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WIND ENERGY POTENTIAL, PROGRESS AND CHALLENGES IN BANGLADESH: A REVIEW

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Abstract
Although Bangladesh has the potential for 100% electricity generation, a power shortage caused by limited fossil fuel supply, alongside a growing fuel crisis, underscores the urgent need to shift towards sustainable energy solutions. This review paper delves into the realm of wind energy, assessing its potential as an alternative and renewable energy source within the country. It explores the promising prospects of wind energy, underpinned by the country's favorable geographical and climatic conditions. However, a variety of obstacles that fall into the technological, financial, and environmental categories stand in the way of fully realizing the promise of wind energy. Technical concerns include things like grid integration, intermittency management, and turbine technology. Significant challenges are posed by economic impediments, such as high starting expenses and inadequate finance channels. Furthermore, the complex interactions between wind energy and the environment demand that environmental effects be carefully considered. This study proposes potential solutions that include technology innovation, governmental interventions, financing methods, and environmental management strategies to solve these difficulties. This article has put forth actionable suggestions in three areas: technological, economic, and environmental. In the field of technology, it is important to enhance the design of turbines, including the potential benefits of diffused augmented wind turbines (DAFT) and building augmented wind turbines (BAWT). A stable microgrid system could be a beneficial asset for Bangladesh's current circumstances. In addition to cooperation between development financial institutions (DFIs) and government, Feed-In-Tariffs (FITs) and green bonds could serve as effective mechanisms for funding renewable energy projects.

Keywords: Wind energy, Renewable energy, Challenges, Solutions.

Nomenclature

AGL	Above Ground Level	ANFIS	Adaptive Neuro-Fuzzy Inference System
HAWT	Horizontal Axis Wind Turbine	DAFT	Diffuser-Augmented Wind Turbine
VAWT	Vertical Axis Wind Turbine	BAWT	Building-Augmented Wind Turbine
DFIG	Doubly-Fed Induction Generator	PPPs	Public-Private Partnerships
PMSG	Permanent-Magnet Synchronous Generator	FiT	Feed-in-Tariff
AWE	Bio-gas Generator		
SODAR	Sonic Detection and Ranging		

1.0 INTRODUCTION

From the start of 2022, the world was facing a huge crisis in energy supply. The main reason for this is the Russia-Ukraine war (Hutter & Weber, 2022). Europe relies significantly on Russia for its petroleum and natural gas (Wolff, 2022). In 2021, 40% of the natural gas consumed by Europeans originated from Russia (Marcin, 2022). More than 25% of the crude oil imported by the EU is sourced from Russia (Liadze et al., 2023). Fossil fuels still accounted for 37% of EU electricity production in 2021 (Baskutis et al., 2021). As a result, the war situation may have an impact on electricity generation. But yet, developed countries like EU nations can manage the electricity gap because they are also using their renewable energy resources. In the year 2021, electricity generated in European countries from renewable energy resources was 37% (Zeraibi et al., 2021). But here comes the critical situation for a country like Bangladesh, which is heavily dependent on its fossil fuel-based electricity production (Das & Hoque, 2014). There is a supply shortage because Bangladesh needs to import fossil fuel via different nations. To meet the increasing energy need, the government of Bangladesh must import power from nearby nations like Nepal and India. (Singh, 2013).

Furthermore, 75% of the nation's electricity is generated by natural gas, with coal coming in second and emitting more pollutants (Halder et al., 2015). In August 2022, government raised fuel prices by more than 50% in just a week (BFP, 2022). The government attributes the rise in oil prices to the aftermath of the Ukrainian conflict. The rise in fuel prices directly affects the field of transportation and people's lifestyles. In Bangladesh, the cost of necessities increased by up to 14% in a single week following a record increase in fuel costs (FPH, 2022). And also, from the starting of the summer in 2022, Bangladesh is facing massive power cuts. Though Bangladesh has the capacity to generate 100% electricity for the whole nation (Rahman et al., 2012). The administration claims that load shedding has to happen because there is a lack of fossil fuels. The Power development Board of Bangladesh (PDB) created a load shedding schedule for different cities (TBS, 2022). And it affecting some parts of the city for up to 13 hours power cuts also. In rural regions, authorities are turning off the power for as long as five or six hours per day, while load shedding occurs many times a day in Dhaka. The largest power plant in the country, Payra 1320 MW Thermal Power Plant, totally shuts down on June 5, 2023, due to a scarcity of coal (Correspondent, 2023; PPR Report 2023; Report, 2023). So, it's clear that Bangladesh needs to convert its dependency on fossil fuel regarding electricity production. And it is a well knowing concept that renewable energy can reduced the dependency of fossil fuel on electricity generation. Whenever one talked about the country's electricity crisis problem the first suggestion is come to implement the renewable energy resources. But how far Bangladesh came in now 2022 on its renewable energy-based electricity generation. From data of 2021, the share of electricity production by source was natural gas 68.18%, Oil 17.49%, Coal 12.61%, Hydropower 1.09%, Solar 0.58%, Bioenergy 0.04% and wind is 0.01% (Ourworldindata, 2022).

According to the sustainable and renewable energy development authority (SREDA) the installed capacity of renewable energy is 948.11 MW is taking the share 3.71 % of the total installed capacity of the nation which is 25585 MW. At present SREDA is doing various projects on solar system, creating solar home system for rural areas, solar street lighting and solar park. According to the national database now there are total of 48 ongoing solar park system and the total installed capacity is 2386.66 MWp. With the fast-growing solar projects of Bangladesh, wind energy can also be the part for future zero carbon energy system.

As of 2022, China ranks first globally in terms of installed wind energy capacity, with an impressive 365,964 MW (IRENA, 2023). The European Union, with a wind power capacity of 202,700 MW, showcases its strong commitment to renewable energy. The United States follows closely with 140,862 MW, reinforcing its prominent role in the wind power sector. Germany, recognized for its leadership in sustainability, has achieved a capacity of 66,315 MW, while India continues to make strides with 41,930 MW. These figures emphasize the global momentum towards cleaner energy, as these nations contribute significantly to advancing wind power technology. According to the (GWEC, 2023), an additional 77.6 GW of wind capacity was added to global power systems in 2022, pushing the total installed wind capacity to 906 GW—a 9% annual increase (GWEC, 2023). In 2022, the onshore wind market added 68.8 GW globally, with China accounting for 52% of that growth. GWEC (Global Wind Energy Council) anticipates that onshore wind installations will exceed 100 GW per year by 2024. Additionally, offshore wind is projected to surpass 25 GW of installations in a single year for the first time by 2025, with a subsequent rapid acceleration in installation rates (GWEC, 2023). The undeniable increase in wind energy production worldwide is a clear sign of its status as a clean and sustainable power source. Following this pattern, nearby India, Bangladesh has made notable advancements in shifting towards renewable energy alternatives. India has achieved significant success in wind energy, producing 68.08 terawatt-hours (TWh) of electricity and ranking as the fifth-largest producer of wind energy globally. At the same time, Bangladesh is continuously making progress in its renewable energy initiatives, showcasing the area's shared dedication to a more environmentally friendly and enduring future. Even though wind energy makes up merely 0.01% of Bangladesh's overall energy production, efforts are being made to increase its presence in the renewable energy industry.

The Bangladesh Power Development Board (BPDB) constructed two wind farms in 2005 as part of a pilot project: one at Kutubdia Island with a 1 MW capacity and one with a 900 kW capacity in Muhuri Dam, Feni (Das et al., 2020). At present there are ongoing 12 projects in Bangladesh and the total installed capacity is 359.9 MWp. Table 2 displays Bangladesh's current Wind project status. Subsequent to that, numerous efforts were launched with the aim of setting up wind turbines for power generation. Regrettably, these projects did not come to fruition. Within the Master Plan covering the period from 2011 to 2016, formulated by the Ministry of Power, Energy and Mineral Resources of the Bangladesh Government, there was a targeted goal of generating 100 MW of power from wind energy by 2013 in Anwara, Chittagong (Baky et al., 2017). This envisioned plan was designed to function as an Independent Power Production Model.

The development of wind energy projects requires long-term wind speed data, yet it has been discovered that the wind speed data provided by the Bangladesh Meteorological Department (BMD) are inconsistent and have a significant analysis risk for theoretical power generation. However, research conducted along the coast have revealed that typical annual wind speeds can reach 6.5 m/s when measured 50 m above ground level (AGL). With assistance from the Local Government Engineering Department (LGED), the Bangladesh Centre for Advanced Studies (BCAS) monitored wind direction and speed at 25m height at 7 places close to the shore in 1996–1997 (Alam & Azad, 2014). The Wind Energy Resource Mapping (WERM) study involved the LGED evaluating 20 sites across Bangladesh at various heights (Alam, 2006).

Discussions and debates over Bangladesh's potential for wind energy are still going on at the moment. In order to plan future wind energy projects, Das et al. claim that the offshore wind speed must be thoroughly documented (Das et al., 2020). According to satellite data, offshore wind speeds are a little bit greater than those in the coastal zone. The EU can be used as an example in this situation because it benefits from offshore wind energy production and has about 70% of the world's installed wind energy capacity. By 2030, 350 GW of wind energy is expected to be produced in the EU, which will meet 24% of the region's electricity needs (Shaikh et al., 2017). According to Kahn et al. (Khan et al., 2014), it is difficult to extract wind energy because of low wind speeds. Even though several wind projects were initiated as experiments from 2005, no on-grid wind projects that could send power to the country's systems existed until 2023. The nation's first grid-connected (Khurushkul 60 MW wind farm) wind facility went operational on May 26, 2023, adding an average of 20 MW of power to the national grid per day (Alam, 2023).

According to a recent study, natural gas, coal, and diesel power plants emit 0.566 kg, 0.90 kg, and 0.76 kg of CO_2 per kilowatt-hour, respectively (Karmaker et al., 2020). By 2040, CO_2 emissions are expected to reach their high at 58.97 Mtoe, according to Hasan and Chongbo's projections of the analysis' results (Hasan & Chongbo, 2020). According to a study, a 1 MW wind energy generation capacity erected at 60 m AGL in the Charfashion & Monpura site has the potential to generate 2.79 GWh/year of clean energy, thereby reducing CO_2 emissions by 1,781,688 tonnes per year (Islam et al., 2021).

Table 1: Research findings about the wind speed in various locations

Author	AGL	Location	Time	Annual wind Speed	Tool
(Alam & Azad, 2014)	20 m	Kuakata Sitakunda Kutubdia	April – September	4.18 3.60 3.59	Weibull Based approach
(Azad & Alam, 2010)	20 m	Pakshey river delta region	April- October	3.6 – 4.1	Weibull Based approach
(Islam et al., 2014)	10 m	Coxs Bazar	November April	2.17 2.90	Weibull based approach
(Khadem & Hussain, 2006)	50 m	Kutubdia	September-August	5.1 – 5.8	Wind Atlas Analysis and Application Program (WAsP)
(Khan et al., 2014)	50-70 m	Rangamati Bandarban Teknaf	April - August	2.02 2.28 3.9	Weibull based approach
(Al Mamun et al., 2015)	50 m	Parky Beach (Chittagong)	Whole year	6.73	HOMAR
(Islam et al., 2021)	100 m	Charfashion Monpura	Whole year	7.3	Statistical Analysis
(Hossain et al., 2015)	30 m	Kuakata (Patuakhali)	Whole year	4.14	HOMAR

Numerous researchers have diligently investigated the viability of wind energy in Bangladesh, employing numerical analyses to determine optimal wind speeds. However, a comprehensive review addressing the feasibility of wind energy, along with the associated challenges and potential remedies, remains conspicuously absent. This paper embarks on a mission to rectify this gap by not only surveying the advancements in Bangladesh's wind energy landscape but also delving into the hurdles that impede its progress. The primary objective of this paper is to shed light on the collective body of work that has been dedicated to comprehending the wind energy potential within Bangladesh. By undertaking an exhaustive analysis, this study aims to unravel the existing limitations that have hindered a robust wind energy sector. Furthermore, the paper undertakes the task of dissecting these obstacles and juxtaposing them with insights gleaned from research in developed nations. By drawing parallels with successful initiatives from countries with advanced wind energy infrastructure, potential solutions to Bangladesh's unique challenges can be extrapolated. In essence, this research paper stands as a beacon illuminating the current state of wind energy endeavors in Bangladesh. It endeavors to not only catalog accomplishments but also to critically assess setbacks. By harnessing knowledge from more established wind energy markets, this paper aspires to chart a path toward surmounting challenges and harnessing the full potential of wind energy in Bangladesh.

1.1 Wing Energy System

Wind energy harnesses the kinetic energy of the wind to generate electricity. Wind turbines are the principal technology utilised to capture this energy. Blades, a rotor, a generator, a nacelle, a tower, a controller, and an inverter are all vital components of these turbines (Nix, 1995).

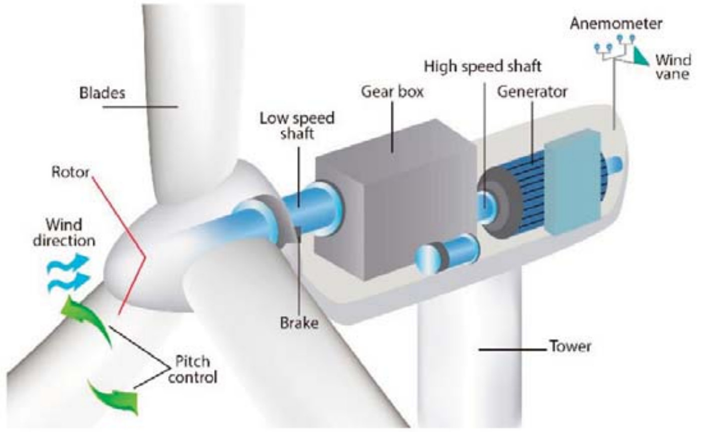


Figure 1: Major components inside a wind turbine

The wind strikes the turbine's blades to start the operation. These blades are aerodynamically built, allowing them to efficiently collect the energy of moving air. As the wind pushes against the blades, depending on the type of turbine, they begin to revolve around a horizontal or vertical axis. The rotating blades are joined to a central hub to form the turbine's rotor. This rotor is linked to a generator through a shaft. As the blades turn, they spin the rotor of the generator, which is surrounded by a magnetic field. This rotation causes an electrical current to flow through the coils of the generator, transforming the mechanical energy of the wind into electrical energy. All of these critical components are housed within a protective structure known as the nacelle, which is usually perched atop a tall tower. Elevating the turbine in this manner is essential because wind speeds increase with height, allowing the turbine to capture stronger and more consistent winds. To ensure efficient and safe operation, wind turbines are equipped with controllers and inverters. The controller monitors the turbine's performance and adjusts its orientation to optimize power production. Inverters convert the electricity generated from alternating current (AC) to direct current (DC) for distribution through power lines to the electrical grid. There are different types of wind turbines, including horizontal-axis wind turbines (HAWT), vertical-axis wind turbines (VAWT), Darrieus turbines, Savonius turbines, and hybrid designs (Almotairi et al., 2016). HAWTs are the most common and have blades that rotate around a horizontal axis. They are strongly advised because, even on a small scale, they tend to be more efficient (Eggers et al., 2001). VAWTs, on the other hand, have blades that rotate around a vertical axis and can capture wind from any direction. Darrieus and Savonius turbines have unique designs suitable for specific applications, while hybrid turbines combine features of both HAWTs and VAWTs to maximize energy capture under varying wind conditions. Figure 2 displays various schematic designs of wind turbines, although in Bangladesh, the established wind turbines follow a HAWT design.

In present wind energy landscape, the doubly-fed induction generator (DFIG) and the permanent-magnet synchronous generator (PMSG) stand out as the most widely employed generators (Chowdhury, 2014). The DFIG configuration incorporates a scaled-down version of the back-to-back (BtB) power electronics converter, effectively curbing the overall expenses of the wind generation system (Lilla, 2019). In the contemporary era, floating wind turbines employ Horizontal Axis Wind Turbines (HAWT) mounted on movable platforms, enabling the extraction of wind energy from deep-sea locations unsuitable for traditional construction (Rehman et al., 2023). This adaptability allows for optimization of wind yield, accommodation of fishing vessels and shipping routes, and the potential return to the coast for upgrades or intricate maintenance tasks.

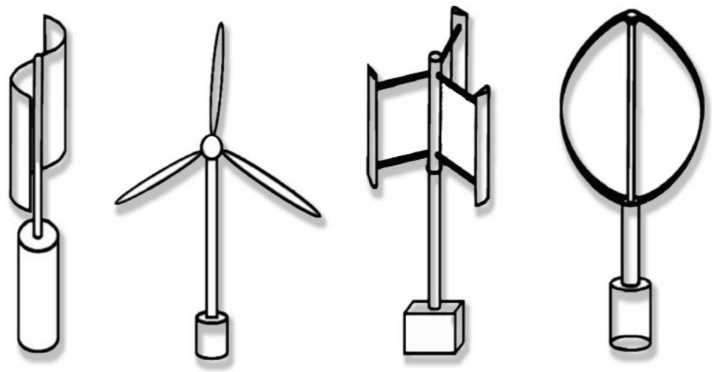


Figure 2: Schematic of different designs of wind turbines

A notable example is Hywind, the pioneer commercial floating wind farm established in 2017 off the Scottish coast (Cruciani, 2019). Comprising five turbines, it generates a total of 30MW of environmentally friendly energy. Another innovative approach shifts away from conventional blades, focusing instead on harvesting energy through the air flow-induced vibrations of mechanical systems—a concept known as "aeroelastic phenomena" (Boretto, 2019). Vortex Bladeless technology, depicted in Figure 3, represents a silent "vortex-induced vibration resonant wind generator" that taps into wind energy through a phenomenon called "vortex shedding" (Beitollahi et al., 2022). Meanwhile, pushing the boundaries of unconventional wind energy, concepts within the airborne wind energy (AWE) realm have captured investor interest (Schmidt et al., 2022). As defined by Airborne Wind Europe, an association dedicated to this emerging subsector, AWE concepts revolve around flying blades or wings tethered to the ground. The fundamental principles involve either incorporating mini-wind turbines and generators onto the flying wing or utilizing the wing to pull on the tether, causing it to unwind from a ground-based drum, thereby driving the generator (Malz et al., 2022).

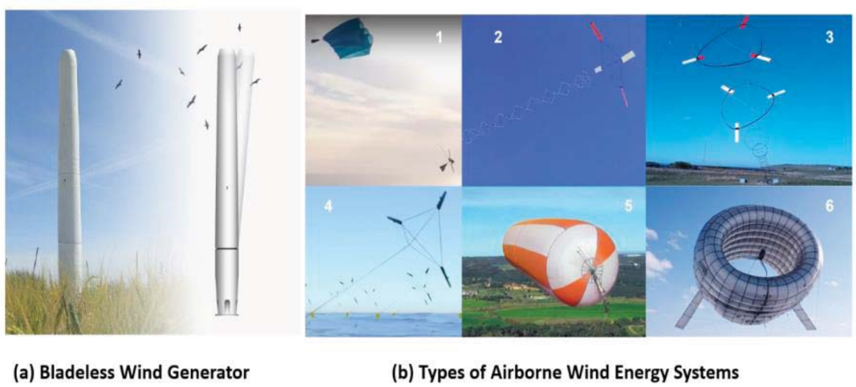


Figure 3: Emerging Wind Energy Technologies

2. Prospect of wind energy in Bangladesh

Bangladesh is in South Asia that shares borders with Myanmar (Burma) to the southeast and India to the west, north, and east. Between latitudes 20°34' and 26°38' North and longitudes 88°01' and 92°41' East is where it is located. Bangladesh has roughly 750 km long coastline belt. In addition, it boasts a mountainous shoreline of over 200 km and a large number of tiny islands in the Bay of Bengal. Over Bangladesh, there is a mild north-easterly trade wind and land breeze in the winter and a strong south-westerly trade wind and sea breeze in the summer. Good wind speeds have been observed throughout Bangladesh in order to produce wind energy. Figure 3 shows the amount of wind energy that can be harvested at a height of 25 metres in six potential seashore locations, Patenga, Kuakata, Kutubdia, Char Fashion, Teknaf, and Cox's Bazar (Amin, 2015).

So, from the figure we can say that Bangladesh has a better wind speed to generate sufficient energy. The robust monsoonal winds originating from the Indian Ocean in the south-southwest direction, having traversed a considerable distance over the ocean's expanse, make their way into the coastal zones of Bangladesh. These prevailing trade winds sweep across the nation during the period from March to October. The velocity of these winds is amplified upon encountering the distinctive V-shaped coastal topography of our country (Ahmmed et al., 2001). This wind travels through Bangladesh with a speed between 3 and 6 m/s on average (Ullah et al., 2012).

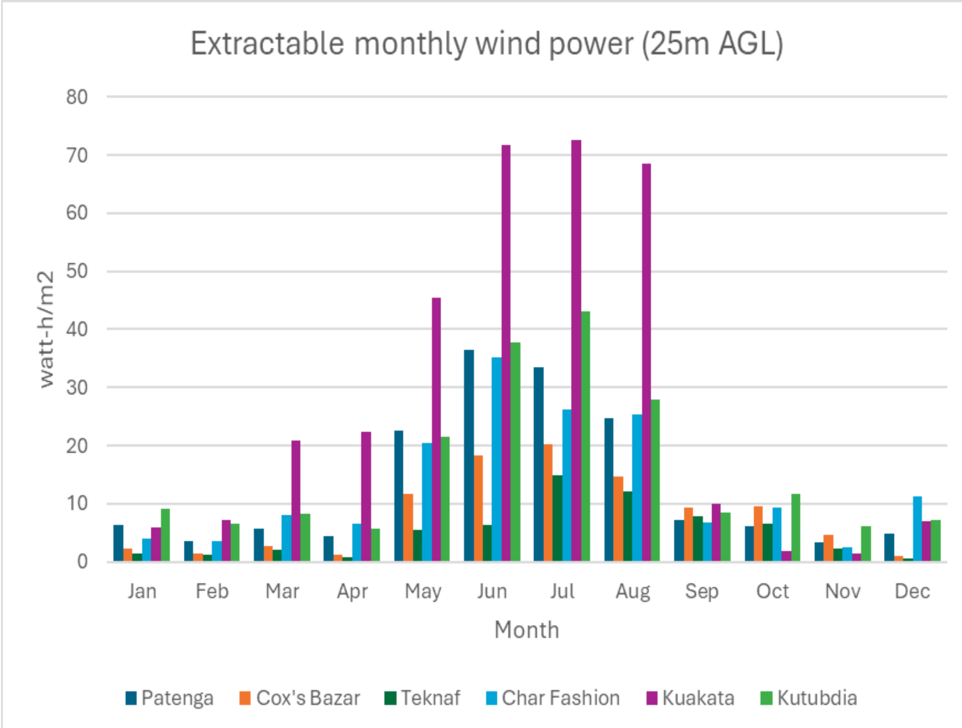


Figure 4: Extractable monthly wind power

The study of Babu et al. (Babu et al., 2022) observed that Kuakata is the best location among these six locations for utilising wind energy during peak hours. Subsequently, Patenga, Kutubdia, and Char Fashion show great promise for the production of wind energy.Subsequently, Patenga, Kutubdia, and Char Fashion show great promise for the production of wind energy.Numerous studies have been conducted to determine Bangladesh's potential for wind energy. The outcome of these wind studies suggests various coastal areas of Bangladesh, including Patenga, Cox's Bazar, Sitakundu, Teknaf, Saint Martin's Island, Char Fashion, Kutubdia, and Kuakata, as potential locations for wind energy harvesting (Buckley, 2016; Mondal & Denich, 2010; Saifullah et al., 2016; Sattar et al.; Staffell & Pfenninger, 2016). In region-by-division comparisons, the Chittagong division had the highest wind power density and wind energy density (Mondal et al., 2022). A previous study comparing the wind speeds of Bangladesh, Germany, and Jordan demonstrated that Bangladesh's wind power potential is comparable to that of other countries that generate wind energy (Rahman, 1996). According to Saifullah et al. (Saifullah et al., 2016), a near-shore wind farm can generate 1,855.2 MW of electricity. A recent study asserts that moderate wind speeds (4-5 m/s) can cover approximately 40.85% of Bangladesh's geographical area. Additionally, high wind speeds (5-6 m/s) and very high wind speeds (above 6 m/s) are estimated to occupy 0.59% and 0.01% of Bangladesh's geographic area, respectively (Islam et al., 2022). Wind kinetic energy is converted into electrical energy by wind turbines by first turning it into rotating kinetic energy inside the turbine. The quantity of energy produced by a wind system mostly relies on the wind speed and the turbine's swept area. Equation 1 can be used to represent the power output of a wind turbine (Manyonge et al., 2012).

$$P = \tfrac{1}{2} \rho A \vartheta^3 C_p \qquad (1)$$

Where, C_p = Power coefficient

ρ = density (kg/m^3)

A = swept area (m^2)

υ = wind Speed (m/s)

The power production of a wind turbine is proportional to the cube of wind speed; however the actual power output is more complicated. Therefore, Wind speed is a key component in producing a lot of power because to its cubic connection. If the wind speed at the location is sufficient, the turbine can generate a large amount of electricity that is desirable. So the actual wind speed is the most crucial element in determining how much wind energy may be produced in a given area. Based on altitude and location, wind speed varies. stronger vertical distances from the ground typically have stronger wind speeds. Since various areas (such as the city, the countryside, and plains or the sea) will have distinct wind profiles, it is crucial to measure and study the vertical profile of wind speed. Thus one can more accurately estimate the potential produced power by understanding the local wind profile. Because of there are fewer obstacles (such as trees and buildings) that might obstruct the wind, the plains and coastal regions are ideal locations for wind power plants.

Figure 5: Khurushkul, Cox's Bazar 60 MW On-Grid Wind Turbine

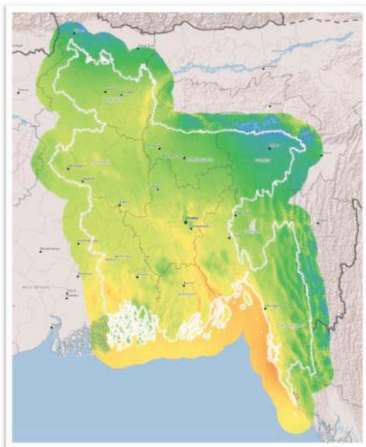
Table 2: Wind projects status of Bangladesh (SREDA)

Technology	Location	Capacity	Financial Agency	Present Status
Wind (On-Grid)	Kutubdia Upazila, Cox's Bazar	1 MW	BPDB	Completed & Running
	Kutubdia Upazila, Cox's Bazar	1 MW	BPDB	Completed & Running
	Sonagazi, Feni	900 kW	BPDB	Completed & Running
	Sirajgonj	2 MW	BPDB	Implementation Ongoing
	Chakaria, Cox's Bazar	60 MW	BPDB	Implementation Ongoing
	Maheshkhali, Cox's Bazar	100 MW	CPGCBL	Under planning
	Sonagazi, Feni	30 MW	BPDB	Under planning
	Mongla, Bagerhat	55 MW	BPDB	Under planning
	Cox's Bazar	50 MW	BPDB	Under planning
	Chadpur	50 MW	BPDB	Under planning
	Patuakhali	10 MW	RPCL	Under planning
	Cox's Bazar ((Feasibility study on going)	0 kW	BPDB	Under planning

Locations with an average annual wind speed of 20 km/h, a hub height of 30 m, and a power density of at least 150 W/m2 are ideal for wind energy sites. Locations should also take into account the nine-meter rule for the height of the wind turbine above the highest structure (both natural and man-made) to prevent reduced wind speed because of surface friction (Wood, 2001).

Both BRAC and Grameen Shakti, non-governmental organizations, attempted to assess the potential of wind power in Bangladesh. During the initial stage, BRAC effectively set up 11 small wind turbines in different coastal areas, while Grameen Shakti placed two wind generators at a shrimp farm in Chakaria, Chittagong, with capacities of 300 W and 1 KW each (Zaman).To enhance its initiatives, Grameen Shakti later installed an additional four small wind turbines in Barguna District, located in southern Bangladesh. The primary objective of these efforts was to examine if the utilization of wind power could benefit small enterprises and populations in remote rural areas. In addition to the power generated by small diesel generators and solar photovoltaic systems, these initiatives were also improved. Their primary objectives were to boost small businesses, agriculture, and provide power to isolated areas without access to the grid.

In 2014, propelled by the Department of Electricity and aided by the technical expertise of USAID, Bangladesh embarked on its inaugural endeavor to amass wind power data, adhering to global standards—an initiative sustained until 2017. Come 2018, the US National Renewable Energy Laboratory (NREL), the project's implementing entity, delivered a comprehensive report to the Department of Energy. Utilizing three years' worth of meticulously gathered data, NREL crafted a national wind map. Figure 2(a) elegantly illustrates the wind map of Bangladesh, accentuating data gleaned from nine strategically chosen locations at 50 AGL and 100 AGL, meticulously extracted from the Global Wind Atlas database (atlas, 2023).



(a)

Location	Mean Wind Speed at 50 AGL (m/s)	Mean Wind Speed at 100 AGL (m/s)	Coordinates
Rajshahi (Lalpur, Natore)	4.29	4.95	24.17035°N 88.90734°E
Chandpur	4.84	5.46	23.21116°N 90.64237°E
Sitakunda, Chattogram	5.5	6.19	22.60416° N 91.6601° E
Parkay Beach, Chattogram	5.49	6.11	22.18513°N 91.81767°E
Gouripur Mymensingh	3.44	4.11	24.71546°N 90.4668°E
Madhupur Tea Estate, Habigonj	3.23	3.85	24.37778°N 91.57462°E
Dacope, Khulna	4.55	5.15	22.47342°N 89.56826°E
Inani Beach, Cox's Bazar	5.58	6.16	21.14732°N 92.07575°E
Badarganj Rangpur	3.87	4.62	25.60641°N 89.06877°E

(b)

Figure 6: Wind Mapping (a), Details of Wind Measurement at Nine Locations (b)

3. Challenges of wind energy in Bangladesh

As a developing country in South Asia, Bangladesh has been exploring the potential of wind energy to meet its growing energy demand. However, there are several challenges that hinder the development and utilization of wind energy in the country. One of Bangladesh's biggest problems with wind energy is the absence of reliable wind resource data. The nation lacks a thorough wind atlas that offers in-depth details on the wind speed, direction, and other elements that are essential for determining a site's potential for producing wind energy. Because of the absence of data, it is challenging for developers to find ideal locations for wind energy projects and for the government to decide how to proceed with wind energy development. In (Ahmmed et al., 2001), agreed on this point and claimed that a major obstacle to the growth of wind energy in Bangladesh is the lack of accurate data on available wind resources. To solve this issue, their study suggests setting up meteorological stations and gathering long-term wind data. The high initial cost of wind turbines and related infrastructure is a key obstacle for wind energy in Bangladesh. Many developers may find it difficult to enter the market for wind energy projects since they demand substantial investments in wind turbines, towers, and other equipment. Wind energy struggles to compete with other energy sources that are currently more economical because to the high initial cost. A study by Noviedo and Mahmud (2013) found that one of Bangladesh's biggest problems is the high capital cost of wind energy projects. The report suggests putting laws and incentives into place to encourage the development of wind energy and lower the initial investment cost. To solve this issue small scale wind projects had taken but the results of small capacity wind turbines that have been erected and are being managed by private or public organizations in various locations throughout Bangladesh are not very promising (Hossain & Ahmed, 2013). Another key obstacle to the development of wind energy in Bangladesh is the lack of adequate transmission infrastructure (Amin et al., 2019). Large-scale wind energy projects cannot be implemented in the nation due to the underdeveloped transmission infrastructure. The amount of wind energy that may be generated is constrained by this restriction, which makes it challenging to link wind energy projects to the grid. The growth of wind energy in Bangladesh faces considerable obstacles due to a lack of transmission infrastructure, according to (Hossain & Ahmed, 2013). To make it easier to integrate wind energy into the grid, the report advises building new transmission lines and improving current infrastructure. The absence of awareness and assistance from stakeholders is another obstacle for wind energy in Bangladesh. The general public, investors, and many legislators are unfamiliar with wind energy's potential advantages. The advancement and success of wind energy projects may be hampered by this lack of knowledge and assistance. The study by David Bidwell in Michigan, US claimed, support for commercial wind energy is mostly based on the idea that wind farms would boost local economies (Bidwell, 2013).

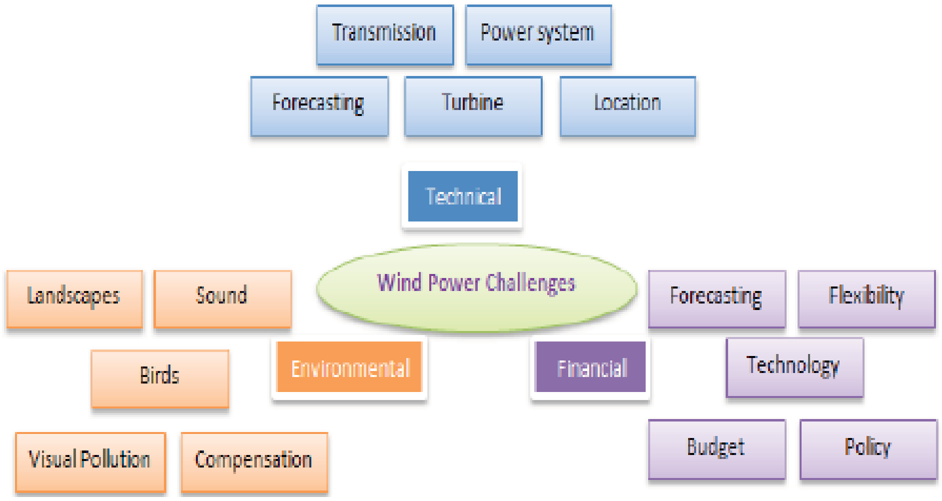


Figure 7: Overviews of challenges encountered in the implementation of wind power (Rahaman & Hassan).

According to Khan et al. (Khan et al., 2004) found that a major obstacle to the growth of wind energy in Bangladesh is a lack of awareness and support. The report suggests launching public education and awareness efforts to advance wind energy and broaden stakeholders' acceptance of it.

3.1 Technical challenges

However, despite their numerous advantages, the technical challenges that come with their implementation cannot be ignored. The wind energy has shown to be a reliable source of renewable energy, building and operating wind turbine technology comes with several difficulties that are sometimes overlooked but have real, observable effects (Apunda & Nyangoye, 2017). One major technical challenge is the intermittent nature of wind as a source of energy. The mechanical processes used in producing electricity from wind turbines convert all of the wind's fluctuation into electric power called "intermittent". Wind speed and direction vary over time and are influenced by factors such as weather conditions and terrain. This unpredictability makes it difficult to generate a consistent and reliable power supply.

Though introducing wind power to power networks will benefit them by lowering pollution from the production of electricity and power system operating expenses because conventional power plants use less fuel (Ummels, 2009). Nevertheless, the difficulties include how wind energy affects the electrical grid, how much it costs to operate the system, the quality of the power, and power imbalances (grid stability). Since wind energy production locations are frequently located far from areas of consumption, the limited capacity of the grid (lines and stations) might pose a serious issue (Ahmed et al., 2020). Power quality issues including voltage stationary variations (downs, interruptions, and raises in voltage; voltage dips), voltage transient variations (flicker), harmonics, frequency changes, and low power factor can be brought on by the location and intermittent nature of wind turbine machines. Particularly inductive wind turbines have a tendency to take in reactive power from the system and create a low power factor (Georgilakis, 2008). While Bangladesh is currently in the pilot phase of integrating wind power into the grid, it is anticipated that as this system matures in the near future, certain challenges will need to be addressed. According to a study, the existing poor quality of the grid infrastructure has a detrimental impact on the performance of wind electric generators, and these wind generators can also contribute to power quality issues (Venkatesh, 2002). Consequently, the operational efficiency of wind farms is compromised, leading to diminished grid power quality and increased losses for both utilities and other consumers.

Typically, assessments of wind resources involve amalgamating real-time observations with simulated data. However, owing to the absence of prior data at standard wind turbine hub heights (80 m and above) in Bangladesh, NREL procured a limited set of measurement tools—seven wind towers and a Sonic Detection and Ranging unit (SODAR), strategically deploying them at two sites across the country (Jacobson et al., 2018). These instruments facilitated measurements, often at multiple heights, encompassing parameters such as temperature, barometric pressure, relative humidity, wind direction, speed, and sun insolation.

The data collection process encountered various unique challenges, leading to intermittent halts. These challenges encompassed issues like red ants infiltrating a data logger, animal interference causing damage to exposed wires, theft of photovoltaic systems, acts of vandalism, data logger malfunctions, and instances of political unrest. Table 4 delineates the primary reasons for significant data gaps during the project.

Table 3: Reasons for Significant Data Gaps (Jacobson et al., 2018)

Tower and Gap Date	**Explanation**
Chandpur (June – Sept. 2016)	Data logger failure
Mirzapur (Sept. 2016 – Jan. 2017)	Vandalism
Mirzapur (Feb. – Mar. 2017)	Data logger failure
Mirzapur (June – Aug.1 2017)	Data logger failure
Parkay (Mar. – Apr. 2016)	Power system failure
Rangpur (SODAR) (Dec.2016– Mar. 2017)	Progressive failure of a SODAR unit component

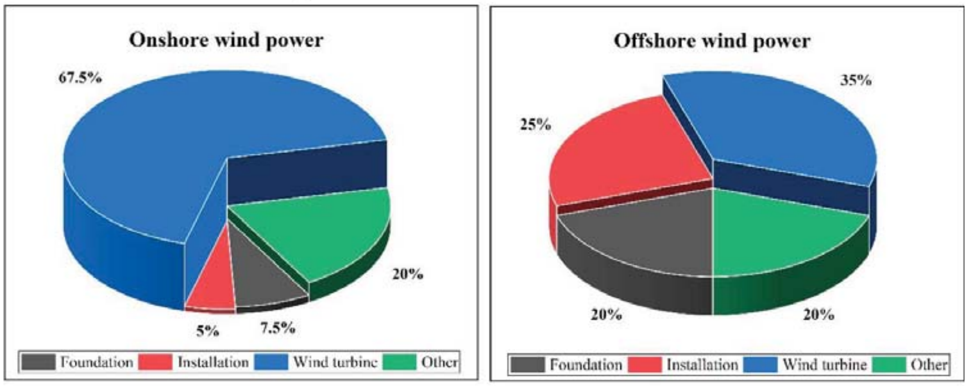
Another technical challenge is the design and engineering of wind turbines. The large-scale wind turbines used in modern wind farms require specialized knowledge and expertise in design, materials, and manufacturing (Hayman et al., 2008). They must be designed to withstand high wind speeds and harsh weather conditions, while also being efficient and cost-effective. In addition, maintenance and repairs of wind turbines can be challenging due to their location in remote areas and the difficulty of accessing them. Designing wind turbines properly is a crucial challenge that requires careful consideration of blade loading and aerodynamic stability. These turbines are subjected to various types of loads such as inertial, gravitational, and aerodynamic, which necessitate the development of accurate mathematical models for calculating material and structural stresses. To address this, many researchers have created models for improved design of both horizontal and vertical axis wind turbines. For example, Ernesto et al. developed a multi-objective optimization approach for designing horizontal axis wind turbines by coupling an aerodynamic model (based on blade element theory) with an evolutionary algorithm (Benini & Toffolo, 2002). Bierbooms utilized a probability-based method to determine the extreme-response of wind turbines, which allowed for better understanding of extreme conditions and improved reliability and optimization of wind turbines (Bierbooms, 2004). Additionally, Petkovic and Shamshirband used adaptive neuro-fuzzy inference system (ANFIS) to analyze various parameters that impact wind energy generation and found that the blade pitch angle is particularly influential (Petković & Shamshirband, 2015). Moreover, wind energy systems require substantial infrastructure investments to transport and distribute the generated energy. This includes building new transmission lines and upgrading existing ones to accommodate the increased energy supply. In addition, energy storage technologies must be developed and improved to enable better management of energy fluctuations and to ensure a reliable energy supply.

Despite the manifold benefits presented by wind energy systems as a sustainable energy alternative, there exist various technical hurdles that demand resolution for their optimal utilization. The advancement of sophisticated wind turbine configurations, innovations in energy storage methods, and the establishment of effective transmission networks will play a pivotal role in surmounting these obstacles and securing a viable and enduring energy landscape.

3.2 Economic challenges

Bangladesh, like many developing countries, faces significant economic challenges in implementing renewable energy projects, including wind energy. And major issues is the financial challenges, such as the high upfront costs of wind energy projects and the lack of access to affordable financing. On the financial side, the high upfront costs of wind energy projects are a significant barrier to investment. Study found that the cost of a wind turbine on average increased from 2008 to a projected $1,500/kW (Bolinger, 2011). According to a study by Das et al. (Das et al., 2017), the capital cost of a 1 MW wind turbine in Bangladesh is approximately $2.8 million, which is much higher than the average cost of electricity in the country. Rahman et al. (Rahman et al., 2017) found the capital cost of a wind-powered system for an off-grid island of Bangladesh to be $63,550.16. According to M.T. Amin, wind electricity generation costs per MWh are 6000.08 BDT, which is still much lower than the per MWh generation cost of solar PV (80000.68 BDT) (Amin, 2015). In comparison to prices in other nations, this cost is still excessive. An onshore wind farm's generation costs in Eupore range from 4.5 to 8.7 cents per kWh (Blanco, 2009). According to the findings of

Ohunakin et al. in Nigeria, the highest average cost per kWh was obtained as $0.0222/kWh (Ohunakin et al., 2012). As depicted in Figure 2, the installation expenses are comparatively elevated, constituting a range of 20% to 30%. Conversely, onshore wind power boasts a lower installation cost, approximately at 5% (Gonzalez-Rodriguez, 2017). The foundation cost for offshore installations ranges between 15% and 25%, whereas onshore wind power incurs a more modest 5% to 10%. Concerning wind turbine expenditure, offshore wind power holds a lower share at around 30% to 40%, contrasting with onshore wind power, where this component is more substantial, ranging from 60% to 75% (Dong et al., 2021). The lack of access to affordable financing is another significant challenge, as banks and financial institutions in Bangladesh have limited experience with financing renewable energy projects.



(a) Cost composition of onshore wind power (b) Cost composition of offshore wind power

Figure 8: The breakdown percentage of the cost associated with a wind energy system (Guo et al., 2022).

Furthermore, the regulatory environment for renewable energy in Bangladesh is not yet fully developed, which makes it challenging to attract private sector investment. According to a report by the World Bank (2019), Bangladesh has made progress in developing policies and regulations to support renewable energy development, but more work is needed to create a favorable investment climate (Sadeque et al., 2014). To overcome these challenges, a comprehensive policy framework is needed that addresses both the technical and financial challenges of implementing wind energy in Bangladesh. This framework should include measures to facilitate the integration of wind power into the grid, promote investment in renewable energy, and provide access to affordable financing. Additionally, the government could consider offering incentives such as tax breaks, subsidies, and feed-in tariffs to attract private sector investment in renewable energy projects.

3.3 Environmental challenges

With the creation of renewable energy and the potential to replace mining operations, air pollution, and greenhouse gas emissions brought on by non-renewable energy sources, the impacts of wind energy on the environment are frequently seen as favourable. But the environmental effects of energy generation are universal, and wind energy is no exception. Wind power facilities do have certain effects on the environment, just like any other energy technology. Wind farms are commonly built on field that has previously experienced land clearance. According to Suaad Jaber, compared to coal mines and coal-fired power plants, the amount of vegetation clearing and ground disturbance needed for wind farms is negligible (Jaber, 2013). A team of NEREL researchers estimates that a 2-MW wind turbine requires a total area of about 0.5 square kilometres (Gaughan, 2018). As reported by Sattar et al. (Sattar et al.), 100 separate 2 MW turbines are needed on a 70 km2 plot of land in order to produce 200 MW of electricity. It has been found that wind resource development may interact with other land uses, and that these other uses may be more valuable than electricity generation (Jafri & Dadhich). M.Wolsink stated that, the largest barrier to using wind as a power source is that it is sporadic and does not always blow when energy is needed. Not all winds can be gathered to coincide with the period of power consumption, and wind energy cannot be stored without the use of batteries (Wolsink, 2000).

The environmental effects of wind-energy amenities can persist over a wide range of temporal and spatial scales, ranging from short-term noise to long-term impacts on habitat structure and species presence. These scales extend from the location of a single turbine to landscapes, regions, and the planet. Additionally, it is probable that many of the impacts are cumulative, and ecological factors might interact in complicated ways at wind energy installations and other locations linked with altered land-use patterns and other human disturbances (Jafri & Dadhich). Birds and bats are killed by wind turbine collisions, most commonly with the turbine blades (Cryan & Barclay, 2009). In a study in US reported 2 039 bird deaths from 128 species were reported by 44 wind sites, and 418 bat deaths from 5 species were reported by 22 facilities (Choi et al., 2020) . Species vary in their susceptibility to collision, the probability that deaths will have large-scale cumulative effects on biotic ecosystems, and the frequency with which their fatalities are identified.

Potential interference with radar and telecommunications systems is one issue with wind turbines (Saidur et al., 2011). The rotating blades of wind turbines can cause reflections and scattering of radio waves, which can interfere with radar systems (Matthews et al., 2008). The radar signals can bounce off the blades and create false echoes, making it difficult for radar operators to accurately detect and track objects such as aircraft or weather patterns. This interference can affect military radar installations, air traffic control systems, and weather monitoring systems. Additionally, wind turbines can also generate electromagnetic interference that can disrupt nearby telecommunications systems, such as wireless communication networks or radio and television broadcasting (Casanova et al., 2008). To mitigate these issues, careful planning and coordination are necessary to ensure that wind turbines are located at a safe distance from critical radar and telecommunications installations.

In (Council, 2007), the establishment and upkeep of wind energy facilities modify ecosystem structure via plant clearance, soil disturbance and erosion risk, and noise pollution. Modification of vegetation, especially forest clearance, provides likely the most important potential alteration through fragmentation and loss of habitat for certain species. When current recreational activities are prohibited or must be rerouted around a wind energy installation, this is a significant concern. Furthermore wind-energy projects generate negative consequences on human health and welfare, the disadvantages are experienced largely by those residing close windfarms that are harmed by sound and shadow flicker.

Table 4: A compilation of surveys regarding the visual effects of wind turbines on residents in various areas.

Place	Wind Turbine's Visual Effects	Ref
Australia	556 individuals concurred on adverse visual effects.	(Lothian, 2020)
Iceland – Burfell windfarm	The majority of residents expressed unfavorable sentiments.	(Ólafsdóttir & Sæþórsdóttir, 2019)
Ireland	Wind turbines are observable across more than 40% of the terrain.	(Hallan & González, 2020)
Greece – Samothraki Island	Approximately 48% of inhabitants held unfavorable opinions.	(Vlami et al., 2020)
ETH Zurich	Visual irritation resulted from wind turbines.	(Schäffer et al., 2019)
Virtual reality	Around 36% of respondents held unfavorable opinions.	(Cranmer et al., 2020)

Landscape views and visual impacts are crucial environmental factors in choosing wind farm applications associated with wind energy development, as landscape and visual impacts are inherently subjective and vary across time and space. Wind development features may have landscape and aesthetic consequences. They include the size, height, quantity, material, and color of the turbines, as well as the access and site tracks, substation buildings, compounds, grid connection, anemometer towers, and transmission lines. According to A. Lothian wind farms should avoid areas with a higher perceived quality of scenery, especially along the coast (Lothian, 2008). Cox's Bazar and Kuakata, in Bangladesh, are renowned for their coastal grandeur. With the largest coastal beach in the world, Cox's Bazar attracts nearly 2 million visitors per year (Dey et al., 2013). However, these two locations have the most wind energy potential. Therefore, the construction of new wind projects may have an effect on the tourism industry of Bangladesh.

The noise generated by wind farms has been one of the most well studied environmental effects of this technology (Kaldellis et al., 2012; Piacsek & Wagner, 2004; Saavedra & Samanta, 2015). Figure 2 illustrates how noisy wind turbines are in relation to their distance. Noise is more easily quantifiable and forecasted than landscape and visual effects. There are primarily two sources of noise from wind turbines: mechanical noise and aerodynamic noise (Pinder, 1992). Mechanical noise is caused by the gearbox and generator, which are essential components of the wind turbine. As the gearbox and generator rotate, they create vibrations and sounds that can be heard in the vicinity of the turbine. These sounds can be low-frequency and may sound like a deep hum or rumble. Aerodynamic noise is caused by the interaction of the turbine blades with the wind. As the wind passes over the blades, it creates turbulent airflow that can cause the blades to vibrate and create noise. The sound generated by the blades can be high-frequency and may sound like a whooshing or swooshing sound.

Overall, while wind turbines do generate noise, the noise levels are generally low and often comparable to background noise in rural areas. Nonetheless, concerns about the impact of wind turbine noise on nearby residents and wildlife have led to the development of noise regulations and guidelines in many countries. Another significant environmental concern that poses both technical and economic sides is the geographical feature of land slope. The evaluation of land slope is crucial when determining the feasibility of wind farm sites in terms of construction costs. Installing wind farms on steep slopes can significantly increase construction expenses.

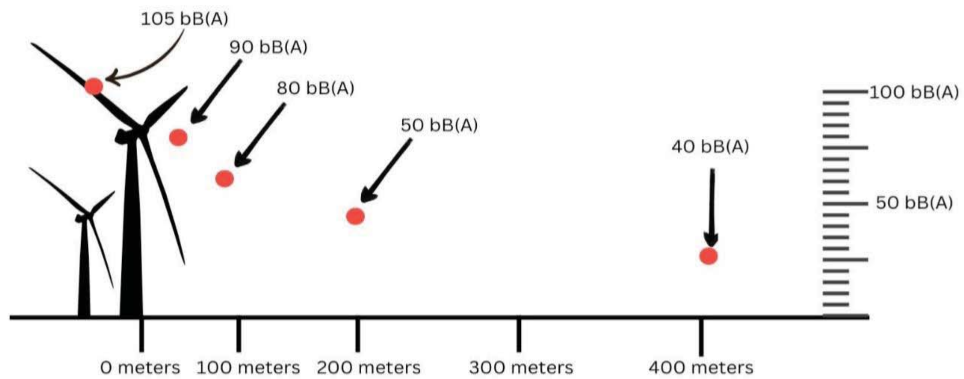


Figure 9: How noisy are wind turbines (Salt & Lichtenhan, 2014)

Furthermore, the land slope is considered a critical factor because it has the potential to accelerate wind speeds through the Venturi effect. The Venturi effect refers to the phenomenon where wind flow is compressed as it passes through a narrow space, such as a valley or a gap between hills (Chaudhari et al., 2013). This compression results in an increase in wind speed, which can be advantageous for wind power generation. A study found that 46.44% of the nation's total land area is ideally suited for the construction of wind farms (Islam et al., 2022).

4. Potential solutions and suggestions

Addressing wind energy's technical, economic, and environmental challenges requires strategic measures tailored to Bangladesh's context. Learning from various literature and developed nations' experiences, the nation can forge solutions. Technical barriers can be surmounted through collaboration with wind technology experts, yielding customized turbine designs and improved materials. Economic hurdles demand policy frameworks like feed-in tariffs, attracting private investment, while partnerships with global organizations could secure funding and expertise. Environmentally, rigorous impact assessments, involving stakeholders, will guide responsible project siting and robust regulatory enforcement. Smart grid integration, mirroring successful models, can accommodate variable wind power via advanced grid technology and energy storage. By embracing these insights, Bangladesh can pave the way for sustainable wind energy, ensuring energy security and holistic development.

4.1 Potential solutions for technical challenges

Short-term fluctuations in wind power production primarily impact the operation of power systems. This includes the management of additional reserves, cyclic losses in conventional power production units, and the effects on transmission or distribution networks. Yet, with the escalation of wind capacity, it becomes imperative to implement measures that safeguard power systems' reliability against potential drawbacks stemming from wind power variations. Effectively handling wind power involves ensuring grid stabilization, bolstering reliability, and providing consistent service for the delivered power. These three attributes play a pivotal role in managing the intermittency of this energy source and enhancing the penetration rate of wind turbines. According to Cimuca (2005), the majority of wind turbines need a strong grid that imposes the frequency and voltage in order to operate effectively and generate electricity. Additionally, this grid must be able to continually absorb the power generated by wind turbines and give the necessary reactive power to the asynchronous generators, for example. In addition to the traditional monitoring role, Chands et al. (1998) claim that the expert-based maintenance methodology has the potential to increase the reliability of systems. Supervisory systems based on expert knowledge, capable of leveraging dynamic system information to enhance their reliability, can be a valuable addition to Bangladesh's situation. The electrical limitations affecting the installation of wind turbines can serve as indicators for identifying the predominant power quality issues that may arise when wind turbines are deployed in vulnerable grid systems (Lundberg, 2000).

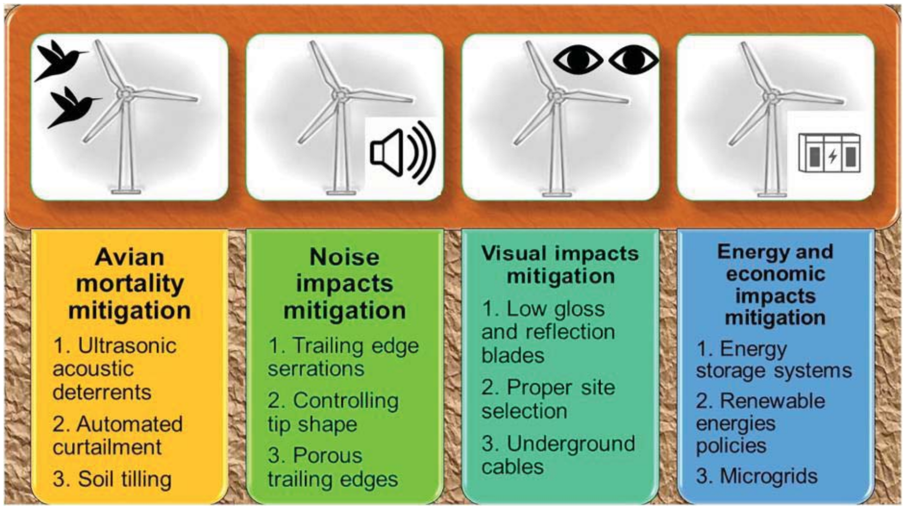


Figure 10: An overview of mitigating measures for challenges related to wind energy sustainability, including noise, visual, energy, and economic consequences, as well as bird mortality (Msigwa et al., 2022).

Turbulence is likely to be produced in places with sharp edges, which will hinder the functioning of the wind turbine. Since turbulence frequently causes vibration in the turbine blades, it is recommended to locate the wind turbine 150 m away from all obstacles (Olabi et al., 2021). The shape of an aerofoil is a critical design parameter that influences the aerodynamics of a blade. Recent advancements in aerofoil technology have increased the energy capture capacity of wind turbines. Padgetl created a damage model that can calculate the strength of fibrous composite materials and predict their failure point. Fuglsang et al. developed the RISO-131 aerofoil family and verified its design. Slender blades are used to enhance the lift coefficient of airfoils while reducing both fatigue and extreme loading. Extensive research has led to the evolution of modern blades, which possess a higher lift-to-drag ratio. Additionally, researchers have investigated design modifications such as diffuser-augmented wind turbines (DAFT) and building-augmented wind turbines (BAWT), where the shape of the building is optimized to increase wind energy.

4.2 Potential solutions for economic challenges

Bangladesh has undertaken and successfully implemented numerous large-scale projects in recent years, including the Padma Bridge, Dhaka Metro Rail, Karnaphuli Tunnel, Ruppur Nuclear Power Plant, etc (Abdilahi et al.). As a developing country, the government must prioritize which projects require the most urgency before implementing any project. The nation frequently overlooks the high upfront cost to engage in renewable energy projects due to the financial load and having loans with international banks.

According to Sovacool one of the best ways to increase access to energy services, especially for the poor, is through public-private partnerships (PPPs) (Sovacool, 2013). Public-Private Partnerships (PPPs) involve collaboration between the government and private sector to finance and implement renewable energy projects. The study by Othman and Khallaf also agreed on the point that PPPs are an alluring delivery option for renewable energy technology in underdeveloped nations (Othman & Khallaf, 2022). Their research identified some crucial success criteria for PPPs implementation: 1. Government support; 2. Existence of a strategic plan and policy framework; 3. Effective handling. 4. Political constancy 5. Stringent laws and rules.

Martin et al. (Martins et al., 2011) analyzed the Portuguese experience applying PPP contracts to the energy industry, specifically in relation to the growth of wind power plants. They asserted that the production of wind energy is increasing, and the business sector is becoming more interested in wind energy projects. Fantozzi et al. (Fantozzi et al., 2014) also proposed that using PPPs would be a way to encourage renewable energy without increasing public debt. Their research analyed two rural communities in Greece and Italy build agro-energy businesses using PPP. According to a case study conducted in Khulna, Bangladesh by Haque et al. (Haque et al., 2020), the PPP initiative improved Khulna's resilience by addressing the pertinent Sustainable Energy Goals (SDGs). Similar to this, Kirikkaleli et al. (Kirikkaleli et al., 2022) suggest using public-private partnerships to invest in the most recent energy innovations in Bangladesh to power that are environmentally friendly. So, it can be said PPPs could be an effective model for financing wind energy projects in Bangladesh.

International Development Finance Institutions (DFIs) such as the World Bank and Asian Development Bank have experience in financing renewable energy projects in developing countries (Donastorg et al., 2017). A $185 million finance agreement was signed by the Bangladeshi government and the World Bank today to add 310 MW of renewable energy producing capacity in 2019 (BANK, 2019). This would result in more dependable, reasonably priced electricity and better air. Utility-scale solar photovoltaic (PV) and rooftop PV will be the project's main areas of concentration in order to open up new markets for the production of renewable energy in the nation. According to Khan et al. (Khan et al., 2022), DFIs can provide financing, technical assistance, and risk mitigation tools to support renewable energy projects in Bangladesh. The study suggests that greater collaboration between DFIs and the government of Bangladesh could help to address the financial challenges of wind energy implementation.

Another solution could be the green bonds, which are debt instruments that are used to finance sustainable projects. Green bonds are a reasonably inexpensive way to finance sustainable investments, according to Agliardi & Agliardi (2019). Based on a study by S.R Rahim, green bonds could be a useful tool for financing renewable energy projects in Bangladesh (RAHIM, 2018). The study suggests that the issuance of green bonds could attract private sector investment and support the development of a domestic green bond market. In a study paper, D. Stojanovi examines the green bond market and identifies the key obstacles that prevent many nations from utilising this new but expanding source of financing for renewable energy (Stojanović, 2020). According to the author, the primary obstacles to the growth of the green bond market are the absence of appropriate institutional arrangements for administering green bonds.

Lastly Feed-In-Tariffs (FITs) can apply, FITs are a policy mechanism that provides a guaranteed price for renewable energy generated by wind turbines. Based on a study by Gómez et al., the subsidy provided by this FIT mechanism makes wind farms in Colombia profitable (Jiménez-Gómez et al., 2018). Nahar et al. (Nahar & Sunny, 2021), claimed FITs could be an effective tool for attracting private sector investment in wind energy projects in Bangladesh. The study suggests that FITs could provide a stable revenue stream for investors and reduce the financial risk associated with wind energy projects.

Offshore wind systems typically experience significantly higher operation and maintenance (O&M) expenses in comparison to onshore systems. Offshore expenses at the bottom end are similar to onshore costs at the top end, but the highest offshore costs can be nearly twice as high as the highest onshore O&M expenses. Nevertheless, offshore systems enjoy higher capacity factors. The rise in cost is mostly due to balance of system components like foundations and logistics. This provides a significant chance to reduce offshore electricity expenses with creative solutions. The IEA predicts that by 2035, the expense of producing offshore wind power will drop but it will remain more expensive compared to other energy sources. At present, the typical expense of an offshore wind farm is approximately 2.75 times greater than that of an onshore system, with variations depending on the location. The maintenance and operational expenses for offshore systems always remain elevated. Although the lowest offshore maintenance cost equals the highest onshore cost, offshore O&M costs that are the most expensive are nearly double. However, even with these challenges, offshore sites provide higher capacity factors, and innovation focused on overcoming them could lead to a substantial decrease in offshore electricity expenses. (Ahmed & Cameron, 2014).

4.3 Potential solutions for environmental challenges

One of the primary concerns with wind energy is the clearing of valuable lands for wind farm installations. To minimize this impact, researchers and industry experts have proposed several solutions. One approach involves utilizing abandoned or underutilized lands, such as brownfields, mining sites, or agricultural areas with low productivity. This practice is known as "repowering" and allows for the redevelopment of already disturbed lands, reducing the need for new land clearing (Hou et al., 2017). Additionally, incorporating offshore wind farms can alleviate land clearing issues (Nicolle, 2013). Offshore wind energy has gained attention as a promising alternative, as it utilizes coastal or offshore areas, minimizing conflicts with existing land uses (Bilgili et al., 2011). Planning areas for windfarm growth, ecological preservation, and maritime logistics requires an immediate statewide survey and assessment of offshore wind resources, marine ecology, and bottom ecosystems (Sempreviva et al., 2008). According to Dinh and McKeogh the supply chain and projects should be designed for the different offshore environment (Dinh & McKeogh, 2019). Next is the visual impact of wind turbines on tourist sites and landscapes is a concern for many communities. Landscape planning and careful site selection can help mitigate this issue. The main consideration while examining the effects on historical, religious, and archaeological sites is that the integrity of the site shouldn't be permanently harmed. Depending on the particulars of the historic resources in question, a wind-energy project may or may not cause resource harm. Strategic placement of wind farms in areas with low visual sensitivity, such as industrial zones or areas with existing infrastructure, can reduce the visual impact on scenic landscapes. Moreover, advancements in turbine design, such as sleeker and less obtrusive structures, have been explored to improve aesthetics. For example, the development of VAWTs has shown promise in reducing the visual impact due to their compact size and unique design (Kumar et al., 2018). While the connection between wind turbines and various bird populations, especially apex birds, is insufficiently explored, there is evidence suggesting that turbines can have detrimental effects on those populations. The United States Fish and Wildlife Service conducted research and presented in Figure 10, which indicates that the number of bird fatalities caused by turbines is relatively low. Nevertheless, it is essential to bear in mind these considerations, and a thorough survey is necessary in the context of Bangladesh.

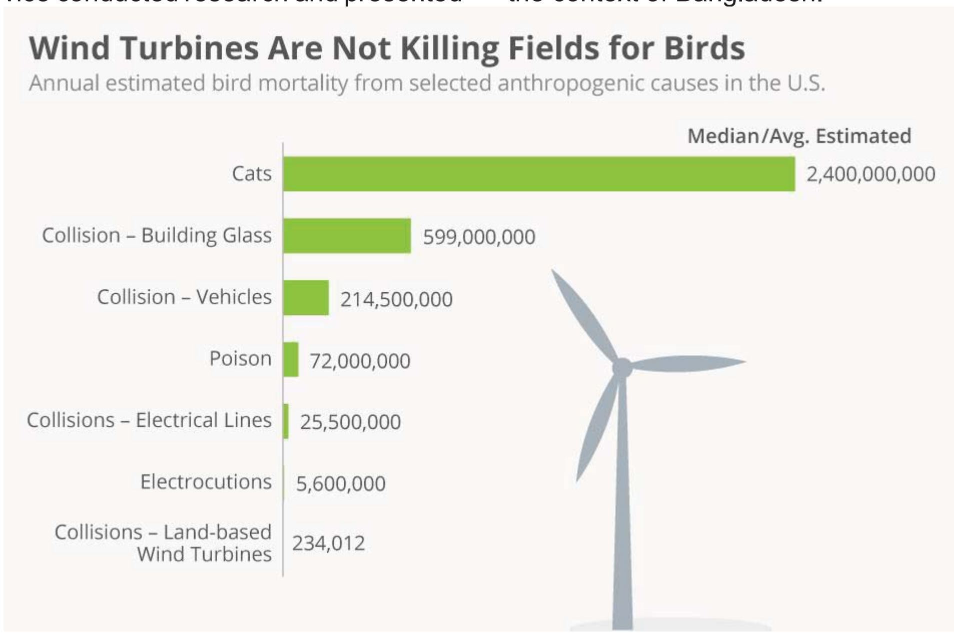


Figure 11: A study on bird mortality due to different causes in the United States (Statista, 2019).

Wind farms can interfere with radar systems, affecting weather data accuracy and potentially impacting aviation safety. Researchers have proposed various solutions, such as developing advanced radar technologies that can filter out wind farm clutter and improve radar data quality (Dutta et al., 2019). Collaboration between wind energy developers, meteorological agencies, and aviation authorities is crucial to developing protocols that ensure wind farms' minimal impact on radar systems (De la Vega et al., 2013). Lastly noise generated by wind turbines can cause disturbances to nearby residents. Several measures can help mitigate noise pollution. Firstly, incorporating setback regulations, which determine the minimum distance between wind turbines and residential areas, can reduce the impact of noise on communities (Stede & May, 2020). Wind turbine manufacturers are continuously working to reduce the noise generated by wind turbines (Jianu et al., 2012). Strategies for reducing mechanical noise include improving the design and construction of the gearbox and generator, using better materials, and implementing more effective noise insulation (Deshmukh et al., 2019). Strategies for reducing aerodynamic noise include improving blade design, reducing the speed of the blades, and optimizing the pitch of the blades.

5. Conclusion

In conclusion, this review paper has traversed the intricate landscape of wind energy prospects and challenges in Bangladesh, offering a comprehensive assessment of the nation's transition from fossil fuels to renewable sources. The pressing need to alleviate the fuel crisis and reduce dependence on finite fossil fuels has been established as a pivotal driver for embracing alternative energy solutions. The potential of wind energy in Bangladesh emerges as a promising beacon, with its geographical and climatic conditions rendering it conducive for harnessing wind power. Despite that, wind energy constitutes only 0.01% of the country's total energy production. The wind energy sector has grown quickly. Its overall capacity that is installed has expanded by roughly a fifth in the period of 10 years. Europe, India, and the worldwide offshore sector have achieved all-time high levels of wind power capacity. In the year 2017, the wind power sector saw growth in more than 90 nations and regions worldwide. China was still the leading player in the wind power sector, with the Asian wind energy market maintaining its global dominance in 2017. North America took the third spot, with Europe holding the second rank. Among the 30 countries, more than 1 GW is their installed capacity, with 9 countries having installed capacity exceeding 10 GW. Onshore wind power's pace of short-term growth has decreased. For the second year in a row, installed capacity of grid-connected electricity fell by 10% in 2017. This trend directly goes against the Sustainable Development Scenario (SDS) as described by the IEA. The SDGs strive for continual growth in onshore wind power initiatives, achieving a 12% annual increase in electricity generation. There was a peak in the development of offshore wind power. The offshore wind power capacity increased by 4.33 GW in 2017, reaching a total installed capacity of 18.81 GW globally. Europe accounts for 72% of the global new market. The Sustainable Development Goals predict a continuous increase in offshore wind power capacity, with Germany expected to reach 150 GW by 2030. Competition in the wind power industry is increasing. In a growing market with a limited base, wind power is now a leading option for new installations as it is cheaper than existing fossil fuels. In 2017, there was a notable drop in tender prices for wind power installations, whether they were onshore or offshore. Policy backing remains essential for sustained growth in the long run. The GWEC predicts that if growth rates remain consistent under the Paris agreement, wind power capacity is projected to reach 2110 GW by 2030. The global wind energy capacity is estimated to reach 5806 GW by 2050. However, accomplishing this goal will necessitate all nations around the world to adopt comprehensive and effective actions against climate change. (Li et al., 2022) The paper illuminated how wind energy could be a key contributor to the country's energy mix, bolstering energy security and sustainability. However, the journey towards a robust wind energy sector is not devoid of obstacles. The identified technical challenges spanning turbine technology, grid integration, and intermittency management, pose significant hurdles. Economic challenges such as high initial costs and financing barriers, along with intricate environmental considerations, further underscore the complexity of the transition. Amidst these challenges, the paper underscored the need for a holistic approach to address the multi-dimensional nature of the obstacles. The suggested solutions, drawn from experiences of established wind energy markets, provide a roadmap to navigate the hurdles. By focusing on technology innovation, fostering conducive policy frameworks, enabling effective financing mechanisms, and implementing proactive environmental management, Bangladesh can steer its wind energy sector toward a resilient and sustainable future. In essence, this review paper serves as a compendium of insights, acknowledging both the potentials and pitfalls that wind energy presents in Bangladesh. It emphasizes the imperative for collaborative efforts among policymakers, industries, researchers, and communities to drive the transition toward a cleaner and more resilient energy landscape. As Bangladesh charts its course into a new era of energy, the lessons drawn from this review paper could play a pivotal role in shaping the trajectory of its sustainable energy future.

As mentioned earlier, a comprehensive wind mapping of Bangladesh is still lacking. Conducting experimental research that explores the correlation between the wind mapping of specific locations and overall economic analysis could provide investors with valuable guidance for funding wind energy projects. Future works can be directed towards addressing these aspects.

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