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► **To cite this version:**

Varha Maaloum, El Moustapha Bououbeid, Mohamed Mahmoud Ali, Kaan Yetilmez, Shafiqur Rehman, et al.. Techno-Economic Analysis of Combined Production of Wind Energy and Green Hydrogen on the Northern Coast of Mauritania. Sustainability, 2024, 10.3390/su16188063 . hal-04699206

HAL Id: hal-04699206

<https://univ-smb.hal.science/hal-04699206v1>





Submitted on 16 Sep 2024

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Article

Techno-Economic Analysis of Combined Production of Wind Energy and Green Hydrogen on the Northern Coast of Mauritania

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Abstract: Green hydrogen is becoming increasingly popular, with academics, institutions, and governments concentrating on its development, efficiency improvement, and cost reduction. The objective of the Ministry of Petroleum, Mines, and Energy is to achieve a 35% proportion of renewable energy in the overall energy composition by the year 2030, followed by a 50% commitment by 2050. This goal will be achieved through the implementation of feed-in tariffs and the integration of independent power generators. The present study focused on the economic feasibility of green hydrogen and its production process utilizing renewable energy resources on the northern coast of Mauritania. The current investigation also explored the wind potential along the northern coast of Mauritania, spanning over 600 km between Nouakchott and Nouadhibou. Wind data from masts, Lidar stations, and satellites at 10 and 80 m heights from 2022 to 2023 were used to assess wind characteristics and evaluate five turbine types for local conditions. A comprehensive techno-economic analysis was carried out at five specific sites, encompassing the measures of levelized cost of electricity (LCOE) and levelized cost of green hydrogen (LCOGH), as well as sensitivity analysis and economic performance indicators. The results showed an annual average wind speed of 7.6 m/s in Nouakchott to 9.8 m/s in Nouadhibou at 80 m. The GOLDWIND 3.0 MW model showed the highest capacity factor of 50.81% due to its low cut-in speed of 2.5 m/s and its rated wind speed of 10.5 to 11 m/s. The NORDEX 4 MW model forecasted an annual production of 21.97 GWh in Nouadhibou and 19.23 GWh in Boulanoir, with the LCOE ranging from USD 5.69 to 6.51 cents/kWh, below the local electricity tariff, and an LCOGH of USD 1.85 to 2.11 US/kg H₂. Multiple economic indicators confirmed the feasibility of wind energy and green hydrogen projects in assessed sites. These results boosted the confidence of the techno-economic model, highlighting the resilience of future investments in these sustainable energy infrastructures. Mauritania's north coast has potential for wind energy, aiding green hydrogen production for energy goals.

Keywords: green hydrogen; levelized cost of electricity; Mauritania; techno-economic feasibility; Weibull distribution; wind energy



Citation: Maaloum, V.; Bououbeid, E.M.; Ali, M.M.; Yetilmezsoy, K.; Rehman, S.; Ménézo, C.; Mahmoud, A.K.; Makoui, S.; Samb, M.L.; Yahya, A.M. Techno-Economic Analysis of Combined Production of Wind Energy and Green Hydrogen on the Northern Coast of Mauritania. *Sustainability* **2024**, *16*, 8063. <https://doi.org/10.3390/su16188063>

Academic Editor: Fernando Lessa Tofoli

Received: 7 August 2024

Revised: 28 August 2024

Accepted: 28 August 2024

Published: 14 September 2024



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1. Introduction

Mauritania possesses outstanding wind and solar energy resources, which are advantageous for the country [1]. If utilized properly for generating clean and affordable electricity, there could be significant production of large-scale green hydrogen and ammonia [2]. These resources could drive significant momentum and help in establishing new industries in the country. Mauritania benefits from exceptional wind resources due to its unique geographical position and favorable climatic conditions. Located to the west of the Sahara, Mauritania is exposed to powerful and regular trade winds blowing from the northeast. In terms of comparison, Mauritania's wind resources surpass those of many West African countries, where wind speeds are generally lower due to different climatic and topographical conditions. For example, in neighboring Senegal, average wind speeds are often below 5 m/s, which limits large-scale wind energy production [3]. Compared to Europe, Mauritania's wind resources rival those of countries like Spain, where coastal regions benefit from similar strong winds due to their proximity to the Atlantic Ocean [4]. Alongside its abundant renewable energy resources, Mauritania's strategic geographic location, adjacent to major global shipping routes, offers easy access to green hydrogen markets. Mauritania possesses promising wind potential because of advantageous wind conditions in specific regions of the country [5]. In particular, the Atlantic coastal region enjoys strong and consistent winds, while the arid region located in the northern part presents opportunities for the expansion of wind farms on a large scale (Figure 1). The government is currently developing a countrywide energy strategy to expand wind energy and diversify electricity production. Wind projects have already been implemented in the country, which include a wind farm with a capacity of 30 MW in Nouakchott, operational since 2014, and a 100 MW wind farm in Boulanoir, planned for 2024. These efforts are designed to offer renewable energy, decrease reliance on non-renewable resources, and support a sustainable energy infrastructure [6].

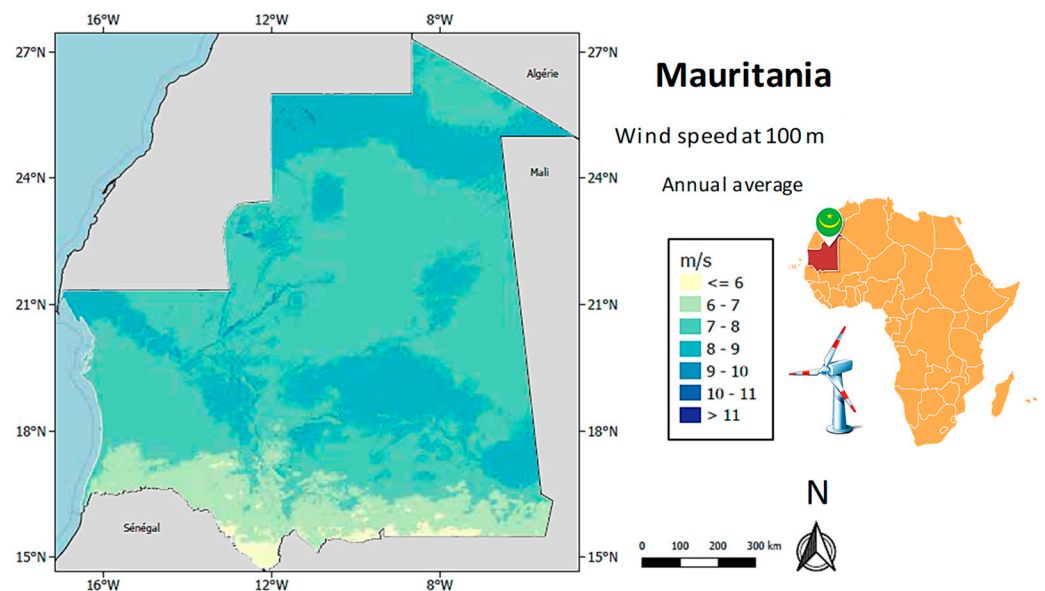


Figure 1. Map of the average annual wind speed pattern in Mauritania.

Despite the high development costs of wind power in Mauritania due to the lack of necessary infrastructure related to installation, engineering, environmental, social, and evaluation costs, the country continues to exploit its wind potential. Wind energy offers portfolio diversification, greenhouse gas (GHG) emission reduction, local job creation, and enhanced energy security [7]. Additionally, it can aid rural electrification, improving living conditions for local communities. In this context, Mauritania has signed several agreements with international companies pioneering green hydrogen projects, such as CWP Global for the AMAN project and Chariot for the NOUR project [8]. CWP Global's

AMAN project aims to establish the country's first hydrogen plant, combining 30 GW of hybrid energy (18 GW of wind and 12 GW of solar photovoltaic power) to generate 10 million tons of green hydrogen and ammonia on a yearly basis. In the same way, the NOUR project aims to create 16 GW of wind and solar energy capacity in order to produce a maximum of 700 kilotons of green hydrogen using seawater electrolysis. Subsequently, the generated hydrogen will be converted into about 4 million tons of green ammonia for export. These projects contribute to Mauritania's transition towards a greener and more eco-friendly economy. The production of hydrogen from green sources involves utilizing renewable energy for the operation of the electrolyzer system rather than relying on fossil fuel energy [9,10]. Green hydrogen can serve as a clean fuel and raw material for residential, commercial, industrial, and transportation sectors [11].

To date, many investigations have been carried out to evaluate the possibility of wind power and characterize wind speed at various sites across the country, as reported in the literature [12–15]. These research projects have demonstrated the significance of evaluating wind energy potential before wind farms are actually built. Internationally, in the Republic of Djibouti, multiple studies have evaluated wind resources and analyzed the feasibility of producing wind energy and green hydrogen from a technological and economic perspective [16,17].

Thiaw et al. [18] suggested using a neural network model to evaluate wind energy potential and predict wind generator production at the Dakar location. A multilayer perceptron neural network was discovered with two hidden layers and one input having three neurons each and one output, effectively modeling the wind speed distribution pattern in the area. The wind speed distribution law's Weibull parameters were also established with a scale factor of 4.9 m/s and a shape factor of 2.19. Didane et al. [19] assessed the wind speed distribution and wind power density on a monthly and yearly basis at thirteen meteorological stations in Chad. The researchers utilized the Weibull distribution function with two parameters to examine the data from each site over a five-year timeframe. Examination of the seasonal changes indicated that increased wind speeds are present during dry weather conditions and significantly decrease during wet weather conditions. Wang et al. [20] conducted a review centered on examining technologies for producing hydrogen using water and biomass. They evaluated different methods of hydrogen production, taking into account the technological, environmental, and economic factors based on these materials, thus providing a comprehensive comparison. The study showed that all methods of producing hydrogen using renewable energy are more eco-friendly compared to methods that rely on fossil fuels. Nevertheless, the study emphasized the need for improvements in the ease of use and cost-efficiency of producing hydrogen from renewable energy sources to facilitate widespread adoption. In their study, d'Amore-Domenech et al. [21] sought to determine the most viable electrolysis technology for short-term application through a comparison based on multiple criteria focusing on environmental, social, and economic aspects. The study found that proton exchange membrane electrolysis at sea showed the most potential for short-term application. In a case study conducted in Morocco, Khouya [22] assessed the levelized costs of energy and hydrogen for wind farms and concentrated photovoltaic thermal systems. The research was conducted using meteorological data from the Tangier area in Morocco. Mathematical models were created to evaluate how well renewable sources generate energy and hydrogen at varying levels of installed power. The findings indicated that the electrolyzer consumed 61 kWh/kg of wind energy and 64 kWh/kg of solar energy. Rezaei et al. [23] analyzed the potential economic outcomes of producing hydrogen and electricity with wind power in different ways. The research found that the cost of wind-derived electricity in various situations would range from USD 32.5 to 75.5/MWh, while the cost of wind-produced hydrogen would vary from USD 1.375 to 1.59/kg. In Pakistan, Shah [24] researched the viability of six different renewable energy sources for producing hydrogen. The findings showed that wind is the most effective technique for generating hydrogen within the country, and

the creation of green hydrogen could be vital in addressing Pakistan's energy crisis and enhancing its upcoming energy safety.

After the 2000s, Almutairi et al. [25] conducted a review study on the economic feasibility of utilizing wind power to produce green hydrogen. The results showed that the cost of producing hydrogen varied between USD 3.88 and 10.82/kg based on the specific wind turbines and electrolyzers used. Motazed et al. [26] examined the generation of hydrogen through high-temperature steam electrolysis by combining process modeling and life cycle assessment to analyze GHG emissions and the cost of hydrogen production. They provided guidance for developers aiming to enhance the proposed system and for policymakers when considering backing hydrogen production technology development. Rezaei et al. [27] conducted a study to explore the economic potential of generating electricity and hydrogen from wind power in various situations. In that particular study, the city of Lutak (known for its abundant wind resources in Iran) was analyzed using mathematical project-assessment methods due to its high wind levels. The findings showed that the price of wind-produced electricity would fall within the range of USD 0.0325–0.0755/kWh, whereas wind-based hydrogen would cost between USD 1.375 and 1.59/kg. In another study, Al-Ghussain et al. [28] examined the potential of using this surplus to produce eco-friendly hydrogen gas. The findings indicated that the solar photovoltaic system had a demand–supply fraction greater than 99%. Nonetheless, the wind-powered system proved to be more cost-effective, with installed renewable energy systems, energy storage systems, and polymer electrolyte membrane capacities at just 23.88 GW, 2542 GWh, and 20.66 GW. In addition, the research revealed that the price of hydrogen is not higher than USD 2.03/kg, which is much less than the projected cost of hydrogen (USD 3/kg) generated using fossil fuel energy systems in 2050. Ahshan et al. [29] carried out research on the financial feasibility of generating hydrogen from wind power in the Sultanate of Oman at 18 sites across the country. They estimated that the LCOE was between USD 0.0349 and 0.0701/kWh without degradation and between USD 0.0398 and 0.0801/kWh with degradation. Osman Awaleh et al. [30] investigated the economic viability of producing green hydrogen through water electrolysis with wind and geothermal energy sources in the Asal-Ghoubbet Rift (AG Rift), Republic of Djibouti. The wind turbine's electricity production cost (USD 0.042/kWh) was said to be more competitive than the dry steam geothermal plant's (USD 0.086/kWh). The findings indicated that generating hydrogen cost between USD 0.672 and 1.063/kg H₂ with a wind-powered electrolyzer and between USD 3.31 and 4.78/kg H₂ with a geothermal-fueled high-temperature electrolyzer.

Upon examining studies conducted in recent years, AlZohbi et al. [31] centered their study on calculating green hydrogen production through electrolysis using wind power at four different sites in Saudi Arabia. They reported that the annual hydrogen production from wind turbines varies from 254,287.7 kg in Rafha to 367,692.5 kg in Dhahran. Findings indicated that the cost of producing hydrogen through wind energy varied between USD 2.82 and 3.81/kg. Ourya [32] evaluated the green hydrogen production in Morocco utilizing a wind and solar photovoltaic hybrid power system. The findings showed that this combination could generate hydrogen at a lower price, particularly in Dakhla, at a levelized cost of hydrogen of USD 2.54/kg. García-Miguel et al. [33] concentrated on the functioning of a hybrid farm combining a wind turbine with both an alkaline electrolyzer and a battery-storage system. The mixed farm functioned in both hydrogen and electricity markets traded one day in advance. The findings showed that when hydrogen prices are low, it could be important to carefully consider the plant configuration to maximize revenue. Furthermore, they concluded that the negative impact of alkaline electrolyzer involvement in the electricity market was evident when hydrogen prices were low. In Croatia, Dumančić et al. [34] introduced a fresh economic viability framework for a facility for converting power into gas that generates green hydrogen at a current wind power plant site and injects it into the gas network. The model uses a 42 MW wind farm, with an optimal 10 MW electrolyzer calculated using 2500 full load hours annually and electricity price projections. They determined that implementing a premium subsidy model was essential to speed up

the installation of electrolyzers in the vicinity of a current wind power facility to enhance the wind farm's profit potential. In the UK, Giampieri et al. [35] conducted an analysis of the technological and economic aspects of different ways to create hydrogen (offshore and onshore) with offshore wind, utilizing hydrogen carriers and considering current and projected costs of production, storage, and transportation technologies. According to their findings, compressed hydrogen generated at sea was found to be the most financially efficient option for projects beginning in 2025 out of all scenarios analyzed. However, they reported that the financial feasibility of this choice was significantly affected by the storage duration and the offshore wind farm's distance from the shore. Nasser et al. [36] developed an atlas from Egypt for producing green hydrogen through water electrolysis using wind and solar energy resources. This study created energy density (kWh/m²), density of hydrogen (kg/m²), cost of generating hydrogen (USD/kg), and CO₂ emission reduction (kgCO₂/m²) maps for the country. Messaoudi et al. [37] utilized Geographic Information Systems (GIS) to analyze wind potential for the generation of green hydrogen in Algeria. Their results indicated a significant potential of producing 1.093 Gt/year of green hydrogen unconstrained and 1.066 Gt/year taking into account the limitations. The average cost of hydrogen production from wind energy in Algeria ranges from USD 1.51 to 15.37/kg based on the availability of wind energy resources and the type of wind turbines selected. Xia et al. [38] suggested a capacity-planning method for a multi-energy system focusing on industrial electricity and hydrogen to promote the use of sustainable energy sources within the region and support the shift towards reducing carbon emissions in industrial environments. The findings showed that the suggested approach successfully tackled the capacity setup of devices in a multi-energy system incorporating electricity and hydrogen while focusing on incorporating renewable energy sources and varying unit cost orders. They stated that wind power was the main provider of eco-friendly electricity in the system. Finally, a separate study conducted by Yang et al. [39] involved designing and economically and technically analyzing six potential situations for on-grid and off-grid systems for producing hydrogen from renewable energy sources, with the selection of the most optimal systems for both options. According to the simulation findings, the hydrogen production system connected to the grid saw a decrease of 3347 kWh in grid-supplied power, while the rate of surplus power generated by the system not connected to the grid dropped from 38.6 to 10.3%, leading to a notable enhancement in the system's performance in both technical and economic aspects.

After reviewing the relevant literature, it was found that none of the previous research had considered the environmental cost when projecting the levelized cost of electricity (LCOE) and the levelized cost of green hydrogen (LCOGH) from wind energy. Given the crucial importance of this cost, the present study proposed an LCOE model that incorporates an environmental cost component. Furthermore, the current analysis included a critical factor, inflation rate, in the classic LCOE model to achieve more accurate results. Additionally, no comprehensive economic evaluation has yet been conducted on wind energy for hydrogen production in Mauritania, a representative country of developing nations. Therefore, this comprehensive investigation aimed to eliminate the existing literature gap mentioned above and shed light on similar analyses in the future.

The current research investigated the economic viability of wind-hydrogen production to advance studies on green hydrogen production and support the Paris Agreement's goal of promoting sustainable development both locally and globally. For this purpose, it was focused on optimizing green hydrogen production costs in the Islamic Republic of Mauritania by understanding the wind sources' availability at multiple sites to map favorable locations for its production. The methodology included selecting suitable areas with favorable potential for wind and solar energy, including near the sea for the electrolysis of water, and using measured data from various measurement masts installed by the Ministry of Energy and Mines. Finally, the study aimed at conducting an analysis of sensitivity to evaluate the influence of various parameters on the system before evaluating additional costs.

2. Materials and Methods

2.1. Site Description and Data Collection

The data presented in this document originate from various coastal sites spanning from Nouakchott to Nouadhibou. A measurement mast was located 28 km south of Nouakchott. The location coordinates and wind speed (WS) measurement heights of this and other masts are presented in Table 1 and the map (Figure 2). The physical site photos of the masts are provided in Figure 3a–d. At Nouamghar, the study employed satellite analysis, one of the most advanced technologies currently available for wind prospecting. Data collection and analysis were conducted by our partner 3Tier, who are recognized in the field of satellite assessment, based on a combination of computer simulations and meteorological observations.

Table 1. Identification of measurement masts.

Site No	Location	Station	Height (AGL) WS Sensors	GPS Position
1	Nouakchott	Measurement Mast	10, 30, and 80 m	17°58'02.80" N 15°58'52.10" W
2	Nouamghar	3Tier Satellites	80 m	19°33'44.49" N 15°55'27.57" W
3	Tasiast	ZX300 Lidar	80 m	20°31'36.85" N 15°59'29.44" W
4	Boulanoir	Measurement Mast	20, 40, and 80 m	21°16'29.07" N 16°47'08.98" W
5	Nouadhibou	Measurement Mast	30, 40, and 80 m	20°53'59.70" N 17°03'36.10" W

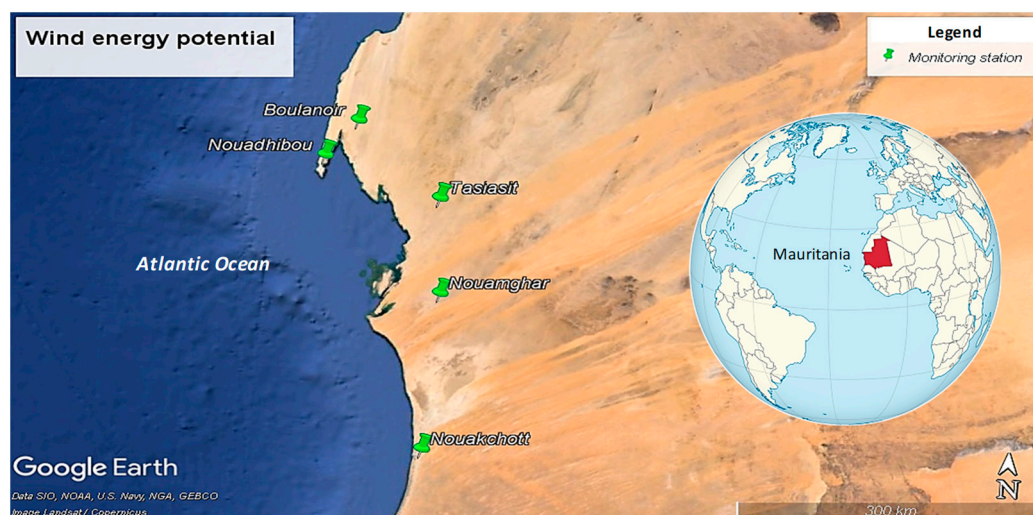


Figure 2. Locations of meteorological measurement masts in Mauritania.

At Tasiast, vertical wind profile data were collected using a ZX300 Lidar measurement station. This device was installed in a container powered by solar panels with battery storage, offering advantages (portability, WS measurements up to 10 heights, etc.) despite its higher initial cost compared to traditional meteorological towers. At Boulanoir, a measurement mast was installed in 2021 for the 100 MW wind farm project. This mast was equipped with sensors to measure the speed and direction of the wind, the temperature, humidity levels, and air pressure. The data were scanned every second and recorded as an average every 10 min. Other masts at Boulanoir and Nouadhibou had a thermometer and an NRG #40C MEASNET-calibrated anemometer with an NRG #200P wind vane, along with boots.

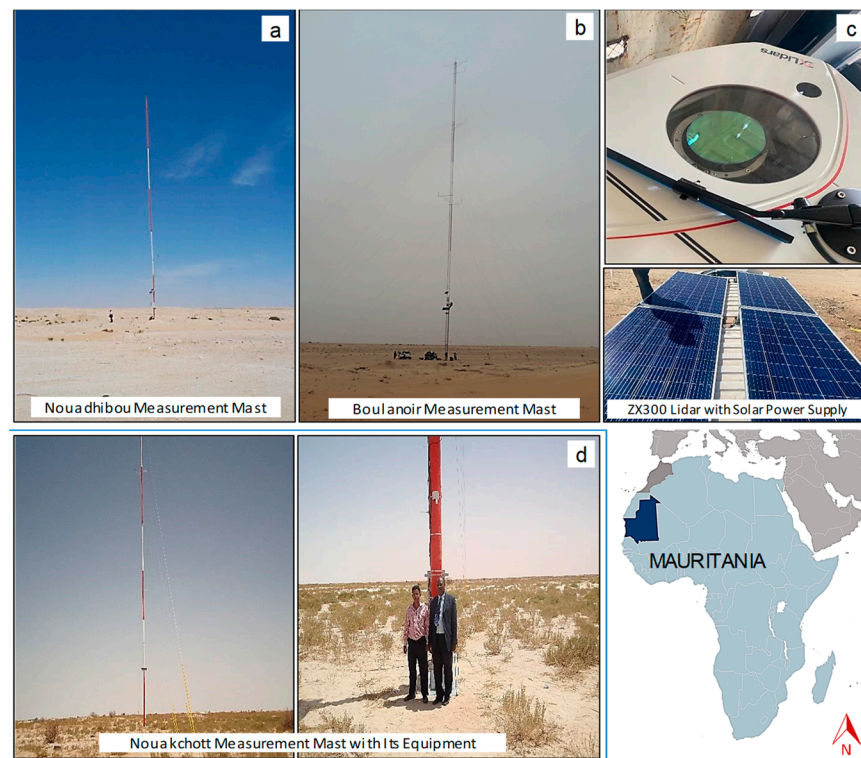


Figure 3. Physical site photos of meteorological measurement masts in Mauritania. (a): Nouadhibou Measurement Mast; (b): Boulanoir Measurement Mast; (c): ZX300 Lidar with Solar Power Supply; (d): Nouakchott Measurement Mast with Its Equipment.

2.2. Weibull Distribution of Actual Wind Speed Data

Over the last few decades, wind power has become more popular due to its eco-friendly characteristics and widespread accessibility. Nevertheless, before setting up the wind turbine, it is vital to have a proper understanding of the parameters related to wind distribution for harnessing wind energy [40]. An essential step in wind farm implementation at a specific site involves conducting an appropriate analysis of wind statistics [5]. Within this framework, the Weibull distribution (named after Swedish mathematician Ernst Hjalmar Waloddi Weibull, who lived from 1887 to 1979) is a continuous probability distribution employed for analyzing life data, representing failure times, and evaluating product dependability. It represents a high likelihood in a probability distribution commonly applied in modeling reliability, survival rates, wind speeds, and other data. It is noted that the Weibull distribution is known for being well-suited to modeling phenomena where the failure or survival rate evolves over time. It is frequently used to analyze product lifetimes, as it can represent a wide range of behaviors, from early failures to an aging phase. In the context of the present study on wind energy, the Weibull distribution is also very well-suited to modeling wind speed distributions. Its flexibility allows for accurate descriptions of wind speed variability, which is crucial for assessing the energy potential of wind sites. In particular, the two parameters of the Weibull distribution (the shape parameter and the scale parameter) offer an adjustment capability that is often superior to that of other distributions, making it a preferred choice for this type of analysis. Therefore, the Weibull distribution was selected for its ability to effectively model data dynamics in certain contexts, such as product lifetime analysis and wind speed modeling.

The two-parameter Weibull probability density function (PDF) is mathematically defined as [5,12,41]

$$f(V; c, k) = \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} \exp \left[- \left(\frac{V}{c} \right)^k \right], \quad V \geq 0; k, c > 0 \quad (1)$$

The Weibull PDF provides the probability of wind speed being V (m/s). The scale parameter c , expressed in m/s, is related to the mean WS through the shape parameter k . Lower values of k indicate wind that is more variable (gusty), while higher values of c indicate greater potential [12]. So far, various methods have been proposed for modeling wind distribution through the Weibull distribution parameters [12,42,43]. In this study, the Weibull parameters were determined using the method of standard deviation of the mean wind speed [44]. The graphical approach was used by converting the two-parameter Weibull cumulative distribution function (CDF) $(F(V; c, k) = 1 - \exp[-(V/c)^k], V \geq 0)$ into its equivalent line. This was performed through a double logarithmic operation on Equation (2) and then rearranging the results [45,46] to obtain Equation (3).

$$\ln\{-\ln[1 - F(V)]\} = k \ln V - k \ln c \quad (2)$$

This technique involves organizing wind speed data into a model of cumulative frequency distribution and plotting the converted data into line graphs. The straight line is defined in the following manner [47]:

$$y = ax + b \quad (3)$$

The regression method is used to determine the values of the shape (k) and scale (c) parameters, as given below.

$$k = a \quad (4)$$

$$b = -k \ln c = -a \ln c \rightarrow c = \exp(-b/a) \quad (5)$$

The wind shear coefficient or power law exponent (α) is a dimensionless parameter that describes the change in horizontal wind speed with altitude. The wind speeds at various elevations are often modeled by a power law, as follows [12,48]:

$$V_2 = V_1 \left(\frac{H_2}{H_1} \right)^\alpha \quad (6)$$

where V_2 and V_1 are the WS values at heights H_2 and H_1 , respectively.

Wind power density (WPD) is a helpful method for approximating the available power density at a specific elevation. It represents the power available for transformation by wind turbines through the rotor-swept area (S_a). The power of the wind hitting the turbine (P_w) can be estimated for a certain swept area and air density (ρ) at a specific location as follows [12,49]:

$$P_w = \frac{1}{2} \rho S_a V^3 \quad (7)$$

The annual energy yield (E_{out}) can be approximated using the capacity factor (C_F), the annual sum of hours (1 year = 8760 h assuming a non-leap year), and the rated power P_R of the wind turbine (kW), as expressed in Equation (8) [5]:

$$E_{out} = 8760 P_R C_F \quad (8)$$

The capacity factor (C_F) is a unitless number ranging from 0 to 1 that shows the relationship between the rated power and the effective actual generated/delivered power. This is calculated as a function of the capacity factor (C_F), average wind speed (\bar{V}), and rotor diameter (D) from the following Equation (9) [3]:

$$C_F = 0.087 \bar{V} - \frac{P_R}{D^2} \quad (9)$$

2.3. Green Hydrogen Production from Wind Energy

In the context of this study, an alkaline electrolyzer (McPhy Energy, Grenoble, France) was used. It was characterized by energy consumption ($E_{electrolyzer}$) of 42 kWh/kg H₂

and a converter with efficiency ($\eta_{converter}$) of 95% [16,50]. The quantity of hydrogen (M_{H_2}) produced by wind energy (E_{out}) can be calculated by utilizing the formula given below [51]:

$$M_{H_2} = \frac{E_{out}}{E_{electrolyzer}} \eta_{converter} \quad (10)$$

To assess and evaluate the feasibility of electricity production from the technology related to wind, the LCOE is used as the primary indicator of the economy. The LCOE represents the total cost of investment required to produce one electrical power unit over a given period. Thus, in the context of wind energy, the subsequent mathematical expression is utilized for assessing the LCOE [16]:

$$LCOE = \frac{PVC}{E_{out}} = \frac{C_I \left(1 + C_{O\&M} \frac{(1+I_d)^t - 1}{I_d(1+I_d)^t} \right)}{8760 P_R t C_f} \quad (11)$$

where t represents the expected lifespan of the commercial wind turbine (year); I_d is the real interest rate (%), taken from the Central Bank of the Islamic Republic of Mauritania as 10.87% and 10.90% (for 2022 and 2023, respectively); and C_I is the initial (capital) cost of investment determined based on the average specific cost (C_{Aspec}) per kW of the turbine's rated power [16].

$$C_I = P_R C_{Aspec} (1 + \text{Variable capital cost as a fraction}) \quad (12)$$

In the present analysis, the average specific cost of the wind turbines was considered as USD 1600/kW. It was presumed that the yearly operation and maintenance expenses ($C_{O\&M}$) would account for 25% of the overall investment [52,53]. In total, 30% of the total cost of the wind turbines was allocated to variable capital expenses [43,54].

2.4. Cost of Green Hydrogen Production

The levelized cost of hydrogen (USD/kg) can be calculated using the subsequent mathematical formulae [23,55]:

$$LCOGH = \frac{C_{electrolyzer} + C_{electricity}}{M_{H_2} T} \quad (13)$$

$$C_{electrolyzer} = C_{u,electrolyzer} \frac{M_{H_2} E_{electrolyzer}}{8760 C_f \eta_{electrolyser}} \quad (14)$$

$$C_{electricity} = LCOE \frac{\sum_{i=1}^t E_{out}}{t} \quad (15)$$

The unit cost ($C_{u,electrolyzer}$) and efficiency of the electrolyzer ($\eta_{electrolyser}$) were assumed to be USD 1600/kW and 95%, respectively. It was assumed that the operation and maintenance cost (O&M) of the electrolyzer would be 25% of the total investment cost, and the electrolyzer's operation life (T) was set at 15 years. The CO₂ emission reduction, due to wind power production, can be calculated as follows [23]:

$$CO_2 \text{ emission reduction} = E_{out} \left(\frac{kWh}{year} \right) 0.277 \left(\frac{kCO_2}{kWh} \right) \quad (16)$$

2.5. Economic Risk Analysis

The net present value (NPV) is a financial indicator showing economic viability by calculating the difference between the present value of cash inflows and the outflows of a project discounted at the time of investment. With a positive NPV, the project shows promise

for investment as revenues surpass expenses given the discount rate. The calculation of the NPV can be performed using this mathematical formula [16,56,57]:

$$\text{NPV} = \text{NPV}(B_A)_{1-n} - [C_I + \text{NPV}(C_A)_{1-n}] \quad (17)$$

$$\text{NPV}(B_A)_{1-n} = B_A \frac{(1 + \text{DR})^n - 1}{\text{DR}(1 + \text{DR})^n} \quad (18)$$

$$\text{NPV}(C_A)_{1-n} = 1 + m \frac{(1 + \text{DR})^n - 1}{\text{DR}(1 + \text{DR})^n} \quad (19)$$

The investment option with the highest NPV should be chosen when comparing mutually exclusive projects [16,57].

$$B_A \frac{(1 + \text{IRR})^n - 1}{\text{IRR}(1 + \text{IRR})^n} - C_I \left[1 + m \frac{(1 + \text{IRR})^n - 1}{\text{IRR}(1 + \text{IRR})^n} \right] = 0 \quad (20)$$

The project with greater investment is likely to have a more attractive NPV compared to the one with lower capital needs. In such circumstances, the benefit–cost ratio (BCR) is a more effective tool for evaluating economic feasibility. BCR is the relationship between the total present value of benefits and the total present value of costs, which encompasses the initial investment, as well [16,57]. It is determined through the equation below.

$$\text{BCR} = \frac{\text{NPV}(B_A)_{1-n}}{C_I + \text{NPV}(C_A)_{1-n}} \quad (21)$$

The payback period (PBP) is a commonly utilized method for evaluating the viability of an investment project, indicating the time needed to recoup the initial investment. It is the period required for the project's cash inflows to match the initial investment outlay. A project is considered promising if the payback period is shorter than its projected lifespan when comparing annual revenues to the investment cost. The payback period is determined using the mathematical formula provided [16,57].

$$\text{PBP} = -\ln \left(1 - \frac{IC_I}{B_A - mC_I} \right) \quad (22)$$

Return on investment (ROI) is a commonly used tool to help with investment choices, offering a consistent way to evaluate the advantages of various investments. The return on investment is determined in the following manner [16,57]:

$$\text{ROI} = \frac{\text{PVB} - \text{PVC}}{\text{PVC}} \quad (23)$$

$$\text{PVC} = C_I + C_{O\&M} \frac{1+i}{r-i} \left[1 - \left(\frac{1+i}{1+r} \right)^n - S \left(\frac{1+i}{1-r} \right)^n \right] \quad (24)$$

$$\text{PVB} = B_A \frac{(1 + \text{DR})^n - 1}{\text{DR}(1 + \text{DR})^n} \quad (25)$$

$$\text{DR} = \frac{1+r}{1+i} - 1 \quad (26)$$

where *PVC* represents the present value cost and *PVB* is the present value of benefits. *DR* stands for the discount rate; *C_{O&M}* is the operating and maintenance cost, assumed to be 25% of the annual turbine cost; *i* is the interest rate; *r* is the inflation rate; and *S* is the salvage value, which was estimated to be 10% of the overall investment cost according to the Central Bank of Mauritania. Herein, *m* and *n* values are taken as 3.5% and 20 years, respectively.

3. Results and Discussion

3.1. Variation of Wind Speed and Wind Direction in Coastal Sites

The monthly evolution of the average WS is a crucial parameter for the planning, operation, and optimization of wind farms, and it contributes to maximizing the energy output. The monthly average WS values over the entire data-collection period (from 1 January 2022 to 31 December 2023) for the five sites at a height of 80 m above ground level (AGL), are summarized in Table 2. The annual average WS (last row in Table 2) increased gradually from Nouakchott (7.6 m/s) to Nouadhibou (9.8 m/s). In Nouakchott, the average wind speed ranged from 6.3 m/s in September to 9.3 m/s in May, with an average of 7.67 ± 0.99 m/s. Similarly, at Mamghar and Tasiast, the minimum WS values of 6.7 and 6.9 m/s were observed in the month of November, while maximum values of 9.1 and 8.8 m/s were observed in May. Generally, higher WS values were found during May/June, while lower values were found in the winter months.

Table 2. Description of WS and C_f values over the data-collection period at 80 m AGL.

Month	Nouakchott		Nouamghar		Tasiast		Boulanoir		Nouadhibou	
	V (m/s)	C_f (%)	V (m/s)	C_f (%)	V (m/s)	C_f (%)	V (m/s)	C_f (%)	V (m/s)	C_f (%)
January	7.8	47.1	8.0	50.6	8.2	49.8	8.4	50.9	8.5	53.5
February	8.0	48.6	8.0	49.5	8.0	50.1	8.3	51.8	8.8	54.0
March	8.6	51.6	8.3	53.5	8.2	50.2	8.8	52.7	9.7	55.6
April	9.2	54.4	8.7	55.3	8.4	52.5	9.4	54.3	10.9	56.2
May	9.3	54.4	9.1	54.7	8.8	55.7	10.2	55.5	11.9	57.5
June	8.0	48.4	8.5	55.2	8.6	54.1	10.4	56.8	12.1	57.4
July	7.2	48.1	7.6	53.8	8.0	55.6	9.6	54.8	10.8	54.1
August	6.8	41.9	7.1	46.8	7.5	50.0	9.2	51.3	10.4	52.3
September	6.3	36.6	6.9	44.8	7.3	48.8	9.1	51.7	10.1	51.0
October	7.0	45.5	7.3	49.1	7.4	50.2	8.4	54.5	9.6	47.3
November	6.6	38.1	6.7	40.8	6.9	44.3	7.4	42.8	7.9	46.4
December	7.2	48.0	7.3	49.7	7.4	52.1	7.5	45.7	7.6	43.9
Minimum	6.30	36.60	6.70	40.80	6.90	44.30	7.4	42.8	7.60	43.90
Mean	7.67	46.89	7.79	50.32	7.89	51.12	8.89	51.9	9.86	52.43
SD	0.99	5.66	0.76	4.53	0.59	3.17	0.95	4.06	1.46	4.46
Maximum	9.30	54.4	9.10	55.3	8.80	55.70	10.40	56.8	12.10	57.50

In order to evaluate the seasonal fluctuation of the wind speed at all locations, the data are arranged by month and depicted graphically in terms of monthly wind speeds (Figure 4). The peak monthly average wind speeds were noted from February to June at all locations: $V = 8.62 \pm 0.63$ m/s for Nouakchott, $V = 8.52 \pm 0.41$ m/s for Nouamghar, $V = 8.40 \pm 0.32$ m/s for Tasiast, $V = 9.42 \pm 0.90$ m/s for Boulanoir, and $V = 10.68 \pm 1.42$ m/s for Nouadhibou, as shown in Table 2. The slowest average wind speed was recorded in August, September, and October across all sites.

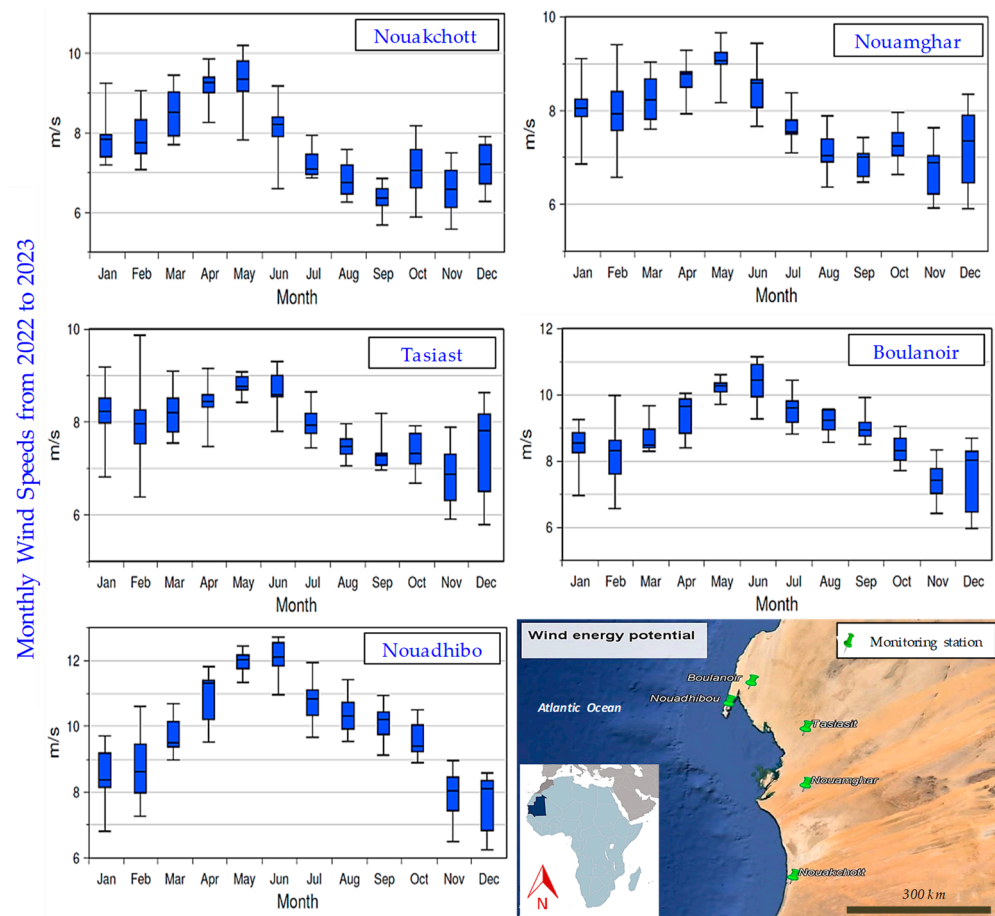


Figure 4. Variation in wind speed on a monthly basis for the five different locations (Nouakchott, Nouamghar, Tasiast, Boulanoir, and Nouadhibou) from 2022 to 2023.

In this study, wind rose diagrams (Figure 5) were utilized to show the dominant wind direction at each location. A wind rose indicates the frequency at which the wind blows from a given direction (north, east, south, west, etc.). Each directional segment represents a specific frequency, with spaces between concentric circles representing increments of 10% frequency. For instance, a segment pointing upwards (north, N) and spanning three circles means the wind blows from the north approximately 30% of the time. Directional segments are set at 22.5-degree intervals, as shown in Figure 5. At Nouakchott and Nouamghar, the wind blows mostly from the N, NNW, and NNE, while at Tasiast, Boulanoir, and Nouadhibou, it blows mostly from the NNE and NE. These wind rose charts, designed for a particular location, can assist in positioning wind turbines when they are being installed.

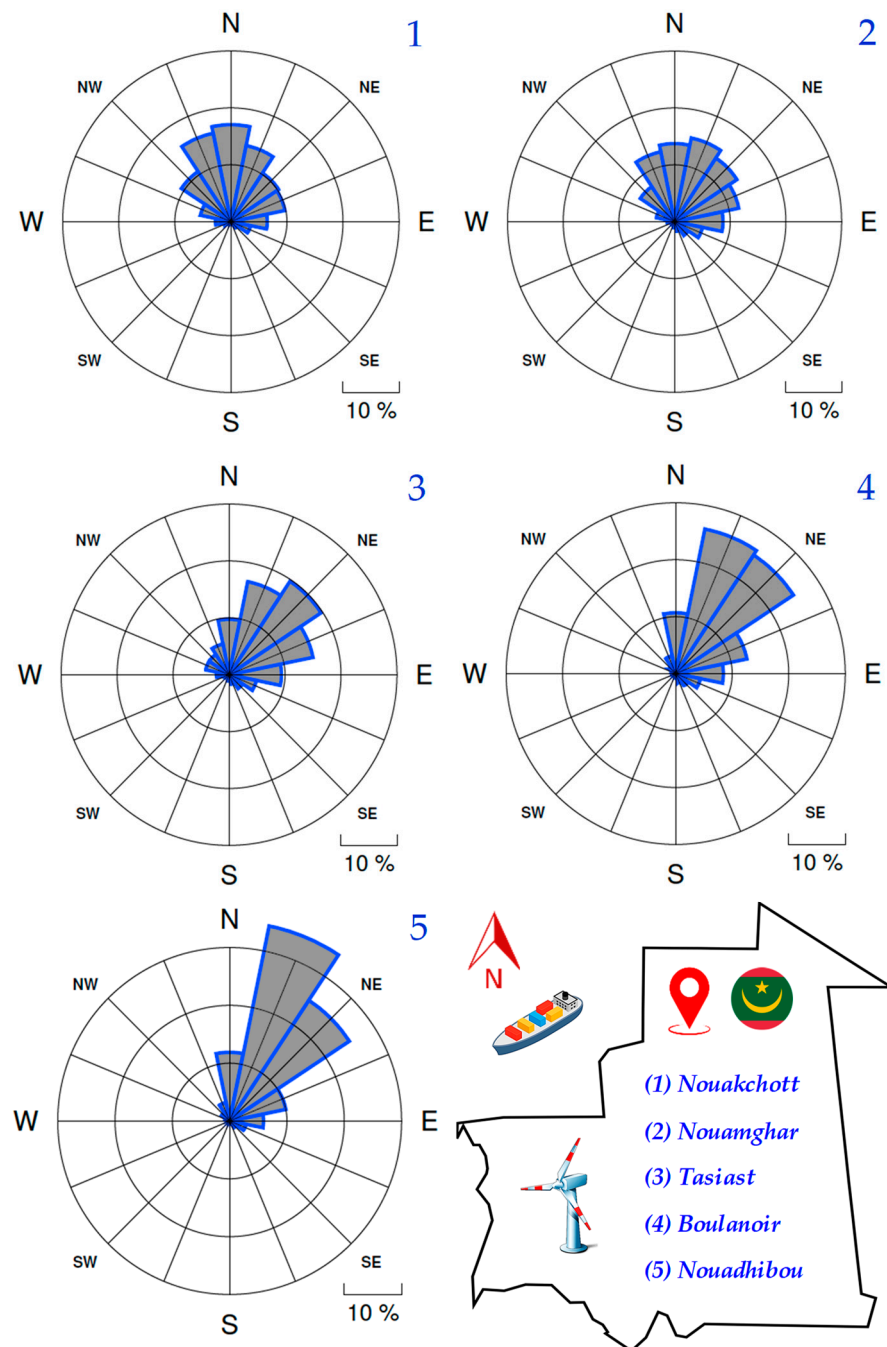


Figure 5. Wind rose diagrams (N: north; NE: north-east; E: east; SE: south-east; S: south; SW: south-west; W: west; NW: north-west) for the five sites (Nouakchott, Nouamghar, Tasiast, Boulanoir, and Nouadhibou).

3.2. Estimation of Weibull Parameters for Wind Speed Data

The actual wind speed data for the five selected sites at 80 m AGL were modeled using the Weibull probability density function. It was evident from the frequency distribution data that the two-parameter Weibull distribution is capable of representing the actual WS at all of the sites. In this study, the Weibull parameters were estimated using MATLAB® R2023a software (MathWorks Inc., Natick, MA, USA) based on the least-squares method (graphical method). The simulations were conducted on a Casper Excalibur PC with an Intel® Core™ i7-7700HQ CPU operating at 2.81 GHz with 16 GB of RAM and a 64-bit Windows 10 system. As illustrated in Figures 6 and 7, the shape parameter (k) values are determined to be 3.31, 3.40, 3.22, 3.27, and 3.15 for the sites of Nouakchott, Nouamghar,

Tasiast, Boulanoir, and Nouadhibou, respectively, at an altitude of 80 m. Furthermore, the scale factor (c) ranged from 8.52 m/s in Nouakchott to 10.98 m/s in Nouadhibou.

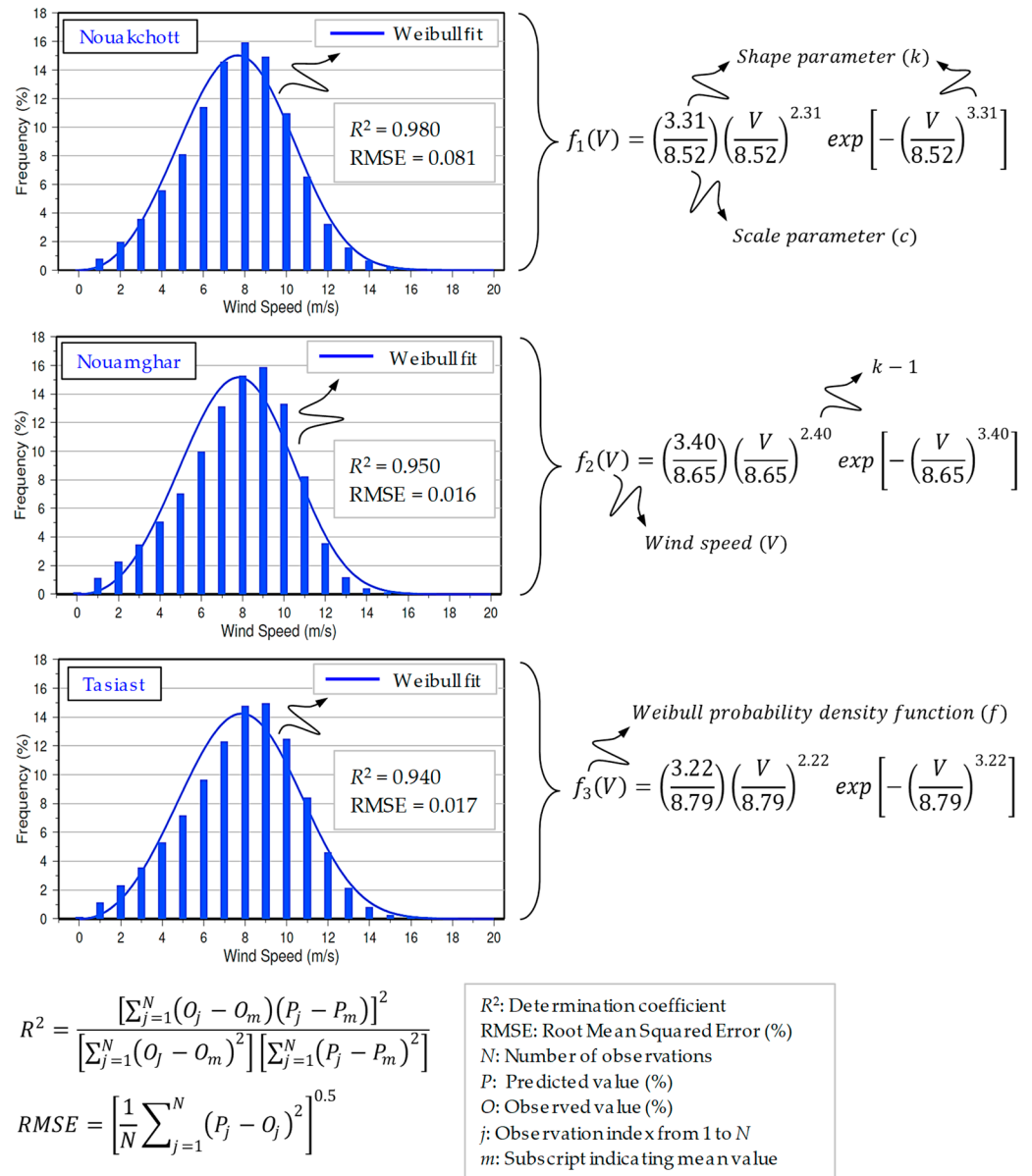


Figure 6. Frequency distribution of wind along with the Weibull distribution curve for Nouakchott, Nouamghar, and Tasiast.

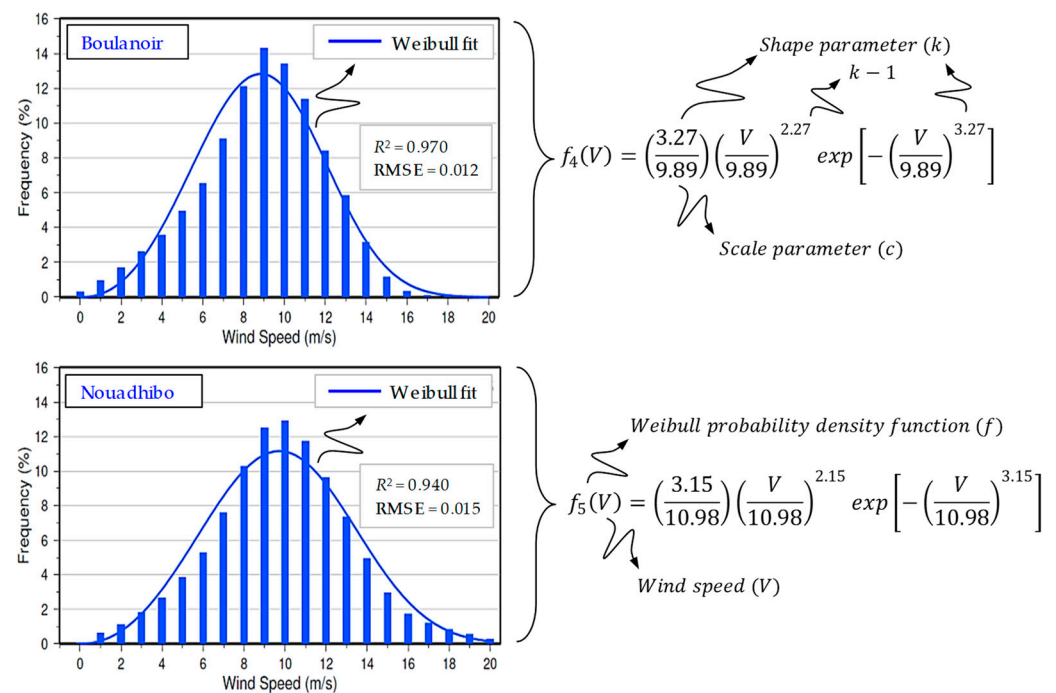


Figure 7. Frequency distribution of wind along with the Weibull distribution curve for Boulanoir and Nouadhibou.

Figures 8 and 9 show the daily fluctuations in wind speed, reflecting changes observed throughout a typical 24 h day. These variations are generally influenced by a combination of meteorological, geographical, and seasonal factors. The daily fluctuations in wind speed are directly linked to the heating and cooling patterns of the Earth's surface. At sunrise, the Earth's surface starts to warm up, causing the air above it to heat and creating a thermal difference with the higher atmosphere. This warming causes warmer air near the ground to rise, forming a low-pressure area. In response, cooler air from surrounding areas moves towards this low-pressure zone, generating winds that typically peak in the afternoon.

Conversely, in the evening and night after sunset, the Earth's surface cools faster than the air above it, reversing the process observed during the daytime. Cooler air near the surface begins to descend, creating a high-pressure area. Warmer air from the surroundings then moves towards the high-pressure zone, producing winds that can be particularly strong from January to July, especially around 18:30 and 08:30 h. Moreover, proper understanding of the diurnal variation of WS is critical to better utilize the generated wind power according to the nature of the load center.

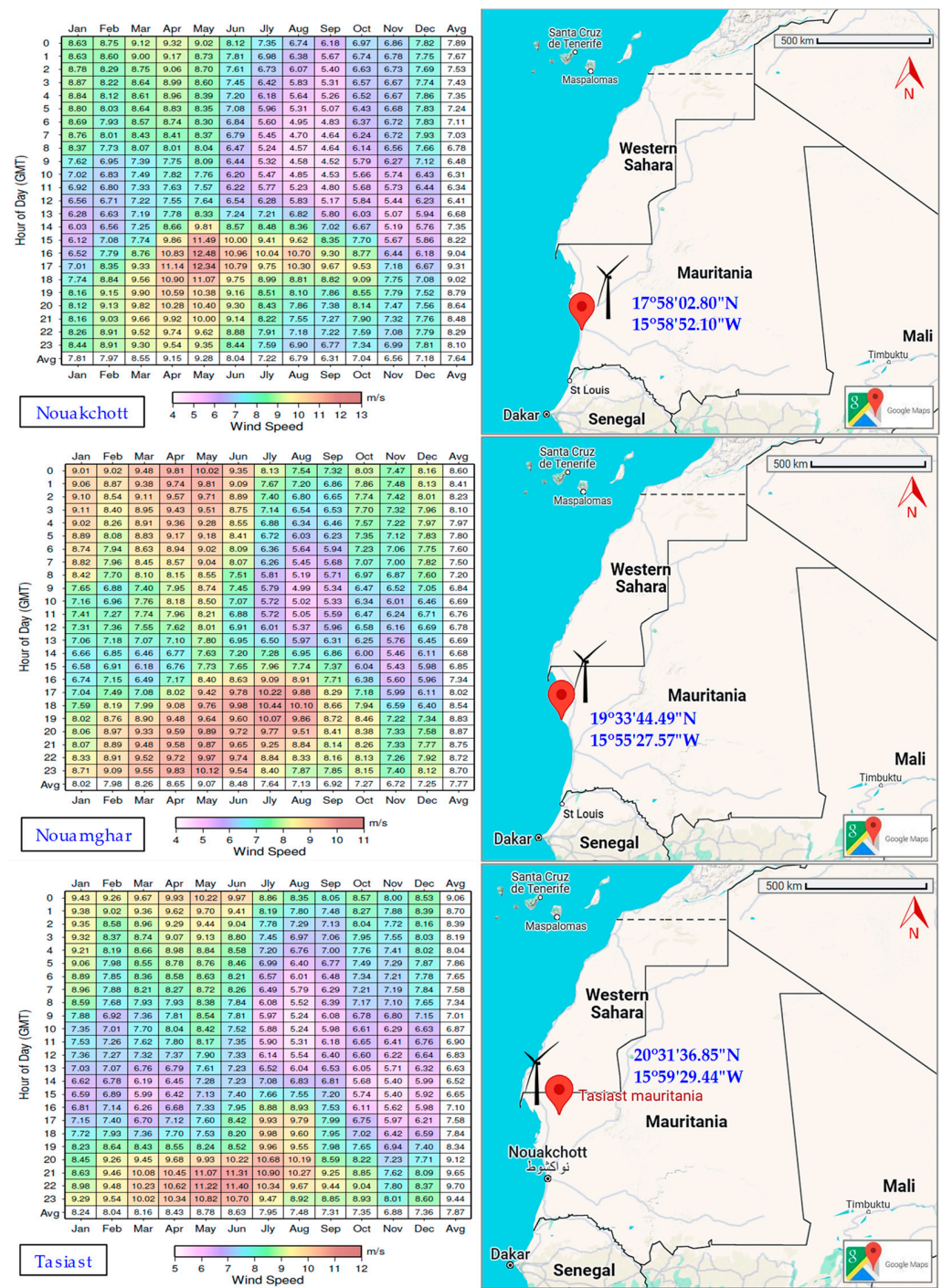


Figure 8. Variations in wind speeds throughout different seasons and times of the day at 80 m for Nouakchott, Nouamghar, and Tasiast during the period 2022–2023.

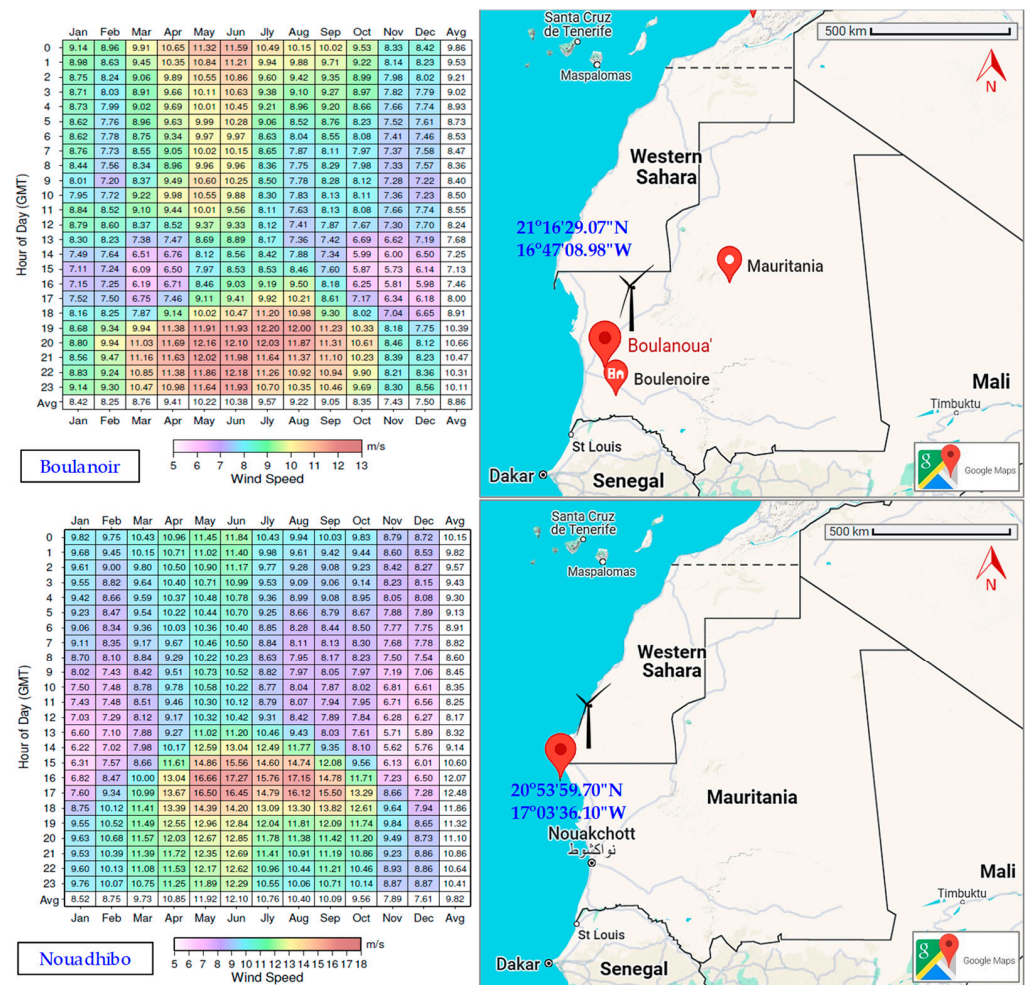


Figure 9. Variations in wind speeds throughout different seasons and times of the day at 80 m for Boulanouir and Nouadhibou during the period 2022–2023.

3.3. Annual Energy Production and Capacity Factor

The total energy generated and the capacity factor of the turbine are critical factors used to evaluate the effectiveness and economic feasibility of wind power in certain areas. Table 3 provides an overview of the data, including the yearly quantity of hydrogen generated at each location. Nouadhibou has the highest yearly energy output, reaching 8271.87 MWh to 21,975.21 MWh with wind turbines V120-1.5 and NORDEX 4 MW, with capacity factors of 57.03% and 51.99%. The lowest annual energy yields of 5756.88 MWh and 15,268.55 MWh, with C_F values of 43.81% and 43.57%, are observed in Nouakchott (Table 3). The energy produced is influenced by the wind conditions and the equipment used, such as the turbine type and the rated capacity, at each location. As a result, Nouadhibou and Boulanouir are suggested as the top locations for building wind farms to generate clean energy and produce green hydrogen.

Wind turbines from five manufacturers were selected to determine which models would be suitable for the local climatic conditions at the selected sites. It should be noted that larger wind turbines often require more complex and costly transport and installation infrastructure. Roads, bridges, and lifting equipment must be adapted to these sizes, which can pose logistical challenges, especially in Mauritania and at targeted sites. While larger-capacity turbines may have a lower LCOE, the initial costs for purchase, transport, and installation may be higher. It is crucial to evaluate the overall costs against the potential benefits to determine whether the investment is justifiable in the specific context of the project.

Table 3. Yearly amount of energy produced (MWh/year), capacity factor (%), and amount of green hydrogen generated (tH₂/year) at each location.

Wind Turbines	Nouakchott			Nouamghar			Tasiast		
	E_{out}	C_f	M_{H_2}	E_{out}	C_f	M_{H_2}	E_{out}	C_f	M_{H_2}
V120-1.5 MW	5756.88	43.81	130.22	5985.51	45.55	135.39	6099.83	46.42	137.97
AEROMASTER AM 2 MW	8688.36	49.59	196.52	8993.20	51.33	203.42	9145.63	52.20	206.87
Gamesa G114-2.5 MW	9607.55	43.87	217.31	9988.61	45.61	225.93	10,179.14	46.48	230.24
GOLDWIND 3.0 MW	13,353.89	50.81	302.05	13,811.16	52.55	312.40	14,039.80	53.42	317.57
NORDEX 4 MW	15,268.55	43.57	345.36	15,878.25	5.31	359.15	16,183.09	46.18	366.05

Wind Turbines	Boulanoir			Nouadhibou		
	E_{out}	C_f	M_{H_2}	E_{out}	C_f	M_{H_2}
V120-1.5 MW	7243.01	51.64	153.49	8271.87	57.03	169.50
AEROMASTER AM 2 MW	10,669.87	49.26	195.20	12,041.68	52.74	209.00
Gamesa G114-2.5 MW	12,084.44	40.92	202.70	13,799.21	52.23	258.73
GOLDWIND 3.0 MW	16,326.16	57.73	343.17	18,383.88	53.77	319.63
NORDEX 4 MW	19,231.57	48.02	380.56	21,975.21	51.99	412.08

The capacity factors of the five turbines are presented in Table 3. From the data presented in this table, the GOLDWIND 3.0 MW wind turbine shows the highest C_f values of 50.81%, 52.55%, 53.42%, 57.73%, and 53.77% at Nouakchott, Nouamghar, Tasiast, Boulanoir, and Nouadhibou compared to other models. This could be due to its slow starting speed of 2.5 m/s and its maximum speed of 10.5 to 11 m/s. Therefore, this turbine can capture more wind at low speeds and operate longer at its maximum rated power. However, the annual energy yields may be higher for larger rated power wind turbines, as indicated by data given in Table 3. For example, the NORDEX 4 MW rated power wind turbine has the lowest capacity factor for all selected sites but higher annual energy yields. With the suggested wind turbine designs, wind power from different locations was harnessed to create environmentally friendly hydrogen. It was recorded that maximum annual hydrogen yields of 209.0 to 412.08 tH₂ were obtained from wind energy generated by the 2.0 MW Aeromaster and 4 MW NORDEX nominal-capacity wind turbines at the Nouadhibou site (Table 3). The next best location in terms of annual green hydrogen production was found to be Boulanoir, based on clean energy produced by the same type of turbines mentioned above. It should be noted that among the locations studied, Nouakchott was the least-preferred location for green hydrogen production.

The LCOE and LCOGH, calculated considering the wind power, electrolyzer resources, and other financial parameters, are presented in Table 4. In general, irrespective of the wind turbine type, the minimum LCOE of <USD 6.5 cents/kWh and LCOGH of <USD 190 cents/kg were found at Nouadhibou, while the higher values of >USD 7.5 cents/kWh for the LCOE and >USD 220 cents/kg for the LCOGH were observed at Nouakchott, Nouamghar, and Tasiast. The main results of the present research reveal that among the countries studied, hydrogen produced from wind energy stands out as the most cost-effective option in several cases. For example, in Oman [29], the LCOE ranges from USD 0.0349 to 0.0701/kWh, with an LCOGH of USD 6.5/kg. These differences can be attributed to local factors, such as the availability of wind resources, infrastructure costs, and government subsidies. Conversely, in Afghanistan and Algeria, the costs are higher. In Afghanistan [23], the LCOE ranges from USD 0.063 to 0.079/kWh, while the LCOGH is between USD 2.118 and 2.261/kg. In Algeria [58], the LCOE ranges from USD 0.087 to 0.1142/kWh, and the LCOGH is between USD 2.158 and 2.261/kg. The higher costs here may be due to specific challenges, such as limited access to production technologies, less developed infrastructure, and increased operating costs. Significantly higher costs have also been observed in Djibouti [16], where the LCOE ranges from USD 6.94 to 13.13/kWh and the LCOGH ranges from USD 1.79 to 3.33/kg. These variations are likely related to particular geographical and economic conditions, such as the scarcity of local

energy resources and high logistical costs. In the context of the current analysis, the values obtained for the LCOE range from USD 5.649 to 6.5/kWh, while the LCOGH values range from USD 1.85 to 2.11/kg. These results reflect the local specifics of our site as well as the economic and technical parameters unique to it. Therefore, the differences between the present LCOE and LCOGH values and global averages or results from other countries can be explained by these contextual factors. Table 5 provides the annual reduction of CO₂-equivalent GHG emissions achieved by producing green hydrogen using wind power. As shown in Table 5, the maximum annual reductions in CO₂ emissions are 4229.39, 4398.28, 4482.72, and 6087.13 Mt, corresponding to the NORDEX 4 MW wind turbine at the Nouakchott, Nouamghar, Tasiast, Boulanoir, and Nouadhibou sites. Similarly, the minimum CO₂-reduction values are observed, corresponding to the V120 wind turbine of 1.5 MW rated capacity.

Table 4. Levelized cost of electricity (USD cents/kWh) and levelized cost of green hydrogen production (USD cents/kg H₂) at each location.

Wind Turbines	Nouakchott		Nouamghar		Tasiast		Boulanoir		Nouadhibou	
	LCOE	LCOGH	LCOE	LCOGH	LCOE	LCOGH	LCOE	LCOGH	LCOE	LCOGH
V120-1.5 MW	8.15	265.41	7.84	255.28	7.69	250.49	6.48	210.96	5.67	184.72
AEROMASTER AM 2 MW	7.90	238.9	7.88	232.37	7.51	226.95	6.43	194.53	5.70	172.37
Gamesa G114-2.5 MW	8.93	270.05	8.59	259.75	8.75	256.88	7.10	214.7	6.22	188.02
GOLDWIND 3.0 MW	7.71	233.15	7.46	225.44	7.33	221.76	6.31	190.71	5.60	169.37
NORDEX 4 MW	8.20	266.86	7.88	256.63	7.73	251.78	6.51	211.88	5.69	185.42

Table 5. Annual reduction of CO₂ emissions (MtCO₂/year) at each location.

Wind Turbines	Nouakchott	Nouamghar	Tasiast	Boulanoir	Nouadhibou
V120-1.5 MW	1594.66	1657.99	1689.65	2006.31	2491.12
AEROMASTER AM 2 MW	2406.68	2491.12	2533.34	2955.55	3335.55
Gamesa G114-2.5 MW	2661.29	2766.84	2819.62	3347.39	3822.38
GOLDWIND 3.0 MW	3699.03	3825.69	3889.02	4522.35	5092.33
NORDEX 4 MW	4229.39	4398.28	4482.72	5327.14	6087.13

The detailed analysis of the net present value (USD), the benefit–cost ratio (BCR), and the payback period (year) was conducted based on the methodology expressed earlier. The resulting data are provided in Table 6. All five wind sites showed positive NPV values, indicating their capacity for producing profitable cash flows over their lifetime. NPV is a critical indicator that considers the time value of money, thus reflecting the net value created by the project after accounting for the invested capital cost. At all of the sites and subject to all types of wind turbines, the BCR is above 2.0, indicating that for every monetary unit invested, there is more than one unit of expected benefit (Table 6). This confirms that the projects will be economically profitable and generate returns that justify the initial funding. In relation to the payback period (PBP), which typically lasts around three years per location, it signifies the duration needed to recoup the initial investment through the project’s generated cash flows. A relatively short PBP like this is favorable, as it indicates a quick recovery of costs and early profitability of the project. According to Table 6, the PBP value at the Nouadhibou location is surprisingly high, even with its advantageous wind conditions. Even though the investment recovery time is longer than anticipated, this delay can be explained by various factors other than wind conditions. The payback period may be notably prolonged by the substantial project expenses, like infrastructure, equipment, and installation costs. Despite having ideal wind conditions, the high initial costs may cause a delay in the return on investment, especially because Nouadhibou is the furthest site from the capital in terms of transportation.

Table 6. Net present value (USD), benefit–cost ratio (BCR), and payback period (year) of the wind turbines.

Wind Turbines	Nouakchott			Nouamghar			Tasiast		
	NPV	BCR	PBP	NPV	BCR	PBP	NPV	BCR	PBP
V120-1.5 MW	2,741,290	2.05	7.0	2,849,880	2.1	6.9	2,849,830	2.1	6.9
AEROMASTER AM 2 MW	5,356,236	2.85	4.3	5,635,061	2.9	4.1	5,356,225	2.9	4.3
Gamesa G114-2.5 MW	7,295,029	3.34	3.3	7,295,869	3.3	3.3	7,696,457	3.5	3.2
GOLDWIND 3.0 MW	9,234,532	3.78	2.7	9,234,993	3.8	2.7	9,235,703	3.8	2.7
NORDEX 4 MW	11,600,176	4.11	2.2	11,599,609	4.1	2.2	11,600,525	4.1	2.2
Wind Turbines	Boulanoir			Nouadhibou					
	NPV	BCR	PBP	NPV	BCR	PBP			
V120-1.5 MW	2,850,013	2.1	6.9	1,314,279	1.5	10.6			
AEROMASTER AM 2MW	5,356,389	2.9	4.3	3,298,980	2.2	6.0			
Gamesa G114-2.5 MW	7,295,540	3.3	3.3	4,490,841	2.5	4.7			
GOLDWIND 3.0 MW	9,235,853	3.8	2.7	6,203,526	2.9	3.6			
NORDEX 4 MW	11,600,025	4.1	2.2	7,488,330	3.0	3.0			

In summary, these economic performance indicators (BCR, NPV, and PBP) collectively confirm the economic viability of the five studied sites: Nouakchott, Nouamghar, Tasiast, Boulanoir, and Nouadhibou. These statistics show that the suggested initiatives will not just be economically feasible but also appealing to investors and stakeholders keen on advancing wind energy and green hydrogen. These results strengthen the credibility of the techno-economic model used in the analysis, thus highlighting the robustness of the planned investments in these sustainable energy infrastructures.

The wind capacity in the northern coastal area, especially close to the oasis, is vast, with an average yearly wind speed of 9.8 m/s at 80 m AGL along a distance exceeding 600 km. This wind potential can be effectively exploited to generate electricity, which could be used to produce green hydrogen. This would significantly contribute to the national electricity demand while combating climate change through a substantial reduction in CO₂ emissions.

The suggestion for a fresh wind farm plan, similar to Nour and Aman in this area, has the potential to significantly enhance the social, environmental, and economic situations of the nearby populations. Moreover, the new wind farm would greatly decrease dependence on traditional power plants that usually rely on oil and gas and are susceptible to price changes. The results of this study show that a wind project for green hydrogen production is both technically and economically feasible in this area, with costs that are competitive and attractive to public and private developers.

4. Conclusions

The current research evaluated the wind power possibility at five locations on the Mauritania coast by examining wind speed information, modeling wind energy production, and producing green hydrogen from wind energy. The study also conducted an economic risk analysis related to electricity and green hydrogen production. Here are the main findings derived from the present work.

- (1) Average wind speeds range from 7.6 m/s to 9.8 m/s at the five sites. Nouadhibou and Boulanoir recorded the top yearly average wind speeds of 9.8 m/s and 8.9 m/s, respectively, at 80 m AGL, with a predominant wind direction from the north to the north–northeast across all sites.
- (2) The greatest annual energy yield of 21.97 GWh, with a capacity factor of 51.99%, was determined for the NORDEX 4 MW model at Nouadhibou. The simulation resulted in an LCOE between USD 5.69 and 6.51 cents/kWh, which is lower than the local electricity tariff in Mauritania. The price of green hydrogen production was cost-effective, with the LCOGH varying from USD 1.85 to 2.11/kg H₂ for the five proposed wind farms in this study. This is technically favorable for setting up wind turbines

with a power output of 18 GW for the Nour project and 12 GW for the AMAN project across these five sites.

- (3) The five locations have the capacity to generate significant energy exceeding Mauritania's needs that can potentially be partly supplied to Europe and Africa in a mutually beneficial partnership. The reduction in CO₂ emissions, according to proposed commercial turbines for the five sites, annually varies between 1594.66 Mt of CO₂ for the V120-1.5 MW model and 6087.13 Mt for the NORDEX 4 MW model, respectively, for the Nouakchott and Nouadhibou sites.
- (4) The economic assessment revealed that the LCOE varied between USD 5.601 and 8.93 cents/kWh across the various sites, which is lower than the existing electricity tariff in Mauritania. The yearly output of green hydrogen for a 4 MW NORDEX wind turbine in Nouadhibou was projected to be 412.08 tH₂, with the LCOGH set at USD 185.42 cents/kg H₂.
- (5) The current research offers a useful approach for evaluating renewable energy and green hydrogen projects in northern Mauritania. The proposed method can assist decision makers in planning and implementing wind energy and green hydrogen initiatives. Ultimately, it is crucial to interact with native populations and assess the societal effects of implementing a large number of wind turbines in the area.

Author Contributions: Conceptualization, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; data curation, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; formal analysis, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; funding acquisition, V.M., M.M.A., K.Y. and A.M.Y.; investigation, V.M., M.M.A., K.Y. and A.M.Y.; methodology, V.M., M.M.A., K.Y. and A.M.Y.; project administration, V.M., M.M.A., K.Y. and A.M.Y.; resources, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; software, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; supervision, V.M., M.M.A., K.Y. and A.M.Y.; validation, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; visualization, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; writing—original draft, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y.; writing—review and editing, V.M., E.M.B., M.M.A., K.Y., S.R., C.M., A.K.M., S.M., M.L.S. and A.M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by ANRSI (Agence Nationale de la Recherche Scientifique et de l'Innovation) Mauritania. (funding data confirmation).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

Acknowledgments: This work was carried out as part of the Ph.D. thesis of Varha Maaloum, completed under the supervision of Ahmed Mohamed Yahya. The authors also acknowledge the valuable insights of the reviewers and the academic editor, who have contributed extensively to improving the article's quality.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following symbols and abbreviations are used in this manuscript:

a	Slope of the fitted regression line (k)
AGL	Above ground level
b	Ordinate intercept of the fitted regression line ($klnc$)
B_A	Annual income generated from electricity sales (USD)
BCR	Benefit–cost ratio (dimensionless)
c	Scale parameter or characteristic life for Weibull PDF (m/s)
C_A	Annual operation and maintenance cost (USD)
C_{Aspec}	Average specific cost of the wind turbines (USD/kW)

$C_{electricity}$	Cost of wind-generated electricity (USD)
$C_{electrolyzer}$	Cost of electrolyzer (USD)
C_f	Capacity factor of wind turbine (%)
CFD	Cumulative distribution function
C_I	Initial (capital) investment (USD/kW)
$C_{O\&M}$	Operation and maintenance cost (USD)
$C_{u,electrolyzer}$	Unit cost of electrolyzer (USD/kW)
CO ₂	Carbon dioxide
D	Rotor diameter (m)
DR	Discount rate (%)
$E_{electrolyser}$	Energy consumption by electrolyzer (kWh/kg)
E_{out}	Total amount of energy used by generated H ₂ (MWh/year)
exp	Exponential function
$f(V; c, k)$	Two-parameter Weibull PDF
$F(V; c, k)$	Two-parameter Weibull CFD
GHG	Greenhouse gas
GIS	Geographic Information Systems
Gt	Gigaton
GWh	Gigawatt (GW) hour
H_1	Height of measuring wind speed (m)
H_2	Height of wind turbine tower (m)
I_d	Real interest rate (%)
i	Interest rate (%)
ln	Natural logarithm
IRR	Internal Rate of Return (%)
k	Shape parameter or slope for Weibull PDF (dimensionless)
kCO ₂	Kilos of CO ₂
kWh	Kilowatt hour
LCOE	Levelized cost of electricity (USD/kWh)
LCOGH	Levelized cost of green hydrogen (USD/kg H ₂)
m	A percentage of initial (capital) investment (%)
M_{H_2}	Mass of produced hydrogen (ton H ₂ /year)
Mt	Metric ton
MWh	Megawatt (MW) hour
n	Lifespan of the project (year)
NPV	Net present value (USD)
$NPV(B_A)_{1-n}$	Cumulative NPV of all the costs (USD)
$NPV(C_A)_{1-n}$	Cumulative NPV of all benefits over the project's lifespan (USD)
PBP	Payback period (year)
PDF	Probability density function
P_R	Rated power (kW)
PVB	Present value of benefits (USD)
PVC	Present value cost (USD)
P_w	Power of the wind hitting the turbine (kW)
r	Inflation rate (%)
R^2	Determination coefficient (dimensionless)
RMSE	Root Mean Squared Error (%)
ROI	Return on investment (%)
S	Salvage value (USD)
S_a	Rotor swept area (m ²)
SD	Standard deviation (m/s or %)
t	Expected lifespan of the commercial wind turbine (year)
tCO ₂	Tons of CO ₂
tH ₂	Tons of H ₂
T	Lifetime of electrolyzer (year)
\bar{V}	Average wind speed (m/s)
V_1	Wind speed at the measurement height (H_1)
V_2	Wind speed at the measurement height (H_2)

WPD	Wind power density (kW/m ²)
WS	Wind speed (m/s)
x	Independent (response) variable dataset ($\ln V$)
y	Dependent (predictor) variable dataset ($\ln\{-\ln[1 - F(V)]\}$)
<i>Greek symbols</i>	
α	Wind shear coefficient or power law exponent (dimensionless)
$\eta_{\text{converter}}$	Converter efficiency (%)
$\eta_{\text{electrolyser}}$	Electrolyzer efficiency (%)
ρ	Air density at a specific location (kg/m ³)

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