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Sustainable wind energy potential in Sandwip and Kalapara coastal regions of Bangladesh: A way of reducing carbon dioxide emissions

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ABSTRACT

An enormous amount of power is required in a rising nation like Bangladesh, where achieving economic growth without endangering the environment is a burning issue. The majority of people who live in coastal areas of Bangladesh do not have sufficient access to electricity. There are almost 40 million people living along Bangladesh's 724-km shoreline. Furthermore, it is remarkable that coastal regions have year-round winds, strong enough to generate enormous amounts of power. The viability and promise of wind energy in Bangladesh's southern regions are highlighted in this study. The places demonstrate the possibility for cheaper power production at 30 m–40 m altitudes. The rate of electricity does, however, rise with height. The main objective of this study is to analyze the prospect of wind energy in Sandwip and Kalapara coastal areas of Bangladesh. The data from 1990 to 2020 was taken from the database from the Bangladesh Meteorological Department (BMD) and NASA's NREL (National Renewable Energy Laboratory). These data sources were used to determine the wind power density, wind power output, energy yield, and finally estimate the CO_2 emission reduction. In this paper, a novel approach to the wind energy on selected coastal area is presented and realistic calculation of energy output is carried out of the planned wind system. Finally calculated the realistic CO_2 emission reduction by using this approach for a sustainable future. Estimation reveals that about 162.43 GWh of electricity can be generated annually by installing 684 wind towers on southern Kalapara (Khepupara) area and about 257.25 GWh of electricity can be generated annually by installing 1024 wind tower on the periphery of Sandwip area. So, if 1,768 wind turbines are installed on the Sandwip and Kalapara coastal region instead of burning fossil fuels, about 1,11,373.29 tons of CO_2 will be prevented from being emitted annually.

1. Introduction

Without a balance between the supply and demand of energy, no country can reach its highest level of development [1]. Energy is the foundation of survival and progress of social life and is essential for economic and environmental development and safety of a country [2]. The global demand of energy is expanding as the evolution of civilization advance from modern to ultramodern. No country is able to promote and experience its development without effective energy utilization [3]. Every moment of the life, energy

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Table 1
Existing studies on wind energy in Bangladesh.

Author	Title of Article	Objectives	Findings	Research gap
Islam et al., 2022 [18]	Assessing wind farm site suitability in Bangladesh: a GIS-AHP approach	Evaluating Bangladesh's viability as a location for wind farm sites is the main goal of this essay.	Bangladesh has a fantastic chance to use wind energy because of its large area.	They didn't estimate total energy output and they didn't calculate the estimated decrease in CO_2 emissions.
Alam et al., 2021 [19]	Investigating the Prospect of Rooftop Flapping Wind Turbine in Bangladesh	This study's major focus is on environmentally benign, fairly slow-flapping wind turbines that can easily operate in or close to urban areas or on rooftops.	Rooftop flapping wind turbine can generate electricity with low wind speed at Dhaka and Cox's Bazar areas.	Although this research focuses on a rooftop wind energy in Dhaka and Cox's Bazar, no estimation was taken regarding the total energy output and reduction of CO_2 emission.
Madlool et al., 2021 [20]	Investigation on wind energy for grid connection in Bangladesh: Case study	The main objective of the research is to investigate the grid connected wind energy potential of Chittagong, Bangladesh.	By choosing appropriate sites and examining the wind speed data of those places, a feasibility analysis is carried out on the wind energy project in Chittagong.	Although the energy output and cost analysis were calculated in this study, no effort was made to assess how much CO_2 was reduced.
Shaikh et al., 2017 [21]	Potentiality of wind power generation along the Bangladesh coast	This study's goal is to find wind energy by concentrating on coastal regions of Bangladesh.	Harvesting wind energy has enormous advantages for Bangladesh.	Avoid to calculate realistic energy output and refrain from estimating the decrease in CO_2 emissions.
Islam et al., 2016 [22]	Study of wind power in different parts of Bangladesh	The study's objective is to assess the viability of wind energy in various regions of Bangladesh.	This paper examines the potential for and viability of wind energy in several regions of Bangladesh. This paper also examines electricity generating and wind turbine cost analyses. Different wind power classes and scales are also covered in the paper.	Avoid making accurate energy output calculations and abstain from making CO_2 emission reduction estimates.
Ghosh et al., 2014 [23]	Wind energy assessment using Weibull distribution in coastal areas of Bangladesh	The goal of this investigation is to evaluate Bangladesh's potential for wind energy, particularly in coastal regions.	Cox's Bazar site is the most appropriate location regarding wind energy potential.	Although this research focuses on a suitable location for wind energy in Cox's Bazar, no estimation was taken regarding the emission of CO_2 reduction.
Saifullah et al., 2016 [24]	Wind energy potential in Bangladesh	The objectives of the research is to evaluate Bangladesh's wind energy potential as a long-term remedy for the country's energy crisis.	A number of 5104 wind turbines can produce 1855.25 MW of electricity as part of a near shore wind farm. It can compensate for 56 % of the electricity shortage in 2016.	Avoid to calculate realistic energy output and refrain from estimating the decrease in CO_2 emissions.
Abdullah and Islam, 2013 [25]	Prospects of wind energy in the coastal region of Bangladesh	The paper's objective is to analyze the prospects of wind energy in the coastal region of Bangladesh.	At a very affordable rate, electricity can be produced using wind energy. If there is a generation capacity of power above 800 MW, the cost per unit will be lower.	They did not compute the expected reduction in CO_2 emissions, nor did they estimate overall energy output.
Islam et al., 2013 [26]	Analysis of wind characteristics and wind energy potential in coastal area of Bangladesh: case study	The study's objective is to assess the feasibility of wind energy in Cox's Bazar areas of Bangladesh.	This study tries to describe the wind speed and nature and evaluate the wind energy density in Cox's Bazar.	They make no attempt to estimate the reduction in CO_2 emissions, annual energy production, or wind power output.
Azad and Alam, 2012 [27]	Wind power for electricity generation in Bangladesh	The study aims to conduct systematic long-term observations of the wind regime in a total of 20 eligible areas of Bangladesh, including the Chittagong Hill Tracts region.	The Kutubdia is the most potential location for producing electricity from wind energy. All the population of Kutubdia will receive the power facility if the wind power project is expanded with good designing.	They don't even try to estimate the annual energy production and CO_2 emissions reduction.
Nandi et al., 2012 [28]	Potential of Wind and Solar Electricity Generation in Bangladesh	This article's primary objective is to evaluate Bangladesh's existing wind and solar energy potential.	According to the paper, Kutubdia and Kuakata have an opportunity to generate wind energy.	They used wind data from June 2005 to December 2006, for analysis of wind resource assessment. They do not attempt to compute of the wind energy output, annual energy yield, and estimation of the CO_2 emission reduction.
Hossain et al., 2011 [29]	Feasibility study of wind energy in Bangladesh: a way towards sustainable development	The objective of this research is to evaluate the viability of using wind power for electrical and mechanical energy.	Wind energy will play a supporting role in meeting the nation's rising energy needs with improved wind turbine design, a	Avoid creating precise predictions for energy output and refrain from making CO_2 emission reduction estimations.

(*continued on next page*)

Table 1 (*continued*)

Author	Title of Article	Objectives	Findings	Research gap
			financial package, political commitment to large-scale wind projects through public sector initiatives.	
Nandi and Ghosh., 2010 [30]	Techno-economical analysis of off-grid hybrid systems at Kutubdia Island, Bangladesh	Finding a better energy source for the Kutubdia island to replace the current diesel generator is the goal of this study.	Since Kutubdia has a momentous wind speed, it is possible to use hybrid power systems in sites with prospective wind resources.	The study is limited with Kutubdia Island. They use limited as well as old data from 1992 to 2003.
Khan and Alam, 2004 [31]	Wind energy in Bangladesh: prospects and utilization initiatives	This study's goal is to analyze the prospects of wind driven pumps and wind electricity is the primary goal of this research.	Higher wind speeds are present from May through August. Wind pumps can power irrigation systems and running ice mills during those times in the coastal remote areas.	Avoid making accurate energy output calculations and abstain from making CO_2 emission reduction estimates.

consumption is increasing because of the advancements of technology with high demand, occasionally, wasteful practice of electro-mechanical and electronic devices [4,5]. Usually, 75 % of the world's electricity is produced by use of fossil-based fuels that release a massive amount of greenhouse gases (GHGs) into the atmosphere as well as causes of environmental pollution [6–8]. Although the biggest source of fuel for the world's power plants are coal, oil and natural gas, the realization is that they are significant contributor to environmental problems and makes the people to search for alternatives power sources other than fossil fuels [9]. In addition, it has been estimated that the world's fossil fuel reserves would run out in a few decades and these are insufficient, expensive, and scarcer rapidly [7,10,11]. To meet their electrical needs, many countries are shifting to renewable energy sources in order to sustain energy security [12]. Moreover, nuclear power plants are even more unsafe, hazardous and risky for life. If the nuclear plant goes exploded due to earthquake or other accidental activities? what will be the solution?

The government of Bangladesh (GoB) needs to purchase energy from nearby nations like India and Nepal to fulfil the rising demand [13]. Moreover, 75 % of the country's energy is produced from natural gas, with coal coming in second place and being both expensive and dirty [14]. Attaining the Sustainable Development Goals, or SDGs, outlined by the U.N. at the Paris Climate Agreement (CoP21) in 2015 will help lower the world's carbon footprint, Bangladesh should choose to diversify its energy by introducing local RE sources. This will improve energy security while also reducing carbon emissions.

So that, it is necessary to be in continuous search for viable alternative renewable sources of energy that could assist to reduce the need for fossil fuels, which might show a key part in the energy security of the country. Wind power potential is considered as a significant RE source worldwide [15]. Expanding wind energy deployment is essential for green initiatives to combat GHG emissions, minimize air pollution, and increase the energy security [16]. Due to the fact that a significant amount of the land in Bangladesh is used for agriculture or other reasons, there is not enough space to build large renewable solar power plants. We are essentially missing out on huge prospects from wind energy industry because of the lack of knowledge we have about wind energy technology and advantages.

Due to its geographic position, the prospect for clean renewable energy sources in Bangladesh is substantial [17]. Currently, switching to sustainable sources of power like wind and solar power is the best course of action. Humans have been harnessing wind energy, a renewable energy, for thousands of years. Wind energy is the term used to describe the method by which the wind is utilized to generate mechanical force to rotate the wind turbine and ultimately produce electricity by generator from the naturally moving air in the Earth's atmosphere. Coastal regions, offshore islands, riverbanks, and other inland open spaces with strong wind speeds offer a significant opportunity for power production. Bangladesh has a shoreline that stretches for 574 km and several tiny islands in the Bay of Bengal, where there are strong south-westerly trade winds and sea breezes in the summer and soft north-easterly trade winds and land breezes in the winter. In addition to solar, coastal and offshore wind may provide the most potential to support Bangladesh's development of renewable energy. In reality, wind speeds are substantially greater and can generate far more electricity with offshore wind energy than with onshore farms now in operation. Also, an offshore wind farm has a far less environmental impact because it does not take up precious land or include problems like land acquisition.

In previous research [18,19], coastal and hilly locations were thoroughly analyzed for prospective wind resources to install either wind or hybrid power production installations. The focal locations are mostly located in Chittagong, Sitakundu, Coxs' Bazaar, Rangamati, Khagrachari, Teknaf, Kutubdia, and Kuakata [20–22]. Conventional wind energy research has also been conducted in Bangladesh [23–30], but no one has worked on the estimation of CO_2 emission reduction.

The two primary components of wind strength are frequently diurnal and seasonal variations. With a peak in the afternoon and a low in the morning, the diurnal variation of the wind likewise displays erratic wind behaviour [19–21]. It also indicates that the afternoon is the best time to capture wind energy. The summer (April–September) and winter (October–March) are the seasons with the biggest seasonal fluctuations in low-pressure systems and storm wind speed, respectively. If the correct turbine technology is applied, Bangladesh has the potential to produce the most wind energy during the monsoon season. In summer, trade winds from the southwest and sea breezes dominate the massive amounts of atmospheric oscillation, whereas in winter, moderate trade winds from the northeast and land breezes take the lead. This denotes a consistent wind direction, which might be beneficial to wind power plants.

However, a few studies on the prospects for wind energy in Bangladesh [18–30] have all focused on the conventional, potential of wind energy systems in the country, but nobody has attempted to make the "realistic calculation of the wind power output, annual energy yield, and estimation of the CO_2 emission reduction" shown in Table 1.

Modern RE technologies are continually developing new ways to capture electricity by converting efficiency with novel ideas and substances. This motivates scientists, scholars, and researchers to explore suitable sites for implementing renewable energy sources (RE) like solar PV, wind, or hybrid solar-wind and roughly estimating energy creation. Therefore, the aforementioned research demonstrates that renewable wind energy production is essential to satisfy increasing energy needs for a sustainable future as well as environmental protection. The study's primary objectives are to analyze the potential for wind energy, as well as to compute the wind energy output, yearly energy yield, and ultimately, estimate the CO_2 emission reduction.

In this research, the wind power prospects in the offshore and coastal regions of Bangladesh are carefully explored, and the viability of utilizing wind turbines, energy output, and cost estimates, are also examined. In order to address the country's energy crisis sustainably, it also attempts to evaluate Bangladesh's potential for wind energy. The research's novelty lies in its (a) design the arrangement of the wind farm along the southern coastal region of the Sandwip and Khepupara area of Bangladesh, (b) calculating the realistic energy production of the planned wind farm system, and (c) estimation of the reduction in CO_2 emissions to the environment instead of fossil fuel-based power generation.

The article's remaining portions have been split into four sections. The present status of global wind power and present status of wind power in Bangladesh are both discussed in Section 2. The materials and methods are presented in Section 3, which also covers the study area, data source and processing, data analysis, and calculation of energy output. The determination of monthly average wind

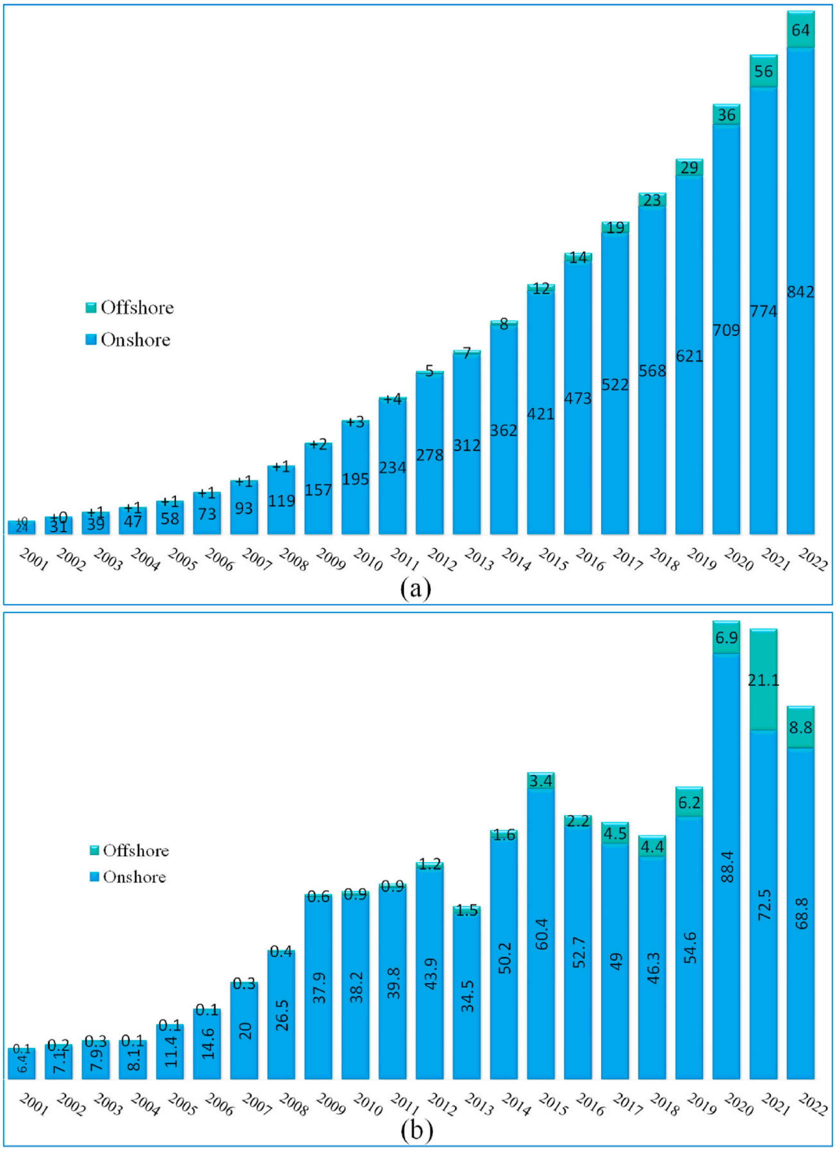

Fig. 1. (a) The historical progress of the total number of wind energy installations worldwide (2001–2022) [GWEC, 2023]. (b) The historical development of new wind power plants worldwide (2001–2022) [Source: Author's creation based on [32] data].

speed, vertical extrapolation of wind data at various heights, estimation of wind power density (WPD), selection of wind turbine with operating principles, determination of wind power, determination of wind energy yield, and estimation of CO_2 emission reduction are all included in Section 4's results and discussion. Finally, the conclusion section brings the article to a close.

2. Wind energy scenario

2.1. Present status of global wind energy

Fig. 1 (a) depicts the historical development (2001–2022) of all wind power installations worldwide, whereas Fig. 1 (b) depicts the historical development (2001–2022) of all new wind power installations worldwide.

More than 842 Gigawatt (GW) of wind energy (onshore) and 64 GW of wind energy (offshore) were produced globally in 2022, generating a total of 906 GW, an increase of 15 % over 2021, and adding over 77.6 GW (68.8 GW of new capacity from onshore and the rest from offshore) to the global grid [32]. This highlights the remarkable resilience and upward trajectory of the worldwide wind industry. The Top ten nations for worldwide onshore and offshore wind power installations in 2022 are shown in Fig. 2 (a), while the Top 10 countries for global yearly new additions in 2022 are shown in Fig. 2 (b). China and the USA together accounted for 57 % of the onshore total and 71 % of the offshore total global installation, whereas China and the UK combined accounted for 60 % of the onshore total and 71 % of the offshore total global new installation [32]. Wind energy is a plentiful and endless resource that produces electricity without consuming fossil fuels or polluting the atmosphere. Countries that deploy wind energy can use the extra revenue to

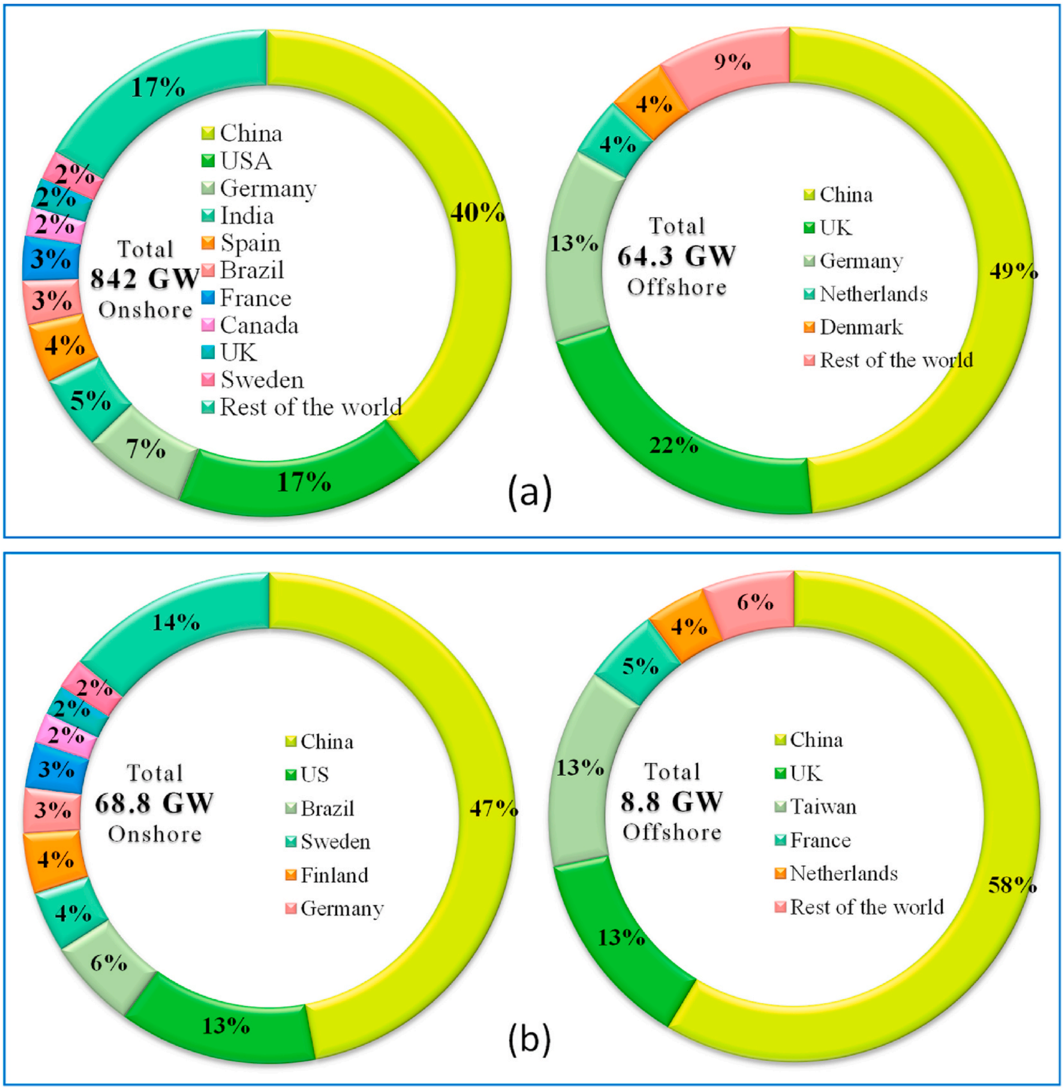

Fig. 2. (a) Top 10 nations for onshore and offshore wind power installations globally in 2021; (b) top 10 nations for yearly new additions globally (onshore and offshore) data [Source: Author's creation based on [32] data].

pay for educational expenses, cut taxes, and fund initiatives related to local infrastructure etc.

2.2. Present status of wind energy in Bangladesh

Bangladesh is located in a tropical climatic condition, thus there is enough wind flow throughout the year, particularly in the southern region of Bangladesh during the summer when a strong trade wind blow [33]. The prospective places for wind farms include in coastal seaside zones, seaward islands, where wind speed is favourable, however not all locales have the capacity to capture wind power. Bangladesh's coastline is approximately 710 km long and covers a total area of 47,201 km^2, of which 37,000 km^2 are located within a 50 m depth zone [34,35]. The biggest sea beach in the world, termed Cox's Bazar Sea Beach, is located at the north of the Bay of Bengal [36]. Moreover, several islands are also located here. These are all prospective locations for installing wind farms to produce wind power.

In Bangladesh, three wind farms with a total power output of 2.9 MW have already installed and operating at Kutubdia (Cox's Bazar) and Sonagazi (Feni); two additional plants with a capacity of 62 MW are currently undergoing construction at Chakaria (Cox's Bazar) and Sirajganj sadar; and three additional plants with a capacity of 295 MW are in the planning stages at Kalapara (Patuakhali), Chandpur sadar, Cox's Bazar, Mongla, Sonagazi-2, and Maheshkhali (Cox's Bazar), shown in Fig. 3 [37]. Also, the GoB announced plans for three new wind farms with 150 MW capacity, to be built at Chandpur, Khulna's Dakop upazila, and Cox's Bazar's Inani Sea Beach [38,39].

3. Materials and methods

A preliminary analysis revealed that the country's coastal zone comes under the area of interest because it has the highest priority for mean wind speed. Wind speed data from 19 distinct locations between the years of 1990–2020 are used in this research.

The obtainable wind speed data is collected at the recommended atmospheric altitude of 10 m, converted up to 150 m data (with 10 m interval) using the standard conversion technique, and then examined on a monthly, and annual basis. Wind power density is estimated at various locations using this wind speed data in order to classify them into various power classes. Moreover, calculation of wind power output, and wind energy yield were obtained. Finally, the amount of CO_2 emission reduction was calculated, shown in Fig. 4.

3.1. Study area

The coastal and offshore regions of Bangladesh were taken into consideration for this study. The coastal zone of Bangladesh covers 47,201 square km, or 32 % of its entire landmass. Around 35 million people live in the coastline region of Bangladesh and approximately 70 islands could be found along Bangladesh's coast [34]. Among them, the coastal regions of Sandwip and Khepupara were taken into consideration for this study, as indicated in Fig. 5.

Sandwip is situated in the northeast of the Bay of Bengal in close proximity of the seaport city of Chittagong and is located in between the longitudes of 91°17′ and 91°37′ east and the latitudes of 22°16′ and 22°43′ north. It is situated at the Meghna River's mouth in the Bay of Bengal and is separated from the Chittagong coast by Sandwip Channel. On Sandwip Island, there are 62 mahallas, 34 villages, and fifteen wards. The area of Sandwip island is 762.42 sq km, with 50 km (31 km) long and 5–15 km (3.1–9.3 mi) wide [41].

Khepupara is situated in the patuakhali district of Kalapara Upazila, which is situated between 21°48 and 22°05 north latitudes and 90°05 and 90°20 east longitudes. The region is bounded to the north by Amtali Upazila, to the south by the Bay of Bengal, to the east by the Rabnabad Channel and Amtali Upazila, and to the west by Amtali Upazila [42].

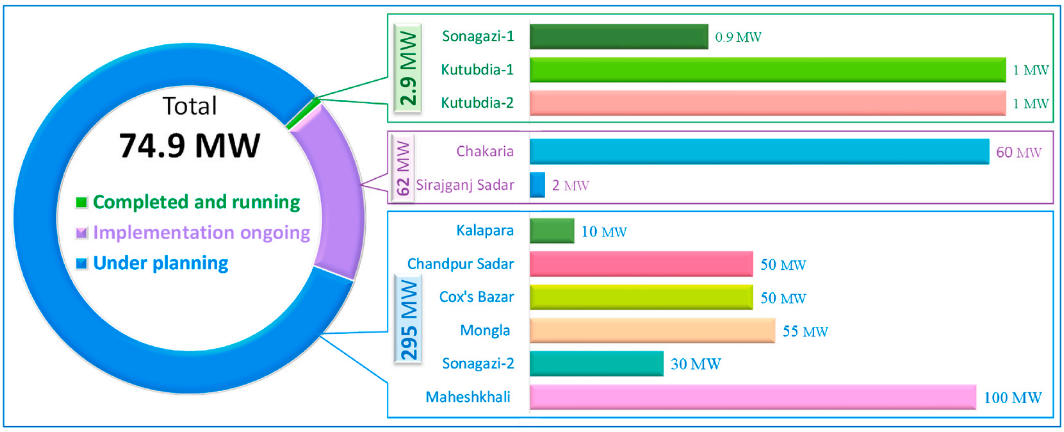

Fig. 3. Bangladesh's current wind energy situation [Source: Author's creation based on [37] data].

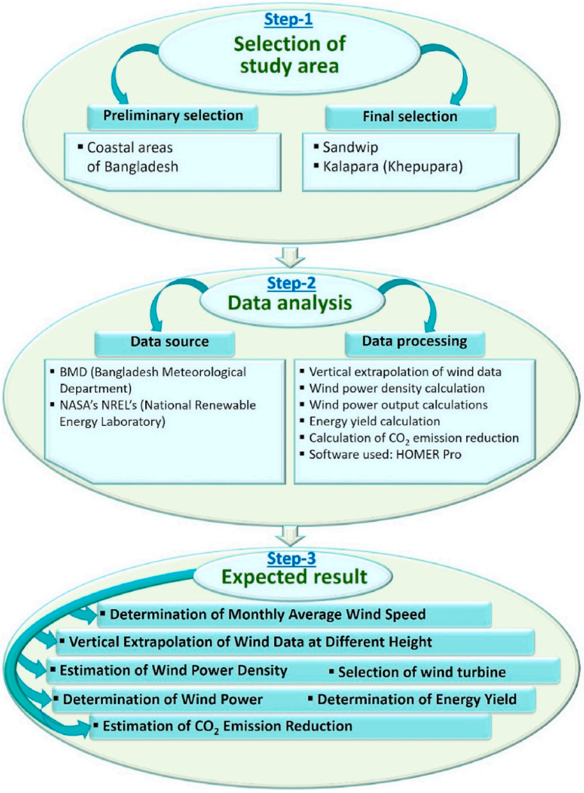

Fig. 4. Methods of the research.

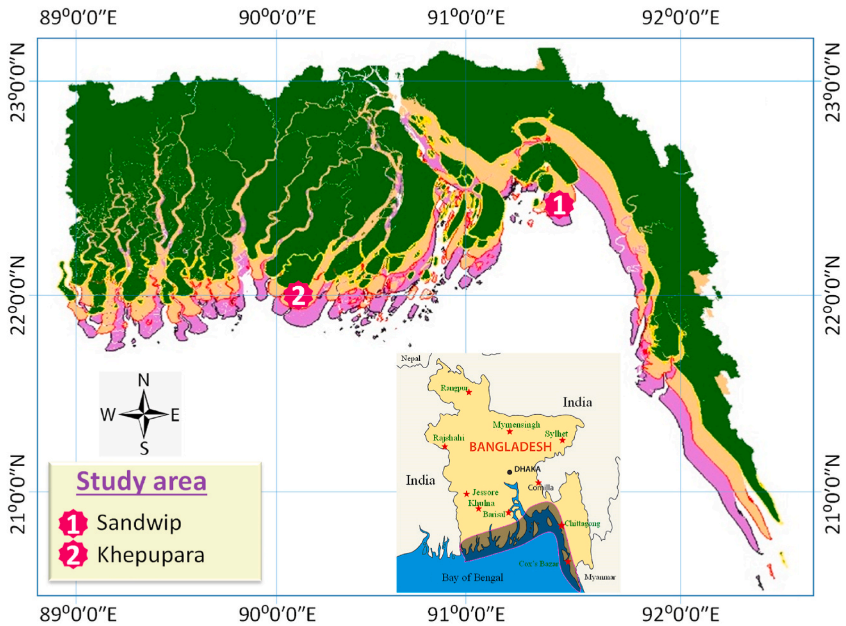

Fig. 5. Location of the study area [Source: Author's creation and modified after [40]].

3.2. Data source and data processing

Globally, there are several databases available that can be used such as the NASA's National Renewable Energy Laboratory [43], and the database of the Bangladesh Meteorological Department [44], which provide past data spanning several years from any region of the world identified by latitude and longitude. For the purpose of gathering hourly wind data, 19 stations of the Bangladesh Meteorological Department (BMD) have been selected, where data are typically collected as time series of 1 min averaged data. Every site employ anemometer of 10 m above the ground. The weighted average method was used to convert the 1-min wind speed data into 10-min averaged wind speed data, which were then processed and analyzed using the appropriate computer tools in accordance with the standard guidelines of the International Electro-technical Commission (IEC; one of the international standards and conformity assessment bodies for all fields of electro-technology). To calculate amount of wind energy and energy output, total number of collected wind data was cross-checked by BMD and NREL using HOMER Pro software. BMD provided only wind speed data at a normal meteorological height of 10 m. By using a common conversion procedure, this data was transformed from 10 m to 150 m with 10 m interval.

3.3. Data analysis and energy output calculation

3.3.1. Vertical extrapolation of wind data

Obstacles and the roughness of the ground severely break the wind. The wind is no longer impacted by the surface when it is located high above the earth, in the unaltered air layers of the geostrophic wind. Wind speed varies with height between these two extremes. Vertical wind shear is the name given to this occurrence. The logarithmic wind profile is a reliable indicator of vertical wind shear in an environment with neutral stratification and flat terrain.

Usually, wind speed data are measured from the Bangladesh meteorological stations at a 10 m height. In literature, there are several relationships that may be used to compute wind speed at any height [45–47]. To calculate the wind speeds at different altitudes above ground, a suitable and mathematical model was used. In wind energy studies, 'Log laws' have used to model the vertical profile of wind speed over regions of homogenous, flat terrain.

Log law: The log law states that the increase in wind speed with height in the bottom 100 m can be explained by a logarithmic expression that determines the wind speed v_2 at a given height h_2 in relation to the original height h_1 and speed v_1, assuming a logarithmic vertical profile of wind speed function of the roughness length ***r***.

Using the log law, this calculator extrapolates the wind speed at a specific height. This logarithmic equation [48] may be used to represent the rise in wind speed with height in the lowest 150 m:

$$v_2 = v_1 \left[\frac{\ln\left(\frac{h_2}{r}\right)}{\ln\left(\frac{h_1}{r}\right)} \right] \tag{1}$$

Height h_1 is used to determine the reference wind speed, v_1. v_2 is the wind speed at height h_2, and ***r*** is the length of the roughness, shown in Table 2.

3.3.2. Wind power density calculation

Wind resource availability at a potential site may be assessed using wind power density. The amount of energy that is available at the location to be converted by a wind turbine is indicated by the wind power density, which is expressed in watts per square meter [50]. In compared to mean wind speed, wind power density (WPD) has been shown to be a more accurate indicator of a site's capability for producing wind energy. It is inversely related to the cube of both the air density and the instantaneous short-term average wind speed. This takes into account the combined impacts of the wind speed frequency distribution and the wind speed cube [51]. The wind power density (WPD) for several samples can be calculated by the following formula [52]:

$$WPD = \frac{1}{2} \times \rho v^3 \tag{2}$$

Table 2
Roughness Classes and Lengths of terrain surface [49].

Roughness class	Roughness length, ***r***	Land cover types
0	0.0002 m	Water surfaces: seas and lakes
0.5	0.0024 m	Smooth, open landscape, like concrete, airport runways, trimmed grass, etc.
1	0.03 m	Without any hedges or fences, open agricultural terrain, possibly some distant structures, and gently rolling slopes
1.5	0.055 m	Agricultural land with a few buildings and 8 m high hedges separated by more than 1 km
2	0.1 m	Agricultural land with a few buildings and 8 m high hedges separated by approx. 500 m
2.5	0.2 m	Agricultural land with many trees, bushes and plants, or 8 m high hedges separated by approx. 250 m
3	0.4 m	Towns, villages, agricultural land with many or high hedges, forests and very rough and uneven terrain
3.5	0.6 m	Large towns with high buildings
4	1.6 m	Large cities with high buildings and skyscrapers

Where, ρ is the mean air density ($1.225 kg/m^3$, constant value depending on the atmospheric pressure at sea level as per U.S. Standard and at $15^\circ C$); v is the wind speed (m/s).

Hence, the mean wind power density for any given time period can be computed using the following formula [53]:

$$\overline{WPD} = \frac{1}{2n}\rho\sum_{i=1}^{n} v^3 = \frac{1}{2}\rho\overline{v}^3 \quad (3)$$

Where, n is the total number of data used during the specified period.

Once WPD is calculated at different places using equation (2), different wind power class are assigned for them using Table 3.

3.3.3. Wind power output calculations

The wind power is calculated by the following equation [55]:

$$P = \frac{1}{2} \times \rho \times A \times v^3 \quad (4)$$

Where, P is the power output (in watts); ρ is air density (kg/m^3); A is the cross-sectional area of wind or, swept area of blade or circular area (πr^2) or ($\pi d^2/4$) in (m^2); v is the oncoming wind velocity (m/s).

Suppose, the Northwind 100C turbine's potential wind power at three different wind speeds is calculated as follows. This is the updated Northwind 100A from the previous model. The results of the computations will be displayed when the velocity is doubled and then tripled. Think about the increase in power that will result from doubling and tripling the velocity:

The standard air density is 1.225 kg/m^3. The radius of the turbine is 12 m, which has a 24 m diameter. As a result, the turbine's swept area πr^2,

$$\pi r^2 = 3.14159\ (12^2) = 452.4\ m^2$$

Initially, if there will be start with a 5m/s wind.

At 5m/s,

$$P = 34636.875W = 34.636kW$$

At 10m/s,

$$P = 277.095kW\ (8 \text{ times as large})$$

At 15m/s,

$$P = 935.196kW\ (27 \text{ times as large})$$

When the velocity doubles, the power increases by a factor of 8, and when it triples, it increases by a factor of 27. This is the case since the velocity is cubed, resulting in $2^3 = 8$ and $3^3 = 27$.

3.3.4. Energy yield calculation from a single wind tower (**in KkWh**) E_y

In this research, the yearly energy yield is calculated by the following equation:

$$E_y = (P \times C_p \times 8760) \quad (5)$$

Where, P is the wind power output; C_p is the power coefficient or power efficiency (0.474) which measures the proportion of wind energy that is transformed into useable energy; and 8760 is used for yearly ($365 \times 24 = 8760$) energy yield.

The Betz Limit: Albert Betz, a German scientist, conducted various tests and came to the conclusion that no wind turbine could convert more than 59.3 % of the kinetic energy of the approaching wind into useful energy just by rotating rotor blades. How did he

Table 3
Classes of wind power density [54].

	10 m		Hub Heights	
Wind Power Class	Wind Power Density (W/m^2)	Wind Speed (m/s)	Wind Power Density (W/m^2)	Wind Speed (m/s)
1	0–100	0–4.4	0–200	0–5.6
2	100–150	4.4–5.1	200–300	5.6–6.4
3	150–200	5.1–5.6	300–400	6.4–7.0
4	200–250	5.6–6.0	400–500	7.0–7.5
5	250–300	6.0–6.4	500–600	7.5–8.0
6	300–400	6.4–7.0	600–800	8.0–8.8
7	400–1000	7.0–9.4	800–2000	8.8–11.9
8	>1000	>9.4	>2000	>11.9

arrive at this 59.3 % maximum figure, which is today recognized as the Betz limit.

The turbine efficiency might be defined as the ratio between the output power, P_{OUT}, and the wind energy available flowing into the blades, P_{IN}. Based on the assumption that the entire rotor area experiences a homogenous, centrally directed wind flow that moves at a constant speed. On the basis of these two variables, the turbine's efficiency [56] is therefore represented as:

$$\eta = P_{OUT} / P_{IN} \tag{6}$$

Hence, it must be equal to "1" ($\eta = 1$) for a typical wind turbine to be 100 % effective. However, because of design, friction, and windage effects, the utmost efficiency that may be obtained is actually expressed as a percentage of the Betz limit.

The "theoretical" power output [55] from a wind turbine, shown in equation (4), may thus be represented by the following modified equation [56]:

$$Power\ (w) = \frac{1}{2} \times \rho \times A \times v^3 \times 0.593 \tag{7}$$

Where, The Betz Limit of 59.3 % (0.593), which equates to the highest value of the power coefficient, has been used in place of C_p. It is really impossible for turbines to operate at 100 % efficiency, even while rotating at maximum speed.

Depending on the manufacturer and design, modern wind turbines have an efficiency range of 60–80 %. Hence, if researcher suppose that the manufacturer has deemed their brand-new wind turbine generator to be 80 % efficient, it will convert 80 % of the Betz Limit into energy. Hence, $0.8 \times 0.593 = 0.474$ (or 47.4 %) would be the C_p of wind turbine. In other words, instead of converting 80 % of the available wind energy into useful power, the selected wind turbine would only do so at a rate of 47.4 %.

3.3.5. Calculation of CO_2 emission reduction E_{365}

The annual CO_2 emission reduction is calculated by the following equation [10]:

$$E_{365} = (E_t \times EF) \tag{8}$$

Where, E_{365} is the annual CO_2 emission; E_t is the annual electricity production per single wind turbine; and EF is the CO_2 emission Factor per MWh.

4. Result and discussion

In this research, wind speed data from 1990 to 2020 have been examined statistically. A better approach for vertical extrapolation of wind data, known as "Power Law," was considered through calculation. Moreover, calculation of wind power density, wind power, and wind energy yield were obtained. Finally, the amount of CO_2 emission reduction was obtained. On the basis of hourly, monthly, seasonal, and annual analysis, the most significant findings of this study are conveyed.

Data on wind speed has been retrieved from 19 distinct stations of Bangladesh Meteorological Department (BMD purchased data).

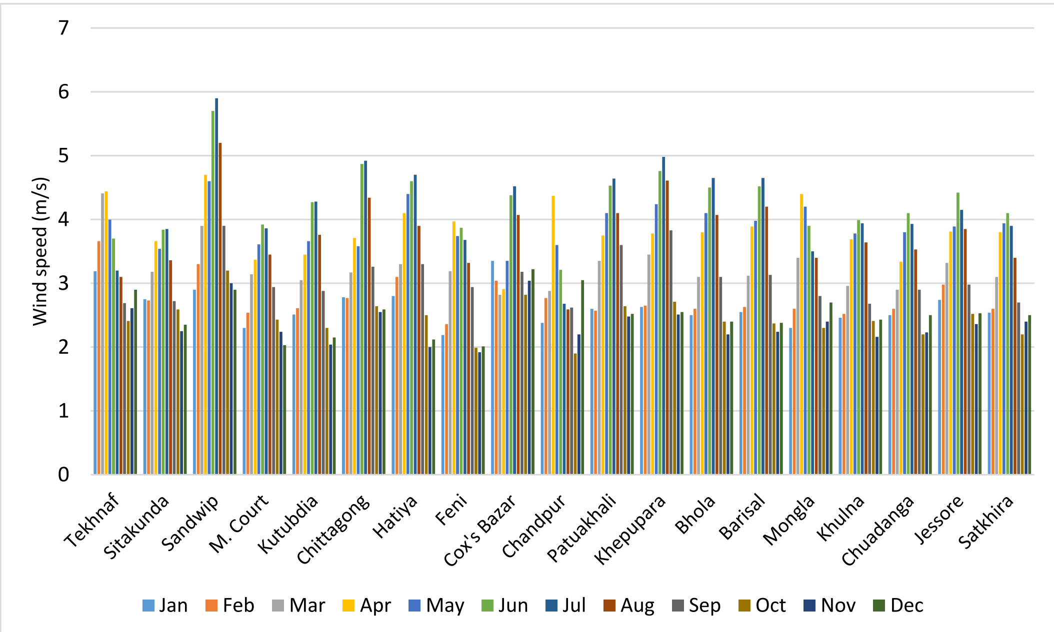

Fig. 6. Average wind speed of 19 selected locations at 10 m height [Source: Author's creation based on [44] data].

This data was gathered, and the methods mentioned previously in section 3 was used to calculate the necessary wind energy output as well as how much CO_2 gas emissions will be reduced annually.

4.1. Determination of monthly average wind speed

For 19 coastal zones in Bangladesh, at 10 m height, average wind speeds (1990–2020) were computed using BMD data. Fig. 6 shows the monthly average wind speed at 10 m height of 19 selected locations of coastal areas of Bangladesh.

The highest wind speed occurs during the month of June (at M. court, Feni, Khulna, Chandpur, Jessore, and Satkhira), July (at Sitakunda, Sandwip, Kutubdia, Chittagong, Hatiya, Cox's Bazar, Patuakhali, Khepupara, Bhola, and Barisal), and frequently in April (at Teknaf, and Chandpur). Among them the highest wind speed was shown at Sandwip (maximum 5.9 m with an average 4.1 m), and Khepupara (maximum 4.98 m with an average 3.56 m). That's why, in this research, Sandwip and Khepupara have been considered for wind energy generation, shown in Fig. 7.

4.2. Vertical extrapolation of wind data at different height

Height affects wind speed. The vertical profile of wind speed was modelled using the mathematical "Log Law" model. The wind speed is extrapolated using this calculator for a specific height. Using the mathematical model annual average data from all stations were computed to predict wind speeds. The results are displayed in Fig. 8.

"Wind speed changes throughout the year. The average wind speed in the Sandwip area was 4.09 m/s (at 10 m height), and gradually increases with increasing height to 7.53 m/s (at 150 m height), shown in Table S1. The average wind speed of Khepupara was 3.56 m/s (at 10 m height), and increased significantly with height to 7.37 m/s at 150 m, shown in Table S2."

At 30 m height, the minimum wind speed was 3.6 m/s during the month of November at Khepupara area, where as the maximum wind speed was 7.15 m/s during the July. At 30 m height, the minimum wind speed of Sandwip was 3.89 m/s during the month of December to January, whereas the maximum wind speed was 7.91 m/s during the July, shown in Fig. 8. The projected wind speed is sufficient for the various wind turbines on the market to produce wind electricity.

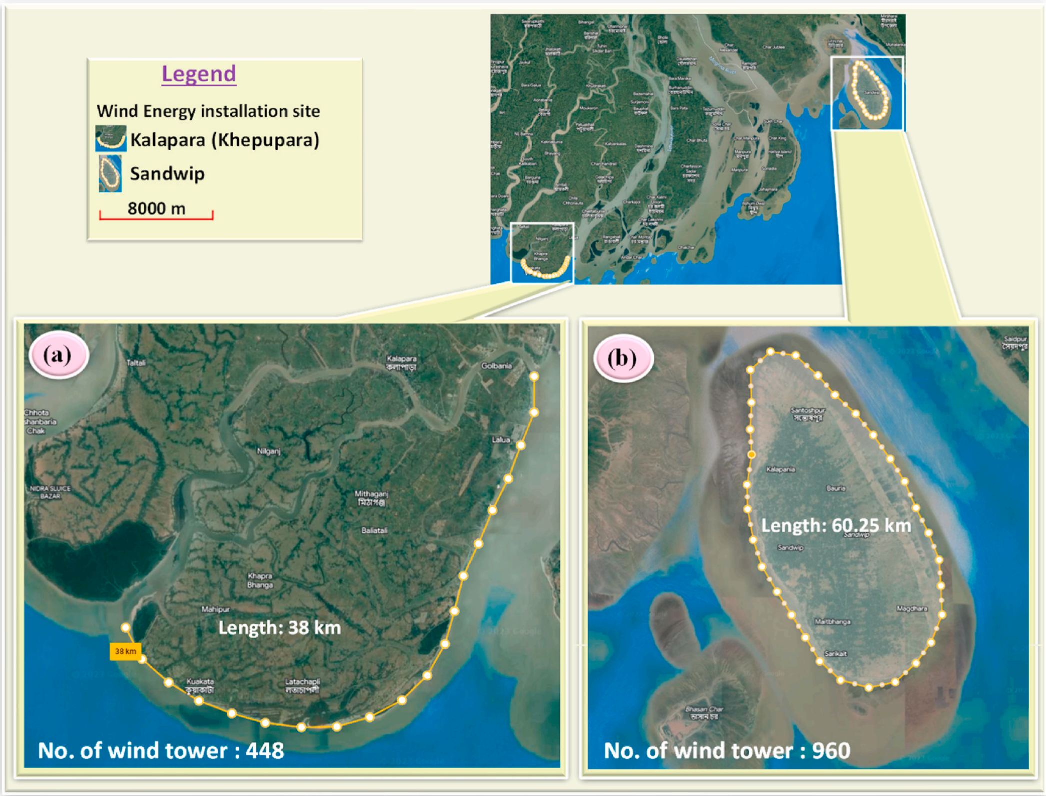

Fig. 7. Wind energy installation site: (a) Kalapara (Khepupara), and (b) Sandwip coastal area [Source: Authors creation].

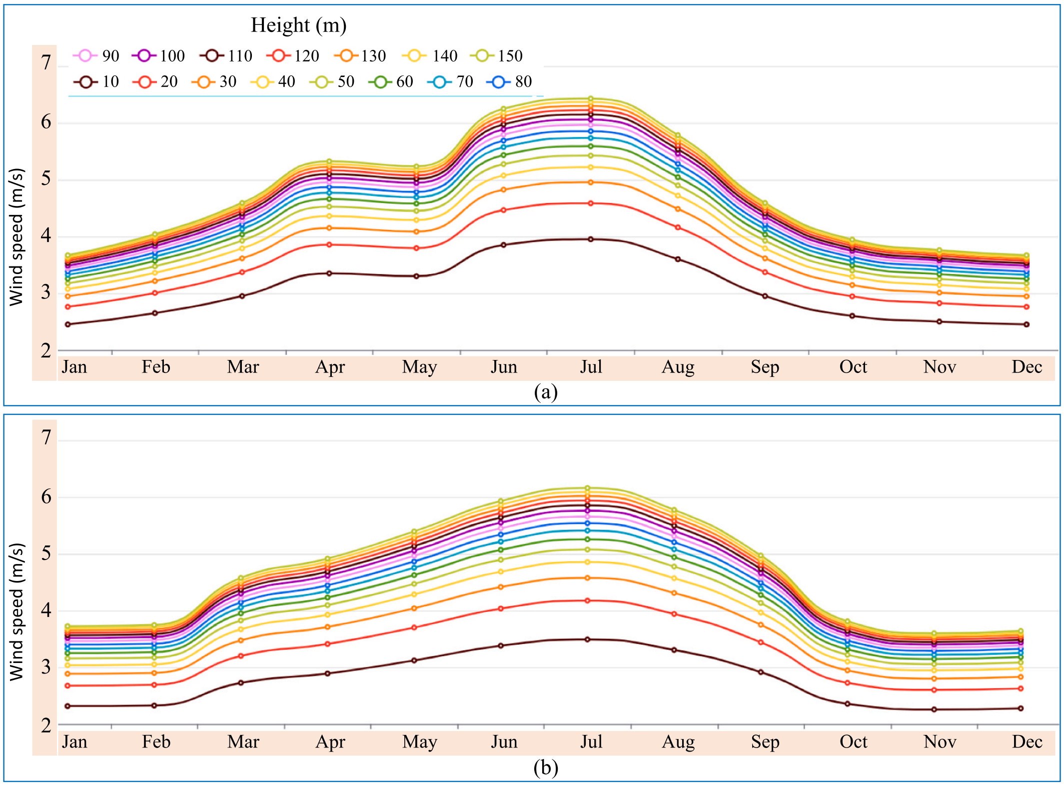

Fig. 8. Vertical extrapolation of monthly average wind speed in (a) Sandwip, and (b) Khepupara station at different height [Source: Author's creation based on [44] data].

4.3. Estimation of wind power density (WPD)

For each of the two stations—Sandwip and Khepupara—average wind power density has been estimated using equation (3). Using the wind speed information from Table S1 and Table S2, the computed power density in W/m^2 at different height for each station is shown in Table S3 and Table S4.

Sandwip has the maximum wind power density at 30 m height, with 122.47 W/m^2. Khepupara, which has an average wind density of 122.41 W/m^2 at 40 m height. As wind speed is known to increase as turbine height rises, it stands to reason that wind power density will rise as well.

As seen in Table 4, the wind power density has grown with height as predicted. According to the computed wind power density, Sandwip fall into power classes 2 at heights of 30–40 m, 3 at 50–60 m, 4 at 70–90 m, 5 from 100 to 130 m, and 6 at 140–150 m.

Table 4
Wind power density and wind power class at Sandwip and Kalapara area at different heights.

	Sandwip		Kalapara	
Height	Wind power density	Wind power class	Wind power density	Wind power class
10	50.77	1	32.97	1
20	91.14	1	68.3	1
30	**122.47**	2	97.43	1
40	148.61	2	**122.41**	2
50	171.39	3	144.65	2
60	191.41	3	164.72	3
70	209.67	4	183.01	3
80	226.44	4	199.87	3
90	241.8	4	215.55	4
100	256.19	5	230.4	4
110	270.02	5	244.43	4
120	282.46	5	257.45	5
130	294.51	5	269.93	5
140	306.05	6	281.76	5
150	316.79	6	293.32	5

Similarly, Kalapara (Khepupara) fall into power classes 2 at heights of 40–50 m, 3 at 60–80 m, 4 at 90–110 m, and 5 from 120 to 150 m.

4.4. Selection of wind turbine

In this research, "Aeolos-H 100 kW wind turbine" is proposed to install on the research areas. With no gearbox or booster device, the Aeolos-H 100 kW wind turbine employed a three-phase direct-drive generator. Compared to an induction generator with a gearbox or booster, it is more dependable and efficient. A touch screen Programmable Logic Controller (PLC) is used to operate the 100 kW wind turbine. The Aeolos-H 100 kW wind turbine has three types of safety precautions: pitch control, PWM dump loading system, and hydraulic braking system. The 100kw wind turbine has a remote monitoring mode. Using the internet, operator can access the wind turbine control panel from anywhere. Customers may get on-grid and off-grid wind power solutions from Aeolos-H 100 kW wind turbines. It is a profitable investment project in powerful wind source nations like Italy, Greece, Spain, the United Kingdom, France, Australia, Germany, the United States, and Romania [57]. The specification of the turbine is shown in Table 5.

The planned wind turbine's predicted approximate power output and annual energy yield at various hourly and yearly wind speeds are illustrated in Fig. 9.

Fig. 10(a) illustrates the power output of 1.01 kW, 1.86 kW, 3.14 kW, 5.00 kW, and 8.30 kW of the chosen AEOLOS wind turbine (100 kW) at wind speeds of 3 m/s, 3.5 m/s, 4 m/s, 4.5 m/s, and 5 m/s, and so on. According to Fig. 10(b), this turbine produces an average annual energy production of 39 MWh, 100 MWh, 184 MWh, and 273 MWh against the average yearly wind speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s respectively.

4.4.1. Influencing factors of wind turbine

There are some influencing factors of wind turbine/power that are (i) hub height, and (ii) difference in temperature and landscape.

(i) **Hub height:** As wind power is proportional to the cube of wind speed, even small increases in wind speed would have a significant economic impact. One method to bring the turbine into stronger winds is to raise the hub height. The following equation [48] can be used to quantify the effect of tower height:

$$\frac{v_2}{v_1} = \left[\frac{h_2}{h_1}\right]^{\alpha}$$

Where, v_1 is the wind speed at height h_1; and v_2 is the wind speed at height h_2 (In Bangladesh, the reference height for weather stations is 10 m); α is the friction coefficient indicating the topography.

Less surface disturbances would be experienced with an increase in hub height due to stronger winds at higher altitudes. Such increases of hub height would also relocate turbines to locations with improved resource quality, i.e., higher above the ground where the wind resource is subject to less surface disturbances. Similar tendencies are now present in Europe, notably in Germany, where regular installed hub heights have crossed 100 m (m) since 2009 and turbine height deployments averaged 116 m in 2014, with some occurrences topping 140 m [58].

(ii) **Difference in temperature and landscape:** The difference in temperature influences wind pressure, which in turn impacts wind velocity, direction, and the power generated by wind turbines. The power production from a wind turbine is a function of air density. Air density relies on air pressure. Topographical characteristics are crucial to the construction of a wind farm. Two more elements that might affect the speed of air flowing across the surface are air pressure and temperature. Large height, warm, and rising air are associated with low pressure. High pressure, on the other hand, is associated with chilly, low-altitude air that is sinking.

4.5. Determination of wind power

The calculated average wind power per single wind turbine in the Sandwip area was 57.64 kW (at 30 m height), and gradually

Table 5
Details/Specification of the selected AEOLOS Wind Turbine (100 kW).

Rated power and maximum output power	100 kW and 120 kW
Generator	Direct-Drive Permanent Magnet Generator
Number of Blade/s	3 Glass Fiber Blades
Diameter of the rotor blades	24.5 m (80.4 ft)
Swept Area	**471.2 m^2**
Start-up, rated, and survival wind speed	2.5 m/s (5.6 mph); 10 m/s (22.3 mph); & 59.5 m/s (133.1 mph)
Controller	Programmable logic controller with Touch Screen
Safety and Security System	Pitch Control, Electrical Brake & Hydraulic Brake
Turbine Weight	8350 kg (18408.6 lbs)
Noise	60 db(A) @ 7 m/s
Range of temperatures	−20 °C to +50 °C
Lifespan of a Design	20 (Twenty) Years

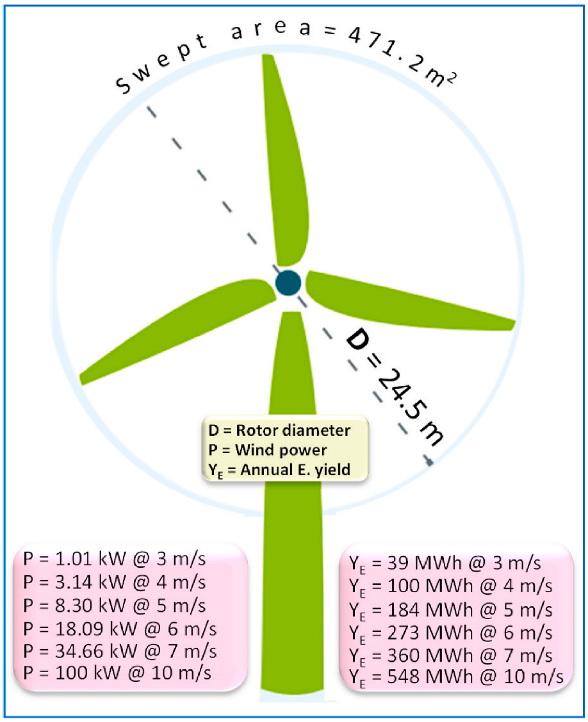

Fig. 9. Power output and annual energy yield of the proposed AEOLOS Wind Turbine (100 kW) [Source: Author's creation based on [57] data].

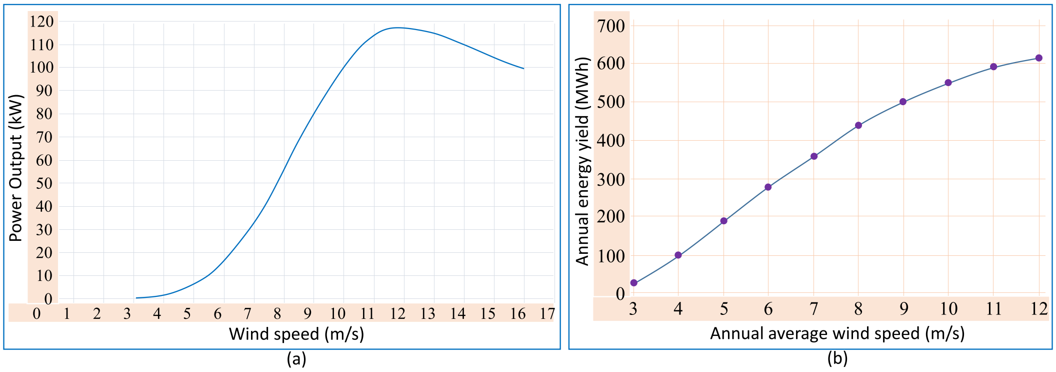

Fig. 10. (a) Power curve, and (b) annual energy yield of the selected AEOLOS Wind Turbine (100 kW) [Source: Author's creation based on [57] data].

increases with increasing height to 149.02 kW (at 150 m height), shown in Table 6. Similarly, the calculated average wind power per single wind turbine in the Khepupara (Kalapara) area was 45.91 kW (at 30 m height), and gradually increases with increasing height to 138.21 kW (at 150 m height), shown in Table 7. Out of the 19 stations, Sandwip has shown the highest wind energy production. The second-highest power production location, however, has been found in Kalapara (Khepupara).

4.6. Determination of wind energy yield

It is typically noted that the yearly average wind speed of Sandwip and Kalapara (Khepupara) was at least 5 m/s (Fig. 11). In the research regions of Sandwip and Kalapara (Khepupara), wind power densities of 122.47 (at 30 m height) and 122.41 (at 40 m height) which is economically feasible to extract wind energy shown in Table S3 and Table S4. The "100 kW Northwind 100C" wind turbine model is proposed to calculate power output.

The calculated average wind energy yield per single wind turbine in the Kalapara (Khepupara) area was 237.48 MWh (at 40 m height), and progressively rises as height increases to 569.04 MWh (at 150 m height), shown in Table 8. Similarly, the Sandwip area was 237.32 MWh (at 30 m height), and gradually rises with height to 613.55 MWh (at 150 m height), shown in Table 8. Sandwip has

Table 6
Average hourly wind power output (kW) for different months for a single wind turbine at Sandwip coastal and offshore area.

Month	Height														
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Jan	7.04	12.59	16.99	20.63	23.76	26.48	29.02	31.32	33.54	35.43	37.39	39.19	40.82	42.48	43.95
Feb	10.37	18.61	25.09	30.35	35.00	39.19	42.72	46.21	49.34	52.33	55.15	57.78	60.18	62.65	64.87
Mar	17.12	30.74	41.29	50.14	57.78	64.55	70.80	76.37	81.47	86.42	91.15	95.22	99.42	103.30	106.83
Apr	29.96	53.73	72.17	87.58	101.13	113.20	123.72	133.82	142.84	151.12	159.13	166.82	174.13	180.39	186.79
May	28.09	50.41	67.79	82.22	94.81	105.94	116.01	125.20	133.82	141.76	149.44	156.24	163.24	169.23	175.37
Jun	53.45	96.05	129.21	156.24	180.39	201.41	221.09	238.19	254.55	269.98	284.30	297.36	309.89	321.85	334.10
Jul	59.27	106.38	142.84	173.52	200.05	223.27	245.11	264.22	282.59	299.13	315.37	329.35	343.74	357.54	369.66
Aug	40.58	72.86	97.73	118.86	136.96	152.81	167.42	181.02	193.35	204.84	215.34	225.47	235.15	244.33	252.96
Sep	17.12	30.74	41.29	50.14	57.78	64.55	70.80	76.37	81.47	86.42	91.15	95.22	99.42	103.30	106.83
Oct	9.46	16.99	22.79	27.73	31.92	35.65	38.96	42.24	44.94	47.76	50.14	52.61	54.87	56.90	58.97
Nov	7.79	14.03	18.75	22.79	26.30	29.39	32.12	34.79	37.17	39.42	41.29	43.46	45.19	46.98	48.54
Dec	6.34	11.54	15.71	19.17	22.16	24.75	25.43	29.21	29.58	31.32	36.08	36.95	36.29	39.88	39.42
Ave	**23.88**	**42.89**	**57.64**	**69.95**	**80.67**	**90.10**	**98.60**	**106.58**	**113.72**	**120.49**	**127.16**	**132.97**	**138.53**	**144.07**	**149.02**

Table 7
Average hourly wind power output (kW) for different months for a single wind turbine at Kalapara (Khepupara) coastal and offshore area.

Month	Height														
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Jan	5.25	10.85	15.46	19.46	23.11	26.30	29.21	31.92	34.37	36.73	38.96	41.05	42.97	44.94	46.72
Feb	5.37	11.14	15.84	19.89	23.59	26.83	29.77	32.52	35.22	37.61	39.88	42.00	43.95	45.95	47.76
Mar	11.85	24.58	35.00	43.95	52.05	59.27	65.83	71.82	77.44	82.97	87.97	92.36	96.89	101.13	105.49
Apr	15.59	32.32	45.95	57.78	68.45	77.81	86.42	94.40	101.99	109.08	115.54	121.76	127.70	133.31	138.55
May	22.00	45.45	64.87	81.85	96.47	109.98	122.25	133.31	143.92	153.95	163.24	171.67	180.39	188.09	196.01
Jun	31.13	64.55	91.95	115.54	136.43	155.66	172.90	188.74	203.46	217.49	230.65	242.79	254.55	265.86	276.66
Jul	35.65	73.90	105.49	132.27	156.24	177.87	198.02	216.06	232.90	249.01	264.22	278.34	292.09	304.48	317.21
Aug	28.28	58.67	83.73	105.05	124.21	141.22	156.81	171.67	184.86	197.35	209.70	221.09	231.40	242.02	251.37
Sep	16.21	33.54	48.02	60.18	71.14	81.10	89.95	98.15	105.94	113.20	120.30	126.69	132.79	138.55	144.47
Oct	5.74	11.85	16.99	21.38	25.26	28.65	31.92	34.79	37.61	40.11	42.48	44.94	46.98	49.07	51.23
Nov	4.56	9.46	13.47	16.99	20.04	22.79	25.26	27.73	29.77	31.92	33.75	35.65	37.39	38.96	40.58
Dec	4.79	9.91	14.15	17.79	20.93	23.92	26.48	29.02	31.32	33.33	35.43	37.39	39.19	40.82	42.48
Ave	**15.53**	**32.18**	**45.91**	**57.68**	**68.16**	**77.62**	**86.23**	**94.18**	**101.57**	**108.56**	**115.18**	**121.31**	**127.19**	**132.76**	**138.21**

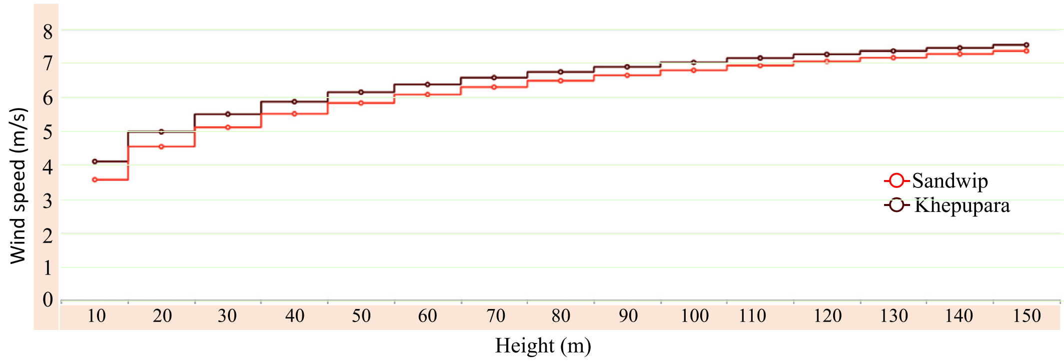

Fig. 11. Yearly average wind speed in Sandwip and Kalapara (Khepupara) station at 10 m–150 m height (with 10 m interval) [Source: Author's creation based on [44] data].

Table 8
Wind energy yield (MWh) for a single wind turbine at 10 m–150 m height (with 10 m interval) in Sandwip and Kalapara (Khepupara) coastal area.

Location	Height	Wind Power (W) $\left(P = \frac{1}{2}\rho A V^3\right)$	Wind Power (kW)	Energy Yield (kWh) ($E = P \times C_p \times 8760$)	Energy Yield (MWh)
Kalapara (Khepupara)	10	15535	15.53	63940	63.94
	20	32185	32.18	132491	132.49
	30	45911	45.91	189021	189.02
	40	57677	57.68	237480	**237.48**
	50	68160	68.16	280628	280.63
	60	77616	77.62	319577	319.58
	70	86234	86.23	355026	355.03
	80	94177	94.18	387758	387.76
	90	101567	101.57	418184	418.18
	100	108563	108.56	446963	446.96
	110	115177	115.18	474219	474.22
	120	121311	121.31	499458	499.46
	130	127189	127.19	523667	523.67
	140	132764	132.76	546599	546.6
	150	138211	138.21	569038	569.04
Sandwip	10	23883	23.88	98319	98.32
	20	42889	42.89	176587	176.59
	30	57636	57.64	237315	**237.32**
	40	69947	69.95	287998	288
	50	80670	80.67	332135	332.13
	60	90099	90.1	370960	370.96
	70	98600	98.6	405956	405.96
	80	106580	106.58	438811	438.81
	90	113722	113.72	468208	468.21
	100	120492	120.49	496081	496.08
	110	127161	127.16	523543	523.54
	120	132972	132.97	547464	547.46
	130	138529	138.53	570356	570.36
	140	144069	144.07	593165	593.17
	150	149024	149.02	613545	613.55

shown the maximum wind power generation among the all 19 stations. The generated electricity will be used to supply the energy to the national grid of Sandwip Island and adjacent areas.

The "100 kW Northwind 100C" wind turbine type has 24.5 m-diameter rotor blades. Two rotor blades have a combined diameter of 49 m in this manner. if there were a 6-m space between each rotor blade. then there will be a 55 m space between the two wind towers. This allows for the placement of about 18 wind towers within a linear distance of 1 km, as illustrated in Fig. 12.

The projected length of the installable wind tower in the Kalapara coastline region was 38 km; 684 wind towers could be placed there and produce a total of 162.43 GWh of power annually. Similar to this, in the Sandwip region, a total of 1084 wind towers with an installable length of 60.25 km might be constructed, with the potential to produce 257.25 GWh of power annually. As a result, 419.68 GWh of electricity will be the estimated total wind energy production for all 1768 wind turbines in the Kalapara (Khepupara) and Sandwip region.

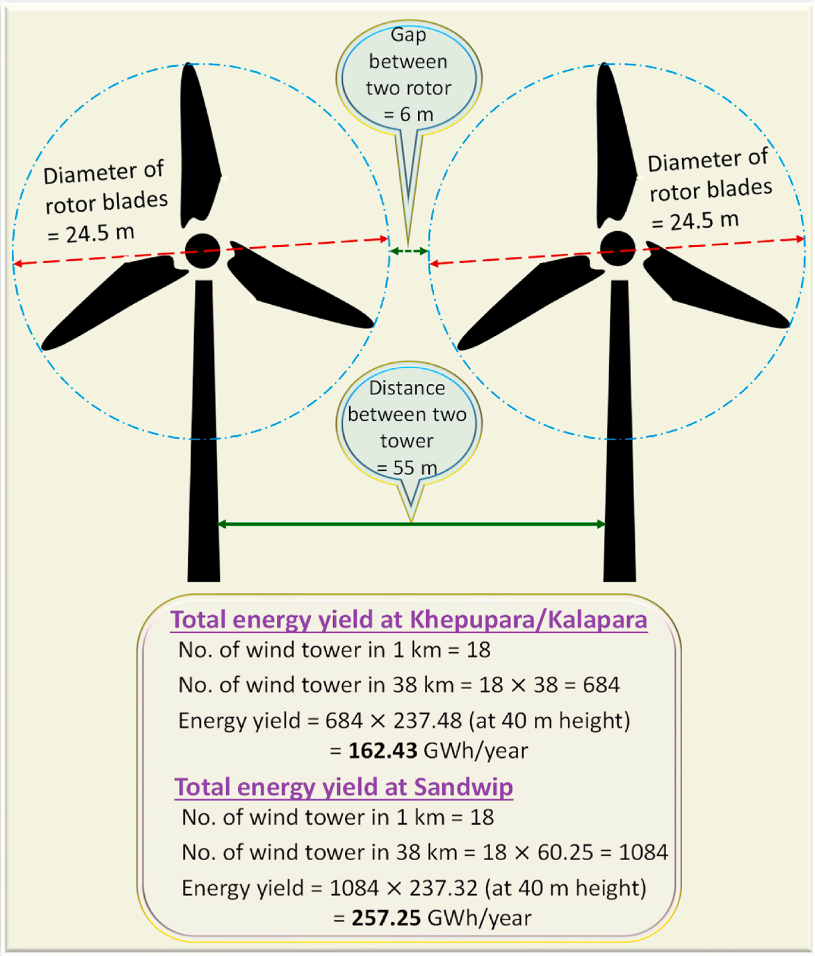

Fig. 12. Total energy yield at Khepupara (Kalapara), and Sandwip coastal area [Source: Author's creation].

4.7. Estimation of CO_2 emission reduction

Estimates of CO_2 emissions from primary energy use for electricity production in Bangladesh using fossil fuels are obtained by dividing the amount used of each type of energy source (coal, oil, and natural gas) by the IPCC's "Carbon dioxide Emissions Factors" [17], shown in Table 9.

In this research, a single wind turbine will be able to generate about 237.48 MWh of power at Khepupara (Kalapara) and 237.32

Table 9
Compared to fossil fuel (natural gas, oil, coal) electricity production, wind energy reduces CO_2 emissions.

Zone	Source of Fuel (Non-renewable)	Generated Electricity (MWh) per turbine	CO_2 Emissions Factor (kg CO_2/ MWh)	CO_2 Emission (kg) per turbine	CO_2 Emission (ton) per turbine
Kalapara	Natural gas	237.48	201.96	47,961	47.2
	Furnace oil	237.48	263.87	62,664	61.67
	Diesel	237.48	266.76	63,350	62.35
	Coal	237.48	345.96	82,159	80.86
	Annual CO_2 emission reduction from **single wind turbine** per **year**				**63.02 ton**
	Annual CO_2 emission reduction from **684 wind turbine** per **year**				**43,105.68 ton**
Sandwip	Natural gas	237.32	201.96	47,929	47.17
	Furnace oil	237.32	263.87	62,622	61.63
	Diesel	237.32	266.76	63,307	62.31
	Coal	237.32	345.96	82,103	80.8
	Annual CO_2 emission reduction **from single wind turbine** per **year**				**62.975 ton**
	Annual CO_2 emission reduction **from 1084 wind turbine** per **year**				**68,267.61 ton**

*Annual CO_2 emission = (Yearly generated electricity × CO_2 Emission Factor per MWh).

MWh of electricity at Sandwip. If this amount of energy were to be produced using fossil fuels such as coal, natural gas, furnace oil, or diesel, an average of 63.02 tons of CO_2 would be emitted into the atmosphere. So, if 1,768 wind turbines (684 in Kalapara and 1084 in Sandwip) are installed on the Sandwip and Kalapara coastal region instead of burning fossil fuels, about 1,11,373.29 tons of CO_2 will be prevented from being emitted annually.

5. Conclusion

This research presents the prospect of wind energy in southern coastal Bangladesh particularly in Sandwip and Kalapara coastal areas of Bangladesh. The facts given show that Bangladesh's generation of renewable energy is currently in its early stages, but it has a bright future. It is typically noted that the yearly average wind speed of Sandwip and Kalapara (Khepupara) was at least 5 m/s. In the research regions of Sandwip and Kalapara (Khepupara), wind power densities of 122.47 (at 30 m height) and 122.41 (at 40 m height) which is economically feasible to extract wind energy. The calculated average wind energy yield per single wind turbine in the Kalapara (Khepupara) area was 237.48 MWh (at 40 m height) and the Sandwip area was 237.32 MWh (at 30 m height.

This research suggests a high-performance wind turbine type of "100 kW Northwind 100C". The rotor blades of the wind turbine are 24.5 m in diameter. In this way, the diameter of two rotor blades together is 49 m. A 55 m distance would exist between the two wind towers if there were a 6-m separation between each rotor blade. Accordingly, it is possible to set up roughly 18 wind towers within a linear distance of 1 km. The projected length of the installable wind tower in the coastal region of Kalapara was 38 km, where a total of 684 wind towers could be placed and provide a combined 162.43 GWh of power annually. Similar to this, the projected length of the installable wind tower in the Sandwip region was 60.25 km long, where a total of 1084 wind towers could be placed and could produce a total of 257.25 GWh of power annually. As a result, the region around Kalapara (Khepupara) and Sandwip will generate 419.68 GWh of power from the 1768 wind turbines that make up the overall wind energy production.

In this study, a single wind turbine will be able to produce roughly 237.48 MWh of energy in Khepupara (Kalapara) and 237.32 MWh at Sandwip. An average of 63.02 tons of carbon dioxide (CO_2) would be released into the environment if as much energy were produced using fossil fuels like coal, natural gas, furnace oil, or diesel. Thus, if 1,768 wind turbines (684 in Kalapara and 1084 in Sandwip) are put in place along the Sandwip and Kalapara coastlines, 1,11,373.29 tons of carbon dioxide will not be released into the atmosphere each year. It would be a good substitute for relying solely on natural gas.

This study will promote feasibility studies of Bangladesh's wind energy sector and aid in the evaluation of the country's wind energy potential. This study will assist future planning and management for the installation of wind power plants in a sustainable manner, as well as investors, shareholders, researchers, and decision makers in the public and private sectors, in realizing the wind energy potential of Bangladesh's coastal regions of Sandwip and Kalapara. Lastly, the results of the current state of the art may convince stakeholders to invest in the energy sector with more confidence, supporting Bangladesh's efforts to cut carbon emissions.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

CRediT authorship contribution statement

Md. Abdullah-Al-Mahbub: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abu Reza Md. Towfiqul Islam:** Supervision & Review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e23982.

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