Wind Energy Potential and Economic Feasibility in Mauritania: A Multi-Site Evaluation of Three Wind Turbines

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ABSTRACT

This study evaluates the performance of various wind turbine models for different regions of Mauritania, focusing on offshore and onshore sites, considering wind speed data from four locations, Nouakchott, Nouadhibou, Aleg, and an offshore area near Nouakchott, over four years (2021-2024). Three turbine models XEMC Ltd XE93, Ecotecnia ECO80, and Siemens Gamesa SG132 were evaluated for their suitability to local wind conditions. Key parameters, such as wind speed, turbine efficiency, and energy production costs, were analyzed to determine the most suitable turbines and locations for wind farm development. The results show that coastal and offshore areas, particularly Nouadhibou and the Atlantic offshore zone, offer the highest wind potential with competitive energy production costs. The findings support the development of wind farms in these regions as a strategic investment to advance Mauritania's renewable energy goals.

Keywords-renewable energy; wind energy; coastal wind energy; energy planning; energy cost

I. INTRODUCTION

For several years now, environmental and ecological issues, energy consumption in all its forms, and polluting effects, mainly due to the combustion of fossil fuels, have been at the core of concerns about sustainable development and environmental protection in debates on the future of Mauritania [1]. Previous studies have explored the potential for wind energy in North Africa, but only limited studies have focused on the performance of specific wind turbine models under unique coastal and offshore conditions in Mauritania. This study evaluates the utilization of three turbine models in four regions of Mauritania. Although Africa has great potential, due to abundant natural resources such as solar, wind, hydroelectric, and biomass energy, challenges remain in harnessing renewable energy, particularly in terms of infrastructure, financing, and technical training. Against this disadvantage, Mauritania has recognized the importance of the energy transition in recent years and has set the goal of achieving a 50% share of renewable energy in its total energy consumption by 2030 [2]. North African countries, such as Algeria, Morocco, Tunisia, Libya, Mauritania, and Egypt, have a strong renewable energy potential due to intense sunshine and wind. Mauritania is known for its wind potential, especially along its Atlantic coast, with wind speeds regularly exceeding 7 m/s on more than 700 km, and benefits from exceptional sunshine (more than 3,000 hours per year), making it ideal for solar and wind energy production [3]. Mauritania is one of the most developed countries in the region in terms of wind energy, with the 101 MW Boulenoire wind farm in the north, the 30 MW Nouakchott wind farm, the 50 MW Toujounine plant, and the 15 MW Sheikh Zayed plant. Thus, this study analyzes wind speeds in different regions of Mauritania (both onshore and offshore) to determine the most suitable areas for wind farm construction [4].

Integrating renewable energy into the existing electricity grid brings many challenges and opportunities. Economic issues such as diversification and interdependence of renewable energy require advanced forecasting techniques and robust energy management strategies to ensure sustainability and reliability [5]. Furthermore, the development of energy storage technology is important to reduce instability in renewable energy production [6]. New solutions have been proposed to solve these problems, including smart energy technology and external demand management [7]. Initial investment remains a barrier to widespread adoption [8]. Many regions have utilized policies, such as subsidies and tax incentives, to encourage investment in renewable energy [9]. In addition, the integration of renewable energy has positive economic benefits, including job creation and the promotion of local economies [10]. Reducing greenhouse gas emissions and air pollution can help improve public health and mitigate the effects of climate change [11]. Life cycle assessments of renewable energy systems have shown that they have a better environmental impact than fossil fuels [12]. However, issues such as land use and resource use associated with the development of renewable energy sources must be carefully addressed [13]. This work searched for the best wind turbines on the market suitable for these areas, and at the same time examined the most important economic and financial aspects.

II. ENERGY PRODUCTION

A. *Wind Kinetic Energy and Power Models for Wind Turbines*

The amount of energy available in the wind and the way a wind turbine captures it depends on several physical factors. These models make it possible to calculate the power generated by the turbine from the wind speed [14]. The power available in the wind is the amount of energy that can be extracted by the turbine per unit of time. Using the kinetic energy of the wind, power is obtained using the following equation:

$$P_{wind} = \frac{1}{2}\,\rho\,.A.V^3 \qquad (1)$$

where ρ is the air density (in kg/m³), often approximated to 1.225 kg/m^3 at 15°C at sea level, A is the area swept by the turbine blades (in m²), which is calculated from the blade radius R of the turbine, and V is wind speed (in m/s) [15]. This power is available in the wind before the turbine captures any of it. This depends on the speed of the wind, the area swept by the blades, and the density of the air [16]. Not all the kinetic energy of the wind can be captured by the turbine due to the conservation of momentum. If the turbine captured all the energy, the wind would slow down completely, which would stop the flow of air, preventing any energy production. Therefore, the power that can be extracted is limited [17]. The wind turbine is based on the Betz limit, which stipulates that the turbine can only extract 59.3% (or 16/27) of the kinetic energy available in the wind, i.e. the maximum power coefficient C_p is 0.59, so the real power captured by the turbine is:

$$P_{real} = \frac{1}{2}\,\rho\,.A.V^3.C_P \qquad (2)$$

where C_p is the power coefficient, which depends on turbine design and wind speed and generally varies between 0 and 0.59. Wind kinetic energy and power models for wind turbines are essential for understanding and predicting energy production. The relationship between wind speed, blade swept area, and power coefficient is crucial for wind turbine sizing and optimization. The Betz limit imposes a fundamental constraint on the extraction of energy from the wind, but with modern designs, turbines are capable of producing a significant fraction of this available energy [18].

B. *Measured Wind Data in Selected Sites*

Wind speed is a key criterion for selecting a wind turbine, and each model has an optimum wind speed range in which it works best. Therefore, it is essential to know the average wind speed at the installation site. Wind speed varies considerably depending on geographical location, topography, and local climatic conditions. Therefore, wind speed is an essential factor in determining the location and profitability of a wind farm [19]. A wind speed survey can identify areas with consistent and strong winds to ensure that the turbines will operate to their full potential and produce the required wind energy efficiently and economically. Turbines must operate at a range of wind speeds. In general, the wind speed must be at least 3 to 4 m/s for the turbines to start producing electricity [20]. The optimum wind speed is generally between 12 and 14 m/s. If the wind speed exceeds a certain threshold (around 25 m/s), the wind turbines automatically shut down to prevent damage. This study analyzed the monthly and annual average wind speed for four successive years (from 1 January 2021 to 31 December 2024) in four regions of the country: the Nouakchott South zone, the 5 km zone in the Atlantic Ocean on the Nouakchott side, the Nouadhibou zone, and the Aleg zone, at a height of 90 m. Figures 1 to 4 demonstrate a wind speed comparison for these locations for 2021, 2022, 2023, and 2024.

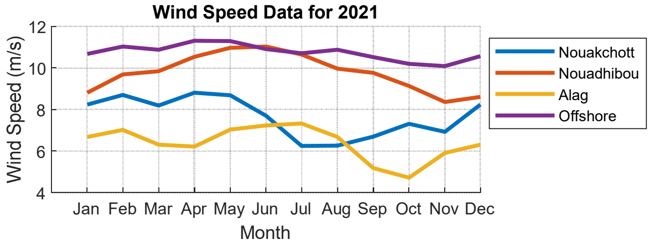

Fig. 1. Wind speeds in 2021.

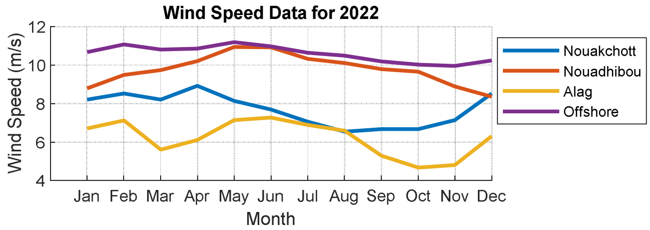

Fig. 2. Wind speeds in 2022.

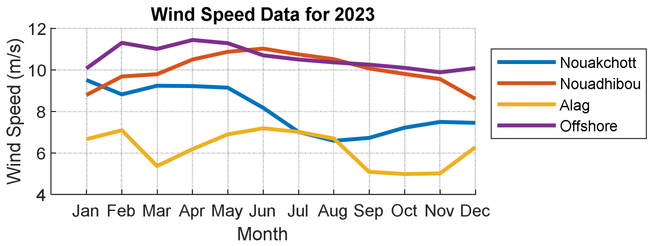

Fig. 3. Wind speeds in 2023.

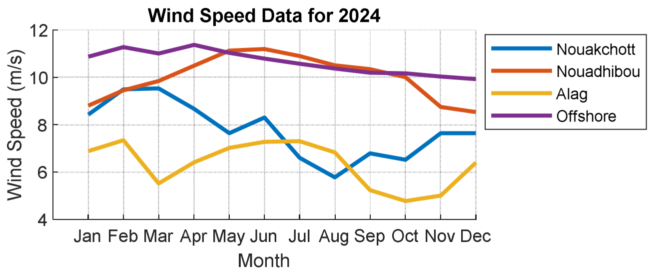

Fig. 4. Wind speeds in 2024.

The annual variation in wind speed at a height of 90 m shows that the area 5 km out into the Atlantic Ocean is the windiest, with an average wind speed of 10.83 m/s, closely followed by the Nouadhibou region, with an average wind speed of 9.81 m/s. On the other hand, the Aleg area has the lowest average annual wind speed, at 6.28 m/s. In conclusion, the first three zones are suitable for the installation of wind farms, in particular the 5 km zone in the Atlantic Ocean and the Nouadhibou region, where the average annual wind speed exceeds 9 m/s.

III. WIND TURBINES

The choice of a wind turbine depends on numerous technical, environmental, and economic criteria. A thorough study of local wind conditions, energy requirements, and profitability is essential to select the most suitable turbine for each wind project. This study considered the following main criteria for choosing a wind turbine. Wind speed is a key criterion, as each turbine model has an optimum wind speed range at the installation site where it works best. The height of the mast is also important when choosing a turbine, as it affects energy production since the speed of the wind generally increases with altitude [21]. The higher the mast, the more wind the turbine can capture, particularly in areas where the wind is stronger at higher altitudes. The power rating is an essential parameter when choosing a wind turbine, as it indicates the amount of energy it can produce under optimum conditions (average wind). It is important to choose a turbine that satisfies the site's energy demand, as well as its capacity to connect to the electricity grid [22].

As shown in Table I, the efficiency of a turbine is measured by its capacity factor, which represents the amount of energy actually produced compared to the theoretical amount of energy it could produce under ideal conditions [23]. The higher the efficiency, the more energy the wind turbine will generate, which is essential to maximize the yield of a wind power project. The lifespan of wind turbines is a key factor in the choice of equipment. Modern turbines have a lifespan of 20 to 30 years. Therefore, it is essential to consider the longevity of the turbine when planning investments and possible repairs or replacements.

TABLE I. SPECIFICATIONS OF XEMC LTD WIND TURBINE

Manufacturer	**XEMC Ltd**
Model	XEMC Ltd XE93
Rated power	2 MW
Starting speed	3.0 m/s
Nominal wind speed	12.0 m/s
Cut-off speed	25.0 m/s
Rotor diameter	93.4 m
Number of blades	3
Mast length	90 m
Grid frequency	50.0 Hz
Output voltage	690 V
Weight of the rotor	47.5 t
Nacelle weight	84.5 t
Power limitation	Steel tube
Life expectancy	20 to 25 years
Type of installation	On- offshore

TABLE II. SPECIFICATIONS OF ECOTECNIA WIND TURBINE

Manufacturer	**Ecotecnia**
Model	Ecotecnia-ECO80
Rated power	2 MW
Starting speed	3 m/s
Nominal wind speed	12 m/s
Cut-off speed	25 m/s
Rotor diameter	80 m
Number of Blades	3
Mast length	90 m
Grid frequency	50.0 Hz
Output voltage	690 V
Weight of the rotor	18 t
Nacelle weight	64 t
Power limitation	Pitch
Life expectancy	20 to 25 years
Type of installation	On- offshore

TABLE III. SPECIFICATIONS OF SIEMENS GAMESA WIND TURBINE

Manufacturer	**Siemens Gamesa**
Model	Siemens Gamesa SG132
Rated power	3.4 MW
Starting speed	3,0 m/s
Nominal wind speed	12,5 m/s
Cut-off speed	25 m/s
Rotor diameter	132 m
Number of blades	3
Mast length	90 m
Grid frequency	50.0 Hz
Output voltage	690 V
Weight of the rotor	145t
Nacelle weight	165t
Power limitation	Pitch
Life expectancy	20 to 25 years
Type of installation	On- offshore

IV. FARMS' LOCATIONS WIND SPEEDS

To effectively design wind energy projects, it is necessary to provide information about specific weather and topographic conditions such as wind speed [24]. This study used wind speed data from four different locations and applied them to these wind turbine designs to evaluate which is most suitable for the specific wind conditions at each location. The average monthly wind speed in four specific regions (Nouakchott, Nouadhibou, Alag, and the coastline) is important in this selection. The wind turbine models examined are: Xiangdian Group XE93 wind turbine, made in China, with rated power of 2 MW, starting speed of 3.0 m/s, rated speed of 12.0 m/s, and cut-off speed of 25.0 m/s. This model is designed for areas where wind speeds frequently reach the nominal speed range and provide good visibility. Ecotecnia ECO80, made in Spain, is the same as the previous model, with a power of 2 MW, a starting speed of 3.0 m/s, and a nominal speed of 12.0 m/s. Also, the SG 3.4-132, made in Germany, is ideal in medium to high wind sites, where customers require nominal powers higher than 3.4 MW with an optimum levelized cost of energy, rotor diameter of 132 m, and nominal power of 3.465 MW. This model is particularly suitable for coastal or seaside areas where wind speeds are high and constant.

A. XEMC Ltd XE93 (2 MW)

The performance of the XEMC Ltd XE93 turbine in the locations under evaluation is shown in Figures 5 to 8.

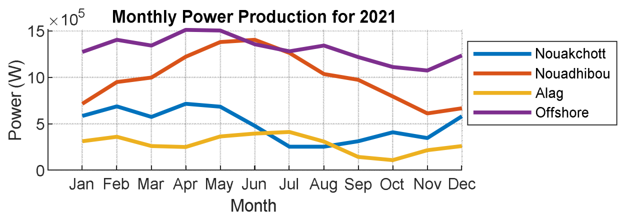

Fig. 5. Performance of XEMC Ltd XE93 under the wind speeds measured in 2021.

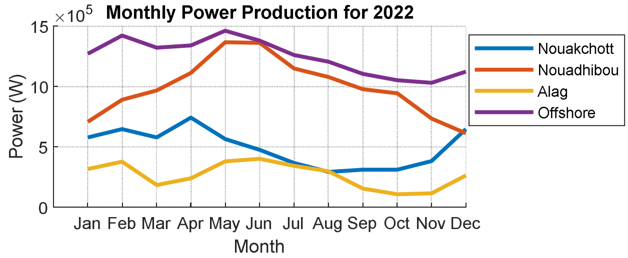

Fig. 6. Performance of XEMC Ltd XE93 under the wind speeds measured in 2022.

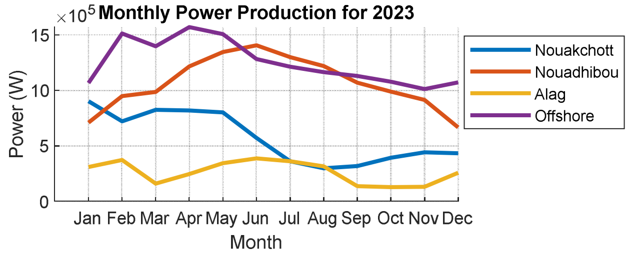

Fig. 7. Performance of XEMC Ltd XE93 under the wind speeds measured in 2023.

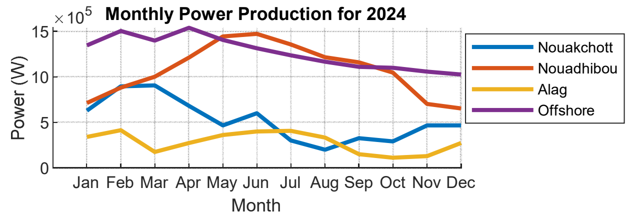

Fig. 8. Performance of XEMC Ltd XE93 under the wind speed measured in 2024.

B. Ecotecnia-ECO 80 (2 MW)

The performance of the Ecotecnia-ECO80 turbine in the locations under evaluation is shown in Figures 9 to 12.

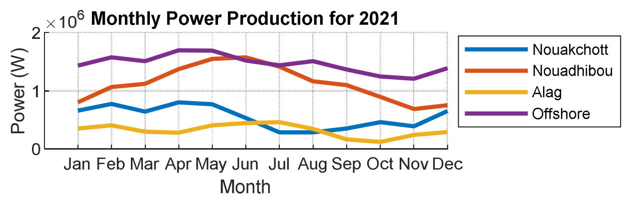

Fig. 9. Performance of Ecotecnia-ECO80 under the wind speeds measured in 2021.

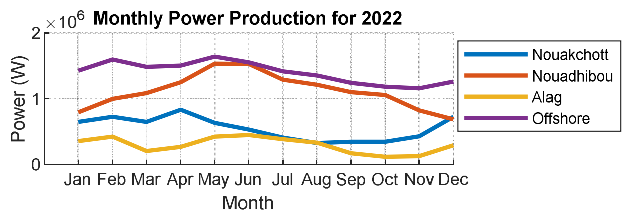

Fig. 10. Performance of Ecotecnia-ECO80 under the wind speed measured in 2022

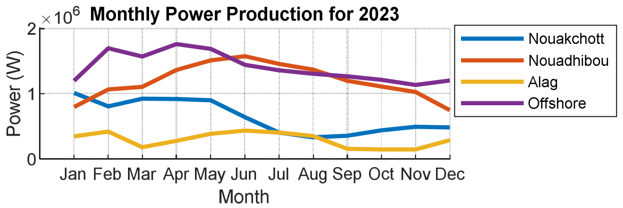

Fig. 11. Performance of Ecotecnia-ECO80 under the wind speeds measured in 2023.

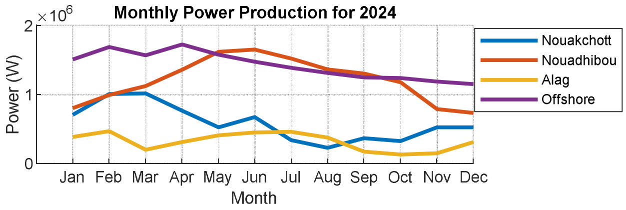

Fig. 12. Performance of Ecotecnia-ECO80 under the wind speeds measured in 2024.

C. Siemens Gamesa SG-132 (3.4 MW)

The performance of the Siemens Gamesa SG-132 turbine in the locations under evaluation is shown in Figures 13 to 16.

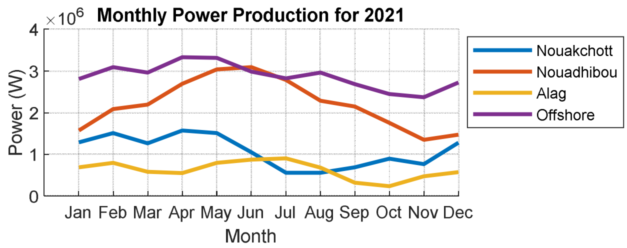

Fig. 13. Performance of Siemens Gamesa SG-132 under the wind speeds measured in 2021.

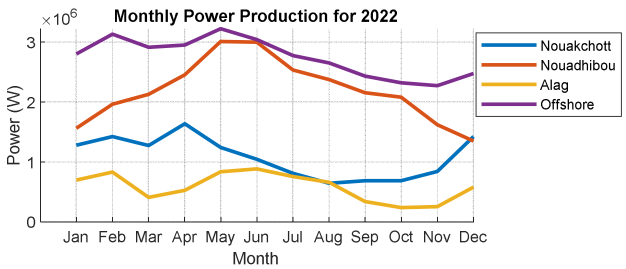

Fig. 14. Performance of Siemens Gamesa SG-132 under the wind speeds measured in 2022.

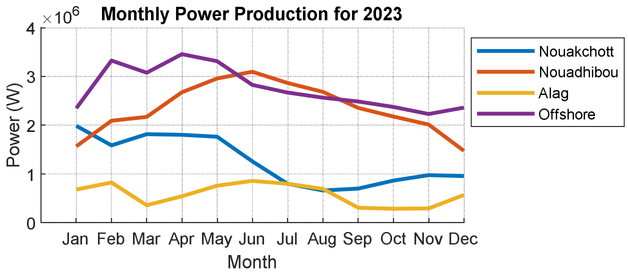

Fig. 15. Performance of Siemens Gamesa SG-132 under the wind speeds measured in 2023.

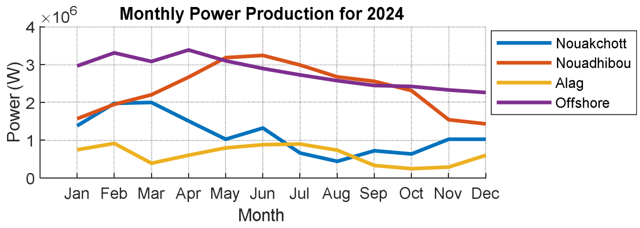

Fig. 16. Performance of Siemens Gamesa SG-132 under the wind speeds measured in 2024.

V. RESULTS AND DISCUSSION

Depending on the wind speeds in each region, the choice of turbine is based on the turbine's ability to generate energy in the specific wind speed ranges. To assess which model would be the most suitable, simulation data of turbines with wind speeds in the four selected regions over four years is needed [25]. In the Nouakchott location, the wind speed is between 7.02 m/s and 9.5 m/s, with an average of 7.5 m/s. These average winds suggest that turbines such as XEMC Ltd XE93 or Ecotecnia ECO80 would be the best choice for the region, as they are rated for these conditions. At the Nouadhibou location, wind speeds ranged from 8.5 m/s to 11.08 m/s, with an average of 9.39 m/s. These conditions fit all the turbines studied, but the Siemens Gamesa SG132 was efficient at wind speeds of 12 m/s while using more hot air to generate more power. In the Alag location, the wind speed varies between 4.98 and 7.19 m/s, which indicates low wind speed. Turbines with a low starting speed, such as XEMC Ltd XE93 or Ecotecnia ECO80, may be suitable for this region. Finally, in the Atlantic Ocean zone (offshore), in a location 5 km from the coast, the wind speeds are higher and vary between 8.12 and 11.45 m/s. This turbine has more power, can produce more, and performs well in the continuous winds of the coastline.

For areas such as Nouadhibou and offshore, more powerful turbines such as the Siemens Gamesa SG132 are recommended, while for areas with colder winds, such as Nouakchott and Alag, a 2 MW turbine would be more suitable.

A. Economic Study for the Construction of a Wind Farm

Calculating the energy (kWh) production cost of a turbine in US dollars involves using a mathematical model that considers some costs and characteristics [26]. This model is important in estimating electricity production costs to measure revenue.

B. Initial Investment Cost (CAPEX - Capital Expenditure)

This includes the cost of purchasing and installing the turbines, as well as the cost of necessary components such as foundations, cabling, transformers, and power lines. If the system is connected to the grid, there are additional costs to establish this connection. All capital expenditures are the result of all initial costs.

C. Operating and Maintenance Costs (OPEX - Operational Expenditure)

These include the costs of labor, spare parts, and maintenance services required to ensure proper turbine operation. They also include insurance costs for turbines and other infrastructure, as well as costs related to project management, taxes, and staff salaries [27, 28]. These costs are recurring and must be considered over the entire life of the turbine.

D. Turbine Lifetime

The useful life of a turbine is estimated to be 30 years, although this can vary depending on the specific installation and maintenance [29]. During this time, the turbine will produce electricity and generate revenue.

E. Energy Production (kWh)

The energy produced by a turbine per year is expressed in kWh. This calculation depends on various factors, such as wind speed, water flow, and turbine efficiency [30, 31]. Total production over the life of a turbine is usually estimated based on annual production and years of operation.

F. Cost of Production per KWh

The generation cost per kWh is calculated by considering the capital expenditures (CAPEX) and operating expenditures (OPEX) over the entire life of the wind turbine. The general formula for calculating the generation cost per kWh can be expressed as follows:

$$C_{Kwh} = \frac{CAPEX + (OPEX \times T)}{E_{total}} \quad (3)$$

where C_{Kwh} is the production cost per kWh in dollars, $CAPEX$ is the total initial investment cost, $OPEX$ is the total annual operating cost, T is the lifetime of the turbine in years, and E_{total} is the total amount of energy produced over the turbine's lifetime (in kWh) [32]. The proposed turbine lifetime is 30 years. Total production over 25 years (E_{total}) is given by the estimated annual production kWh/year × 30 years. Tables II to V demonstrate the associated costs and the cost of energy.

TABLE IV. ENERGY COSTS AT THE SITE OF NOUADHIBOU

Turbine	**Ecotecnia ECO80**	**XEMC Ltd XE93**	**Siemens Gamesa SG132**
Initial investment cost (CAPEX)	$2.5 million	$2.6 million	$3.8 million
Annual operating cost (OPEX)	$50,000	$50,000	$65,000
Estimated annual production (Kwh)	11318400	11793600	20304000
Total production over 25 years (E_{total}) in Kwh	282960000	294840000	507600000
Price per kWh (C_{Kwh})	$0.0132	$0.0130	$0.0106

TABLE V. ENERGY COSTS AT THE OFFSHORE SITE

Turbine	**Ecotecnia ECO80**	**XEMC Ltd XE93**	**Siemens Gamesa SG132**
Initial investment cost (CAPEX)	$2.6 million	$2.7 million	$3.9 millions
Annual operating cost (OPEX)	$50,000	$50,000	$65,000
Estimated annual production (kWh)	12700800	13392000	23760000
Total production over 25 years (E_{total}) in kWh	317520000	334800000	594000000
Price per kWh (C_{Kwh})	$0.0124	$0.0118	$0.009

TABLE VI. THE ENERGY COSTS IN THE SITE OF NOUAKCHOTT

Turbine	**Ecotecnia ECO80**	**XEMC Ltd XE93**	**Siemens Gamesa SG132**
Initial investment cost (CAPEX)	$2.5 million	$2.6 million	$3.8 million
Annual operating cost (OPEX)	$50,000	$50,000	$65,000
Estimated annual production (kWh)	8199150	8765210	18144000
Total production over 25 years (E_{total}) in kWh	204978750	219130250	453600000
Price per kWh (C_{Kwh})	$0.0183	$0.0175	$0.0120

TABLE VII. ENERGY COSTS AT THE SITE OF ALAG

Turbine	**Ecotecnia ECO80**	**XEMC Ltd XE93**	**Siemens Gamesa SG132**
Initial investment cost (CAPEX)	$2.5 million	$2.6 million	$3.8 million
Annual operating cost (OPEX)	$50,000	$50,000	$65,000
Estimated annual production (kWh)	2764800	3041280	6393600
Total production over 25 years (E_{total}) in kWh	69120000	76032000	159840000
Price per kwh (C_{Kwh})	$0,0542	$0,0506	$0,0340

These data indicate a clear correlation between higher wind speeds and increased energy production in kWh in certain areas. These areas, where the winds are stronger, are characterized by a relatively low energy production cost. The data show that during months when the average wind speed is higher, energy prices are lower, indicating that an increase in wind speed leads to a decrease in energy costs, which is particularly advantageous for the wind energy sector [33].

The results also reveal that coastal areas, such as those of Nouadhibou and the maritime zone around Nouakchott, are particularly well-suited for the establishment of wind farms in Mauritania. These regions benefit from favorable conditions for the development of large-scale wind energy projects [34]. The investment would represent an important strategic step to improve Mauritania's energy self-sufficiency. Additionally, these projects could pave the way for opportunities to export wind energy to neighboring countries, contributing to diversifying the country's revenue sources. Although the initial cost of setting up these projects may be high, the investment proves to be profitable in the long term. Profits generated by the sale of electricity produced by these wind farms can finance the creation of new production sites, thus strengthening the country's energy self-sufficiency and market stability. For example, in the areas of Nouadhibou and the maritime region around Nouakchott, the average price of kWh is $0.009, while in Nouakchott, this price rises to $0.0106. It is also important to note that Siemens Gamesa SG-132, Ecotecnia ECO80, and XEMC Ltd XE93 turbines have shown remarkable performance in areas with high wind speeds and produce a significant amount of kWh at a very competitive production price, helping to reduce energy costs. Among them, the Siemens Gamesa SG132, although efficient, has a lower unit price per kWh [35, 36]. However, since the Alag region records the lowest wind energy production among the four regions analyzed, it has a higher cost per kWh ($0.0542). In conclusion, the establishment of wind farms is suggested in the Nouadhibou and offshore regions, and the future of the wind energy sector in Mauritania looks very promising.

VI. CONCLUSION

This study provides new contributions to the research on wind energy in Mauritania through a comparative analysis of several turbine models to address the gaps in local wind evaluations. In contrast to previous studies, which often focused on singular arm models and broad estimation, this study provides a detailed assessment of both the potential for land and offshore wind energy, providing insight into optimal turbine selection for various locations. Additionally, the economic feasibility analysis provides a comprehensive cost assessment for investors and decision-makers. Due to the distinction between offshore financial impacts compared to offshore facilities, this study serves as a valuable reference for future wind energy projects in the region. This approach not only confirms these results but also highlights the unique properties of Mauritania's wind energy potential. By bridging these knowledge gaps, this study can be the basis for well-discovered decisions in the field of national renewable energy, paving the way for further research related to network integration, political frameworks, and socioeconomic effects of wind energy acceptance.

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