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Assessment of Barriers to Wind Energy Development Using Analytic Hierarchy Process

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Abstract: Despite the vast potential of wind energy, it has yet to be implemented widely in Bangladesh. Several barriers play major roles in obstructing the wind energy sector's development in Bangladesh. Hence, it is necessary to identify these barriers to progress this sector's growth. The analytic hierarchy process (AHP) is a multi-criteria decision-making method that can rank alternatives by considering multiple factors. It is a valuable tool for complex decision-making problems with multiple criteria, and their relationships must be clarified. So, in this analysis, AHP is used to rank the barriers related to wind energy development in Bangladesh. First, six main barriers and eighteen sub-barriers have been identified from a detailed and comprehensive literature review. The main barriers are categorized into technical, administrative, policy and political, economic, social, and geographic. After that, a questionnaire was sent to experts to obtain their opinions on these barriers. Based on the analysis, it was found that, with a weighted score of 0.46, technical barriers were the most significant ones. Administrative barriers ranked second with a weighted score of 0.21, and social barriers ranked last with a weighted score of 0.03. Among the sub-barriers, risks associated with technology were found to be the most significant, while land use conflict was found to be the least significant. Finally, several recommendations are provided to overcome the wind energy barriers in Bangladesh. The findings of this study can help policymakers and stakeholders develop strategies to overcome the barriers to wind energy development in Bangladesh.

Keywords: AHP; wind; renewable energy; multi-criteria decision analysis; Bangladesh; barriers

1. Introduction

As cities began to develop, energy demand increased tremendously [1,2]. Fossil fuels have been used to meet this demand globally [3]. A significant 4% annual growth in the number of conventional power plants since 1997 has increased air pollution and endangered human health [4,5]. These power plants are responsible for one-third of the world's glasshouse gas (GHG) emissions. The main GHGs that have a negative impact on the global climate order are carbon dioxide (CO_2), nitrous oxide (NOx), and sulfur dioxide (SO_2) [6,7]. NOx generated by power plants can form ozone, resulting in environmental photochemical pollution [8]. Even though technical developments in power plants have significantly reduced SO_2 and NOx emissions, climate change brought on by CO_2 emissions continues to be a severe and divisive issue [9]. According to estimates, 5% of fossil fuel-based power plants account for 73% of the world's CO_2 emissions from electricity production, which is highly concerning for the environment [4,10]. In underdeveloped nations, the situation is considerably more dire. For instance, Bangladesh is anticipated to produce 83,000 metric tonnes of CO_2 and 132,520 GWh of electricity from conventional power plants in the 2024–2025 fiscal year, making it the top CO_2 emitter in the world [11]. Therefore, to ensure a low-carbon future and fulfill the Sustainable Development Goals (SDGs), it is required to adopt decarbonization technologies to cut CO_2 emissions and accelerate economic development [12]. Renewable energy can be beneficial in this regard [13].

In the wake of the recent Russia–Ukraine war, European nations are anticipated to take considerable action to reduce their reliance on Russian oil and gas [14]. As a result, a space has been further opened for renewable energy to influence world politics, undermining the dominance of oil and gas exporters [15]. By the end of 2019, renewable energy sources generated more than 27% of the world's electricity, with wind turbines and solar photovoltaics (PV) contributing about 11% each [16]. By the 21st century, it is anticipated that solar and wind energy will increase globally more quickly than other energy sources [17]. In this context, wind energy can offer grid and off-grid consumers more dependable and efficient power and thus show promise to achieve SDG 7, which means that everyone can afford dependable, sustainable, and modern energy [4].

Generally, two extraction devices, horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs), harness wind energy. HAWTs have been widely used between these devices in offshore and onshore locations because of their high power conversion efficiencies. These devices can produce megawatts of power. However, in spite of their commercial success, the large size of HAWTs (rotor diameters over 100 m) presents some logistical problems. HAWTs require large amounts of space in water bodies or land, as the optimum spacing along the wind direction in a HAWTs wind farm could extend up to 15 times the turbine rotor's diameter or greater. Also, HAWTs require complex yaw control, as they have to face the incoming wind for optimum power production. On the other hand, VAWTs do not require complex control, as their performance is not sensitive to wind direction. Additionally, VAWTs do not create more turbulence in the air downwind of the turbine, and this disturbance returns to the normal state, unlike in HAWTs [18].

The number of residents living in Bangladesh is 166 million, and by 2041, this number will rise to 189 million [19,20]. This year (2041) is significant for Bangladesh because the country aims to achieve high-income status within that year. Bangladesh must put industrialization first to become a high-income nation, which demands a reliable supply of electricity [21]. However, the electricity demand will be 19,034 MW in 2021 and rise to 82,292 MW in 2041 [22]. Bangladesh should be self-sufficient in energy generation to satisfy this future increase in electricity demand and become a high-income nation [23,24]. As of August 2018, Bangladesh's current energy mix consisted of 64% natural gas, 21% furnace oil, 6% diesel, 5% power imports, 2% hydro, 2% coal, and 0.1% renewable energy. Despite making up most of Bangladesh's energy mix, natural gas reserves will run out by 2028 if new gas fields are not found [25]. Bangladesh's government relies on imported fuel to power its diesel power plants because it has no oil resources. Therefore, relying on imported fuel cannot be considered a suitable method of achieving self-dependency in electricity production. For its coal-fired power plants, Bangladesh also depends on Australia, India, Indonesia, and Mozambique. However, because Bangladesh's bituminous coal reserves are comparably high-quality and will be depleted by 2050, using them rather than importing them is preferable [22]. In addition, a study from the International Energy Agency states that 30% of the CO_2 emissions in the globe come from the generation of energy using coal [26]. Therefore, using coal is against SDG Goals 13 (Climate Actions) and 7 (Affordable and Clean Energy) [27]. Also, Bangladesh needs more suitable places to set up nuclear power plants since it is a densely populated country. However, with the help of Russia, a 2400 MW nuclear power plant has been established in Ruppur, Bangladesh. However, more is needed to meet energy demand by 2041 [22]. Considering these challenges, Bangladesh must focus more on renewable energy, like wind (Table 1).

Table 1. Different studies conducted to determine wind resource potential in Bangladesh.

Projects	Ref.	Location	Duration	Wind Speed (Highest/Average)
Joint study by NREL and USAID	[22]	All of Bangladesh	2014 (June)–2017 (December)	Highest: Offshore and coastal belt, 7.5 ms^{-1} at 120 m
CPGCBL	[28]	Matarbari Island	2017 (February)–2018 (February)	Average speed 5.76 ms^{-1} at 100 m
WERM project by LGED	[22]	20 sites (including seven from WEST)	2003–2006	Wind speed for Kuakata is 4.2 ms^{-1} at 30 m height
FEDI, appointed by NWPGCL	[28]	Kolapara, Patuakhali	2017–2019	Average speed 5.47 ms^{-1} at 120 m height
EGCB	[28]	Sonagazi, Feni	2017 (June)–2018 (September)	Average speed 5.38 ms^{-1} at 100 m
WRAP of BPDB by Pan Asia Power Services Ltd.	[28]	Kuakata, Mognamaghat, Parky beach, and Muhuri Dam	Between 2003 and 2005	Highest wind speed in Kuakata is 6.9 ms^{-1}
BCSIR & IFRD	[22]	Meghnaghat, Saint Martin, and Teknaf	2001 (January)–2002 (April)	Highest wind speed in Saint Martin is 4.7 ms^{-1} at 30 m height.
WEST by BCAS, backed by ETSU of UK and LGED	[28]	Patenga, Char Fasson, Noakhali, Kutubdia, Teknaf, Kuakata, and Cox's Bazar	1995–1997	Highest wind speed in Kuakata is 4.54 ms^{-1} at 25 m height
TERNA by BAEC, Backed by REVB1 of GIZ	[28]	Patenga, Feni, Anwara, and Teknaf	1995–1997	Highest wind speed in Teknaf is 4.3 ms^{-1} at 20 m height

Wind energy has enormous potential in Bangladesh. The country has a coastline of nearly 700 km, with strong and persistent winds. The country's wind energy potential is predicted to be greater than 50 gigawatts (GW). Wind energy growth in Bangladesh is consistent with the country's larger sustainable development objectives (SDGs). SDG 7 seeks widespread availability of reliable, affordable, and modern energy services. SDG 13 calls for swift action to avert climate change and its effects. Wind energy development in Bangladesh is still in its early phases. However, the nation's commitment to the environment and sustainable energy goals could benefit significantly from unlocking the huge potential of wind energy. The government's encouragement of wind energy development is praiseworthy. Bangladesh can fulfil its sustainable development goals while reducing its susceptibility to climate change by investing in wind energy. Several studies have researched the potential of wind energy in Bangladesh. A feasibility study in Chittagong, Bangladesh, claimed vast wind energy potential in Chittagong. For this study, the number of wind turbines required, and their maintenance and operational costs were also determined for their proposed sites [29,30]. Similar observations were also made for Bangladesh's coastal region, as presented in Figure 1. From Figure 1, Kuakata and Kutubdia have significant wind resource potential compared to other locations in Bangladesh. Wind speed seems to be higher from June to August. Amin estimates that, except for natural gas and local coal, the unit cost of electricity for wind is far lower than any other fossil fuel and non-conventional energy sources [31]. Sandwip was found to be an exceptional place for wind energy by Azad et al. after performing numerous Weibull distribution techniques [32]. Patenga was also an attractive place for wind energy [33]. This study measured wind speed at 20 m to obtain to this outcome. Another study used the HOMER model and NASA's SSE wind energy database to generate a wind map [34]. The study also identified the Enercon (E33) 330 kW turbine as the best wind turbine for Bangladesh for harnessing wind energy. A survey conducted jointly by USAID and NREL in 2018 reported that Bangladesh has the potential to generate 30 GW of energy from wind. This proves a promising aspect of wind energy in Bangladesh [35]. The wind resources of different parts of Bangladesh can be found in Figure 2.

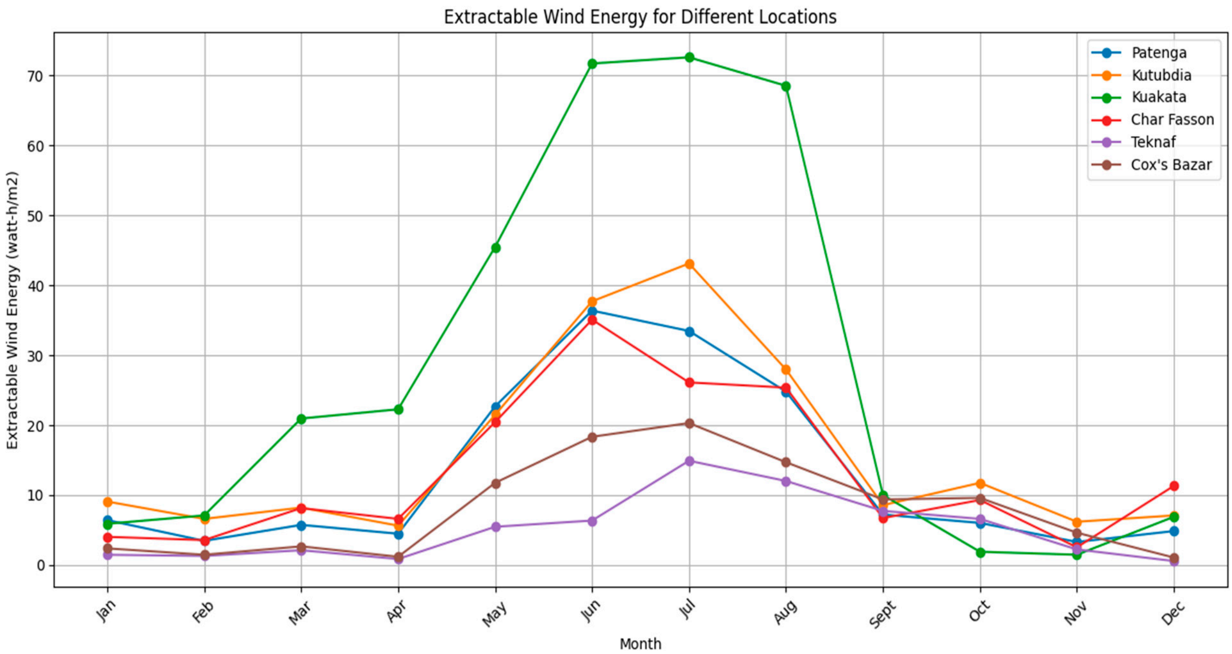

Figure 1. Wind energy resources at 25 m height at different locations in Bangladesh [22].

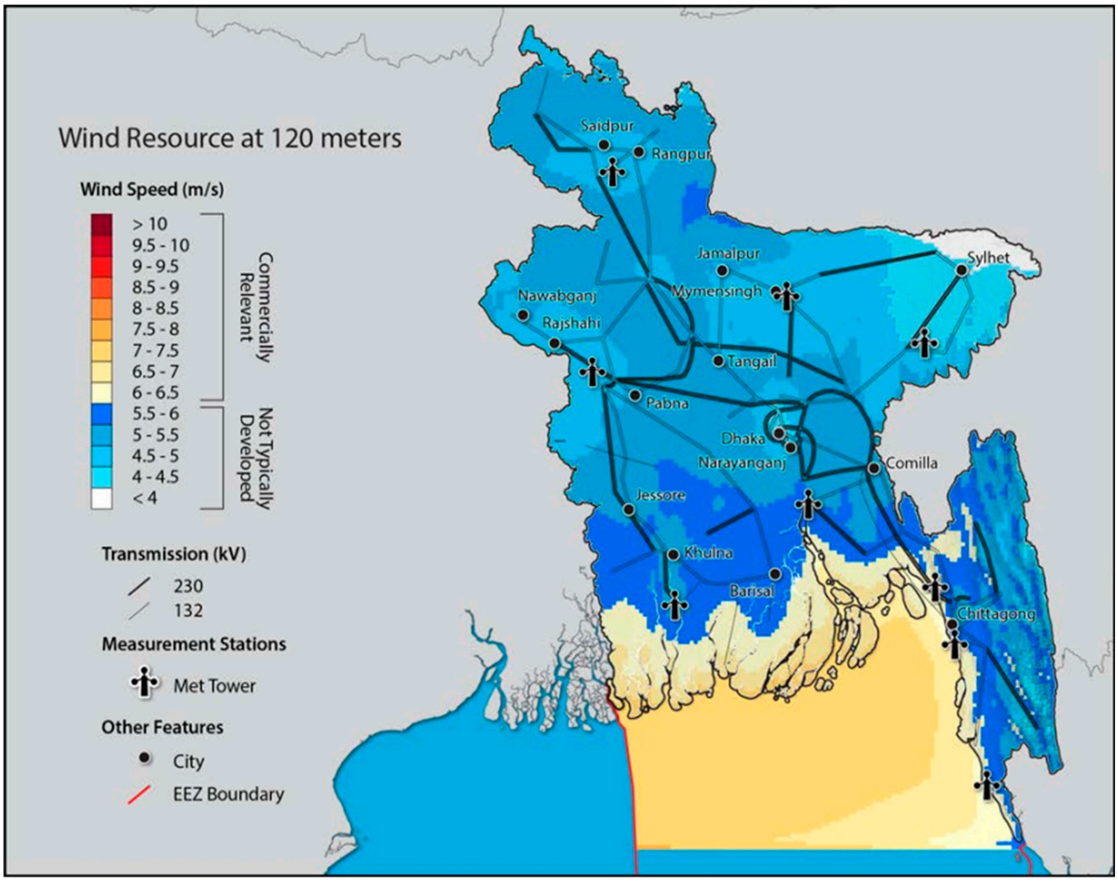

Figure 2. Wind energy potential map in Bangladesh (adapted from reference [22]).

Despite this vast potential, wind energy development is restricted in Bangladesh. From the literature review, it is clear that many studies have explored the feasibility of wind energy in Bangladesh. However, barriers that hinder wind energy development are yet to be identified. Several studies have used the analytic hierarchy (AHP) process to identify many countries' main barriers to renewable energy (RE) development. Pathak et al. used AHP and modified Delphi method to rank barriers to RE technologies in India [36]. In Malawi, Africa, AHP was used to rank the barriers of RE development. In contrast, Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was used to rank the solutions of these barriers [37]. Solangi et al. also took this same approach for Pakistan [38]. Ghimire and Kim used AHP to determine the barriers to RE development in Nepal, while Yadav et al. identified barriers to biogas technology in India using AHP [39,40]. Shahzad et al. found financial and regulatory frameworks as the main barriers to Pakistan using Pythagorean fuzzy AHP [41]. Meanwhile, obstacles to RE adoption in Chile were identified by Nasirov et al. using AHP [42]. This study found that institutional and technological barriers are the main barriers. Table 2 reports similar studies considering the multi-criteria decision analysis (MCDM) approach to rank and prioritize barriers. This study highlights the obstacles relevant to Bangladesh's context and geographic location by reviewing the literature from several studies and reports undertaken in other countries. So, in this analysis, an MCDM method named the analytic hierarchy process (AHP) has been employed to identify the main barriers to wind energy deployment in Bangladesh. An extensive literature review was performed to determine these barriers. Government reports, websites, research, and review articles were used for this literature review.

Table 2. Barrier analysis to RE adoption in various countries using MCDM approach.

Description	Location	Method	Major Barriers	Reference
Identifying barriers to the promotion of RE	Pakistan	Pythagorean fuzzy AHP	Financial and regulatory	[41]
Barriers and solutions of RE development	Pakistan	AHP, Fuzzy TOPSIS	Financial and political	[38]
Prioritizing barriers to RE development	India	AHP, Modified Delphi	Policy and technical	[36]
Prioritizing barriers to offshore wind energy	India	Fuzzy AHP	Financial and technical	[43]
Ranking of barriers to RE development	Nepal	AHP	Political and policy, economic	[39]
Prioritization of strategies to remove obstacles to RE development and adoption	Ghana	CRITIC, Fuzzy TOPSIS	Technical and financial	[44]
Obstacle analysis of solar PV adoption	Iran	Fuzzy AHP, Fuzzy TOPSIS	Economic and organization	[45]
Barrier determination of solar PV development	Iran	Fuzzy BWM	Support and economic	[46]
Prioritizing barriers to smart energy cities	Turkey	Fuzzy Z-numbers, DEMATEL, cognitive mapping	Economic and policy	[47]
Barriers to RE adoption and development	Chile	AHP	Institutional and technological	[42]
Evaluating obstacles to and solutions for implementing sustainable and green practices	Yemen	Fuzzy AHP, Fuzzy TOPSIS	Managerial and political	[48]
Analyzing barriers to mini-grid deployment	Myanmar	AHP	Economic and technical	[49]

The novelty of this study lies in the following aspects:

- It is the first study to use the AHP to identify and rank the barriers to wind energy deployment in Bangladesh.
- A comprehensive set of criteria to assess barriers, including technical, administrative, policy and political, economic, social, and geographic barriers, are investigated.
- A detailed analysis of the relationships between the barriers and their impact on wind energy deployment are carried out.

- The study identifies the most significant barriers to wind energy deployment and provides recommendations for overcoming them.

The paper is organized into five sections. Section 2 presents the energy scenario in Bangladesh. The comprehensive methods and approaches are outlined in Section 3. The analysis and evaluation of barriers to wind energy development in Bangladesh are described in Section 4. The discussion is delivered in Section 5. The study ends with a conclusion in Section 5.

2. Energy Scenario in Bangladesh

According to the latest statistics, as of January 2022, Bangladesh produced the highest energy of 13,525 MW, while the total installed capacity was reported to be (as of August 2022) 22,612 MW. The most significant energy came from the private sector (47.39%), followed by the public sector (40.02%) [50]. The rest came from joint ventures. Foreign countries' contribution to Bangladesh's energy consumption was 8.50%. Most electricity (65%) is generated from natural gas (Figure 3). Apart from power generation, natural gas is widely used in industrial, residential, and commercial sectors. However, this percentage came down to 42% due to the shortage of natural gas (Figure 4) [50]. If this continues, the reserve of natural gas will be depleted in the near future. Urgent response is necessary, and shifting to renewable resources is a potential solution to reduce over dependence on natural gas.

In 2021, fossil fuels supplied 99.35% of primary energy. The renewable sources supplied the rest [51]. As a result, huge amounts of CO_2 are released into the atmosphere. In 2021, Bangladesh emitted 99,297.30 kt of CO_2 into the atmosphere [22]. To overcome this problem, the Bangladesh government proposed a new electricity mix plan integrating a large share of renewables (Figure 5). Figure 5 shows that by 2041, Bangladesh plans to obtain 15% of its electricity from sustainable energy sources [22]. For this, Bangladesh will mainly depend on solar and wind energy resources.

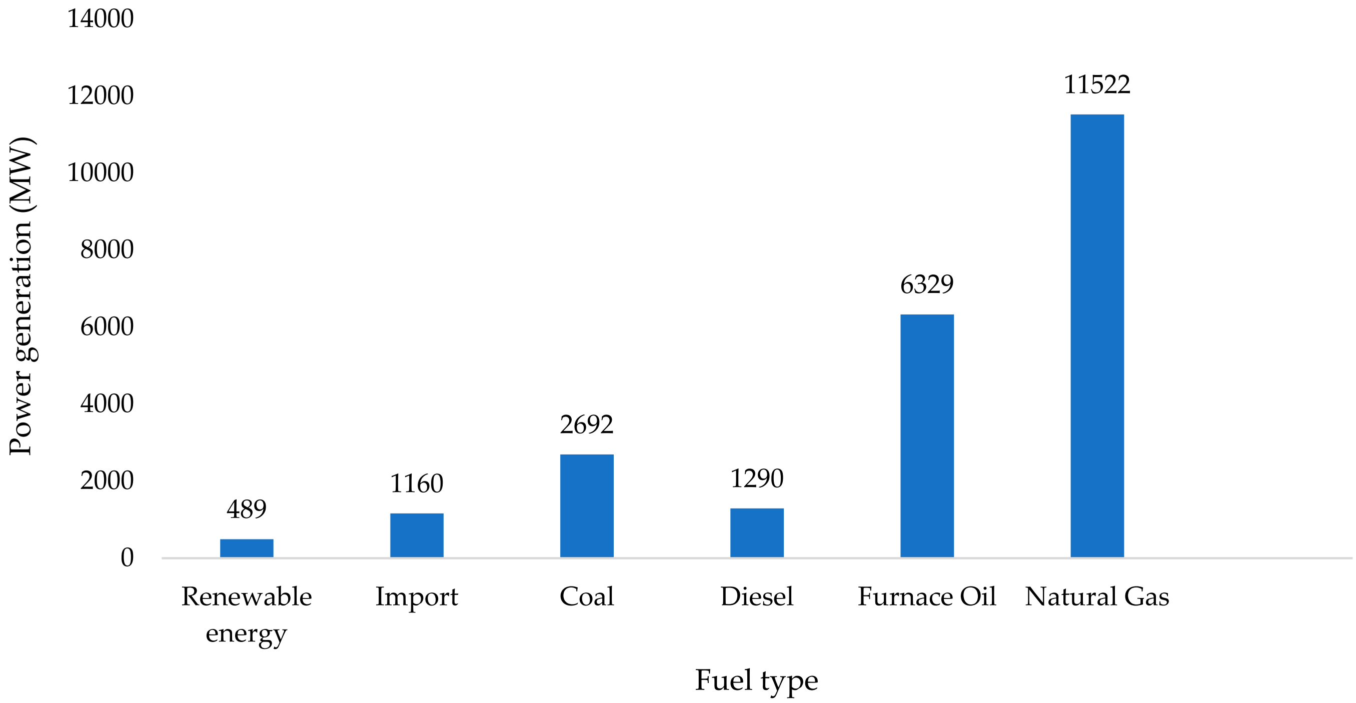

Figure 3. Bangladesh's electricity generation scenario by January 2023 (MW) [52].

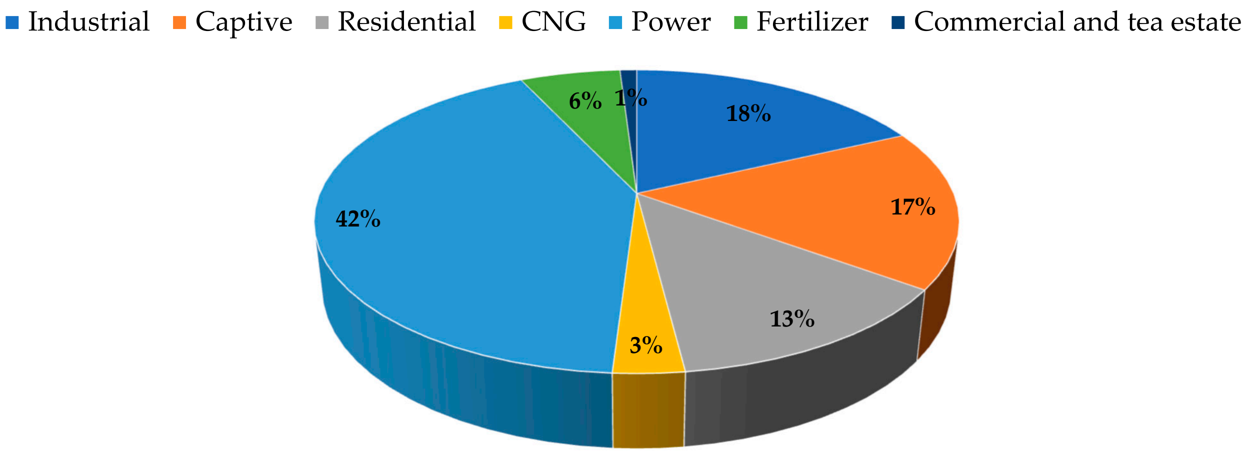

Figure 4. Natural gas contribution in various sectors of Bangladesh [50].

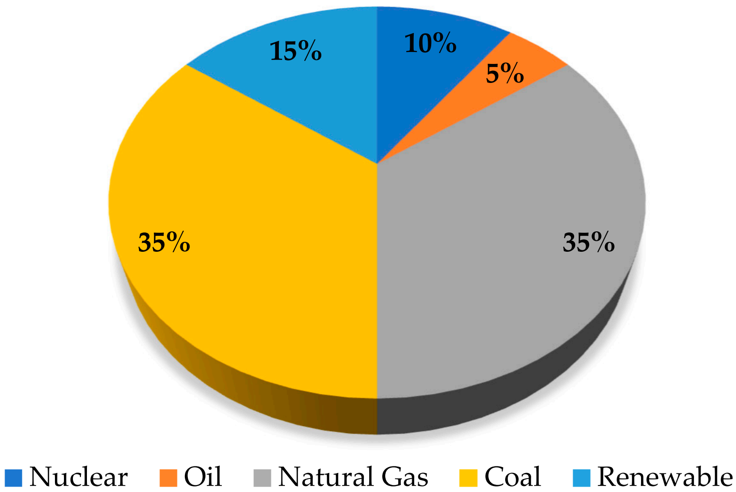

Figure 5. Energy mix considered by Bangladesh government for 2041 [22].

As previously stated, several studies conducted feasibility studies to find the wind resource potential of different parts of Bangladesh. It should be noted that the highest wind speed found in Kuakata by the WEST project conducted in 1995–1997 was 4.54 ms^{-1}. Another survey conducted by the WRAP project in 2003 found a wind speed of 6.9 ms^{-1} for the same location. Since more recent measuring instruments are more precise than older ones, wind readings from current studies are more largely accepted than those from earlier analyses. After analyzing the one-year wind data from the WEST project, Amin calculated the amount of energy that could be extracted from the wind (Figure 1). Table 1 shows how much wind energy can be harvested at 25 m in six potential seashore locations, including Cox's Bazar, Patenga, Kuakata, Teknaf, Char Fashion, and Kutubdia [22,31]. From the table, it is also clear that significant wind energy can be generated between May and August. From the table, it is evident that the highest wind power available is 7.5 ms^{-1} at 120 m in offshore and coastal areas. A joint study by NREL and USAID measured the wind speed at 120 m height and prepared a wind map. The report stated that Bangladesh has more than 20,000 km^2 of land on which to harness wind power. From the wind map (Figure 2), it can be seen that all the coastal areas of Bangladesh fall under the commercially relevant category. All coastal areas have wind speeds between 6.5 and 7 ms^{-1}. Another good thing is that Bangladesh can generate energy from offshore wind (wind velocity 7–7.5 m/s) [35,53]. Wind energy growth in Bangladesh represents a possible path for meeting the country's expanding energy needs while reducing dependency on fossil resources. This transformation, however, has its challenges, obstacles, and concerns.

Due to its dependence on imported fossil fuels, Bangladesh faces energy security issues, making its energy industry vulnerable to international price swings and supply interruptions [54]. Wind energy's intermittent nature adds another layer of complexity to the energy mix, creating concerns about grid stability and energy reliability [55]. Due to conventional infrastructure, wind power integration into existing energy infrastructure is a significant concern. Despite significant advances in wind turbine technology in recent years, a technological gap has developed in Bangladesh's wind energy sector. A lack of access to cutting-edge wind turbines and components can hamper wind farms' efficiency and performance [56]. Furthermore, an absence of regional research and development initiatives in wind energy technology presents obstacles to adapting to local conditions. Wind energy is frequently produced in remote or rural places, demanding significant changes to the electrical system and infrastructure to deliver power to urban centers [56]. This poses logistical and financial issues for the government and energy authorities, who must ensure that wind energy is efficiently delivered and distributed. Bangladesh's regulatory system for renewable energy, particularly wind power, has progressed but still confronts challenges. Inconsistencies in policy, insufficient incentives, and lengthy approval processes might deter investors and project developers [57]. A robust and stable policy framework is critical for attracting private investment and creating a favorable environment for wind energy growth.

It is critical to balance the benefits of renewable energy with environmental concerns. Wind farms may have environmental consequences like bird and bat collisions, noise pollution, and aesthetics changes to the area. Furthermore, procuring land for wind farm installations might be difficult due to conflicting land-use needs for agriculture and other reasons. Financing appropriate wind energy projects remains a serious concern [55]. Wind farms' high upfront capital expenditures and concerns about the return on investment can deter potential investors. This hurdle can be overcome by developing novel finance sources and connecting with international organizations. Wind energy initiatives require public knowledge and social acceptance to succeed. A lack of understanding of the benefits of wind energy and worries about visual impact or interruptions to residents can contribute to opposition. To address these problems, effective community participation and education programs are required. With its vulnerability to sea-level rise and extreme weather events, climate change poses a considerable threat to Bangladesh. Wind energy can help to reduce greenhouse gas emissions, but its long-term impact on climate change mitigation must be carefully assessed. Bangladesh can benefit from international cooperation and partnerships to overcome these difficulties. Collaborative activities can facilitate the development of the wind energy sector by providing access to technology transfer, financial support, and expertise [54].

Analyzing wind energy barriers in Bangladesh with the Analytic Hierarchy Process (AHP) demonstrates an effective tool for dealing with complicated decision-making processes. To begin, AHP allows for the identification of critical aspects influencing wind energy projects, such as environmental effects, economic feasibility, and societal acceptance. This organized method supports stakeholders in assessing the multifaceted nature of wind energy development. Furthermore, AHP supports prioritizing various aspects, allowing decision-makers to consider them in order of priority. In the context of Bangladesh, where land-use conflicts and environmental issues abound, AHP can assist in determining which criterion should be prioritized when designing wind energy projects. This guarantees that resources are used wisely, and the most pressing concerns are addressed [58]. AHP also makes it possible to reduce the negative repercussions of wind energy growth in Bangladesh. AHP promotes transparency and consensus-building by incorporating many stakeholders in decision making, such as local communities and environmental organizations. Furthermore, it aids in evaluating alternative solutions and mitigation methods, ensuring that wind energy development is consistent with sustainable practices and the country's energy goals [59]. Applying AHP to detect and reduce wind energy development in Bangladesh provides a methodical and comprehensive strategy. It enables decision-makers to make educated choices, prioritize essential aspects, and effectively involve stakeholders, ultimately contributing to the country's wind energy sector's long-term success.

3. Methods

3.1. Analysis of Different Barriers to Wind Energy Deployment in Bangladesh

An extensive literature review was performed to identify the main barriers to wind energy deployment in Bangladesh. Science Direct, PubMed, Google Scholar, and Scopus databases were used. Identified barriers are mainly classified as technical, administrative, policy and political, economic, social, and geographic.

3.1.1. Social Barriers (SB)

Social barriers are generally linked to social acceptance while implementing wind energy projects. Three social obstacles were found in Bangladesh after the literature review.

Inadequate Awareness among Consumers (SB1)

Despite being expensive, wind energy offers several benefits, including environmental friendliness and natural replenishment [60]. Unfortunately, many consumers do not have sufficient knowledge of how wind energy operates or works. They often underestimate the contribution of wind energy in fighting climate change and promoting a green future. People need to be made aware of the existence or benefits of wind energy technologies. People in Bangladesh do not have access to information about them [61]. Therefore, more widely disseminated knowledge may boost people's desire to use wind energy sources.

Customers' Inability to Spend (SB2)

Wind energy often needs upfront investments, and for many people, the price of purchasing and installing wind turbines and potential grid connectivity costs can be a major barrier. In countries like Bangladesh, where it is considered that wind energy technologies will be implemented in rural and distant locations, the local people have few other means of income [61]. As a result, many people need help to afford wind energy options.

Absence of Knowledge (SB3)

Due to a lack of knowledge, consumers might lose out on cost-saving options and opportunities to curtail their carbon footprint. Additionally, this lack of information might lead to misunderstandings and doubts regarding the dependability and effectiveness of wind energy installations. It is crucial that public organizations, industries, and financial institutions need to know the diverse potential of wind technologies sufficiently. Without this knowledge, proper policies will not be developed. As a result, investors might feel hesitant to invest in the project [62].

3.1.2. Geographic Barrier (GB)

Due to the highly hilly regions, Bangladesh is facing several problems in implementing wind energy projects, and these problems are given below.

Transportation (GB1)

Wind turbines are often concentrated in rural places with restricted road access for transportation. Furthermore, wind turbine components, like blades, nacelles, and towers, are heavy and big. Transporting these components sometimes requires special permits from relevant authorities. Roads and bridges might need to be strengthened or widened to acclimatize the size and weight of these components. As a result, project prices and completion times are increased [63,64].

Disorganized Households (GB2)

Households are scattered in Bangladesh due to the country's geographic layout. A significant investment is needed to set up and maintain the infrastructure, like transformers and transmission lines. The requirement for voltage regulation and servicing in faraway regions and the continual expansion of the distribution network to meet population growth further increase this expenditure. Owing to this, it becomes expensive to distribute the generated power [64,65].

Land-Use Conflicts (GB3)

Suitable land identification for wind energy implementation is essential for developing this technology. Since Bangladesh is a densely populated country, the available land resources can be considered for agricultural or urbanization purposes. Also, due to the visual impact and potential noise generation, local communities may hesitate about wind projects. Local communities may also hesitate if there is consideration of wind energy development projects in places with significant cultural significance preservation and heritage preservation efforts. As a result, conflicts may arise between local communities and the government about the suitable use of available land [66].

3.1.3. Policy and Political Barriers (PBs)

Political and policy barriers (PBs) define a country's solidity of political and policy cycles. The government develops guidelines based on a supply-side standpoint. PBs can affect wind energy development in a country. According to a literature review, three barriers exist in Bangladesh.

Inadequately Transparent Decision-Making Process (PB1)

Stakeholders want transparent decision-making mechanisms for wind energy development. This results from the need for open decision-making processes when disseminating information to stakeholders, consistent consultations prior to decisions, and the lack of communication to be addressed [55]. To effectively assess risks and profits, stakeholders require a stable and predictable regulatory environment. The regulatory environment and approval delays may need clarification as unclear decision-making procedures deter investment.

Less Emphasis on Wind (PB2)

Due to its unpredictable nature, wind energy is not considered a practical option at the policy-making stage. The decision to upgrade the existing grid network to incorporate intermittent wind has been hampered by an absence of prioritization, eventually reducing the penetration level [54]. Also, due to the lower priority on wind energy, responsible authorities may allot fewer resources (in terms of both workforce and funding) to assist the growth of this sector. This will lead to slower development of a project, fewer incentives, and limited research and development actions.

Corruption (PB3)

Many developing countries need help executing projects due to corruption in this sector. Bribes need to be provided to complete the project, which, as a result, disheartens stakeholders from discussing social issues regarding projects with the government [67].

Due to corruption and based on self-interest, many regulators and policymakers might choose specific projects or businesses over others, which can result in inadequate usage of resources and hinder the implementation of cost-effective wind energy projects that benefit the environment.

3.1.4. Technical Barrier (TB)

Compared to developed countries, wind energy is relatively new in developing nations. There is a lack of technical resources for research and development (R&D) activities in developing countries. So, developing countries like Bangladesh need to rely on technology transfer from rich and developed countries.

Lack of Research and Development (R&D) (TB1)

R&D is needed to reduce costs and solve technical issues. It is also necessary to make the wind energy more competitive with conventional fuels. With R&D funding, nations or regions can avoid being left behind in the worldwide market for wind energy. Without R&D, these nations may be at a competitive disadvantage compared to regions producing cutting-edge wind energy solutions. R&D is also needed to solve many problems like the intermittency of wind energy. But the practice of R&D is limited in Bangladesh due to constraints in financial and human resources [68].

Unpredictable Supply (TB2)

Renewable energy technologies are less reliable than conventional energy sources [69]. Also, supply and demand must be balanced for electricity systems to remain dependable and stable. The unpredictable nature of wind energy can make it difficult to balance supply and demand, particularly when wind conditions change quickly.

For example, the generation of power fluctuates due to changing wind conditions [54,70,71]. When the share of wind power is increased, the power system faces electrochemical oscillations and frequency deviations [72–74]. This problem can be amplified during storms as the wind speed constantly fluctuates [75,76].

Risks Associated with Technology (TB3)

Risk plays a significant role in the development of any project (including wind) [77]. Wind turbines can face several problems, like gearbox failure, DC offset, control blade integrity, tracking, and wear and tear due to exposure in harsh environments [75,78]. But wind projects are generally located in remote places without a skilled labor force. As a result, maintenance and repair work becomes delayed. Due to these technical uncertainties, private companies often prefer to invest in something other than wind energy projects [79].

3.1.5. Economic Barriers (EBs)

EBs play an essential role in the development of wind energy projects. The lack of funds and limited market potential for wind is the primary concern in wind energy deployment. Three EB were identified after literature review.

High Capital Cost (EB1)

The first significant economic barrier to renewable energy development is the high capital cost [80–84]. The cost of energy generation is relatively higher for wind energy than other conventional energy sources because wind energy technology is comparatively new in developing countries [85]. Limited funding can force project delays, resulting in failed chances to produce energy and advance renewable energy goals. Also, high capital costs make attracting and securing favorable investments challenging.

Subsidy to Fossil Fuels (EB2)

Subsidies to conventional fuels make fossil fuels cheaper than wind energy. As a result, wind energy cannot compete with conventional sources [86]. This will slow down the growth of wind energy and can discourage potential developers and investors from investing in it. Also, subsidies to fossil fuels can make people believe that these conventional forms of energy are necessary and dependable, thus undermining public support for wind energy.

Small Market Size (EB3)

The market size has a significant influence on investment. There needs to be more markets for wind energy in Bangladesh. Due to this, the private sector feels more interested in investing in something other than wind energy [55]. Also, without more market opportunities, there will be less demand for this technology. As a result, the price will not go down, eventually causing higher prices for equipment and installation. In addition, a smaller market size means there is limited revenue potential compared to investment costs. Investors and developers often look for a large market to maximize project returns.

3.1.6. Administrative Barriers (ABs)

More than policy is needed to ensure the efficient delivery of government services. An effectual administrative system is critical for reaching the development target. Three ABs were observed after the literature review for Bangladesh.

Absence of Competent Workforce (AB1)

Wind turbines are generally located in rural places with a need for more skilled human resources [87]. The project will be completed with skilled workers, and the completed tasks may be up to the standard. Moreover, with a skilled workforce, the project may be completed without any safety incidents. When there is a shortage of professional labor, the cost of acquiring and keeping qualified personnel can climb dramatically, which can raise the entire cost of wind energy projects.

Absence of Effective Coordination (AB2)

The same task may occasionally be performed by different government agencies or other development organizations; this is known as work duplication or work area overlap. The permitting procedure of wind energy projects involves different organizations, which delays project implementation. Therefore, effective coordination is the key to achieving development in this sector [88]. Engaging and addressing the public's concerns regarding land use conflicts and other issues is also necessary, and failure to effectively coordinate can lead to public opposition.

Inadequate or Absence of Clear Regulations, Standards, and Policies (AB3)

Clear and supportive regulatory frameworks are crucial to offer direction, ensure stability, and lure investment into the wind energy sector. When there is an absence or lack of regulatory framework, developers need more precise direction on navigating the legal and regulatory prerequisites. Also, without technical, economic, or environmental standards, developers may not know if their project meets the required criteria [89]. This can cause delays in the project's implementation. The barriers and sub-barriers identified in this study can be found in Figure 6.

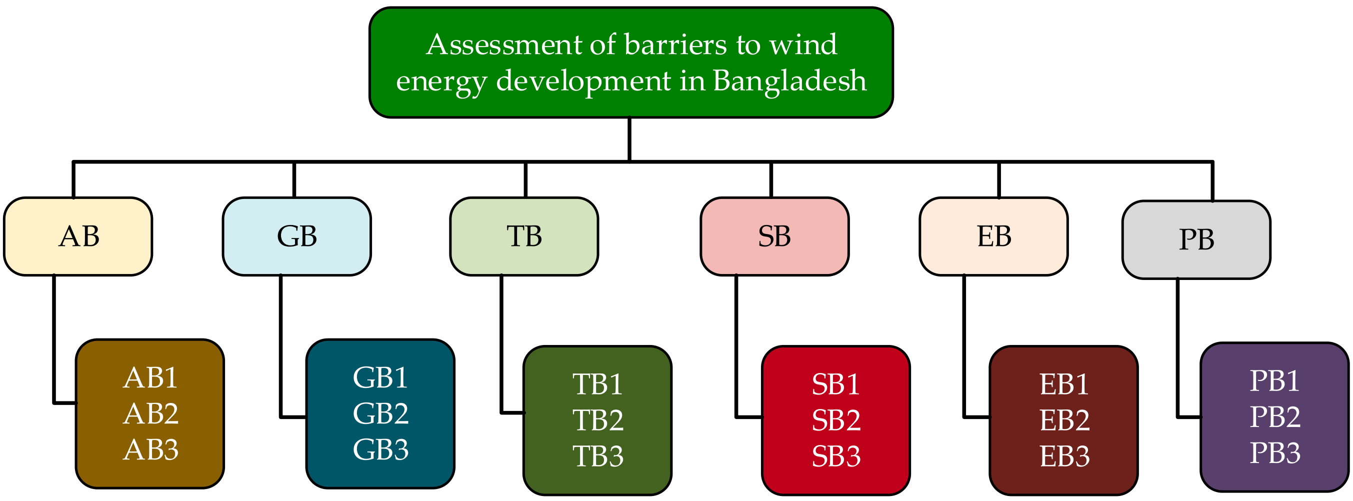

Figure 6. Barriers and sub-barriers identified in this study.

3.2. Analytic Hierarchy Process (AHP)

In decision-making problems, AHP is widely used to facilitate complex problems by decomposing them into a hierarchical framework [90]. At the beginning of the AHP analysis, the research goal stands at the top of the hierarchy, followed by the criteria and sub-criteria. The decision alternatives are put at the last level, and a pairwise comparison is performed at each step or level. Our analysis aims to identify the barriers and sub-barriers of wind energy development in Bangladesh. A literature review was conducted to identify these barriers. After that, a questionnaire was sent to experts to obtain their opinions on these barriers. Experts have to meet the minimum educational requirement of a master's degree. Respondents or experts are chosen from various fields, such as academics, engineers, etc. Their argument is based on Satty's fundamental scale, which is used to perform pairwise comparisons [91]. The scale is given in Table 3.

Table 3. Satty's fundamental scale for pairwise comparison matrix [92].

Importance Intensity	Meaning
1	Equal importance
2, 4, 6, 8	Midway values
3	Moderate importance
5	Strong importance
7	Extreme importance
9	Extremely more important

Here, a score of 1 shows that both activities contribute equally to the overall objective, while a score of 9 suggests that one activity is intensely preferred. The consistency ratio (CR) is calculated to evaluate the consistency of the outcomes. The CR is the ratio between the consistency index (CI) and random index (RI). The RI values for up to ten criteria can be found in Table 4.

Table 4. RI values for up to ten criteria [36].

Criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.40	1.49

In AHP, a CR up to 0.1 is acceptable. The optimal CR value is 0 [38]. The necessary equations to find the CR can be found below [39].

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

where λ_{max} is the eigenvalue of each matrix and n is the number of criteria. Details regarding the AHP can be found in [40,91]. Similarly, the above procedures are followed and executed for the sub-barriers. The flowchart of the adopted methodology can be found in Figure 7.

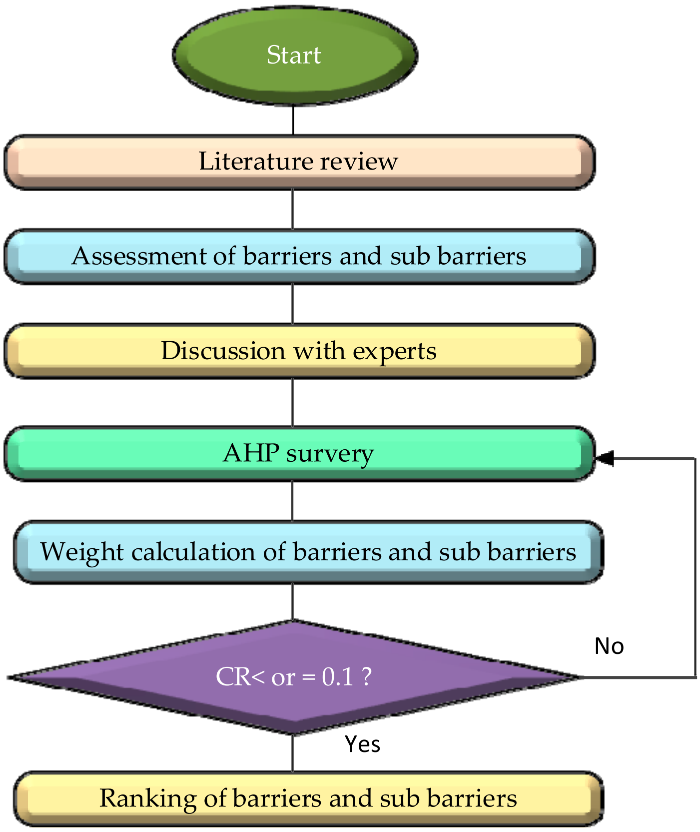

Figure 7. Flowchart of the applied method in this study.

4. Results and Discussion

4.1. Ranking of Barriers

First, a pairwise comparison matrix is created to determine the main barrier, which can be found in the table. Expert opinions have been used to create the matrix. Then, AHP was used to determine the weight. After completing the pairwise comparison, normalization was carried out. After that, the eigenvalue and consistency ratio were calculated. A pairwise comparison of the main barriers can be found in Table 5.

Table 5. Pairwise comparison of the main barriers.

Barriers	EB	PB	SC	GB	AB	TB
EB	1	3	4	5	0.5	0.25
PB	0.33	1	3	4	0.25	0.2
SB	0.25	0.33	1	2	0.25	0.2
GB	0.2	0.25	0.5	1	0.2	0.11
AB	2	4	4	5	1	0.25
TB	4	5	5	9	4	1

From the table, it can be seen that all the diagonal values (from top left to bottom right) are one. This means that each criterion or barrier has equal importance to itself. Also, according to experts, policy barriers are three times more influential than social barriers. Similar analyses can also be conducted for other barriers. Table 6 denotes the priority weight calculations of barriers using the AHP. Barriers are ranked according to the calculated weight, and TB stands at the top, followed by AB. The CR is found to be 0.06, which is less than 0.1. This proves that the data are consistent. Chisale and Lee determined the renewable energy adoption barriers for Malawi of Africa and found that economic barriers are the most significant [37]. The same outcome was also observed for Nepal and Pakistan [38,39]. These studies found that political and economic barriers are the top two barriers hindering renewable energy (RE) technology adoption. However, Al Asbahi et al. ranked political and technical barriers as the highest barriers for Yemen decreasing the growth of RE adoption [48]. Pathak et al. also used MCDM analysis to find that policy and technical barriers play a crucial role in renewable energy adoption in India [36].

Table 6. Ranking of main barriers.

Barriers	Priority Weight	Rank
EB	0.16	3
PB	0.09	4
SB	0.05	5
GB	0.03	6
AB	0.21	2
TB	0.46	1

4.2. Ranking of Sub-Barriers

Figure 8 states the local weights of sub-barriers. Considering the technical category, it is found that TB3 (risk associated with technology) stands in first compared to TB2 and TB1. TB3 is 167% higher than TB1 and 43% higher than TB2. Similarly, for economic barriers, EB1 has the highest weight (0.64), followed by EB2 (0.26) and EB3 (0.1). The consistency ratio for all sub-barriers was also found to be consistent. PB3 > PB2 > PB1 is observed among political sub-barriers, while SB2 > SB1 > SB3 is found for social barriers. For social and geographical sub-barriers, SB3 > SB2 > SB1 and GB1 > GB3 > GB2 are observed, respectively. The overall ranking of the eighteen sub-barriers can be found in Table 7. The global weight of these sub-barriers can be found after multiplying the weight with the local weights.

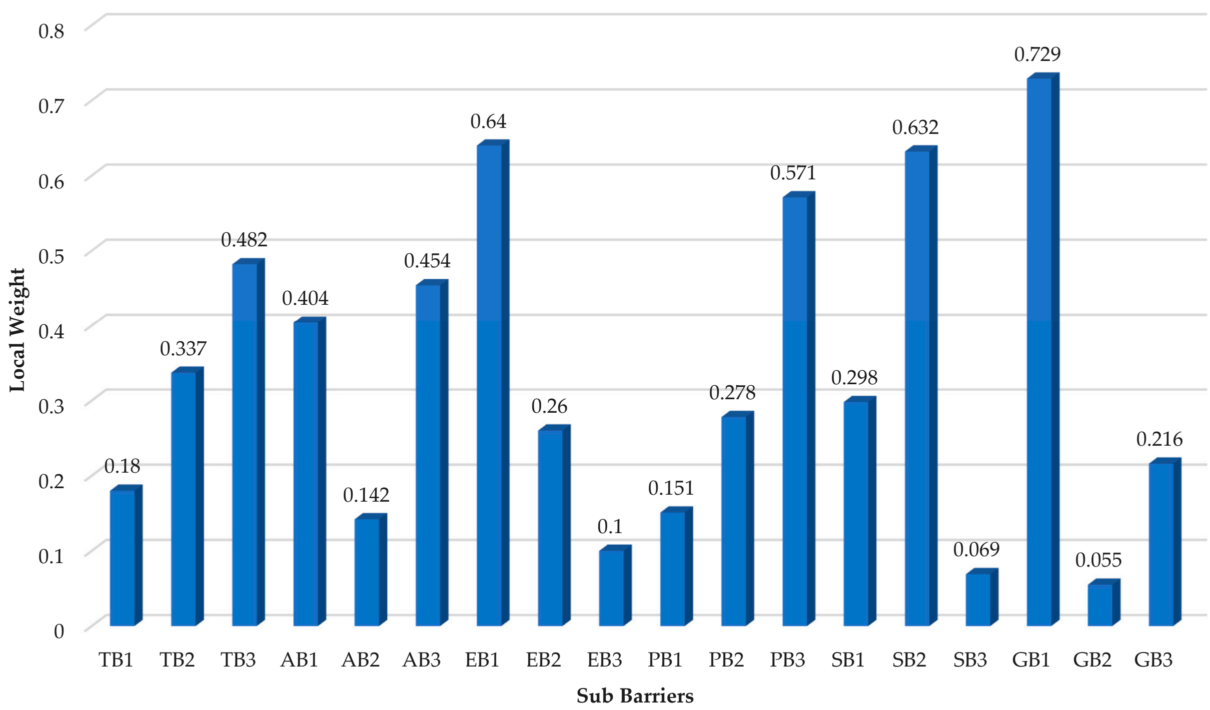

Figure 8. Local weights of sub-barriers.

Table 7. Overall ranking of eighteen sub-barriers.

Barriers	Sub-Barriers	Code	Weight	Local Weight	Global Weight	Ranking
Technical (TB)	Lack of R&D	TB1		0.18	0.0828	6
	Unpredictable supply	TB2	0.46	0.337	0.1550	2
	Risks associated with technology	TB3		0.482	0.2217	1
Administrative (AB)	Absence of competent workforce	AB1		0.404	0.0848	5
	Absence of effective coordination	AB2	0.21	0.142	0.0298	10
	Inadequate or absence of clear regulations, standards, and policies	AB3		0.454	0.0953	4
Economic	High capital cost	EB1		0.64	0.1024	3
	Subsidy to fossil fuels	EB2	0.16	0.26	0.0416	8
	Small market size	EB3		0.1	0.016	13
Policy and political barriers (PB)	Inadequately transparent decision-making process	PB1		0.151	0.0135	15
	Less emphasis on wind	PB2	0.09	0.278	0.0250	11
	Corruption	PB3		0.571	0.0513	7
Social barriers (SB)	Inadequate awareness among consumers	SB1		0.298	0.0149	14
	Customers' inability to spend	SB2	0.05	0.632	0.0316	9
	Absence of Knowledge	SB3		0.069	0.00345	17
Geographic barrier (GB)	Transportation	GB1		0.729	0.0218	12
	Disorganized households	GB2	0.03	0.055	0.00165	18
	Land-use conflicts	GB3		0.216	0.0064	16

4.3. Discussion

According to experts, the cluster of technological obstacles is what is preventing Bangladesh from developing its wind energy industry. These barriers are formidable walls that prevent the country's expansion and integration of this renewable energy source. Parallel to this, there are administrative barriers that, despite being considerably less overpowering, still significantly add to the difficulties this industry faces. Looking more closely at the technical obstacles, the pervasive uncertainty about the efficiency and dependability of wind energy technology emerges as a glaring problem that looms large. Since most wind turbines are installed in remote or off-grid areas, providing the local community with the necessary knowledge and expertise becomes crucial. This knowledge can be conveyed through focused initiatives that increase awareness and convey crucial understanding. Therefore, it is crucial to set up thorough training facilities that enable people in these communities to comprehend the complexities of wind energy and actively interact with and overcome the obstacles preventing its advancement. In addition to raising knowledge and understanding, integrating wind energy systems with other sustainable technologies like solar, storage, and biogas is an intelligent way to overcome these obstacles [93–96]. The symbiotic combination of resources effectively solves the unpredictable nature that frequently afflicts the energy supply. A more stable and dependable energy infrastructure can be created by connecting these various energy sources, removing many of the technological barriers currently preventing the widespread use of wind energy. Technological complexities frequently cause problems, and wind energy is no exception. The development of straightforward yet efficient algorithms and diagnostic techniques is crucial for resolving these technical difficulties. To address intermittency and improve grid stability, integrating energy storage solutions to make wind energy a more dependable power source can be viable. Some of these technologies are cheap, and their resources are abundant in nature [97]. Another helpful option is to allocate investment in improving the national grid's infrastructure so that renewable energy sources like wind can be integrated. Voltage source grid-connected inverters are often employed to connect the renewable energy system to the utility grid. However, these also have stability issues, such as harmonic and frequency instability [98,99]. Utilizing innovative grid technologies to optimize power distribution, reduce losses, and provide a steady supply while managing the fluctuation of wind energy can be helpful too. Due to the high level of complexity and involvement of many stakeholders in wind projects, risk assessment should also be carefully carried out in the planning stage to tackle all the challenges posed by numerous risks [100]. Businesses investing in R&D for wind energy projects should be incentivized through tax credits and deductions to remove R&D barriers. Different techniques and control algorithms can be used to tackle tracking and DC offset problems [101,102]. By doing this, the challenges posed by difficulties and technical obstacles can be methodically removed, creating an atmosphere better suited to the smooth operation of wind energy systems [78].

Focusing on economic obstacles, these obstacles can seriously limit the development of wind energy projects. An all-encompassing strategy is essential to moving beyond these obstacles. Financial incentives, grants, and loans can be crucial in reducing the financial barriers that frequently turn away potential investors and stakeholders [89,90]. To spread the benefits to disadvantaged groups in society, special attention must also be paid to subsidizing the adoption of wind energy [91]. The shift to wind energy can be driven by redirecting subsidies away from fossil fuels and towards cleaner, more sustainable energy sources like wind. Economic pressures can be lessened, making wind energy a more viable and affordable option for a broader range of people. Government involvement is crucial for creating an atmosphere that will encourage the growth of wind energy. Establishing clear and open wind energy policies that draw stakeholders and offer a planned framework for development is essential to this [90]. To further ensure a streamlined and accelerated road toward wind energy integration, good collaboration between public and private entities is crucial to avoiding obstacles in project planning and execution, as well as high capital costs. The government should promote the usage of wind energy in various sectors, for instance, transportation, heating, or cooling, to create a large market. Geographic barriers are also problematic, especially in a country like Bangladesh with a diversified topography. Two concurrent tactics should be used to address this. First and foremost, training local workers in the relevant skills is crucial. This removes a further barrier by creating local employment possibilities and guaranteeing that technical skills are easily accessible. A robust transportation infrastructure is required to navigate the nation's many terrains to exploit wind energy resources regardless of geographic limitations [89,91]. Comprehensive site assessment and selection should be made to reduce conflicts with other land users. Zoning laws and land-use guidelines should be created to identify locations for the growth of wind energy while safeguarding other land uses. Decentralized wind farms can be considered as a potential solution for disorganized households. The need for extensive transmission lines is reduced since these small farms can feed power directly into the local grid. It is critical to execute a multifaceted strategy to lessen the barriers of inadequate awareness among consumers, customers' financial constraints, and the absence of knowledge. This includes public awareness campaigns to familiarize consumers with wind energy benefits, financial incentives to make wind technology reasonable, and developing user-friendly resources and community engagement measures to improve consumer understanding and faith in wind energy solutions. Unhindered wind energy expansion in Bangladesh requires a coherent and comprehensive strategy to overcome various obstacles. These obstacles can be removed through focused campaigns, education and training programs, regulatory changes, financial incentives, and tactical coordination. Bangladesh's policymakers and stakeholders may play an essential role in boosting wind energy development by making financial incentives available for wind energy projects, streamlining the process for obtaining wind energy venture permits, increasing public understanding of the advantages of wind energy, investing in wind energy technology research and development, and grid expansion and modernization. Thus, a path toward a future powered by wind energy may be identified, encouraging Bangladesh to have a sustainable and prosperous energy environment.

5. Conclusions

Wind energy can help Bangladesh to achieve sustainable development. Although it has several benefits, this technology has yet to be utilized properly in Bangladesh. Several obstacles are responsible for the slow adoption of this technology in Bangladesh. This study determines these barriers and uses AHP to rank them. This research found that uncertainties associated with this technology (0.2217) and unpredictable supply (0.1550) are the main barriers to developing this sector. This research is vital since it systematically identifies challenges and outlines guiding ideas for stakeholders interested in and working on wind energy. Also, this study will give academics and decision-makers a road map for addressing the energy crisis and problems with wind energy in Bangladesh.

There are several limitations in this analysis. The opinions and expertise of the selected experts who took part in the survey significantly impacted the study's conclusions. The number of specialists in the sample may be biased, and their perspectives may not accurately reflect all of the sector's stakeholders. Data accessibility may have been restricted, particularly for some sub-barriers. This could have impacted the accuracy of the AHP analysis for particular factors. The AHP methodology requires subjective judgements in assigning weights and priorities to criteria and sub-criteria. While every attempt was made to assure objectivity and consistency throughout the process, some subjectivity may still occur.

For the future direction of the study, conducting a comprehensive financial analysis to overcome different barriers and expanding the expert panel to include different stakeholder groups can be considered. Moreover, a comparative analysis of various approaches to wind energy development could be conducted in Bangladesh, and other similar socio-economic and environmental contexts could be taken into account to better understand the challenges and opportunities towards sustainable development goals.

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Nomenclature

BAEC	Bangladesh Atomic Energy Commission
BCAS	Bangladesh Center for Advanced Studies
BCSIR	Bangladesh Council for Scientific and Industrial Research
BWM	Best Worst Method
CPGCBL	Coal Power Generation Company of Bangladesh Limited
CRITIC	Criteria Importance through Intercriteria Correlation
DEMATEL	Decision making trial and evaluation laboratory
EGCB	Electricity Generation Company of Bangladesh
ETSU	Energy Technical Support Unit
FEDI	Fujian Electric Power Survey and Design Institute
GIZ	German Agency for International Cooperation
IFRD	Institute of Fuel Research and Development
LGED	Local Government Engineering Department
NWPGCL	Northwest Power Generation Company Limited
NREL	National Renewable Energy Laboratory
TERNA	Technical Expertise for Renewable Application Project
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
USAID	United States Agency for International Development
WERM	Wind Energy Resource Mapping Project
WEST	Wind Energy Study Project
WRAP	Wind Resource Assessment Program

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