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Linear Fresnel Reflector Power Plants in Algeria: Energy, Economic, and Environmental Analysis

The Algerian government seeks to provide all the **resources** *available to it to exploit* **every** *available energy source in all Algerian provinces. Accordingly, this paper aims to present an energy, economic, and environmental study of linear Fresnel reflector solar power plants using the system advisor model in four strategic Algerian regions (Ain Aménas, Gassi-Touil, Hassi R'mel, and El-Oued). The studied solar power plants can produce between 318.75 GWe and 379.29 GWe annually at a levelized cost of electricity ranging between 0.093 \$/kWh and 0.11 \$/kWh. In addition, the annual avoided CO_2 emissions are between 143.41 kt and 170.87 kt, equivalent to 0.473 kg CO_2/1 kWh of electricity, meaning that environmental tax savings will range between 2.08 and 2.48 million dollars annually. The results obtained are very encouraging for decision-makers and investors, as the net capital investment (between 642.67 and 642.82 million dollars) can be recovered in less than 10.2 years, with the power plant capable of operating for 25 consecutive years.* [DOI: 10.1115/1.4067541]

Keywords: solar energy, linear Fresnel reflector, solar power plants, solar electricity production, avoid CO_2 emissions, thermal power

1 Introduction

With the potential depletion of fossil fuel reserves and their noticeable effects on the environment, along with the increasing energy consumption in all countries of the world [1], including Algeria, especially after the globalization of trade and exchanges between countries, it is necessary to accelerate and plan for finding available and clean energy sources. These sources should serve as the best alternative and solution, guaranteeing both qualitative and quantitative energy sufficiency while ensuring energy transfer that is not harmful to the environment. Therefore, the exploitation of renewable energy sources of various kinds (biomass, geothermal, hydro, solar, and wind) is the best solution to provide energy to any part of the world, depending on the renewable energy sources available in that region [2–4]. It is essential to expedite the exploitation of available renewable energy sources to ensure reliable supplies in terms of quality under safe operating conditions for humans, facilities, and the environment.

The quest to develop ways to exploit renewable energy in Algeria is now a national reality and a major requirement **to serve** social,

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economic, and environmental development. It will contribute significantly to ensuring sustainable development, which **is the best solution** for the transition from hydrocarbon energy without compromising environmental safety and human health [5–7]. This strategic choice adopted by the Algerian state is driven by the enormous potential of solar energy that can be harnessed [8–10]. It is expected that solar energy exploitation in Algeria will achieve success in terms of electricity production [11–13].

Concentrating solar power plants (CSP) use reflective mirrors to focus direct sunlight and generate electricity. **CSP's thermal energy** can be stored and used to produce electricity day or night, as needed. Currently, in many parts of the world, CSP power plants are increasingly being used to reduce greenhouse gas emissions and diversify energy sources in various countries. CSP power plants such as parabolic trough collectors (PTCs), linear Fresnel reflectors (LFRs), heliostat power plants, and parabolic dish collectors have been used to generate solar thermal electricity [14–16]. PTC and heliostat power plants can be combined with steam cycles from 10 MW to 100 MW, while LFR plants can produce thermal electricity from 5 MW to 250 MW, and parabolic dish collector power plants can generate electric power from 0.01 MW to 1 MW [17].

This study aims to comprehensively assess the potential of electricity production using LFR reflector mirrors, using the system advisor model (SAM). It will analyze the performance, as well as the economic and environmental aspects of LFR power plants in several Algerian regions, including Ain Aménas, Gassi-Touil, Hassi R'mel, and El-Oued, as shown in Fig. 1. These regions were carefully selected due to their strategic proximity to industrial and agricultural hubs, thus contributing significantly to the country's economic development.

Among what is mentioned in the literature about LFR technology, Bellos [18] has summarized a critical review containing the progress made in the design and applications of LFR technology up to 2019. Bellos et al. [19–21] conducted studies to improve the optical behavior of LFR technology. Additionally, Bellos et al. [22–26] completed experimental and numerical studies on LFR technology, especially in Greece. The studies by Bellos et al. have also demonstrated the possibility of using LFR technology for heating industrial oils and salts, as well as in industrial processes [27,28]. Ghodbane et al. conducted experimental, computational fluid dynamics modeling, and numerical studies on Fresnel technology as a solar water heater in the Algerian region of Blida [29,30]. Said et al. [31,32] conducted experimental and numerical studies on LFR-type solar water heaters in the Algerian region of Blida. The studies by Ghodbane et al. demonstrated the possibility of using LFR technology to drive ejector air conditioners [33,34], as

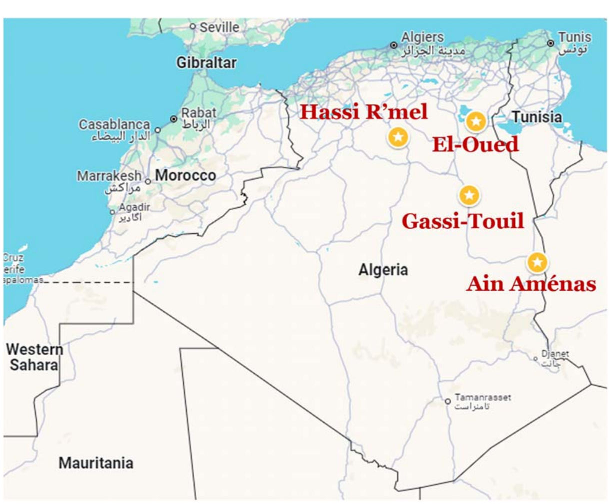

Fig. 1 Selected regions for the establishment of LFR power plants

the use of LFR with the ejector eliminated the most electricity-consuming gas compressor in the air conditioner refrigeration chain. Barbón et al. studied the effect of a solar tracking system on small LFRs in terms of design and construction [35–37], particularly in urban applications [38–40]. Montes et al. made significant contributions to the design of the multi-tube absorber for LFR technology to improve its thermal efficiency [41]. To improve the LFR energy performance, Bellos et al. conducted a study on the role of nanofluids (CuO/Syltherm 800 nano-oil) as well as adding the inner fins to the receiver tube for improving the LFR energy performance [42]. Bellos and Tzivanidis conducted a multi-criteria evaluation study of an LFR with the use of nano-oil (CuO/Syltherm 800 nano-oil) [43]. Ghodbane et al. studied the possibility of improving the LFR thermal performance by using MWCNTs/water nanofluids by 4.6% compared to pure water [44]. According to Said et al. [45], the LFR thermal performance can be improved by a value of 2.75% when using rGO-Co_3O_4/water hybrid nanofluids. For industrial applications, the study of Ghodbane et al. demonstrated that using MXene/silicone nano-oil as a working fluid for LFRs can improve heat transfer by 15.50% [46], as the use of nanotechnology in industrial applications, especially for energy storage, has very promising prospects [47–49]. Encouraging the installation of solar power plants in Algeria, the results of studies by Ghodbane et al. support moving forward toward with the establishment of LFR solar power plants [11–13], which are generally less expensive than PTC power plants due to their simpler design [18], as LFRs use inexpensive and less complex linear mirrors, which reduces manufacturing and installation costs, as well as maintenance costs. In contrast, PTC systems require precise parabolic trough-shaped mirrors and sophisticated tracking systems, which results in higher costs. Although LFRs may be slightly less efficient under certain conditions, their lower cost makes them a more economical option when budget is a major constraint.

2 Materials and Methods

Compared to CSP power plants, photovoltaic power plants are more versatile due to their flexibility in installation on a small or large scale, their adaptability to different climates, including cloudy conditions, and their ability to operate in both connected and isolated areas. They offer a rapid response to energy needs and are more easily scalable [50,51]. However, CSP power plants have specific advantages, including their integrated thermal storage capacity, which allows them to produce energy even after sunset, offering better continuity in the supply of electricity. In addition, CSPs are particularly effective in regions with strong direct sunlight, where they can generate large amounts of energy more stably and constantly compared to PV power plants. Therefore, solar concentrators focus direct sunlight to heat a working fluid to a high temperature to produce superheated steam suitable for multiple uses such as electricity production, refrigeration, air conditioning cycles, industrial processes, and seawater desalination. CSP power plants cover a wide variety of systems available in terms of solar radiation concentration, choice of working fluid (heat transfer fluid), and storage mode.

This study evaluates the energy, economic, and environmental performances of LFR power plants in four Algerian regions using SAM software, based on their geographical coordinates and annual climate data. SAM allows modeling the efficiency of power plants according to local weather conditions, taking into account transient effects such as start-up/stop cycles and thermal losses. It helps to optimize the design of renewable energy projects by adjusting thermal parameters according to climate fluctuations. Therefore, this study is based on the use of LFR reflectors, consisting of reflective plane mirrors that pivot around an axis to reflect direct sunlight toward a fixed receiver tube. This solar reflector contains a receiver tube into which the working fluid flows, thus capturing useful solar energy. For detailed information on the optical and thermal behavior of LFR reflectors, as well as the mathematical equations that govern them, please refer to Refs. [18,46]. The

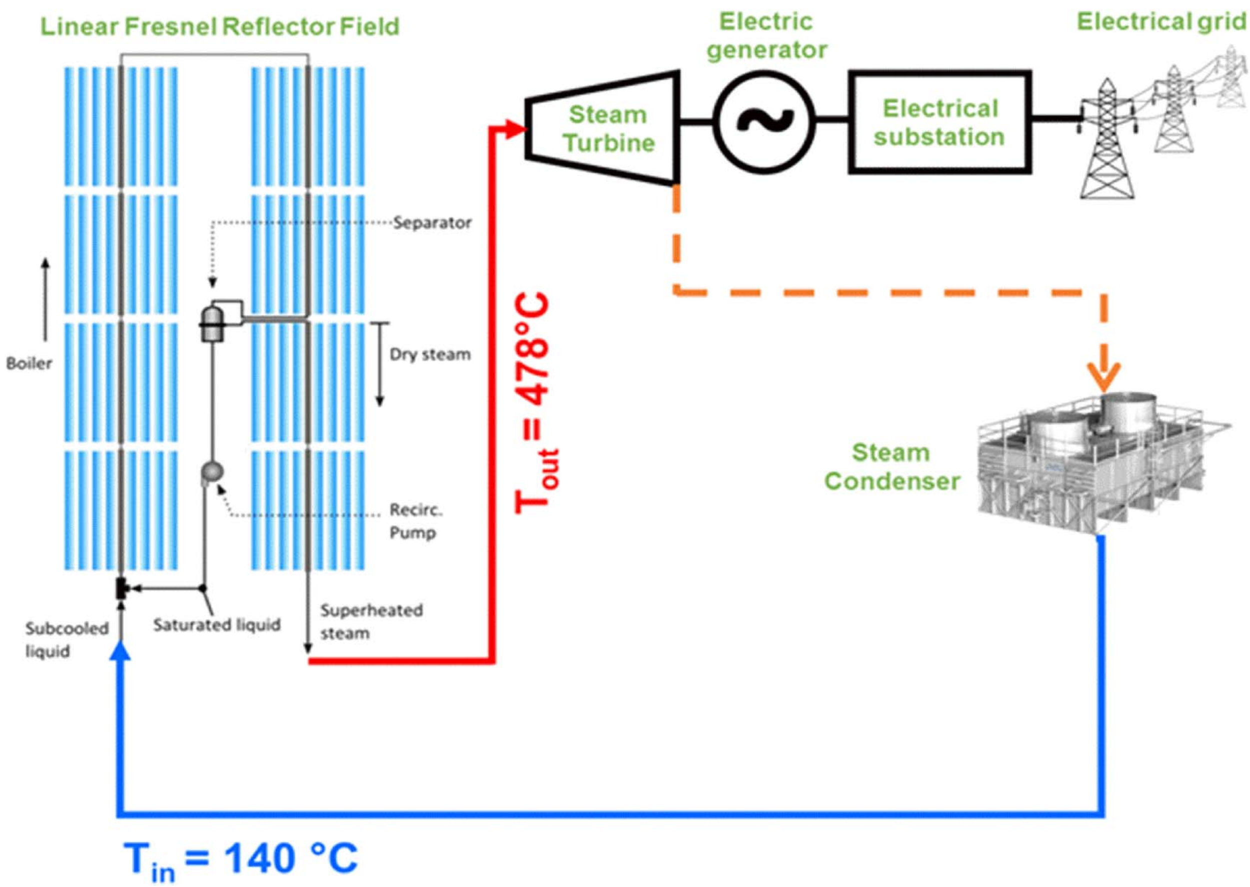

Fig. 2 Schematic diagram of the studied station

LFR power plant components are shown in Fig. 2, while the specifications of the studied solar power plant are shown in Table 1. To install this type of solar plant somewhere, these basic conditions must be met:

- Adequate direct sunlight during the year
- Large areas should be available to build solar power plants
- Infrastructure must be available, as it ensures access to sites, facilitates connection to the electricity grid, and supports the logistics and maintenance of the installations, thus optimizing the performance and sustainability of the projects [12,13,18]
- For countries planning to build solar power plants, there must be economic opportunities for investment in solar energy

Table 1 Characteristics of the studied LFR power plants

Item	Value
Multiple solar	2.1
Field aperture	1,531,364 m^2
LFR module length	44.8 m
LFR module width	11.465 m
Focal length	7.4 m
Loop collectors	16
Reflective aperture area	513.6 m^2
Number of loops	186
Steam flow configuration	RCO
Turbine output (nominal capacity)	125 MWe
The efficiency of the net design cycle	37.1%
Field inlet temperature	140 °C
Output temperature of the field	478 °C
Turbine inlet pressure	90 bar
Design point field pressure drop	14.85 bar
Cooling type	Dry

The above four conditions are met in the Algerian Sahara, especially in the selected regions. For this reason, this study has been proposed.

As for the LFR power plants, SAM software relies on two steam flow configuration options:

- **Recirculated option (RCO)** [13]: In this configuration, the water is heated from the saturated liquid state to a very high temperature, passing through two phases to become steam above the saturation temperature (i.e., superheated steam). The first stage results in a water–steam mixture. These two are separated in the separator, where water is pumped back into its loop, while the steam is sent to the second stage and heated to a temperature above saturation (i.e., becoming superheated steam) before being sent to the turbine;
- **OTO** [13]: In this configuration, water is heated from the saturated liquid state to a very high temperature in a single path through the absorber tube in each loop, turning it into superheated steam.

As for the studied LFR power plants, the net generated power can reach 117.5 MW without the need for any fossil energy source. Additionally, they rely on superheated steam generation using the RCO option as the steam flow configuration.

3 Results and Discussion

The SAM program performs calculations at regular intervals to estimate the electrical productivity of LFR power plants, where it generates time series representing monthly electricity production over a year, depending on the accuracy of the meteorological data for selected regions. In this study, the results will be presented as annual averages of the hourly data, allowing to evaluate the performance for a typical day of the year, where the annual average of weather data, optical and thermal efficiency, LFR power plant output, levelized cost of electricity (LCOE), CO_2 mitigation, and water consumption will be presented.

3.1 Weather Data for the Selected Regions.

This work evaluates the impact of geographical variations (latitude, longitude, altitude) and climatic conditions (direct sunlight, air temperature, wind speed, etc.) on the efficiency and productivity of LFR solar power plants. Table 2 summarizes the geographical coordinates and annual averages of meteorological data of the selected regions, based on 2022 data. Figures 3(*a*)–3(*c*) show the evolution of the hourly annual average of climatic factors in the selected regions. According to Fig. 3(*a*), Ain Aménas records the highest average annual direct sunlight with 756 W/m^2, followed by Gassi-Touil (721 W/m^2), Hassi R'mel (710 W/m^2), and El-Oued (650 W/m^2). These sunlight levels, presented in Table 2 and Fig. 3(*a*), are promising for electricity generation, particularly in the industrial and agricultural sectors. Since El-Oued is an agricultural region, while the others are industrial, electricity consumption is significant. LFR plants offer a viable solution to provide clean and affordable electricity, thereby reducing dependence on fossil fuels and energy costs, especially in Algeria, where electricity generation still relies heavily on fossil fuels.

From Fig. 3(*b*), Gassi-Touil records the highest annual average ambient air temperature at 30.5 °C, followed by Ain Aménas (29.76 °C), El-Oued (28.41 °C), and Hassi R'mel (26.53 °C). As for wind speed, Fig. 3(*c*) shows that Hassi R'mel has the highest annual average with 4.15 m/s, followed by Ain Aménas (4.11 m/s), El-Oued (4.01 m/s), and Gassi-Touil (3.94 m/s). Therefore, these climatic data (direct sunlight, ambient air temperature, and wind speed) are essential to optimize the design and efficiency of LFR plants, as they directly influence energy productivity and thermal performance in each region.

3.2 Energy Analysis

3.2.1 The Annual Average Efficiency of the Linear Fresnel Reflector Power Plant. The optical analysis of an LFR is complex and requires detailed information on the reflector geometry and dimensions as well as error distributions. LFRs convert direct sunlight into superheated steam used in direct steam generation power plants. Two key indicators evaluate the performance of LFR plants: the field optical efficiency, which measures the energy collected relative to the incident energy, and the field thermal efficiency, which evaluates the useful heat transmitted to the working fluid. Generally, the energy absorbed by the receiver tube depends on the entire CSP configuration.

Regarding the LFR optical efficiency, it relates to parameters such as the reflectivity of mirrors, intercept factor, receiver tube absorptivity, glass tube transmissivity, defects during assembly of mirrors, defects during solar tracking, cleanliness of mirrors, loss factors by blocking and shading at zero incidence angles, correction coefficient for the longitudinal incidence angle, and correction coefficient for the transversal incidence angle. In other words, LFR optical efficiency is directly related to operational conditions (the intrinsic factors related to the LFR reflector) as well as place factors (factors related to the sun's position).

The LFR receiver tube is the place of various heat exchanges, where it receives the concentrated solar flux, heats up, and then transfers this heat to the working fluid that passes through it. However, not all the concentrated solar flux received by the receiver tube is transmitted to the working fluid; a part is lost through radiation, convection, and conduction, but radiative losses are predominant, then the convection and conduction losses. Therefore, the LFR thermal characterization consists of quantifying the reflector losses by focusing on the receiver tube, glass tube, and working fluid assembly. Figures 4(*a*) and 4(*b*) show the evolution in the optical and thermal efficiency of the field LFR reflectors.

By analyzing the curves in Fig. 4(*a*) representing the average annual optical efficiency on an hourly scale, it is noted that the annual average of the maximum optical efficiency that the studied

Table 2 Characteristics of the studied LFR power plants

Region	Ain Aménas	Gassi-Touil	Hassi R'mel	El-Oued
Latitude (deg)	28.05	30.53	32.93	33.61
Longitude (deg)	9.58	6.46	3.26	6.94
Altitude (m)	560	203	773	44
Direct sunlight (kWh/m^2/day)	6.77	6.27	6.45	5.57
Average air temperature (°C)	21.9	22.9	19.2	22
Average wind speed (m/s)	3.2	3	3.2	3.1

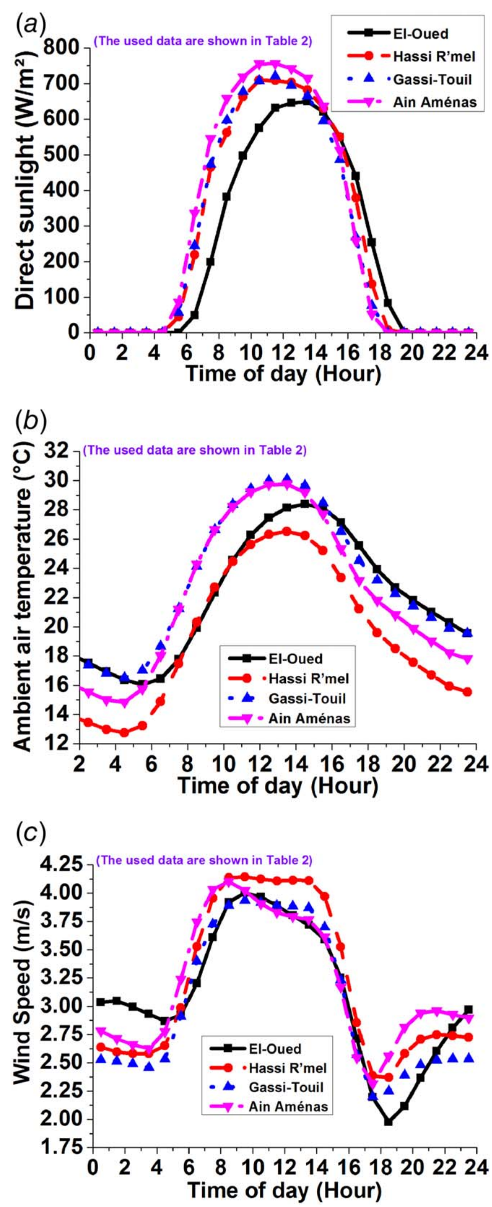

Fig. 3 Change in weather data against time: (*a*) direct sunlight, (*b*) ambient air temperature, and (*c*) wind speed

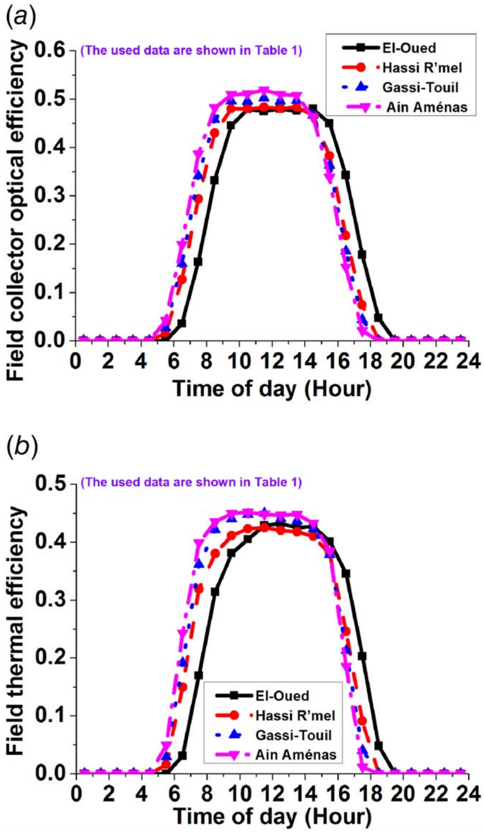

Fig. 4 Field collector efficiency against time: (*a*) optical efficiency and (*b*) thermal efficiency

power plant can reach for Ain Aménas is 51.88%, followed by Gassi-Touil region with 50.22%, then Hassi R'mel region with 48.34%, and finally El-Oued with 47.96%. Figure 4(*b*) shows the change in field thermal efficiency, as it is noted that the annual average of the maximum thermal efficiency that the LFR power plant can reach for Ain Aménas is 45.17%, followed by Gassi-Touil region with 44.97%, then El-Oued with 43.24%, and finally Hassi R'mel region with 42.52%. Here it is noted that the LFR thermal efficiency is directly related to the amount of direct sunlight reflected on the LFR reflective mirrors. The greater the amount of direct sunlight in the region, the greater the amount of LFR thermal efficiency in that region, and this is very evident when linking the curves of Figs. 3(*a*) and 4(*b*) to each other and then understanding the relationship between them. Therefore, both optical and thermal efficiencies for all selected areas are acceptable because LFR technology has a rather low performance compared to other solar concentrators such as parabolic trough collectors, but the advantages of LFR technology are numerous:

- First, its flat mirrors are easier to manufacture and cheaper than parabolic trough collectors;
- Second, its flat mirrors are less affected by wind (mechanical stresses imposed by the wind thrust are reduced thanks to the flat arrangement of the mirrors) compared to curved mirrors [18,46];
- Third, the infrastructure of LFR power plants is less expensive compared to parabolic trough power plants.

For more details on the energy balance analysis of LFR reflectors, it is recommended to see Refs. [12,46], as for PTC collectors, it is advisable to see Refs. [5,6,52].

3.2.2 The Annual Average Productivity of Linear Fresnel Reflector Power Plants. Regarding the LFR solar field, it is based on several lines of linear Fresnel reflectors connected in parallel to obtain the required heat supply for the working fluid (superheated steam) and thus the heat energy required to rotate an electricity-generating turbine, this allows the production of the required electrical energy. Each reflector line comprises several modules connected in series and the module is composed of several rows of flat mirrors whose slope changes continuously to follow the sun's position. The reflective mirrors are mounted on a fixed steel structure placed near the ground and concentrate the direct sunlight on a fixed receiver tube installed several meters above the plane of the reflective mirrors. In most cases, the receiver tube includes secondary reflectors that redirect incoming direct sunlight to the receiver tube. The LFR rows are aligned along the north–south direction and are equipped with a single-axis tracking system to follow the sun's path, i.e., the LFR has a north–south horizontal axis with an east–west tracking system.

Regarding the power cycle block, it is based on a Rankine cycle (RC) unit, where thermal energy produced by the solar field is used to produce superheated water steam which is used to operate the RC turbine which produces electricity. The superheated water steam produced expands in the turbine, then is cooled in the steam condenser, and is compressed before returning to the receiver tube head. The cycle is repeated until sunset. In general, the cycle steam temperature at the RC inlet is about 478 °C, and at the outlet, it is about 140 °C as shown in Fig. 2. However, in the LFR power plants studied in this paper, these parameters change according to the climatic conditions of the LFR power plant installation site, as illustrated by Figs. 5(*a*)–5(*c*). Figure 5(*a*) shows the change in the steam temperature cycle at the RC inlet, Fig. 5(*b*) shows the change in steam temperature at the RC outlet, and Fig. 5(*c*) shows the change in steam pressure at the RC inlet for all the studied LFR power plants from sunrise to sunset.

It is noticeable from Figs. 5(*a*)–5(*c*) that the change in the operational parameters is directly affected by the change in the weather data from one region to another, especially the change in direct sunlight. This is because the change in the LFR thermal efficiency is directly affected by direct sunlight, which increases the amount of useful energy gained by steam. This is very clear in Fig. 3(*a*), which shows that the Ain Aménas region has a greater amount of direct sunlight. As a result, the region achieves the highest thermal efficiency in its solar power plant (see Fig. 4(*b*)). This generates a positive effect, making it the region that will produce the largest amount of energy in the form of heat for steam that will rotate the turbine. This is evident in Fig. 5(*a*), which shows a daily average steam temperature at the turbine inlet of 469.56 °C at a pressure of 82.35 bar. For the other regions, the average steam temperatures at the turbine inlet are as follows: 462.25 °C at a pressure of 79.76 bar, 449.71 °C at a pressure of 77.9 bar, and 448.37 °C at a pressure of 78.75 bar for Gassi-Touil, Hassi R'mel, and El-Oued, respectively. These are very acceptable values that allow the production of significant amounts of electricity as shown in Fig. 6. Regarding the daily average steam temperature at the turbine outlet, it is very similar for all regions, at 143 °C.

Figure 6 shows the change in electrical power output over time. From this figure, it can be concluded that the average electricity production for the studied power plants is 1039.13, 977.72, 936.96, and 873.27 MWe/day for Ain Aménas, Gassi-Touil, Hassi R'mel, and El-Oued, respectively. Once again, the direct sunlight intensity effect on the productivity of the studied LFR power plants is quite evident, as the Algerian region of Ain Aménas produces the highest average daily electricity production due to the abundance of direct sunlight solar radiation in this area.

Also, the rest of the regions where the feasibility of installing the LFR power plant was studied provided very acceptable electrical production, given that the study was conducted based on weather data for the year 2022. Regarding cycle efficiency, as shown in Fig. 7, the average daily efficiency of the electricity production cycle is 38%, 36%, 34%, and 32% for Ain Aménas, Gassi-Touil, Hassi R'mel, and El-Oued, respectively.

The results of the energy analysis highlight the crucial importance of choosing an optimal installation site for an LFR power

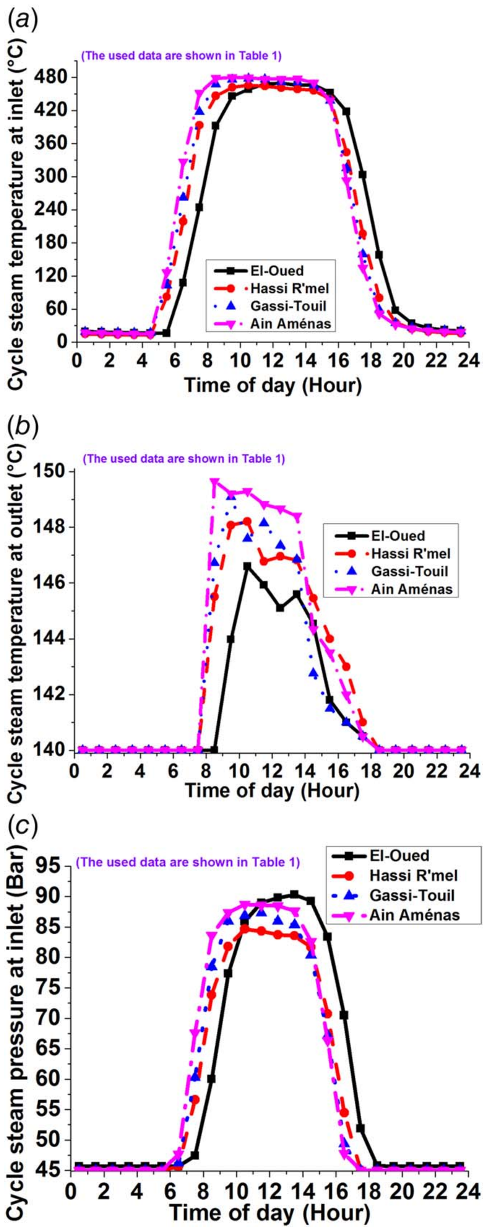

Fig. 5 Change in the operating parameters of the LFR power plants against time: (*a*) cycle steam temperature at RC inlet versus time, (*b*) cycle steam temperature at RC outlet versus time, and (*c*) cycle steam pressure at RC inlet versus time

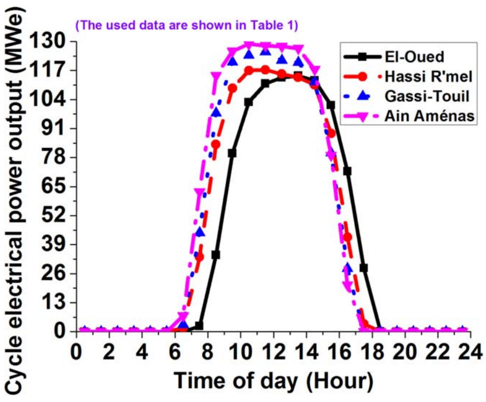

Fig. 6 Change in electrical power output against time

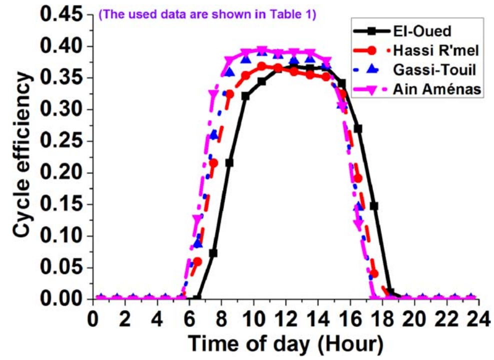

Fig. 7 Change in cycle efficiency against time

plant, as factors such as direct sunlight, air temperature, wind speed, and geographical position directly influence productivity and profitability. The performances obtained in the four studied regions demonstrate Algeria's strong potential for LFR power plants, due to its economic diversity (agriculture, gas, oil, etc.). Therefore, Ain Aménas stands out as the most suitable site, followed by Gassi-Touil, Hassi R'mel, and El-Oued, according to 2022 meteorological data.

3.3 Economic Analysis. Another perspective of this paper is to conduct an economic investigation of the studied LFR power plants based on the change in climatic conditions for the selected regions, where it will search for the maximum net present value (NPV) and minimum LCOE. The LCOE includes all investment and operating costs. In Algeria, Executive Decree No. 17-98 of Feb. 26, 2017, amended and supplemented by Executive Decree No. 17-204 clarifies all tender procedures for the production of electricity from renewable energy or cogeneration and its transfers to the national electrical supply systems [13,53]. The aforementioned decree aims to set a ceiling of 01 kWh of electricity, i.e., to reduce the construction cost of solar power plants in Algeria, while maintaining the quality that guarantees technical, economic, and environmental standards to achieve a balance between the costs of construction, operation and the selling price of energy. In this study, the LFR power plants were simulated based on the financing criteria given in Table 3.

According to Algerian government decrees [13,53], and to ensure the renewable origin of electricity produced in solar power plants, any solar power plant installed in Algeria must obtain from the Algerian Electricity and Gas Regulatory Commission a renewable origin guarantee certificate for the electricity produced therein. This certificate must be obtained before starting the operation of the solar power plant. Likewise, the investor must provide the solar power plant with all data measuring tools to determine the actual capacities of the solar power plant according to the actual climatic data of its location. These capacities are tracked and evaluated by energy auditors from the Algerian government. Additionally, all equipment and measuring tools present in the installation are subjected, after installation, to pre-operational checks to verify the accuracy of their performance, conformity, and compliance with the recommended specifications by accounting and management organizations. Moreover, all solar power plant equipment, measuring tools, and measuring instruments installed are subject to periodic and unannounced checks under the supervision of the Algerian Electricity and Gas Regulatory Commission.

The criteria for calculating the electricity ceiling are related to the following:

- First, the total cost of the investment, which is represented in all the expenses incurred to build the project from the acquiring costs and land development, the costs of acquiring and installing the equipment of the LFR power plant, as well as the costs of connecting to the electrical network for distribution;

Table 3 Financial data entered into the SAM program

	Parameter	Value
Solution mode	IRR target	11%
	IRR target year	9 years
	Power purchase agreement price escalation	1%/year
Analysis parameters	Analysis period	25 years
	Inflation rate	4.81%/year
	Real discount rate	3%/year
	Nominal discount rate	9.76%/year
Tax and insurance rates	Federal income tax rate	30%/year
	State income tax rate	7%/year
	Sales tax	5% of the total direct cost
	Insurance rate per year	0.5% of the installed cost
	Assessed percent	100% of the installed cost
Project term debt	DSCR	1.3
	Tenor	18 years
	Annual interest rate	7%
	Up-front fee	2.75% of the total debt
Reserve accounts	Interest on reserves	1.75%/year
	Working capital reserve	6 months of operating costs
	Debt-service reserve account	6 months of principal and interest payments

Table 4 Costs of the studied LFR power plants

	Element	Cost (million dollars)
Direct capital costs $307.32 million	Site improvement	30.57
	Solar field	229.28
	Heat transfer fluid system	50.44
	Power plant	143.75
	Contingency (7%)	31.79
Indirect capital costs $36.60 million	EPC and owner cost	53.44
	Total land cost	6.05
Sales tax	$19.44 million	
Total installed costs	$564.73 million	

- Second, all expenses necessary for the operation and maintenance of the LFR power plant during the project life. Regarding the concession rental costs and project financing costs, they are included in operating costs.

The LCOE is a key factor in evaluating the profitability of the studied LFR power plants that will be built in the selected regions in Algeria, as it is the main criterion for selecting investors who will build the LFR power plants. According to the power purchase agreement for this study, issued by the Ministry of Energy in Algeria, the LCOE is determined for 25 years from the date of starting the operation of the studied power plants, where the term of the purchase contract between the investor and the distributor is considered the project life for calculating the ceiling price [13].

Table 4 contains details of the expenses included in the costs of constructing, operating, and maintaining the studied LFR power plants.

All expenses and costs shown in Table 4 have been taken into account to calculate the LCOE, as Table 5 shows the results of the economic analysis of the studied power plants, from which the following can be concluded:

- Regarding net capital cost, it is the total cost minus cash incentives. In this study, it ranges from $642.67 million for El-Oued power plant to $642.82 million for Ain Aménas power plant. Accordingly, the young LFR technology in Algeria can be exploited in solar power plants by adopting direct steam generation technology, which is based on the LFR reflectors with the Rankine cycle, knowing that the annual direct sunlight varies in the four regions selected for the study, from 2033.05 kWh in El-Oued to 2471.05 kWh in Ain Aménas;
- The four studied regions, benefiting from strong direct sunlight, allowed an annual electricity production of 379.29 GWe in Ain Aménas with an LCOE of 0.093 $/kWh, 356.87 GWe in Gassi-Touil with an LCOE of 0.099 $/kWh, 342 GWe in Hassi R'mel with a LCOE of 0.103 $/kWh, and 318.75 GWe in El-Oued with a LCOE of 0.11 $/kWh. These results show that Ain Aménas is the most efficient in terms of both production and cost;
- Regarding investor NPV over the project life, it exceeded $19.34 million for all sites;
- Regarding developer NPV over the project life, it exceeded $45.48 million for all sites.

Table 5 Summary of the economic analysis of the studied LFR power plants

Region	Ain Aménas	Gassi-Touil	Hassi R'mel	El-Oued
Annual direct sunlight (kWh/year)	2471.05	2288.55	2354.25	2033.05
Net capital cost ($m)	642.82	642.76	642.73	642.67
Total operating and maintenance costs for the analysis period ($m)	507.97	504.24	501.8	497.86
Total project revenue for the analysis period ($m)	1576.15	1573	1570.94	1567.62
Net project revenue for the analysis period ($m)	425.37	426	426.42	427.09
Developer NPV over the project life ($m)	45.48	45.54	45.57	45.62
Investor NPV over the project life ($m)	19.34	19.34	19.35	19.36
Levelized cost of electricity ($/kWh)	0.093	0.099	0.103	0.11
Annual electricity production (GWe/year)	379.29	356.87	342	318.75

In all the selected sites, the payback period of the net investment of the LFR plants is approximately 10.2 years from their official commissioning. After this period, the net project revenues for the analysis period are respectively \$427.09 million for El-Oued, \$426.42 million for Hassi R'mel, \$426 million for Gassi-Touil, and \$425.37 million for Ain Aménas, reflecting high profitability in the long term.

A comparison will be made between the LCOE of fossil electricity in Algeria and the thermal electricity of the studied LFR power plants, and Table 6 contains a comparison between the LCOE of the studied stations and the LCOE of different renewable technologies for electricity production. On Sept. 13, 2024, the fossil electricity LCOE in Algeria was 0.04 \$/kWh for residential LCOE, and 0.035 \$/kWh for business LCOE (this price changes daily according to the price of the Algerian dinar against the US dollar in the global market) [54].

The results of this study revealed that the LCOE for the studied LFR power plants ranged between \$0.093/kWh in Ain Aménas and \$0.11/kWh in El-Oued, with Gassi-Touil and Hassi R'mel having LCOEs of \$0.099/kWh and \$0.103/kWh, respectively. These values position LFR power plant technology within a competitive range compared to other renewable energy sources. While the LCOE of LFR power plant is higher than that of onshore wind power stations (\$0.033/kWh) and PV power stations (\$0.049/kWh), geothermal power stations (\$0.056/kWh), bioenergy power stations (\$0.061/kWh), it remains comparable to offshore wind plants (\$0.081/kWh). Most notably, LFR power plants outperform conventional CSP technology, which has an LCOE of \$0.118/kWh. However, the LCOE for LFR power plants is still higher than fossil-based electricity in Algeria, where costs are \$0.035/kWh for commercial use and \$0.04/kWh for residential use. These findings highlight the need to optimize the performance and cost-efficiency of LFR technology to enhance its economic appeal.

Despite these challenges, the strategic importance of LFR power plants for Algeria lies not only in their environmental benefits (such as reduced CO_2 emissions and increased energy mix diversity) but also in their potential to secure energy independence and foster economic growth. By adopting this technology, Algeria can reduce its reliance on fossil fuels, meet domestic energy demands sustainably, and position itself as a leader in clean energy production. Additionally, the growing competitiveness of LFR power plant technology offers Algeria a unique opportunity to export electricity to foreign markets, particularly to neighboring regions with rising demand for renewable energy. Such a move could strengthen Algeria's position on the global energy stage while contributing to its economic and environmental goals.

Therefore, the economic analysis revealed that LFR plants can be successfully implemented in the regions studied, thus constituting a profitable project and adaptable to other Algerian provinces. These results should encourage the Algerian government to develop a legislative framework favorable to investment in renewable energies, particularly in the thermal electricity sector, thus strengthening the country's commitment to a sustainable energy transition.

Table 6 Comparison of LCOE with other renewable source technologies

Technology/Region	LCOE (\$/kWh)
Onshore wind power stations [55]	0.033
PV power stations [55]	0.049
Geothermal power stations [55]	0.056
Bioenergy power stations [55]	0.061
Hydropower power stations [55]	0.061
Offshore wind power stations [55]	0.081
CSP power plants [55]	0.118
The studied LFR power plants	Ain Aménas power plant (0.093 \$/kWh) Gassi-Touil power plant (0.099 \$/kWh) Hassi R'mel power plant (0.103 \$/kWh) El-Oued power plant (0.11 \$/kWh)

3.4 Environmental Analysis. The technological developments introduced in solar power plants (thermal and photovoltaic power plants) will lead to a significant improvement in their efficiency and performance, given that the current solar electricity price is constantly declining by 89% for PV electricity and 69% for CSP electricity compared to previous years [55]. These two factors will lead to a significant expansion in the installation of solar power plants around the world, which will result in the creation of real job positions at many job levels (creation of real opportunities for green jobs).

As is known, Algerian electricity production depends on natural gas by 99%, which is a fossil resource that is depleting and contributes significantly to the emission of gases that threaten the ozone layer and contribute to global warming, especially CO_2. Currently, the Algerian government has decided to go ahead with investing in the construction and installation of solar power plants and their accompanying facilities to encourage investments outside the hydrocarbon sector, and Algeria has made great efforts to develop all energy sectors that depend on the exploitation of renewable energy sources because Algeria has great potential renewable energy sources, especially solar energy.

As the results of the energy and economic analysis showed, the installation of LFR power plants in the Algerian provinces is a successful and effective project. Moreover, these power plants are environmentally friendly, as they can reduce CO_2 emissions in large quantities, which will contribute to preserving the ozone layer, and will also contribute to reducing global warming, which will benefit the Algerian government by saving environmental taxes that were paid as fines for CO_2 emissions.

As shown in Fig. 8, among the most important conclusions of the environmental analysis of the studied electrical stations are the following:

- The studied LFR power plants will avoid CO_2 emissions ranging from 143.41 kt to 170.87 kt annually, depending on the location chosen to install the solar electric station. Therefore, in Algeria, the electricity production from the solar power plant will avoid the emission of 0.473 kg CO_2/1 kWh of electricity;
- The studied LFR power plants will result in saving environmental tax funds between 2.08 and 2.48 million dollars annually, depending on the location chosen to install the solar electric station;
- The total consumption of water by the LFR power plants varies between 143,403.33 m^3 and 170,862.5 m^3 annually, depending on the location chosen to install the solar electric station, of which 3675.27 m^3 is fixed for washing the LFR reflective mirrors. Note that in the studied LFR power plants, the production of 1 kWh of electricity requires a

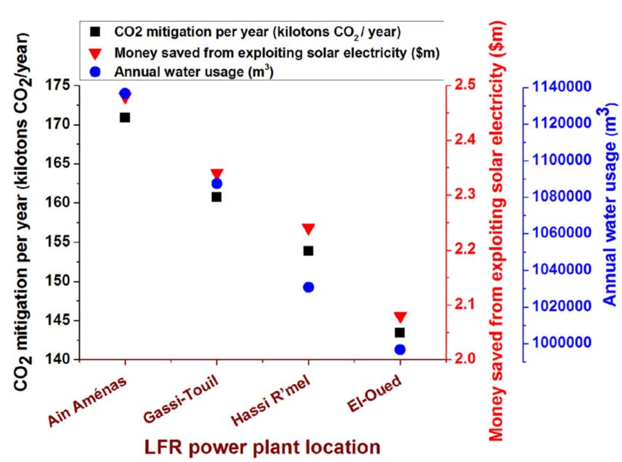

Fig. 8 Summary of the environmental analysis of the studied LFR power plants

water quantity of 3.19 L, to produce superheated water steam for the Rankine cycle excluding the amount of water used to wash the reflective mirrors. Regarding the annual consumption for washing reflective mirrors, it is 2.4 l/m^2.

After analyzing the results obtained energetically, economically, and environmentally for the Algerian regions that were taken as a model for installing LFR power plants, it is concluded that generating electricity with renewable energy in Algeria is a successful and effective project that will contribute to solving the energy problem nationally and has the potential to export internationally, because Algeria has large renewable energy, especially in the solar energy, where it is possible to build and install national solar power plants with international specifications, by exploiting all available capabilities (human and material).

4 Conclusions

Algeria has significant renewable energy potentials, including solar energy, which can be exploited to produce electricity by using LFRs. This study demonstrates the possibility of constructing LFR power plants, as the paper presents the following results:

- Based on the energy and economic analysis obtained in the four regions studied, LFR power plants can produce between 318.75 GWe and 379.29 GWe annually at an LCOE between 0.093 $/kWh and 0.11 $/kWh;
- Economically and for all regions, the Investor's net present value over the project life exceeded $19.34 million;
- Economically and for all regions, the developer's net present value over the project life exceeded $45.48 million;
- Environmentally and for all regions, the avoided CO_2 emissions range from 143.41 kt to 170.87 kt, which is 0.473 kg CO_2/1 kWh of electricity;
- The considered power plants would save environmental tax funds between 2.08 and 2.48 million dollars per year.

All the obtained results encourage the Algerian government to harness all the human and material capabilities to exploit them in installing national solar power stations with international specifications.

Author Contribution Statement

All authors equally contributed to the current work.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

CSP = concentrating solar power
DSCR = debt-service coverage ratio
EPC = engineering, procurement, and construction
IRR = internal rate of return, %
LCOE = levelized cost of electricity, $/kWh
MWCNTs = multi-walled carbon nanotubes
NPV = net present value, $
OTO = once-through option
RC = Rankine cycle
RCO = recirculated option
SAM = system advisor model

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