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Research paper

Evaluating the Performance of Parabolic Trough Solar Power Plants in Algerian Deserts: A Case Study of Andasol-1

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ABSTRACT

Electricity generation through renewable energy sources is essential for addressing environmental and economic challenges caused by reliance on fossil fuels. The global energy sector is rapidly transitioning towards sustainable and renewable energy sources, with concentrated solar power (CSP) emerging as a promising technology, particularly parabolic trough solar power plants. This study examines the performance of the Andasol-1 Parabolic Trough Solar Power Plant, with a 50 MWe power output, in various locations of the Algerian desert, including Bechar, Djanet, and Tamanrasset regions. A detailed overview of the technical specifications of the Andasol-1 facility is presented, and a comprehensive economic and energy analysis is carried out using the System Advisor Model (SAM) software. Our findings indicate that the Djanet region emerged as the most favorable site for CSP deployment, with a capacity factor of 53.7% and a Levelized Cost of Electricity (LCOE) of 16.84 ¢/kWh, offering the best balance of energy yield and cost efficiency. These results contribute to the global transition to clean and economically advantageous energy sources and provide valuable insights into the viability and efficiency of CSP technologies in dry climates.

1. INTRODUCTION

The global energy landscape has experienced a significant transformation in recent years, characterized by an increasing shift towards sustainable and renewable energy sources. Concentrated solar power (CSP) has emerged as a highly promising technology in this field, offering the potential for efficient

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electricity generation and thermal energy storage. Given the pressing challenges of climate change and the need for sustainable energy solutions, CSP technologies, mainly parabolic trough solar power plants, have garnered substantial attention within the renewable energy research community.

Parabolic trough solar power plants are among the most well-developed and widely adopted CSP technologies. These plants utilize parabolic mirrors to concentrate sunlight onto a receiver pipe, heating a transfer fluid, typically oil or molten salt, which generates steam to power a turbine for electricity production. A notable advantage of these systems is their capability to integrate thermal energy storage systems, as demonstrated by power plants such as Nevada Solar One in the USA and Andasol-1 in Spain. This integration enables electricity generation even during periods without sunlight, significantly enhancing the plant's operational flexibility and reliability (Fig. 1).

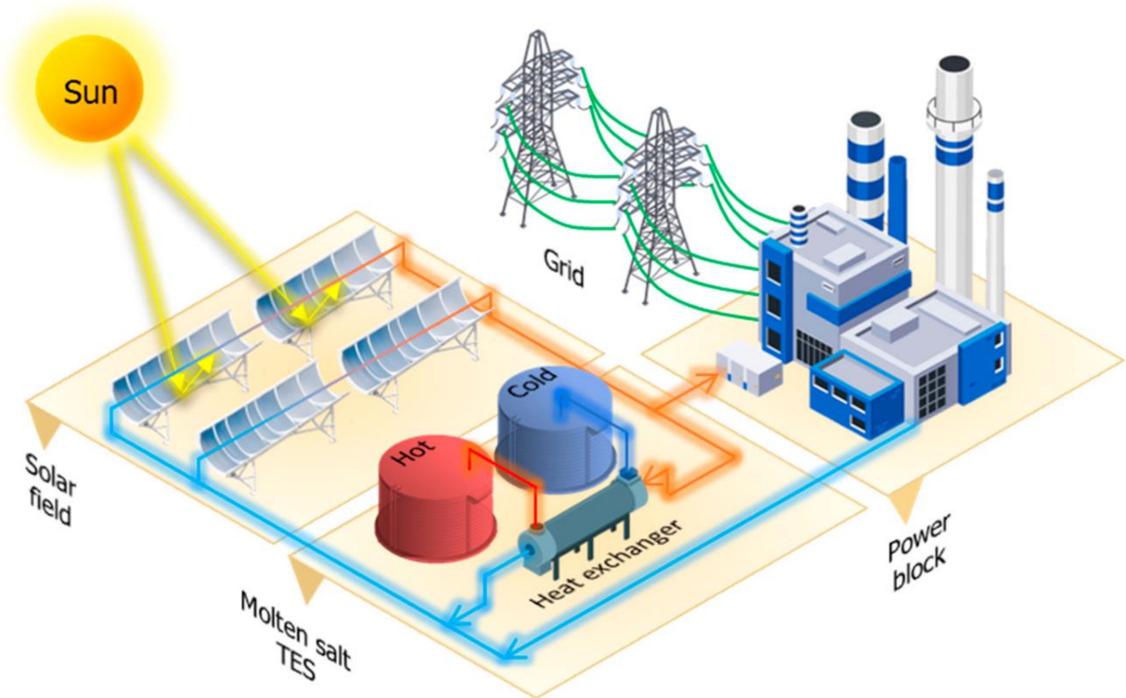

Fig 1. Operation of a parabolic trough CSP system with thermal energy storage and electricity generation turbine *(Prieto, Blindu, Cabeza, Valverde, & García, 2024)*.

Located in Aldeire, Spain, Andasol-1 is Europe's first large-scale solar power plant with full thermal storage capability. With an installed capacity of 50 MW and an investment of approximately 310€ million, Andasol-1 has set a precedent for expansive CSP projects. Its successful operation has demonstrated the feasibility and efficiency of thermal storage in mitigating the intermittent nature of solar energy, thereby contributing to the stability of the power grid (Solar Millennium AG, 2005).

Despite the proven success of Concentrated Solar Power (CSP) technologies in various regions, there is still a significant research gap in understanding their performance in desert environments. With its abundant solar resources, the Algerian desert presents an ideal yet challenging setting for CSP deployment. Factors such as high solar radiation, extreme temperatures, and dust accumulation offer opportunities and obstacles for CSP technologies.

The Study conducted by Boukelia et al. (2015) focused on designing and optimizing parabolic trough solar thermal power plants that used heat transfer fluids, therminol VP-1 and solar salt, integrated with thermal energy storage and a fuel backup system. These studies targeted a 50 MWe energy output and involved a parametric analysis of solar multiple and full load hours. The performance of these plants was compared with the Andasol 1 reference plant, considering energy and exergy efficiencies, capacity factor, annual power generation, water consumption, and land usage. The results of this study affirm that after optimization, Tamanrasset emerges as the best location for the erection of a parabolic trough solar thermal power plant, boasting a low Levelized Cost of Electricity (LCOE) of 8.48 ¢/kWh, and a high annual power generation exceeding 266 GWh with a Capacity Factor (CF) of 54.6%.

In addition, Dobos et al. (2014) researched the current simulation engine for CSP models in SAM. They implemented equivalent models for six CSP system models and demonstrated the effectiveness of the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). SAM successfully integrated annual time series power production models with financial models to estimate the levelized cost of energy (LCOE) and other relevant metrics for renewable energy projects. Moreover, the preliminary results of these simulations showed excellent alignment with accepted TRNSYS-based models and a significant reduction in simulation time for specific models. This allowed for more extensive plant configuration analysis and facilitated grid-integration studies that required numerous simulations.

Another study by Azouzoute et al. (2020) used meteorological data from sixty-two locations in the Middle East and North Africa (MENA) region to simulate the technical and economic performance of a 50 MWe CSP plant. The results demonstrated the region's potential for competitive electricity production (11.58 ¢/kWh) compared to Spain by indicating large-scale CSP plant installations and sustainable development opportunities.

Montes et al. (2009a) conducted an economic analysis on the impact of the solar multiple on the annual performance of a 50 MW CSP plant with thermal storage and an auxiliary natural gas boiler. The results demonstrate that the cost of electricity increases with the solar multiple, while fuel consumption remains unaffected. This can be attributed to the increase in stored energy. Additionally, their findings indicated a Capacity Factor (CF) of 41.67% and a Levelized Energy Cost (LEC) of 78.68 €/MWhe (Montes et al., 2009a). In another study, they performed an economic optimization of the solar multiple for a solar parabolic trough installation without thermal storage. The study is grounded in the simulation of annual performance, where the annual electricity production is calculated for different sizes of parabolic trough panels. It was observed that large solar field sizes without thermal storage would result in poor profitability (Montes et al., 2009b).

Garcia et al. (2011) executed a simulation to replicate the performance of Parabolic Trough solar power plants with a thermal storage system. The objective of this model is to facilitate electricity production forecasting in various stages of planning, design, construction, and operation of such plants. The performance of a 50 MWe power plant is analyzed and matched against precise data from a similarly sized facility operated by ACS Industrial Group in Spain, demonstrating the model’s high accuracy through this comparison.

Kariuki et al. (2012) investigated the variation of parameters, such as the solar multiple and collector size, with and without thermal storage, in a parabolic trough power plant in Kynnie. The SAM software was used to establish the economic optimization of solar energy. It was observed that an increase in the solar multiple leads to a rise in collector surface area, allowing the storage to receive more heat. This enhances electricity production and ensures the proper functioning of the plant.

Abbas et al. (2013) performed numerical simulations using the SAM software to assess the parabolic trough solar power plant's technical feasibility and economic reliability for electricity production in adverse Algerian climatic conditions. The study evaluated energy and financial performance to meet a target electricity production of 100 MWt. In another study, Saleem & U1 Asar (2014) investigated the implementation of a parabolic trough power plant in Pakistan. The study focused on various parameters, including wind speed, slope, land use, transportation lines, road and railway networks, water resources, and natural gas availability. The study's main objective was to determine the optimal location for the power plant to achieve green energy objectives. By comparing the costs with conventional fossil fuels and existing renewable energy plants in Pakistan, the researchers concluded that the parabolic trough power plant competes effectively in the country's energy market.

Ikhlef and Larbi's study on Hassi R'mel's solar power plant in Algeria optimized design parameters to achieve a minimum LCOE of 5.83 €/kWh and a capacity factor of 60%, producing 118.26 GWh annually. The findings highlight the economic benefits of wet cooling and the suitability of Therminol VP1 as a heat transfer fluid, validating concentrating solar power's potential in solar-rich regions (Ikhlef & Larbi, 2020). In another study, the researchers studied the 25 MW solar energy output of the Hassi R'Mel hybrid gas-solar plant and explored efficiency improvements with different thermal storage systems. Using SAM software, they conducted numerical simulations and presented a thermodynamic mathematical model to optimize the plant's performance. This model, encompasses both the thermodynamic and operational aspects of the plant. Algeria's favorable sunlight conditions supported the advancement of solar technologies (Ikhlef & Larbi, 2018). During the same year, Ikhlef and Larbi conducted a study aimed at a technical and economic analysis of electricity production through a parabolic trough concentrating solar power plant for the regions of Tamanrasset, Béchar, Biskra, and Ghardaïa. In this study, they presented both the technical and economic mathematical models employed by the System Advisor Model (SAM) software. This comprehensive model facilitated the assessment of the potential and viability of harnessing solar energy in these specific Algerian regions, focusing on optimizing the plant's performance and cost-effectiveness (Ikhlef & Larbi, 2018)

Our study aims to address the research mentioned above gap by analyzing the performance of the Andasol-1 CSP plant across different locations within the Algerian desert. Using the System Advisor Model (SAM) software, a comprehensive assessment of the plant's technical and economic performance will be carried out in three distinct Algerian locations: Bechar, Djanet, and Tamanrasset regions. These locations are selected based on their diverse climatic and environmental conditions, allowing for a holistic evaluation of the potential for CSP implementation in desert regions.

2. METHODOLOGY

This study focuses on evaluating the adaptability and performance of the Andasol-1 Parabolic Trough Solar Power Plant in three different locations of the Algerian desert: Bechar, Djanet, and Tamanrasset regions. These locations were carefully selected based on critical factors such as high solar radiation intensity, climate variability, and geographical diversity. These criteria ensure a comprehensive understanding of the CSP plant's performance under different desert environmental conditions. Table 1, provided below, displays the meteorological and geological data for the selected regions. These regions were explicitly chosen for their important solar radiation intensity within the country.

To conduct the technical and economic analysis of the Andasol-1 plant in these locations, we utilized the System Advisor Model (SAM) software. SAM, developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), is a widely recognized performance prediction and financial modeling tool for renewable energy analysis. It allows users to model energy output and assess the financial feasibility of renewable energy projects under various environmental and economic conditions.

The technical analysis focuses primarily on the energy output of the Andasol-1 plant, considering factors such as solar irradiance, temperature, and plant efficiency. Using SAM, we simulate the power plant's performance in each location over a typical meteorological year by incorporating local weather data to assess energy output variations.

Table 1. Meteorological and Geological Data for Selected Regions.

	Bachar	Djanet	Tamanrasset
Latitude (°E)	31.62	24.55	22.78
Longitude (°N)	-2.23	9.48	5.52
Altitude (m)	772	1 035	1377
DNI (KWh/m²)	2925	2539	2812
GHI (KWh/m^2)	2251	2299	2382
Ambient temperature (°C)	21.9	23.8	22.8
Wind speed (m/s)	4	3.2	3.6

Table 2. Technical Input Data: Comparison with Andasol 1 Power Plant Parameters (Solar Millennium AG, 2005).

	Variable	SAM Input	Andasol 1
Climate	Location	Bechar TMY3	Granada (EPW)
		Djanet TMY3	
		Tamanrasset TMY3	
Solar field	Field aperture	510 000 m^2	510 120 m^2
	Irradiation at design	950 W/m^2	700 W/m^2
	Field HTF fluid	Therminol VP1	Therminol VP1
	Design loop outlet temp	391°C	393°C
	Number of SCA per loop	8	4
Collector (SCAs)	Configuration name	EuroTrough ET150	EuroTrough ET150
Receivers (HCEs)	Configuration name	Schott PTR-70	Schott PTR-70 and Solel UVAC models
Power Cycle	Capacity - Design gross output	50 MW	49.9 MW
	Cycle thermal efficiency	0.356	0.381
	Aux heater outlet set temp	391°C	393°C
Thermal Storage	Full load hours of TES	7.5 hr	28,500 t salt for 7.5 peak load hours
	Tank height	14 m	14 m

The economic analysis includes an assessment of capital and operational costs, potential revenue, and return on investment for the CSP plant in each location. SAM's comprehensive financial model estimates these economic parameters, taking into account location-specific factors such as installation costs, maintenance expenses, and local energy market trends.

Data for this study were obtained from reliable sources. Meteorological data for each location were obtained from METEONORM software (Table 1). Technical specifications and operational details of the Andasol-1 plant were sourced from published reports and operational records. Economic data, including costs and market prices, were gathered from industry reports and local energy authorities (Solar Millennium AG, 2005). Table 2 illustrates the technical parameters used as input data in the SAM simulations compared to those of the Andasol 1 power plant. Table 3 illustrates the financial parameters used as input data in the SAM simulations compared to those of the Andasol 1 power plant.

As previously stated in the previous tables, our objective was to incorporate technical and economic data that closely mirror those of the Andasol 1 power plant. This was done to facilitate a comprehensive comparison of the simulation results.

This study acknowledges certain limitations and assumptions in the methodology. The accuracy of SAM predictions depends on the reliability of input data, particularly meteorological data. Additionally, the economic analysis assumes stable market conditions and does not consider potential policy changes or subsidies that could affect the project's financial viability.

Table 3. Financial Input Data: Comparison with Andasol 1 Power Plant Parameters (Solar Millennium AG, 2005).

	Variable	SAM Input	Andasol 1
Direct capital costs	Site Improvements	25.00 $/m^2$	28.00 $/m^2$
	Solar field	150.00 $/m^2$	-
	HTF System	70.00 $/m^2$	78.00 $/m^2$
	Storage	62.00 $/kWht	78.00 $/kWht
	Fossil Backup	0.00 $/kWe	60.00 $/kWe
	Power Plant	910.00 $/kWe	850.00 $/kWe
	Balance of plant	100.00 $/kWe	105.00 $/kWe
	Fixed Cost by Capacity	65.00 $/kW-yr	66.00 $/kW-yr
	Variable Cost by Generation	4.00$/MWh	3.00$/MWh
	Estimated total installed cost	$327*10^6$ $	$327*10^6$ $
Financial parameters	Analysis period	25	25

3. RESULTS AND DISCUSSIONS

3.1. Validation

Table 4 presents a comprehensive validation analysis, comparing the results obtained from the SAM software simulation with the actual performance of the Andasol 1 power plant. The simulation inputs, derived from the system specifications outlined in section 2, have been thoroughly validated against the Andasol 1 power plant outcomes. The table meticulously outlines the key simulation results. It provides the percentage variance between the estimated values from the SAM simulation and the verified data reported by the Andasol 1 power plant. Additionally, it is noteworthy to mention that the performance of the Djanet site is significantly greater than that of the site in Spain. This can be attributed to the desertic nature of the Djanet site and its possession of more accurate meteorological data.

Table 4. Validation Analysis: SAM Simulation versus Andasol 1 Power Plant Performance (Solar Millennium AG, 2005).

	SAM Outputs Djanet region	**Andasol 1 power plant**	**Difference (%)**
Annual Energy AC	225,821,248 kWhe	179,103,000 kWhe	23.07%
PPA price real	39.28 ¢/kWh	37.05 ¢/kWh	5.84%
LCOE Nominal	22.83 ¢/kWh	27.83 ¢/kWh	19.73%
LCOE Real	16.84 ¢/kWh	15.841 ¢/kWh	6.11%
Capacity Factor	57.3%	41.50%	31.98%

3.2. Technical Results

We utilized METEONORM 7 software to determine the meteorological data for the selected region (1991-2010), including Direct Normal Irradiance, ambient temperature, wind speed, and relative humidity. We specifically chose the month of July to present the most optimal values, as this month represents the highest solar irradiance durations of the year. By selecting the monthly average of July, we focused on the most potential and performant period, representing the most favorable case annually.

Fig. 2 illustrates the hourly profiles of dry temperatures for the Bechar, Djanet, and Tamanrasset regions, depicted by the blue, red, and green lines. These lines clearly illustrate the characteristic diurnal cycle typically found in desert environments. The temperatures in all three locations rise throughout the day and peak in the afternoon due to intense solar heating. After sunset, the temperatures rapidly decrease, indicating a swift cooling process. These graphs suggest consistency in regional climate and hint at potential local geographic or atmospheric factors that may influence thermal patterns. Understanding these temperature dynamics is essential for efficiently operating concentrated solar power (CSP) plants. The peak temperatures provide insights into the potential thermal efficiency. At the same time, the nightly lows offer valuable information regarding environmental cooling effects, which are essential for effectively managing the CSP plant's thermal systems. In terms of temperature, the figure indicates that Bechar experiences the highest temperatures, followed by Djanet and then Tamanrasset.

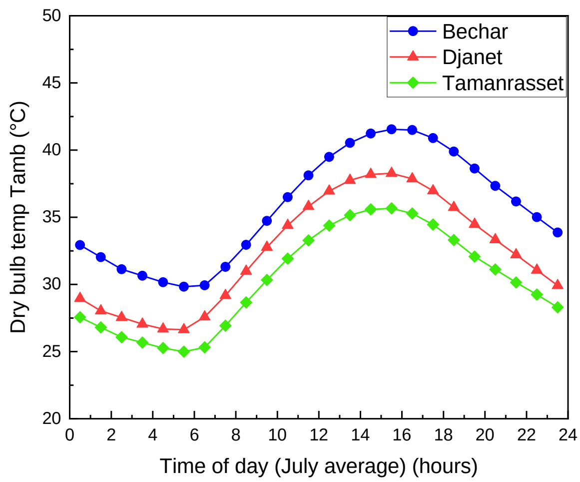

Fig 2. Dry Temperature Variations Over Time (Hours) in July: 1991-2010 Average Data.

Based on the DNI beam irradiance Fig. 3, it can be observed that the Djanet site exhibits the highest irradiance, followed by Tamanrasset and Bechar in that order. The graph depicting the Direct Normal Irradiance (DNI) in July for Bechar, Djanet, and Tamanrasset reveals that solar radiation reaches its peak at midday for all three locations, which corresponds to the sun's zenith position and suggests a significant potential for solar power generation. The similarity in radiation levels among the locations implies a consistent solar resource in the Algerian desert, which is advantageous for implementing concentrated solar power (CSP) systems. Moreover, the symmetrical shape of the irradiance curves around the peak indicates a stable and predictable solar environment, which is vital for ensuring CSP systems' effective design and operation.

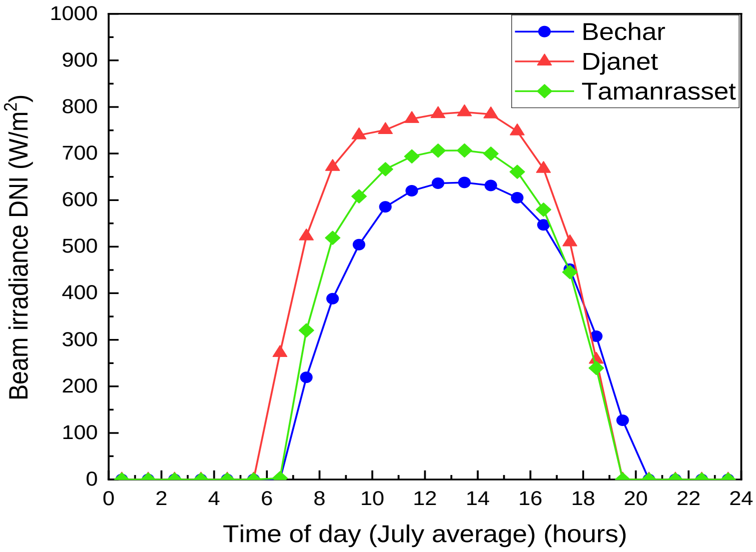

Fig 3. DNI Variations Over Time (Hours) in July: 1991-2010 Average Data.

Fig. 4 depicts the relative humidity trends for the three selected regions. It demonstrates the typical daily cycle observed in desert regions, with lower relative humidity during the hottest hours and higher levels during cooler periods such as night or early morning. This fluctuation is significant for concentrated solar power (CSP) operations. High humidity can increase the risk of corrosion in thermal systems and impact atmospheric transparency, potentially reducing the solar radiation reaching the CSP plant's mirrors and receivers. Understanding these patterns is essential for optimizing CSP plants' performance and maintenance schedules in arid climates.

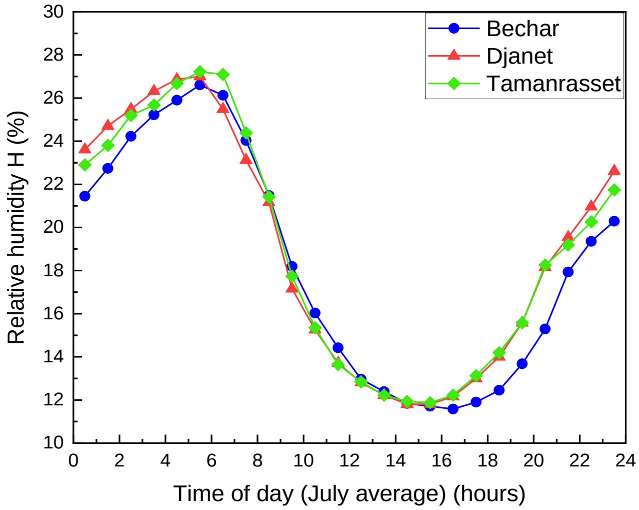

Fig 4. Relative Humidity Variations Over Time (Hours) in July: 1991-2010 Average Data.

Similarly, Fig. 5 displays wind speed variation for Bechar, Djanet, and Tamanrasset, which shows pronounced daily fluctuations. Two notable peaks suggest increased wind activity during specific hours. This pattern is characteristic of desert regions, where thermal heating during the day and cooling at night create pressure differentials that drive up wind speeds. This information is vital for renewable energy strategies, particularly in optimizing wind turbine operation for energy generation and addressing the cooling demands within CSP plants. It also ensures the necessary structural resilience against the mechanical stresses imposed by the desert wind.

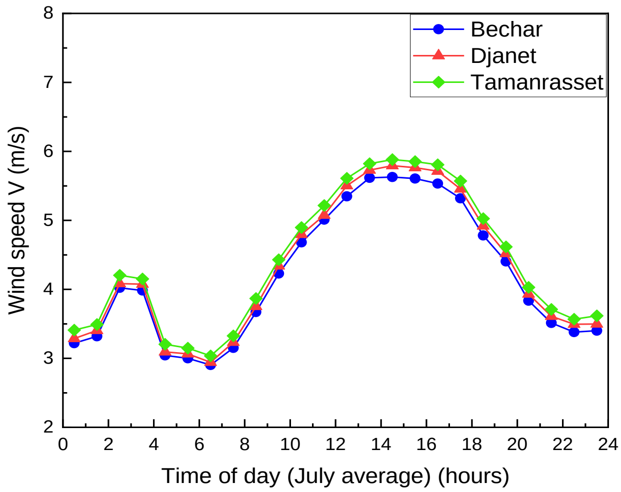

Fig 5. Wind Speed Variations Over Time (Hours) in July: 1991-2010 Average Data.

Fig. 6 demonstrates the variation in electric power production from sunrise to sunset across Bechar, Djanet, and Tamanrasset. The power output aligns with the daily pattern of solar radiation, reflected in the Direct Normal Irradiance (DNI) and ambient temperatures, confirming the direct relationship between incident solar energy and electricity generation. Notably, the consistency of reaching nominal power levels between 11:00 AM and 6:00 PM across all regions indicates a significant window for optimal power generation. This period corresponds with peak solar hours, where the sun is high and DNI values are at their maximum. Such information is important for designing and operating solar power systems, enabling them to capitalize on peak production periods while also considering the need for energy storage or auxiliary systems to provide power outside these peak hours. Additionally, the sharp decline in power after 6:00 PM underscores the importance of thermal storage or hybrid systems to maintain a steady power supply after sunset.

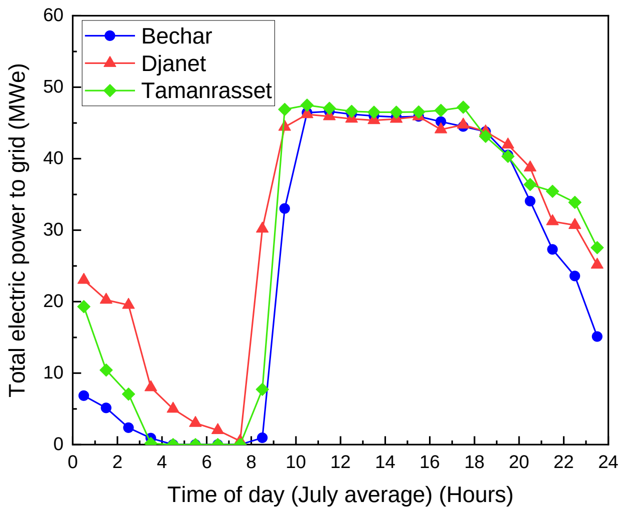

Fig 6. Temporal Variation of Electric Power Output in July: 1991-2010 Average Data.

3.3. Financial Results

In Fig. 7, the levelized cost of electricity (LCOE) is presented, revealing distinct cost patterns across different sites. The Djanet site is the most economically advantageous, with the lowest LCOE. The Tamanrasset region follows closely, where the LCOE is recorded at 17.45 $/kWh. In contrast, the Bechar site demonstrates lower production levels and consequently incurs a higher LCOE of 18.9 $/kWh. This observed variation highlights the economic nuances inherent in the electricity generation capacities of these particular locations.

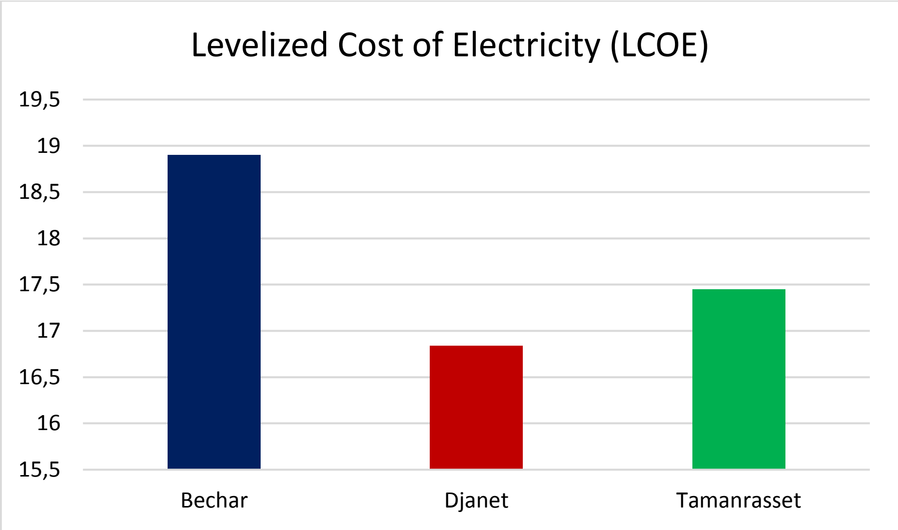

Fig 7. The Levelized Cost of Electricity (LCOE)

3.4. Djanet Results

The following figure (Table 8) was captured for the Djanet region. It is a matrix that summarizes all the outcomes of the simulations. The Djanet site was chosen to present all the results because it represents the best results.

The "Annual AC Energy in Year 1" exceeds 225 million kWhe, representing the actual AC energy output after accounting for losses in DC conversion. The high-capacity factor of 57.3% indicates efficient utilization in relation to the plant's maximum output. Allocating a significant amount of energy for freeze protection is crucial in colder temperatures. The "First year kWh/kW" metric at 5,018 measures productivity per installed kW.

The "PPA Price in Year 1" is set at 0.5 $/kWh, with a modest 1% escalation rate in the Power Purchase Agreement, which helps mitigate potential energy price volatility. The competitive nominal and real levelized costs of energy offer a comprehensive assessment of production costs throughout the project's lifetime. A strong financial profile is demonstrated by a net present value (NPV) of 546,830,080 $ and an internal rate of return (IRR) of 90.93%.

Water usage, totaling 46,241 m³, is of particular significance, especially in a desert environment where water scarcity may have additional economic and environmental implications. Considering water usage becomes essential for long-term sustainability.

In summary, the solar power project demonstrates both technical and economic feasibility through efficient energy output, a well-structured Power Purchase Agreement, and a robust financial profile. Factors such as the financing structure and water usage require careful management to ensure long-term sustainability and profitability.

Our research findings reveal variations in the performance of the Andasol-1 Parabolic Trough Solar Power Plant across different desert locations. The regions with the most sunlight and least cloud cover demonstrated the highest levels of electricity generation efficiency. Djanet emerged as the ideal site from an energy and economic standpoint, making it a highly favorable choice for future investments in concentrated solar power plants.

Table 5. SAM Metric table output for Djanet region.

Metric	Value
Annual AC Energy in Year 1	225 821 248 kWh-e
Annual Freeze Protection	839 653 kWh-e
Annual TES Freeze Protection	839 653 kWh-e
Annual Field Freeze Protection	0 kWh-e
Capacity factor	57.3%
Power cycle gross electrical output	256 482 912 kWh-e
First year kWh/kW	5 018
Gross-to-net conversion	88.0%
Annual Water Usage	46 241 m^3
PPA price in Year 1	50.00 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	53.26 ¢/kWh
LPPA Levelized PPA price real	39.28 ¢/kWh
LCOE Levelized cost of energy nominal	22.83 ¢/kWh
LCOE Levelized cost of energy real	16.84 ¢/kWh
NPV Net present value	$546 830 080
IRR Internal rate of return	90.93 %
Year IRR is achieved	20
IRR at end of project	90.93 %
Net capital cost	$332 190 048
Equity	$135 692 560
Size of debt	$196 497 504
Debt percent	59.15%

4. CONCLUSION

The transition to renewable energy is a strategic step for environmental sustainability and a financially prudent decision in the long term. Our comprehensive analysis of the performance of the Andasol-1 Parabolic Trough Solar Power Plant in the diverse terrains of the Algerian desert underscores the feasibility of solar power in arid regions. By carefully adjusting the input parameters of Andasol-1, we have successfully minimized the Levelized Cost of Electricity (LCOE) and maximized annual energy production. Our study shows that Djanet emerges as the most promising location among the evaluated sites, offering the best balance of energy yield and cost efficiency, closely followed by Tamanrasset and Bechar. These findings confirm that Parabolic Trough technology has significant potential to increase renewable electricity production in the Algerian desert, providing a solid blueprint for future solar energy projects in similar environments. These results strengthen the argument for expanding solar energy infrastructure in Algeria and contribute to the global narrative of transitioning to clean and economically advantageous energy sources.

NOMENCLATURE

AC	Alternating Current	LCOE	Levelized Cost of Electricity
¢	Cent (as a monetary unit (1¢ = 0.01$)	MW	Megawatt
CSP	Concentrated Solar Power	MWe	Megawatt Electrical
DC	Direct Current	NPV	Net Present Value
DNI	Direct Normal Irradiance	PPA	Power Purchase Agreement
GHI	Global Horizontal Irradiance	SAM	System Advisor Model
HCE	Heat Collection Element	SCA	Solar Collector Assembly
IRR	Internal Rate of Return	TES	Thermal Energy Storage

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