher than the parabolic trough area by 25%. This increase in collectors' area increased the net capital cost of the solar tower configuration over the parabolic trough net capital cost by 15%. On the other hand, the annual power produced and the water consumed by the power plant with the solar tower configuration are approximately 20% higher than those of the same power plant with the parabolic trough collectors configuration; thus, a reduction in the levelized cost of energy is denoted in the case of the solar tower, however, concerns regarding environmental impacts arise. Among many simulated parameters, only three major factors have been considered to evaluate the two proposed configurations with GIS aid. Those parameters are the annual power production, water consumption, and LCOE, which are presented in Table 7.

In addition to the results illustrated in Fig. 3, the GIS maps visualized in Figs. 4, 5, and 6 reveal that the water consumption of plants located in the northern zones (Mediterranean and Suez Gulf) is less compared to those in the central, eastern, and southern zones, respectively, for both technologies' configurations. Moreover, the LCOE has been driven by the estimated annual power production. The lowest levelized cost of energy is achievable in the central zones, followed by the eastern and southern zones, respectively. Finally, the highest LCOE is in the northern zones for both technologies' configurations.

The annual power produced by the plants located in the central zone (Nile zones) is higher than plants in the southern region (Aswan), eastern zone (Red Sea), and northern zones (the Mediterranean Sea and Suez Gulf), respectively. The results obtained comply with the operational nature of steam power plants in hot, arid regions, as the water that is used to cool down the power block consequently has a high temperature, reducing production and efficiency (Hoffmann et al. 2013). The eastern zone showed promising results close to the central zones, having a high annual power production together with an adequate amount of water consumption and a low LCOE, unlike the northern zone results for both technologies' configurations, as illustrated in Fig. 7. It is worth mentioning that parts of the southern locations have been selected for PV projects that are already installed, such as the Benban PV power plant (Mohamed and Maghrabie 2022), and parts of the northern locations have been selected for wind projects that are already in operation, such as the Zaafarana and Gabal Elzeit wind farms (Aliyu et al. 2018).

In summary, the parametric study demonstrates that the eastern regions are the most suitable location for

Table 7 PTC and CST simulation results for the 28 locations devoted to renewable energy projects

Technology	Parabolic trough			Solar tower		
Parameter	Annual power MWh/year	Annual water usage m³/year	LCOE USD/kWh	Annual power MWh/year	Annual water usage m³/year	LCOE USD/kWh
Red Sea Zone						
Hurghada Alahyaa	450,000	91,400	0.0671	664,200	104,120	0.0524
Hurghada km10	445,600	90,883	0.0678	652,700	103,290	0.0532
Marsa Alam	429,100	89,097	0.0703	619,200	100,870	0.0559
Gebel Elzeit	437,200	89,761	0.0690	647,600	102,730	0.0536
Sharm Elshaeikh	429,500	89,310	0.0702	638,800	102,390	0.0543
Suez Gulf Zone						
L1	342,500	79,678	0.0873	501,200	92,250	0.0683
L2	356,100	81,093	0.0841	521,800	93,703	0.0657
L3	335,400	78,926	0.0891	492,300	91,615	0.0694
L4	347,500	80,215	0.0861	510,400	91,901	0.0671
El Galalah	365,100	81,514	0.0821	533,600	92,244	0.0643
Mediterranean Sea Zone						
Ras Elhekma	376,400	82,739	0.0797	551,500	95,470	0.0623
Baghoush	384,600	83,521	0.0781	563,800	96,312	0.0611
El Mathany	364,300	81,432	0.082	531,500	94,032	0.0646
El Hammam	354,000	80,487	0.084	511,700	92,764	0.0669
West and East Nile Zone						
L1	433,100	88,998	0.0697	649,100	132,610	0.0584
L2	437,000	89,684	0.0691	659,700	103,530	0.0575
L3	443,500	90,279	0.0681	661,000	103,630	0.0574
East Nile Zone						
East Wind 1	420,600	87,873	0.0716	609,800	100,020	0.0567
East Wind 2	435,800	89,560	0.0692	660,200	103,540	0.0527
East Solar 1	441,300	90,005	0.0684	651,900	102,970	0.0533
East Solar 2	449,000	90,974	0.0673	682,500	105,140	0.0510
East Solar 3	431,900	88,892	0.0698	646,700	102,460	0.0537
Zm1	447,100	90,648	0.0676	663,200	103,780	0.0524
Zm2	433,200	89,188	0.0696	640,700	102,180	0.0542
Zm3	442,300	90,263	0.0683	669,800	104,240	0.0520
Zm4	422,100	87,836	0.0714	628,900	101,180	0.0551
Aswan						
Benban	396,400	80,039	0.0758	564,900	97,428	0.061
Fares	396,300	85,987	0.0758	564,200	97,356	0.061

implementing both proposed configurations. However, the results reveal that the central solar tower (CST) generates a significantly higher annual power output compared to the parabolic trough collector (PTC) configuration, which is consistent with the findings reported by Amani et al. (2022). Nonetheless, the results of the proposed model are in
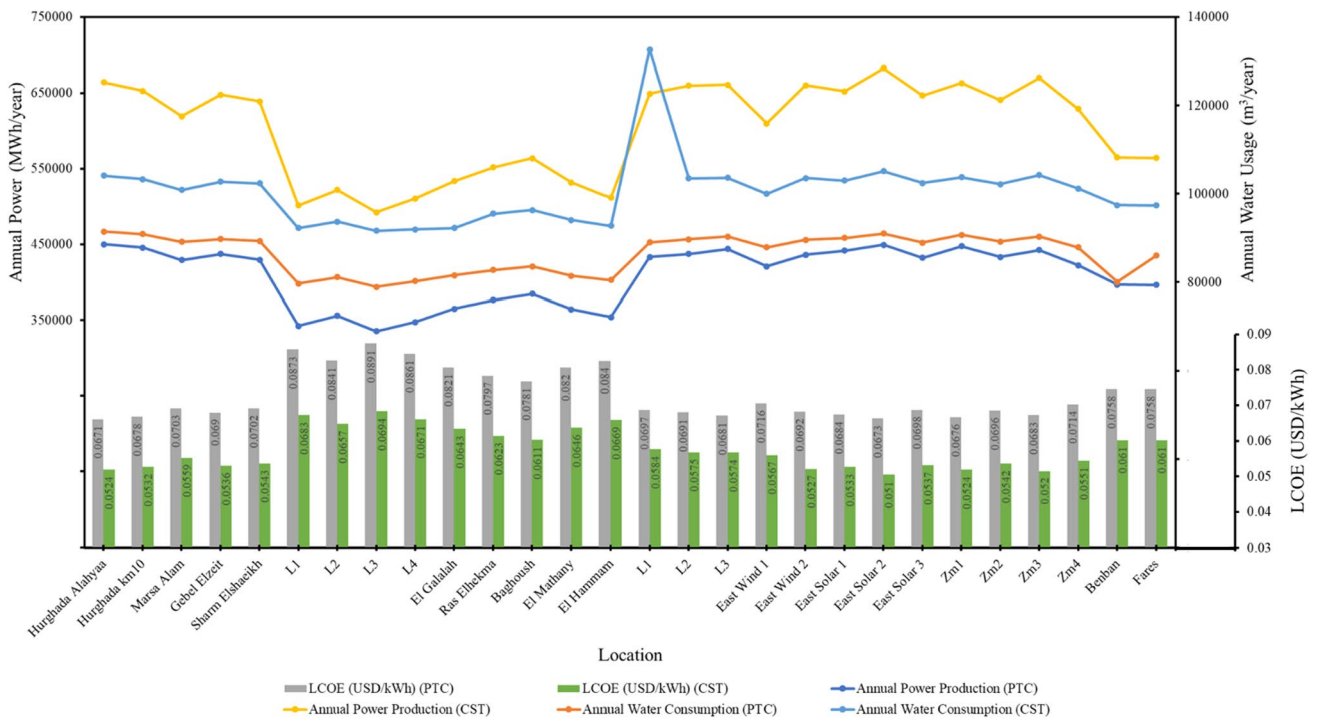
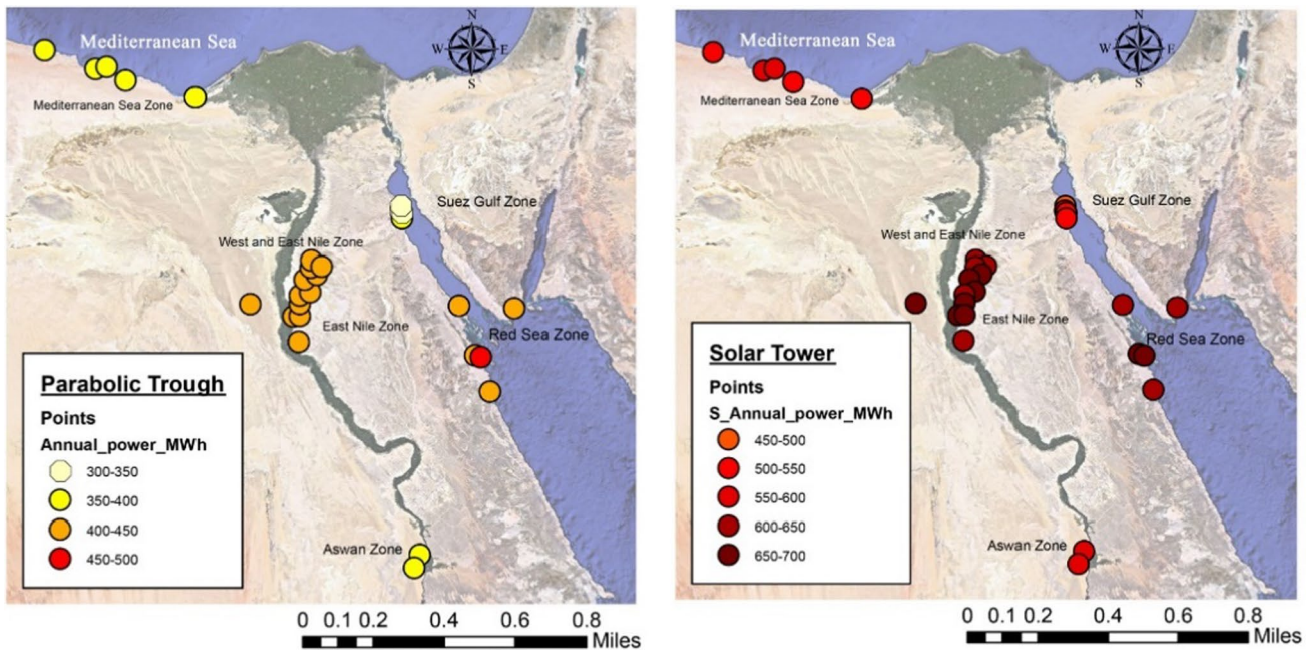**Fig. 3** PTC and CST trends of power production, water consumption and LCOE for different locations in Egypt

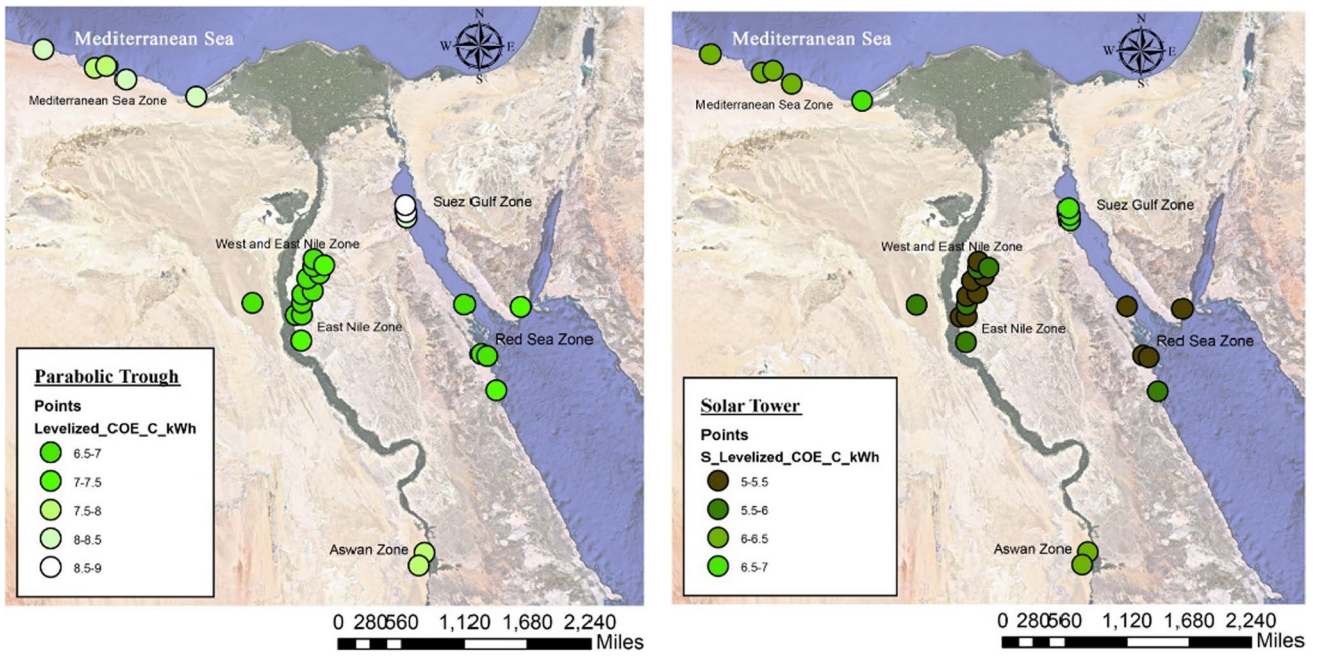**Fig. 4** GIS mapping for annual power production (MWh/year)

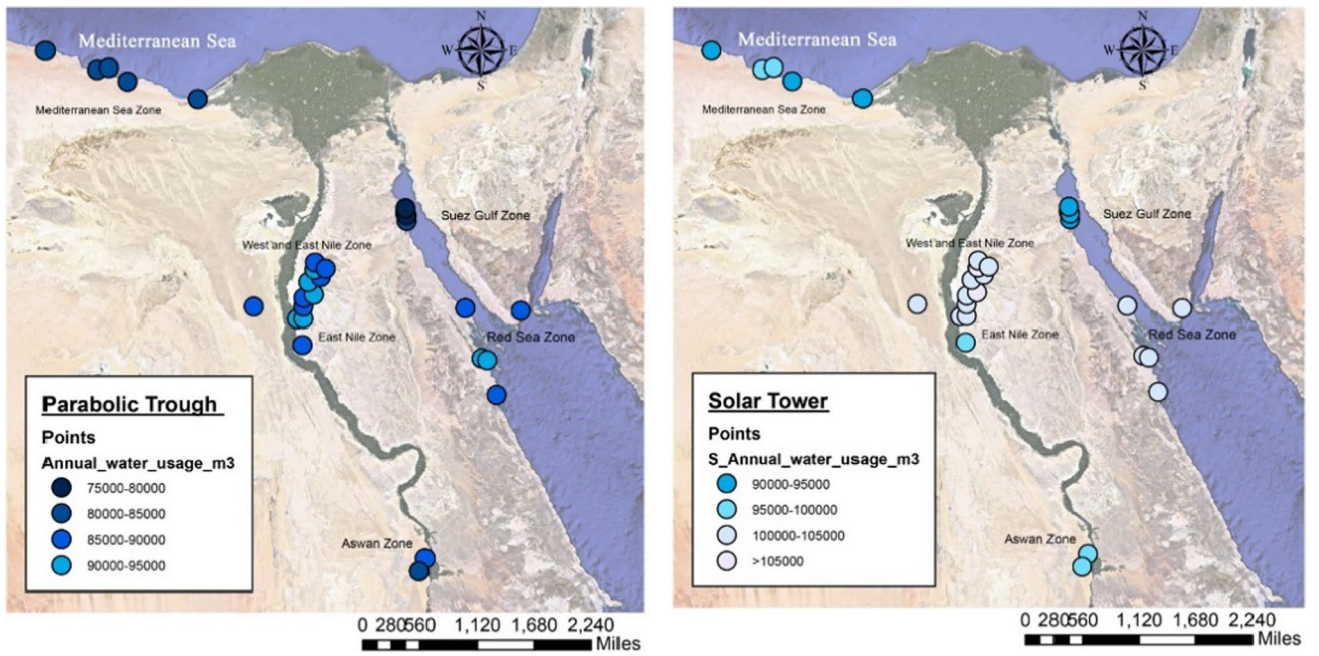**Fig. 5** GIS mapping for levelized cos of electricity (cents/MWh)

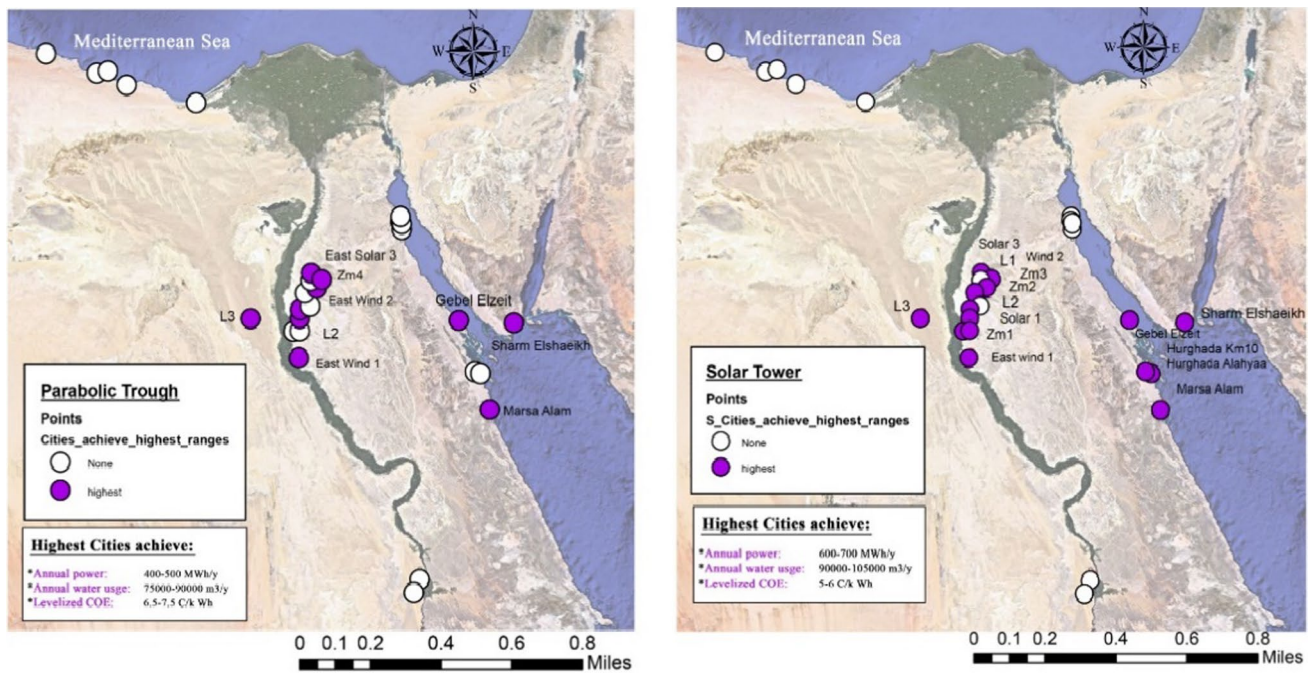**Fig. 6** GIS mapping for annual water consumption (m³/year)

Fig. 7 GIS mapping indicating the geographic regions achieving promising outcomes

agreement with research conducted by Ahmad and Zeeshan (2023), declaring that the use of CST results in greater water consumption, making the decision to use CST dependent on water availability in the region. Additionally, the GIS maps presented in Fig. 6 provide valuable information to the New and Renewable Energy Authority (NREA) and the Ministry of Electricity and Renewable Energy in Egypt, allowing them to make informed decisions regarding site and technology selection for renewable energy projects in the 28 locations earmarked for sustainable development.

Conclusion and prospects

A thermo-economic model has been established using SAM software to investigate the feasibility of implementing concentrated solar power plants in various locations in Egypt. Two proposed models were examined to indicate the optimum site-specific CSP technology to be employed in each location devoted to renewable energy development in Egypt. Moreover, a comparative study was conducted on an

annual basis between the three major parameters affecting decision-making when considering implementation, which are power productivity, water consumption, and the LCOE. The Geographical Information System was used to illustrate the results from the 28 locations in order to establish a strategic planning guide for Egypt's sustainable development. The key findings from the simulations were as follows:

- The solar tower configuration requires 25% more land than the parabolic trough configuration. This increase in collector area elevated the solar tower's net capital cost by 15% above the parabolic trough.
- For both technologies, plants in the northern zones (Mediterranean and Suez Gulf) consume less water than those in the central, eastern, and southern zones.
- Plants implemented in the central zone (Nile zones) generate more annual electricity output than plants in the southern region (Aswan), eastern zone (Red Sea), and northern zone (Mediterranean Sea and Suez Gulf), respectively.
- According to the parametric analysis, the eastern zones have been shown to be an advantageous area for implementing both indicated technologies.

In conclusion, setting up a prediction tool that anticipates the amount of energy available in different locations has the capability of providing Egypt with an environmentally friendly renewable energy source, encouraging the rapid urban expansion of sustainable cities.

Despite the fact that power productivity, water consumption, and LCOE are considered reliable parameters in order to select the optimum site-specific CSP technology, further research is recommended to investigate the results presented using several sustainability assessment tools, including exergo-economic and exergo-environmental approaches, as elaborated in recent studies conducted by Rahnama et al. (2019), Aghbashlo et al. (2020). Furthermore, setting a deterministic analysis can pave the way for adding supplementary modifications to the proposed models. For instance, Moharram et al. (2021a; b) investigated cogeneration hybrid plants that can produce power and fresh water simultaneously.

Availability of data and materials Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Approved.

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