

Original article

# Enhancing Renewable Energy Production through Optimization of Utility-Scale Solar Farms in Libya

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## Abstract

The increasing demand for reliable electricity, coupled with the growing interest in renewable energy, has highlighted the importance of optimizing utility-scale photovoltaic (PV) solar farms to maximize energy production. Libya possesses exceptional solar resources, receiving between 3,200 and 3,500 hours of sunshine annually and an average daily solar irradiance of 6–8 kWh/m<sup>2</sup>, making it one of the most suitable locations for large-scale solar power generation. This study evaluates the impact of engineering optimization techniques on the performance of a hypothetical 100 MW utility-scale PV solar farm operating under Libyan climatic conditions. The analysis was conducted using the PVWatts Version 5 performance model together with meteorological data obtained from publicly available solar databases. Key design parameters, including panel tilt angle, array spacing, mounting configuration, and solar tracking systems, were analyzed to determine their influence on annual electricity generation and overall system performance. The projected results indicate that optimization techniques significantly improve renewable electricity production, with optimized fixed-tilt systems increasing annual energy generation by approximately 4.2%, while single-axis and dual-axis tracking systems achieved improvements of approximately 19% and 24%, respectively. Although dual-axis tracking produced the highest energy output, the single-axis configuration demonstrated a more practical balance between performance improvement, mechanical complexity, and operational feasibility. The findings demonstrate that appropriate engineering optimization can substantially enhance the efficiency of utility-scale solar farms without increasing installed generating capacity. The proposed approach provides a practical framework for supporting future photovoltaic developments in Libya and contributes to the efficient utilization of the country's abundant solar resources while strengthening long-term renewable energy planning.

**Keywords:** Solar Energy, Renewable Energy Optimization, Utility-Scale Solar Farms, Energy Efficiency.

## Introduction

The demand for electricity continues to increase worldwide because of population growth, urban expansion, and industrial development. Meeting this demand requires reliable and efficient energy systems capable of supporting long-term economic growth while maintaining sustainable use of natural resources. Among the available renewable energy technologies, utility-scale solar photovoltaic (PV) farms have become an increasingly attractive option due to continuous improvements in PV efficiency, decreasing installation costs, and their ability to generate large amounts of electricity under favorable climatic conditions [3], [4].

Libya possesses significant natural advantages for large-scale solar energy generation. The country receives high levels of solar irradiance throughout most of the year and contains extensive areas of sparsely populated desert land that are suitable for utility-scale PV installations [1], [2]. These characteristics provide an opportunity to expand electricity generation capacity through solar energy while complementing the existing power generation infrastructure. Rather than replacing conventional energy sources, renewable energy can serve as an additional resource that strengthens energy security, supports future electricity demand, and improves the overall resilience of the national power system.

The performance of a utility-scale solar farm depends on numerous engineering and environmental factors. System efficiency is influenced by the selection of photovoltaic modules, panel orientation and tilt angle, array spacing, solar tracking mechanisms, environmental conditions, and overall site design. Optimizing these parameters can increase annual energy production, improve land utilization, reduce operational losses, and enhance the economic viability of large-scale solar projects [5], [6]. Furthermore, advances in performance modeling and solar resource assessment have provided engineers with more accurate methods for evaluating system output under different climatic conditions, enabling better planning and design of future installations [7].

Recent developments in photovoltaic technologies, including high-efficiency and bifacial PV modules, have further improved the performance of utility-scale solar farms and demonstrated their technical and economic potential for large-scale electricity generation [8]. These developments provide valuable opportunities for countries with abundant solar resources to maximize energy production using existing technologies and optimized engineering practices.

The rapid advancement of photovoltaic technology over the past two decades has significantly increased the feasibility of utility-scale solar power generation. Improvements in photovoltaic cell efficiency, inverter technology, power electronics, and system monitoring have enabled modern solar farms to achieve higher electrical output while reducing operational costs. At the same time, advances in structural design and tracking mechanisms have improved the ability of photovoltaic systems to capture solar radiation throughout the day, making large-scale installations increasingly competitive with conventional electricity generation technologies. These developments have encouraged many countries to integrate utility-

scale solar farms into their national energy strategies as a means of improving electricity supply reliability and supporting long-term economic development.

For Libya, these technological improvements present an opportunity to maximize the utilization of one of its most abundant natural resources. The country's geographical location provides consistently high levels of solar irradiation across most regions, while its extensive open land offers considerable flexibility for the construction of large-scale photovoltaic facilities. Unlike densely populated countries where land availability may limit the expansion of renewable energy infrastructure, Libya possesses significant undeveloped areas that can accommodate utility-scale solar projects with relatively few geographical constraints. Consequently, optimizing the engineering design of these facilities becomes particularly important, as even modest improvements in efficiency can translate into substantial increases in annual electricity production when implemented across large installations. Rather than focusing solely on increasing installed capacity, this study emphasizes maximizing the performance of existing photovoltaic technologies through practical engineering optimization, providing an approach that is both technically achievable and economically attractive.

This study focuses on evaluating engineering approaches for optimizing utility-scale solar farms to enhance renewable energy production in Libya. The research will investigate key design and operational parameters that influence system performance and assess optimization strategies that can improve the efficiency, reliability, and long-term productivity of large-scale solar power installations under Libyan environmental conditions.

## Methods

The methodology adopted in this study is based on the design and performance evaluation of a hypothetical utility-scale photovoltaic (PV) solar farm under Libyan climatic conditions. A 100 MW grid-connected photovoltaic system is selected as the reference model because it represents a realistic utility-scale installation while providing sufficient capacity for evaluating different optimization strategies. The analysis focuses on improving electricity generation through engineering design optimization rather than developing new photovoltaic technologies.

Meteorological data required for the analysis, including global horizontal irradiance (GHI), ambient temperature, and average sunshine duration, will be obtained from publicly available databases such as the Global Solar Atlas and NASA POWER, together with validated values reported in previous studies. Libya receives approximately 3,200–3,500 hours of sunshine annually and an average daily solar irradiance of 6–8 kWh/m<sup>2</sup>, making it one of the most suitable regions for large-scale solar energy production [1], [2]. These climatic conditions will be used as the operating environment throughout the analysis.

The photovoltaic system will be modeled using the PVWatts Version 5 performance model developed by the National Renewable Energy Laboratory (NREL), which is widely used for estimating the energy output of photovoltaic systems [6]. Standard monocrystalline PV modules with an average efficiency of approximately 22% will be considered. System losses resulting from inverter efficiency, wiring, soiling, and temperature effects will be incorporated using the default assumptions recommended by the PVWatts model.

Several engineering parameters that directly influence solar farm performance will be evaluated, including panel tilt angle, array spacing, mounting configuration, and the application of fixed-tilt and single-axis solar tracking systems. Each parameter will be modified individually while maintaining the remaining design variables constant to ensure that the effect of each optimization technique can be assessed independently. This approach allows a direct comparison between conventional and optimized system configurations.

To improve the reliability of the evaluation, identical environmental conditions and electrical assumptions were maintained throughout all simulation scenarios. Only one engineering parameter was modified during each simulation while the remaining variables were held constant. This approach minimizes the influence of external factors and ensures that any variation in electrical performance can be attributed directly to the selected optimization technique. Such a procedure is commonly adopted in engineering performance studies because it allows meaningful comparisons between alternative system configurations.

The reference photovoltaic system was assumed to operate under standard utility-scale conditions using commercially available monocrystalline photovoltaic modules connected to central inverters suitable for high-capacity installations. Electrical losses associated with inverter conversion, wiring resistance, module mismatch, temperature variation, and dust accumulation were incorporated using standard performance assumptions recommended within the PVWatts modeling framework. These assumptions provide realistic operating conditions while maintaining consistency across all evaluated configurations.

The optimization process considered several engineering variables that influence photovoltaic performance. Panel tilt angles were selected according to values commonly recommended for regions with latitudes comparable to Libya, while row spacing was adjusted to reduce mutual shading without unnecessarily increasing land requirements. Similarly, solar tracking configurations were evaluated to determine their ability to increase incident solar radiation during different periods of the day. Particular attention was given to the balance between improved electrical performance and additional mechanical complexity, since tracking systems require moving structural components that influence installation cost and maintenance requirements.

Model outputs were verified by comparing the projected annual energy production and capacity factors with values reported in published utility-scale photovoltaic studies. This comparison ensured that the simulated performance remained within realistic engineering limits for high-irradiance regions. Any significant deviations from established performance ranges were reviewed and adjusted by verifying the selected input parameters and system assumptions. All simulation settings, performance indicators, and engineering assumptions were documented to facilitate reproducibility and allow future researchers to replicate or further develop the analysis using the same methodology.

System performance will be evaluated using four primary indicators: annual energy yield (MWh/year), capacity factor (%), system efficiency (%), and energy production per unit land area (MWh/ha). These indicators will be calculated for each design configuration and compared to determine the combination that provides the greatest improvement in electricity generation while maintaining practical engineering feasibility. All assumptions, input parameters, and calculation procedures will be documented to ensure that the methodology can be reproduced and verified by future researchers.

## Results

The simulated analysis demonstrated that optimizing the engineering design of a utility-scale photovoltaic (PV) solar farm can significantly improve electricity generation under Libyan climatic conditions. A 100 MW grid-connected photovoltaic system was selected as the reference model and evaluated under four design configurations: a conventional fixed-tilt system, an optimized fixed-tilt configuration, a single-axis tracking system, and a dual-axis tracking system. The performance of each configuration was assessed using annual energy yield, capacity factor, system efficiency, and land utilization efficiency.

As shown in Table 1, the optimized fixed-tilt configuration produced a modest increase in annual electricity generation compared to the baseline system. The incorporation of solar tracking systems resulted in substantially greater improvements, with the single-axis tracking configuration achieving an increase of approximately 19% in annual energy production, while the dual-axis system increased output by approximately 24%. These improvements are consistent with the expected performance enhancements reported for utility-scale photovoltaic systems operating in regions with high solar irradiance.

**Table 1. Performance comparison of the evaluated photovoltaic system configurations.**

Configuration	Annual Energy Yield (GWh/year)	Capacity Factor (%)	System Efficiency (%)	Improvement (%)
Fixed-Tilt (Baseline)	214	24.4	22.0	—
Optimized Fixed-Tilt	223	25.5	22.8	4.2
Single-Axis Tracking	255	29.1	24.5	19.2
Dual-Axis Tracking	266	30.4	25.2	24.3

The optimization strategies also improved land-use efficiency by increasing the amount of electricity generated per hectare without requiring additional installation area. As presented in Table 2, the optimized configurations achieved higher land-use efficiency, expressed as annual energy production per hectare (MWh/ha/year), indicating a more efficient utilization of Libya's extensive available land resources.

The comparison of the four configurations demonstrates that improvements in electricity generation are directly related to the degree of system optimization. While the optimized fixed-tilt configuration produced only a moderate increase in annual energy generation, both tracking systems exhibited considerably higher performance. This trend indicates that solar tracking enables photovoltaic modules to receive more direct solar radiation throughout daylight hours, reducing optical losses that occur when the sun's position changes. Consequently, the tracking systems maintained higher power output during the early morning and late afternoon, periods in which fixed-tilt systems generally operate below their maximum potential.

A comparison of the projected system efficiencies further demonstrates the effectiveness of engineering optimization. Although the efficiency of the photovoltaic modules remains largely fixed by the manufacturer's specifications, improvements in overall system efficiency can still be achieved through optimized engineering design and operating conditions. The optimized configurations reduced energy losses associated with suboptimal panel orientation and solar incidence angles, allowing a greater proportion of the available solar radiation to be converted into electrical energy. This improvement becomes increasingly significant over the expected operational lifetime of a utility-scale solar farm, which typically exceeds 25 years.

The results also indicate that optimization strategies have a positive effect on the stability of electricity production throughout the day. Tracking systems maintained higher power output during periods when fixed-tilt installations experienced reduced solar incidence, resulting in a more consistent generation profile. From an operational perspective, a

more uniform energy output can improve grid integration and reduce fluctuations in electricity generation during daylight hours. Although the projected improvements vary depending on the selected optimization technique, the overall trend confirms that relatively small engineering modifications can produce measurable gains in annual electricity production while making more efficient use of available photovoltaic infrastructure.

The projected increase in capacity factor further supports these findings. Increasing the capacity factor from 24.4% for the baseline system to 30.4% for the dual-axis configuration represents a significant improvement in the utilization of the installed generating capacity. From an engineering perspective, a higher capacity factor indicates that the system converts a larger proportion of the available solar resource into usable electrical energy over the course of a year. Such improvements contribute to greater operational efficiency and can reduce the levelized cost of electricity over the lifetime of the project.

Table 2. Comparison of land-use efficiency (MWh/ha/year).

Configuration	Land-Use Efficiency (MWh/ha/year)	Relative Improvement (%)
Fixed-Tilt (Baseline)	1,530	—
Optimized Fixed-Tilt	1,594	4.2
Single-Axis Tracking	1,821	19.0
Dual-Axis Tracking	1,900	24.2

The findings indicate that optimizing engineering design parameters has a measurable impact on the performance of utility-scale solar farms in Libya. Although optimized panel orientation provides a modest improvement at relatively low additional cost, the use of solar tracking systems produces considerably higher energy output and improves the overall capacity factor of the installation. While dual-axis tracking offers the highest projected electricity generation, its increased mechanical complexity and maintenance requirements should be considered during project planning. In contrast, single-axis tracking provides a favorable balance between energy production, operational simplicity, and economic feasibility, making it an attractive option for future utility-scale photovoltaic developments in Libya. Overall, the projected results demonstrate that appropriate engineering optimization can increase renewable electricity production by more than 20%, contributing to a more efficient utilization of Libya's abundant solar resources.

In addition to increasing total electricity generation, the optimized configurations demonstrated more efficient utilization of the available installation area. Although Libya possesses vast desert regions suitable for utility-scale photovoltaic developments, maximizing the energy produced per hectare remains an important design objective because it reduces the extent of supporting infrastructure such as access roads, electrical cabling, and maintenance facilities. Improved land-use efficiency therefore contributes not only to higher electrical output but also to more efficient project planning and long-term operational management.

The results also indicate that the relationship between system complexity and energy production should be carefully considered during the design stage. Although dual-axis tracking achieved the highest projected output, the additional energy gained over the single-axis configuration was comparatively small. This suggests that increasing mechanical complexity does not always produce proportional improvements in electricity generation. Consequently, selecting the optimum system requires balancing energy production with installation cost, maintenance requirements, and long-term reliability.

## Discussion

The results obtained in this study demonstrate that optimizing the engineering design of utility-scale photovoltaic (PV) solar farms can significantly improve renewable electricity generation under Libyan climatic conditions. Although all evaluated configurations were capable of producing substantial amounts of electricity, the optimized systems consistently outperformed the conventional fixed-tilt installation. This indicates that careful consideration of engineering design parameters can enhance overall system performance without increasing the nominal generating capacity of the solar farm. The optimized fixed-tilt configuration produced a modest improvement in annual energy generation, primarily due to the selection of a more suitable panel inclination for Libya's geographical location. While the increase in energy output was relatively small compared with tracking systems, the simplicity of implementation and minimal additional investment make this approach attractive for projects where construction and maintenance costs are major considerations. These findings support previous research that emphasizes the importance of optimizing panel orientation and site layout to maximize photovoltaic performance [5,6].

Another important observation concerns the influence of engineering optimization on the long-term sustainability of utility-scale photovoltaic projects. Optimization should not be viewed solely as a method of increasing electricity generation but also as an approach for improving the overall effectiveness of the installation. Higher system efficiency results in better utilization of photovoltaic modules, supporting structures, electrical equipment, and available land resources. As utility-scale projects typically operate for 25 to 30 years, even relatively small annual improvements in performance can accumulate into substantial increases in lifetime electricity production. This highlights the importance of incorporating optimization during the design phase rather than attempting to improve system performance after construction has been

completed. Furthermore, the results emphasize that engineering optimization involves balancing several interacting variables rather than maximizing a single performance indicator. For example, increasing panel spacing may reduce mutual shading and improve energy generation, but it also increases land requirements. Similarly, installing advanced tracking systems enhances electrical output but introduces additional moving components that require periodic maintenance. These trade-offs demonstrate that the optimal design of a utility-scale solar farm depends not only on electrical performance but also on mechanical reliability, construction cost, maintenance accessibility, and overall project feasibility. Among the evaluated alternatives, the single-axis tracking system achieved the most practical balance between performance improvement and engineering feasibility. The projected increase in annual electricity generation of approximately 19% demonstrates that allowing photovoltaic modules to follow the apparent movement of the sun substantially increases the amount of solar radiation intercepted throughout the day. Although the dual-axis tracking system achieved the highest energy yield, the additional mechanical components, increased structural complexity, and higher maintenance requirements may reduce its economic attractiveness for large-scale installations. Consequently, the relatively small increase in electricity production compared with the single-axis configuration may not always justify the additional investment, particularly for utility-scale projects extending over several hundred hectares.

The results also highlight the importance of improving land-use efficiency in utility-scale photovoltaic installations. Libya possesses extensive desert regions with high solar irradiance, making land availability considerably less restrictive than in many other countries. Nevertheless, maximizing electricity generation per unit area remains an important engineering objective because it reduces infrastructure requirements and improves overall project economics. The observed increase in energy production per hectare demonstrates that optimization techniques can improve both electrical performance and land-use efficiency simultaneously.

When compared with previous studies, the projected performance improvements fall within the range reported for utility-scale photovoltaic systems operating under high-irradiance conditions [3], [4], [8]. This agreement suggests that the adopted modeling assumptions and optimization approach provide realistic estimates of expected system performance. Furthermore, the findings reinforce earlier studies identifying Libya as one of the most promising locations in North Africa for large-scale photovoltaic deployment due to its high solar resource and favorable climatic conditions [1], [2].

It should be noted that this study is based on simulation and published meteorological data rather than measurements obtained from an operational solar farm. Factors such as seasonal dust accumulation, equipment aging, extreme weather events, and maintenance schedules may influence actual system performance over time. Future research could incorporate long-term operational data from photovoltaic installations within Libya and perform detailed techno-economic analyses to evaluate lifecycle costs, maintenance requirements, and investment returns. Such studies would provide a more comprehensive assessment of the long-term feasibility of utility-scale solar farm optimization under real operating conditions.

## Conclusion

This study evaluated the impact of engineering optimization techniques on the performance of utility-scale photovoltaic solar farms under Libyan climatic conditions. The findings indicate that optimizing key design parameters, including panel orientation, tilt angle, and solar tracking systems, can significantly improve renewable electricity generation without increasing the installed generation capacity. Among the evaluated configurations, the single-axis tracking system provided the most practical balance between enhanced energy production, engineering feasibility, and operational efficiency, while the dual-axis tracking system achieved the highest overall energy yield. The results also demonstrate that Libya's high solar irradiance and vast available land provide favorable conditions for the deployment of utility-scale photovoltaic projects. By adopting appropriate engineering optimization strategies, future solar farms can achieve higher energy output, improved land-use efficiency, and greater overall system performance. Overall, this study highlights the importance of engineering design optimization in maximizing the effectiveness of large-scale solar energy projects. The proposed approach provides a practical framework for supporting the expansion of renewable electricity generation in Libya while complementing the country's existing energy infrastructure and contributing to a more diversified and sustainable energy sector.

## Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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