Comparative Assessment of Wind Energy Yield Estimation Using New European and Global Wind Atlases

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Abstract:- Accurate wind resource assessment is a fundamental requirement for wind farm planning, turbine selection, and reliable estimation of long-term energy production. Mesoscale wind atlas frameworks, particularly the New European Wind Atlas (NEWA) and the Global Wind Atlas (GWA), are increasingly used to derive site-specific wind climatology and support preliminary feasibility studies. However, their predictive performance is strongly influenced by terrain complexity, surface roughness, and atmospheric flow conditions. In this study, a systematic and comparative assessment of wind resource characterization and annual energy yield estimation is conducted using NEWA and GWA across four representative environments: forested terrain, mountainous terrain, offshore marine conditions, and normal inland terrain. Height-dependent wind statistics were extracted from both atlases and processed using Rayleigh and Weibull parameterization, Hellmann power-law extrapolation, and probabilistic turbine power curve integration to estimate hub-height wind conditions and annual energy yields. The resulting predictions were validated against reference datasets from the Bavarian Energy Atlas and official offshore production data, and relative errors were quantified to evaluate model reliability. In parallel, a bibliometric analysis of peer-reviewed literature published between 2002 and 2026 was performed to examine research trends, thematic evolution, and methodological developments related to wind atlas applications and wind energy yield assessment, providing a broader scientific context for the study. The results indicate that both atlases perform well under homogeneous inland and offshore conditions, while prediction errors increase in forested and mountainous regions due to unresolved microscale flow effects and enhanced surface roughness. The findings highlight the terrain-dependent strengths and limitations of NEWA and GWA and emphasize the need for hybrid correction approaches and site-specific calibration to improve prediction accuracy. Overall, the study provides a validated methodological framework for the application of wind atlas data in technical and pre-investment wind energy assessments.

Keywords*:* Wind resource assessment; energy yield estimation; Weibull distribution; wind shear extrapolation; mesoscale modeling; wind power density; terrain effects.

Acronyms

NEWA	New European Wind Atlas
GWA	Global Wind Atlas
WRF	Weather Research and Forecasting model
CFD	Computational Fluid Dynamics
PDF	Probability Density Function
EPF	Energy Pattern Factor
AEP	Annual Energy Production

CF	Capacity Factor
FLH	Full Load Hours
WAsP	Wind Atlas Analysis and Application Program
GIS	Geographic Information System
WGS84	World Geodetic System 1984
WAM	Wind Atlas Methodology
ERA5	Fifth Generation European Centre for Medium-Range Weather Forecasts Atmospheric Reanalysis

Nomenclature

Symbols	Quantity	Units
A	Weibull scale parameters	$m.s^{-1}$
k	Weibull shape parameters	-
K_1, K_2	Weibull shape parameters at lower and higher reference height (Z_1,Z_2)	-
Z_1, Z_2	Lower and higher reference height of (Z_1,Z_2)	m
V_1, V_2	mean wind speed at height (Z_1,Z_2)	$m.s^{-1}$
A_{rayle}	Rayleigh scale parameters	$m.s^{-1}$
V_{mean}	Mean wind speed	$m.s^{-1}$
V_{hh}	Wind speed at hub height	$m.s^{-1}$
ρ	Air density	$kg.m^{-3}$
ρ_{hh}	Air density at hub height	$kg.m^{-3}$
α	Hellmann wind shear exponent	-
P_{ds}	Wind power density	$kg.m^{-3}$
P_i	Turbine electrical power at bin i	kW
h(V)	Weibull probability density function	-
E_i	Energy contribution of bin	kWh
E	Annual energy yield	MWh
P_{Wind}	Theoretical wind power	W
CF	Capacity factor	%
FLH	Full load hours	h

ΔV	Wind speed bin width	m.s^{-1}
T	Annual operating time	h

1. Introduction

The accurate assessment of wind resources is an essential precondition for evaluating the technical and economic feasibility of wind power projects. In recent years, advances in mesoscale atmospheric modeling, computational fluid dynamics, and high-resolution climatological datasets have significantly improved the precision of site-specific wind characterization [19] [24]. Modern wind atlas frameworks integrate long-term numerical weather prediction outputs with microscale terrain corrections to generate spatially and temporally resolved wind statistics, which are essential for turbine siting, energy yield simulation, and operational performance evaluation [24].

The New European Wind Atlas (NEWA) and the Global Wind Atlas (GWA) are widely recognized reference systems for wind resource assessment. Both frameworks aim to connect large-scale atmospheric simulations with area-specific wind conditions; however, they differ in modeling approaches, spatial resolution, and treatment of terrain effects. NEWA emphasizes high-resolution regional downscaling and extensive validation across Europe, while GWA provides harmonized global wind resource estimates using standardized microscale correction techniques, resulting in variations in accuracy depending on terrain complexity and application scale [23] [24].

In this context, the present study conducts a detailed wind resource assessment and annual energy yield estimation by deriving height-dependent wind statistics from both atlases across diverse terrains, including offshore, flat inland, forested, and mountainous regions. The methodology involves estimating Weibull and Rayleigh distribution parameters [21], extrapolating wind characteristics to turbine hub height using analytical wind shear models, and calculating annual energy production through probabilistic integration of wind speed distributions with turbine power curves. The estimated yields are compared with historical production data from sources such as the Bavarian Energy Atlas and offshore measurement platforms to quantify relative errors and assess terrain-dependent accuracy and consistency of each atlas formulation [20] [22] [23]. This comparative analysis highlights the strengths and limitations of atlas-based techniques and contributes to the development of more robust approaches for wind energy planning and engineering.

The New European Wind Atlas revolutionized regional wind resource mapping. Sanz Rodrigo et al. (2020) described NEWA using the Weather Research and Forecasting (WRF) model combined with OpenFOAM-based CFD downscaling to obtain a 30-year climatology (1989–2018) at 3 km spatial and 30-minute temporal resolution[1]. Validation on 291 measurement masts in Europe showed high results, achieving a mean bias of 0.29 ± 0.76 m/s compared to ERA5 reanalysis. However, uncertainties over 1 m/s were reported in complex terrains, emphasising the continued difficulty in representing microscale flow. A further offshore validation by Meyer et al. (2022) showed NEWA proved to be of less bias than ERA5 with a little decrease in correlation, and both datasets underestimated extreme wind speed. Spectral correction factors were used to facilitate long-term return wind estimates[2]. Similarly, Murcia et al. (2022) reported that using hybrid NEWA-terrain-aware corrections was an approach to obtain precise power predictions, demonstrating the value of mesoscale and microscale information integration[3].

The NEWA framework has been further refined through an investigation into terrain and atmospheric stability effects. Karagali et al. (2018) applied Doppler lidar measurements in a synchronized manner to demonstrate strong terrain induced variability of semi-forested areas, whereas Sanz Rodrigo et al. (2018) identified that mesoscale-microscale models combine for systematic rotor-equivalent wind speed overestimations[4][5][1]. Cheynet et al. conducted comparative analyses (2022, 2025) and Soukissian et al. (2025) showed that alternative regional datasets like NORA3 and CERRA sometimes outperformed NEWA in offshore and Mediterranean climates[7][8]. However, the recent advances suggested by Dörenkämper et al. (2020) and Hahmann et al. (2020) had minimized bias through improved WRF settings and roughness parametersization[9][10].

The Global Wind Atlas presents a globally scalable approach to wind resource assessment. Davis et al. (2023) utilized the WRF–WAsP coupling Numerical Wind Atlas Method to present GWA, resulting in a spatial resolution of the order of 250 m worldwide[13]. Cross-country validation showed low mean bias, and robust offshore behavior. However, Bhukya Ramdas et al. (2022) have also observed a reduced accuracy in complicated or island terrains due to non-comprehensive local flow effects[14]. Other recalibration techniques such as kriging correction proposed by Duc et al. (2022) resulted in a significant reduction in regional RMSE[15]. Moreover, Gruber et al. (2019, 2021) showed that GWA-implemented bias corrections increased the quality of global products of reanalysis, such as MERRA-2 and ERA5, but regional discrepancies were still there[16].

As a whole, the literature mentions synergistic strengths of the two atlases. NEWA presents better regional resolution and physical realism and rigorous validation throughout Europe, whereas GWA offers a broader scope, normalized workstreams, and simplifies systems for worldwide applications. Both platforms have advanced wind energy modeling greatly, but there remain challenges in modeling the terrain complexity, extreme wind events and site–specific biases. That is, further advances in adaptive corrections and hybrid numerical–statistical methods are needed to enhance the accuracy of wind atlas–based predictions.

1.1. Bibliometric study

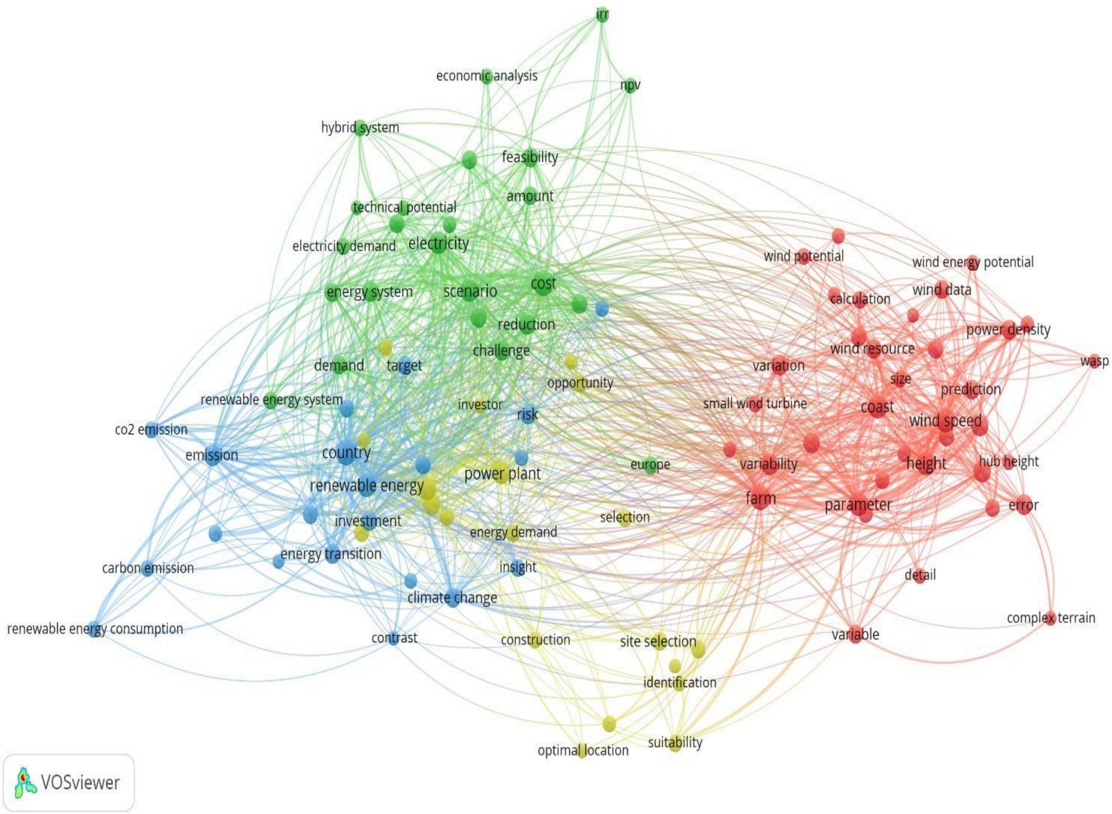

Figure. 1 Temporal evolution of WAM research via bibliometric insights

A bibliometric analysis was performed to systematically map the scientific development of wind energy atlas–based research using a dataset of more than 100 peer-reviewed papers retrieved from the Official database, spanning from 2002–2026. The generated network from VOSviewer shows the existence of many thematic clusters, where node size denotes keyword frequency and link strength reflects the extent of co-citation or conceptual linking between research terms. The red cluster is mainly related to the technical analysis of wind resources with microscale parameters such as wind speed, hub height, wind resource, power density, prediction and terrain complexity. These expressions have direct relevance to wind atlas methods, vertical extrapolation, and yield calculation, which constitute the fundamental technical basis for the present study. The green cluster focuses on system-level and techno-economic evaluation themes (in scope of feasibility, cost, scenario analysis and electricity demand) reflecting the interplay of wind resource evaluation and planning and investment decisions. The blue cluster looks at renewable energy transition and environmental impact, including emissions, carbon reduction, energy systems, etc. and thus relates wind atlas applications to broader sustainability goals.

The yellow cluster also reflects a scenario for site selection and suitability analysis, with a spatial optimization and resource mapping approach with direct support from wind atlases. The bibliometric structure suggested that from early wind characterization studies, research was evolving to integrated decision-support frameworks that combine resource modeling, economic feasibility, and environmental performance, which are now combined. The prominence of words related to wind speed distribution, power density, and terrain effects illustrates that accurate wind atlas data are still key to reliable energy yield prediction. It thus directly sustains the motivation of the present paper: Comparison of Yield for NEWA vs. GWA, an assessment to compare performance across a range of terrain categories of both the New European Wind Atlas and Global Wind Atlas. In the context of the broad scientific terrain, this study established that advancing atlas-based wind resource estimation is technically feasible as much as it is relevant to current research priorities in both wind energy engineering and sustainable power system development.

2. Experimental Design and Methodology

The wind resource parameters derived from NEWA and GWA serve as the inputs for calculating the site, specific energy yields and for benchmarking the WAM performance in the actual atmospheric and terrain environments.

2.1. Wind Data Acquisition via NEWA

New European Wind Atlas (NEWA) provides wind resource information using a structured workflow integrating mesoscale and microscale data. From this point once the user selects a particular study location on the web-based map interface or enters its geographic coordinates the process takes place within dedicated modules of mesoscale and microscale to extract wind and atmospheric parameters. The user selects horizontal wind on the mesoscale module and accesses the climate wind mean dataset. This dataset offers the long-term mean wind speed profiles with height, typically in the range of 50 m to 500 m above ground level, allowing measurements for both wind shear and vertical wind speed variation relative to individual turbine hub heights. Air density also is obtained by selecting the air density parameters and the climate mean, giving the long-term mean air density of the selected location.

The data produced at mesoscale provides the reference data in evaluating the large-scale atmospheric patterns and the height dependent wind behavior[19]. The analysis then follows the microscale module, which also includes adaptation of local terrain effects and surface roughness from the microscale analysis by fine-tuning the downscaling. In this section, the Weibull distribution parameters shape parameters (k) and scale parameters (c) are extracted, representing the distribution of wind speed statistics at the location, for the heights of the hub 50 m to 200 m and being required inputs to estimate energy yield and perform probabilistic wind analysis. The mesoscale wind profiles and air density information along with microscale Weibull parameters will generate a standardized methodology and the same methodology is reproducible for a site-specific wind resource determination in NEWA. Such a step-wise structure enables validation and application of the Wind Atlas Method, particularly for users who need well-defined vertical wind properties and statistically robust results for assessing wind energy yield.

2.2. Wind Data Acquisition via GWA

Global Wind Atlas (GWA) offers a complete collection of wind resource datasets in an interactive web-based platform for preliminary wind energy analysis and turbine performance evaluation. On visiting GWA's website, the user is shown visualization and data extraction options on potential information relating to the wind. First, the user searches for or chooses a specific location through the interactive map or enters exact coordinates. Once the target location is selected, the user navigates to the layer (mask) selection panel at the left-hand side of the interface. In this panel, the mean wind speed layer is selected and the wind speed is analyzed as a function of height, generally between 10 m and 200 m above ground level. The corresponding mean wind speeds for the selected heights are shown on the right-hand side of the interface, where the user can record or extract height-dependent wind speeds. GWA does not only provide mean wind speed, but also additional wind resource parameters including wind frequency distributions, mean wind power density, and mean wind speed profiles at multiple hub heights.

Moreover, it supports temporal wind datasets of hourly and monthly wind speed variation data, providing diurnal and seasonal wind patterns at the selected locations. In addition, GWA comes with a turbine selection module that will give the user a variety of commercially available wind turbines, sorted by rated power (MW), to choose from. The platform provides the power curve data for a chosen turbine and local wind resource characteristics, and integrates those data with local available information on the associated wind resources. Using this integration, GWA provides estimates of major performance indicators such as the annual energy yield and capacity factor, allowing site-specific turbine suitability assessment and preliminary feasibility investigation. A comprehensive GWA workflow can systematically extract wind resource characteristics, temporal variability, and turbine performance metrics to enable consistent and transparent application of wind atlas data to perform a wide range of wind energy yield estimation and comparative analysis.

3. Site Characterization and Preprocessing

3.1. Offshore Area

The offshore case study is conducted at the London Array Offshore Wind Farm in the outer Thames Estuary around 20 kilometer from Ramsgate, United Kingdom. The offshore areas presented are representative of marine boundary-layer properties such as very low surface roughness, minimal terrain-induced turbulence, and unobstructed wind flow over open water are characteristic to the area as a whole and, therefore, allow for a uniform wind field profile for accurate wind resource assessment. The site, defined by WGS84 geographic coordinates, results in consistent data retrieval from both the New European Wind Atlas and the Global Wind Atlas, and allows for reproducible comparisons of mesoscale predictions with captured performance[22]. The wind farm enjoys over 600 megawatts installed capacity and recorded operating data, and is also a representative and reliable benchmark for offshore energy yield estimation methods.

3.2. Mountain Region

The onshore, mountainous case study represents the Ernersdorf–Berching wind farm, closer to Berching in southern Germany, which is situated at an elevation of approximately 500 metres above mean sea level. The site is of moderately complex inland terrain and is associated with rolling hills, elevation gradients, and heterogeneous land cover, which result in terrain-induced flow acceleration, increased turbulence, and directional variability, leading to non-uniform wind fields typical for mountainous conditions. The wind farm, a single Vestas V112-3.0 MW turbine, is defined using WGS84 coordinates to be in a constant spatial orientation to both the New European Wind Atlas and the Global Wind Atlas. The turbine has a rotor diameter of one hundred twelve metres and a rated capacity of three megawatts. Due to the complex topography on the site and as recorded in operations, it serves as a representative benchmark for assessing the performance and reliability of mesoscale wind atlas–based resource assessment and energy yield prediction methods in terrain-affected onshore environments.

3.3. Normal Terrain

The onshore case study is related to the Adlholz–Hahnbach Wind Farm situated near Hahnbach in the Upper Palatinate region of Bavaria, Germany. The area has a gently undulating land surface and open agricultural area, along with relatively sparse vegetation leading to moderate surface roughness and comparatively smooth wind movement, relative to woods or mountains. Although mild elevation changes create local effects in terms of speed-up at ridgelines and limited turbulence in sheltered zones, the total boundary-layer system seems to be typical of the typical rural onshore condition. Its position is specified using precise WGS84 coordinates to a level that is consistent with both the New European Wind Atlas and the Global Wind Atlas, which are key for reliable mesoscale wind data extraction for the resource assessment and energy yield estimation. With modern utility-scale turbines, the site offers a practical and technically useful benchmark for assessing wind atlas–based prediction accuracy in comparison to typical inland terrain conditions.

3.4. Forest Area

An onshore case study is the Schnaittenbach–Buchberg Wind Farm situated near Schnaittenbach in the vicinity of Kemnath, within Bavaria, Germany. This site is located in a predominantly forested upland region characterized by moderately complex terrain and extensive woodland cover, where dense vegetation and irregular topography increase surface roughness and promote enhanced turbulence, wind shear, and localized flow distortions that affect turbine inflow conditions. The site is defined by using WGS84 coordinates for continuity with the New European Wind Atlas and with the Global Wind Atlas while allowing reliable extraction and comparison with mesoscale wind resource information. Equipped with modern utility-scale turbines to provide a realistic operational environment for performance evaluation, the wind farm can also serve as a suitable test case to ascertain the accuracy and robustness of wind atlas-based resource estimation in challenging forested inland conditions.

4. Turbine Power Curve Characterization

To guarantee an accurate and site-specific energy yield estimation, power curves furnished by the manufacturer are applied for four representative turbine configurations that correspond to the selected study environments-forested terrain, mountainous terrain or above the sea level area, offshore conditions, and normal inland terrain or local terrain with the same turbine model applied for both the Mountain and Sea-level sites to enable consistent comparative assessment under similar onshore operating characteristics.

4.1. Manufacturer-Specified Power Curve for Energy Yield Estimation under Forest Terrain Conditions

Table 1: Power curve for Nordex N117/2400

V(m/s)	P_{el} (kW)	$C_{p,real}$
0.0	0.0	0.000
1.0	0.0	0.000
2.0	0.0	0.000
3.0	25.0	0.141
4.0	82.0	0.195
5.0	354.0	0.430
6.0	643.0	0.452
7.0	1,038.0	0.460
8.0	1,525.0	0.452
9.0	2,037.0	0.424
10.0	2,326.0	0.353

11.0	2,400.0	0.274
12.0	2,400.0	0.211
13.0	2,400.0	0.166
14.0	2,400.0	0.133
15.0	2,400.0	0.108

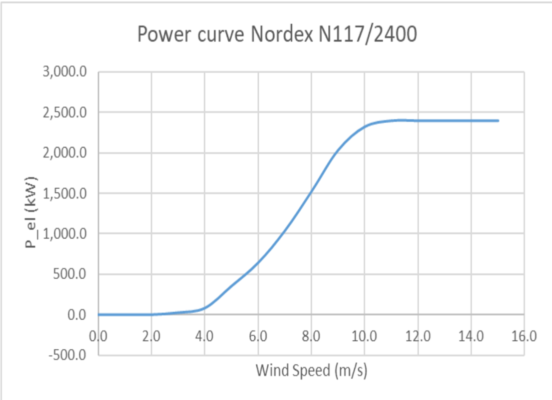

Figure. 2 Manufacturer Power Curve of the Nordex Wind Systems N117/2400 Wind Turbine (Electrical Power Output versus Wind Speed)

As shown in the power curve graph, and the manufacturer-level tabulated data for the respective Nordex N117/2400 turbine, the result indicates that a zero power output is achieved for the turbine below the cut-in wind speed of approximately three meter per second, after which the electrical output increases nonlinearly with wind speed, reaching from 25 kilowatts at three metres per second to approximately 2037 kilowatts at nine meter per second. It is also demonstrated in the table that the turbine achieves its power rating at 2400 kilowatts at approximately 11 meter per second and a peak power coefficient of aerodynamic efficiency of 5 to 7 m/s within the intermediate wind speed range. Beyond the rated region (top of that graph), the curve shows that the power constant points up to 15 m/s, which corresponds to pitch controlled operation where output is controlled, thus safe and stable at high wind speeds.

4.2. Manufacturer-Specified Power Curve for Energy Yield Estimation under Mountain region and Normal Terrain Conditions

Table 2: power curve for Vestas V112/3075

V (m/s)	P_{el} (kW)	$C_{p,real}$
0.0	0.0	0.000
1.0	0.0	0.000
2.0	0.0	0.000
3.0	26.0	0.160
4.0	133.0	0.344
5.0	302.0	0.400
6.0	554.0	0.425
7.0	907.0	0.438
8.0	1,375.0	0.445
9.0	1,958.0	0.445
10.0	2,585.0	0.428

11.0	2,997.0	0.373
12.0	3,067.0	0.294
13.0	3,075.0	0.232
14.0	3,075.0	0.186
15.0	3,075.0	0.151

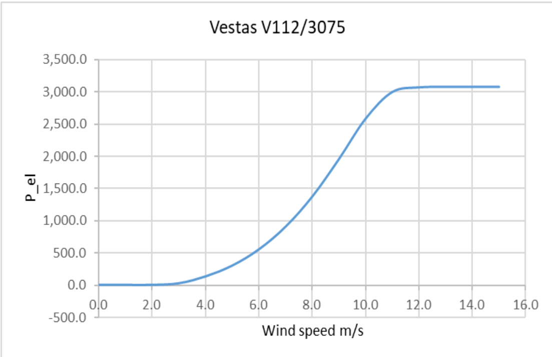

Figure. 3 Manufacturer Power Curve of the Vestas Wind Systems V112/3075 Wind Turbine (Electrical Power Output versus Wind Speed)

The Power Curve Graph by the manufacturer with the compiled Performance data for the Vestas Wind Systems V112/3075 turbine shows that wind speed and electrical output with respect to real power coefficient in the range of operation are related. From the graphs and table, it can be seen that output begins at the cut-in speed of about 3 m/s and increases nonlinearly with wind speed, starting from 26 kilowatts at 3 meter/s and increasing to 2,585 kilowatts at 10 m/s, indicating efficient aerodynamic energy conversion at a peak of 0.44–0.45 power coefficients. At around 12 m/s, the curve reaches a plateau at the rated power of 3,075 kilowatts, where the output remains constant due to regulator operation, indicating stable rated operation, which forms the basis of the future work on the energy yield.

4.3. Manufacturer-Specified Power Curve for Energy Yield Estimation under Offshore Conditions

Table 3: power curve for Siemens SWT 3.6

V (m/s)	P_{el}(kW)	$C_{p,real}$
0.0	0.0	0.000
1.0	0.0	0.000
2.0	0.0	0.000
3.0	0.0	0.000
4.0	80.0	0.227
5.0	238.0	0.346
6.0	474.0	0.398
7.0	802.0	0.425
8.0	1,234.0	0.438
9.0	1,773.0	0.442
10.0	2,379.0	0.432
11.0	2,948.0	0.402

12.0	3,334.0	0.350
13.0	3,515.0	0.290
14.0	3,577.0	0.237
15.0	3,594.0	0.193
16.0	3,599.0	0.160
17.0	3,600.0	0.133
18.0	3,600.0	0.112

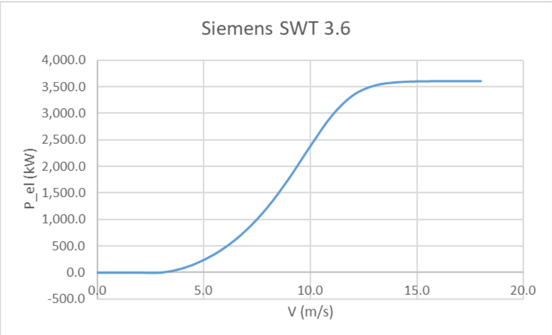

Figure. 4 Manufacturer Power Curve of the Siemens Wind Systems SWT 3.6 Wind Turbine (Electrical Power Output versus Wind Speed)

The electrical power output vs wind speed for the Siemens SWT-3.6 turbine and the corresponding table provide discrete numerical values of power and power coefficient. Power generation starts at approximately 4 m/s, then increases steadily through the partial-load region, reaching a rated output of about 3.6 MW near 13–14 m/s, after which it plateaus, indicating controlled operation at constant rated power. The variation of the power coefficient, peaking around 0.44 at moderate wind speeds, reflects efficient aerodynamic energy conversion before gradually decreasing at higher speeds due to turbine regulation and safety controls.

5. Wind Resource Parameter Estimation and Height Extrapolation Methods for calculating NEWA

5.1. Procedure for estimating the yield by using NEWA

To account for vertical wind shear, atmospheric density variation, and statistical wind speed distribution, a set of analytical relationships is applied to extrapolate wind and meteorological parameters to the turbine hub height.

The Rayleigh scale parameters are calculated from the measured mean wind speed to describe the wind speed probability distribution at the reference height [25] [26].

$$A_{rayleigh} = \frac{2 \times V_{mean}}{\sqrt{\pi}} \quad (1)$$

The Hellmann exponent is determined using wind speeds at two heights to quantify vertical wind shear and to show how surface roughness affects the wind speed at various altitudes [27] [28] [29].

$$\alpha = \frac{ln(\frac{V_1}{V_2})}{ln(\frac{h_1}{h_2})} \quad (2)$$

Using the power-law method, the scale parameters at hub height are computed and the effect of wind shear from the difference in measurement height between the reference and the desired height is considered [30] [31] [32].

$$A_{hh} = A_{rayleigh} \times (\frac{hh}{Z_1})^{\alpha} \quad (3)$$

The Weibull shape parameters at the required height is estimated by linear interpolation of two reference data points (high and low altitude) representing the variation in wind pattern with altitude [26] [27] [33].

$$K_{hh} = K_1 + (\frac{K_2 - K_1}{Z_2 - Z_1}) \times (hh - Z_1) \quad (4)$$

The air density at hub height is obtained from a linear interpolation between the measured density values as the air density is adjusted for altitude-dependent atmospheric contributions in the energy calculations [34] [35].

$$\rho_{hh} = \rho_1 + (\frac{\rho_2 - \rho_1}{Z_2 - Z_1}) \times (hh - Z_1) \quad (5)$$

Wind speed at hub height is derived using power-law wind profiles and the mean wind speed is projected from the reference height to the turbine hub height [28] [30].

$$V_{hh} = V_{Z_1,mean} \times (\frac{hh}{Z_1})^{\alpha} \quad (6)$$

A wind speed bin width of ΔV = 0.5 m/s has been used to derive the wind speed distribution to determine energy yield for calculations.

A Weibull probability density function h(V) is utilized to estimate the frequency of occurrence of a wind speed distribution according to its site-specific shape and scale parameters [25] [33].

$$h(V)=\frac{K}{A}\times(\frac{v}{A})^{K-1}\times e^{(-(\frac{V}{A})^{k})} \quad (7)$$

The individual output of the electrical power, P_i (kW), for each wind speed bin comes from the manufacturer supplied turbine power curve.

The energy contribution E_i Each wind speed interval is determined as the product of turbine power, frequency, width of the wind speed bin, and operating time, adjusting for air density [32] [34] [35].

$$E_i = P_i \times h_i \times \Delta V \times \Delta T \times \frac{\rho_{hh}}{\rho_{Standard}} \quad (8)$$

The theoretical wind power P_{Wind} is estimated using the kinetic energy flux relation incorporating hub-height air density and the cube of wind speed [28] [36].

$$P_{Wind} = \frac{1}{2}\times \rho_{hh} \times h_i \times \Delta V \times (v_i)^3 \quad (9)$$

The total annual energy yield ΔE is obtained by summing the energy contributions over all wind speed intervals [30] [35].

$$\Delta E = \sum \Delta E_i \quad (10)$$

The capacity factor represents the ratio of actual annual energy production to the maximum possible energy output at rated power over the same period [28] [34].

$$\text{Capacity factor} = \frac{Annual\ yield}{Time \times power\ of\ turbine} \times 100, \quad (11)$$

The full load hours indicate the equivalent number of hours the turbine would operate at rated power to produce the annual energy yield [35].

$$\text{Full load hours} = \frac{Annual\ yield}{power\ of\ turbine}, \quad (12)$$

The relative error quantifies the percentage deviation between the calculated annual yield and the reference wind atlas yield [32] [37].

$$\text{Relative error} = \frac{Annual\ yield\ from\ bavarian\ wind\ atlas - calculated\ annual\ yield}{calculated\ annual\ yield} \times 100 \quad (13)$$

5.2. Wind Resource Assessment and Energy Yield Estimation Using NEWA for the Forest Terrain Site

For the forest-area wind energy assessment, a rotor diameter of 117 m, a standard air density of 1.225 kg·m^{-3}, a hub height of 141 m, and an annual operational period (ΔT) of 8760 h are adopted as the reference turbine and environmental parameters for subsequent calculations.

Table 4: Height-dependent wind resource parameters obtained from NEWA for a Forest region

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean} m/s
100	2.1	7.26	1.16	5.82
150			1.16	6.44
200	2.02	8.8	1.16	6.86

Wind resource characterization and energy yield estimation for the forested onshore site were performed systematically using the New European Wind Atlas based on Equations (1) to (13), utilizing a statistical–analytical framework. The site is situated at approximately 642 meter above sea level and height-dependent wind statistics were initially extracted at reference heights of 100, 150, and 200 meter. The mean wind speed of 5.82 meter per second at 100 meter computed the Rayleigh scale parameters as from Equation (1) 6.57 meter per second. Also, at 200 meter, a higher mean speed of 6.86 meter per second generated the Rayleigh scale parameters of 7.74 meter per second, which showed an increasing wind energy potential as the height increased.

Further, The Hellmann exponent was analyzed by using wind speeds for two elevations based on Equation (2), yielding shear coefficients of 0.25 within the 100 to 150 m and 0.24 beyond the 100 to 200 m interval representing the improved vertical shear linked to ruggedness of forest. After calculating with these shear parameters the scale parameters at hub height was estimated based on the power-law relationship formulated by Equation (3), yielding a scale of 7.16 meter per second at hub level. The aerodynamic Weibull shape parameters and air density at the central hub height were determined by linear interpolation between reference levels using Equations (4) and (5), with 2.07 and 1.16 kilograms per cubic metre respectively. The mean wind speed at the hub height was then estimated on the power-law wind pattern described in (6), giving 6.34 meter per second. The wind speed domain was discretized (with a bin width ΔV of 0.5 meter per second) for energy value calculation and the Weibull probability density function in (7) was then utilized to calculate the frequency of occurrence in each wind speed.

The electricity output for each interval was calculated from the turbine maker power curve Nordex N117/2400 from the literature, and the energy contribution for each bin was calculated through Equation (8), and the available wind power was estimated by using Equation (9). The total annual power production was derived by summing every contribution as in Equation (10). The performance indicators were then calculated, relying on Equations (11) and (12), yielding an annual energy yield that was anticipated to be 7,714.23 megawatt-hours, capacity factor of 36.69% and equivalent full load hours of around 3,214.3 hours per annum. These results show that the wind energy potential for the forest terrain can be moderate, stable and reliable, thus confirming how effective the NEWA-based statistical and extrapolation methodology is for reliable energy yield prediction under complex surface roughness conditions.

5.3. Wind Resource Assessment and Energy Yield Estimation Using NEWA for the Mountain Area

For the mountainous onshore site, the wind energy assessment is conducted using a turbine with a rotor diameter of 112 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 140 meter, and an assumed annual operating duration of 8760 hours as the reference technical and environmental parameters for subsequent calculations.

Table 5: Height-dependent wind resource parameters obtained from NEWA for above the sea-level area

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
100	2.02	7.70	1.16	6.48
150			1.16	6.93
200	1.96	9.18	1.16	7.22

The mountainous onshore site evaluated by the New European Wind Atlas applied the analytical framework from Equations (1) to (13) for wind resource characterization and the annual energy yield estimation. The site is located at about 642 m above sea level at which the height-dependent wind statistics were extracted, from an aerial viewing distance of 100, 150, and 200 meter. The Rayleigh scale parameters was obtained from the mean wind speed of 6.48 meter per second at 100 m (Eq 1): 7.31 meter per second. The average wind speed for 200 m was 7.22 meter/second with a Rayleigh scale parameters of 8.15 meter/s, confirming that the effect of height on wind energy potential was anticipated to increase. Vertical wind shear was found from the Hellmann exponent calculated in relation to wind velocities at various heights (according to Eq (2)). 0.17 shear coefficients are obtained for the length 100-150 m and 0.16 shear coefficients for the length 100-200 m covering moderately complex mountainous landscapes. The resulting energy shear exponent allowed us to extrapolate the scale parameters to the height of the vertical turbine hub using a power-law formulation in Eq (3), resulting in a hub-height scale parameters of 7.73 meter/sec. The Weibull shape parameters and air density at hub height were calculated from linear interpolation using Equations (4) and (5), with values of 2.00 and 1.16 kilograms per cubic metre, respectively. The mean wind speed at hub height was determined by power-law wind profile from Equation (6), calculated as an extrapolation of 6.85 m.

For predicting yield, the domain of wind speed was discretized into a bin width of 0.5 m/s and values of frequency of occurrence of the wind speed classes were computed via the Weibull probability density function introduced in Equation (7). Equation (9) was used to consider available wind power. Summing up the total annual energy production according to Equation (10), performance indicators were calculated from Equations (11) and (12). Such a process gave an annual energy yield of approx. 9,341.93 MWh, or 34.68% capacity factor and approx. 3,038.0 equivalent full load hours/year. The hub-height mean power density was calculated as 356.99 watts per square metre with favourable wind availability confirming the practicality of the NEWA-based extrapolation and statistical yield estimation methods for the mountainous regions.

5.4. Wind Resource Assessment and Energy Yield Estimation Using NEWA for the Offshore Region

For the offshore wind resource assessment, the analysis is conducted using a turbine with a rotor diameter of 107 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 87 meter, and an assumed annual operational duration of 8760 hours, which serve as the reference technical and environmental parameters for subsequent energy yield calculations under marine boundary-layer conditions.

Table 6: Height-dependent wind resource parameters obtained from NEWA for the Offshore region

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
50	2.14	9.97	1.24	8.46
100	2.1	10.40	1.24	8.86
150			1.24	9.1
200	1.96	10.85	1.24	9.28

For the offshore site evaluated using the New European Wind Atlas, wind resource characterization and annual energy yield estimation were performed using the analytical framework described in

Equations (1) to (13). Data were retrieved for the marine wind climate derived from the altitude of which is about 22 meter above sea level, where height-dependent wind statistics were sourced at reference wind heights of 50, 100, 150, and 200 m. At 50 meter, the Rayleigh scale parameters value of 9.55 meter per second was calculated through the mean wind speed calculated using the equation (1) and was 8.46 meter per second. At 100 m, the average wind speed reached 8.86 meter per second with a Rayleigh scale parameters of 10.00 meter per second, whereas at 200 m the average wind speed reached 9.28 meter per second which has yielded a scale parameters of 10.47 meter per second, reflecting the uninterrupted enhancement of wind energy potential with height under offshore conditions.

Vertical wind shear was expressed with the Hellmann exponent from the equation (2), which yielded a consistent shear coefficient of 0.07 at 50 to100 m and 100 to200 m, as expected for weak shear and low roughness over open water. Based on this shear coefficient the Rayleigh scale parameters was fitted to the turbine hub height by power-law relation of (equation (3)), which gives us hub height scale parameters of 9.91 m/s. Substituted with Equations (4) and (5) the Weibull shape parameters and air density at hub height were obtained by linear interpolation and had the shape factor of 2.11 and air density of 1.24 kilograms per cubic metre. The average wind speed for hub height was then forecast by the power-law wind profile in the application equation (6), which provided an extrapolated result of 8.78 meter per second.

To quantify the energy yield, we developed a standard form of wind speed that was discretized through bin width of 0.5 meter per second and Weibull probability density function in Equation (7) to find the frequency of occurrence of each wind speed. The output of electrical power from Siemens SWT-3.6 turbine; and the energy yield of each of the two bins is calculated with Equation (8), and the available wind yield is analyzed with Equation (9). The combined annual energy output was calculated from summation (10), and the relevant performance indicators were computed from Equations (11) and (12). It obtained an annual energy generation of approximately 14,867.24 megawatt-hours of energy by the means of the procedure, equal from the capacity factor of 47.14 % and the equivalent full load hours per year of 4,129.8 in 4,129.8 equivalent full load hours every year that validated the feasibility of maintaining a high wind power source value as well as the high energy capacity of the offshore facility.

5.5. Wind Resource Assessment and Energy Yield Estimation Using NEWA for the Normal Terrain

For the Normal terrain onshore site, a turbine with a rotor diameter of 112 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 140 meter, and an annual operating duration of 8760 hours is adopted as the reference configuration for the wind resource and energy yield assessment.

Table 7: Height-dependent wind resource parameters obtained from NEWA for the Local Terrain

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s

100	2.04	6.84	1.19	5.95
150			1.19	6.5
200	2.01	8.52	1.19	6.88

The wind resource characterization and annual energy yield estimation for the local terrain site measured with the New European Wind Atlas was carried out by applying the analytical framework referred to in Equations (1) to (13). The site was situated at an elevation of approximately 642 meter above sea level and is height-dependent with reference elevations of 100, 150, and 200 meter, which also accounts for wind statistics. Based on (1), for the Rayleigh scale parameters, mean wind speed was calculated for 100 meter at 5.95 m/s (6.71 m/s). The increased wind speed of 6.88 meter per second, also noted from 200 m (Rayleigh scale parameters: 7.76 m/s), indicates a moderate increase in wind energy potential with height.

Vertical shear was estimated by the Hellmann exponent as expressed in equation (2), yielding the values of 0.22 for the 100 - 150 m interval and 0.21 for the 100 - 200 m interval, which is found to be consistent with the presence of moderate wind shear and roughness in the inland terrain. With these shear coefficients, the scale parameters was extrapolated to the turbine hub height by the power-law equation formulated in (3), yielding the hub height scale parameters of 7.22 m/s. The Weibull shape parameters and air density at hub height was established by linear interpolation at reference heights using Equations (4) and (5), achieving a shape factor of 2.03 and an air density of 1.19 kilograms per cubic metre. Following that, the hub-height mean wind speed was interpolated based on the power-law wind profile in Equation (6) to yield 6.40 meter per second.

For energy yield calculation, the range of wind speed was discretized at the width of a bin of 0.5 meter per second and the Weibull probability density function in Equation (7) was used for frequency of each wind speed interval. Electrical power output was derived from the manufacturer's power curve for the Vestas V112-3.075 MW turbine, and the energy contribution for each wind speed section used for building energy production was determined with Equation (8), and available wind power had been calculated using Equation (9). The sum of annual energy production was then estimated by the summation in Equation (10) (the sum of the total annual energy produced), from which the capacity factor and equivalent full load hours were calculated using Equations (11) and (12). The conclusion of this process yielded an estimated annual energy yield of 8,442.18 megawatt-hours, which was equivalent to a 31.34% capacity factor and 2,745.4 equivalent full load hours per year, giving moderate but stable wind power potential under the local inland terrain conditions.

6. Wind Resource Parameter Estimation and Height Extrapolation Methods for GWA

When statistical data regarding the wind resource parameters specific to the site is not directly available from the Global Wind Atlas, accurate estimation of wind resource parameters along with their height variability is particularly important for reliable energy yield prediction. In this research, followed a power density–based approach to derive the Weibull shape and scale parameters from the available wind statistics so that wind speed can be reconstructed at hub height[18]. Afterwards, these estimated parameters are used to determine the wind frequency distribution as well as to perform the stepwise calculation of annual energy yield.

6.1. Steps for estimating the yield by using GWA

The wind power density (P_{ds}) is calculated as the cube of wind speed multiplied by air density to quantify the kinetic energy available in the wind stream[18].

$$P_{ds} = \frac{1}{2}\rho v^3 \quad (14)$$

The energy pattern factor (EPF) represents the ratio of the mean cubed wind speed to the cube of the mean wind speed and characterizes the variability of the wind speed distribution[18].

$$\text{EPF} = \frac{v^3}{V^3} \quad (15)$$

The Weibull shape parameters (K) is estimated from the energy pattern factor to describe the spread and consistency of wind speed fluctuations[18].

$$\text{K} = 1 + \frac{3.69}{EPF^2} \quad (16)$$

The Weibull scale parameters (A) is computed from the mean wind speed and the shape parameters to define the characteristic wind speed of the Weibull distribution[18].

$$\text{A} = \frac{v}{\gamma(1+\frac{1}{K})} \quad (17)$$

A wind speed bin width of ΔV = 0.5 m/s, is adopted to discretize the wind speed distribution for energy yield calculations.

The Weibull probability density function h(V) is used to quantify the frequency of occurrence of each wind speed interval based on the site-specific shape and scale parameters [25] [33].

$$\text{h(V)}=\frac{K}{A} \times (\frac{v}{A})^{K-1} \times e^{(-(\frac{V}{A})^k)} \quad (18)$$

The electrical power output P_i(kW) corresponding to each wind speed bin is obtained from the manufacturer-provided turbine power curve.

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The energy contribution E_i Each wind speed interval is calculated as the product of turbine power, wind frequency, wind speed bin width, and operating time, with optional correction for air density [32] [34] [35].

$$E_i = P_i \times h_i \times \Delta V \times \Delta T \times \frac{\rho_{hh}}{\rho_{Standard}} \quad (19)$$

The theoretical wind power P_{Wind} is estimated using the kinetic energy flux relation incorporating hub-height air density and the cube of wind speed [28] [36].

$$P_{Wind} = \frac{1}{2} \times \rho_{hh} \times h_i \times \Delta V \times (v_i)^3 \quad (20)$$

The total annual energy yield ΔE is obtained by summing the energy contributions over all wind speed intervals[30] [35].

$$\Delta E = \sum \Delta E_i \quad (21)$$

The capacity factor represents the ratio of actual annual energy production to the maximum possible energy output at rated power over the same period[28] [34].

$$\text{Capacity factor} = \frac{Annual\ yield}{Time \times power\ of\ turbine} \times 100, \quad (22)$$

The full load hours indicate the equivalent number of hours the turbine would operate at rated power to produce the annual energy yield [35].

$$\text{Full load hours} = \frac{Annual\ yield}{power\ of\ turbine}, \quad (23)$$

The relative error quantifies the percentage deviation between the calculated annual yield and the reference wind atlas yield [32] [37].

$$\text{Relative error} = \frac{Annual\ yield\ from\ bavarian\ wind\ atlas - calculated\ annual\ yield}{calculated\ annual\ yield} \times 100 \quad (24)$$

6.2. Wind Resource Assessment and Energy Yield Estimation Using GWA for the Forest Terrain Site

For the forest-region assessment using the Global Wind Atlas, a turbine configuration with a rotor diameter of 117 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 141 meter, and an annual operating duration of 8760 hours is adopted as the reference basis for wind resource characterization and energy yield estimation.

Table 8: Height-dependent wind resource parameters obtained from GWA for the Forest Region

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
100.00	2.25	6.03	1.225	5.34
150.00			1.225	6.2
200.00	2.23	7.75	1.225	6.86

The forested onshore site was examined in a Global Wind Atlas study and wind resource parameters at reference heights of 100 m and 200 m were obtained to profile the vertical wind in high surface roughness region of forest terrain. Mean wind speed was 5.34 m/sec at 100 m, with mean power density 160 watts/m2 at standard air density of 1.225 kg/m3. The cubic mean wind speed was determined (using the wind power density relationship given in Equation (14)) and the energy pattern factor was obtained (according to Equation (15)). These values were used to find the Weibull shape and scale parameters with Equations (16) and (17) providing a shape factor of 2.25 and a scale parameters of 6.03 meter per second. At 200 m, average wind speed was 6.86 m/s and power density was 342 W/m2, resulting in respective Weibull parameters of 2.23 and 7.75 m/s, respectively, which demonstrates the predicted increase in wind energy potential with height; intermediate values at 150 m denote a gradual vertical shift of wind properties.

The scale parameters was interpolated in order to give the hub-height condition and the wind profile was drawn using Hellmann power-law and shear exponents were computed between 100 and 150 meter as 0.37 and 100 to 200 meter as 0.36; both shear expressions represent improved wind shear because of the roughness of the forests. This procedure yields hub-height wind parameters with Weibull scale parameters 6.84 meter per second; 2.25 Weibull shape factor found through linear interpolation; 1.23 kilograms per cubic metre air density; and an extrapolated wind speed of 6.06 meter per second. For the energy yield determination, the value of the wind speed range, which can be discretized up to 0.5 meter per second, is obtained by using a bin width and applying the Weibull probability density computed by Equation (18), to assign frequency of occurrence for each class of wind speed. A corresponding turbine power output was obtained using the power curve of the manufacturer and the energy contribution of each class was calculated using Equation (19) and summed to obtain the annual energy yield Equation (21). Next, the capacity factor and equivalent full load hours were determined according to Equations (22) and (23). The obtained scale showed that annual energy production would be estimated to be 7,488.86 megawatt-hours, with a capacity factor of 35.62 percent and approximately 3,120.4 equivalent full load hours per year, indicating moderate but stable wind energy potential in forested inland areas.

6.3. Wind Resource Assessment and Energy Yield Estimation Using GWA for the Mountain Region

For the assessment of the Mountain Region, a reference turbine configuration comprising a rotor diameter of 112 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 140 meter, and an assumed annual operating duration of 8760 hours is adopted as the basis for subsequent wind resource and energy yield calculations.

Table 9: Height-dependent wind resource parameters obtained from GWA for above the sea-level area

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
100.00	2.31	7.40	1.225	6.56
150.00			1.225	7.31
200.00	2.34	8.98	1.225	7.96

Based on reference heights of 100 m and 200 m, wind resource parameters for the mountainous site assessed using Global Wind Atlas were developed to characterize the vertical wind profile in high-complexity and elevated terrain conditions at the level of around 642 meter above sea level. Mean wind speed of 6.56 meter per second at 100 m with corresponding mean power density of 290 watts per square metre and air density of 1.225 kilograms per cubic metre were calculated. Using the wind power density formulation provided in Eq (14), the cubic mean wind speed was estimated and energy pattern factor was found following Eq (15). These values were used to find the Weibull shape and scale through Equations (16) and (17), obtaining a shape factor of 2.31 and a scale parameter of 7.40 meter per second. Enhanced wind conditions at 200 meter had a mean wind speed of 7.96 meter per second and a power density of 512 watts per square metre, respectively, yielding corresponding Weibull parameters of 2.34 and 8.98 meter per second.

The Rayleigh scale parameters of 7.40 and 8.98 m/s and intermediate values at 150 m indicate a gradual vertical transition of wind parameters through elevation, as expected. Hub height conditions were identified by interpolating the scale parameters and performing vertical extrapolation using the Hellmann power-law profile at shear exponents calculated between 0.27 (100 to 150 metre) and 0.28 (100 to 200 metre) intervals. This yielded an output of a hub-height Weibull scale parameters of 8.10 meter per second, a shape factor of 2.32 calculated using linear interpolation, an air density of 1.23 kilograms per cubic metre, and an estimated mean wind speed of 7.18 meter per second.

During estimation of the energy yield, dispersion of the wind speed field was performed with the bin width value of 0.5 meter per second and the Weibull probability density function as mentioned in Eq (18) was used to calculate the frequency of occurrence of each interperiodic wind speed. Using the turbine power curve, electrical power production for each bin was identified, and the energy contribution of each class was analyzed according to Equation (19). The theoretical wind power was determined based on an evaluation in Eq (20), and the sum of total annual energy generated was calculated based on contributions as set forth in Eq (21). Performance scores were then established (Eq (22) and (23)) yielding annual energy production of 10,725.23 MWh (capacity factor 39.82%, annual full load hours approx 3,487.9) of the entire load. These results are indicative of favourable wind conditions and support the applicability of the GWA-based statistical and extrapolation technique for energy yield estimation in mountainous areas.

6.4. Wind Resource Assessment and Energy Yield Estimation Using GWA for the Offshore Region

For the offshore site assessment, a reference turbine configuration with a rotor diameter of 107 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 87 meter, and an annual operating duration of 8760 hours is adopted as the basis for wind resource characterization and energy yield estimation under marine boundary-layer conditions.

Table 10: Height-dependent wind resource parameters obtained from GWA for above the Offshore area

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
50	2.54	9.67	1.225	8.58
100.00	2.46	10.33	1.225	9.16

150.00			1.225	9.54
200.00	1.96	10.85	1.225	9.84

Where the offshore site evaluated with New European Wind Atlas was extracted at reference heights of 50 and 100 m of height with reference wind resource the variables of weather conditions under low roughness boundary-layer conditions at elevations of approximately 22 m above sea level respectively. Over 50 m, the average wind speed was 8.58 meter/s and the mean power density at standard air density was 599 watts/m2. The Weibull parameters were calculated based on Equations (16) and (17), reaching a shape factor of 2.54 and scale parameters of 9.67 meter per second. The mean wind speed at 100 meter increased to 9.16 meter per second, with a power density of 748 watts per square metre, resulting in a shape factor of 2.46 and scale parameter of 10.33 meter per second. NEWA provided even more height-dependent parameters at 150 meter and 200 meter, which confirmed this expected wind potential increase at elevation, weibull scale parameters of 10.85 meter per second at 200 meter.

The respective Rayleigh scale parameters increased from 9.68 meter/second at a distance of 50 meter to 10.34 meter/second at 100 meter and 11.10 meter/second at 200 meter, reflecting a vigorous and vertically persistent offshore wind regime. For hub-height conditions, the Rayleigh scale parameters was interpolated, and vertical extrapolation performed with the Hellmann wind profile with shear exponents from 0.09 for the 50 to 100 metre interval and 0.10 for the 100 to 200 metre interval, indicating a weak wind shear typically observed over open water. By applying logarithmic mean of 9.04 m/s through the estimated hub-height parameters of 10.20 m/s, we observed a Weibull shape factor of 2.48, air density 1.23 kg/m3, and an extrapolated mean wind speed of 9.04 m/s. The Weibull probability density function indicated in (18) was applied to compute occurrence frequency for each wind speed class for energy yield estimation, as the Wind Speed Domain was discretized using bin width of 0.5 meter per second. The electrical power output was determined from the manufacturer's power curve of the Siemens SWT-3.6 turbine, and from Equation (19) energy contribution of each wind speed bin was determined and summed to calculate the yearly electrical power yield referred to in Equation (21). The related wind power availability is estimated by utilizing Equation (20), and performance measurement indicators are specified using Equations (22) and (23). So, with this method, the estimated total energy production was 15,751.52 megawatt-hours, equivalent to 0.016 terawatt-hours with a capacity factor of 49.95 percent and approximately 4,375.4 equivalent full load hours per year, thus reinforcing the high wind power potential and operational performance of the offshore site.

6.5. Wind Resource Assessment and Energy Yield Estimation Using GWA for the Normal Terrain

For the normal terrain site assessed using the Global Wind Atlas, a reference turbine configuration with a rotor diameter of 112 meter, a standard air density of 1.225 kilograms per cubic metre, a hub height of 140 meter, and an annual operating duration of 8760 hours is adopted as the basis for wind resource characterization and subsequent energy yield estimation under typical inland conditions.

Table 11: Height-dependent wind resource parameters obtained from GWA for above the Flat Terrain

height z, m	Weibull k	Weibull A, m/s	density, kg/m^3	V_{mean}, m/s
100.00	2.29	6.50	0	5.69
150.00			0	6.52
200.00	2.33	8.02	0	7.11

For the typical inland land-form landscape identified by the Global Wind Atlas, the wind resource values were at 100 m and 200 m that initially described the vertical wind profile at an altitude of around 642 m above sea. The mean wind speed was 5.76 m/s at 100 m with the same mean power density of 198 watts per square metre at a common air density of 1.225 kilograms per cubic metre. A cubic average power per square meter of wind speed was tested with the wind power density equation (14), and the energy-pattern factor was calculated with the air energy equation (15). We further derived Weibull shape and scale parameters from these values according to Equations (16) and (17), which give a shape factor of 2.29 and a scale of 6.50 meter per second. At 200 meter, the average wind speed grew up to 7.11 m/s along with a power density of 367 watts per square metre, and the energy pattern energy factor was equal to 1.67 and the Weibull parameters of 2.33 and 8.02 m/s were obtained. The associated Rayleigh scale parameters were calculated as 6.42 m/s at 100 m and 8.02 m/s at 200 m, as was anticipated for an increase in the wind intensity with height, but intermediate values at 150 m point at a slow shift in the wind regime. Hub height wind parameters were calculated by interpolating the Rayleigh scale parameters, and vertical extrapolation was done using the Hellmann power-law profile with shear exponents of 0.34 for the interval of 100–150 m and 0.32 for the interval of 100–200 m.

This process yielded a hub-height Weibull scale parameters of 7.19 meter per second, a shape factor of 2.30 obtained by linear interpolation, an air density of 1.23 kilograms per cubic metre, and an estimated mean wind speed of 6.37 meter per second. The wind speed distribution was then discretized using a bin width of 0.5 meter per second as well as using the Weibull probability density function given in Equation (18) to find the frequency of occurrence for each wind speed class to estimate energy yield. The same power output was gained from Vestas V112-3.075 MW turbine manufacturer's power curve, and the annual energy yield of each wind speed bin was estimated using Equation (19) and summed to obtain energy contribution according to (21). Available wind power was calculated from Equation (20) and performance measures from Equations (22) and (23). Upon the operation of this method, the annual energy generation was projected to be 8,448.57 megawatt-hours and it was considered as 31.36 % (capacity factor) and 2,747.5 Equivalent Full Load Hours per year (amount to) moderate but stable wind energy capacity under typical inland terrain.

7. Results and Discussion

The annual estimates of energy yield using the New European Wind Atlas (NEWA) and the Global Wind Atlas (GWA) were assessed for four representative terrain types forest, mountainous, offshore and normal inland landscape compared with reference production measurements from the Bavarian Energy Atlas and to an official operational source for the offshore case [22]. This comparison allows for a systematic verification of the predictive power of mesoscale wind atlas frameworks for different surface roughness and terrain complexity. The results show that wind energy yield estimation using both NEWA and GWA performs well for normal and offshore terrains, where surface conditions are relatively uniform and wind flow is stable.

In contrast, higher deviations are observed in hilly and forested terrains. In hilly areas, complex wind behavior such as flow acceleration, separation, and increased turbulence is not fully captured by wind atlas models, leading to overestimation of energy yield. Similarly, in forested regions, increased surface roughness and canopy drag reduce wind speeds, but these effects are simplified in wind atlas parameterization. As a result, wind atlas–based yield estimates are less accurate in complex terrains compared to normal and offshore areas. In the case of the forested onshore site, the NEWA-based methodology offered an annual yield of 7714.23 MWh, while the GWA-based method yielded only a slightly lower estimate of 7488.86 MWh, which was in comparison to the Bavarian Energy Atlas reference value of 6338.8 MWh. As a result, both atlases overestimated the energy production in relation to the baseline dataset with relative errors running between around −17 percent for NEWA and −15 percent for GWA. The lesser deviation observed for GWA indicates better performance in forested terrain, based on the terrain correction and roughness parameterization approach. The discrepancies in both models might be attributed to canopy-induced turbulence that remains unresolved and local sheltering effects that mesoscale downscaling cannot capture. Higher wind speeds and vertical shear gave a more substantial average predicted energy for the mountain area. For the Mountain region, The yield estimation of NEWA is about 9341.93 MWh, and GWA is about 10,725.23 MWh, both more than the Bavarian Energy Atlas comparison for 7482.0 MWh. Relative errors were more strongly, more than reported for the forest case, at −19.9 percent for NEWA and −30.2 percent for GWA. Nevertheless, while both approaches provided a measure of increased wind potential with elevation, the largest deviation seen for GWA suggests that the complex orography and flow acceleration caused by terrain may continue to be less resolved through its generalized microscale correction scheme. NEWA exhibits a relatively superior agreement, which might be due to increased spatial and temporal resolution and detailed mesoscale-microscale coupling due to Europe. On an offshore case, the forecast annual energy production was compared with official output data of about two point five terawatt-hours, rather than the Bavarian Energy Atlas. The wind atlas products underestimated the large-scale output to a very large extent, with the New European Wind Atlas with about 2.60 terawatt-hours and the Global Wind Atlas with about 2.76 terawatt-hours for the modeled Multiple-turbine arrangement (175 Turbines). However, relative error analysis showed that Global Wind Atlas agreed more with reference data, with a much lower deviation of approximately −9.31percent compared with the New European Wind Atlas (−3.91), which exhibited a larger deviation. The global atlas performed significantly better for the offshore boundary-layer conditions, which are relatively homogeneous and characterized by low surface roughness, lower turbulence intensity, and less complex underlying terrain, allowing mesoscale models of the atmosphere to better describe the wind field. Overall, as expected, both atlases provided relatively equal and consistent performance over normal inland terrain, as moderate roughness and less complicated topography facilitate accurate yield prediction with relatively small modeling bias. For Normal area, The NEWA estimated 8442.18 MWh and GWA estimated 8448.57 MWh, relatively matching the Bavarian Energy Atlas reference of 8210.6 MWh. The relative errors were minimal, varying by, in effect, −2.7 percent for NEWA and −2.6 for GWA methods. This substantial agreement indicates that moderately flat ground and limited surface complexity are the best conditions for wind atlas-based yield estimation with homogeneous flow and normal shear profiles.

In conclusion, the comparability shows that the complexity of terrain heavily contributes to the predictive power of both wind atlas perspectives. NEWA performs slightly better in Mountains and Forest environments, whereas GWA is more consistent when deployed on mountainous terrains with higher regional resolution. Both set atlases demonstrate peak performance above normal inland and Offshore topography. These results verify that the mesoscale wind atlases yield an efficient and reproducible basic means of evaluating energy yield and that site-specific corrections and local measurements are still critical, in complex terrains, to alleviate the systematic bias and increase forecast reliability.

8. Conclusion

In this study, we provided systematic and quantitative comparison of annual energy yield estimation on four typical terrain classes such as offshore, normal inland, forested, and mountainous environments using the New European Wind Atlas (NEWA) and the Global Wind Atlas (GWA). A common analytical framework with Rayleigh–Weibull statistical modeling, Hellmann wind shear extrapolation, hub-height parameters correction, and probabilistic turbine power-curve integration was utilized to ensure methodological consistency across atlases. Subsequently, the predicted annual energy production (AEP), capacity factor and full load hours were validated against the reference production datasets in order to determine predictive reliability. Outcomes indicate that the highest effect on atlas accuracy is terrain complexity. Both atlases obtained wide agreement in homogeneous and low-roughness areas. Among the controls on normal inland terrain, deviations were almost absent (<3%), confirming that mesoscale climatological modeling represents boundary-layer flow well from moderate roughness. Offshore conditions had stable behavior as well, in which the smaller turbulence and regular marine flow resulted in an enhanced large-scale atmosphere-based structure with reduced prediction errors and substantial capacity factors.

By contrast, complex(hilly, forest) terrains resulted in systematic bias. Forested/ Mountain landscapes presented a large gap (15 to 30%) due to uncorrected microscale impacts (including canopy drag, terrain-induced acceleration and locally produced turbulence) that cannot be fully accounted for by mesoscale downscaling. NEWA typically offered a consistent estimation even though it is found in complicated topography due to its relatively higher regional resolution and detailed CFD-based corrections compared to GWA, which for more consistent estimates in smoother terrain due to global climatological coherence. Both atlases are dependable first-order tools for preliminary feasibility studies and pre-investment testing, but their use in isolation in complex terrains might result in overestimation of the energy yield. Thus, this study suggests that atlas outputs be coupled with local measurement, microscale correction and site-specific calibration to improve accuracy. The results show that atlas-based approaches are suitable for rapid wind resource screening but show the importance of hybrid modeling approaches in advanced and accurate energy prediction in multivariate environments.

9. Reference

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