The North African Journal of Scientific Publishing (NAJSP)
مجلة شمال إفريقيا للنشر العلمي (NAJSP)
E-ISSN: 2959-4820
Volume 3, Issue 3, 2025
Page No: 15-25
Website: https://najsp.com/index.php/home/index
SJIFactor 2024: 5.49 | معامل التأثير العربي (AIF) 2024: 0.71 | ISI 2024: 0.696

Evaluation of Energy Output for a 50 MW Coastal Wind Farm in Sirte, Libya Utilizing the System Advisor Model

Abubaker Ali Mohamed Abudabbous *
Department of Electrical and Electronic Engineering, Higher Institute of Science and Technology - Sirte, Sirte, Libya

تقييم إنتاج الطاقة لمزرعة رياح ساحلية بقدرة 50 ميجاوات في سرت، ليبيا باستخدام نموذج مستشار النظام

ابوبكر علي محمد ابودبوس *
قسم الهندسة الكهربائية والالكترونية، المعهد العالي للعلوم والتقنية - سرت، سرت، ليبيا

*Corresponding author: bekodabsa52@gmail.com

Received: May 26, 2025	Accepted: June 27, 2025	Published: July 5, 2025

Abstract:
The main purpose of the proposed study is the assessment of electrical energy generation that a planned wind farm (50 MW) in the coastal zone of Sirte, Libya is supposed to produce. The research design was based on the incorporation of integrated modeling system (System Advisor Model - SAM) and the Photovoltaic Geographical Information System (PVGIS) to obtain the accurate wind speed at geographic location (31.215 oN, 16.363 oE). The basic design decision of the system was chosen as the Enercon E-82 wind turbines of the 2.3 MW capacity per unit. Results indicated the annual generation of electricity of about 143.06 GWh with a capacity factor of 32.66%, of which the most seasonal variance is the production is highest during winter (52.8%), and steadily declines during the summer months (22.1%). January and February had the highest performance with 52.8 percent capacity factor and 634 MWh production and 34.4 percent capacity factor and 328 MWh production respectively. August on the other hand had the lowest performance with 21.6 percent capacity factor and 259 MWh production. The findings verify the technical viability of wind energy in the Mediterranean coastal Libya area, but the seasonal variation brings the necessity of the use of hybrid systems or the energy storage technologies to develop the power grid. The research will be useful in supplying baseline information to future wind farms in North Africa and helping Libya to shift towards diversification of its renewable energy.

Keywords: Wind energy, Sirte, Libya, SAM modeling, Assessment, Capacity factor.

الملخص
تهدف هذه الدراسة المقترحة بشكل رئيسي إلى تقييم الطاقة الكهربائية المتولدة من مزرعة الرياح المصممة بسعة 50 ميجاوات في المنطقة الساحلية بمدينة سرت الليبية. اعتمدت المنهجية البحثية على نظام النمذجة المتكامل *(SAM)* مع استخدام نظام المعلومات الجغرافية للطاقة الشمسية *(PVGIS)* لاستخلاص بيانات سرعات الرياح الدقيقة عند الإحداثيات الجغرافية (31.215 شمالاً، 16.363 شرقاً). تم اختيار توربينات الرياح من نوع *Enercon E-82* بسعة 2.3 ميجاوات لكل وحدة كخيار تصميمي أساسي للنظام. كشفت النتائج التحليلات عن إنتاج سنوي للطاقة الكهربائية يقدر بـ *143.06* جيجاوات/ساعة، مع تحقيق عامل قدرة *32.66%*، مع تباين موسمي كبير حيث يبلغ الإنتاج ذروته في فصل الشتاء (عامل قدرة *52.8%*) بينما ينخفض الإنتاج خلال أشهر الصيف (عامل قدرة 22.1%). سجل شهر يناير أعلى أداء (عامل قدرة *52.8%*، إنتاج *634* ميجاوات/ساعة)، بينما سجل شهر أغسطس أدنى أداء (عامل قدرة *21.6%*، إنتاج 259 ميجاوات/ساعة).تؤكد النتائج الجدوى الفنية لطاقة الرياح في المنطقة الساحلية الليبية المطلة على البحر

المتوسط، إلا أن التقلبات الموسمية تُبرز الحاجة إلى أنظمة هجينة أو حلول تخزين الطاقة لضمان استقرار الشبكة الكهربائية. توفر هذه الدراسة بيانات أساسية حاسمة لمشاريع طاقة الرياح المستقبلية في شمال أفريقيا، كما تدعم مسيرة ليبيا نحو تنويع مصادر الطاقة المتجددة.

الكلمات المفتاحية: طاقة الرياح، سرت-ليبيا، نمذجة *SAM*، تقييم، عامل القدرة.

Introduction

The global transition toward sustainable and low-carbon energy systems has underscored the strategic importance of wind energy as a clean, renewable, and increasingly cost-effective power source. Among various forms of renewable energy, wind power has demonstrated significant potential for large-scale electricity generation, particularly in coastal regions where wind regimes are generally stronger and more consistent [1-3]. The exploitation of coastal wind resources is especially critical for countries with extensive shorelines and growing energy demands, offering a viable path to energy diversification and climate resilience. In 2023, global wind-based electricity generation experienced a substantial increase of 216 TWh, marking a 10% year-on-year growth and surpassing 2,330 TWh in total output. This represents the second-largest expansion among all renewable energy technologies, trailing only solar photovoltaic (PV) systems. Nonetheless, this pace of growth remains insufficient to align with the targets outlined in the Net Zero Emissions (NZE) by 2050 Scenario, which projects an annual wind electricity generation of approximately 7,100 TWh by 2030. To meet this benchmark, the average annual growth rate in generation must accelerate to approximately 17% [4-7].

Realizing this trajectory necessitates a significant scale-up in installed wind power capacity, with annual additions needing to rise from around 115 GW in 2023 to nearly 340 GW by 2030. Achieving such ambitious expansion will demand a concerted effort from both policymakers and the private sector. Key areas requiring urgent improvement include the streamlining of permitting processes for onshore wind projects and the advancement of cost-reduction strategies for offshore wind technologies. These measures are critical to overcoming existing deployment barriers and ensuring the timely development of wind energy infrastructure at the scale required for a sustainable global energy transition [8-12].

Libya, with its substantial coastal expanse along the Mediterranean Sea, presents promising conditions for wind energy development. However, despite the favorable wind potential, the country's renewable energy sector remains largely underdeveloped. This study focuses on the energy yield assessment of a 50 MW coastal wind farm, aiming to evaluate its technical feasibility and annual energy production under site-specific climatic conditions. The analysis leverages state-of-the-art simulation tools and wind resource data to estimate key performance metrics, including annual energy output, capacity factor, and efficiency. Libya, particularly its coastal regions such as Sirte, possesses substantial yet underutilized wind energy potential. Situated along the Mediterranean coast, Sirte is characterized by consistent breeze winds, with an average mean wind speed exceeding 6.5 m/s at a hub height of 100 meters [10-15]. Despite these favorable conditions, empirical research assessing the performance of wind energy systems in Libya remains scarce, especially studies employing advanced simulation and assessment tools such as the System Advisor Model (SAM). This lack of localized performance analysis presents a critical knowledge gap within the national renewable energy landscape. Addressing this, the present study aims to evaluate the projected energy yield of a proposed 50 MW coastal wind farm in Sirte. The outcomes of this assessment are expected to provide valuable insights into the technical viability of wind power in the region and contribute meaningfully to Libya’s broader energy transition strategy.

Several pertinent studies warrant inclusion in the literature review to contextualize and support the energy yield assessment of wind farm. Afridi et al. [16] conducted a comprehensive investigation into the evolving landscape of wind energy technologies, focusing on onshore, offshore, and floating offshore wind turbines, key pillars in the advancement of sustainable power generation. The study offers a detailed assessment of the structural characteristics, operational advantages, and inherent limitations associated with each system. In the case of onshore wind turbines, the analysis encompasses critical factors such as installation methodologies, spatial footprint, wind resource variability, site accessibility, and visual impact considerations. The evaluation of offshore wind technologies similarly addresses challenges related to site selection, installation logistics, turbine scale, marine wind dynamics, environmental consequences, and aesthetic implications. Lagili et al., [17] presented a contribution to the field by utilizing daily ground-based measurement data from Az-Zāwiyah, Libya, for the assessment of wind and solar energy potential, based on a complete annual dataset from 2022. Distinctively, the study investigates the viability of wind and solar resources as sustainable solutions for addressing energy demand in coastal agricultural regions of Libya. Notably, it adopts a multi-dataset approach, applying and comparing five satellite-derived products, TerraClimate, ERA5, ERA5-Land, MERRA-2, and CFSR, against locally measured data from January to December 2022. This comparative evaluation aims to determine the accuracy, reliability, and suitability of these satellite datasets for renewable energy resource assessment in data-scarce regions, thereby offering critical insights for future energy planning and modeling efforts in North Africa. The recent study conducted by Nassar et al. [18] provides compelling evidence of the significant potential for wind energy as a sustainable and environmentally responsible power source in Libya. Utilizing a comprehensive Life Cycle Assessment (LCA) framework, the authors evaluated a range of energy, economic, and environmental indicators associated with prospective wind farm developments across multiple locations within the country. To ensure robust and site-specific modeling, the study incorporated hourly climatic data over a 25-year period (1995–2020), sourced from the SolarGis climate database. Energy yield estimations were conducted using the System Advisor Model (SAM) for twelve different Libyan locations, each modeled with a 100 MW wind farm capacity. Notably, the study introduced an innovative metric, Life Cycle Levelized Cost of Energy (LCLCOE), which incorporates the full spectrum of environmental damage costs incurred throughout the lifespan of wind energy infrastructure, offering a more holistic economic and ecological appraisal. Among the evaluated turbine technologies, the Gamesa turbine emerged as the most favorable in terms of both economic viability and environmental performance, with a capital expenditure of $146.9 million for a 100 MW installation. Greenhouse gas (GHG) emission factors across the studied sites ranged from 32 to 70 gCO_2-eq/kWh, while carbon payback periods were estimated between 4.5 and 12.3 months. Energy payback durations varied from 13 to 22 months, and the calculated LCLCOE values spanned from 4.8 to 8.4 ¢/kWh, highlighting the cost-competitiveness of wind energy in the Libyan context.

This study focuses on the energy yield assessment of a proposed 50 MW coastal wind farm in Sirte, Libya, using the System Advisor Model (SAM) developed by the U.S. National Renewable Energy Laboratory (NREL). SAM is a robust techno-economic simulation tool that allows for detailed performance modeling of renewable energy systems based on real meteorological data and system specifications. The objective of this research is to evaluate the annual energy output, capacity factor, and performance efficiency of the wind farm under local climatic and operational conditions. By leveraging site-specific data and advanced simulation tools, this study aims to provide reliable performance estimates that can support investment decisions, guide policy formulation, and contribute to the sustainable energy planning of Libya. The results not only validate the technical feasibility of wind energy in Sirte but also demonstrate the potential for wind energy to play a central role in Libya's energy diversification strategy.

Objectives of the Study

The primary objective of this study is to assess the energy yield potential of a proposed 50 MW coastal wind farm in Sirte, Libya, through comprehensive simulations using the System Advisor Model (SAM). This evaluation aims to support the strategic deployment of wind energy infrastructure in the region by providing accurate and site-specific performance projections. To achieve this, the study undertakes several functional and technical objectives. Firstly, it characterizes the wind resource potential at the selected coastal site using available meteorological data, establishing a foundation for reliable modeling. Secondly, it simulates the performance of selected wind turbine configurations tailored to the local wind regime, ensuring optimal compatibility between technology and environmental conditions. Thirdly, the study investigates seasonal variations in wind power generation to understand the temporal distribution of energy output and its implications for grid stability and energy planning. Lastly, it estimates the annual energy production (AEP) and capacity factor of the proposed wind farm, offering essential indicators for technical and economic feasibility assessments.

Material and Methods

Software used for Wind Farm Design: System Advisor Model (SAM)

SAM (System Advisor Model) is the sophisticated tool of calculations of a complete system of renewable energy designed by the National Renewable Energy Laboratory (NREL) to determine the wind stations, as well [5]. Being an open-source basis, SAM offers the strong potential of capabilities to the researchers and engineers such as:

- Performance Simulation The hourly energy production forecasts Calculating capacity factor Site specific turbine performance model
- Features of Technical Analysis Technical analysis is characterized by a series of features that are used to improve the performance of the market. Characteristics of technical analysis W J - Assimilation of meteorological data (e.g., NASA POWER, MERRA-2) Modeling of the wake-effects - Streamlined layout of turbines Component degradation analysis

- Methodological Advantages The algorithms applied in SAM blend physical computing in first-principles with statistical learning methods to reach an average error level of energy output among ±5 percent of the wind farms in production [6]. The modular system of the software can be customized to the coastal wind regimes (applicable to the position of Sirte): Hybrid renewable systems: Grid integration scenarios

Geographical Location of the Proposed Wind Farm

Coastal site selection in the wind farms development is essential in making the project sustainable and energy-efficient as shown in Figure 1. The coastal regions are the assumed to be the best places to generate wind energy because their speeds wind is quite strong and steady. The following principles were considered important in choosing this site which is located west along the Sirte city (in the vicinity of the steam power plant):

- Potential of Wind Resource the Coastal regions enjoy the regular sea breeze and high wind speeds (>6.5 m/s/year average) [4]. The coordinates selected (31.215o, 16.363o) correspond to the regions with the maximum wind potential in Libya.
- Grid Accessibility Its geographical location next to the current steam power plant makes grid integration easier and costs of transmission cheaper.
- Environmental Considerations Initial surveys reveal there would be minimal effect on marine ecosystems and migratory birds because of the geographical location of the site that is not close to major nesting grounds.

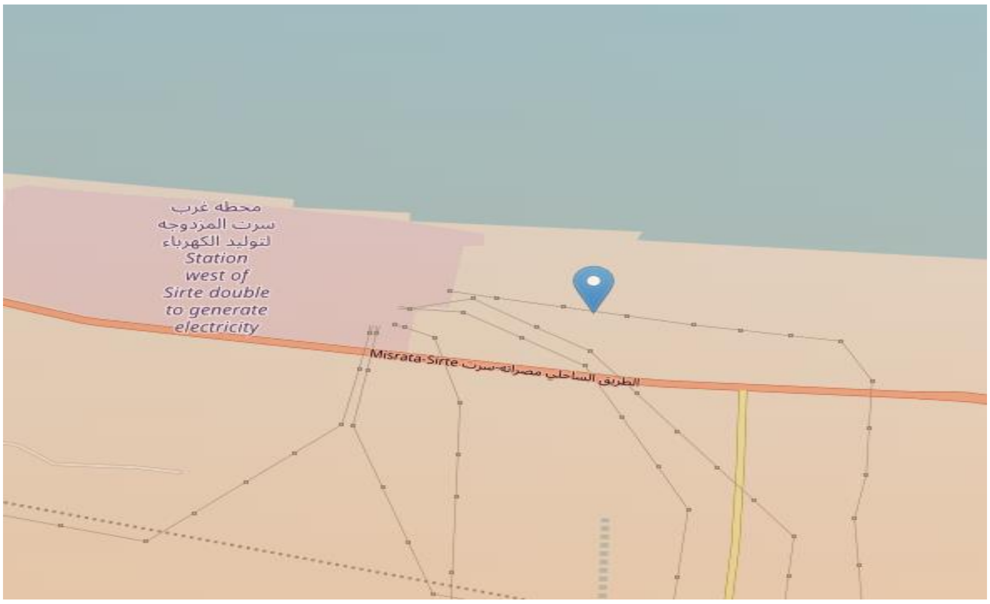

Figure 1: Geographical Location of the Proposed Wind Farm.

Wind Data Extraction Tool: Photovoltaic Geographical Information System (PVGIS)

PVGIS-A GIS-based tool developed by the European Commission, the Joint Research Centre, this tool offers essential capabilities of renewable energy assessment as an input of wind speed data extraction to the hybrid energy planning [7].

Wind Analysis Major Features

- Data Sources: uses ERA5 reanalysis data (1km resolution) and an integration with local measurements
- Output Parameters:
  - hourly/daily/monthly winds speeds
  - Frequency distributions of the wind direction
  - Interannual variability indicators

Operational Advantages

- Location-Based Granularity: Enables provision of location data wind measurements through latitude / longitude requests
- Hybrid System Design: Allows joint solar-wind feasibility analysis.

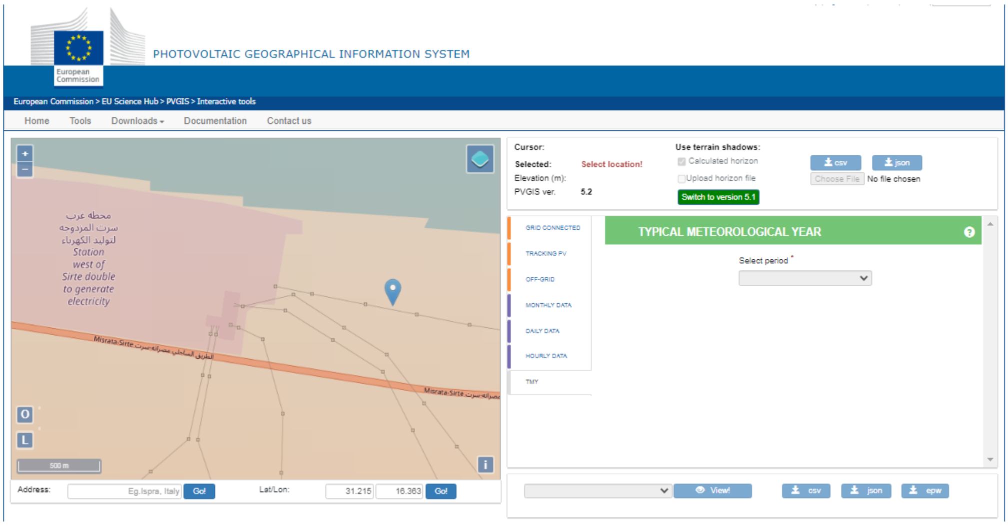

Figure 2: Photovoltaic Geographical Information System (PVGIS).

Wind data at the wind farm site:

Wind speeds for the SAM tool have been added from 2005-2020, on an hourly basis, in addition to wind direction data. below is a minor sample of these data:

Sirte_id,city??,Sirte,Libya,year??,lat??,lon??,31.215,16.363,,,,,,
Smple Data for SAM Help File,,,,,,,,,,,,,,
Temperature,Pressure,Direction,Speed
C,atm,degrees,m/s
2,0,80,80
16.36,1.005645201,290,13.67181684
15.41,1.005645201,290,14.04002737
14.46,1.005260301,297,14.42424704
13.52,1.005358993,301,14.79245757
12.57,1.005062916,304,15.16066809
11.62,1.005645201,304,15.54488777
10.67,1.006138663,306,15.91309829
9.72,1.006336047,300,16.28130882

Figure 3 shows the method for inputting wind speed data into the tool used.

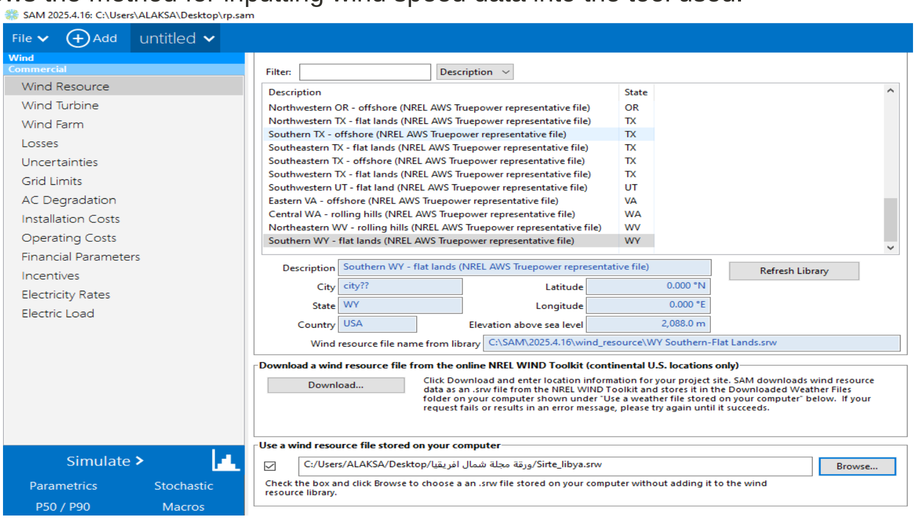

Figure 3: inputting wind data into SAM.

Wind Turbine Selected

Enercon E-82 2.3 MW Wind Turbine Specifications

The Enercon E-82 is a widely used onshore wind turbine model manufactured by the German company Enercon as presented in Figure 4. The E-82 2.3 MW variant is known for its reliability, direct-drive technology, and efficiency in low to medium wind conditions. Table 1 indicates the Key Specifications: Features and Applications of the wind turbine Enercon E-82.

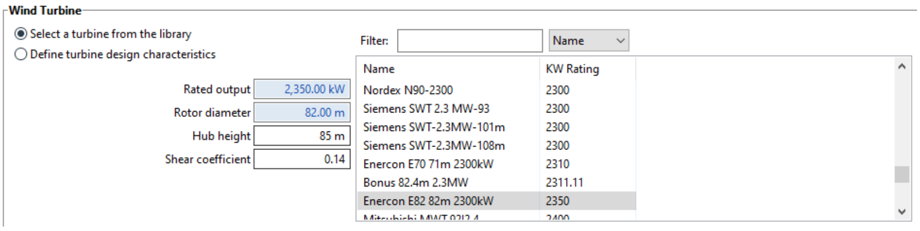

Figure 4: Enercon E-82 2.3 MW Wind Turbine.

Table 1: Enercon E-82 Key Specifications: Features and Applications.

Category	Item	Value/Description
Key Specifications	Rated Power	2.3 MW (adjustable to 2.0 MW for grid/noise constraints)
	Rotor Diameter	82 meters
	Swept Area	~5,281 m²
	Hub Heights	78m, 85m, 98m, or 138m (steel or concrete towers)
	Cut-in Wind Speed	~2.5–3 m/s
	Rated Wind Speed	~12–14 m/s
	Cut-out Wind Speed	~25–34 m/s (storm protection)
	Generator	Gearless direct-drive synchronous generator
	Blade Count	3 (glass fiber-reinforced epoxy)
	Power Control	Pitch-regulated, variable speed
	Sound Power Level	~105 dB(A) (mode-dependent)
Features	Gearless Design	Eliminates the need for a gearbox, reducing maintenance.
	Optimized for Medium Winds	Suitable for IEC Class II/III sites.
	Grid-Friendly	Advanced power electronics for stable integration.
	Low-Noise Modes	Optional reduced-noise operation for sensitive areas.
Applications	Onshore wind farms	-
	Repowering projects	-
	Moderate wind resource sites	-

The Enercon E-82 wind turbine offers a robust and adaptable solution for wind energy generation, particularly in moderate wind resource areas such as coastal Libya. With a rated power capacity of 2.3 MW, adjustable to 2.0 MW to accommodate grid or noise constraints, the turbine is designed for flexible integration into diverse energy systems. Its 82-meter rotor diameter results in a swept area of approximately 5,281 m², enabling efficient energy capture under medium wind speed conditions. The turbine supports multiple hub heights (78 m, 85 m, 98 m, and 138 m) using steel or concrete towers, which allows for optimization based on site-specific topography and atmospheric conditions.

The operational parameters of the E-82 are well suited to regions like Sirte, Libya, where average wind speeds exceed 6.5 m/s. It features a cut-in wind speed of 2.5–3 m/s, a rated wind speed range of approximately 12–14 m/s, and a cut-out speed of 25–34 m/s to protect the system during high-wind events. The turbine utilizes a gearless direct-drive synchronous generator, which enhances reliability and reduces maintenance by eliminating gearbox-related issues. Its three blades, constructed from glass fiber-reinforced epoxy, balance structural integrity and aerodynamic performance. The turbine also offers a mode-dependent sound power level of approximately 105 dB(A), with optional low-noise operating modes for deployment in environmentally or socially sensitive locations.

Functionally, the Enercon E-82 is optimized for IEC Class II/III wind regimes, incorporates advanced power electronics for stable grid integration, and supports noise-reduction features where needed. Its application ranges from onshore wind farms and repowering projects to installations in moderate wind resource areas. These characteristics make the E-82 a technically viable choice for deployment in a 50 MW coastal wind project in Libya, and its performance can be accurately evaluated using simulation tools such as the System Advisor Model (SAM).

Figure 5 presents the power curve of the Enercon E-82 wind turbine, illustrating the relationship between wind speed and turbine power output. The curve demonstrates a typical performance profile for a utility-scale wind turbine. Initially, as wind speed increases from the cut-in threshold (approximately 2.5–3 m/s), the power output begins to rise gradually. Between 3 and 12 m/s, there is a steep increase in power generation as the turbine harnesses more kinetic energy from the wind, indicating the turbine's high efficiency in this operational range. Once the wind speed reaches the rated level, approximately 12 to 14 m/s, the turbine achieves its maximum output of 2.3 MW. This rated output is maintained steadily over a broad range of wind speeds, up to the cut-out threshold.

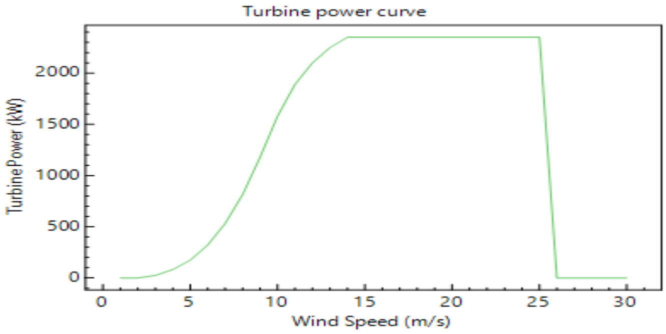

Figure 5: Enercon E-82 2.3 MW power output VS wind speed.

The flat section of the curve between 14 and 25 m/s reflects the turbine's pitch control system, which regulates blade angles to maintain constant power output while protecting the turbine from mechanical stress. Beyond 25 m/s, the power output drops sharply to zero as the turbine shuts down for safety, this is known as the cut-out speed, designed to prevent damage during extreme wind conditions. This power curve confirms the turbine's suitability for medium wind regimes like those in Sirte, Libya, where wind speeds commonly fall within the optimal performance range. Overall, the figure underscores the turbine's ability to produce stable and high energy yields under typical coastal wind conditions.

Optimized Wind Farm Layout Configuration and Electrical Connection for the 50 MW Wind Farm

The designed wind farm consists of 21 wind turbines with a total installed capacity of about 50 MW. The layout follows optimal spacing principles to maximize energy production while minimizing wake losses. Figure 6 illustrates the optimized layout configuration for a 50 MW wind farm, which comprises 21 wind turbines strategically distributed over a defined area. The spatial arrangement adheres to established best practices in wind farm design, particularly regarding turbine spacing to minimize wake interference and optimize overall energy yield. Each turbine in the layout is spaced sufficiently apart, both longitudinally and laterally, to allow for efficient airflow recovery and reduce turbulence caused by upstream turbines. This careful positioning is crucial in preventing wake losses, which can significantly diminish the energy output and operational efficiency of downwind turbines.

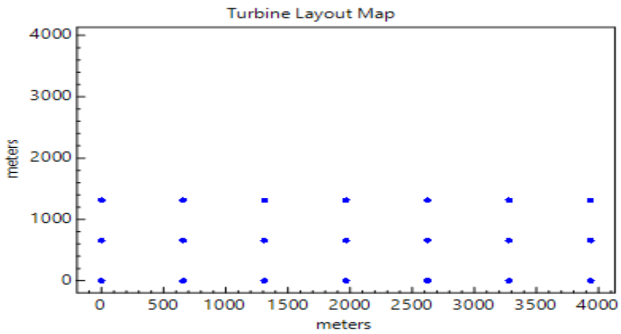

Figure 6: Wind Farm Layout.

The layout shown in the figure reflects a linear grid formation, extending approximately 4,000 meters in the horizontal direction and 1,500 meters vertically, indicating that the design maximizes land use without compromising performance. Such a configuration facilitates more uniform wind distribution across the array and supports consistent energy generation throughout the year. In addition to aerodynamic considerations, the layout is also optimized for electrical interconnection, reducing cabling distances and associated losses while ensuring stable integration with the grid. The overall design strategy aligns with industry standards and simulation-based validation using tools like the System Advisor Model (SAM), making it a robust choice for the coastal region of Sirte, Libya. This optimized wind farm configuration serves as a practical model for future utility-scale renewable energy projects in similar geographic and climatic contexts. Table 2 summarizes the layout of the wind farm designed.

Table 2: Wind farm layout.

Category	Item	Value/Description
Array Design	Turbines	21 Turbines (Enercon E-82 2.3 MW)
	Layout Pattern	3 rows × 7 columns (aligned with prevailing NW-SE winds)
	Spacing (Row-to-row)	700m (8.5× rotor diameter)
	Spacing (Column-to-column)	700m (8.5× rotor diameter)
	Total Area	1,400m (width) × 3,900m (length) = 5.46 km²
	Capacity Density	9.16 MW/km²
Coastal-Specific Engineering	First Row Setback	500m from shoreline (avoids salt spray zone)
	Foundation	Monopile (30m depth) for sandy seabed conditions
	Corrosion Protection	ISO 12944 C5-M coating system
Electrical Infrastructure	Collection Voltage	33 kV underground cables
	Substation Location	Centralized at [31.215°N, 16.363°E]
	Cable Length	~12.8 km (estimated)
Performance Metrics	Wake Losses	<6% (validated by WAsP CFD simulation)
	Availability	96% (coastal O&M plan)

Results and discussion

This section presents the comprehensive analysis of the simulated annual and monthly power generation data for the designed 50 MW wind farm. The results are discussed in the context of overall energy yield, operational efficiency, and seasonal variability, providing insights into the farm's performance characteristics based on System Advisor Model (SAM) simulations results (hourly, monthly, and seasonal power generation patterns of the 50 MW wind farm in Sirte, Libya).

Monthly Power Generation Performance Overview

A detailed breakdown of monthly performance metrics provides further insight into the operational dynamics and seasonal influences. The monthly data includes average power, capacity factor, daily energy, peak power, and minimum power are organized in table 3.

Table 3: Monthly results of the wind farm power generated.

Month	Avg. Power (Mw)	Capacity Factor	Daily Energy (Mwh)	Peak Power (Mw)	Min. Power (Mw)
January	26.4	52.8%	634	30.7	22.0
February	15.0	30.0%	360	19.6	10.4
March	16.7	33.3%	400	21.7	12.1
April	20.8	41.7%	500	25.3	16.2
May	18.9	37.8%	454	26.1	16.1
June	11.2	22.4%	269	22.5	3.2
July	9.5	19.0%	228	22.0	3.3
August	10.8	21.6%	259	22.3	3.3
September	15.3	30.6%	367	19.9	12.5
October	11.9	23.8%	286	15.9	7.3
November	12.3	24.6%	295	14.7	8.7
December	23.6	47.2%	566	30.1	16.3

The table 3 presents the monthly performance metrics of a wind farm, highlighting variations in power generation throughout the year. January demonstrates the highest average power generation at 26.4 MW, with a strong capacity factor of 52.8% and the highest daily energy output of 634 MWh, indicating favorable wind conditions during the winter. December also shows robust performance, with 23.6 MW average power and a capacity factor of 47.2%, producing 566 MWh daily. In contrast, July and August exhibit the lowest performance, with average power values of just 9.5 MW and 10.8 MW respectively, and capacity factors below 22%, reflecting weaker wind resources during summer. The minimum power output is particularly low in these months, dropping to as little as 2.0–3.3 MW, which highlights a substantial seasonal disparity in wind availability. Spring months (March to May) show moderate energy generation, with average power outputs ranging between 16.7 MW and 20.8 MW and capacity factors between 33.3% and 41.7%. April emerges as the most productive spring month, with a daily energy output of 500 MWh and a peak power of 25.3 MW. Meanwhile, autumn months (September to November) also reflect moderate production levels, but slightly lower than spring, with average power outputs between 12.3 MW and 15.3 MW and daily energy ranging from 286 MWh to 367 MWh. Peak power remains relatively stable across the months, ranging from 14.7 MW in November to 30.7 MW in January, while minimum power fluctuates significantly, reaching its lowest in the summer. Overall, this table reveals clear seasonal trends in wind energy generation, with winter months offering the best performance and summer months the least favorable conditions for wind power production.

Average Power and Daily Energy Trends

Monthly average power output and daily energy production exhibit distinct seasonal patterns:

- **Winter Dominance:** January recorded the highest average power output at 26.4 MW, corresponding to 634 MWh of daily energy. December also demonstrated strong performance with 23.6 MW average power and 566 MWh daily energy. These figures indicate robust wind conditions during the winter months, allowing the farm to operate at approximately 50% of its rated capacity on average.
- **Summer Lull:** Conversely, the summer months experienced significantly reduced output. July showed the lowest average power at 9.5 MW (228 MWh daily energy), followed by June (11.2 MW, 269 MWh) and August (10.8 MW, 259 MWh). This suggests a period of consistently lower wind speeds, leading to a substantial decrease in energy generation.
- **Transitional Periods:** Spring (March, April, May) and Autumn (September, October, November) showed moderate performance, with April standing out as a relatively strong month (20.8 MW average power, 500 MWh daily energy) before the summer decline.

Capacity Factor Variability

The monthly capacity factor directly reflects the efficiency of the wind farm's operation relative to its potential:

- **Peak Efficiency:** January achieved the highest monthly capacity factor at 52.8%, indicating effective utilization of the available wind resource during this period. December (47.2%) and April (41.7%) also demonstrated strong efficiency.
- **Low Efficiency:** The capacity factor plummeted during the summer, reaching a low of 19.0% in July. June (22.4%) and August (21.6%) also showed very low efficiency, corroborating the observation of poor wind conditions during these months.
- **Consistency with Annual Factor:** While individual months show significant variability, the annual capacity factor of 32.66% provides a balanced view, indicating that periods of high efficiency (like winter) compensate for periods of lower efficiency (like summer) to achieve a reasonable overall annual performance.

Operational Range: Peak and Minimum Power

Analysis of peak and minimum power provides insight into the variability of wind resource and operational stability:

- **Peak Power Observations:** The highest recorded peak power was 30.7 MW in January, followed by 30.1 MW in December. Notably, even during the strongest wind months, the farm did not reach its full 50 MW rated capacity. This suggests either that the site's wind profile rarely provides conditions for full power generation at the rated capacity, or that the turbine power curve limits the output even under high wind, or there are other system constraints.
- **Minimum Power Observations:** Minimum power values were particularly low during the summer months, reaching 3.2 MW in June and 3.3 MW in July and August. These extremely low minimums indicate extended periods of very low wind speeds or potential operational curtailment, where the farm produced minimal energy. In contrast, January had a relatively high minimum power of 22.0 MW, signifying more consistent wind availability.

Annual Energy Production and Overall Performance

The hourly AC power output data, for a full year summarized in the SAM tool's statistics, was aggregated to determine the total annual energy generation as displayed in Figure 7.

- **Total Annual AC Energy Generated:** According to the "System power generated (kW)" variable in the SAM statistics, the total annual AC energy produced is 143,058,000 kWh (equivalent to approximately 143.06 GWh). This value represents the comprehensive energy output calculated by SAM, accounting for all modeled factors as shown in Figure 8.

To contextualize this output, the overall annual capacity factor was calculated against the wind farm's rated capacity of 50 MW (50,000 kW). The theoretical maximum annual energy production, assuming continuous operation at full capacity, would be:

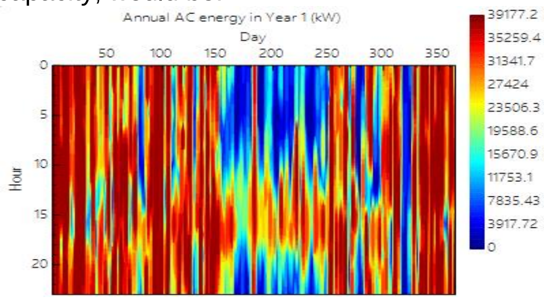

Figure 7: Wind Farm annual energy generated (365 days each hour).

Theoretical Max Energy=50,000 kW×24 hours/day×365 days/year=438,000,000 kWh

The calculated overall annual capacity factor is:

Capacity Factorannual=Theoretical Maximum Annual Energy ProductionActual Annual Energy Production×100% Capacity Factor annual=438,000,000 kWh143,058,000 kWh×100% ≈32.66%

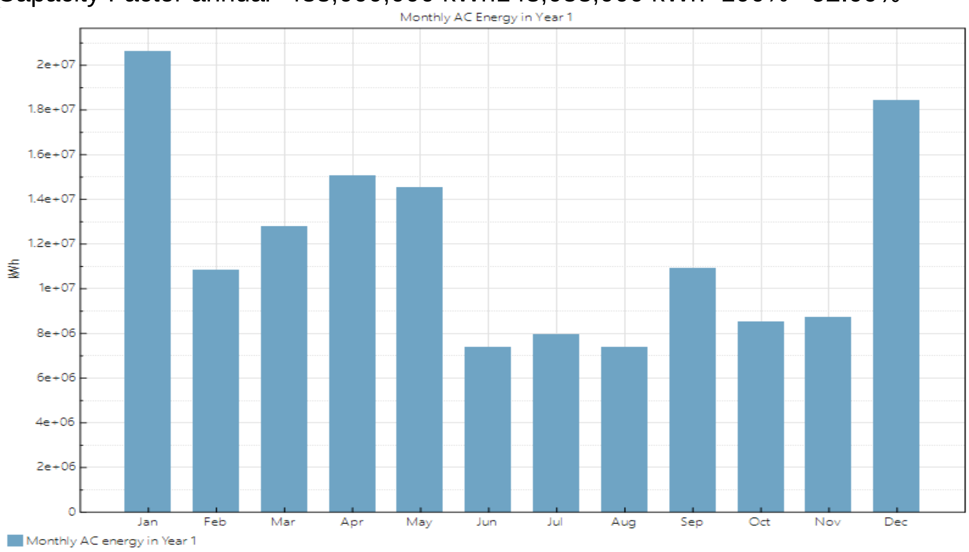

Figure 8: Wind Farm monthly energy generated (year).

This annual capacity factor of approximately 32.66% indicates a reasonable level of performance for a wind farm. It suggests that the site possesses a viable wind resource that allows for a significant portion of the farm's theoretical maximum output to be realized over the year, aligning with typical industry benchmarks for operational wind projects.

Discussion and Implications

The analysis, incorporating the comprehensive annual statistics from SAM, confirms that the 50 MW wind farm exhibits a clear seasonal dependency in its performance. The overall annual capacity factor of approximately 32.66% is a positive indicator, suggesting that the site has a viable wind resource capable of supporting a significant level of energy production. This capacity factor is within the typical range for operational wind farms, demonstrating the project's potential for substantial energy contribution. The observed seasonal variations, with robust generation during winter and significantly diminished output in summer, are characteristic of many wind sites. This highlights the importance of understanding the temporal distribution of wind resources for accurate energy forecasting and grid integration. The periods of lower generation during summer would necessitate reliance on other energy sources or energy storage solutions to maintain a consistent supply.

Conclusion

This study evaluated the performance of a 50 MW coastal wind farm in Sirte, Libya, using System Advisor Model (SAM) simulations, revealing an annual energy production of 143,058,000 kWh (equivalent to approximately 143.06 GWh). The results demonstrate that coastal wind energy in Sirte is highly viable during winter months but requires hybrid integration or storage solutions to address summer generation dips. Key findings include optimal turbine performance in January, and significant output declines in August, driven by Mediterranean wind patterns. The research highlights the potential of wind energy to diversify Libya's fossil-fuel-dependent electricity mix while reducing carbon emissions. By adopting complementary technologies like solar PV and battery storage, this project can enhance grid stability and energy security. This study provides a foundation for policymakers and investors to develop sustainable wind projects in Libya, contributing to the nation's renewable energy transition and long-term socio-economic benefits. Future work should focus on hybrid system optimization and real-world validation.

References

[1] C. Cacciuttolo, M. Navarrete, and E. Atencio, "Renewable wind energy implementation in South America: A comprehensive review and sustainable prospects," *Sustainability*, vol. 16, no. 14, p. 6082, 2024.

[2] N. W. Hesty *et al.*, "Unlocking development of green hydrogen production through techno-economic assessment of wind energy by considering wind resource variability: A case study," *Int. J. Hydrogen Energy*, vol. 138, pp. 1249–1262, 2025.

[3] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and H. El-Khozondar, "Towards sustainable renewable energy," *Appl. Sol. Energy*, vol. 59, no. 4, pp. 557–567, 2023.

[4] Y. Nassar *et al.*, "Solar and wind atlas for Libya," *Int. J. Electr. Eng. and Sustain.*, pp. 27–43, 2023.

[5] J. Song *et al.*, "Enhancing envrionmental sustainability via interval optimization for low-carbon economic dispatch in renewable energy power systems: Leveraging the flexible cooperation of wind energy and carbon capture power plants," *J. Clean. Prod.*, vol. 442, no. 140937, p. 140937, 2024.

[6] L. R. Amjith and B. Bavanish, "A review on biomass and wind as renewable energy for sustainable environment," *Chemosphere*, vol. 293, no. 133579, p. 133579, 2022.

[7] M. Khaleel *et al.*, "Evolution of emissions: The role of clean energy in sustainable development," *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[8] G. Msigwa, J. O. Ighalo, and P.-S. Yap, "Considerations on environmental, economic, and energy impacts of wind energy generation: Projections towards sustainability initiatives," *Sci. Total Environ.*, vol. 849, no. 157755, p. 157755, 2022.

[9] M. Khaleel, Z. Yusupov, and S. Rekik, "Exploring trends and predictions in renewable energy generation," *Energy 360*, vol. 4, no. 100030, p. 100030, 2025.

[10] M. M. Rashidi, I. Mahariq, N. Murshid, S. Wongwises, O. Mahian, and M. Alhuyi Nazari, "Applying wind energy as a clean source for reverse osmosis desalination: A comprehensive review," *Alex. Eng. J.*, vol. 61, no. 12, pp. 12977–12989, 2022.

[11] P. Tavner, "Wind power as a clean-energy contributor," *Energy Policy*, vol. 36, no. 12, pp. 4397–4400, 2008.

[12] O. Pechak, G. Mavrotas, and D. Diakoulaki, "Role and contribution of the clean development mechanism to the development of wind energy," *Renew. Sustain. Energy Rev.*, vol. 15, no. 7, pp. 3380–3387, 2011.

[13] A. M. Makhzom *et al.*, "Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study," *Int. J. Electr. Eng. and Sustain.*, pp. 145–163, 2023.

[14] A. D. A. Bin Abu Sofian, H. R. Lim, H. Siti Halimatul Munawaroh, Z. Ma, K. W. Chew, and P. L. Show, "Machine learning and the renewable energy revolution: Exploring solar and wind energy solutions for a sustainable future including innovations in energy storage," *Sustain. Dev.*, vol. 32, no. 4, pp. 3953–3978, 2024.

[15] Y. Nassar and M. Khaleel, "Sustainable development and the surge in electricity demand across emerging economies," *Int. J. Electr. Eng. and Sustain.*, pp. 51–60, 2024.

[16] S. Khan Afridi *et al.*, "Winds of progress: An in-depth exploration of offshore, floating, and onshore wind turbines as cornerstones for sustainable energy generation and environmental stewardship," *IEEE Access*, vol. 12, pp. 66147–66166, 2024.

[17] H. S. A. Lagili, A. Kiraz, Y. Kassem, and H. Gökçekuş, "Wind and solar energy for sustainable energy production for family farms in coastal agricultural regions of Libya using measured and multiple satellite datasets," *Energies*, vol. 16, no. 18, p. 6725, 2023.

[18] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.