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Enhancing Solar Power Generation in Libya Using Solar Tracking Systems: A Study to Determine the Optimal Technology

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ABSTRACT

Libya enjoys an average of up to 3,200 hours of sunshine annually. However, when using fixed solar panels, only around two hours of vertical sunlight can be effectively utilised due to the sun's rotation around its axis and the Earth. Since solar panels generate electricity most efficiently when the sunlight falls perpendicularly on their surface, there is a need to enhance these systems in order to increase the number of effective hours throughout the day. For this purpose, single-axis solar tracking structures are selected. These systems are equipped with tracking devices that follow the sun from early morning until sunset, thereby increasing the productivity of power generation. Another type of solar tracking system is the dual-axis structure, but this is neither necessary nor suitable in Libya due to the stability of the tilt angle. Dual-axis systems are more costly and are generally used in countries where the solar angle varies significantly. In Libya, the tilt angle remains largely stable, with only minor variations from east to west, which can be adjusted based on the site of the solar farm and kept fixed while still tracking the sun's movement from sunrise to sunset. Studies have shown that using single-axis solar tracking structures can achieve up to 35% higher productivity compared to fixed solar panel structures, with lower cost and maintenance requirements than dual-axis systems.

Keywords: Energy Yield, Tilt Angle, Renewable Energy, Solar Panel Mounting Structure.

تحسين أنتاج الطاقة الشمسية في ليبيا باستخدام انظمة تتبع للشمس ودراسة اي نوع الافضل في ليبيا

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ملخـــــــص البحـــــــث

ليبيا تتمتع بعدد ساعات يصل الى 3200 ساعة سنويا فعند استخدام اللوحات الشمسية الثابتة لا نستفيد الا من ساعتين تقريبا من اشعة الشمس العمودية على اللوحات وذلك لدوران الشمس حول نفسها وحول الأرض ولان لوحات الطاقة الشمسية لا تولد طاقة الا من اشعة الشمس الساقطة عموديا على لوحات الطاقة الشمسية فيجب تحسين هذه المنظومات لزيادة عدد الساعات المستفاد منها خلال اليوم والاستفادة منها بأكثر عدد ساعات اشعة شمس ساقطة عموديا على اللوحات فنجد ان هياكل طاقة شمسية ذات المحور الواحد هي الأمثل, تزود هذه الهياكل بأجهزة تتبع من ســاعات الشــمس الأولى الى الغروب وذلك لزيادة الإنتاجية في توليد الطاقة ويوجد نوع اخر من منظومات الطاقة الشــمســية وهي الهياكل ذات المحورين ولا نتطرق الى هذا النوع ولا نحتاج اليه في ليبيا وذلك لثبوت زاوية

الميل, هذا النوع اكثر تكلفة ويستخدم في الدول التي تتغير بها زاوية الميل وفي ليبيا نلاحظ ثبوت هذه زاوية واختلافها اختلاف بسيط من الشرق الى الغرب ويتم تعديل هذه الزاوية حسب موقع المزرعة وتكون ثابتة مع تتبع اشعة الشمس من ساعات الشروق الي الغروب, ووجد عند استخدام هياكل الطاقة الشمسية ذات المحور الواحد زيادة الإنتاجية بنسبة 35% اكثر من هياكل الالواح الشمسية الثابتة وكذلك تكلفة وصيانة اقل مقارنة بهياكل الواح الطاقة الشمسية ذات المحورين.

الكلمات الدالة: هياكل الألواح الشمسية، طاقات متجددة، زاوية الميل، إنتاجية الطاقة.

1. INTRODUCTION

Solar energy is a prominent renewable and sustainable resource, offering a viable alternative to dependence on fossil fuels [1]. Libya possesses exceptional potential for harnessing this resource due to its favorable climate and geographical location, which provides vast, suitable areas for the establishment of large-scale solar farms [2]. A significant advantage of solar power is that, once constructed, the farms have minimal operational fuel costs, requiring only routine maintenance [3].

The global impetus for adopting renewable energy sources like solar and wind power is driven by the finite nature and volatile prices of fossil fuels, alongside environmental concerns [4]. Studies indicate that global fossil fuel reserves may be depleted within 50 years, necessitating a urgent transition to sustainable alternatives. For Libya, this makes the diversification of its energy portfolio through solar, wind, and hydropower a strategic imperative. Among these, solar energy stands out as the most promising due to the country's high solar irradiance and extensive desert land [5].

A key challenge in maximizing solar energy capture is the inefficient utilization of daily sunlight. In fixed-tilt panel systems, the angle of incidence is optimal for only a short period each day, around two hours, when the sun is perfectly perpendicular to the panels. This results in a significant loss of potential energy, as Libya receives up to 3,200 hours of sunshine annually [6]. To address this limitation, this research investigates the implementation of single-axis solar tracking systems. These systems utilize motors and sensors to continuously orient the panels towards the sun, maintaining a near-perpendicular angle to solar radiation throughout the day.

This study aims to demonstrate that such tracking technology is a practical and effective method to substantially increase energy yield (output) and enhance the efficiency of solar power generation in Libya.

1.1 literature review and background

1.1.1 Renewable Energy Potential in Libya

A study demonstrated that wind and solar energy—including both photovoltaic (PV) and concentrated solar power (CSP)—are capable of meeting a significant portion of Libya's electricity demand. The study indicated that establishing a 1,000 MW alternative power plant with a 40% capacity factor would prevent the emission of approximately 3.82 million tons of CO_2, thereby saving an estimated $286.329 million annually in carbon taxes [7].

1.1.2 Electricity Supply-Demand Gap

Another study highlighted that the General Electricity Company (GECOL) has faced a persistent supply-demand gap in recent years. In 2018, demand exceeded generation capacity by approximately 2,185 MW [8].

This reality has forced the company to implement load-shedding measures to maintain grid stability and prevent system collapse.

1.2 National Renewable Energy Strategy

A further study confirmed the Libyan government's renewable energy strategy, which aims to increase the share of renewables in the energy mix to 10% by 2025 and 30% by 2030. This goal is supported by the country's abundant solar resources, estimated at 3,200 annual sunshine hours and average solar irradiance

of 6 kWh/m²/day. The study focused on designing a 100kW solar power generation system, emphasizing the design and simulation of a PV system comprising solar panels, a DC-DC boost converter, and an MPPT controller [9].

As a result, we see that most existing studies on solar energy in Libya focus on improving productivity under fixed solar irradiation hours due to stationary panels set at a fixed angle. However, they have not sufficiently explored methods to increase the number of peak sun hours. Since energy cannot be created or destroyed, it is essential to maximize the utilization of available solar energy by increasing the hours during which sunlight strikes the panels perpendicularly. This can be achieved using solar tracking systems—either single-axis or dual-axis—depending on the solar farm's location and its distance from the equator.

Solar energy systems are primarily categorized into two technological pathways: Photovoltaic (PV) systems, which convert sunlight directly into electricity using semiconductor materials via the photovoltaic effect, and Concentrated Solar Power (CSP), which utilizes mirrors to concentrate solar radiation for thermal electricity generation [10].

For utility-scale and distributed generation, PV systems represent the most scalable solution and are implemented in three principal configurations:

1. Fixed-Tilt Systems: Panels are mounted at a stationary angle as shown in Fig 1. While simple and low-cost, they suffer from inefficient energy capture as they cannot follow the sun's movement [11].

Fig 1. Structure of fixed solar panel [12].

2. Single-Axis Tracking Systems: These systems rotate on one axis (typically horizontal) to follow the sun's east-to-west trajectory, maintaining a superior angle of incidence as shown in Fig 2. and increasing energy yield by 25-35% compared to fixed-tilt systems [13].

A single-axis solar tracker must also integrate a motor for movement and a sensor (or astronomical algorithm) for sun positioning to effectively follow the sun's east-to-west trajectory to maximize energy yield [14].

Fig 2. Structure of single-axis solar tracking system[15].

3. Dual-Axis Tracking Systems: Panels track the sun's movement both daily and seasonally, theoretically maximizing energy capture but at

significantly higher capital and maintenance costs, making them less economically viable for many applications [13].

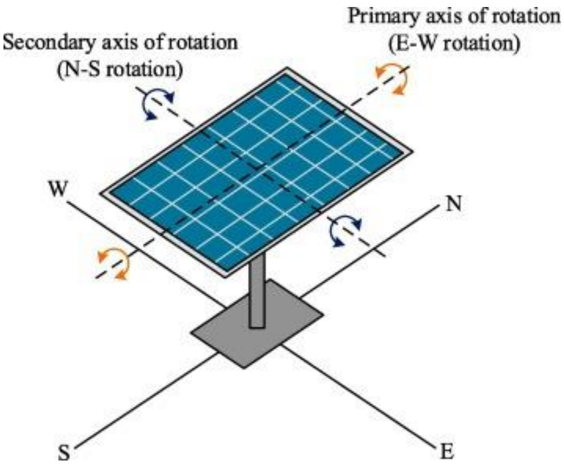

Fig 3. Structure of dual-axis solar tracking system[16].

2. MATERIALS AND METHODS

This study utilized PVsyst as the primary simulation tool to evaluate and compare three photovoltaic system configurations: fixed-tilt, one-axis tracking, and two-axis tracking. Simulations were conducted using Meteonorm 8.2 synthetic weather data for Al Zawia, Libya (latitude 32.76°N, longitude 12.73°E). Each model included battery storage using Lithium-ion (LFP) technology. The simulations analyzed system performance parameters including specific energy yield (kWh/kWp/year), performance ratio (PR), solar fraction (SF), and system losses. The aim was to determine the optimal configuration for maximizing solar energy generation in Libya's climatic and geographic conditions.

The analysis and decision-making process to determine the optimal system among the three options—single-axis trackers, dual-axis trackers, or fixed panels—was based on Libya's geographical location and its position relative to the equator and the Tropic of Cancer (latitude and longitude), as well as the sun's path from sunrise to sunset and the tilt angle. Libya enjoys a relatively stable solar path with only minor variations between summer and winter, and receives approximately 3,200 hours of solar irradiation per year [6]. Libya is situated between approximately 19° and 33° north of the equator, north of the Tropic of Cancer located at 23.5° north, and extends between approximately 9° and 25° east of Greenwich.[17] For example, the capital, Tripoli, is located at approximately 32.9° north latitude and 13.2° east longitude.

Due to Libya's relatively consistent solar trajectory, we selected single-axis solar tracking structures, which allow for the selection of a fixed tilt angle between summer and winter that remains nearly optimal, with only a minimal deviation of 8 to 15 degrees. This deviation is considered negligible, making it unnecessary to consider dual-axis solar panels [18], due to their higher costs. Dual-axis systems require an additional axis, sensor, and motor, along with near-continuous mechanical movement, which we anticipate would lead to increased maintenance issues and higher costs, while offering only a marginal improvement in productivity [19].

To ensure the reliability of the analysis, this study integrated both empirical solar resource data and simulation-based performance modeling. Solar irradiation and geographical information were obtained from the World Bank's SolarGIS database and Meteonorm 8.2**,** representing long-term meteorological averages for Libya. The PVsyst software was employed to simulate and compare the performance of three photovoltaic configurations—fixed-tilt, single-axis tracking, and dual-axis tracking—using identical site conditions, system sizes, and component specifications. The simulations produced detailed outputs including specific energy yield (kWh/kWp/year), and Levelized Cost of Energy (LCOE). for data validation and visualization. These tools collectively ensured a comprehensive and quantitative evaluation of the optimal solar technology for Libyan climatic conditions. To ensure the best productivity, highest durability, and lowest costs, single-axis panels emerged as the ideal solution for achieving optimal energy output, maximum robustness, and minimal expenses. In this system, the panels are fixed at a tilt angle corresponding to the local latitude and track the sun's path along a single axis. The optimal angles for cities in Libya are as follows:

Table 1. Optimal Fixed Tilt Angles for Major Libyan Cities**.**

City	Latitude	Fixed tilt angle (annual)
Tripoli	32.9° ≈ 33°	33°
Benghazi	32.1° ≈ 21°	21°
Misrata	32.4° ≈ 32°	32°
Sebha	27.0° ≈ 27°	27°
Ghat	25.1° ≈ 25°	25°
Tobruk	32.1° ≈ 32°	32°

Libya possesses an exceptional solar energy resource, as illustrated by this SolarGIS map produced for the World Bank Group's ESMAP program [20] in Fig 4. The data, representing the long-term average from 1994-2018, shows most of the country receives a very high global horizontal irradiation (GHI) of 6.6 to 7.0 kWh/m² per day, with yearly totals exceeding 2410 kWh/m². This world-class solar potential indicates high viability for both utility-scale solar farms and decentralized photovoltaic systems, offering a clear pathway for energy diversification and economic development beyond hydrocarbons [20].

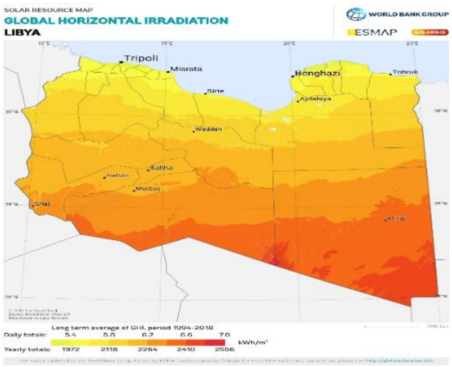

Fig 4. Solar Resource Potential of Libya based on Global Horizontal Irradiation [20].

2.1 Capital Cost Analysis

The capital expenditure (CAPEX) for solar farms varies significantly depending on the technology employed. The cost of single-axis solar farms is more expensive than fixed ones. The metal structure is more expensive than fixed structures in terms of the cost of the rotating shaft, the electric motor mounted on the rotating shaft, the sensor, and the electrical panel controlling the sensor and motor.

Dual-axis farms are more expensive in terms of adding an additional shaft, motor, and sensor [21].

The remaining costs are the same for connections, while the energy storage room, and the storage batteries are the same in all solar farms. The storage room must be kept at a low temperature, as the batteries contain chemicals that could cause a thermal runaway due to high temperatures, especially in the summer.

When compared to other renewable energy sources, utility-scale solar PV often presents a lower Levelized Cost of Energy (LCOE) in the Libyan context [22].

wind energy is much more expensive than solar panels due to the high cost of wind turbines. Hydropower is also more expensive due to the need to build giant dams to supply them with hydropower generation systems.

2.2 Operational & Maintenance (O&M) Costs

a) Fixed-Tilt Solar Energy Systems

In a fixed-tilt configuration, solar panels are installed at a permanent, stationary angle. These systems are typically deployed on building rooftops or across large-scale solar farms. Their defining characteristic is that they do not move to track the sun. This type of system offers significant advantages in terms of cost, as it requires lower installation, operational, and maintenance expenses. Consequently, fixed-tilt panels represent the most economical option among the three solar configurations discussed.

b) Single-Axis Tracking Systems

This system type involves mounting the panels on metal structures equipped with a rotational axis, a sensor, an electronic control panel, and a motor. Maintenance concerns for this configuration are primarily related to potential failures of the sensor, control panel, or motor. The rotational axis itself, however, is engineered with a robust mechanical design that ensures reliable operation for many years [23]. While the initial investment and maintenance are higher than for fixed-tilt systems, single-axis trackers offer a balance between cost and increased energy generation [24].

c) Dual-Axis Tracking Systems

In a dual-axis system, panels are mounted on metal structures that feature two axes of movement (X and Y). This requires two electric motors, a sensor, and an electronic control unit. The primary drawback of this design is its high cost and complexity. Maintenance can be challenging and expensive due to potential failures in either of the motors, the sensor, the control unit, or the complex mechanical pivot points. The intricate manufacturing and mechanical movement make dual-axis systems the most expensive option in terms of both initial investment and long-term upkeep [25] [26].

Lastly, the selection of the optimal solar panel configuration for Libya was determined through a systematic evaluation of technical performance, economic feasibility, and practical maintainability. The analysis conclusively demonstrated that while fixed-tilt systems offer the lowest capital cost, their significantly lower energy yield makes them a suboptimal choice for maximizing Libya's solar potential. Conversely, dual-axis tracking systems, despite providing the highest theoretical energy gain, were deemed unsuitable due to their substantial cost premium and increased mechanical complexity, which would lead to higher maintenance burdens and a less favorable lifecycle cost.

Therefore, based on this multi-criteria analysis, the single-axis solar tracking system was identified as the optimal solution. It represents the most effective compromise, delivering a substantial increase in energy production—estimated at 25-35% over fixed-tilt systems—while maintaining a manageable level of cost, complexity, and long-term operational risk. This configuration is perfectly suited to Libya's high solar irradiance and relatively stable solar path, ensuring maximum energy capture and return on investment.

3. RESULTS AND DISCUSSION

Using PVsyst simulations for Al Zawia, Libya, three photovoltaic configurations were analyzed: fixed-tilt (914 kWp), one-axis tracking (1,421 kWp), and two-axis tracking (1,410 kWp). The results revealed significant differences in performance and system utilization as shown in Table 2. The one-axis system achieved a total useful energy output of 1,173.1 MWh/year, which is almost identical to the dual-axis system (1,173.1 MWh/year), while the fixed-tilt system produced less than the previous two. The one-axis system also maintained a 100% solar fraction with zero missing energy, whereas the fixed-tilt system recorded a 98.9% solar fraction. Despite the dual-axis configuration capturing the highest solar radiation (2,894.7 MWh/year), its excess unused energy (57%) made it less efficient overall. However, the one-axis tracking system presented the best balance between high yield and practical efficiency for Libya’s stable solar path.

Table 2. PVsyst Simulation Results and Economic Comparison of the Three PV Configurations**.**

System Type	Fixed Tilt	Single-Axis Tracker	Dual-Axis Tracker
Power (kWp)	914	1421	**1410**
Useful Energy (MWh/year)	1160.6	1173.1	**1173.1**
LCOE (USD/kWh)	0.065	0.059	**0.071**
Remarks	Low cost, lowest yield	Best balance between cost and output	Highest cost, marginal yield gain

These results confirm that while both tracking systems outperform fixed structures in total solar capture, the one-axis tracker achieves comparable output to the dual-axis design at significantly lower capital and maintenance costs. It therefore offers the optimal solution for Libya, combining high performance with mechanical simplicity and cost efficiency.

From literature and regional studies, the following approximate gains are observed for different PV tracking systems relative to fixed-tilt installations:

Table 3. Annual Energy Yield Gain in PV Tracking Systems.

System Type	Annual Energy Yield Gain
Single-Axis Tracker	~ **20-30%** higher output than fixed-tilt under conditions similar to Libya (clear skies, high irradiance).
Dual-Axis Tracker	**5-15%** higher output relative to single-axis.

These gains assume optimal fixed tilt angles, minimal shading, and good maintenance.

For Libya specifically, a study in Eastern Libya confirms that tracking panels receive more radiation than stationary fixed panels [27].

Looking at Fig 5. Fig 6. Fig 7. The Daily Input/Output diagrams from PVsyst clearly illustrate the performance behavior of the three photovoltaic configurations—fixed-tilt, one-axis tracking, and two-axis tracking. The fixed-tilt system shows a strong linear relationship between daily solar irradiance and energy output, indicating stable but limited performance due to its static positioning. In contrast, the one-axis tracking system extends the effective irradiance range up to around 10 kWh/m²/day, displaying a higher and more efficient energy response with a mild plateau at high radiation levels, which reflects optimal utilization of available sunlight throughout the day. The two-axis tracking system captures slightly higher solar input (up to 12 kWh/m²/day), but its graph exhibits greater data dispersion and an earlier performance plateau, suggesting diminishing returns caused by system saturation and mechanical complexity.

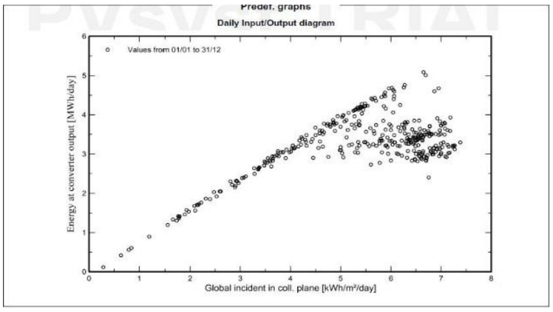

Fig 5. Daily Input/Output Diagram for Fixed-Tilt PV System.

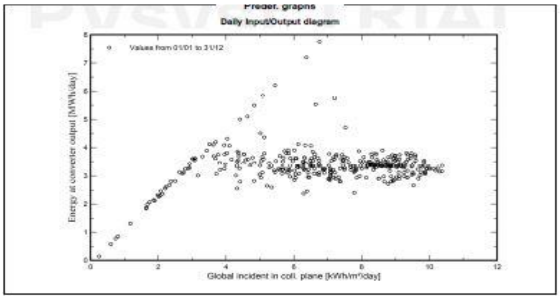

Fig 6. Daily Input/Output Diagram for One-Axis Tracking PV System.

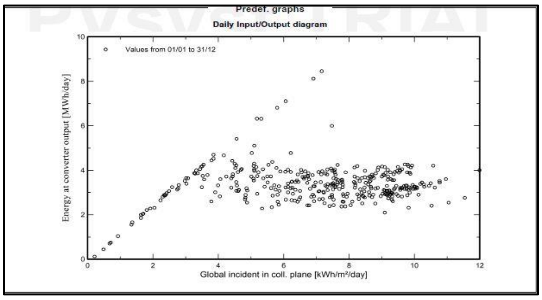

Fig 7. Daily Input/Output Diagram for Dual-Axis Tracking PV System.

Overall, these diagrams confirm that the one-axis tracking system provides the most balanced and efficient performance, maintaining a strong correlation between solar input and output energy while avoiding the instability and added costs observed in the dual-axis configuration, making it the most suitable option for Libya's consistent solar conditions.

Technical and Economic Justification for Selecting Single-Axis Systems in Libya

- Why Single-Axis Tracking is Sufficient for Libya's Conditions?

Libya's geographical location offers a key advantage: a relatively consistent solar path throughout the year. The sun's position changes only minimally with the seasons, and this slight variation can be effectively compensated for by installing the panels at a fixed, optimal tilt angle based on the local latitude [28]. The difference between this fixed angle and the ideal angle that changes daily throughout the year is estimated to be only 8 to 15 degrees. Since this angular difference is small, its impact on energy output is negligible and can be practically disregarded.

Therefore, by fixing the panels at an angle that represents an average between summer and winter positions, while enabling them to track the sun from east to west, the system achieves its primary goal: significantly increasing the number of hours during which sunlight strikes the panels at a near-perpendicular angle. This process begins at sunrise, substantially extending the peak production period. Naturally, total energy production remains higher in summer than in winter due to longer daylight hours, which is a natural factor independent of the tracking system.

- Why Dual-Axis Panels are Considered Cost-Ineffective?

The primary reason dual-axis systems are not viable in Libya boils down to the law of diminishing returns. In exchange for a very minor increase in energy output (typically only 5-10% more than a single-axis system), the initial capital cost rises substantially due to the additional axis, the second motor, and the more complex control system [19].

Furthermore, the added mechanical complexity makes these systems:

1. More prone to failures due to the increased number of moving mechanical parts.
2. More difficult and costly to maintain, a problem that is compounded in Libya's vast desert areas where corrosion and erosion from harsh environmental conditions accelerate wear and tear.

Consequently, the operational drawbacks and significantly higher additional costs are not justified by the modest gain in energy production. This makes the single-axis tracker the optimal choice in the Libyan context, offering the best balance of efficiency, reliability, and economic feasibility.

4. CONCLUSIONS

This study has demonstrated that Libya is endowed with an exceptional solar energy resource, a fact robustly confirmed by authoritative sources like the World Bank Group's SolarGIS map, which indicates a dominant Global Horizontal Irradiation (GHI) range of 6.6 to 7.0 kWh/m²/day across most of the country [20]. Given this immense potential, solar power stands as a strategic imperative for diversifying Libya's energy portfolio, enhancing its energy security, and fostering sustainable economic development.

To complement the qualitative and theoretical analysis, PVsyst 8.0.17 simulations using Meteonorm 8.2 data for Al Zawia, Libya, were conducted to quantitatively compare fixed-tilt, one-axis, and two-axis photovoltaic configurations. The results showed that while the fixed-tilt system achieved a useful energy output of 1,160.6 MWh/year, the one-axis tracker generated 1,173.1 MWh/year and the two-axis tracker achieved a similar yield of 1,173.1 MWh/year but with slightly lower efficiency and higher system complexity. Despite the dual-axis system's marginally higher solar capture, its excessive unused energy (over 57%) and elevated capital and maintenance costs reduce its practicality. In contrast, the one-axis configuration reached the lowest Levelized Cost of Energy (LCOE) at 0.059 USD/kWh, demonstrating superior economic viability and efficient utilization of available solar resources**.**

The analysis conclusively identifies the single-axis solar tracking system as the optimal solution for Libya. It effectively addresses the inherent limitation of fixed systems by maintaining a near-perpendicular solar incidence throughout the day, thus increasing energy yield by approximately 25–35%. Furthermore, given Libya's stable solar trajectory and moderate latitude north of the Tropic of Cancer, the performance advantage of a second tracking axis is negligible and does not justify the additional investment and operational risks. Therefore, based on both the simulation evidence from PVsyst and the techno-economic assessment, the widespread adoption of single-axis tracking technology is the most practical and effective pathway to significantly boost solar energy yield and efficiency in Libya, directly supporting the national renewable energy target of achieving a 30% share of renewables by 2030.

Future Work

Site-Specific Techno-Economic Analysis: This research provides a high-level comparative analysis. A critical next step is to conduct detailed, site-specific techno-economic feasibility studies for single-axis tracker farms in different regions of Libya (e.g., coastal Tripoli vs. desert Sabha).

Grid Integration and Stability Studies: The impact of large-scale integration of variable solar power, even with tracking systems, on the stability of Libya's existing grid (managed by GECOL) remains a significant gap. Future research must focus on grid integration studies, analyzing the need for grid reinforcements, energy storage solutions (batteries), and smart grid management systems to ensure reliable power delivery.

Dust Accumulation and Mitigation Strategies: A major operational challenge in the Libyan desert environment is the rapid accumulation of dust on PV panels, which can severely degrade performance. This study did not address this issue. Future work should quantitatively analyze the soiling losses on tracking systems and investigate the cost-effectiveness of different mitigation strategies, such as automated cleaning systems, anti-soiling coatings, and optimal cleaning schedules.

Hybrid System Optimization: Finally, future research should explore the potential of hybrid renewable systems. This includes optimizing combinations of single-axis solar PV with other resources, such as wind power (in coastal areas) or concentrated solar power (CSP) with thermal storage, to provide a more stable and dispatchable power supply that can meet base-load demand.

ACKNOWLEDGMENT

The PV performance simulations and economic comparisons presented in this study were conducted using PVsyst 8.0.17 software with Meteonorm 8.2 meteorological data for Al Zawia, Libya. This ensured accurate, location-specific analysis to determine the most suitable

PV tracking system under Libyan environmental conditions.

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