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Harnessing the power of wind: a comprehensive analysis of wind energy potential in Dhaka city

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Abstract

This study gives a thorough analysis on the wind energy potential in Dhaka, Bangladesh, utilizing data from NASA Power's remote sensing tools and weather data from the Bangladesh Meteorological Department (BMD). The wind speed data collected over a 22 year period at an altitude of 10 m. The results indicate that 3.07 m per second (ms^{-1}) is Dhaka city's typical wind speed, while the maximum wind speeds were recorded in June and July. A Weibull distribution is used to observe the wind data, as well as to calculate the Weibull form parameter of 2.65 and the scale parameter of 3.43 ms^{-1}. Based on these parameters, the most probable wind speed along with the wind speed carrying maximum energy were calculated 2.83 ms^{-1} and 4.28 ms^{-1}, respectively. The highest density of energy has been found in the month of July with a value of 52.11 W/m^2. According to the study, the south is the most prominent wind direction for Dhaka city. Moreover, the study analyzes the relations between energy density and other variables, like wind speed, humidity, dry bulb temperature, etc. Positive correlations between energy density, wind speed, and dry bulb temperature imply that the higher wind speeds and dry bulb temperatures result in greater energies. The study's conclusions offer intuitive information about Dhaka City's potential for wind energy and can support direct future efforts to pursue this green resource in alignment with the Sustainable Development Goals (SDGs) of Bangladesh.

Keywords Energy density, Micro wind turbines, Renewable energy, Weibull distribution, Wind energy

Introduction

With the growing demand for clean and sustainable energy sources, wind energy has emerged as a promising alternative to conventional energy sources in many countries (Maklad et al., et al. 2018). Bangladesh, being one of the most densely populated countries in the world, is facing a significant challenge in meeting the energy demand of its rapidly growing population (Islam et al., et al. 2017). To address this issue, the country is increasingly turning to alternative energy sources like wind, solar, and hydropower, to expand its energy mix as well as relies less on conventional petroleum and coal. The number of plants utilizing renewable energy sources has to rise to maintain economic progress (EECA, 2010). In this way, the design and installation of small wind turbines helps to meet the region's energy needs(Cabello & Orza, 2010; Gagliano et al., et al. 2013; Li et al., et al. 2014; Lu & Sun, 2014; Nouni et al., et al. 2007). Technology advancements guarantee ongoing enhancements to wind turbine performance and size. According to the quality of energy produced by the turbines, wind turbine performance and efficiency are rising (Chang et al., et al. 2003; Eskin et al., et al. 2008; Getachew & Bjorn, 2009; Himri et al., et al. 2008; Mithraratne, 2009; Rosen et al., et al. 1999).

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Building placement can have an impact on wind speed measurements in metropolitan areas (Bivona et al., et al. 2003; Lu & Sun, 2014). For enterprises that use tiny wind turbines, a two-parameter Weibull probability distribution should be used for wind prediction in this situation (Dhunny et al., et al. 2015; Elliot & Infield, 2014).

Among the renewable energy sources, wind energy has the prospective to play a substantial role in Bangladesh's power mix, particularly in urban areas where there is a high demand for electricity. Dhaka, the capital city of Bangladesh, with a population over 21 million people, has a high potential for wind energy generation due to its location in the flat and open deltaic plain of the Ganges–Brahmaputra-Meghna (GBM) basin (Hossain et al. 2017). However, there is a lack of comprehensive studies on the wind energy prospective of Dhaka city, particularly at the rooftop level.

To address this gap, this investigation aims for assessing the wind power potential of Dhaka city at the rooftop level using data from NASA Power (remote sensing data) at a height of 10 m. The contribution of this research stands out in several key dimensions:

Firstly, comprehensive rooftop-level analysis

With a focus on Dhaka's rooftop-level wind energy potential, this study breaks new ground in conducting a thorough analysis. While previous studies have shed light on wind energy in more general contexts, the current work explores the unique opportunities and conditions found in the capital city and provides insights that are essential for the successful deployment of rooftop wind energy installations.

Secondly, innovative utilization of NASA power data

Furthermore, our study creatively uses NASA Power remote sensing data to obtain a comprehensive picture of wind patterns at a height of ten meters. This methodological innovation improves the accuracy and dependability of our results, differentiating our study from others in terms of analytical rigor and offering fresh perspectives on the methodology used in wind energy studies.

Finally, rigorous analysis of feasibility factors

Finally, the study will analyze the wind speed, Weibull parameters, energy density, and other related parameters to determine the feasibility of utilizing wind energy on rooftops in Dhaka city.

In addition to evaluating the wind power potential in Dhaka, this study aims to make a substantial contribution to the broader discussion on wind energy by providing insightful analysis that can guide sustainable energy projects, especially in highly populated urban areas.

Literature Review

Wind energy as a global renewable resource

Wind energy has become an increasingly important source of renewable energy worldwide due to its abundance, sustainability, and environmental benefits (Fadare & Okonkwo, 2018). Wind energy technology has been rapidly advancing in recent years, with improvements in turbine efficiency and design resulting in increased energy production and reduced costs (Nasir et al., et al. 2019). Moreover, the potential of wind energy to contribute significantly to the transition toward sustainable energy systems is increasingly recognized worldwide (Manwell et al., et al. 2010).

Global assessments of wind energy potential

Several researches have been carried out to assess the potential wind energy in various areas around the world. For example, Jovanović et al. (2019) conducted a study on wind energy potential in Serbia, while Aslan et al. (2020) investigated wind energy potential in Turkey and Bhattacharya et al. (2019) conducted a similar analysis for Mumbai city in India. These studies aim to identify regions with high wind speeds and favorable conditions for wind energy generation, contributing to the global understanding of wind resource assessment (Khan et al., et al. 2017).

Wind energy landscape in Bangladesh

In Bangladesh, wind energy has not yet been widely adopted as a significant source of renewable energy (Rahman et al., et al. 2020). Despite its significant potential, wind energy remains underutilized in Bangladesh (Hossain et al., et al. 2017). However, a number of research projects have explored the potential for wind energy in Bangladesh. Islam et al. (2019) conducted a study on wind energy potential in coastal areas of Bangladesh, while Kibria et al. (2020) assessed the wind energy potential for northern Bangladesh. These studies highlighted the wind energy potential for Bangladesh and suggested that further research is needed to fully evaluate the feasibility of wind energy projects across the nation. However, limited research has been conducted specifically on wind energy potential in urban areas like Dhaka City, highlighting the need for comprehensive assessments in such contexts (Islam et al., et al. 2018). Moreover, city urban areas are not explored as micro wind turbines are available now-a-days. Even though there is a lot of potential for the rooftops to be utilized, most of them are underused in Bangladesh. In this planning, the primary factors used to estimate data are the altitude of the nation, historical wind speeds, and meteorological characteristics. The literature uses a number of techniques to calculate wind potential (Carta et al., et al. 2009; Lim & Jeong, 2010; Olayinka & Olaolu, 2012; Sultan & Yassine, 2015; Ba et al., et al. 2017; Thapelo et al. 2018).

Research gap and the specific context of Dhaka city

Although there is a wealth of literature on wind energy potential worldwide, there is a significant lack of analysis that specifically addresses the urban context of Dhaka City. Although earlier research has looked at the potential for wind energy in different places, there is still a lack of a thorough knowledge of the wind dynamics in Dhaka City. This study attempts to close this gap by carrying out a thorough analysis specifically designed for Dhaka City's urban environment. Through the use of weather data from the Bangladesh Meteorological Department (BMD) and NASA Power data, this study aims to offer an improved comprehension of wind patterns and potential inside city borders.

Finding important topics that haven't been sufficiently explored in earlier studies strengthens this gap analysis even more. In particular, few studies have explored the complexities of wind dynamics within metropolitan locations like Dhaka City, despite the fact that others have looked at wind energy possibilities in larger regional contexts. By offering a thorough evaluation of wind energy potential at the micro level and concentrating specifically on metropolitan regions with unused rooftop spaces, this study seeks to close this gap.

This research seeks to advance knowledge of urban wind energy utilization and micro-scale renewable energy methods by drawing similarities with studies like Idriss et al. (2020) on wind energy potential and micro-turbine performance in Djibouti-city, Djibouti. By making these efforts, the study hopes to advance knowledge and educate sustainable energy programs in Dhaka City and beyond by offering insightful information on elements of wind energy potential assessment in urban contexts that have not yet been explored, aligning with the objectives outlined in 'Power from the people: A guide to Micro-generation' (EECA, 2010).

This improved gap analysis emphasizes the distinct contributions the current study makes to the body of existing literature in addition to highlighting the particular research issues it addresses.

Methodology

Data collection

NASA Power provided wind speed data for the Dhaka City area for the years 2000–2021, and the data access viewer may be found at https://power.larc.nasa.gov/data-access-viewer/. The dataset, which includes 8036 data points in total, was gathered at a height of 10 m above ground level and at a daily temporal resolution. This allowed for the detailed temporal profile of wind patterns to be obtained over the designated time period. Additionally, manual data were gathered from the Bangladesh Meteorological Department regarding meteorological characteristics such as pressure, humidity, dry bulb temperature, maximum temperature, and minimum temperature. Because of the great spatial resolution of the wind speed data from NASA Power, it was possible to analyze the wind patterns in the Dhaka City area in detail.

Data preprocessing

The collected wind speed data were cleaned and missing or invalid data points were identified and removed. A commonly used method for detecting outliers in data preprocessing is the standard deviation method, which was used to identify outliers in this step. In particular, data points were evaluated according to how different they were from the average wind speed; those that deviated over a predefined cutoff were regarded as outliers. To further guarantee the coherence of the dataset, consistency tests were carried out, which involved comparing the dataset with nearby measurements to find any anomalies or sudden deviations. To preserve data quality, any data points marked as anomalies or displaying irregularities were either eliminated from the dataset or subjected to additional validation. The goal of this thorough preparation method was to improve the dataset's integrity and dependability for further analysis. The data was then averaged monthly and analyzed for statistical parameters such as Weibull Scale and Shape parameters using the following equations:

$$A = \left(\frac{1}{n}\right) * \sum Vi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i).}$$

$$K = \left(\frac{1}{n}\right) * \sum((Vi - Vm)/A)^3 \quad \ldots\ldots\ldots\ldots \quad \text{(ii).}$$

where A is the Weibull scale parameter, K is the Weibull form parameter, V_i is the wind velocity at the i-th data point, V_m is the most probable wind velocity, and the entire amount of data points is n.

The most probable wind speed, V_F (ms^{-1}) and the extreme energy V_E (ms^{-1}) carrying by the wind velocity are determined by the subsequent way:

$$V\text{F} = A((K - 1)/K)^{1/k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iii).}$$

$$V\text{E} = A((K + 2)/K)^{1/k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iv).}$$

Energy density calculation

The energy density was calculated using the following formula:

$ED = 0.5 * \rho * (Vw)^3$ …………………………….. (v).

Where ED is the energy density, ρ is the density of air, and the speed of the wind is V_w.

These measurements provide information on the microturbine's performance with respect to wind potential, site-specific wind characteristics, and energy output. The turbine should be installed in the location and wind performance to determine the potential of wind energy (Olayinka & Olaolu, 2012).

Visualization

The visualization in the paper depicts the probability density function (PDF) and cumulative distribution function (CDF) of wind speed in Dhaka city at 10 m height. The PDF shows the distribution of wind speed values in the dataset, while the CDF represents the cumulative proportion of observations below a certain wind speed. Additionally, this study presents visualizations for the typical monthly speed of the winds, the relationship between the density of energy and the speed of the wind as well as other parameters such as humidity, dry bulb temperature, etc., the monthly energy density, the detailed monthly wind rose, the annual wind direction diagram, annual Weibull distribution.

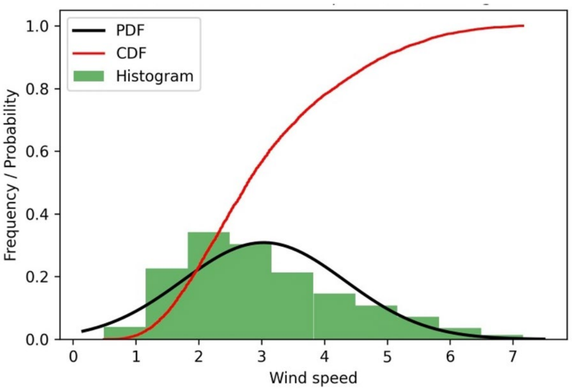


Fig.1 Statistical computations at an altitude of 10 m height for 22 years data

Results

Daily data on wind speeds at 10 m height are collected from remote sensing tools for Dhaka. CDF and PDF appear in Fig. 1. This graph expressed the recorded wind speed data. The most common wind speed, 3.07 ms^{-1} with a chance of 51%, is identified by the density function of the probability curve. The CDF also shows that approximately 90% of the observations fall below 7.0 ms^{-1}.

To determine the wind energy potential, Fig. 2 shows the most probable speed of the wind (V_F) and the speed of the wind that carries the extreme energy (V_E) for each month (22 years typical). The readings of V_F are varied between 1.80 ms^{-1} (in October) and 4.31 ms^{-1} (in July). Furthermore, the measurements of V_E are fluctuated between 2.89 ms^{-1} (in November) and 5.85 ms^{-1} (in July). These two values included in wind turbine design calculation (Akpinar & Akpinar, 2005; Oyedepo & Adaramola, 2012).The readings of V_F along with V_E were calculated by formulas (iii) as well as (iv).

Table 1 displays the features of monthly average wind velocity and the other potential variables for wind power. The findings indicate that the obtained calculations for the A and K factors fall within the ranges of 2.37–4.93 ms-1 and 2.01–3, respectively. The lowermost value of the average wind speed, 2.10 ms^{-1}, was recorded in November and the greatest value, 4.37 ms^{-1}, was recorded in July. It has been noticed that the speed of the

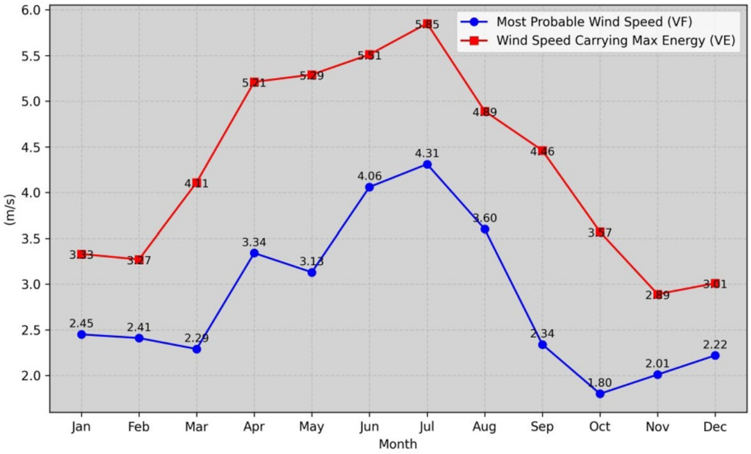


Fig. 2 Comparing the periodic V_F and V_E

Table 1 Investigation of Dhaka City's velocity of wind trends across the time period under consideration

Month	Average wind speed V_{av} (ms^{-1})	Weibull scale parameter, A (ms^{-1})	Weibull form parameter, K (ms^{-1})	Most probable wind speed V_F (ms^{-1})	Wind speed carrying max energy, V_E (ms^{-1})	Dry bulb temp. (Celsius)	Humidity (%)	Max temp. (Celsius)	Min temp. (Celsius)	Energy density, ED (w/m2)
Jan	2.5	2.81	3	2.45	3.33	18.40	69.70	28.6	9.40	9.75
Feb	2.49	2.76	3	2.41	3.27	21.80	62.60	32	11.70	9.59
Mar	2.79	3.04	2.17	2.29	4.11	26.40	60.60	36.5	15.50	13.62
Apr	3.67	4.11	2.49	3.34	5.21	28.40	69.40	37.1	18.90	30.94
May	3.63	4.02	2.29	3.13	5.29	28.70	75.80	36.6	20.20	29.94
Jun	4.18	4.65	3	4.06	5.51	28.90	81.60	35.7	22.70	45.52
Jul	4.37	4.93	3	4.31	5.85	28.60	83.00	34.2	24.00	52.11
Aug	3.73	4.12	2.99	3.60	4.89	28.90	82.00	34.7	24.20	32.54
Sep	2.93	3.22	2.07	2.34	4.46	28.50	82.20	34.9	23.60	15.65
Oct	2.25	2.53	2.01	1.80	3.57	27.40	77.70	35.5	20.00	7.13
Nov	2.10	2.37	2.74	2.01	2.89	24.00	72.00	32.5	15.40	5.80
Dec	2.24	2.54	3.00	2.22	3.01	19.80	72.20	29.1	11.20	6.99
Annual	3.07	3.43	2.65	2.83	4.28	25.82	74.07	33.95	18.07	21.63

wind measurements is comparatively significant between April and August. The remaining months have modest wind speeds (2.10–2.93 ms-1). Additionally, in terms of energy density, November sees a minimum of 5.8 w/m^2 and July sees a maximum of 52.11 w/m^2. Furthermore, The United States Department of Energy (DOE) has suggested a classification scheme that divides wind energy resources into six groups based on annual average wind speed and the corresponding energy density. In this case, Class 1 energy is defined as having an energy density of less than 150 W/m^2 and a typical wind velocity of 3.07 ms^{-1}.

One popular technique for displaying the speed of the wind as a purpose of orientation is the wind rose diagram. According to 22 years of data, Fig. 3(a) displays how often the frequency curve with a relative frequency of various gust velocity sorts at the study location. There are sixteen sectors in the diagram, each of which represents a cardinal or intercardinal direction. The relative frequency of wind events coming from a given direction is indicated by the length of the bars in each sector. Southern breezes are the predominant wind direction throughout the year (25%). South-southeast wind (SSE: 17%) is the second-most prevalent wind component that has been noted.

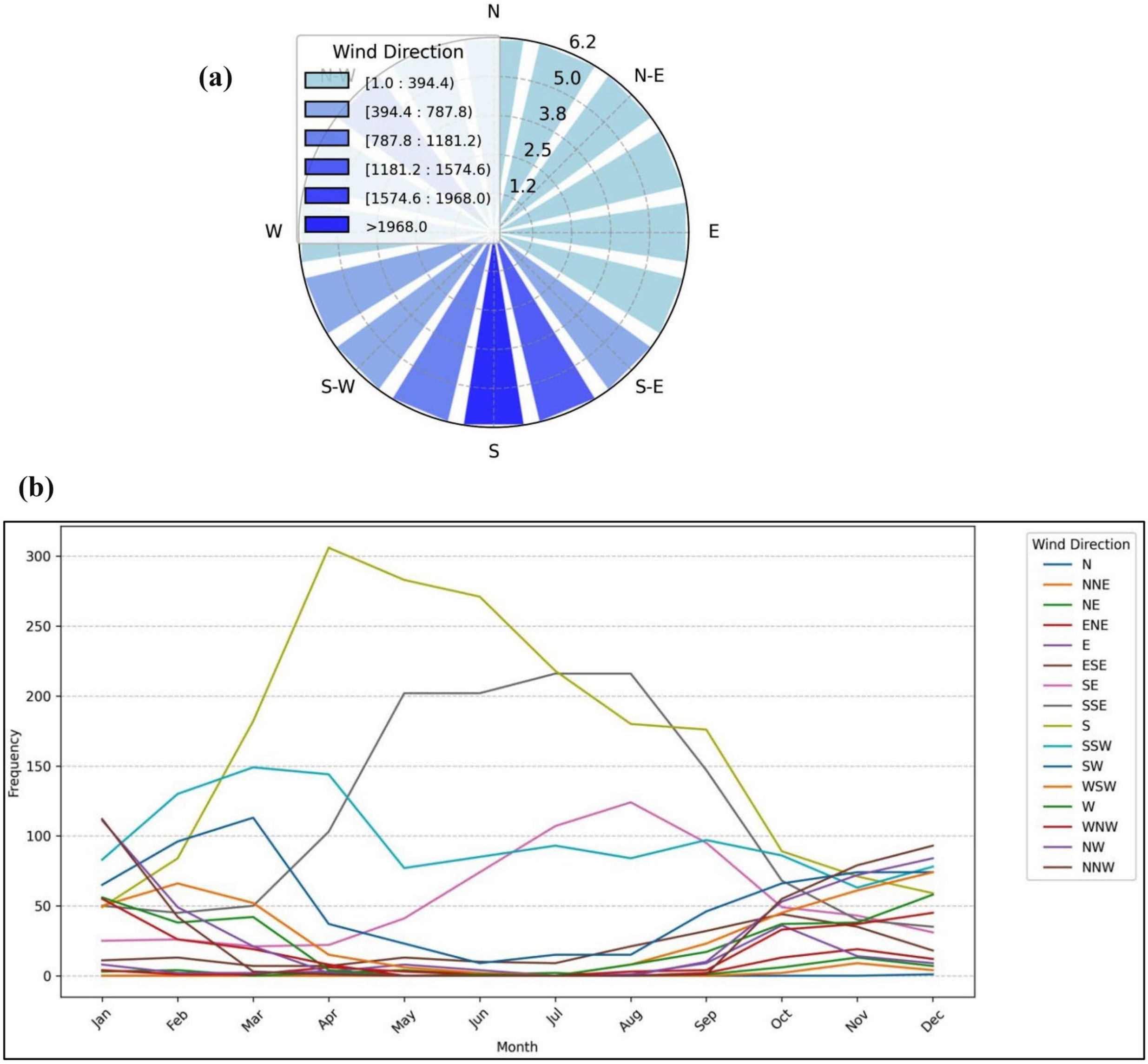


Fig. 3 **a** Annual frequencies of wind rose. **b** precise monthly average frequencies at 10 m hub altitude for the most prominent breeze direction in Dhaka City

A detailed representation of the year-round variations in wind direction frequencies is given by the line graph in Fig. 3(b). The months are represented on the x-axis, while the frequency of wind occurrences is indicated on the y-axis. Each line represents a certain direction of wind. The chart highlights the dynamic nature of wind patterns across the seasons by revealing unique patterns in wind direction frequencies for each month. The line chart shows that the winds from the southern (S) and south-southeast (SSE) directions regularly have greater peaks over a period of several months. This indicates that these wind directions have a prevalent and persistent wind pattern during those times.

The average energy density along with monthly average wind speed profile aimed at Dhaka City for the 22 year timeframe are shown in Fig. 4

In Fig. 4a, b, the graphical representation elucidates the annual variations in average monthly wind velocity and energy density, aligned with the corresponding values delineated in Table 1. This visual presentation serves to underscore the seasonal patterns inherent in the dataset, providing a dynamic visualization of the temporal fluctuations in both wind velocity and energy density. This visual insight enhances the understanding of the annual dynamics, reinforcing the observed patterns in the tabulated data.

Figure 5 shows the correlation between different parameters. The range of a correlation score is from −1 to + 1, with + 1 indicating an extremely positive relationship and −1 indicating a significant negative relationship. In general, moderate toward strong correlations are defined as those with correlation coefficients larger than 0.5. Figure 5 demonstrates that the relationship among the energy density and wind velocity has the greatest positive value, 0.99. The second highest positive number, 0.71, for the correlation between energy density and minimum temperature is also present. 0.66 has the third-highest association with the dry bulb temperature. 0.57 is the fourth-highest association with humidity. As a result, energy density and humidity, dry bulb temperature, wind speed, and lowest temperature are significantly correlated and can be used to estimate the wind speed at urban areas.

In this study, the correlation between energy density and four additional factors—wind speed, humidity, lowest temperature, and dry bulb temperature is revealed. Figure 6's regression plots illustrated the factors' relationships and revealed a linear one. The data trend is represented by the line of best fit on the plot, and the slope of the line illustrates the connection between the variables. The plot also highlighted any extreme numbers or outliers that might influence the analysis. The positive correlation between energy density and wind speed in Fig. 6a implies that greater wind speeds are related to higher energy densities. The positive correlation between energy density and dry bulb temperature as well as minimum temperature in Fig. 6b, c also indicates that higher temperatures are linked to higher energy densities. The positive correlation between energy density and humidity in Fig. 6d is somewhat counterintuitive, as higher humidity might be expected to result in lower energy density due to increased air density. However, this positive correlation could be due to other factors, such as the effects of humidity on wind patterns or the overall weather conditions that affect energy density.

The Swiss tool for wind energy statistics was used to determine a weibul distribution (Windenergie-Daten der Schweiz, 2023). The Weibull distribution of wind speed for 22 years of data is shown in Fig. 7. The match of the

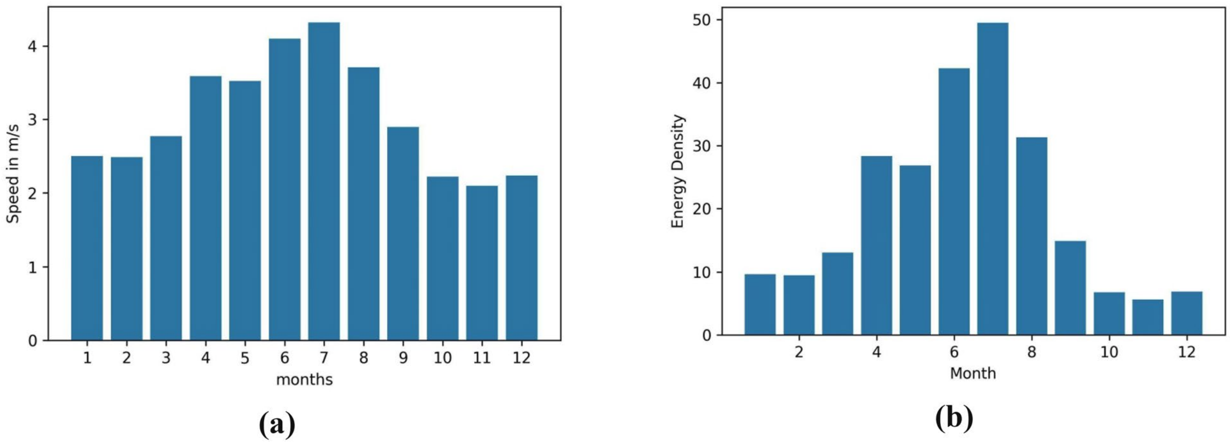


Fig. 4 The graphs show the mean monthly values of the whole-year data set covering 2000–2021 for (**a**) wind fluctuations and (**b**) energy density variations

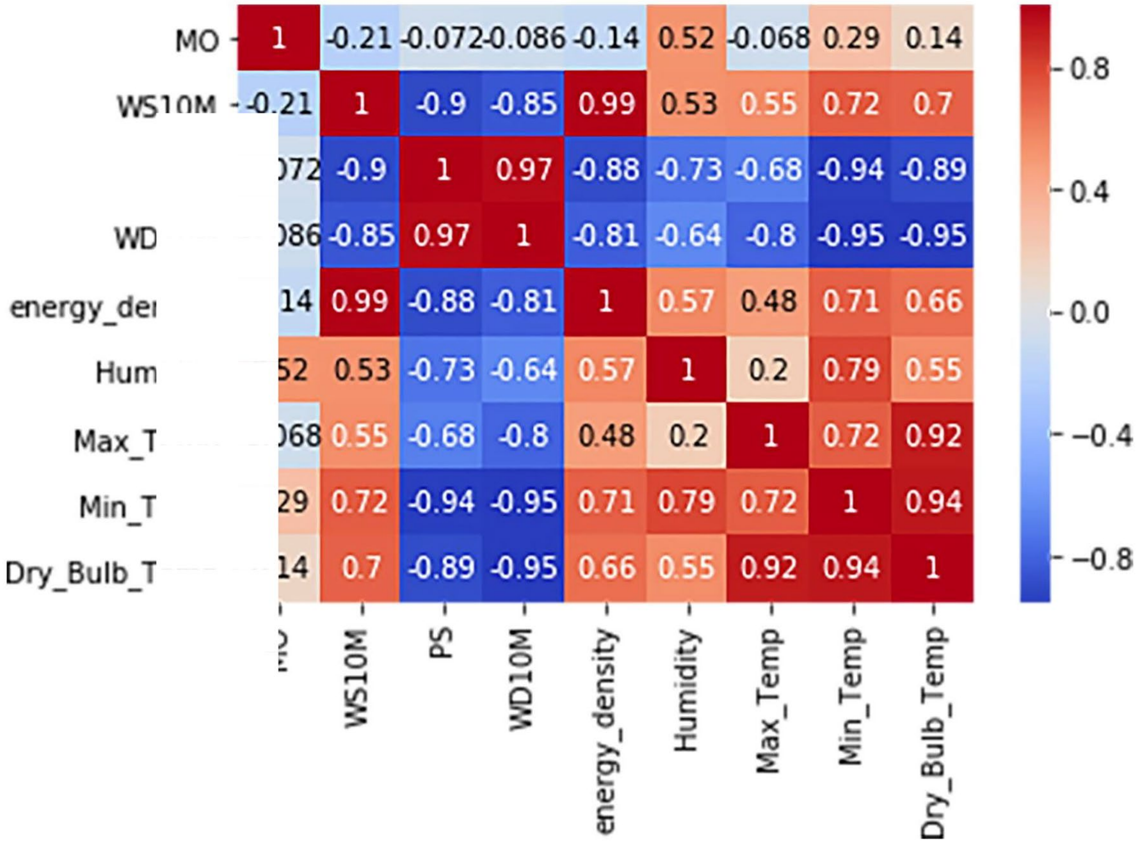


Fig. 5 Correlation Heat map of parameters

Weibull distribution to the data is represented by the red line. The calculated Weibull constraints (A = 3.43 ms^{-1} as well as K = 2.65 ms^{-1}) indicate that the wind speed in Dhaka city follows a Weibull distribution.

Analysis of wind turbine performance

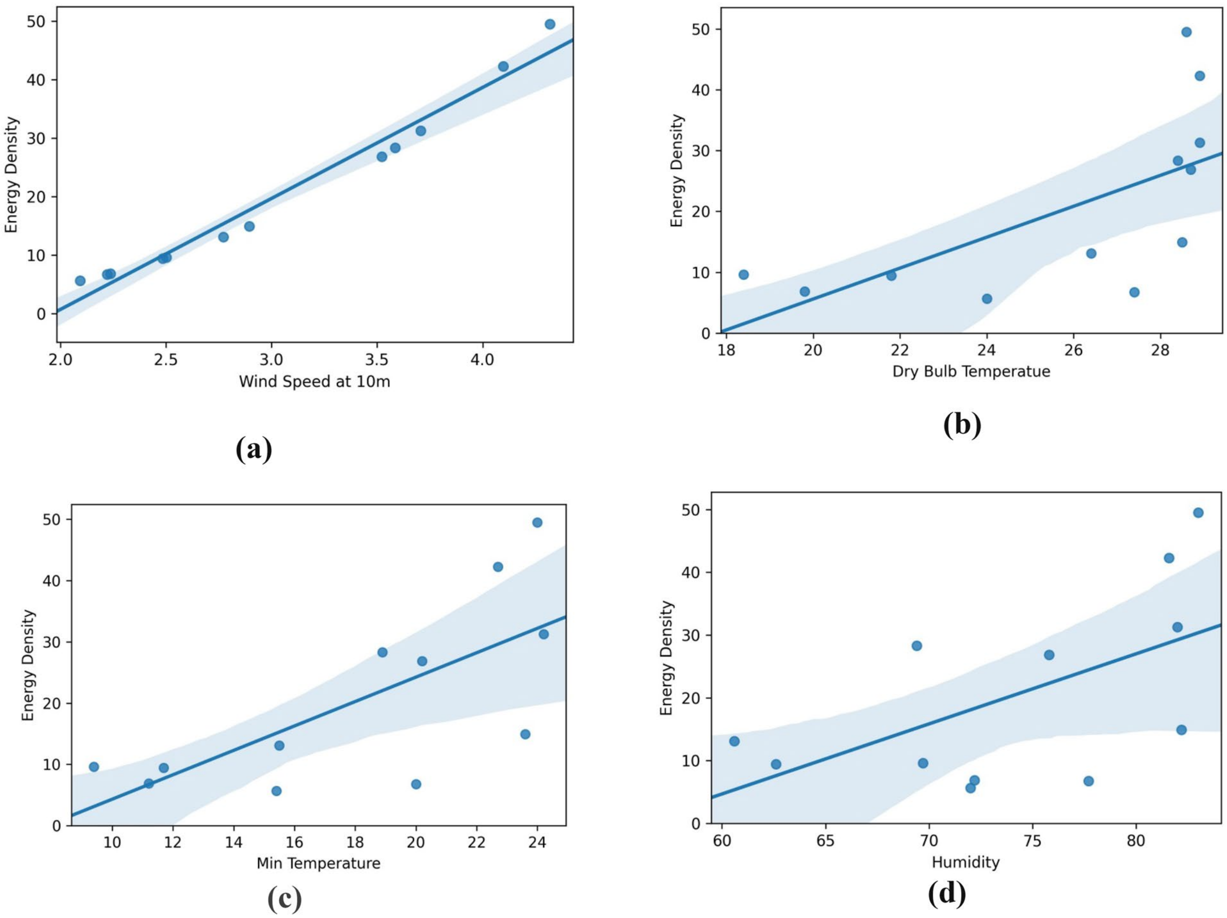
Three commercial wind turbines were chosen based on the site's wind speed profile. Each turbine has unique technical characteristics, including hub height, rotor diameter, cut-in (Vc), rated (Vr), and cut-off (Vf) wind speeds, as well as rated electrical power (PeR). Table 2 contains these specifics, and Table 3 summarizes the simulated outcomes for three distinct Aeolos micro wind turbine types. The Swiss tool was used to get the simulated results.

541 kWh of power were produced annually by the Aeolos 1 kW turbine type, which had a rotor diameter of 2 m and a capacity of 1 kW. With a 4.3% capacity factor, it could run for 378 full load hours annually and 7,834 h total working time.

Aeolos V 300 W turbine type, on the other hand, produced 155 kWh annually with a rotor diameter of 1.2 m and a capacity of 300 W. This turbine variant produced 387 full load hours annually and 5684 total working hours per year while running at a slightly higher capacity factor of 4.4%.

With a rotor diameter of 1.2 m and a 0.3 kW capacity, the Aeolos H 300 W turbine type also produced 458 kWh of power annually. Among the three turbines, this type demonstrated the highest capacity factor, which was 5.5%. This led to an annual total of 5684 h of operation and 572 full load hours.

For each turbine model, graphical representations are given to provide a thorough knowledge of the power generation characteristics. The power curves, power production distributions, and wind speed distributions for the Aeolos 1 kW, Aeolos V 300 W, and Aeolos H 300 W turbine models are shown in the Fig. 8. The efficiency and performance of each turbine under various wind conditions are highlighted in these visualizations, which help to clarify the relationship between wind speed and power generation.



(a)

(b)

(c)

(d)

Fig. 6 Regression Plots illustrating the relationship between energy density and (**a**) Wind speeds, (**b**) Dry Bulb Temperature, (**c**) Minimum Temperature and (**d**) Humidity

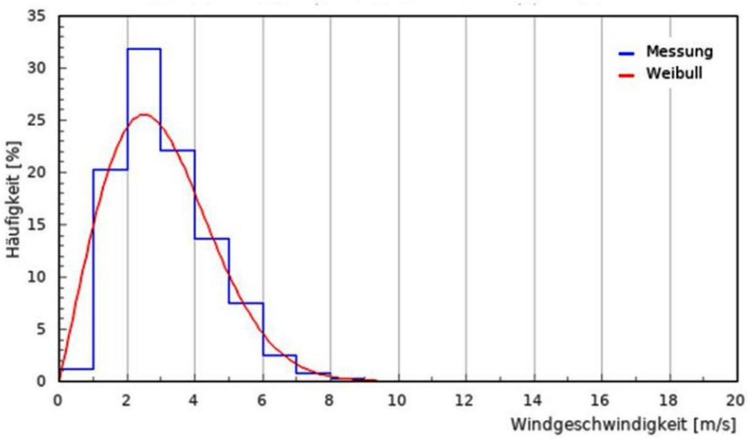


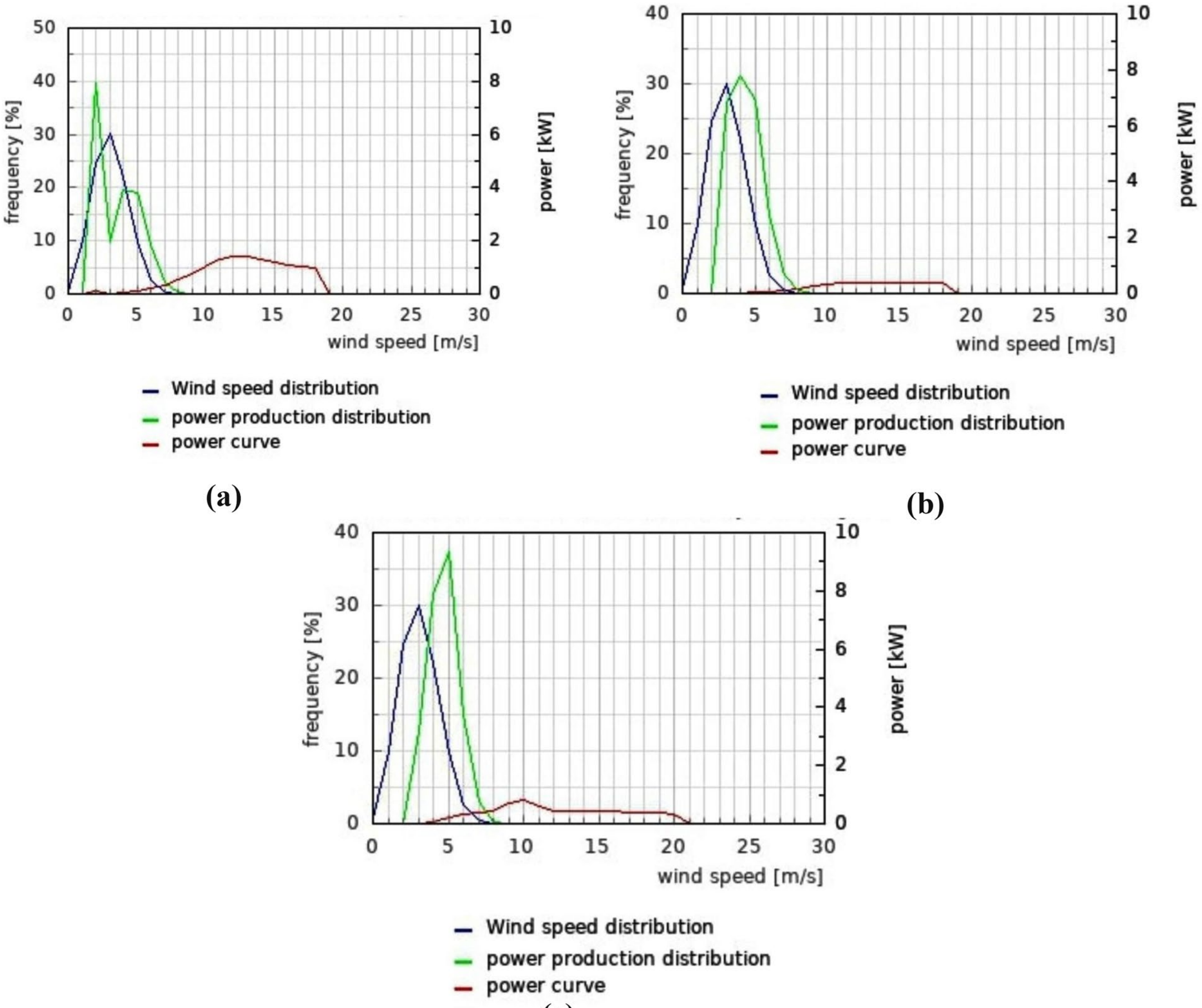
Fig. 7 Weibul Distribution for 22 years data series covering 2000–2021

Table 2 Technical details of the wind turbine model from different manufacturers

Turbine index	Wind turbine model	Vc (m/s)	Vf (m/s)	Vr (m/s)	Hub height (m)	Rotor diameter (m)	PeR (kW)
A	Aeolos–H 300W	1.5	50	10	1.6	1.2	0.3
B	Aeolos–V 1 kW	1.5	50	10	2.8	2	1
C	Aeolos–V 300W	1.5	50	10	1.6	1.2	0.3

Table 3 Simulated outcomes for three distinct Aeolos micro wind turbine types

Producer	Turbine type	Capacity (kW)	Rotor diameter (m)	Power production (kWh/year)	Capacity factor (%)	Full load hours (h/year)	Operating hours (h/year)
Aeolos	Aeolos– 1 kW	1	2	541	4.3	378	7834
Aeolos	Aeolos– V 300W	0.3	1.2	155	4.4	387	5684
Aeolos	Aeolos– H 300W	0.3	1.2	458	6.5	572	5684



(a)

(b)

(c)

Fig. 8 Power generation characteristics for each turbine model: **a** Aeolos-V 1 kW, **b** Aeolos-V 300W and **c** Aeolos-H 300W

A more nuanced interpretation of the simulated results can be attained by combining these graphical insights with the tabulated data, which will help to further the understanding of the research area's potential for wind energy.

Discussion

The results of this study are consistent with previous studies conducted in other regions of the world. For instance, a study conducted in India reported a typical wind velocity of 3.28 ms^{-1} in the city of Mumbai (Bhattacharya et al., et al. 2019). Another study in Pakistan found a usual wind speed of 3.14 ms^{-1} in the city of Lahore (Khan et al., et al. 2017). However, it should be noted that these studies used different methodologies and periods of analysis, which may account for the observed differences.

The calculated Weibull factors ($A=3.43$ ms^{-1} and $K=2.65$ ms^{-1}) indicate that the wind speed in Dhaka city follows a Weibull distribution. This distribution is commonly used to model wind speeds for the purpose of designing wind turbines (Manwell et al. 2010). The most probable wind velocity of 2.83 ms^{-1} suggests that the majority of the time, the wind speed in Dhaka city is relatively low, which may limit the potential aimed at wind energy generation.

Despite the low wind speed, the calculated energy density (ranging from 5.80 to 52.11 W/m2) and wind speed containing the extreme energy (4.28 ms^{-1}) indicate that Dhaka city still has the ability to produce wind energy; which have been noticeably demonstrated in the simulation results for three micro wind turbines. The findings indicate that Dhaka has the potential to develop small-scale wind turbine applications. To determine the best options for varying scale wind power generation, a thorough study on power feasibility should be conducted in larger geographical areas of Dhaka.

It might be feasible to tap into this potential and help the nation meet its renewable energy goals by making use of the city's unused rooftop space. This not only aligns with established global research developments but also presents a unique path for Dhaka city to contribute substantially to national renewable energy objectives.

Conclusion

The findings of this research show that Dhaka city has a sizable wind energy potential at 10 m height, with an average energy density of 21.34 W/m2 over the 22 year period from 2000 to 2021. These findings are consistent with previous studies that have shown the potential for wind energy to be a viable alternative energy sources in urban parts (Gipe, 2004); (Islam et al., et al. 2018). Utilizing unused rooftop space for wind energy generation can greatly improve the city's overall energy mix, lessen reliance on fossil fuels, and lessen the adverse effects of climate change.

Furthermore, the incorporation of simulated outcomes from three micro wind turbine models emphasizes the viability of using wind power in Dhaka even further. The noteworthy energy production capabilities of the Aeolos 1 kW, Aeolos V 300 W, and Aeolos H 300 W turbines highlight the potential of micro wind turbines to support the city's renewable energy objectives.

This research also emphasizes the significance of precise and trustworthy data in determining an area's potential for wind energy. A valuable resource for this study was the combination of BMD data and NASA Power remote sensing data, which enabled for a high-resolution evaluation of wind energy prospective (United States Department of Energy, 2019).

Policy implications and future directions

This study delineates critical policy directions for Dhaka City and its neighboring urban regions, considering the Sustainable Development Goals (SDGs). Although primarily quantitative, integrating qualitative dimensions can significantly enhance insights for policymakers.

The micro wind turbine models from Aeolos manufacturers' simulation findings provide insight into the real-world consequences of utilizing wind energy in cities such as Dhaka. The research shows that rooftop wind energy systems have the ability to support localized energy production, even in cities with relatively moderate wind speeds. The Aeolos 1 kW, Aeolos V 300 W, and Aeolos H 300 W turbine models exhibit varying capacities and efficiencies, indicate the feasibility of integrating wind energy into Dhaka's renewable energy portfolio.

Future investigations should thoroughly assess the viability and financial sustainability of rooftop wind energy systems specifically within Dhaka. This comprehensive analysis should include grid connectivity, installation costs, and micro wind turbine technology to shape supportive policies for adopting renewable energy in urban settings.

Exploring rooftop wind energy potential, particularly within Dhaka and its nearby urban areas, holds significant promise for meeting localized energy demands characterized by high energy density. An interdisciplinary approach, merging quantitative and qualitative methodologies, is pivotal to derive comprehensive insights essential for formulating robust policy recommendations in alignment with sustainable development goals.

Limitations

While this study contributes valuable insights into Dhaka city's wind energy potential, it is essential to acknowledge certain limitations that warrant consideration. First, the analysis focuses on a specific altitude of 10 m, and variations in wind patterns at different elevations may exist. Future research could explore a broader range of altitudes to provide a more comprehensive understanding of the vertical distribution of wind energy.

Second, the study primarily relies on quantitative data, and a qualitative exploration of factors influencing wind energy adoption in Dhaka city is not extensively addressed. Incorporating qualitative methodologies could offer a more nuanced understanding of social, cultural, and economic factors affecting the feasibility and acceptance of rooftop wind energy systems.

Additionally, the investigation predominantly centers on Dhaka city, and the findings may not be entirely generalizable to other urban areas in Bangladesh or diverse geographical contexts. Future studies should consider expanding the geographical scope to enhance the external validity of the findings.

The temporal scope of this study covers a 22 year period from 2000 to 2021. While this duration provides a comprehensive analysis, it is important to recognize that climate patterns and energy demands may have evolved since then. Ongoing monitoring and analysis are crucial to capture dynamic changes in wind patterns and energy needs.

Furthermore, economic factors, policy frameworks, and technological advancements, which play pivotal roles in the feasibility of wind energy projects, are subject to change. This study does not delve deeply into the dynamic interplay of these factors over time, representing an avenue for future research.

In conclusion, while this study contributes valuable findings, these limitations underscore the need for future research endeavors to delve deeper into specific aspects, providing a more holistic and contextually rich understanding of rooftop wind energy adoption in urban settings.

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Author contributions
Mohammad Liton Hossain: Conceptualization, data collection, and methodology are all within his control. In addition to creating the figures and visuals, he also developed the software for data analysis and wrote the major manuscript text. The manuscript will then be reviewed and edited. Dr. S. M. Nasif Shams: supervision and direction during the entire research process, review and rewriting of the work, as well as the provision of insightful advice. Dr. Saeed Mahmud Ullah: study supervision and advising roles; evaluation and modification of the paper; and involvement in the research plan and methodology. All writers have read and acknowledged the final document.

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Declarations

Ethics approval and content to participate

As this research represents personal research for a Ph.D. program and does not involve an ethics committee or institutional review board, formal ethics approval was not required. Nevertheless, Each and every study participant gave their informed permission.

Content for publication

The approval of each author has been obtained for the official release of this text.

Data availability

The information along with resources used in this research is accessible upon request from the author the author who wrote it.

Competing interests

The writers claim to have no competing interest.

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