Int. J. Renew. Energy Dev. 2023, 12(4), 767-778

Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Assessment of the technical-economic performance and optimization of a parabolic trough solar power plant under Algerian climatic conditions

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Abstract. In this study, the design, analysis and optimization of the performance of a concentrated solar power plant that is based on the parabolic trough technology with a capacity of 100 MW equipped with a thermal energy storage system were conducted, in two representative sites in Algeria (Tamanrasset and M'Sila). The System Advisor Model software is used to evaluate the technical and economic performances of the two proposed power plants, in addition to carrying out the process of optimizing the initial design of the two power plants by finding the optimal values of the solar multiple and full load hours of the thermal energy storage system, with the aim of increasing the annual energy production and reducing the levelized cost of electricity. The results of the performance analysis conducted on the optimized design showed that the optimum values of the solar multiple and full load hours of the thermal energy storage system for the proposed power plant at the Tamanrasset site were found to be 2.4 and 7 h, respectively, with an annual electricity production of 514.6 GWh, and a minimum value of the levelized cost of electricity of 6.3¢/kWh. While the optimum performance of the proposed plant at the M'Sila site can be achieved by selecting a solar multiple of 3 and 7 h for thermal energy storage system, with a high annual energy production of 451.84 GWh and a low value of the levelized cost of electricity of 7.8¢/kWh. The results demonstrate that CSP plants using parabolic trough technology can increase energy security in the country, while reducing environmental concerns associated with the use of fossil materials.

Keywords: Solar energy, Concentrated solar power, Parabolic trough power plant, System Advisor Model (SAM).

Received: 4th May 2023; Revised: 18th June 2023; Accepted: 29th June 2023; Available online: 5th July 2023

1. Introduction

The needs of mankind for energy are increasing every year, this is due both to the growth of the population, the development of production and technology, and to the increase in energy consumption in everyday life. As human demand for modern energy supply increases, attention to solar energy becomes more intense. Consequently, there are active plans to utilize solar energy for different processes to minimize energy demand from conventional energy supply sources (Bouguila & Said, 2020).

The production of electric energy by exploiting renewable energies, especially solar energy, is a challenge of great importance for the coming years (Keykhah *et al.*, 2021). In fact, Algeria's electric power needs are rising every day. Moreover, Algeria will need more energy to implement its development plans. Today, most of the energy production in Algeria comes from fossil sources, the intensive use of these sources leads to the depletion of its reserves and thus the insecurity of energy in the country, because it is not considered a renewable energy source, in addition to the negative effects on the environment (greenhouse gas emissions). With Algeria's energy demand expected to increase by about 53%, its current reservoirs of conventional energy resources are expected to sufficiently support the country's electricity production for about 50 years (Benhadji Serradj *et al.*, 2021).

In order to remove all these restrictions, the Algerian state must turn to renewable energies, especially solar energy, to exploit it in order to meet the increasing demand for energy in the country. Algeria is the largest country in Africa in terms of area, located in the center of North Africa on the Mediterranean coast, between latitudes 19° and 38°N and longitudes 8°W and 12°E, with an area of 2,381,741 km², and a transitional climate, from maritime in the northern regions to semi-arid and arid in the central and southern regions (Benhadji Serradj *et al.*, 2021; Keykhah *et al.*, 2021). As it is located within the sun belt region, Algeria has great potential for solar energy. It has one of the highest solar energy deposits in the world (Abbas *et al.*, 2013; T. E. Boukelia *et al.*, 2015b). The northern region sees approximately 2650 hours of the insolation time annually, while in the southern region it reaches about 3500 hours (Stambouli *et al.*, 2012).

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https://doi.org/10.14710/ijred.2023.54056
ISSN: 2252-4940/© 2023.The Author(s). Published by CBIORE

The energy transition is Algeria's path to a secure, environmentally friendly and economically prosperous future. The central element of this transition is the restructuring of our energy supply towards the use of renewable energies. This means that renewable energy will become our primary source of electricity. In recent years, there has been an increase in the level of use in the electricity sector.

In response to the high demand for energy and the negative impacts on the environment, researchers around the world are working to find more sustainable alternative energy technologies.

Among the power generation technologies that have been developed, concentrated solar power (CSP) systems are a direct alternative to power plants based on fossil fuels. CSP plants can contribute 6% of the world's electric power demand by 2030 and 12% by 2050 (Islam *et al*., 2018).

CSP appears to be the method of choice for large capacity, utility-scale electric generation in the near term. This technology has the possibility of energy storage and auxiliary heat production during sunlight unavailability.

In CSP systems, sunlight is concentrated using mirrors to create heat, then the heat is used to create steam, which is used to drive turbines and generators, just like in a conventional power station. Since solar energy is not very dense, it is necessary to concentrate the solar radiation to obtain high temperatures that can be exploited to produce electricity (Islam *et al*., 2018; Stambouli *et al*., 2012). According to the concentrating geometry, CSP systems can be classified into point and linear concentrators; solar tower and dish solar systems use point concentrators, while parabolic trough and linear Fresnel collectors use linear concentrators (T. E. Boukelia *et al*., 2015a; El Gharbi *et al*., 2011).

The CSP plants have economic justification only for locations where direct normal irradiation (DNI) values are greater than 5.5 kWh/m^2/day or (2000 kWh/m^2/year) (Hirbodi *et al*., 2020).

The parabolic trough technology power plant is one of the best proven CSP systems for its maturity and applicability in arid and semi-arid regions (Reddy & Kumar, 2012). CSP-based technology is suitable for high DNI areas (Praveen *et al*., 2018).

With sunlight concentrated approximately 70-100 times by parabolic trough mirror technology, the operating temperature achieved is in the range of 350-550°C (Ummadisingu & Soni, 2011). The thermal energy collected at the solar field level is transported by a heat transfer fluid (HTF) that circulates through the solar receivers and returns to a series of heat exchangers in the power block where superheated high-pressure steam is generated. The power block actually used in solar power plants is the steam cycle which uses a steam turbine generator to produce electrical energy (Lovegrove & Csiro, 2012).

Most designs of commercial parabolic trough technology CSP plants contain a solar field and a power block, and in order to maintain a constant electrical energy production both thermal energy storage (TES) and fuel backup systems can be used (T. E. Boukelia *et al*., 2015a). The majority of CSP plants using parabolic trough technology are equipped with TES system to ensure constant energy production and to extend the plant's operating time during times of low or absent solar radiation (Bouguila & Said, 2020).

Reddy et al. (Reddy & Kumar, 2012) conducted a technical and economic study of a 5 MW CSP plant with parabolic trough technology at 58 sites in India. The results showed that the annual electricity production in the studied sites ranged between 11 and 18 MW, and the levelized cost of electricity (LCOE) in Jodhpur site amounted to 11.00 and 11.84 Indian rupees/kWh for the plant that uses oil and water as HTF, respectively. Kalogirou (Kalogirou, 2013) analyzed the technical characteristics, the cost of electricity produced and land area required, for three types of CSP technology (parabolic trough, solar tower and solar dish) in Cyprus. The results indicate that the CSP plant with a parabolic trough and a TES system with a capacity of 4 h is the best option for installation in Cyprus, since it has a high annual efficiency and does not require a large land area.

A study by Guzman et al. (Guzman *et al*., 2014) where the performance of a parabolic trough CSP plant with TES system for the city of Barranquilla (Colombia) is simulated for find the ideal plant design optimization and the key design parameters. The results showed that the studied plant could contribute 50% of the city's electrical consumption, and through the optimization results it was found that the solar multiple (SM) is 2 and 6 hours for the capacity of the TES system. Bhuiyan et al. (Bhuiyan *et al*., 2020) carried out a study to optimize key design parameters of a parabolic trough CSP plant, in addition to evaluating the optimum design performance of the plant at eight different sites in Bangladesh. The results showed that the power plant that uses molten salt as a HTF offers better performance compared to the thermal oil plant. Tahir et al. (Tahir *et al*., 2021) evaluated the technical and economic feasibility of a CSP plant with a parabolic trough collector at six sites in Pakistan, and carried out an optimization study to obtain the optimal design of the proposed plants that reduces the LCOE. The results indicated that Pishin site provided the lowest value for LCOE compared to other sites, and in terms of the availability of suitable infrastructure, it is noticed that Quetta site is the ideal site for the construction of these plants. Mohammadi et al. (Mohammadi *et al*., 2021) conducted a technical, economic and environmental analysis of the performance of a solar power plant with a parabolic trough technology for thermal energy production in Salt Lake City (USA). The results revealed that the annual production of the plant amounted to 15,389.24 MWth, at a levelized cost of heat estimated at 26.3 $/MWth, and the results showed the optimization also has a significant impact of the values of the SM, the investment tax credit, and the total cost of the plant on the levelized cost of heat.

Bashir et al. (Bashir & Özbey, 2022) conducted a design study for a hypothetical CSP plant with a parabolic trough collector with a capacity of 80 MW in Sudan, and in order to determine the appropriate sites for the installation of such plants, they analyzed the thermal performance and economic feasibility of the plant studied in 15 sites in Sudan. The results concluded that the city of Wadi Halfa, located in the northern region of Sudan, is one of the suitable sites for the establishment of CSP plants, given that it has the highest rates of DNI, in addition to its good topographical characteristics and favorable climatic conditions. The annual electrical production of the proposed plant at the Wadi Halfa site was 281.145 GWh with an overall efficiency and capacity factor (CF) of 15% and 40.1%, respectively. Through the economic analysis of the plant, the LCOE was 0.155$/kWh.

Focusing on Algeria, Benhadji Serradj et al. (Benhadji Serradj *et al*., 2021) carried out a design and analysis of the technical and economic performance of a power plant using parabolic trough technology in the city of Tamanrasset (southern Algeria). They found that the plant could provide about 78% and 60% of the city's electrical consumption during winter and summer respectively, and that the LCOE was about 0.062$/kWh with a payback period of 8.78 years. Benabdellah et al. (Benabdellah & Ghenaiet, 2021) conducted a techno-economic analysis of the integrated solar combined cycle

(ISCC) power plant that uses parabolic trough technology and is currently operating in the Hassi R'mel region (southern Algeria). The studied plant is equipped with a new TES System. The obtained results show significant improvements in both the overall performance of the studied plant and the efficiency of converting solar energy into electrical energy. The results of the economic evaluation of the studied plant showed that the LCOE was about 9.75 ¢/kWh. In addition, the integration of the TES system into the power plant helps better stability of the grid, and the modified power plant can save about 30 million$ in natural gas consumption. Debbache et al. (Debbache *et al.*, 2018) conducted an investigation study to find out the effect of some parameters of the design of the parabolic trough collector (aperture width and focal distance) on the energy produced for the CSP plant that depends on the parabolic trough technology, proposed in the city of Touggourt (southern Algeria). The results of the study show that the electricity production increases with the increase in aperture width with the smallest focal distance. In addition, it was found that the best design for a parabolic trough collector is an aperture width of 5 m and a focal distance of 0.5 m which leads to an annual production of 30 MWh. Achour et al. (Achour *et al.*, 2018) examined the performance of a power plant based on ISCC technology in southern Algeria by developing a thermodynamic model to evaluate both the overall performance of the hybrid solar power plant and the intensity of solar radiation. The results showed that the efficiency of converting solar energy into electricity during sunny hours reaches 14.4%. In addition, the flow rate of the HTF and the solar incidence angle on the collector surface are among the factors that affect the amount of electricity generated.

From the above literature review, it is clear that the majority of studies related to the design, performance evaluation and optimization of CSP plants with a parabolic trough collector are conducted at sites in Asia, India, Bangladesh, and North and South America. However, the most of the available research works on the deployment of CSP plants with parabolic trough technology in Algeria is generally limited to a preliminary evaluation of the advantages of their installation and a study of their economic feasibility. Numerous researches related to the design, performance analysis and optimization of the parabolic trough CSP plants in Algeria, have been performed. However, to the best knowledge of us, the most of these studies were carried out on grounds located in the southern region of the country. The question arises whether these studies can be used to simulate the parabolic trough CSP plants in northern Algeria such as the M'Sila site which has an important potential solar energy as shown by (Kherbiche *et al.*, 2021). Research in this aspect is very important due to the urgent need to find more sustainable alternative energy technologies such as exploiting renewable energy sources to meet the increasing demand for electricity in Algeria and reducing dependence on traditional energy resources and the resulting negative effects on the environment. For this reason, this study is being conducted to design, analyze and optimize the performance of a 100 MW CSP plant based on parabolic trough technology with a TES system at two representative sites in Algeria. An important aspect of this analysis is the comparison of the results of two representative sites in Algeria (Tamanrasset and M'Sila).

2. Methodology

The design and analysis of the technical and economic performance of the CSP plant based on the proposed parabolic trough technology is carried out at the two selected sites using System Advisor Model (SAM), a software used to design and evaluate the technical and economic potential of solar power plants, and to assist in the decision-making of those involved in the renewable energy industry (Achour *et al.*, 2018). It was developed by the National Renewable Energy Laboratory (NREL).

The methodology of this study consists of the following steps: (i) collecting meteorological data for selected locations, (ii) design of a 100 MW CSP plant with TES, (iii) evaluation of the performance of the preliminary design of the proposed solar power plant in two representative sites in Algeria (Tamanrasset in the far south and M'Sila in the northern region), (iv) study the Environmental impacts: water consumption, carbon dioxide (CO_2) emissions and natural gas preservation, and (v) optimization of the parabolic trough power plant with TES. The main parameters of the optimization process are full load hours of the TES and the SM.

2.1 Site selection and resource assessment

To evaluate the performance of the proposed CSP plant, the SAM software needs the meteorological data for the two selected sites, which were obtained by creating a typical meteorological year 3 (TMY3) weather file data format from the METONORM7 software database. The average daily DNI in Algerian territory ranges between 4.66 kWh/m^2 in the northern regions and 7.26 kWh/m^2 for the southern areas, and this corresponds to 1700 kWh/ m^2/year and 2650 kWh/ m^2/year for the northern and southern regions, respectively (Taqiy Eddine Boukelia & Mecibah, 2013; Kherbiche *et al.*, 2021).

In this study, two representative sites in Algeria providing average annual DNI greater than 5.5 kWh/m^2/day were selected to analyze and optimize the performance of the proposed CSP plant. The two selected sites are Tamanrasset in the far south, and M'Sila for the northern region. The characteristics of the two selected sites, Tamanrasset and M'Sila, are presented in Table 1.

In Figure 1 are shown the monthly changes of average DNI and ambient temperature for the Tamanrasset and M'Sila sites. Comparatively, the Tamanrasset site is characterized by a high irradiation level of more than 7 kWh/m^2/day throughout the year except for the months of September and December. During March, the DNI reached its maximum value of 9.019 kWh/m^2/day, while December recorded its lowest value at 6.703 kWh/m^2/day. It can also be observed that the maximum and minimum values of the average ambient temperature were respectively in the months of June and January, on the other hand the average DNI at the M'Sila site has a maximum during

Table 1
Characteristics of the selected locations analyzed in this study.

Location	Latitude and Longitude	Elevation (m)	Daily Average DNI(kWh/m^2/day)	Daily Average Temperature(°C)
Tamanrasset	22.78° N, 5.51° E	718	7.70	22.8
M'Sila	35.70° N, 4.54° E	476	6.25	21.6

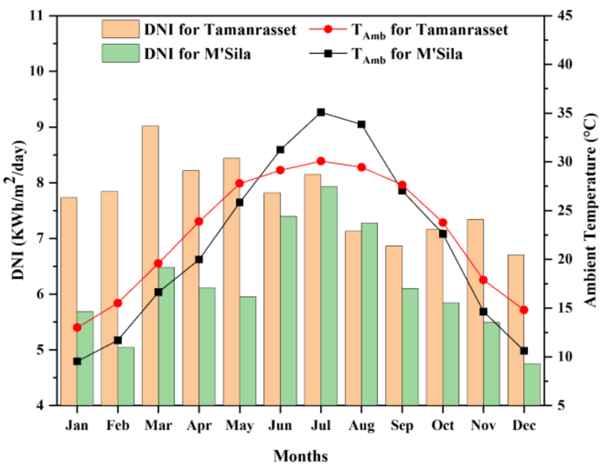

Fig. 1 Average DNI per month and ambient temperature for the two selected sites (Tamanrasset and M'Sila).

July of 7.934 kWh/m²/day and a minimum of 4.753 kWh/m²/day during December. In addition, the average maximum and minimum temperature values were recorded in July and January, respectively.

2.2 Parabolic trough solar thermal power plant

Among the CSP technologies available, the parabolic trough technology is today the most widespread, the most successful and the most developed for the production of electricity (Taqiy Eddine Boukelia & Mecibah, 2013). Figure 2 is a schematic diagram of parabolic trough solar power plants with TES. It can be seen that these power plants consist of three main parts, including the solar field, the TES system, and the power block (Belgasim & Elmnefi, 2014). The solar collectors are arranged in a series configuration known as loops and oriented in a north-south direction to follow the sun from east to west. TES can be used with solar power plants to ensure the continuity of electricity production. Normally, the TES capacity is in the order of several hours during which it is filled with HTF during the day and emptied after sunset so that electricity is still produced even after sunset.

2.3 characteristics of the proposed CSP plant design

The CSP plant subject to this study consists of 898160 m² of solar field reflector based on the one of LS3 Model (LUZ solar collector, third generation). These collectors are equipped with a Schott PTR70 2008 type vacuum receiver tube. The LS3 solar collectors are oriented in the north-south direction and its direction axis is parallel to the horizontal plane. The HTF used in the solar field is Therminol VP-1, and molten salt as the storage fluid, these two traditional HTF fluids are often used in CSP-based power generation systems (Bouguila & Said, 2020).

The solar multiple (SM) is defined as the ratio between thermal power obtained by the solar field at design point and thermal power required by the power block at nominal conditions, and it can be expressed as (Marugán-Cruz *et al.*, 2019) :

$$SM_{design\ point} = \frac{E_{thSF}}{E_{th\ PB}} \quad (1)$$

where: $E_{th\ SF}$ is the thermal energy obtained by the solar field and $E_{th\ PB}$ is the thermal energy required by the power block at nominal conditions.

The proposed CSP plant has a TES system in the form of two circular tanks containing molten salt which consists of 60% sodium nitrate (NaNO3) and 40% potassium nitrate (KNO3) (Purohit & Purohit, 2017). TES system allows the supply of thermal energy to the power block when solar radiation is low or absent during the day or night (Ghodbane *et al.*, 2021).

The full load hours of TES for a CSP plant specifies the number of hours thermal storage can supply energy to the power block to operate at the designed input level (T. E. Boukelia *et al.*, 2015b), and is given by the expression:

$$H_{TES} = \frac{P_{des}\, h_{TES}}{\eta_{des\ cycle}} \quad (2)$$

where: H_{TES} is the thermal energy storage system capacity; P_{des} is the design cycle thermal requirement; h_{TES} the total number of

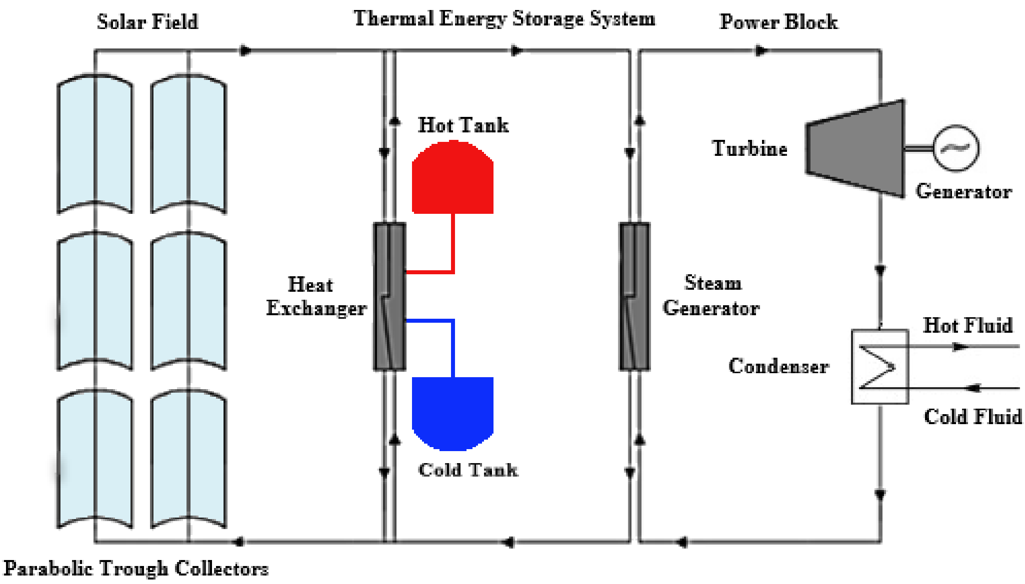

Fig. 2 Schematic diagram of a parabolic trough CSP plant with TES system.

desired storage hours; and $\eta_{des\ cycle}$ the design point cycle efficiency.

For the initial analysis, the value of the SM is set as 2 and the full load hours for TES are taken to be 6 h. The initial design of the 100 MW parabolic trough solar thermal power plant with TES system was carried out in order to evaluate its performance in the cities of Tamanrasset and M'Sila. Optimal values of SM and full load hours for TES will be obtained through the initial design optimization process. Table 2 summarizes the initial design parameters of the proposed CSP plant.

2.3.1 Energy Analysis

The total incident solar energy received by the solar field opening is given as:

$$Q_{inc} = A \cdot \cos\theta \cdot DNI \tag{3}$$

Where A is the Collector's aperture area and θ the Angle of incidence.
The total utile energy delivered by the solar field is presented as:

$$Q_{field} = m_f \cdot (H_{SFo} - H_{SFi}) \tag{4}$$

where: m_f is the mass flow rate of the HTF, H_{SFO} enthalpy at the outlet of solar field, and H_{SFi} enthalpy at the inlet of the solar field.
Therefore, the energy efficiency of the solar field can be found as:

$$\eta_{SF} = \frac{Q_{field}}{Q_{inc}} \tag{5}$$

The power block energy efficiency is expressed as:

$$\eta_{PB} = \frac{W_{net}}{Q_{inp}} \tag{6}$$

Table 2
Characteristics of the proposed parabolic trough power plant (Cáceres *et al.*, 2016; Guzman *et al.*, 2014; Hirbodi *et al.*, 2020).

Characteristics	Value
Solar Field	
Total Field Reflector Area	898160 m^2
Solar Multiple	2
Field HTF Fluid	Therminol VP-1
Number of Loops	206
Single Loop Aperture	4360 m^2
Field HTF Min Operating Temperature	12°C
Field HTF Max Operating Temperature	400 °C
Design Loop Inlet Temperature	293 °C
Design Loop Outlet Temperature	391 °C
Water Usage per Wash	0.7 L/m^2
Number of Washes per Year	63
Collectors	
Collectors Type	Luz LS-3
Reflective Aperture Area	545 m^2
Aperture Width, Total Structure	5.75 m
Length of Collector Assembly	100 m
Number of Modules per Assembly	12
Length of Single Module	8.33 m
Receivers	
Receiver Type	Schott PTR 70 2008
Absorber Tube Inner Diameter	0.066 m
Absorber Tube Outer Diameter	0.07 m
Glass Envelope Inner Diameter	0.115 m
Glass Envelope Outer Diameter	0.12 m
Power Cycle	
Design Gross Output	111 Mwe
Estimated Gross to Net Conversion Factor	0.9
Estimated Net Output at Design (Nameplate)	100 Mwe
Rated Cycle Conversion Efficiency	0.356
Design Inlet Temperature	391 °C
Design Outlet Temperature	293 °C
Condenser Type	Evaporative
Thermal Storage	
Storage Type	Two Tank
Full Load of TES	6 h
Storage Volume	25304.4m^3
TES Thermal Capacity	1870.79MWht
Parallel Tank Pairs	1
Storage HTF Min Operating Temperature	238 °C
Storage HTF Max Operating Temperature	593 °C
Storage HTF Fluid	Hitec Solar Salt

Table 3
The main financial input parameters used in the economic modeling of the proposed CSP plant (Benhadji Serradj *et al.*, 2021; Enjavi-Arsanjani *et al.*, 2015; Ikhlef & Larbi, 2020; Zhang *et al.*, 2013).

Financial Data	Value
Analysis Period	30 years
Loan Term	20 years
Loan Rate	8% years
Inflation Rate	4.6%/year in 2018
Real Discount Rate	4%/year in 2018
Nominal Discount Rate	8.78%/year
Assessed Percent	80% of installed cost
Insurance Rate	0.3% of installed cost
Sales Tax	5% of installed cost
State Income Tax Rate	15%/year
Direct Costs	
Site Improvements	15 $/m^2
Solar Field Cost	150 $/m^2
HTF System Cost	60 $/m^2
Storage Cost	65 $/kWht
Power Block	1150 $/kWht
Balance of Plant	120 $/kWht
Contingency	10% of direct costs
Indirect Costs	
Engineering, Procurement and Construction	13% of direct costs
Other Costs	3.5% of direct costs
Operation and Maintenance Costs	
Fixed Cost by Capacity	70 $/kW-year
Variable Cost by Generation	3 $/MWh

where: W_{net} is the net power generation and Q_{inp} is the total thermal energy received by the power block.
The plant's final energy efficiency is calculated as follows:

$$\eta_{overall} = \frac{W_{net}}{Q_{inc}} \tag{7}$$

The net capacity factor (CF) of a designed CSP plant with a capacity of 100 MW is expressed as:

$$CF = \frac{W_{net}}{ND \cdot \left(24 \frac{h}{day}\right) \cdot plant\ power\ capacit\acute{e}} \tag{8}$$

where: ND is the number of days in a year.

2.3.2 Economic Analysis

The LCOE is one of the most important indicators used in evaluating the economic performance of CSP plants (Azouzoute *et al.*, 2020); it is calculated by dividing the accumulated construction and operating costs of a solar power plant by the total annual energy produced during the operating life of the plant, as given in the following equation (Cáceres *et al.*, 2016):

$$LCOE = \frac{I_0 + \sum_{n=1}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \tag{9}$$

where: I_0 is the initial investment expenditures, C_n is the annual total costs for the year n, Q_n is the electricity produced for the year n, N is the economic life of the power plant, and d is the discount rate.

The assumptions and economic data used in the simulations on the SAM software for the parabolic trough CSP plant are presented in Table 3.

3. Results and discussions

The design, analysis and optimization of the performance of a CSP plant that is based on the parabolic trough technology described in the preceding sections yielded results that are now presented and discussed. It will be seen that CSP plants using parabolic trough technology are one of the most promising technologies in the field of electric power generation in Algeria.

3.1 Performance Analysis of the CSP Plant Design

Figure 3 shows the hourly data of the thermal energy incident on the solar field and the thermal energy produced from the solar field, the input of thermal energy for the power block, the thermal energy stored in the TES system, and the net electrical output of the proposed power plant at the Tamanrasset site. The net electrical output depends on the incident irradiation and the thermal energy input to the power cycle.

The value of the maximum thermal energy incident on the solar field was found to be about 840.53 MW in March, while the maximum value of the thermal energy entered into the power cycle was recorded at about 311.79 MW in March, due to the availability of solar resources for the selected site in this period of the year. During the period from February to October, the solar resources are high, the TES system tank is charged during the day with thermal energy in excess of the power block needs, and at the time of low solar radiation or after sunset, the TES system provides thermal energy to the power block to continue to produce electrical energy.

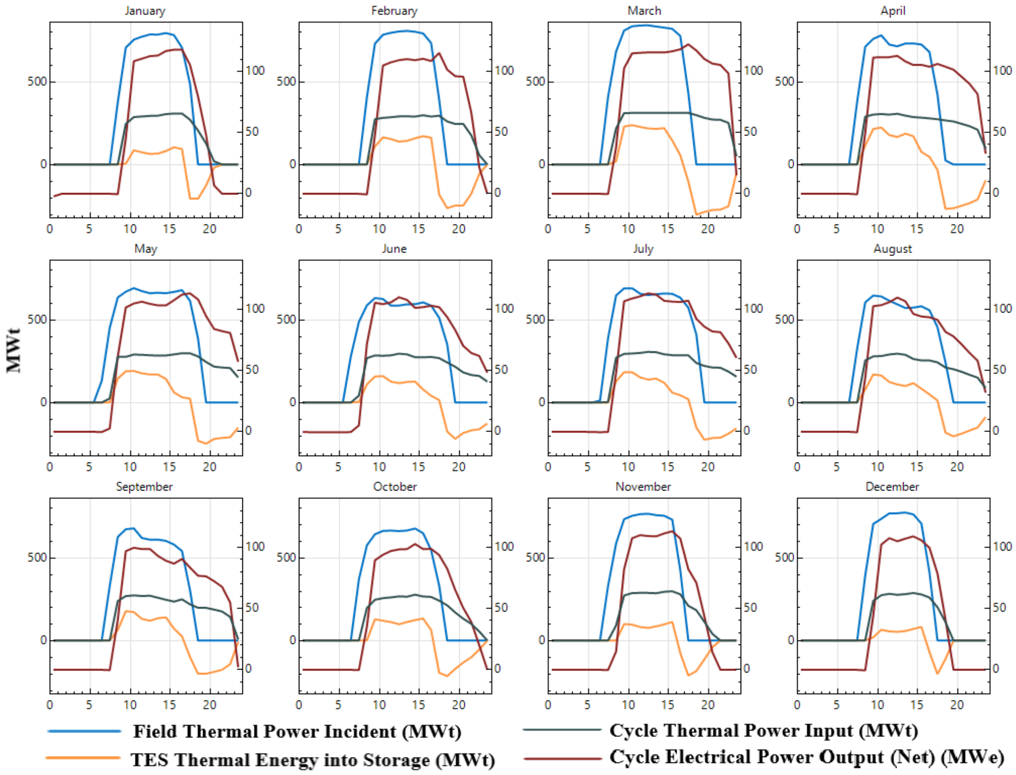

Fig. 3 Field incident solar thermal power, thermal power input for a power cycle and electrical output (Tamanrasset).

Figure 4 presents the hourly data for thermal energy incident on the solar field to the net electrical output of the proposed CSP plant at the M'Sila site. The peak value of the solar thermal incident was found around 705.08 MW in July, which is lower than the maximum recorded at the Tamanrasset site. This is due to the noticeable difference in the values of DNI between the two sites. The maximum thermal energy input to the power block was recorded as 319.29 MW in August. In addition, it should be noted that the TES system during the summer months contributes significantly to extending the period of electrical energy production after sunset, due to the availability of solar resources during this period, while the amount of energy stored in the winter months is very low, which

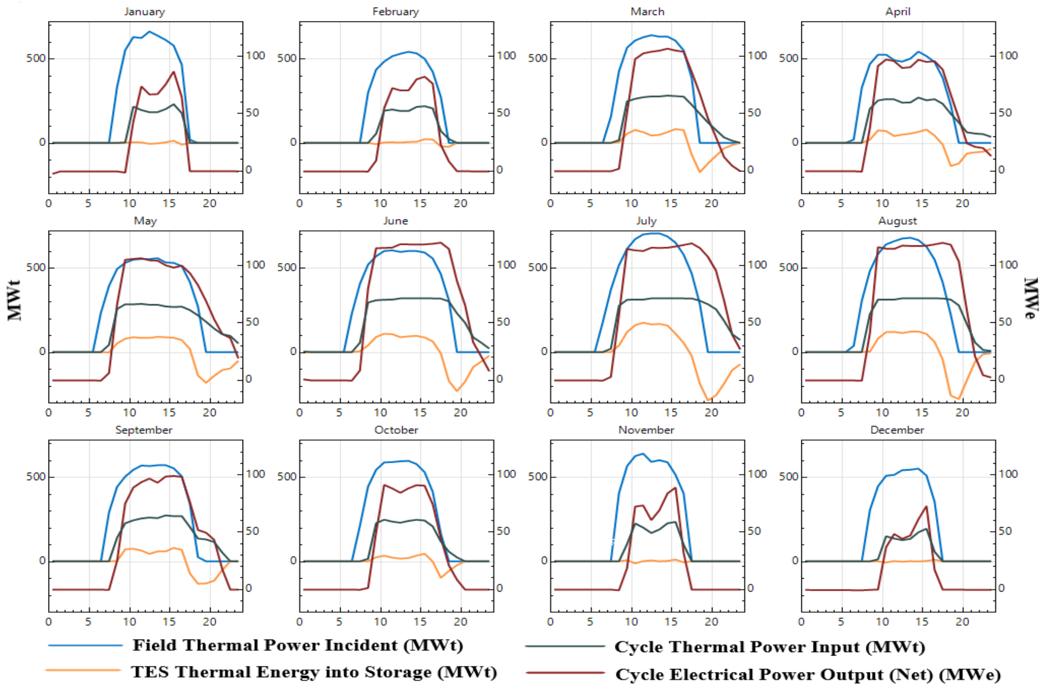

Fig. 4 Field incident solar thermal power, thermal power input for a power cycle and electrical output (M'Sila).

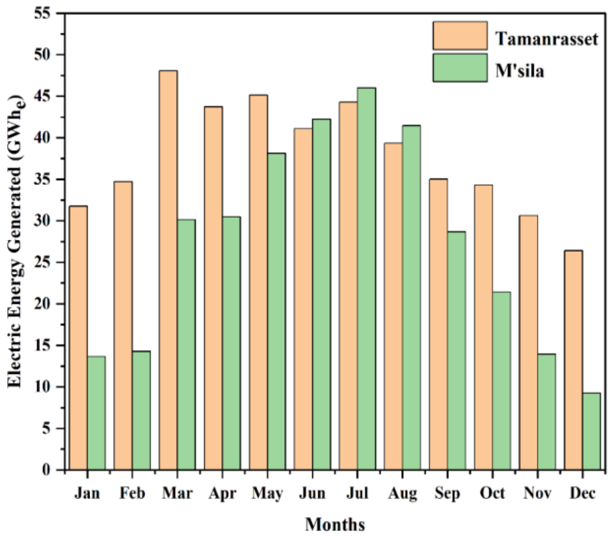

Fig. 5 Monthly energy generation for the proposed parabolic trough power plants in Algeria.

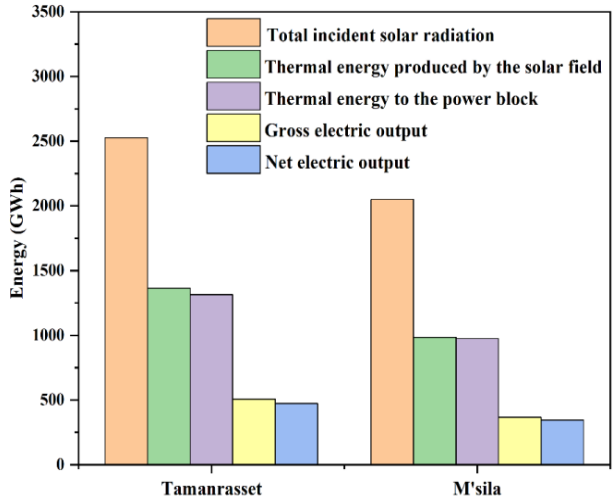

Fig. 6 Annual energy flow of the proposed parabolic trough power plants.

does not allow the system storage extends the duration of electrical energy production until after sunset.

Figure 5 shows the average monthly electric power generation obtained from the proposed CSP plant in both Tamanrasset and M'Sila sites. The monthly energy generated from the parabolic trough power plant in Tamanrasset peaks during the month of March and May, reaching a 48.06 GWh and 45.12 GWh, respectively, the lowest value of the monthly energy generated for the Tamanrasset site was found during the month of December, reaching a value of 26.41 GWh. For the proposed power plant in the M'Sila site, it is seen that the highest monthly production of electric energy was found during the months of June and July, with a value of 42.23 GWh and 45.99 GWh, respectively, and the minimum values of monthly generated energy were found during January and December, which are 13.65 GWh and 9.22 GWh respectively. It is clear that the monthly variation of the net energy production, for each site, almost follows the monthly variation of the DNI. The annual production of energy generated from the two CSP plants was 454.51 GWh, 329.66 GWh for Tamanrasset and M'Sila site, respectively. It can be seen that the proposed power plant in Tamanrasset provided the highest annual generation of electric energy compared to the proposed plant in M'Sila, and the reason is due to the marked difference in the values of DNI, which is shown in Figure 1.

The waterfall diagram in Figure 6 indicates the annual flow of energy from incident solar irradiation on the solar field to net electrical output. It shows the annual energy performance of each component of the proposed power plant at the two selected sites. As for the power plant in the city of Tamanrasset, the total annual solar energy incident on the solar collector amounted to 2552.34 GWh/year, while the amount of thermal energy produced by the solar field amounted to 1362.74 GWh/year. However, the heat energy transferred to the power block is 1314.88 GWh/year. The thermal energy produced from the solar field of the proposed plant at the M'Sila site amounted to 983.7 GWh/year, and the power block received an amount of 974.14 GWh/year. It can be concluded that the main energy losses that occur during energy transfer between the various components of the proposed plant are at the solar field and power block level. The losses in the solar field are found mainly due to the thermal losses in the receivers, while the losses in the power block are the mechanical losses, and the electrical losses necessary to operate the auxiliary equipment.

The annual amount of electrical energy generated from the proposed CSP plant in Tamanrasset was found to be 454.51 GWh, while M'Sila recorded 329.66 GWh, with a CF of 51.9% and 37.7% for Tamanrasset and M'Sila, respectively. In addition, the efficiency value of solar-to-electrical energy conversion was 18% and 16.08% for the two selected sites, respectively. It is clear that the proposed power plant in the city of Tamanrasset offers high performance compared to the power plant in M'Sila, because the levels of solar irradiation in Tamanrasset are higher than M'Sila. Table 4 summarizes the annual performance comparison of the two proposed power plants in Algeria.

3.2 Cost Analysis

The economic study of the two proposed plants is based on a LCOE calculation, the LCOE value ranged between 6.46 ¢$/kW h in Tamanrasset, 8.82 ¢$/kW h in M'Sila.

According to the International Renewable Energy Agency (IRENA) 2020 report, 150 MW of new CSP plants were commissioned globally in 2020 (IREA, 2020). The values of

Table 4
Comparison of annual energy yields for proposed parabolic trough plants in Algeria.

Parameter	Tamanrasset	M'Sila
DNI ($KWh/m^2/year$)	2810.5	2281.25
Annual Power Generation (GWh)	454.51	329.66
Capacity Factor (%)	51.90	37.70
Mean Efficiency of the Solar Field(η_{SF})	53.96	47.98
Mean Efficiency of the Power Block(η_{PB})	34.56	33.84
Mean Efficiency of the Plant($\eta_{overall}$)	18.00	16.08

Table 5

Annual quantities of preserved natural gas, carbon dioxide mitigation and annual water consumption of the proposed CSP plants (m^3).

Parameters	Tamanrasset	M'Sila
Natural gas preservation (m^3)	129,536,887	93,953,884.3
CO_2 Mitigation (m^3)	159,080,387	115,381,963
Water usage (m^3)	1,576,475	1,215,756

LCOEs obtained for the two power plants in this study are lower than the IRENA global weighted average of 0.108 $/kWh in 2020 for CSP plants. The plant located in Tamanrasset provides the highest annual energy production with the lowest LCOE, while the M'Sila plant offers an average annual energy production with a relatively high LCOE.

3.3 Environmental impacts analysis

Considering the energy transition toward clean energy, CSP technologies are more beneficial to the environment because it emits very few damaging pollutants and reduces fossil fuel consumption (Praveen *et al.*, 2018). Therefore, it is necessary to study the environmental impacts of CSP plants in order to estimate their potential benefits. Among these effects are natural gas preservation, carbon dioxide (CO_2) emission, and water consumption. The software SAM is used to calculate the amount of water consumed by these plants. In general, the water use of CSP plants is divided into three main parts, the washing system, the steam generation, and the cooling system. From the obtained results, it is clear that there is a difference in the amount of water consumed by the proposed plants, which is estimated at 1,576,475 m^3 and 1,215,756 m^3 in Tamanrasset and M'Sila, respectively. The proposed CSP plant at the Tamanrasset site consumes more water annually than the proposed power plant in M'Sila.

Reliance on the exploitation of traditional energy to produce electrical energy leads to energy insecurity, in addition to the fact that the exploitation of these resources results in an increase in the amount of CO_2 emitted into the atmosphere, which leads to global warming and climate change (Solomon *et al.*, 2009). To produce 1 kWh of electricity, 0.285 m^3 of natural gas are required (Hassabelgabo Abdelrazig Ibrahim & Mohammed Elmardi Suleiman Khayal, 2020). And 1 kWh of electricity generation produces 0.35 m^3 (0.66 kg) of CO_2 emissions (Brander *et al.*, 2011). The calculations that we have made suggest that the quantities of natural gas and CO_2 emissions that we avoid through our use of CSP plants to generate electricity are very significant quantities compared to conventional electricity generation systems. The results of the environmental impact analysis of the proposed CSP plants, including the amount of natural gas preserved, reduced CO_2 emissions, and annual water consumption are summarized in Table 5.

3.4 Optimization of the initial parabolic trough plant design

The smaller solar field of a CSP plant with parabolic trough technology reduces the thermal energy supplied to the power block, thus reducing the amount of electrical energy produced. The presence of a large solar field means an increase in the thermal energy produced, which is greater than the needs of the power block, and with insufficient storage capacity to store the excess thermal energy, there will be thermal energy loss and an increased investment cost for the CSP plant. Thus, optimization analysis is essential for the whole system.

The optimization procedure helps to determine the lowest value of LCOE with a higher amount of annual electrical energy produced (Awan *et al.*, 2020). Optimization is about finding the combination of the two inputs that minimizes the LCOE while maximizing annual power generation. The variation of two main design parameters, namely the SM and the full load hours of TES, is used to optimize the proposed design.

The size of the solar field has a direct impact on annual electricity production and LCOE. An increase in the SM value leads to a corresponding increase in the solar field aperture and, thus, an increase in the thermal energy produced by the solar field. As a result, more electricity is generated, thus lowering the LCOE value.

The variations of the annual energy production and LCOE with the SM of the proposed CSP plant in both Tamanrasset and M'Sila sites are shown in Figures 7(a) and 7(b), respectively. As shown in Figure 7(a) the LCOE decreases with the increase of the SM that reaches 2.4 for the proposed plant in Tamanrasset,

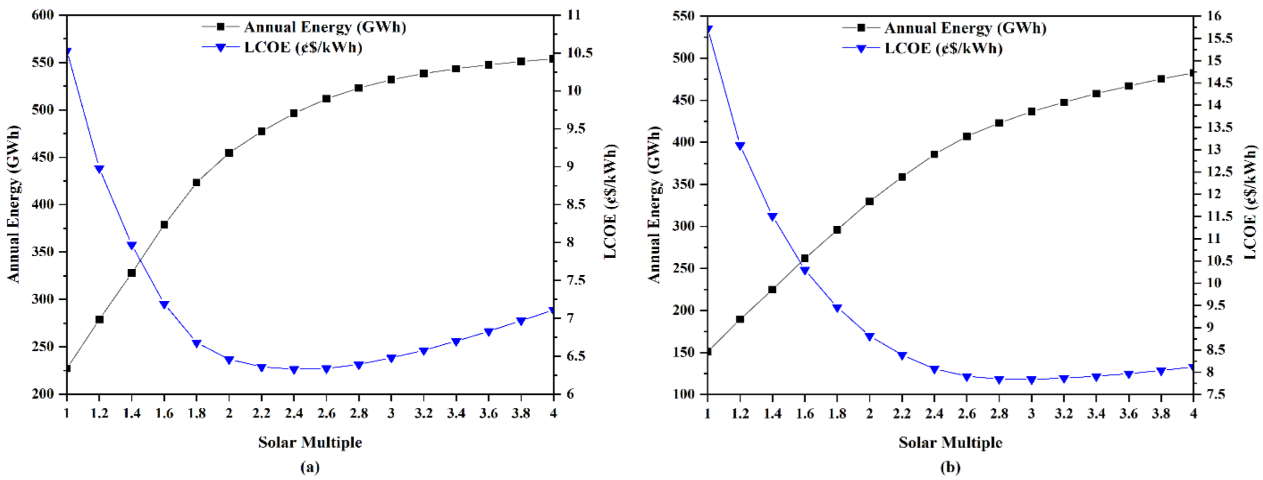

Fig. 7 The variation of annual energy generation and LCOE with SM of the proposed CSP plant in: (a) Tamanrasset and (b) M'Sila.

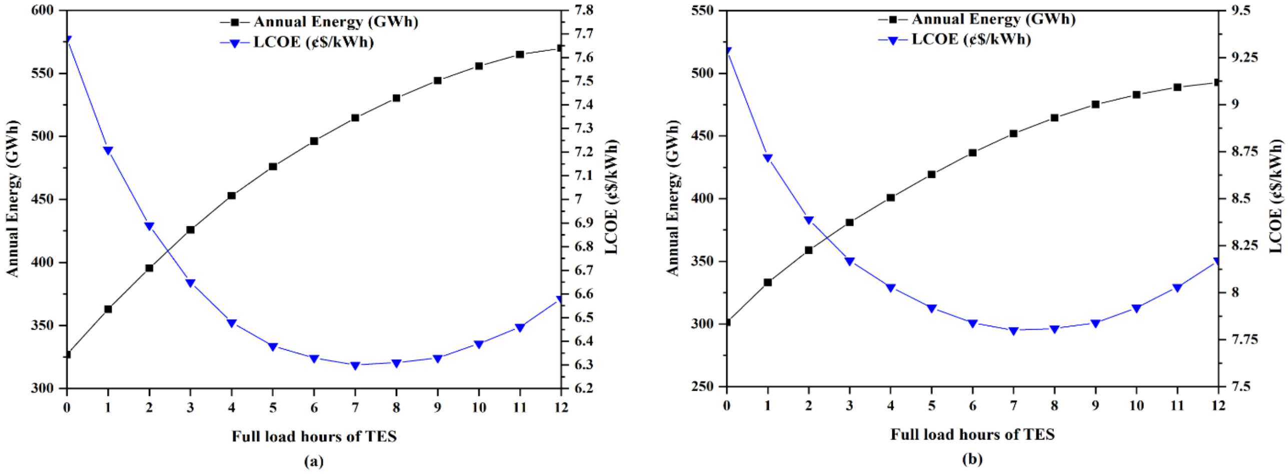

Fig. 8 The variations of annual energy generation and LCOE with full load hours of TES of the proposed CSP plant in (a) Tamanrasset and (b) M'Sila.

beyond this value there is a significant increase in the value of the LCOE with a slight increase in the amount of annual electricity produced. The minimum LCOE was recorded to be around 6.33 ȼ$ /kWh with a SM of 2.4. The LCOE value rises with higher SM values, and this is due to the fact that the capital cost of the plant increases with the increase in the size of the solar field. The annual power output of the plant clearly increases with the increase in SM, but this increase becomes negligible for higher SM values. The optimal values of the SM for the proposed CSP plant in M'Sila was 3 with a LCOE of 7.84 ȼ$ /kWh, in addition to an increase in the annual production of electric energy, as shown in Figure 7(b).

The full load hours of the TES system in the CSP plant are the second design parameter that has been studied for optimization. When solar radiation is low or after sunset the TES system delivers more thermal energy to the power block, thus allowing the plant to generate electricity for longer time intervals. The variations of the annual energy production and LCOE with the full load hours of the TES for the CSP plant proposed at Tamanrasset and M'Sila sites are presented in Figures 8(a) and 8(b), respectively. As shown in Figure 8(a), the LCOE decreases with the increase of the full load hours of the TES, reaching a value of 6.3 ȼ$ /kWh for the Tamanrasset site, the LCOE increases after another increase in the full load hours of the TES system. The lowest LCOE values correspond to 7 h of TES. The optimum full load hours obtained for the proposed power plant at the M'Sila site was 7 h with the lowest LCOE value of 7.8 ȼ$ /kWh, and with an increase in power production as shown in Figure 8(b).

If the full load hours of TES are increased beyond 7 h for both the proposed CSP plants in Tamanrasset and M'Sila, the LCOE value increases with a slight increase in annual energy production because the solar fields of the two power plants are not able to generate enough surplus thermal energy for a large TES system. As for the increase in the LCOE value, the reason is due to the high investment cost of the TES system for both plants. The optimized design results obtained for the two proposed CSP plants are summarized in Table 6. As can be seen from the data in Table 6, it is evident that there is a significant improvement in the amount of annual electric energy produced, CF and LCOE values for the optimized configuration compared to that of the initial design of the two studied plants.

Table 6
Performance comparison of the optimized and initial design of a proposed CSP plant for two sites in Algeria.

Parameters	Tamanrasset		M'Sila	
	Initial	Optimized	Initial	Optimized
Annual energy output (GWh)	454.51	514.6	329.66	451.84
Capacity factor (%)	51.9	58.8	37.67	51.63
Solar multiple	2	2.4	2	3
Full load hours of TES	6	7	6	7
LCOE (ȼ$ /kWh)	6.46	6.3	8.82	7.8

Table 7
Performance comparison of the proposed CSP plant with other similar literature.

Author	Annual Energy Generation (GW h)	Mean Annual Efficiency (%)	LCOE (¢$/kWh)
(Benhadji Serradj *et al.*, 2021)	390.7	15.3	6.2
(Abbas *et al.*, 2013)	223 – 415	13.8 – 16.4	11.93 – 29.58
(Awan *et al.*, 2019)	ranges from 355.18to 397.48	16.73 – 17.93	10.5 – 11
Current Study	451.84– 514.6	16 – 18	6.3 – 7.8

3.5 Comparison of output performance with similar studies

Table 7 presents the results of comparing the performance of the CSP plant with the proposed parabolic trough technology in two locations in Algeria with the results reported in some similar studies on this technology in different locations around the world. According to this Table, it is found that the average plant efficiency and LCOE values are in close agreement with the results obtained in the reviewed literature with a significant increase in the value of the annual energy generated.

4. Conclusion

The present study was conducted to design, analyze and optimize the performance of a concentrated solar power plant based on parabolic trough technology with a thermal energy storage system at two representative sites in Algeria with a wet cooling system, the System Advisor Model software was used to evaluate the performance of the two proposed power plants. The initial analysis of the proposed design showed that the annual production of the proposed concentrated solar power plant in Tamanrasset and M'Sila amounted to 454.51 GWh and 329.66 GWh respectively. It is noteworthy that the annual energy production has a significant relationship with the DNI values and the climatic conditions of the site.

Evaluation of the economic performance of the proposed concentrated solar power plants showed that the power plant in the Tamanrasset site has the lowest LCOE at 6.46 ȼ$/kWh, as for the proposed plant in M'Sila. It is observed that the LCOE is less than 8.82 ȼ$/kWh. Since the two proposed power plants at the two selected sites have the same investment costs estimated at 627,808,128 $ per site, it is important to note that the LCOE values are inversely proportional to the annual production of each plant.

The environmental impact analysis revealed that the proposed CSP plant in the Tamanrasset site consumes more annual water than the proposed power plant in M'Sila. It can be seen that the more arid and desert climate of the site, the greater the annual water consumption of the plant. In terms of the amount of annual carbon dioxide emissions that can be avoided through the use of CSP plants to generate electricity instead of conventional electricity generation systems, the environmental analysis showed that the solar power plant in the Tamanrasset site is able to avoid the amount of carbon dioxide emissions estimated at 159,080,387 m^3, while the proposed plant at the M'Sila site has the lowest annual amount of CO_2 emissions estimated at 115,381,963 m^3. The comparison of the production of electricity through CSP plants and conventional electricity generation systems that depend on fossil resources, shows that a very large amount of natural gas is preserved when using CSP plants.

The optimization procedure is based on considering the lowest value of LCOE with the largest annual energy production. The proposed design optimization process is done by modifying two main design parameters, namely the SM and full load hours of TES. The optimization study showed that there is a significant increase in the annual energy production, reaching 514.6 GWh and 451.84 GWh for the two sites, Tamanrasset and M'Sila, respectively, with a clear decrease in the values of LCOE.

This type of CSP plant, which is based on parabolic trough technology, has shown good results in terms of power generation and the price of electricity production in Algeria. These results may be encouraging for the Algerian government to exploit its large potential of solar energy to generate electricity on a large scale and reduce the use of fossil materials, therefore, the spread of CSP plants in Algeria is a major step for the renewable energy sector in the country, not only to add new energy, but also to increase energy security and address growing environmental problems due to the use of fossil fuels.

Conflicts of Interest: No potential conflict of interest was reported by the authors.

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