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Study of a Wind Pumping System in the Saharan Zone of Chad

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Abstract*: *The wind-powered water pumping system at Gouro and Madadi in Chad is crucial to alleviate the chronic water shortage in these desert regions. The statistical Weibull distribution, using the Moroccan method, gives an annual wind speed scale of 6.55 m/s and 5.85 m/s for these sites, confirming the importance of studying a wind power system. Annual variations in wind speed are significant, and show a seasonal dependence on wind speed. The dominant wind direction is north-easterly, according to the wind rose diagrams, with high frequencies. Seasonal capacity factors for the three wind turbines at the Gouro site range from 0.55 to 0.77, and from 0.48 to 0.70 for the Madadi site, making these areas ideal for wind turbine installation. Monthly daily water flows for the Gouro site range from 8367 m^3/day to 30371 m3/day for the three wind turbines. For the Madadi site, these values range from 8415 m3/day to 21391 m3/day. In view of these results, the wind-powered water pumping system can have a significant impact on the socio-economic development of these regions. By supplying drinking water and irrigating farmland, it can promote food security, economic growth and improved living conditions for local populations.

Keywords*: *Weibull distribution, Wind rose, Capacity factor, Daily flow rate.

I. INTRODUCTION

The world is increasingly facing an energy deficit caused by the depletion of fossil fuels in the near future. The use of fossil fuels is today responsible for climate change, with numerous harmful consequences for the planet and living beings [1,2,3]. The risks associated with the production and consumption of fossil fuels are considerable, and affect several continents and countries around the world, particularly in sub-Saharan Africa. Today, the threat of drought and desertification is creating water crises and plunging many countries into famine. Rising temperatures, heatwaves, massive flooding, tropical cyclones, prolonged drought and rising sea levels are causing loss of life, property damage and population displacement, jeopardizing the future of the African continent [4,5].

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Renewable energy is of crucial importance for Sub-Saharan Africa, as the region faces numerous energy challenges. Most countries in the region have limited access to electricity and water, which limits their economic and social development. Moreover, traditional energy sources such as coal and oil are often costly and polluting. The Saharan part of Chad is a totally desert zone. In this part of the country, the average annual rainfall is around 50 mm [5,6,7]. This means that : springs are very limited and very remote, forcing the population to make long journeys in search of water; these regions of the Sahara are subject to long periods of drought, making access to water more difficult; the water available is often contaminated by bacteria and viruses, leading to water-related illnesses; livestock farmers need water for their herds, adding further pressure on limited water resources; water supply costs are high, making access to water difficult for poorer communities. The large groundwater reserves require energy for pumping. Given the high cost of fuel for pumping with generators, it is difficult to meet the water needs of this population living in this arid environment. And yet, this desert zone has great wind potential. According to a study carried out by NASA [8] and several other researchers [9,10], Chad's northern zone has good wind speeds that can be exploited for energy purposes to meet the population's local electricity and water needs. This study focuses on two towns in the Saharan zone of Chad. According to measurements by the (Agency National for Meteorology) and NASA satellite data, wind speeds at the two sites are 5.8 m/s at Gouro and 5.15 m/s at Madadi, and fall into the moderate wind class on the Beaufort scale. In view of all this information about wind power, one question emerges. How can wind power be effectively used to pump water from the Gouro and Madadi sites, in order to improve access to drinking water, reduce the risk of water-related diseases and contribute to poverty reduction? The objective of the present paper is to evaluate the wind potential for water pumping at the Gouro and Madadi sites in this Saharan part of Chad. In this work, we use the Weibull and Rayleigh statistical distribution method to estimate the probability of occurrence of different wind speeds, which is essential for designing and sizing wind turbines, evaluating wind energy production, and estimating water pumping at the two sites. To achieve this objective, we have structured the work as follows: section I covers the general introduction, section II presents the study sites, section III in turn deals with the methodology and section IV covers the results and finally section V concerns the discussions.

II. PRESENTATION OF THE STUDY AREA

The study area covers two isolated sites, Gouro and Madadi, located in the northern desert region of Chad (figure 1 and table 1).These two towns are also in the Saharan part of the country, with a desert climate and an annual rainfall of barely 100 mm.

Table 1: Coordinates of the Study Area

Site	Latitude	Longitude	Altitude	Data ranges
Gouro	19.5315	19.5692	541.57 m	2010-2020
Madadi	18.451	20.7585	452.43 m	2010-2020

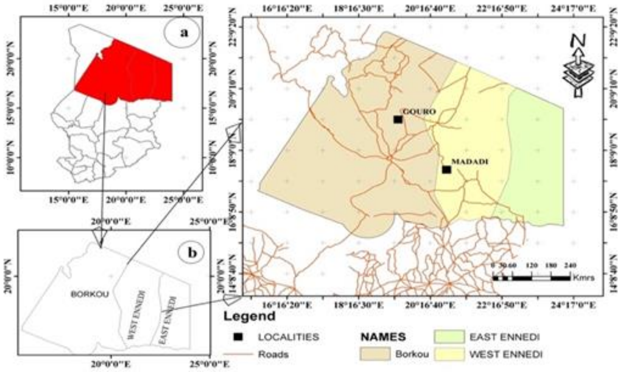

Figure 1: Map of Study Area

III. MATERIALS AND METHODS

A. Materials

The present article, based on the study of a wind pumping potential, requires the use of meteorological data from the target area. We will need equipment for the collection, processing and analysis of meteorological data. The target area is located in the Sahara region, where there is a lack of on-site measuring equipment, so we collect our data from the NASA website. We collect monthly wind speed and wind direction data over a 10-year period, from 2010 to 2020. We are also collecting hourly data to produce wind roses. We will use Microsoft Excel for data processing. We will use MATLAB R2020a to simulate the results, WRPLOT to produce the wind roses and Arcgis to produce a map of the study area.

B. Methodology

i. The Weibull Statistical Distribution Function

The Weibull function is a statistical method commonly used to model the distribution of wind speed in a given area. It is based on two parameters, shape and scale, which are determined from wind speed measurement data. The Weibull distribution function is used to determine the probability of obtaining a certain wind speed in a given area [11,12,13]. This information is essential for the design and optimization of wind energy systems, as it enables us to determine the theoretical electrical power produced by wind turbines. It is given by:

$$fw(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right) \qquad (1)$$

Where k is the (dimensionless) shape parameter which gives the shape of the distribution, c the scale factor in (m/s) and v the velocity.

When the form factor k=2, we obtain the Rayleigh distribution function [14,15] by:

$$fR(v) = \left(\frac{2v}{c^2}\right) exp\left(-\left(\frac{v}{c}\right)^2\right) \qquad (2)$$

C. Method for Determining Weibull Parameters

i. The Moroccan Method

There are several methods for determining Weibull parameters, depending on the site. In our case, we use the so-called Moroccan method. This method is generally used for areas with high wind speeds [16,17,18]. The shape parameter k and the scaling factor c are determined by the following relationships:

$$k = 1 + \left(0.483(\overline{v} - 2)\right)^{0.51} \qquad (3)$$

$$c = \frac{\overline{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \qquad (4)$$

D. Vertical Extrapolation of Wind Speed and Weibull a Parameter for Different Heights

In this study, the wind shear model considered for extrapolating wind profiles is the empirical power law. Equation (5) is therefore used to adjust wind speeds measured at 10 m above ground at the hub heights of WT towers, as well as at certain exposed hilltops or ridges [19][20][22][23][24][25].

$$V_z = V_{10}\left(\frac{z}{10}\right)^{\alpha} \qquad (5)$$

With V_{10} the wind speed at a height of 10 m and V_z the speed at a height of z; z being the altitude. α is the roughness coefficient defined by:

$$C_z = C_{10}\left(\frac{z}{10}\right)^{n} \qquad (6)$$

$$k_z = \frac{k_{10}}{1 - 0.00881 ln(z/10)} \qquad (7)$$

kz is the form factor at height z and Cz is the scale factor at height z.

The exponent n of the power law is given by :

$$n = [0.37 - 0.0088 ln(10)] \qquad (8)$$

i. Wind Turbine Output Power and Capacity Factor

Every wind energy conversion system is designed to operate at maximum efficiency within the limits of the rated wind speed and power. Therefore, once the Weibull scaling and shape parameters are estimated, the performance of a wind turbine at a given location can be easily calculated using the average power and capacity factor. In this work, the electrical power of a model wind turbine is simulated using [21,22] :

$$P_e = \begin{cases} 0 & (v < v_d) \\ P_{en}\dfrac{v^k - v_d^k}{v_n^k - v_d^k} & (v_d \le v \le v_n) \\ P_{eR} & (v_n \le v \le v_c) \\ 0 & (v_c < v) \end{cases} \qquad (9)$$

Where:
Pen: rated electrical power
vd : wind turbine starting speed;
vn : rated speed ;
vc : cut-off speed

The output power of a wind turbine is given by the following relationship:

$$P_s = P_{en}\left\{\frac{e^{-\left(\frac{v_d}{C}\right)^k} - e^{-\left(\frac{v_n}{C}\right)^k}}{\left(\frac{v_n}{C}\right)^k - \left(\frac{v_d}{C}\right)^k} - e^{-\left(\frac{v_c}{C}\right)^k}\right\} \tag{10}$$

The capacity factor, which is described as the ratio between the average output power and the rated output power, is given by the following formula [23,24,25] :

$$C_f = \frac{P_s}{P_e} \tag{11}$$

ii. Usable Wind Energy

The average usable (produced) wind energy is :

$$P_P = \eta P_u \tag{12}$$

With η the machine efficiency and given by [23,24]:

$$\eta = 2\frac{P_n}{\rho A v_n^3} \tag{13}$$

iii. Daily Wind Pump Flow Rate

The wind pump model is given by the equation below, highlighting in particular the relationship between flow rate, head and fluid density [26].

$$\mathrm{Q} = 3600 * 24 * \left(\frac{(\eta * \mathrm{P_u})}{(\rho_e * g * \mathrm{H})}\right) \tag{15}$$

With:

ρe: density of water (ρe=1000kg/m3); g is the acceleration of gravity, (g= 9.81 m/s2), H is the head.

IV. RESULTS AND DISCUSSION

A. Annual Weibull Probability Density for the Sites

The two curves in Figure 2 show the Weibull statistical distributions for the Gouro and Madadi sites using the Moroccan method. The results of the analysis of wind data using the Weibull distribution function for the Gouro and Madadi sites are interesting. The Weibull parameters for the Gouro site indicate a scale factor c of 6.55 m/s and a form factor k of 2.36, while for the Madadi site, these values are 5.81 and 2.24 respectively. The maximum probability is 0.15 for the Gouro site, corresponding to an average velocity scale of 5.5 m/s. For Madadi, the maximum probability density is 0.14 for a maximum velocity of 16 m/s. These results provide valuable information for planning the implementation of wind power projects at these sites. It should be pointed out that the Weibull distribution function is widely used to model wind distribution in renewable energies, making these results particularly relevant to the study of wind energy potential for water pumping and other applications related to the use of wind energy.

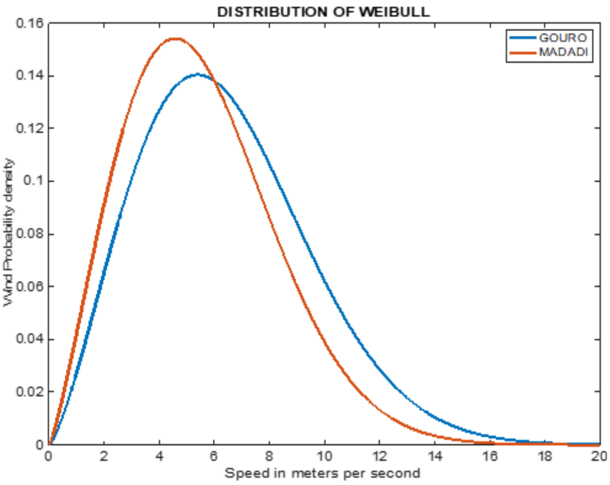

Figure 2: Annual Weibull Distribution for the Town of Gouro and Madadi

B. Monthly Weibull Distribution of Study Sites

Figure 3 shows the various Weibull statistical distribution curves for the Madadi site. Examining these curves in relation to the monthly values of the Weibull parameters for this site, it is clear that the values of k and c vary considerably from month to month. In general, a higher value of k indicates a narrower, more concentrated distribution of wind speed, while a higher value of the scaling factor c indicates a higher average wind speed. Probability density over the whole twelve months ranges from 0.13 to 0.19. In January and February, the values of k and c are relatively high, suggesting that wind speed is relatively concentrated around a higher mean value. In July and August, on the other hand, k values are lower, suggesting that wind speed is more dispersed and variable, while c values are also lower, a lower mean wind speed value. Interestingly, k values increase again in September and October, suggesting that the wind speed distribution once again becomes more concentrated around a higher mean value. Overall, these results underline the importance of taking seasonal variations in wind speed distribution into account when planning and managing wind projects. Figure 4 shows the monthly Weibull distribution for the Gouro site. The Weibull parameters for this site vary considerably from month to month. January and February have the same higher shape parameter value, suggesting a higher concentration during these months. On the other hand, as for the Madadi site, July and August have the lowest values for both parameters, indicating a more dispersed and variable wind speed during these months. Probability density is relatively stable throughout the year, with values ranging from 0.12 to 0.16 for each month. These results also underline the importance of taking seasonal variations into account for a wind power project.

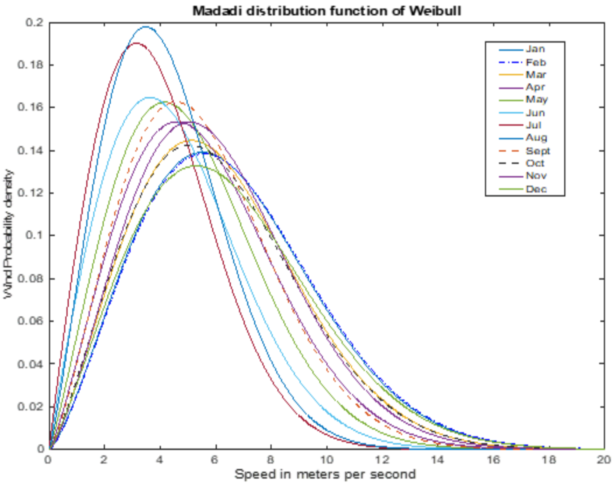

Figure 3: Weibull Distribution of Madadi

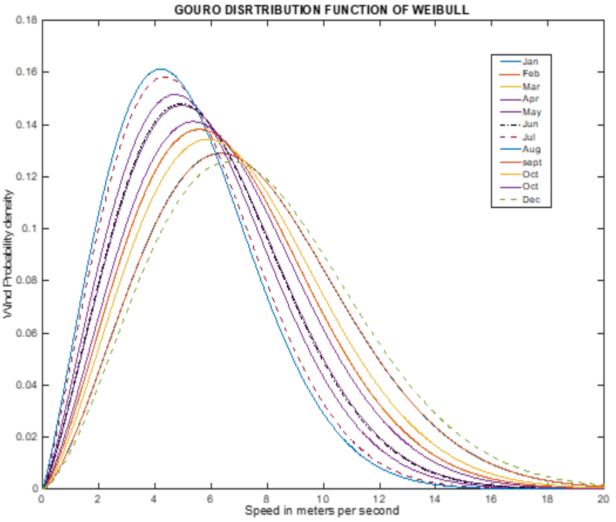

Figure 4: Weibull Distribution of Gouro

C. Monthly Rayleigh Distribution for Both Sites

Figure 5 shows the monthly Weibull distributions for the Madadi site. With the shape parameter fixed at 2, there is a slight seasonal variation in the probability density, which ranges from 0.12 to 0.19, and in the wind speed scale factor, which varies from 5.49 to 7.61. We note that the scale factor values remain high at the beginning of the year, then reach their minimum values in July and August, before rising again in September. In general, the Weibull parameter values are very close to those of Rayleigh. This also shows that the Rayleigh distribution is well suited to characterizing the winds at this site. The values of the scale factors remain very high throughout the year, demonstrating that this site is suitable for the installation of wind-powered water pumping projects and other parallel applications. Figure 6 shows the monthly Rayleigh distribution curves for the Gouro site. As for the Madadi site in Figure 4, the monthly values of the scaling factor remain high throughout the year. However, there is a slight variation in the probability density between 0.12 and 0.19 for the twelve months of the year. We also note a drop in the velocity scale factor values for the months of July and August, which is almost similar to the Weibull distribution.

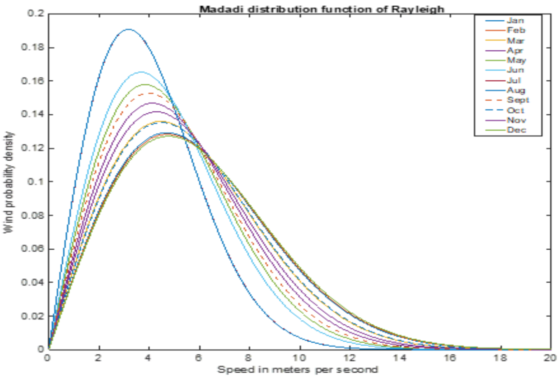

Figure 5: Rayleigh Distribution for the Town of Gouro

D. Wind Rose Diagrams for The Study Area

Figures 6 and 7 show wind rose diagrams for the Madadi and Gouro sites respectively. In both figures, we can see that winds are concentrated in the East-North-East sector, with very high frequencies. Figure 6 for the Madadi site shows that the frequency of calm winds is zero, which explains the predominance of strong winds at this site. The frequency of wind speeds between 8.8 m/s and 11.1 m /s is 70%, suggesting that the area is suitable for wind power generation, as most wind turbines are designed to operate at speeds in this range. The frequency of wind speeds ranging from 5.7 m/s to 8.8 m/s is 56%, which also tells us that the area is very suitable for wind power generation, as wind turbines can operate efficiently at wind speeds in this range. The frequency of wind speeds ranging from 3.6 m/s to 5.7 m/s is 14%, which explains why this area could be used for wind power generation, but with wind turbines specially designed to operate at low wind speeds. Figure 7 in turn shows the wind rose diagram for the town of Gouro. Compared with the Madadi site, wind frequencies are lower, with no calm wind frequency. The frequency of wind speeds ranging from 8.8 m/s to 11.1 m /s is 45%, which clearly explains why the area is highly suitable for a wind power project. The frequency of wind speeds varies from 5.7 m/s to 8.8 m/s, demonstrating the importance of wind at a good range of speeds. Overall, analysis of the wind rose data shows that both sites in the Bodélé triangle area are highly suitable for wind power generation, particularly for turbines designed to operate at medium to high wind speeds.

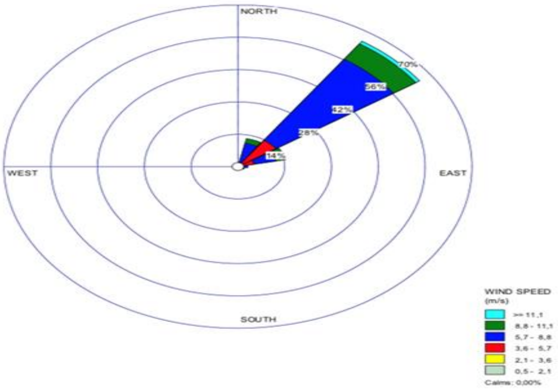

Figure 6: Madadi Wind Rose

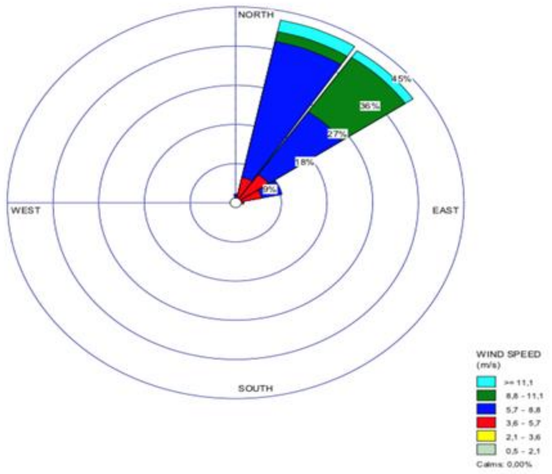

Figure 7: Gouro Wind Rose

E. Applications to Various Wind Turbines in the Study Area

The table below shows the characteristics of three wind turbines marketed for pumping applications on the site.

Table 1: Characteristics of Wind Turbines

Wind turbine	Rated power	Mast heigh	Rotor diameter	Starting speed	Rated speed
VES30	250 kW	49 m	30 m	3.5 m/s	12.5 m/s
G-3120	35 kW	42.7 m	19.2 m	3.5 m/s	9.5 m/s
E-3120	50 kW	42.7 m	19.2 m	3.5 m/s	8 m/s

F. Power Output of Individual Wind Turbines

Figures 8 and 9 show the monthly variations in power output of three wind turbines at the two sites. Figure 8 for the Gouro site shows the monthly variations in power output for three types of wind turbine: the VES30, the G-3120 and the E-3120. The results of the theoretical power calculations were obtained over a twelve-month period, from January to December. The average electrical power of the VES30 wind turbine is around 140 kW over this period, while the G-3120 and E-3120 wind turbines have average power ratings of around 25 kW. These results show a significant difference in power between the VES30 wind turbine and the other two models. This difference can be explained by the fact that the VES30 wind generator is more recent and more efficient than the others. The Gouro site therefore benefits from significant wind power, capable of producing a substantial amount of electricity over a twelve-month period. The VES30 wind turbine produces constant, reliable electrical power, while the G-3120 and E-3120 wind turbines offer lower output due to their less advanced technology. These results are encouraging for the development of renewable energies in the Gouro region. Indeed, the use of wind power reduces dependence on fossil fuels and contributes to the energy transition towards a more sustainable, environmentally-friendly model. In conclusion, the Gouro site boasts high-performance, reliable wind power equipment capable of producing a significant amount of electricity over a twelve-month period. This infrastructure is an example of the ability of renewable energies to meet current energy needs while preserving the environment. Figure 9 shows the monthly power output of the three wind turbines, as before for the Madadi site. Compared with the Gouro site, we note a slight variation in the electrical power produced per wind turbine at this site. The results of calculating the electrical power generated per wind turbine are satisfactory. The average power output of the G-3120 wind turbine is 24.5 kW, that of the E-3120 is 30.57 kW and that of the VES30 is 119 kW. These variations are slightly lower than at the Gouro site. Overall, the results show that both sites benefit from a good wind potential that could help pump water for the local population.

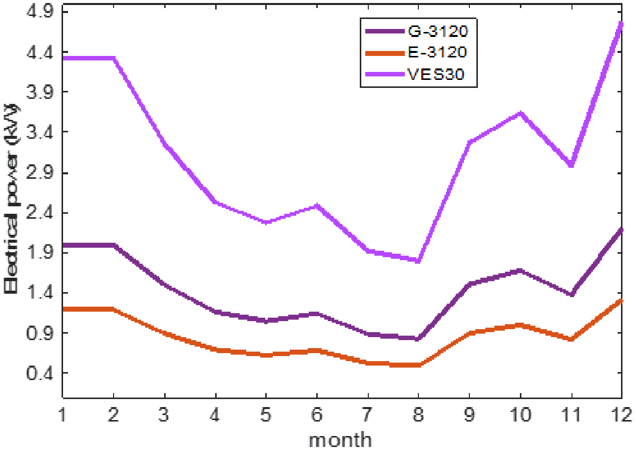

Figure 8: Monthly Power Curves for Gouro Wind Turbines

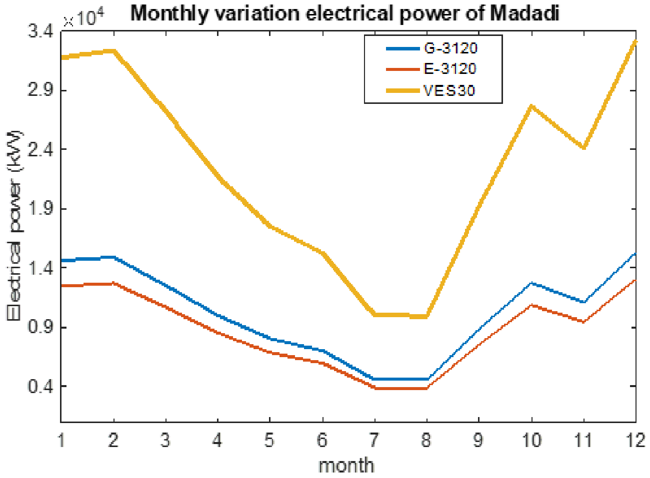

Figure 9: Power Curve for Wind Turbines at the Madadi Site

G. Capacity Factor of Three Wind Turbines

Figures 10 and 11 show the capacity factors of the wind turbines at our two study sites. For the Gouro site, there is a difference in capacity factor. It's important to remember that before any wind energy can be exploited, the capacity value must be greater than 0.26. For the Gouro site, the average capacity factor for G-3120 varies from 0.55 to 0.77. The monthly variations show that it is important to consider the seasonal nature of the power generated per wind generator. Figure 11 shows the capacity factor for the Madadi site. The capacity factors of the wind turbines vary seasonally, with averages ranging from 0.48 to 0.70. This shows that the three wind turbines are

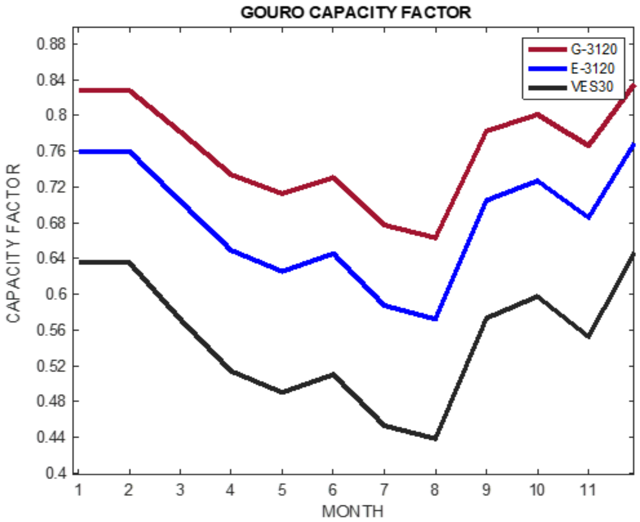

Figure 10: Capacity Factor of Individual Wind Turbines at the Gouro Site

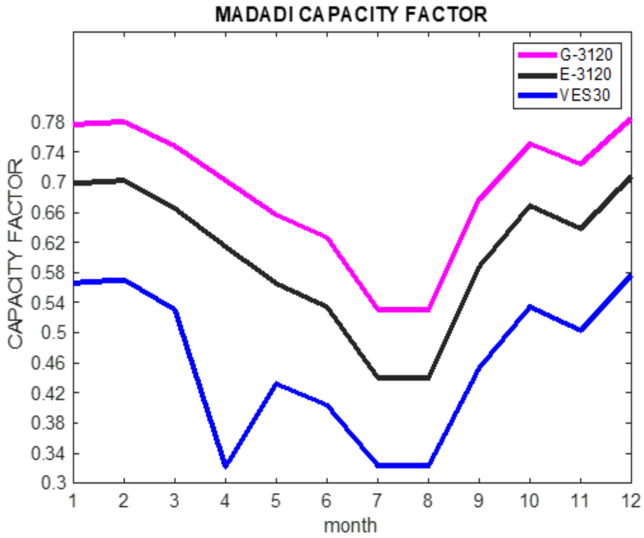

Figure 11: Capacity Factor of the Various Wind Turbines at the Madadi Site

H. Water Flow Rates for Individual Wind Turbines at The Site

Figures 12 and 13 show water flow diagrams for three wind turbines at the two sites. The diagram in figure 13 shows the monthly pumping pattern at the Madadi site. It can be seen that the VES30 wind turbine is the better performer compared with the other two over the twelve months, with an average flow rate of 21391 m3/Day, followed by the E-3120 wind turbine with an average daily flow rate of 8415.2 m3/Day. The diagrams for three wind turbines show that flows are very high from January to February, then decrease in March and reach a minimum in July-August, rising again in September to reach a maximum in December. Figure 14 shows the diagrams for the various wind turbines at the Gouro site. The monthly variation is similar to that observed at the Madadi site. The mean annual maximum flow rate is 30371 m3/day for the VES30 wind turbine, and 14011 m3/day and 8367 m3/day for the G-3120 and E-3120 wind turbines.

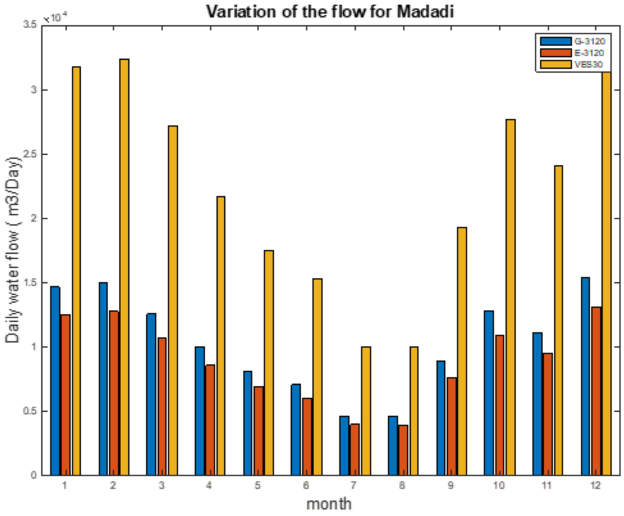

Figure 12: Daily Water Flow at Madadi Site

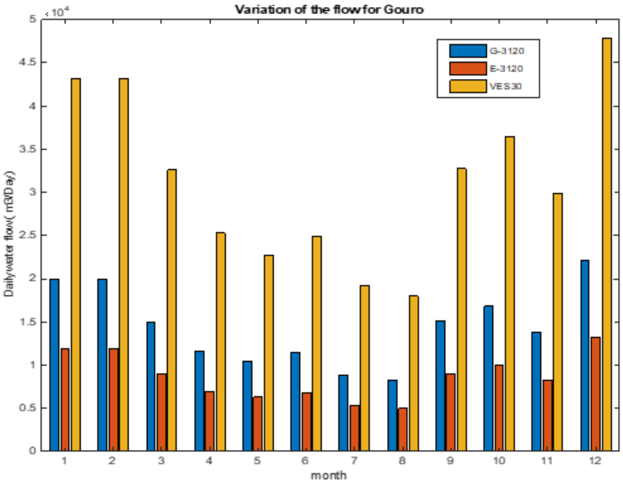

Figure 13: Flow Histogram for Three Wind Turbines at the Gouro Site

V. DISCUSSION

The wind potential of the Gouro and Madadi sites is confirmed by analysis of the Weibull statistical distribution, which gives annual wind speed scales of 6.55 m/s and 5.85 m/s respectively. Annual variations in wind speed indicate a seasonal dependence, with prevailing northeasterly winds. Seasonal capacity factors for the selected wind turbines range from 0.55 to 0.77 for Gouro and from 0.48 to 0.70 for Madadi, demonstrating the viability of wind power projects in these areas. Monthly daily water flows for the three wind turbines range from 8367 m³/day to 30371 m³/day for Gouro and from 8415 m³/day to 21391 m³/day for Madadi, underlining the significant potential for water pumping. The results obtained confirm the high potential of wind energy for the supply of drinking water and irrigation in the desert regions of Chad. Exploiting this potential would reduce dependence on traditional water sources, which are often limited and contaminated, thereby improving public health and food security for local populations.

The use of wind turbines to pump water would also contribute to the fight against poverty by creating economic opportunities and reducing the cost of access to water. The technical and economic feasibility of wind power projects in these regions has been demonstrated by the results of this study. The results of this study are in line with the findings of other studies carried out on wind energy potential in the Saharan zone of Chad [8, 9, 10]. The study makes an important contribution to understanding the wind potential of the Gouro and Madadi sites and to promoting the use of wind energy for sustainable development in these regions. The results of this study have important implications for energy policy and rural development in Chad. They justify the implementation of wind energy projects for drinking water supply and irrigation in the country's desert areas. Further studies are needed to optimize the design and sizing of wind energy systems and to assess the socio-economic impact of wind energy projects. Collaboration between scientific, technical and economic players is essential for the success of these projects and for the promotion of sustainable development in these disadvantaged regions. The study was based on wind speed data over a 10-year period, which may limit the generalizability of the results. The analysis did not consider the impact of local topography on wind potential. Future studies should focus on modeling wind energy production and assessing the environmental impact of wind power projects. Analysis of the wind energy potential of the Gouro and Madadi sites in Chad reveals significant potential for harnessing wind energy for water supply and irrigation purposes. The results demonstrate the technical and economic feasibility of wind power projects in these regions, and underline the important implications of this study for energy policy and rural development in Chad. The implementation of wind power projects would help to improve access to drinking water, promote food security and reduce poverty in these disadvantaged regions.

Based on the results of this study, it is recommended to:

- Conduct further studies to optimize the design and sizing of wind energy systems.
- Assess the socio-economic impact of wind energy projects.
- Promote collaboration between scientific, technical and economic players to ensure the success of these projects.
- Sensitize local populations to the benefits of wind energy and involve them in the project.

VI. CONCLUSION

The analysis of the wind potential of the Gouro and Madadi sites in Chad, carried out as part of this study, reveals strong potential for harnessing wind energy for water pumping purposes. The results show that winds at these sites are predominantly northeasterly, with moderate speeds and good bandwidth. Capacity factors, key indicators of wind project viability, show significant values, confirming the potential for wind power generation at these sites. Estimates of daily water flows show that the wind-powered water pumping system can provide an effective solution to water shortages in these desert regions, helping to improve living conditions for local populations. These encouraging results justify further research and the implementation of wind-powered water pumping projects in these areas. An in-depth techno-economic study is recommended to assess the feasibility and profitability of such projects in the specific context of these arid regions. Exploiting the potential of wind power for water pumping can contribute to renewable energy production and sustainable water management in these disadvantaged regions, thereby promoting socio-economic development and poverty alleviation.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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