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Vertical Characterization of the Wind Energy Resource in Kassa, Guinea, Using NASA POWER and ERA5 Data

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Abstract

This study focuses on the vertical characterization of the wind energy resource in Kassa, Guinea, using NASA POWER and ERA5 data covering the period 2020-2025. Wind characteristics established at the reference height of 10 m were extrapolated to heights of 30, 50, and 100 m using the Justus and Mikhail model. The analysis examines the evolution of mean wind speed, the Weibull parameters k and c, mean wind power density, and the maximum theoretically extractable wind energy according to the Betz limit. The results show a systematic increase in wind energy potential with height. Between 10 and 100 m, the mean wind speed increases from 3.77 to 6.72 m/s for NASA POWER and from 4.10 to 7.21 m/s for ERA5, corresponding to increases of 78.1% and 75.7%, respectively. This evolution leads to a substantial increase in energy potential: the maximum theoretically extractable annual wind energy increases from 208.76 to 1105.69 kWh/m^2 for NASA POWER and from 233.05 to 1246.98 kWh/m^2 for ERA5, corresponding to increase factors of approximately 5.30 and 5.35, respectively. Despite some monthly and seasonal differences, the two data sources show a broadly similar vertical trend. However, the values obtained at 30, 50, and 100 m result from extrapolation using the Justus and Mikhail model based on the reference data at 10 m and do not constitute independent ob-

servations at these heights. Therefore, the common vertical trend obtained for NASA POWER and ERA5 results from applying the same model to both datasets and does not constitute independent validation of either data source. These results provide a basis for further studies focusing on the selection and sizing of wind turbines adapted to the site characteristics.

Keywords

Kassa, Wind Energy, NASA POWER, ERA5, Vertical Extrapolation, Weibull Distribution, Energy Potential

1. Introduction

The development of renewable energy has become a major issue for the diversification of power systems and the reduction of their dependence on fossil resources. Among these resources, wind energy is of particular interest because of its availability and its potential for utilization in a wide range of geographical settings. However, its exploitation requires prior and sufficiently accurate characterization of the wind regime, since the available resource varies considerably over time, across space, and with height above ground level.

Wind resource assessment is based in particular on the analysis of wind speed, its statistical distribution, and the corresponding power density. The Weibull distribution remains one of the most widely used models for this characterization through its shape parameter k and scale parameter c. Recent studies confirm the relevance of this approach. Ali *et al.* [1] investigated the accuracy of different methods for estimating Weibull parameters at various heights and showed that height affects both the estimated parameters and the performance of the methods used. Kutty *et al.* [2] also analyzed wind characteristics and wind energy potential using eleven methods for estimating Weibull parameters, confirming the importance of the choice of statistical method in wind resource assessment.

The vertical dimension of the wind resource is also a determining factor. A recent study conducted in Hong Kong using multi-instrument observations highlighted significant variations in wind shear and wind energy potential with height [3]. Similarly, Spiru and Simona [4] used the Weibull distribution to characterize the wind resource and assess wind power density at a height of 80 m, emphasizing the importance of characterizing the resource at heights representative of wind energy exploitation. More recently, a study devoted to vertical extrapolation also highlighted the importance of validation and of accounting for the uncertainties associated with models used to transfer wind characteristics from one height to another [5].

In the African context, the limited availability of long-term local meteorological measurements often leads to the use of satellite-based datasets and reanalysis products. Kassem *et al.* [6], in a study covering several sites in Libya, compared different gridded datasets, including ERA5, for wind resource assessment and the esti-

mation of Weibull parameters. These approaches demonstrate the usefulness of reanalysis and satellite-based data when local observations are insufficient, while also emphasizing the need to examine differences that may arise from the data source used.

In Guinea, studies devoted to wind energy potential remain relatively limited. On the island of Kassa, Camara *et al.* [7] compared NASA POWER and ERA5 data over the period 2020-2025 and identified both marked seasonality in the wind regime and differences between the two data sources. In a complementary study, Camara *et al.* [8] further assessed the wind energy potential of Kassa at the reference height of 10 m, notably by characterizing the Weibull distribution, wind power density, and the corresponding wind energy. These two studies therefore provide a reference basis for extending the analysis of the wind resource beyond the 10 m height.

The present study builds on these previous works by specifically addressing the vertical dimension of the wind energy resource in Kassa. Its objective is to analyze the evolution of mean wind speed, the Weibull parameters k and c, mean wind power density, and the maximum theoretically extractable wind energy as the height increases from 10 m to 30, 50, and 100 m, separately for NASA POWER and ERA5. This approach aims to determine the effect of height on the energy potential of the site and to assess whether the differences between the two data sources persist with increasing height.

The specific contribution of the present study lies in extending the characterization of the Kassa wind resource to the vertical dimension. Unlike previous studies [7] [8], which focused on the characterization and comparison of wind resources at the reference height of 10 m, this study analyzes the variation in wind speeds and Weibull parameters at heights of 30, 50, and 100 m through vertical extrapolation. It thus makes it possible to assess the influence of height on wind resource characteristics and the theoretical energy potential of the site, while examining the sensitivity of the results to the extrapolation assumptions.

The remainder of this paper is organized as follows. Section 2 presents the study site, the reference data, the vertical extrapolation method, and the methods used to assess wind power and energy. Section 3 presents and discusses the evolution of wind speed, Weibull parameters, and energy potential at the different heights using NASA POWER and ERA5 data. Finally, Section 4 summarizes the main findings and presents the conclusions of the study.

2. Materials and Methods

2.1. Study Site Description and Reference

2.1.1. Location and Description of the Study Site

Kassa Island is located off the coast of Conakry, in the Îles de Loos archipelago, along the Atlantic coast of the Republic of Guinea. The reference site considered in this study is located at the geographical coordinates 9.477˚N and 13.749˚W, identical to those used in our previous studies devoted to the characterization and

assessment of the wind energy potential of Kassa [7] [8]. Its insular location and exposure to the Atlantic Ocean make it particularly suitable for the study and exploitation of wind energy resources.

Figure 1 shows the location and topographic configuration of the study area. The island has a contrasting topography, with elevations ranging from low-lying coastal areas to areas exceeding 100 m above sea level. The area considered in this study is mainly located in the central and northeastern parts of the island, which are characterized by relatively high elevations. This topographic configuration is an important factor to consider when analyzing the wind energy potential of the site.

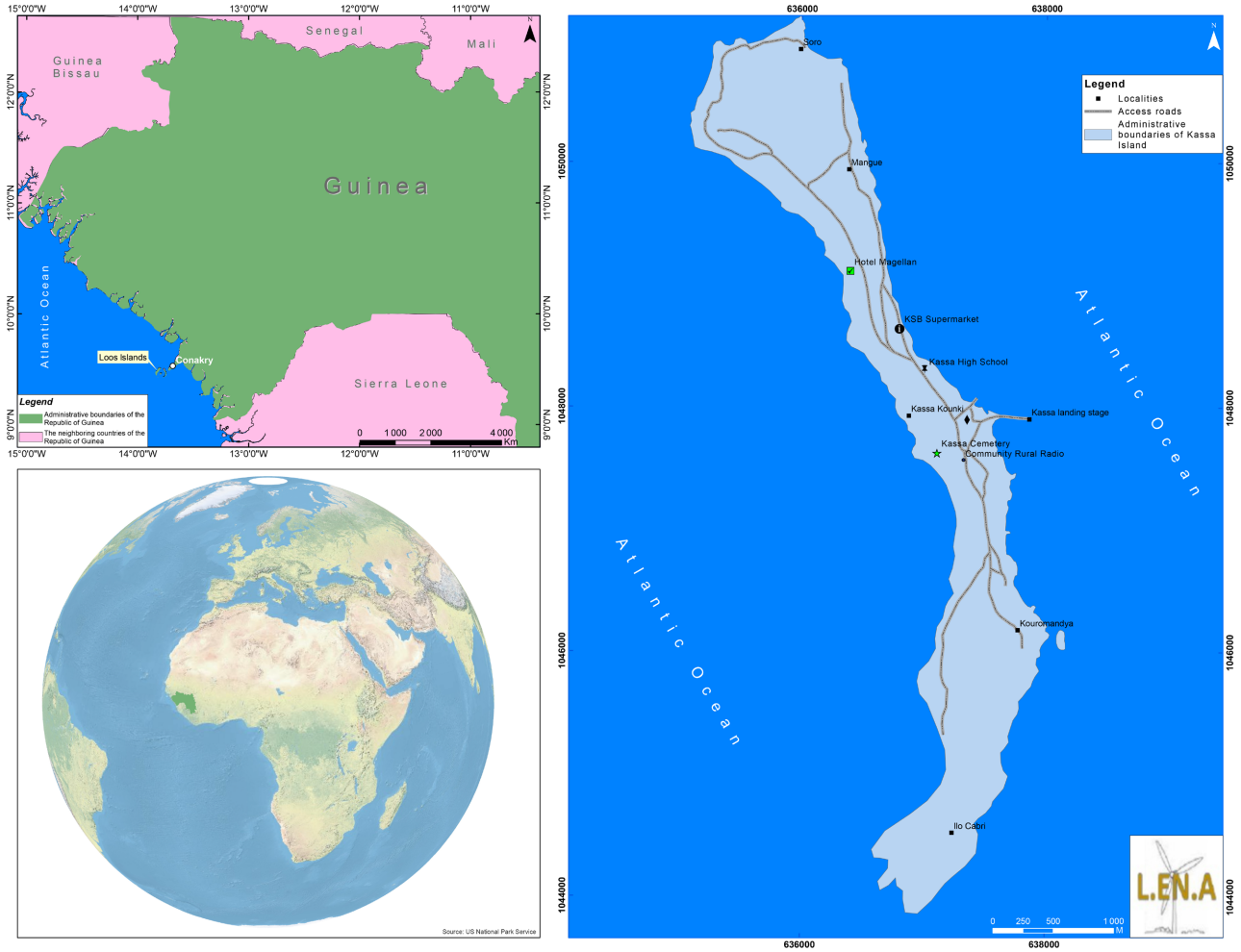


Figure 1. Location and topographic configuration of the study area on Kassa Island, Guinea.

2.1.2. Reference Wind Data

The wind data used in this study were obtained from the NASA POWER and ERA5 databases and cover the period 2020-2025. They correspond to the Kassa site, located at the geographical coordinates 9.477˚N and 13.749˚W, and are considered at the reference height of 10 m, in accordance with previous studies conducted at the same site [7] [8].

The NASA POWER data used in this study are derived from the MERRA-2-based product. The variable considered is the wind speed at 10 m (WS10M), provided directly by NASA POWER, with a spatial resolution of 0.5˚ latitude × 0.625˚ longitude. For ERA5, the zonal u_{10} and meridional v_{10} wind components at 10 m were extracted on a 0.25˚ × 0.25˚ grid. The resulting wind speed at 10 m was calculated as:

$$V_{10} = \sqrt{u_{10}^2 + v_{10}^2}$$

The data cover the period 2020-2025 and correspond to the Kassa reference point located at 9.477˚N and 13.749˚W. The resulting time series were then used to determine the monthly wind characteristics considered in the present study.

The analysis period extends from January 1, 2020, to December 31, 2025. The original time series were grouped by month to determine, for each data source, the monthly characteristics of the wind regime over the entire study period. The wind speeds presented in this study therefore correspond to multi-year monthly averages, while the Weibull parameters at 10 m are those determined from the reference data in the previous study [8]. These monthly values at 10 m constitute the input data for the extrapolation model applied at heights of 30, 50, and 100 m.

In [7], NASA POWER and ERA5 data were comparatively analyzed, particularly in terms of wind speeds and their seasonal variability. This first study established the general characteristics of the wind regime in Kassa and assessed the differences between the two data sources.

In [8], the analysis was further developed at the reference height of 10 m through the statistical characterization of the wind regime using the Weibull distribution. The shape parameter k and scale parameter c were determined from the monthly mean wind speeds and their corresponding standard deviations for NASA POWER and ERA5. The corresponding wind power and energy characteristics were also evaluated. These results at 10 m are used in the present study as reference data for analyzing their vertical evolution.

In the present study, the monthly mean wind speeds V_1 and the Weibull parameters k_1 and c_1 determined at the reference height:

$$z_1 = 10 \text{ m}$$

are used as input data for analyzing the vertical evolution of the wind resource. They are used to determine the corresponding characteristics at the following heights:

$$z_2 = 30 \text{ m}, 50 \text{ m and } 100 \text{ m}.$$

The extrapolation is performed separately for NASA POWER and ERA5 in order to preserve the specific characteristics of each data source and assess the influence of height on the wind resource in Kassa. This approach extends the results obtained at 10 m without repeating all the analyses already carried out in the two previous studies.

The following subsection presents the method adopted for vertical extrapolation and the equations used to successively determine V_2, k_2 and c_2, from the

reference characteristics V_1, k_1 and c_1.

2.2. Vertical Extrapolation of Wind Characteristics

Wind speed varies with height above ground level. Therefore, wind resource assessment requires the determination of wind characteristics at heights greater than that of the reference data. Several approaches are used for vertical extrapolation, including the power law, the logarithmic law, and methods based on the extrapolation of the parameters of the Weibull distribution [9]. The power law has the particular advantage of being compatible with the vertical extrapolation of the Weibull distribution, thus allowing the evolution of wind speed and its statistical parameters with height to be investigated jointly [9] [10].

In this study, the Justus and Mikhail model was selected because of its compatibility with the wind characteristics available at the reference height of 10 m and with the Weibull distribution used to characterize the wind regime at Kassa [10]. In particular, it has the advantage of not imposing a constant wind shear exponent, since this exponent is determined as a function of wind speed. This choice is also suited to the available data, given the absence of simultaneous local measurements at multiple heights and detailed information on surface roughness and atmospheric stability required for the application of more complex models. The model thus allows the simultaneous extrapolation of wind speed and Weibull parameters to the considered heights. However, given the coastal setting and variable topography of Kassa, the extrapolation should be regarded as a model-based estimate of the vertical profile rather than an exact representation of local effects related to surface roughness, atmospheric stability, and topographic acceleration.

The wind speed at height z_2 is determined from the known wind speed at the reference height z_1 using the following relationship [10]:

$$V_2 = V_1\left(\frac{z_2}{z_1}\right)^n \tag{1}$$

where:

- V_1: is the wind speed measured or estimated at the reference height z_1;
- V_2: is the extrapolated wind speed at the target height z_2;
- n: is the vertical wind shear exponent.

In the Justus and Mikhail model, for a reference height of 10 m, the exponent n depends on wind speed and is determined by:

$$n = 0.37 - 0.0881\ln\left(V_1\right) \tag{2}$$

Justus and Mikhail established that, for a reference height of 10 m and wind speed expressed in m/s, the coefficients 0.37 and −0.0881 can be used to represent the variation of the exponent with wind speed. This formulation therefore avoids imposing a constant value of n.

The model also allows the parameters of the Weibull distribution to be extrapolated. This feature is particularly suitable for the present study, since the shape parameter k and scale parameter c at 10 m have already been determined in [8].

The use of the Weibull distribution to statistically characterize the wind speed regime and assess wind energy potential is widely established in the literature [11].

The shape parameter at height z_2 is determined by [10]:

$$k_2 = k_1 \left[\frac{1 - 0.0881 \ln\left(\frac{z_1}{10}\right)}{1 - 0.0881 \ln\left(\frac{z_2}{10}\right)} \right] \tag{3}$$

where:

- k_1 : represents the shape parameter at the target height z_1;
- k_2 : represents the shape parameter at the reference height z_2.

The scale parameter is extrapolated as follows:

$$c_2 = c_1 \left(\frac{z_2}{z_1}\right)^m \tag{4}$$

with:

$$m = \frac{0.37 - 0.0881 \ln\left(c_1\right)}{1 - 0.0881 \ln\left(\frac{z_1}{10}\right)} \tag{5}$$

where:

- c_1 : is the Weibull scale parameter at the reference height, z_1 in m/s;
- c_2 : is the Weibull scale parameter at the target height, z_2 in m/s.

Equations (3) to (5) thus allow the parameters of the Weibull distribution to vary with height while maintaining consistency with the power law used for wind speed [9] [10]. The reference document specifically applies this procedure to *k* and *c*.

It should nevertheless be clarified that the vertical variations of *k* and *c* do not reflect the same physical behavior. The scale parameter *c*, which is directly related to the scale of wind speeds, varies with height in relation to the increase in characteristic wind speed. In contrast, *k*, which reflects the relative dispersion of the wind speed distribution, varies according to the specific empirical relationship of the Justus and Mikhail model [10] and should not be equated with the variation in mean wind speed. The values of *k* obtained at 30, 50, and 100 m therefore represent estimates derived from the extrapolation model rather than parameters determined from wind speed distributions observed at these heights.

In the present study, the reference height is set at:

$$z_1 = 10 \text{ m}$$

The wind characteristics are then successively extrapolated to the heights:

$$z_2 = 30 \text{ m}, 50 \text{ m and } 100 \text{ m}$$

These heights allow the vertical evolution of the wind resource in Kassa to be analyzed from the reference height to heights that are more representative of wind energy exploitation. The same procedure is applied separately to NASA POWER and ERA5 data in order to preserve the specific characteristics of each source and

compare their evolution with height. This approach follows the heights and procedure defined in the reference document.

2.3. Assessment of Wind Energy Potential at Different Heights

After extrapolating the wind characteristics from the reference height of 10 m, the energy potential of the site is assessed at heights of 30, 50, and 100 m. The calculations are performed separately for NASA POWER and ERA5 data in order to analyze the influence of height on the available wind power and energy and to compare the estimates obtained from the two data sources.

2.3.1. Wind Power Assessment

The kinetic power available in the wind flowing through an area AA depends mainly on the air density, the area considered, and the cube of the wind speed. It is determined by the following expression [12]:

$$P_v = \frac{1}{2}\rho \cdot A \cdot v^3 \tag{6}$$

where:

- P_v : represents the power available in the wind in W;
- P : air density in kg/m^3;
- A : area swept by the wind in m^2;
- v : wind speed in m/s.

To characterize the wind resource independently of the dimensions or characteristics of a particular wind turbine, the available wind power density is determined by:

$$P_d = \frac{P_v}{A} = \frac{1}{2}\rho v^3 \tag{7}$$

where:

- P_d : available power density in W/m^2;
- ρ : air density in kg/m^3.

▪ **Available Wind Power Density**

The available wind power density at the site represents the kinetic power carried by the wind per unit area perpendicular to the wind flow. Under standard atmospheric conditions at sea level, the air density can be taken as: ρ = 1225 kg/m.

In the present study, this standard value is adopted as a simplifying assumption to ensure a consistent assessment of wind energy potential at the different heights and for both data sources. However, the actual air density may vary notably with temperature, atmospheric pressure, humidity, and altitude. The use of a constant value of ρ therefore constitutes an approximation that may introduce uncertainty into the estimation of power density.

For a series of n observations, the mean wind power density is determined from the cube of the different observed wind speeds [13]:

$$\overline{P}_d = \frac{1}{2}\rho\left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right) = \frac{1}{2}\rho v_m^3 \tag{8}$$

where:

- $\overline{P}_d$: mean available wind power density expressed in W/m²;
- v_i : wind speed corresponding to the ith observation expressed in m/s;
- i : observation index, dimensionless;
- v_m : equivalent cubic mean wind speed, expressed in m/s;
- ρ : air density expressed in kg/m³;
- n : total number of wind-speed observations considered, dimensionless.

Accounting for the cube of wind speeds is particularly important in wind energy potential assessment because of the cubic dependence of power on wind speed. Recent studies also show that the temporal resolution and smoothing of wind speed data can significantly influence the estimation of wind power density [13].

When the wind speed regime is represented by a Weibull distribution characterized by the parameters k and c, the mean available wind power density can be expressed as:

$$\overline{P}_d = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{9}$$

where:

- $\overline{P}_d$: mean available wind power density expressed in W/m²;
- c : Weibull scale parameter expressed in m/s;
- k : Weibull shape parameter, dimensionless;
- Γ : gamma function, dimensionless.

This formulation makes it possible to directly incorporate the statistical characteristics of the wind speed distribution into the assessment of the wind resource. The use of the parameters k and c to estimate wind power density remains widely applied in recent wind energy potential assessment studies [14].

The influence of these parameters on the energy potential is notably explained by the third moment of the wind speed distribution. The scale parameter c enters to the third power (c^3) in Equation (9), whereas the shape parameter k enters through the gamma term $\Gamma\left(1+3/k\right)$. Thus, the variation in power density with height results from the combined effect of c and k, rather than solely from the increase in mean wind speed.

- **Calculation of the Maximum Theoretically Extractable Power Density According to the Betz Limit**

Since all the kinetic power available in the wind cannot be extracted, the theoretically recoverable fraction is characterized by the power coefficient C_p. The extractable or recoverable power density is expressed as [15]:

$$P_r = C_p P_d \tag{10}$$

Substituting its expression gives: P_d

$$P_r = \frac{1}{2}\rho C_p v^3 \tag{11}$$

where:

- P_r : extractable power density in W/m²;

- P_d : available power density in W/m²;
- C_p : wind-turbine power coefficient.

For an ideal turbine, the power coefficient is limited by the Betz limit:

$$C_{p,max} = \frac{16}{27} \simeq 0.593$$

The maximum theoretically extractable power density then becomes:

$$P_{r,max} = \frac{16}{27} P_d \simeq 0.593 P_d \tag{12}$$

This value represents a maximum theoretical aerodynamic limit and does not correspond to the electrical power actually produced by a real wind turbine. A recent study by Bontempo and Manna numerically confirms the validity of the Betz-Joukowsky limit and its maximum value of 16/27 under the assumptions of the model [15].

Since the present study is devoted to characterizing the wind resource at the site, it does not take into account the performance of specific wind turbine models. This applied analysis, based in particular on the technical characteristics and power curves of wind turbines, is addressed in a separate complementary study.

2.3.2. Wind Energy Assessment

- **Estimation of the Available Wind Energy at the Site**

Power characterizes the instantaneous potential of the wind, whereas the available wind energy takes into account the duration over which this power is considered. The joint assessment of wind power density and the corresponding energy therefore constitutes a commonly used approach for quantifying the wind energy resource of a site [12] [13]. In the present study, the energy assessment is carried out using the mean power densities determined at heights of 10, 30, 50, and 100 m, separately for NASA POWER and ERA5 data.

For each month mm, the available wind energy is determined from the corresponding mean available power density and the number of hours in the month considered [12]:

$$E_{d,m} = \frac{\overline{P}_{d,m} T_m}{1000} \tag{13}$$

where:

- $E_{d,m}$: available wind energy for month m in kWh/m²;
- $\overline{P}_{d,m}$: mean available power density for month m in W/m²;
- T_m : number of hours in the month considered in h.

The monthly duration is determined by: $T_m = 24 N_m$.

where:

- N_m : represents the number of days in the month;
- T_m : in the reference calendar year it is equal to:
  - 744 h for a 31-day month;
  - 720 h for a 30-day month;
  - 672 h for February.

The annual available wind energy is then obtained by summing the available energies of the twelve months:

$$E_{d,ann} = \sum_{m=1}^{12} E_{d,m} \tag{14}$$

This approach makes it possible to account for the specific duration of each month and the seasonal variability of the resource, rather than uniformly applying an annual duration of 8760 h to each monthly mean power density.

- **Estimation of the Maximum Theoretical Energy According to the Betz Limit**

To complete the resource assessment, the maximum theoretically extractable fraction is also determined according to the Betz-Joukowsky limit. This limit sets the maximum theoretical value of the power coefficient of an ideal turbine at 16/27, or approximately 0.593 [15]. Recent studies have numerically confirmed the validity of this limit under the assumptions of the actuator disk model [15].

The maximum theoretically extractable power density for month m is therefore given by:

$$P_{Betz,m} = 0.593 P_{d,m} \tag{15}$$

The corresponding maximum theoretical energy for month m is then determined by:

$$E_{Betz,m} = \frac{P_{Betz,m} T_m}{1000} = \frac{0.593 P_{d,m} T_m}{1000} \tag{16}$$

The annual maximum theoretical energy is finally obtained by summing the twelve monthly values:

$$E_{Betz,ann} = \sum_{m=1}^{12} E_{Betz,m} \tag{17}$$

As an example, for a 31-day month, corresponding to 744 h, a mean maximum theoretically extractable power density of 65.5 W/m^2 corresponds to a monthly energy of:

$$E_m = \frac{65.5 \times 744}{1000} = 48.73 \text{ kWh/m}^2$$

The annual energy is then obtained by summing the twelve-monthly energy values calculated by taking into account the actual number of hours in each month.

In the present study, Equations (8), (9), and (12) are used to determine the mean available and maximum theoretically extractable wind power densities at heights of 10, 30, 50, and 100 m. Equations (13) to (17) are then applied to determine the corresponding monthly and annual energies. The calculations are performed separately for NASA POWER and ERA5 in order to analyze the vertical evolution of the wind energy potential of Kassa.

3. Results and Discussion

The results presented in this section describe the vertical evolution of the wind

resource in Kassa between the reference height of 10 m and the heights of 30, 50, and 100 m. The analysis successively focuses on the mean wind speed, the Weibull parameters k and c, the mean maximum theoretically extractable power density, and the corresponding energy according to the Betz limit. The results obtained from NASA POWER and ERA5 are analyzed separately and then compared in order to assess both the effect of height and that of the data source.

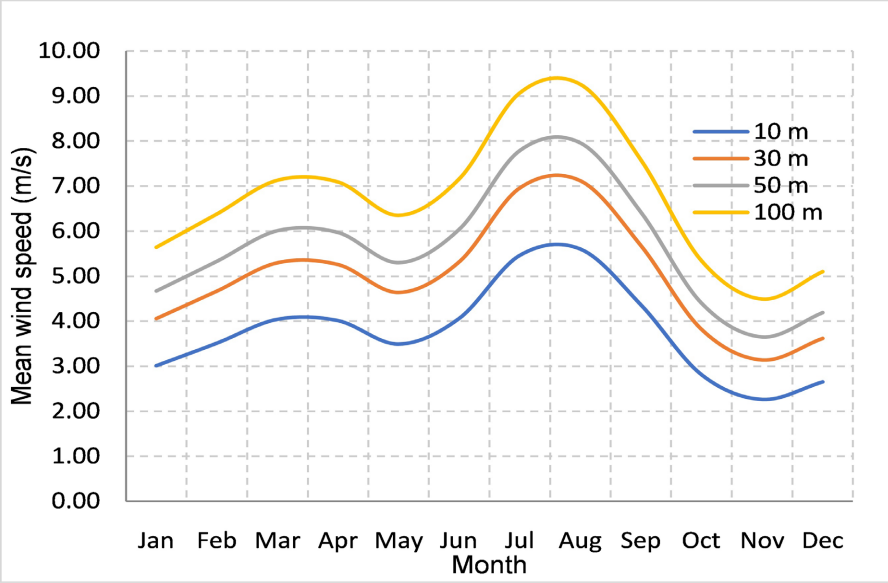
3.1. Vertical Evolution of Wind Speed

The monthly mean wind speeds at 10 m used as reference data were obtained from NASA POWER and ERA5 and were characterized in our previous studies devoted to the wind resource in Kassa [7] [8]. Based on these values, wind speeds were extrapolated to heights of 30, 50, and 100 m using the Justus and Mikhail model presented in the methodology (Table 1).

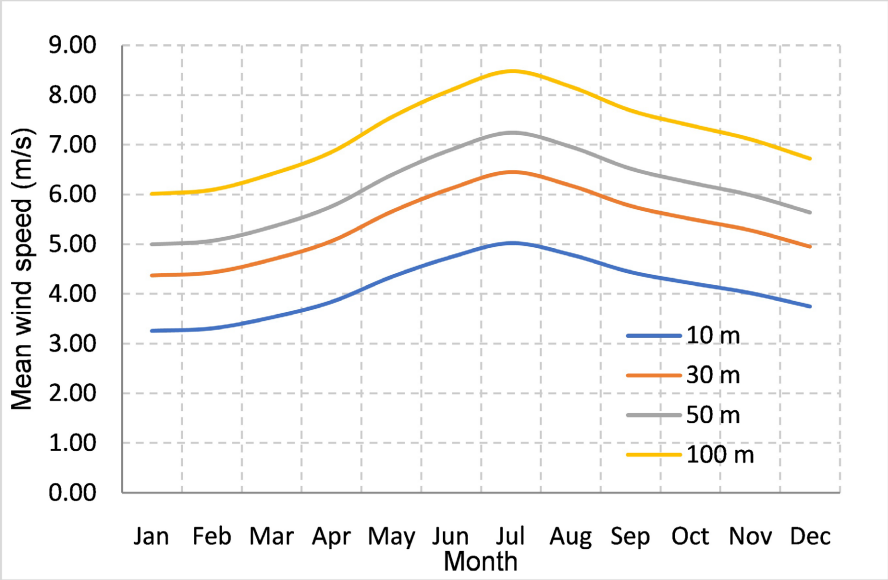
Table 1. Presents the values obtained from the two data sources.

Month	$\bar{v}$ in (m/s) at 10 M		$\bar{v}$ in (m/s) at 30 M		$\bar{v}$ in (m/s) at 50 M		$\bar{v}$ in (m/s) at 100 M	
	NASA	ERA5	NASA	ERA5	NASA	ERA5	NASA	ERA5
January	3.01	3.26	4.06	4.37	4.67	5.00	5.64	6.01
February	3.51	3.31	4.67	4.43	5.33	5.07	6.38	6.09
March	4.04	3.53	5.30	4.69	6.01	5.35	7.13	6.41
April	4.01	3.84	5.26	5.06	5.97	5.76	7.09	6.85
May	3.49	4.34	4.64	5.65	5.30	6.39	6.35	7.55
June	4.06	4.74	5.32	6.12	6.04	6.90	7.16	8.10
July	5.46	5.02	6.96	6.45	7.79	7.24	9.07	8.48
August	5.60	4.79	7.12	6.18	7.96	6.96	9.26	8.17
September	4.36	4.44	5.68	5.77	6.42	6.52	7.58	7.69
October	2.81	4.22	3.82	5.51	4.40	6.24	5.34	7.39
November	2.26	4.02	3.14	5.28	3.65	5.99	4.49	7.11
December	2.65	3.75	3.62	4.95	4.19	5.64	5.10	6.72

The results show a systematic increase in wind speed with height for both data sources. Between 10 and 100 m, the mean wind speed increases from 3.77 to 6.72 m/s for NASA POWER (+78.1%) and from 4.10 to 7.21 m/s for ERA5 (+75.7%). The seasonal pattern remains broadly preserved, with maximum values occurring in July to August, reaching 9.26 m/s for NASA POWER and 8.48 m/s for ERA5 at 100 m. However, differences between the two data sources persist depending on the month. The increase in wind speeds at greater heights therefore suggests a more pronounced increase in wind energy potential.



(a) NASA POWER



(b) ERA5

Figure 2. Monthly evolution of mean wind speed at heights of 10, 30, 50, and 100 m.

Figure 2 clearly highlights the increase in mean wind speed with height for both data sources while preserving the seasonality of the wind regime. The highest wind speeds are generally observed between June and September, particularly at 100 m.

3.2. Vertical Evolution of Weibull Parameters

The vertical evolution of the wind regime is also analyzed through the parameters of the Weibull distribution. The shape parameter k and scale parameter c, determined at 10 m in the previous study [8], were extrapolated to heights of 30, 50, and 100 m using the relationships presented in the methodology.

- **Weibull Shape Parameter *k***

Table 2 presents the monthly values of the Weibull shape parameter *k* at the four heights considered for NASA POWER and ERA5 data.

Table 2. Monthly evolution of the Weibull shape parameter *k* at 10, 30, 50, and 100 m.

Month	Shape Parameter *k* at 10 m		Shape Parameter *k* at 30 m		Shape Parameter *k* at 50 m		Shape Parameter *k* at 100 m	
	k_{nasa}	k_{era}	k_{nasa}	k_{era}	k_{nasa}	k_{era}	k_{nasa}	k_{era}
January	16.82	16.49	18.62	18.26	19.60	19.21	21.10	20.69
February	32.20	18.10	35.65	20.04	37.52	21.09	40.39	22.71
March	30.11	15.11	33.34	16.73	35.08	17.61	37.77	18.96
April	33.99	26.29	37.63	29.11	39.61	30.63	42.64	32.98
May	33.03	79.13	36.57	87.61	38.49	92.20	41.44	99.27
June	17.97	18.88	19.90	20.90	20.94	22.00	22.54	23.68
July	14.05	33.79	15.56	37.41	16.37	39.37	17.63	42.39
August	23.73	58.39	26.27	64.65	27.65	68.04	29.77	73.25
September	21.42	31.96	23.72	35.38	24.96	37.24	26.87	40.09
October	11.45	29.05	12.68	32.16	13.34	33.85	14.36	36.44
November	15.30	15.67	16.94	17.35	17.83	18.26	19.19	19.66
December	13.44	13.23	14.88	14.65	15.66	15.42	16.86	16.60

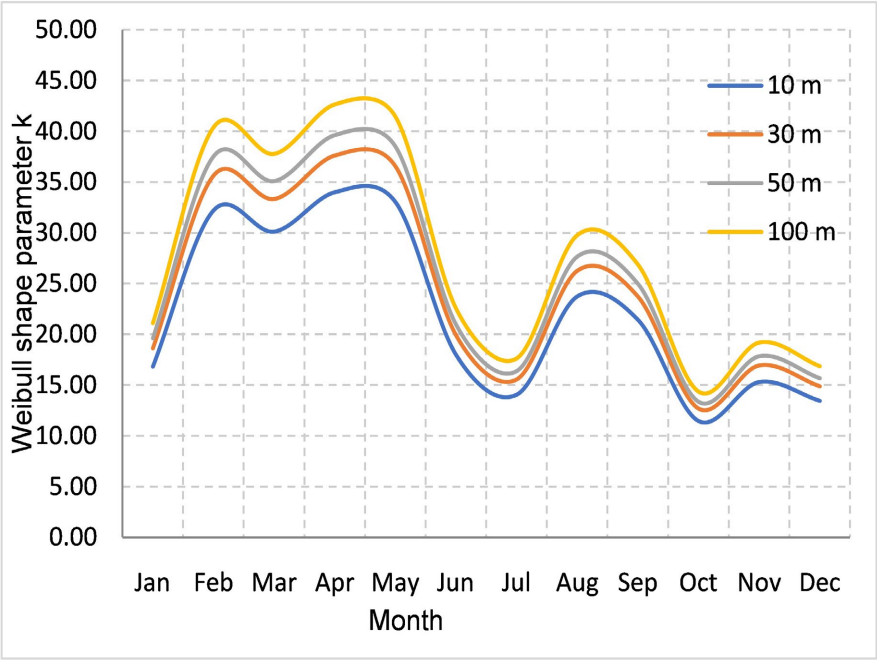
The results show a progressive increase in the shape parameter *k* with height for both data sources. However, differences between NASA POWER and ERA5 persist: for example, between 10 and 100 m, *k* increases from 33.03 to 41.44 for NASA POWER, compared with 79.13 to 99.27 for ERA5 in May, and from 14.05 to 17.63, compared with 33.79 to 42.39 in July. High values of *k* indicate a low relative dispersion of wind speeds, but do not constitute an indicator of the goodness of fit of the Weibull distribution [11] [14].

The particularly high values of *k* observed for certain months should, however, be interpreted by taking into account the nature of the data used. Since the Weibull parameters at 10 m were determined from monthly characteristics, temporal aggregation may reduce the apparent dispersion of wind speeds compared with that observed at finer time steps and may therefore contribute to high values of k. These values thus indicate a strong concentration of wind speeds around their mean value and should not be interpreted as representative of short-term wind variability.

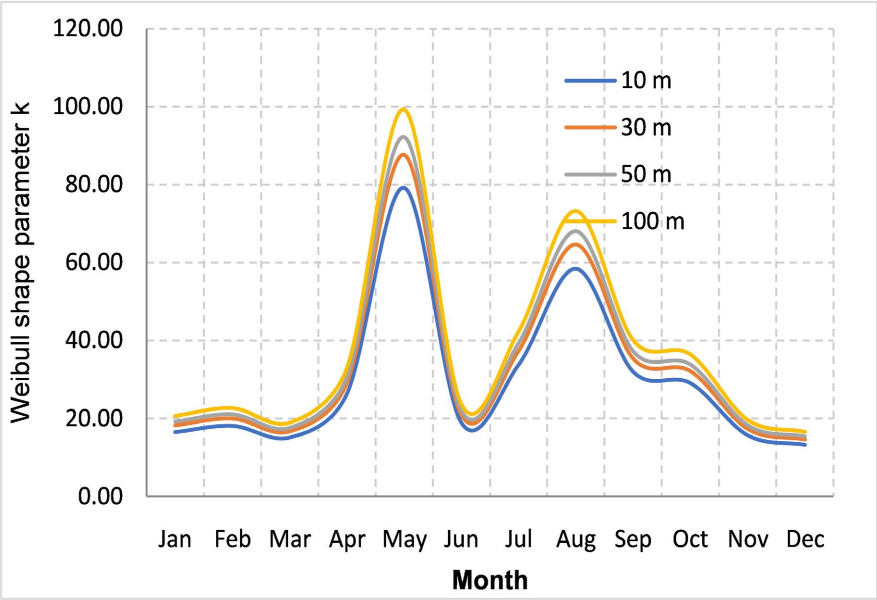
Figure 3 shows an increase in the Weibull shape parameter *k* with height for both data sources. However, the profiles exhibit marked seasonal differences, with ERA5 showing particularly high values in May and August.

- **Weibull Shape Parameter *c***

The scale parameter *c*, which is directly associated with the characteristic level of wind speeds, also varies with height. The values obtained are presented in Table 3.



(a) NASA POWER



(b) ERA5

Figure 3. Monthly evolution of the Weibull shape parameter k at heights of 10, 30, 50, and 100 m.

Table 3. Evolution of the Weibull scale parameter c at 10, 30, 50, and 100 m for NASA POWER and ERA5 (m/s).

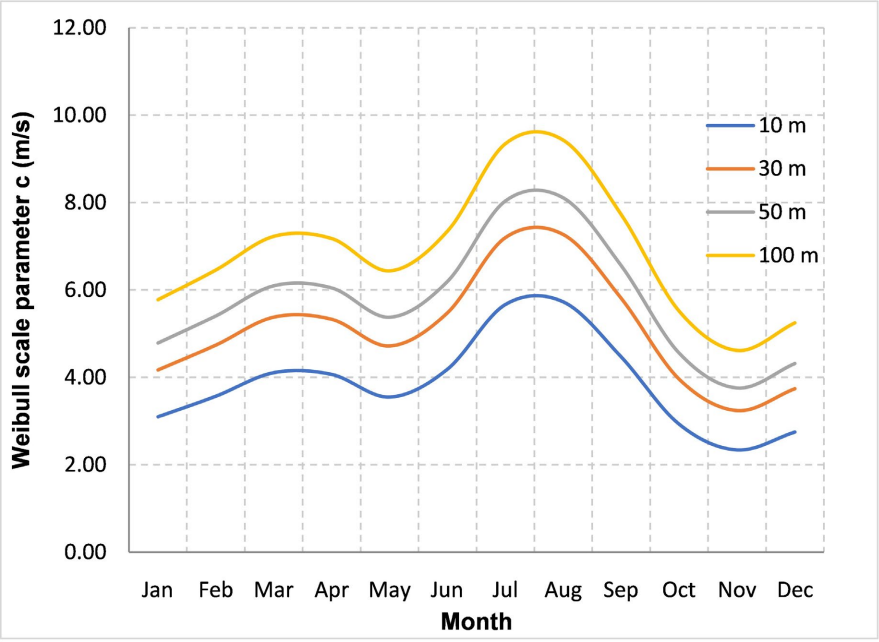
Month	Scale Parameter c (m/s) at 10 m		Scale Parameter c (m/s) at 30 m		Scale Parameter c (m/s) at 50 m		Scale Parameter c (m/s) at 100 m	
	c_{nasa}	c_{era}	c_{nasa}	c_{era}	c_{nasa}	c_{era}	c_{nasa}	c_{era}
January	3.10	3.36	4.17	4.49	4.79	5.13	5.78	6.16

Continued

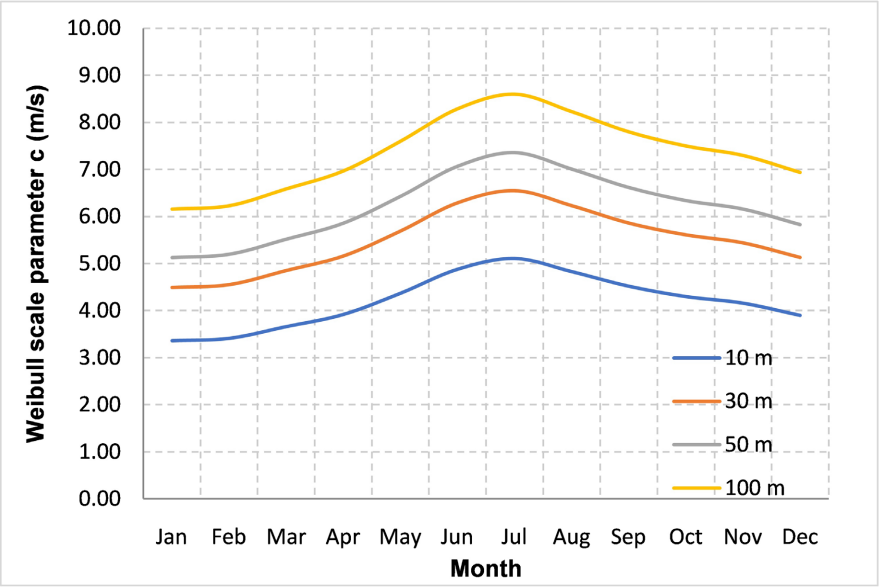
February	3.57	3.41	4.74	4.55	5.41	5.20	6.46	6.23
March	4.11	3.66	5.38	4.85	6.10	5.52	7.23	6.59
April	4.07	3.92	5.33	5.16	6.05	5.86	7.18	6.97
May	3.55	4.37	4.72	5.69	5.38	6.43	6.44	7.60
June	4.19	4.88	5.48	6.29	6.20	7.07	7.35	8.29
July	5.67	5.11	7.20	6.55	8.04	7.36	9.35	8.60
August	5.73	4.83	7.27	6.23	8.11	7.01	9.43	8.23
September	4.47	4.52	5.81	5.86	6.56	6.62	7.73	7.80
October	2.93	4.30	3.96	5.61	4.56	6.34	5.52	7.50
November	2.34	4.16	3.24	5.44	3.76	6.16	4.62	7.30
December	2.75	3.90	3.74	5.13	4.32	5.83	5.25	6.94

The scale parameter c increases steadily with height for both data sources, consistently with the evolution of mean wind speeds. At 100 m, the maximum values are observed in July to August, reaching 9.43 m/s for NASA POWER and 8.60 m/s for ERA5. This increase reflects a shift of the Weibull distribution toward higher wind speeds and thus contributes to the increase in wind energy potential with height [14].

Figure 4 confirms a steady increase in the scale parameter c with height for both data sources. The highest values are mainly observed in July and August, consistent with the seasonal evolution of wind speeds.



(a) NASA POWER



(b) ERA5

Figure 4. Monthly evolution of the Weibull scale parameter c at heights of 10, 30, 50, and 100 m.

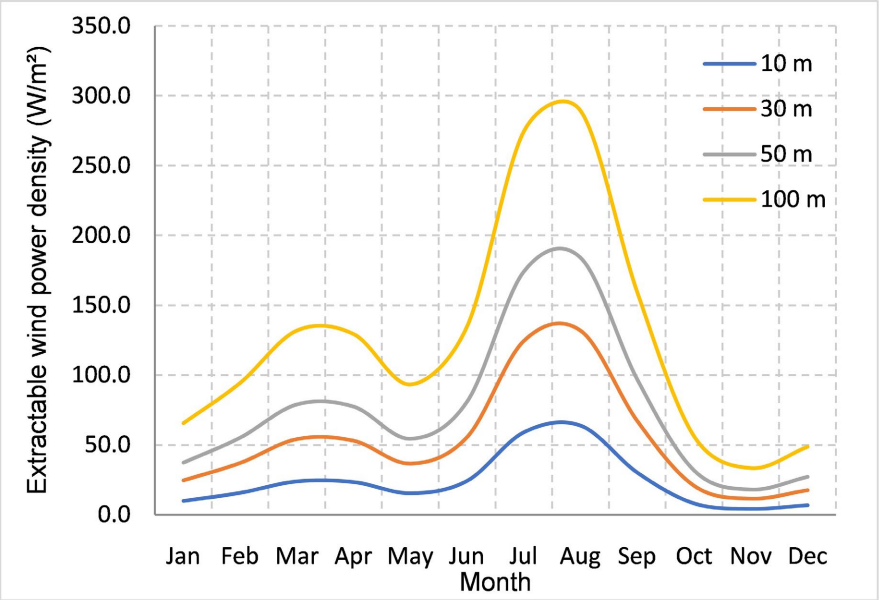
3.3. Vertical Evolution of Wind Power

The mean maximum theoretically extractable power density according to the Betz limit was assessed at heights of 10, 30, 50, and 100 m, based on the wind resource characteristics obtained from NASA POWER and ERA5. The corresponding monthly results are presented in Table 4.

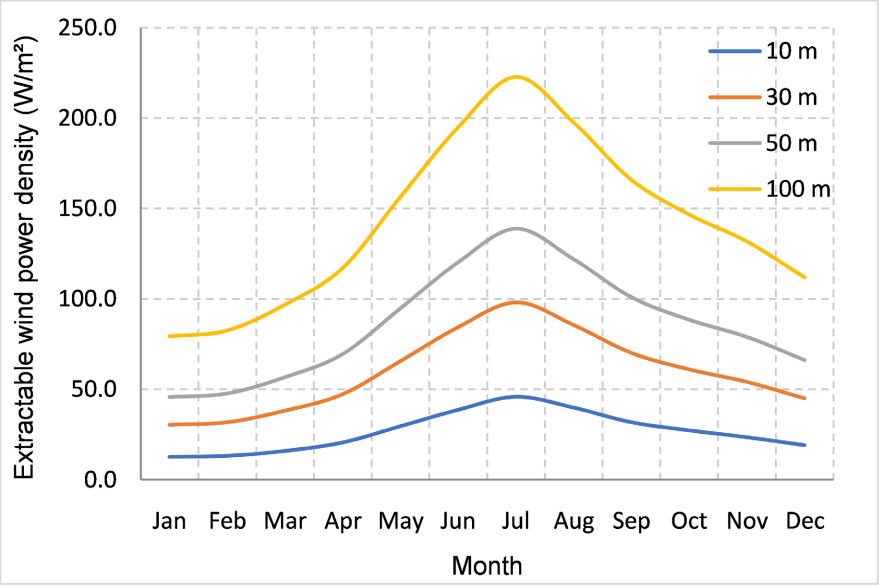
Table 4. Evolution of the mean maximum theoretically extractable power density according to the Betz limit at 10, 30, 50, and 100 m for NASA POWER and ERA5.

Month	Extractable Power Density P_r (W/m²) at 10 m		Extractable Power Density P_r (W/m²) at 30 m		Extractable Power Density P_r (W/m²) at 50 m		Extractable Power Density P_r (W/m²) at 100 m	
	P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}
January	9.9	12.6	24.5	30.4	37.2	45.7	65.5	79.3
February	15.7	13.2	37.0	31.8	55.1	47.7	94.4	82.5
March	23.9	15.9	54.1	38.2	78.9	56.7	131.9	96.8
April	23.4	20.6	52.9	47.3	77.3	69.5	129.3	117.1
May	15.4	29.6	36.5	65.6	54.3	94.8	93.2	156.4
June	24.3	38.7	55.6	84.3	81.0	120.3	135.0	194.9
July	59.1	45.9	124.5	98.0	174.2	138.9	274.7	222.8
August	63.8	39.9	131.7	85.5	183.9	122.0	289.2	197.6
September	30.1	31.8	66.9	70.1	96.6	101.0	159.0	165.9
October	8.1	27.3	20.6	61.0	31.5	88.5	56.0	146.7
November	4.2	23.5	11.4	54.1	17.9	79.0	33.3	131.8
December	6.8	19.1	17.5	45.0	27.0	66.2	48.6	111.9

The results show a strong increase in power density with height for both data sources. For NASA POWER, the highest values are observed in July and August; in August, they increase from 63.8 W/m² at 10 m to 289.2 W/m² at 100 m. For ERA5, high levels are also obtained in June and July, reaching 194.9 and 222.8 W/m², respectively, at 100 m.



(a) NASA POWER



(b) ERA5

Figure 5. Monthly evolution of the maximum theoretically extractable mean power density according to the Betz limit at heights of 10, 30, 50, and 100 m.

Seasonal differences between the two data sources persist with height: NASA POWER notably provides higher values in July to August, whereas ERA5 predom-

inates during several other months, particularly from October to January. These results confirm that increasing height substantially improves the wind power potential of Kassa, while the data source continues to influence its estimation.

These seasonal differences may notably be related to the specific characteristics of the two data sources, including the atmospheric models used, the assimilation methods, and their spatial resolutions. They may lead to different representations of seasonal wind variations at the Kassa site. However, in the absence of in situ measurements that would allow the two data sources to be distinguished, these differences should be interpreted with caution.

Figure 5 highlights a strong increase in extractable power density with height. The maximum values are observed mainly in July to August for NASA POWER, whereas ERA5 exhibits a broader seasonal distribution.

3.4. Vertical Evolution of Wind Energy

The maximum theoretically extractable wind energy according to the Betz limit was determined for each month at heights of 10, 30, 50, and 100 m, taking into account the actual duration of each month. The monthly values, together with the annual totals obtained for NASA POWER and ERA5, are presented in Table 5.

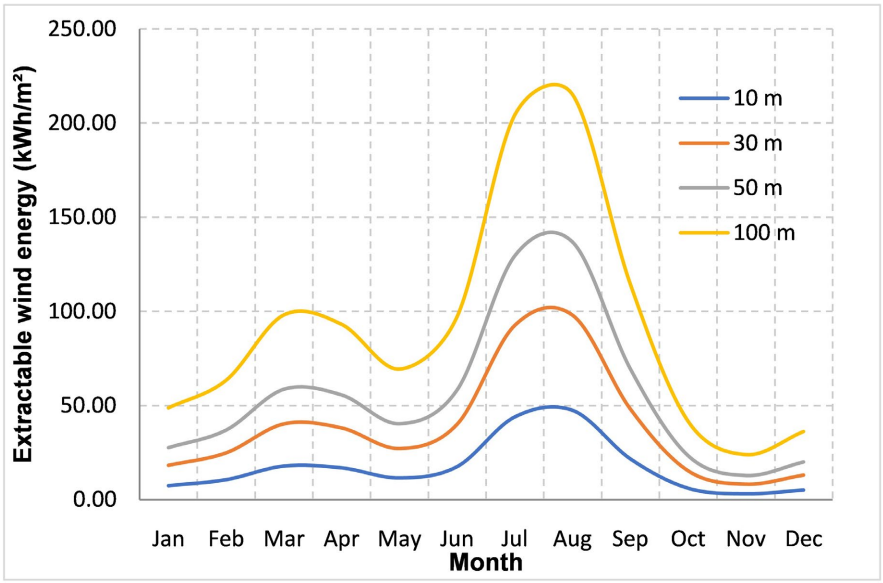
Table 5. Evolution of the maximum theoretically extractable wind energy according to the Betz limit at 10, 30, 50, and 100 m for NASA POWER and ERA5.

Month	T_m (h)	Extractable Energy E_r (kWh/m²) at 10 m		Extractable Energy E_r (kWh/m²) at 30 m		Extractable Energy E_r (kWh/m²) at 50 m		Extractable Energy E_r (kWh/m²) at 100 m	
		P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}	P_{r_nasa}	P_{r_era}
January	744	7.37	9.35	18.23	22.62	27.68	34.00	48.73	59.00
February	672	10.56	8.85	24.86	21.37	37.03	32.05	63.44	55.44
March	744	17.82	11.87	40.25	28.42	58.70	42.18	98.13	72.02
April	720	16.86	14.82	38.09	34.06	55.66	50.04	93.10	84.31
May	744	11.47	22.06	27.16	48.81	40.40	70.53	69.34	116.36
June	720	17.51	27.84	40.03	60.70	58.32	86.62	97.20	140.33
July	744	43.99	34.19	92.63	72.91	129.60	103.27	204.38	165.76
August	744	47.47	29.69	97.98	63.61	136.82	90.77	215.16	147.01
September	720	21.65	22.89	48.17	50.47	69.55	72.72	114.48	119.45
October	744	6.00	20.29	15.33	45.38	23.44	65.84	41.66	109.14
November	720	3.03	16.95	8.21	38.95	12.89	56.88	23.90	94.90
December	744	5.03	14.25	13.02	33.48	20.09	49.25	36.16	83.25
Annual Total	**8760**	**208.76**	**233.05**	**463.95**	**520.78**	**670.17**	**754.16**	**1105.69**	**1246.98**

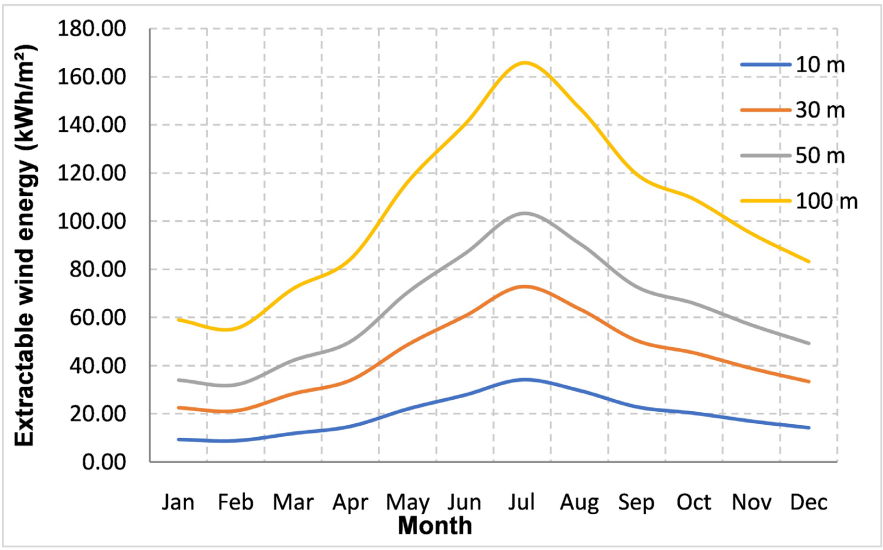
The results confirm a very substantial increase in wind energy with height. For NASA POWER, the annual total increases from 208.76 kWh/m² at 10 m to 1105.69 kWh/m² at 100 m, corresponding to an increase by a factor of approximately 5.30. For ERA5, it increases from 233.05 to 1246.98 kWh/m², corresponding to approx-

imately 5.35 times the value obtained at 10 m.

This substantial increase in annual energy with height does not result from a proportional relationship with the increase in wind speed. It is mainly explained by the cubic dependence of wind power on wind speed ($P \propto v^3$). Thus, a relatively moderate increase in wind speed with height can lead to a much greater increase in power density and, consequently, in the corresponding theoretical energy.



(a) NASA POWER



(b) ERA5

Figure 6. Monthly evolution of the maximum theoretically extractable wind energy according to the Betz limit at heights of 10, 30, 50, and 100 m.

Seasonality remains pronounced: at 100 m, NASA POWER reaches its maximum values in July and August, with 204.38 and 215.16 kWh/m², respectively, while

ERA5 also exhibits high levels during the wet season. Despite some monthly differences, both data sources therefore show that greater heights offer a substantially higher energy potential. However, these values represent maximum theoretical limits according to Betz and not the actual electrical production of a wind turbine.

Figure 6 shows a substantial increase in extractable energy with height for both data sources. Seasonality remains pronounced, with particularly high energy levels during the period from June to September, especially at 100 m.

3.5. Comparative Synthesis of Wind Energy Potential According to Height

The combined analysis of the results highlights a consistent vertical evolution of the different characteristics of the wind resource in Kassa. Increasing the height from 10 to 100 m first leads to a systematic increase in mean wind speeds. The mean monthly values thus increase from approximately 3.77 to 6.72 m/s for NASA POWER and from 4.10 to 7.21 m/s for ERA5, corresponding to increases of approximately 78.1% and 75.7%, respectively.

This evolution is also reflected in the Weibull parameters, particularly the scale parameter c, which systematically increases with height. The effect becomes much more pronounced in terms of energy because of the cubic dependence of power on wind speed. Thus, an increase of approximately 76% - 78% in mean wind speed between 10 and 100 m results in an increase by a factor of more than five in the annual maximum theoretically extractable energy.

The comparison of the annual values clearly summarizes this effect:

Table 6. Comparative summary of the maximum theoretically extractable wind energy and relative differences between NASA POWER and ERA5 according to height.

Source	10 m (kWh/m²)	30 m (kWh/m²)	50 m (kWh/m²)	100 m (kWh/m²)	Increase 10 - 100 m
NASA	208.76	463.95	670.17	1105.69	+429.6%
ERA5	233.05	520.78	754.16	1246.98	+435.1%
Difference between ERA5 and NASA (%)	+11.6%	+12.3%	+12.5%	+12.8%	-

$$\Delta E(\%) = \frac{E_{ERA5} - E_{NASA}}{E_{NASA}} \cdot 100$$

where:

- E_{ERA5} and E_{NASA}: represent the maximum theoretically extractable annual energies estimated from ERA5 and NASA POWER data, respectively;
- ΔE: is the relative difference between the two data sources.

Table 6 confirms the marked increase in energy potential with height for both data sources. Between 10 and 100 m, the maximum theoretically extractable energy increases by 429.6% for NASA POWER and 435.1% for ERA5, corresponding to factors of approximately 5.30 and 5.35, respectively. The direct comparison of

the two data sources shows that ERA5 systematically provides higher annual estimates than NASA POWER. The relative differences, calculated with respect to NASA POWER, are 11.6% at 10 m, 12.3% at 30 m, 12.5% at 50 m, and 12.8% at 100 m. These results show that the relative difference between the two data sources remains fairly similar across the different heights, with a slight increase from 10 to 100 m.

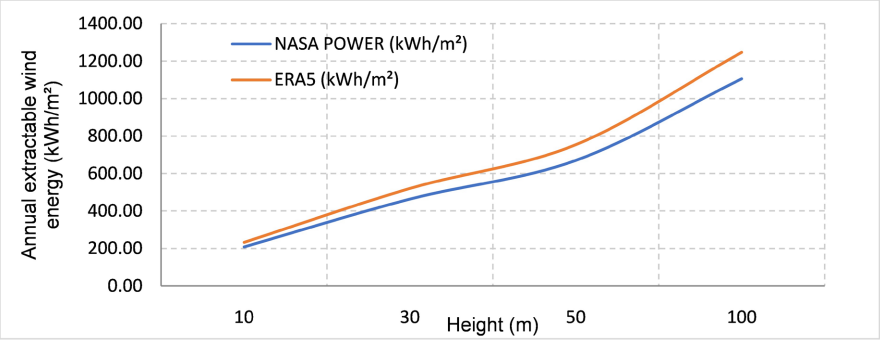


Figure 7. Evolution of the annual maximum theoretically extractable wind energy according to height for NASA POWER and ERA5.

Figure 7 confirms a continuous and pronounced increase in annual energy with height for both data sources. The trends are very similar, with ERA5 values slightly higher than those of NASA POWER at all the heights investigated.

3.6. Sensitivity Analysis of Extrapolation to 100 m

To assess the sensitivity of the results to the choice of extrapolation model, the estimates obtained at 100 m using the Justus and Mikhail model were compared with two alternative scenarios based on the power law with constant wind shear exponents: $n = 1/9 \approx 0.11$ and $n = 1/7 \approx 0.143$ [16].

The 1/7 power law is also commonly used for vertical wind extrapolation and has notably been applied to the assessment of the wind potential of a coastal site [17]. However, the wind shear exponent may exhibit significant variability depending on site conditions and atmospheric stability, particularly in offshore environments [18]. The two selected values are therefore used here as sensitivity scenarios rather than as universally representative values for the Kassa site.

For each of the two sensitivity scenarios, the mean wind speed at 100 m is calculated from the power law according to Equation (1):

$$V_{100} = V_{10}\left(\frac{100}{10}\right)^{n}$$

where:

- V_{100}: mean wind speed extrapolated to 100 m;
- V_{10}: reference mean wind speed at 10 m;
- n: wind shear exponent considered.

The calculations are performed using: $n = 1/9 \approx 0.11$ and $n = 1/7 \approx 0.143$.

Table 7. Sensitivity analysis of the mean wind speed extrapolated to 100 m.

Source	$n = 1/9 \approx 0.11$	$n = 1/7 \approx 0.143$	Justus-Mikhail
NASA POWER	4.86 m/s	5.24 m/s	6.72 m/s
ERA5	5.28 m/s	5.70 m/s	7.21 m/s

The results show that (Table 7) the wind speeds estimated at 100 m are sensitive to the assumed wind shear conditions. For NASA POWER, the mean wind speed at 100 m ranges from 4.86 to 5.24 m/s under the two alternative scenarios, compared with 6.72 m/s using the Justus and Mikhail model.

For ERA5, it ranges from 5.28 to 5.70 m/s, compared with 7.21 m/s using the Justus-Mikhail model.

This sensitivity has a greater impact on the estimation of energy potential because wind power varies proportionally to the cube of wind speed ($P \propto V^3$), according to the relationship presented in the methodology (Equation (6)). These results highlight that the estimates at 100 m depend on the selected extrapolation model and should subsequently be confirmed by in situ measurements at multiple heights.

4. Conclusions

This study characterized the vertical evolution of the wind resource in Kassa, Guinea, between 10 and 100 m, using NASA POWER and ERA5 data. The analysis focused on the evolution of mean wind speed, the Weibull parameters k and c, as well as the corresponding energy potential.

The results show a systematic improvement in wind resource characteristics with height. Between 10 and 100 m, the mean wind speed increases from 3.77 to 6.72 m/s for NASA POWER and from 4.10 to 7.21 m/s for ERA5, corresponding to increases of 78.1% and 75.7%, respectively. This evolution is accompanied by an increase in the Weibull parameters and, more markedly, in the energy potential.

The annual maximum theoretically extractable wind energy according to the Betz limit thus increases from 208.76 to 1105.69 kWh/m^2 for NASA POWER and from 233.05 to 1246.98 kWh/m^2 for ERA5 between 10 and 100 m, corresponding to increases by factors of approximately 5.30 and 5.35, respectively. Despite some monthly differences, NASA POWER and ERA5 therefore exhibit an overall consistent vertical evolution, with ERA5 providing slightly higher annual energy values than NASA POWER at the different heights investigated.

These results highlight the determining influence of height on the wind energy potential of Kassa and show that greater heights, particularly 100 m, offer substantially higher energy conditions than those observed at the reference height of 10 m. However, the values obtained according to the Betz limit represent maximum theoretical limits and do not directly represent the electrical energy production of an actual wind turbine.

It should be emphasized, however, that the values obtained at 30, 50, and 100 m result from extrapolation using the Justus and Mikhail model based on the reference data at 10 m and do not constitute independent observations at these heights. The common vertical trend observed for NASA POWER and ERA5 therefore re-

sults from applying the same model to both datasets and does not constitute independent validation of either data source.

This vertical characterization therefore provides a basis for further studies devoted to the selection of wind turbines suited to the wind regime of Kassa, the assessment of their electrical energy production, and the techno-economic analysis of their implementation.

Author Contributions

This study was carried out through scientific collaboration involving research design, processing and analysis of NASA POWER and ERA5 wind data, vertical extrapolation of wind characteristics to heights of 30, 50, and 100 m, assessment of theoretical wind energy potential, interpretation of the results, and critical revision of the manuscript.

Contributions were allocated according to the authors' respective responsibilities and involvement at different stages of the research. The table below presents the proposed main contributions of each author.

No.	Author	Contributions
1	Mohamed Ansoumane Camara	Study conception and coordination; definition of the research problem and methodology; supervision of NASA POWER and ERA5 data processing; guidance on vertical extrapolation using the Justus and Mikhail model; supervision of wind energy potential assessment; analysis and interpretation of results; manuscript drafting, revision, and final validation.
2	Kadiatou Aïssatou Barry	Support for scientific coordination; literature review; contribution to wind data processing and statistical calculations; participation in energy results analysis; preparation of tables and figures; contribution to manuscript drafting and revision.
3	Ouaïdou Emmanuel	Processing and analysis of NASA POWER and ERA5 wind data; contribution to extrapolation of wind speeds and Weibull parameters to heights of 30, 50, and 100 m; participation in wind power density and theoretically recoverable energy calculations; results analysis and contribution to manuscript drafting.
4	Souleymane Soumah	Contribution to the methodology for assessing wind energy potential; verification of power density and energy calculations based on the Betz limit; comparative analysis of NASA POWER and ERA5 results; scientific interpretation and critical review of the manuscript.
5	Mouhamadou Falilou Ndiaye	Contribution to methodological analysis of vertical extrapolation; examination of the assumptions of the Justus and Mikhail model; participation in sensitivity analysis of extrapolated wind speeds; interpretation of results and scientific revision of the manuscript.
6	Lamine Thiaw	Scientific and methodological expertise; critical examination of vertical extrapolation and statistical wind characterization methods; analysis of Weibull parameters and their influence on energy potential; scientific interpretation of results and critical manuscript revision.
7	Roger Marcelin Faye	Scientific supervision and senior expertise; methodological guidance; critical examination of the vertical extrapolation approach and theoretical wind energy potential assessment; validation of results interpretation; in-depth scientific revision and contribution to final manuscript validation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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