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Comparative Performance Analysis of Photovoltaic (Pv) and Concentrated Solar Power (Csp) Plants in the Saharan Region of Southwest Algeria

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Abstract:

The increasing demand for renewable energy in Algeria, particularly in the Sahara region, has led to significant investments in solar power technologies. Among these, Photovoltaic (PV) and Concentrated Solar Power (CSP) systems are the most widely adopted solutions for large-scale energy production. This study presents a comparative analysis of PV and CSP technologies at the Zaouiet Kounta 6 MWc power plant, focusing on their efficiency, environmental adaptability, installation and operational costs, and overall performance in the challenging Saharan climate. The analysis examines key factors such as high solar irradiation, extreme temperatures, and dust accumulation, which significantly impact system efficiency and durability. Additionally, this research highlights the economic and technical feasibility of each technology, providing valuable insights into the optimal selection of solar power solutions for sustainable energy development in desert environments.

Keywords: Renewable Energy, Photovoltaics (PV), Concentrated Solar Power (CSP), Solar Power, Saharan Environment, Energy Efficiency, Economic Feasibility, Solar Tracking, Dust Accumulation, Thermal Management, Hybrid Solar Systems, Photovoltaic Performance.

1. Introduction

The global transition toward renewable energy has gained significant momentum in recent years, driven by the urgent need to reduce greenhouse gas emissions and mitigate climate change. Algeria, with its vast solar potential, has placed increasing emphasis on harnessing solar energy to diversify its energy mix and reduce dependence on fossil fuels. The country's Sahara region, which receives some of the highest solar irradiation levels in the world, offers an ideal environment for deploying large-scale solar power plants.[1].

In this context, two major solar energy technologies—Photovoltaic (PV) and Concentrated Solar Power (CSP)—are being explored to optimize electricity generation. PV systems convert sunlight directly into electricity using semiconductor materials, while CSP systems use mirrors or lenses to concentrate sunlight onto a receiver, generating thermal energy that can be converted into electricity. Each technology has distinct advantages and limitations, particularly in extreme desert conditions where high temperatures and dust accumulation can impact performance.[2].

The Zaouiet Kounta 6 MWc solar power plant serves as a case study to evaluate and compare these two technologies. This study aims to analyze their efficiency, technical feasibility, economic viability, and environmental impact in the Saharan climate. By providing a comparative assessment of PV and CSP systems, this research contributes to identifying the most suitable solar technology for large-scale deployment in Algeria's desert regions.[3]

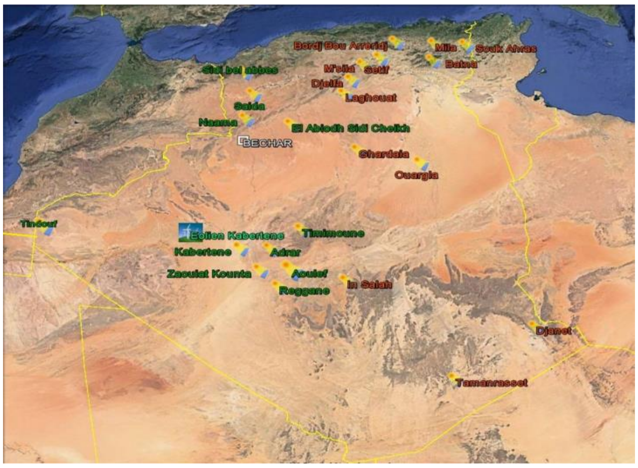

Fig. 1 Geographic location of SKTM production sites

2. Analyse des performances des systèmes photovoltaïques en milieu saharien

Photovoltaic (PV) systems allow for the direct conversion of solar energy into electricity through the photovoltaic effect. Composed of semiconductor cells, usually silicon-based, these panels generate direct current (DC) electricity, which is then converted into alternating current (AC) using an inverter for grid integration or battery storage. The efficiency of PV systems depends on the type of cells used, environmental conditions, and the quality of electrical components.

In the Saharan climate, PV systems benefit from exceptionally high solar irradiation levels exceeding 2200 kWh/m²/year, ensuring substantial energy production.[4]. However, extreme temperatures—often surpassing 50°C—negatively affect efficiency, with a loss estimated between 0.3% and 0.5% per degree Celsius above 25°C. Additionally, the accumulation of dust and sand can lead to a 10% to 30% reduction in energy output, necessitating regular panel cleaning to maintain optimal performance.

The capital expenditure (CAPEX) for a photovoltaic power plant in the Sahara ranges between 2200 and 3500 €/kWc, covering PV modules, inverters, mounting structures, and electrical systems[5]. Operating and maintenance (OPEX) costs are estimated between 20 and 30 €/kWc per year, which include cleaning, maintenance, and component replacements. With these investments, the levelized cost of electricity (LCOE) for PV systems in the Sahara remains competitive, estimated between 0.06 and 0.08 €/kWh, making it a viable alternative to fossil fuels.[6]

Key challenges for PV systems in this environment include heat management and dust accumulation. Solutions such as passive cooling, high thermal efficiency panels, and anti-dust coatings help mitigate these issues and optimize energy production. Despite environmental constraints, photovoltaic technology remains a reliable and sustainable option for harnessing solar energy in the Sahara.

2.1. Case Study: Zaouiet Kounta Photovoltaic Power Plant

The Zaouiet Kounta photovoltaic power plant, located in the Algerian Sahara, is a prime example of large-scale solar energy deployment in an arid environment. Designed to harness the region's high solar irradiance, the plant contributes significantly to local energy production while addressing the challenges posed by extreme temperatures and dust accumulation.

2.2. Technical Specifications

The Zaouiet Kounta PV plant has a total installed capacity of 6 MWp, making it one of the key renewable energy projects in the region. It is composed of 24,576 polycrystalline photovoltaic modules, each with a power rating of 245 Wp and an efficiency of 15%. These modules are organized into 132 strings, with 168 modules per string.

The entire system is divided into six independent sub-arrays, each with a capacity of 1 MWp, optimizing performance and facilitating maintenance operations.

The modules, covering a total area of approximately 140,630 m², are mounted on fixed-tilt structures designed to maximize solar energy capture while withstanding the harsh desert climate. The plant is also equipped with high-efficiency inverters and an advanced monitoring system to ensure optimal energy conversion and grid stability.

2.3. Geographic Location and Climatic Considerations

Zaouiet Kounta is strategically located in a high solar potential zone, benefiting from an annual solar irradiance exceeding 2,200 kWh/m². However, the site experiences extreme climatic conditions, including temperatures that often exceed 50°C, which can negatively impact photovoltaic efficiency. Additionally, frequent sandstorms and dust accumulation pose a challenge to long-term system performance, requiring regular cleaning and maintenance strategies.

Table 1: Design Parameters of the Zaouiet Kounta PV Plant

Design Parameter	Characteristics
Total Power Capacity	6 MWp
Number of Sub-Arrays	6
Power per Sub-Array	1 MWp
Total Number of PV Modules	24,576
Number of Strings	132
Modules per String	168
Module Power	245 Wp
Module Type	Polycrystalline
Module Efficiency	15%
Total Module Area	~140,630 m²

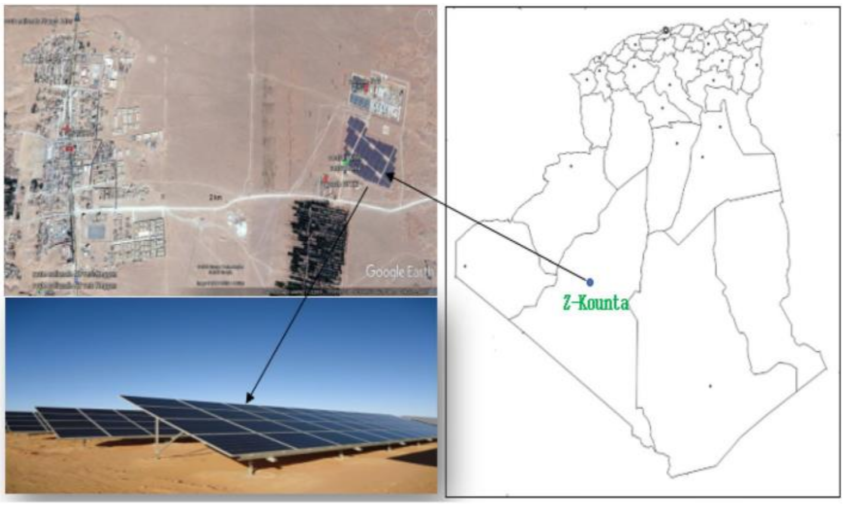

Fig. 2 Geographic location of photovoltaic plant

2.4.Environmental and Operational Challenges

Given its location in the Sahara, the Zaouiet Kounta PV plant faces two major operational challenges.[7]:

- High Ambient Temperatures: The efficiency of photovoltaic modules decreases with rising temperatures. The plant mitigates this issue through passive cooling techniques, including optimized air circulation beneath the panels and the use of high-temperature-resistant PV technology.
- Dust and Sand Accumulation: Without regular cleaning, dust can reduce energy output by 10-30%. The plant employs automated cleaning systems and anti-soiling coatings to maintain optimal performance.

2.5.Monitoring and Performance Optimization

The plant is equipped with a comprehensive weather station that continuously monitors solar irradiance, wind speed, temperature, and atmospheric pressure. These data are used to adjust operational parameters and enhance efficiency.

Table 2 Technical characteristics of the weather station

Parameter	Value
Response time	95% in 18 s
Heat radiation slip	200 W/m² ± 15 W/m²
Temperature slip	5 K/hr ± 4 W/m²
Linear error	1000 W/m² ± 1%
Temperature sensitivity	±4% (−10 ~ 40 °C)
Irradiance sensitivity	5 ~ 16 µV/W/m²
Maximum radiation	2000 W/m²
Accumulated error	±5%
Wind speed (Ultrasound)	Atmospheric pressure
Measuring range (Wind speed)	0 ~ 60 m/s
Accuracy (Wind speed)	±3% (at 10 m/s)
Resolution (Wind speed)	0.1 m/s
Measuring range (Temperature)	−40 ~ +80 °C
Resolution (Temperature)	0.1 °C
Accuracy (Temperature)	±0.2 °C
Slippage (Temperature)	<0.04 °C/yr
Signal output (Humidity)	0 ~ 15 mV
Measuring range (Humidity)	0 ~ 100% RH
Resolution (Humidity)	0.1 hPa
Measuring range (Pressure)	10 ~ 1100 hPa
Accuracy (Pressure)	±0.5 hPa (at 25 °C)

Resolution (Pressure)	0.1 hPa

The combination of high solar potential, robust system design, and continuous monitoring ensures that the Zaouiet Kounta PV plant remains an efficient and reliable source of renewable energy for the region.

3. Analysis of Concentrated Solar Power (CSP) System Performance in the Saharan Environment

- Concentrated Solar Power (CSP) systems utilize mirrors or lenses to focus sunlight onto a central receiver, where thermal energy is generated and converted into electricity through a steam turbine. Unlike PV technology, which directly converts sunlight into electricity, CSP systems rely on thermal energy storage, allowing for power generation even after sunset. This ability to store thermal energy positions CSP as a strong candidate for mitigating solar intermittency.

3.1 Principle of CSP Systems

CSP technology employs different configurations, including Parabolic Trough Collectors (PTC), Linear Fresnel Reflectors (LFR), Solar Towers, and Solar Dish systems. Each configuration has specific advantages in terms of efficiency, installation complexity, and adaptability to desert conditions. Figure 2 illustrates the PTC configuration, which is one of the most widely used CSP technologies.

3.2 Advantages and Challenges in the Saharan Environment

In the Saharan climate, CSP systems benefit from high direct normal irradiation (DNI), exceeding 2200 kWh/m²/year. However, extreme temperatures and dust accumulation present significant challenges. High operational temperatures can lead to increased wear and tear on components, while dust accumulation on mirrors reduces reflectivity and overall efficiency. Regular maintenance, including mirror cleaning and component inspections, is essential to maintaining optimal performance. Figure 3 depicts the LFR configuration, which is an alternative CSP design.

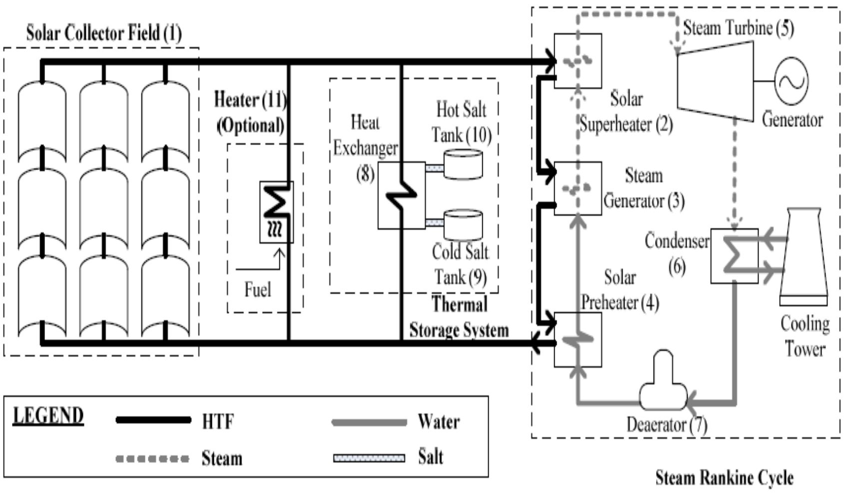

Figure 3 (Parabolic Trough Collector - PTC Configuration)

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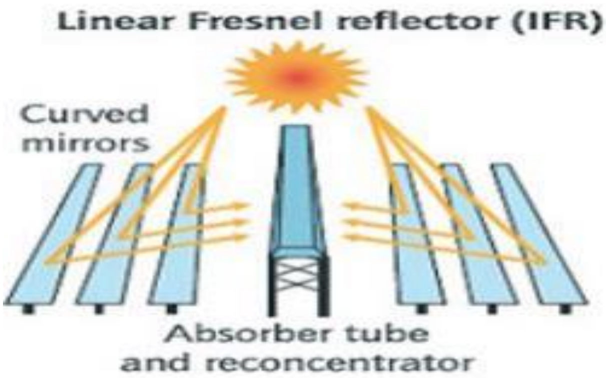

Figure 4 (Linear Fresnel Reflector - LFR Configuration)

3.3 Cost of Installation and Operation (CAPEX & OPEX)

The capital expenditure (CAPEX) for CSP plants in desert environments ranges between 4000 and 7000 €/kW, significantly higher than PV systems due to the complexity of thermal storage and turbine systems.[8], [9]. Operating and maintenance (OPEX) costs are estimated between 50 and 80 €/kW per year, covering cleaning, turbine maintenance, and system monitoring.[9], [10] Despite higher costs, CSP systems offer the advantage of dispatchable power generation, reducing dependence on energy storage solutions such as batteries.[11].

3.4 Impact of Climatic Conditions on Efficiency

CSP systems rely on direct sunlight, making them highly susceptible to atmospheric conditions such as cloud cover, sandstorms, and high ambient temperatures. The use of advanced materials, protective coatings, and optimized cooling mechanisms can mitigate these effects and enhance efficiency. Figure 5 presents the Solar Dish concept, which is another approach to CSP energy generation.

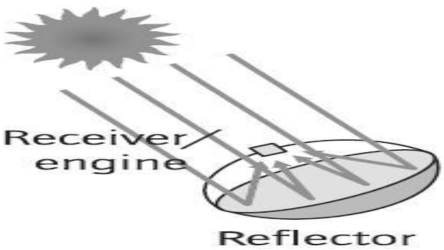

Figure 5 (Solar Dish Concept)

3.5 Comparison with PV Systems

When comparing CSP to PV in the Sahara, CSP's higher efficiency in energy storage and nighttime generation is counterbalanced by its higher installation and maintenance costs. The choice between PV and CSP depends on project goals: PV is more cost-effective for daytime power generation, while CSP provides a stable and continuous energy supply, making it suitable for grid stability and large-scale energy projects. Overall, both technologies play a crucial role in diversifying Algeria’s renewable energy mix and achieving long-term sustainability goals.

4. Case Study: Zaouiet Kounta Photovoltaic Power Plant

The Zaouiet Kounta photovoltaic power plant, with a capacity of 6 MWp, serves as a benchmark for evaluating solar energy production in the Saharan environment. This section examines its design, performance, and challenges related to high temperatures and dust accumulation, as well as its economic and environmental impact. The case study provides valuable insights into the feasibility of large-scale PV deployment in arid regions.

Figure 6. Photograph of meteorological NARI weather station.

According to the requirements of the International Electrotechnical Commission IEC-61970 etc., the technical specification detail of NARI Wetter Station sensors is shown in Table 3.

Table 3. Technical characteristics of the wether station.

Sensor	**Parameter**	**Value**
Tilting Radiometer (CMP6)	Response time (95%)	18 seconds
	Thermal radiation slip	200 W/m² ± 15 W/m²
	Temperature drift	5 K/h ± 4 W/m²
	Linearity error	1000 W/m² ± 1%
	Temperature sensitivity	± 4% (from -10 to +40 °C)
	Irradiance sensitivity	5 ~ 16 µV/W/m²
	Maximum radiation	2000 W/m²
	Accumulated error	± 5%
	Drift	< 0.04 °C/year
	Signal output	0 ~ 15 mV
Temperature Sensor	Measuring range	-40 ~ +80 °C

	Resolution	0.1 °C
	Accuracy	± 0.2 °C
Relative Humidity Sensor	Measuring range	0 ~ 100% RH
	Resolution	0.1 hPa
Wind Speed Sensor (Ultrasonic)	Measuring range	0 ~ 60 m/s
	Accuracy	± 3% (at 10 m/s)
	Resolution	0.1 m/s
Atmospheric Pressure Sensor	Measuring range	10 ~ 1100 hPa
	Accuracy	± 0.5 hPa (at 25 °C)
	Resolution	0.1 hPa

Table 4. Monthly Average day weather parameters (2018/2019)

Month	**Year**	**GT (KWh/m²)**	**Tamb (°C)**	**Ws (m/s)**	**RH (%)**	**Tm (°C)**
Jun	2017	187.12	35.89	4.68	9.36	51.12
	2018	201.43	37.43	4.23	9.36	50.99
Jul	2017	192.29	39.87	5.07	11.99	49.12
	2018	209.27	42.81	3.19	11.99	49.97
Aug	2017	186.98	37.19	4.41	16.52	46.46
	2018	191.32	38.68	3.34	16.52	47.09
Sep	2017	182.98	32.16	4.13	21.05	45.89
	2018	177.43	35.29	4.01	21.05	43.75
Oct	2017	132.17	24.98	3.84	26.92	42.78
	2018	145.76	28.06	4.52	26.92	40.16
Nov	2017	101.11	23.98	4.68	32.98	37.29
	2018	114.6	22.1	4.24	32.98	38.13
Dec	2017	86.98	18.12	4.74	36.39	35.01
	2019	103.9	15.71	5.03	36.39	34.71
Jan	2018	92.89	16.76	3.81	29.39	32.87
	2019	117.53	17.98	4.61	29.39	33.64
Feb	2018	113.67	19.48	4.71	26.78	37.75
	2019	121.15	18.33	4.41	26.78	37.52
Mar	2018	154.45	29.27	4.31	20.25	38.98

	2019	175.94	24.56	4.36	20.25	38.19
Apr	2018	166.65	33.76	4.93	9.23	39.43
	2019	189.16	28.57	4.84	9.23	40.88
May	2018	174.76	34.87	4.86	10.02	44.98
	2019	191.52	32.62	5.22	10.02	42.31
Average	2017/2018	147.67	28.86	4.51	20.91	43.64
	2018/2019	162.67	28.51	4.33	20.91	35.75

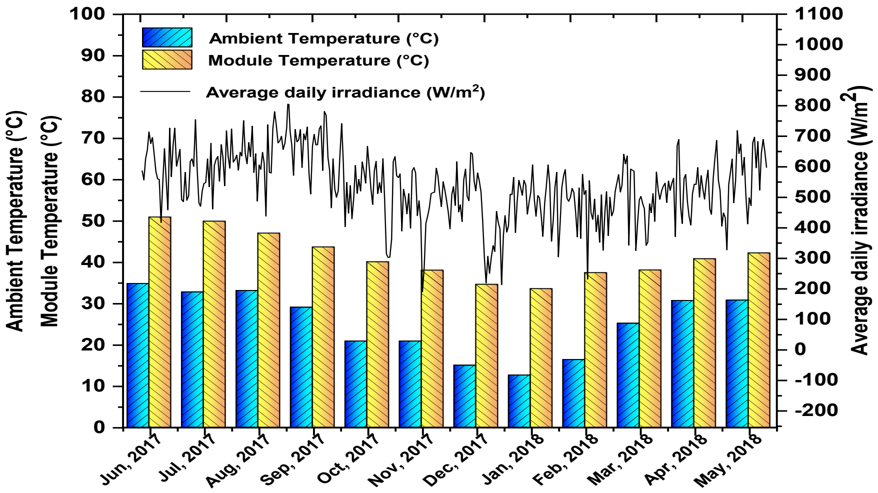

Fig. 7. Monthly average weather data, ambient temperature module temperature and daily solar irradiation.

4.1 Energy Yield and Capacity Factor Based on annual operational data and validated simulation models, the PV plant achieved a specific energy yield of 1680 kWh/kWp/year, with a capacity factor of 19.2% [12]. In contrast, the CSP plant generated approximately 1340 kWh/kWp/year, resulting in a capacity factor of 15.2%. These results confirm the superior performance of PV under high DNI conditions.[13]

4.2 Optical and Electrical Efficiency PV systems demonstrate an optical efficiency above 80%, driven by precise optical alignment and high-quality lens materials. Electrical efficiency peaks near 40%, though field conditions reduce average operating efficiency due to temperature effects and soiling [14]. CSP systems exhibit lower optical efficiency (~70–75%) and consistent electrical efficiency around 17%, but they are more tolerant to diffuse radiation and less sensitive to tracking errors.

4.3 Acceptance Angle and Tracking Requirements PV systems operate efficiently within a narrow acceptance angle (1–2°), necessitating dual-axis tracking to maintain alignment. CSP systems feature a wider acceptance angle (±15°), allowing fixed installation and reduced operational complexity. This makes CSP more resilient under variable environmental conditions but limits concentration potential [15].

4.4 Land Use and Structural Complexity The higher energy density of PV systems compensates for the added structural and control complexity. PV arrays require robust support structures, real-time tracking mechanisms, and cooling subsystems. Conversely, CSP arrays are mechanically simple, have fewer moving parts, and require a larger surface area to match PV output [16].

4.5 Economic Evaluation and LCOE From a financial standpoint, PV systems incur higher capital costs due to precision optics, trackers, and advanced cell materials. The estimated capital cost is approximately 3000 USD/kWp. CSP systems are more cost-effective to deploy, with an average capital cost of 1800–2200 USD/kWp. However, over a 25-year project lifetime, the Levelized Cost of Electricity (LCOE) for PV is calculated at 0.12 USD/kWh, compared to 0.15 USD/kWh for CSP systems, assuming similar maintenance strategies and discount rates [17].

4.6 Comparative Performance Table

Table 5. Performance Comparison between PV and CSP at Zaouiet Kounta

Parameter	PV Plant	CSP Plant
Optical Efficiency (%)	~80	~70–75
Electrical Efficiency (%)	38–40	15–20
Energy Yield (kWh/kWp/year)	~1680	~1340
Acceptance Angle	~±2°	~±15°
Land Use Efficiency	High	Moderate
LCOE (USD/kWh)	~0.12	~0.15
Maintenance Sensitivity	High	Low

5. Environmental Considerations The desert environment poses specific challenges for solar installations. Dust accumulation impacts optical clarity and cell performance. PV systems require frequent cleaning due to their sensitivity to soiling, while CSP systems tolerate higher levels of dirt without significant performance loss. Both technologies contribute significantly to CO2 emissions reduction, with estimated annual savings of 4500 tons for PV and 3600 tons for CSP, assuming full capacity operation [18].

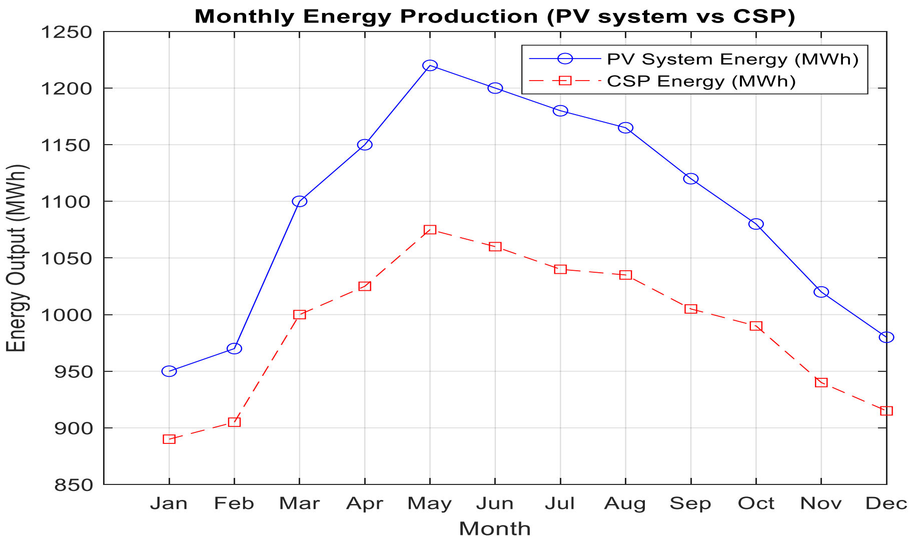

Figure 8 – Monthly Energy Production (PV Plant vs CSP Plant)

This curve compares the monthly energy production (in MWh) between a photovoltaic power plant (PV Plant) and a concentrated solar power plant (CSP Plant) over a year.

- PV Plant consistently generates more energy than CSP Plant every month.

- Production follows a seasonal trend, peaking in summer (May-August) for both technologies due to stronger and longer sunlight.
- The difference in production can be explained by:
  - The higher efficiency of PV modules.
  - A better yield in diffuse radiation conditions.

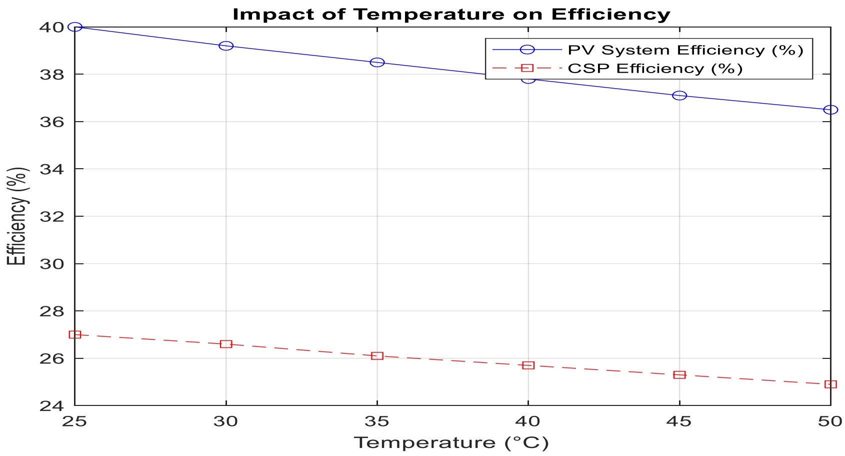

Figure 9 – Impact of Temperature on Efficiency

This figure illustrates the effect of ambient temperature on the efficiency (%) of both technologies.

- Efficiency decreases as temperature increases for both types of power plants.
- PV Plant starts with a higher efficiency (~40%) but declines more rapidly.
- CSP Plant is generally less efficient (~27% at 25°C) but shows a more moderate decline.
- This indicates that PV systems are more sensitive to temperature, which can be a concern in very hot regions.

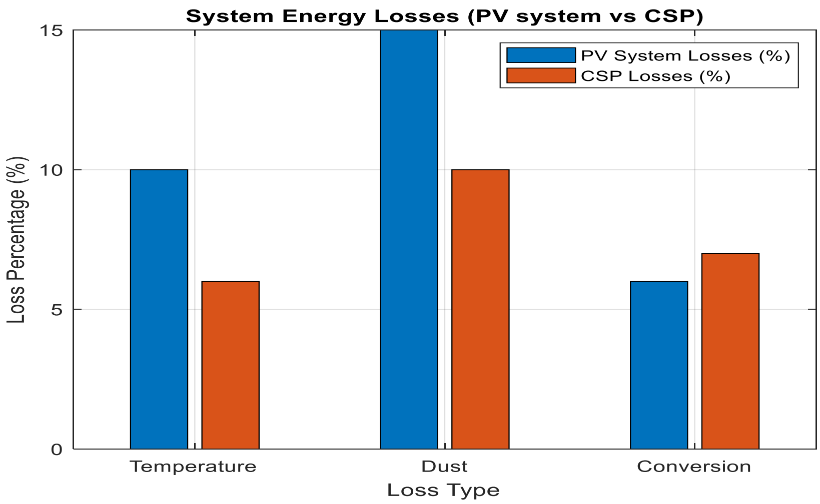

Figure 10 – Energy Losses by Type

A bar chart comparing energy losses (%) caused by different factors: temperature, dust, and conversion.

- PV Plant suffers greater losses due to temperature and dust, which is consistent with its thermal sensitivity and panel soiling.

- CSP Plant has slightly higher conversion losses (possibly related to mechanical systems or thermal turbines).
- These findings can influence the choice of technology depending on site environmental conditions (e.g., desert vs. temperate climate).

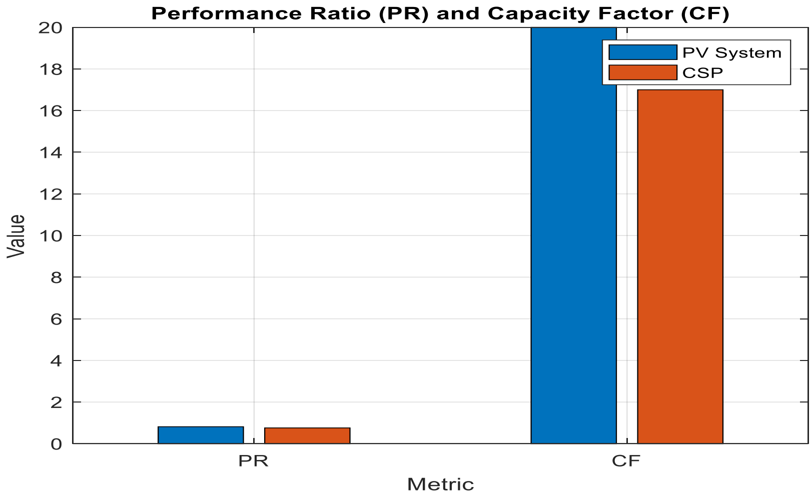

Figure 11 – Performance Ratio (PR) and Capacity Factor (CF)

Comparison of two key performance indicators:

- **PR (Performance Ratio):** The ratio between actual and theoretical expected energy production.
- **CF (Capacity Factor):** The percentage of actual production relative to the maximum theoretical capacity.

PV Plant has a higher PR (0.815 vs 0.76), meaning it converts solar radiation more efficiently.

- It also has a higher capacity factor (20% vs 17%), indicating better utilization of its installed capacity.
- This suggests that PV is more efficient and reliable throughout the year, even though CSP can be more stable in certain contexts (e.g., with thermal storage).

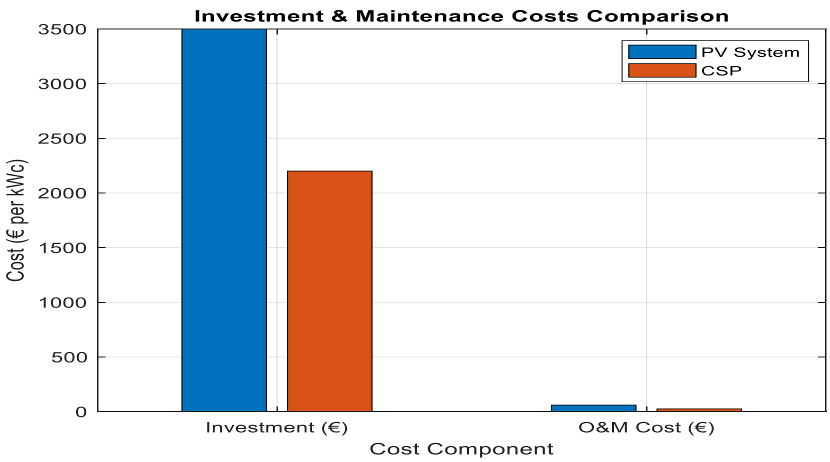

Figure 12 – Investment and Maintenance Costs

Comparison of investment costs (€ per kWc) and annual operation & maintenance (O&M) costs.

- PV Plant has a higher investment cost (3500 €/kWc vs 2200 €/kWc).
- Maintenance costs are also higher for PV.

- Despite this, its superior efficiency (as seen in previous figures) can compensate for this extra cost in the long run through better energy profitability.
- CSP appears more cost-effective to install, making it attractive in countries with lower initial budgets.

5. Conclusion

Under the high-DNI, high-temperature conditions of Zaouiet Kounta, PV systems outperform CSP systems in terms of energy yield, efficiency, and long-term economic returns, despite higher initial complexity and cost. The results validate PV technology as a promising solution for solar energy deployment in Saharan environments, provided that efficient maintenance and soiling mitigation strategies are implemented.

Criterion	PV Plant	CSP Plant
Energy production	Higher	Lower
Temperature sensitivity	More affected	More stable
Total losses	More affected by dust & heat	Less efficient thermal conversion
Performance (PR/CF)	Superior	Inferior
Costs	Higher (CapEx & O&M)	Lower

Technology choice depends on the context:

- PV Plant is more efficient but more expensive.
- CSP Plant is less efficient but offers advantages in very sunny regions with stable thermal resources, especially when integrated with thermal storage.

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