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A Resource-Based Assessment of Renewable Energy Potential in Bangladesh: Challenges and Opportunities

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Abstract

The purpose of this study is to evaluate the renewable energy potential in Bangladesh and examine the policies and challenges influencing its adoption. Bangladesh, with its abundant solar, wind, and biomass resources, holds significant promise for renewable energy development. However, the country faces critical challenges, including inadequate infrastructure, policy barriers, and limited financing, which hinder the widespread adoption of renewable energy technologies. In this study, we conducted a comprehensive analysis of the renewable energy landscape, assessing the potential of different renewable sources and evaluating the impact of existing policies. We also identified key barriers that limit progress in this sector, such as high upfront costs, insufficient regulatory frameworks, and technical limitations. Our findings indicate that while renewable energy could play a transformative role in Bangladesh's energy mix, contributing to energy security and reducing dependence on fossil fuels, substantial policy reforms and investments are needed to fully harness this potential. The study highlights the need for integrated strategies that address technological, financial, and regulatory challenges to promote sustainable energy development. Ultimately, this study underscores the importance of renewable energy as a critical component of Bangladesh's transition to a low-carbon economy, offering pathways for both economic growth and environmental sustainability. The insights provided in this study can serve as a guide for policymakers and stakeholders in shaping a more resilient and sustainable energy future

for Bangladesh.

Subject Areas

Environmental Sciences

Keywords

Energy, Renewable Energy, Policies, Energy Security, Sustainable Development

1. Introduction

Renewable energy has gained significant global attention due to its potential to mitigate climate change and reduce carbon emissions. Bangladesh, like many other countries, faces energy-related challenges, including a shortage of electricity, heavy dependence on non-renewable energy, and increasing demand for electricity. In recent years, Bangladesh has taken steps to promote renewable energy, with a government target to generate 10% of electricity from renewable sources by 2021 [1], later revised to 20% by 2025, showing the importance of renewable energy. Investing in renewable energy could meet rising energy demand, create jobs, reduce energy poverty, and improve energy security. Although Bangladesh has traditionally relied on fossil fuels [2], there has been a significant shift toward renewable energy, driven by sustainable development goals. Hydro, solar, wind, and biomass are ideal renewable sources for Bangladesh, thanks to its abundant sunshine, wind speed, rivers, and biomass feedstock. The focus on renewable energy stems from its environmental benefits and long-term sustainability. In rural areas with limited electricity access, renewable energy is a promising solution for bridging the energy gap. Given the challenges of climate change and resource depletion, investing in clean energy is critical. The growing demand for sustainable energy makes renewable sources vital [3]. Bangladesh has implemented policies to promote renewable energy, emphasizing its role in contributing to sustainable energy systems [4]. This study evaluates the status of renewable energy in Bangladesh, explores its potential as a sustainable energy source, and outlines steps needed to achieve it. It aims to analyze policies, identify opportunities and challenges, and underscore the importance of renewable energy in Bangladesh's sustainable development strategy. The research objectives of this study are as follows:

- Analyzing the status of renewable energy in Bangladesh.
- Assessing the potential and scope of renewable energy in Bangladesh.
- Examining existing policies and regulations to promote the use of renewable energy.
- Identifying challenges faced by the renewable energy sector for enhancing the uptake of renewable energy technologies.

The scope of this study is limited to the renewable energy sector in Bangladesh, focusing on solar, wind, biogas, and hydro, as these are the most promising renewable energy sources in the country. It will also consider the social, economic, and environmental implications of promoting renewable energy and the challenges towards achieving its sustainable and widespread adoption. The global energy landscape is undergoing a transformation, with the increasing focus on renewable energy to address climate change and energy security. Bangladesh, as a developing country, is striving to harness its renewable energy potential to meet growing electricity demand and reduce dependence on fossil fuels [5]. Several studies have examined renewable energy prospects and government policy in Bangladesh. Masud *et al.* [6] provide a comprehensive overview of the state of renewable energy and its potential for growth, highlighting Bangladesh's progress in adopting solar and wind power to meet energy demands and reduce fossil fuel reliance. They also discuss challenges like policy barriers and financial constraints, concluding with recommendations for policymakers to further promote renewable energy. Karim *et al.* [7] assess the current legal and policy framework, highlighting renewable energy's importance for sustainable growth while identifying gaps and challenges in existing laws. Their evaluation offers insights and recommendations to enhance the effectiveness of renewable energy initiatives in Bangladesh. Abdullah-Al-Mahbub and Islam [8] analyze the state of renewable energy in Bangladesh and compare it to global trends. They highlight the significant progress made in adopting solar and wind energy and discuss challenges like policy gaps and financial constraints, offering valuable insights for policymakers. Mojumder *et al.* [9] study the potential and obstacles of renewable energy-based microgrids in Bangladesh, reviewing technologies, policy frameworks, and socio-economic factors influencing microgrid adoption. They highlight the potential of solar, wind, and biomass to address rural energy needs, while discussing challenges such as financing, technical limitations, and regulatory barriers.

In a nutshell, existing studies suggest that renewable energy presents a viable solution to Bangladesh's energy challenges as Bangladesh is facing challenges to meet the demand of energy relying on fossil fuels. These studies also indicate that renewable energy has the potential to significantly contribute to the energy mix in Bangladesh and address the country's energy-related challenges. Analysis of the existing governmental policies indicate a positive climate towards renewable energy, providing a solid foundation for future development in this sector. However, a need for further research, inspection and improvement in this area is essential, to identify appropriate measures that can optimally enhance the deployment and mainstream usage of renewable energy sources, thereby promoting the accessibility of clean and sustainable energy to the people and advancing the country's sustainable development. In this study, we present detailed scrutiny of the prospect of renewable energy. This study has the following contributions:

- Evaluation of the potential and efficiency of different renewable energy sources.
- Estimating renewable energy potential based on geographical and technical factors from available renewable energy resources.

- Assessment of potential of hybrid renewable energy system in Bangladesh based on available renewable energy resources.

2. Methodology

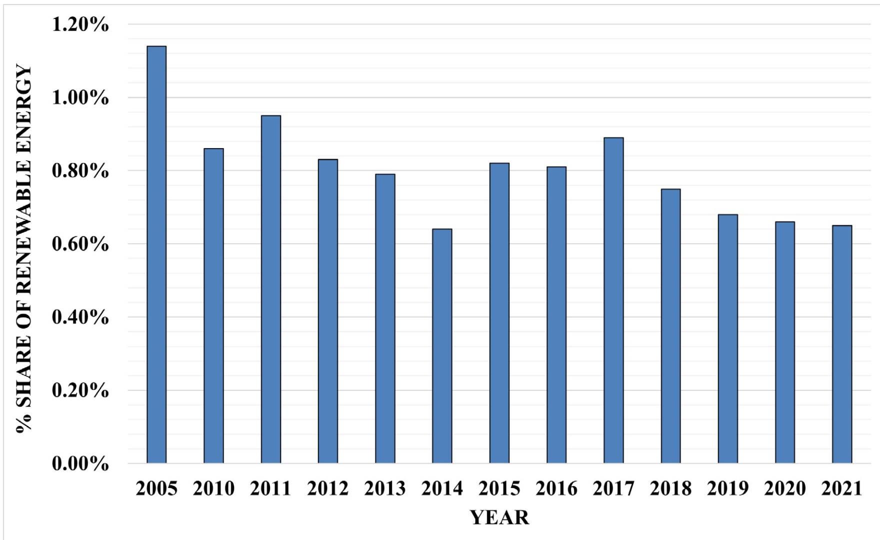
2.1. Current Energy Status in Bangladesh

Bangladesh has been striving to meet its growing energy demands while ensuring sustainable development. The energy mix in Bangladesh primarily consists of natural gas, coal, oil, and renewable energy sources [10]. **Table 1** provides an overview of energy generation from different sectors from 2012 to 2022 [11]. From **Table 1**, it is clear that in recent years, the country has made significant progress in diversifying its energy mix, reducing dependence on fossil fuels, and embracing renewable energy sources. Natural gas is the dominant source of energy in the country, accounting for approximately more than 55% of the total primary energy supply [12]. It is mainly used for power generation and industrial purposes. Bangladesh has limited natural gas reserves and has been actively exploring new fields to meet its growing energy demand. Coal is another important component of the energy mix, contributing around 5% to the total primary energy supply [13]. The country has limited domestic coal reserves but imports coal from countries like Indonesia and Australia [14]. Coal-fired power plants such as Rampal, Payra, Matrbari are being developed to diversify energy sources and reduce dependency on natural gas. Oil plays a minor role in Bangladesh's energy mix, accounting for less than 10% of the total primary energy supply. It is primarily used in the transportation and industrial sectors.

Table 1. Energy generation transition from 2012 to 2022 [11].

Energy	2012-13		2015-16		2021-22	
	Energy Generation (GWh)	% Contribution	Energy Generation (GWh)	% Contribution	Energy Generation (GWh)	% Contribution
Gas	28,119	77.08	35,822	68.63	47,136	55.06
Hydro	894	2.45	962	1.86	744	0.87
Coal	1156	3.17	847	1.62	5342	6.24
Furnace oil	5568	15.26	8673	16.67	22,867	26.71
Diesel	745	2.04	2067	3.96	1483	1.73
Renewable energy	-	-	-	-	323	0.38
Power import	-	-	3822	7.32	7712	9.01
Total	36,482 GWh		52,193 GWh		85,607 MKWh	

Bangladesh's energy mix showcases a commitment to sustainable development, yet the country faces challenges in meeting rising electricity demand, which is approximately 11,000 megawatts (MW) [15]. While the installed capacity is around 20,000 MW and can peak at 24,000 MW [16], factors like insufficient infrastructure, maintenance issues, and low fuel supply hinder progress [17]. **Figure 1(a)** indicates a decline in renewable energy's share since 2000, as reported by the World Bank [18]. The most significant decrease occurred between 2000 and 2005, dropping from 188% to 1.14%. From 2005 to 2010, the decline slowed from 1.14% to 0.86%. Between 2011 and 2019, the share fluctuated between 0.68% and 0.95%, with a further drop to 0.66% in 2020 and 0.65% in 2021. This trend shows an increasing reliance on non-renewable sources, as renewable production has not kept pace with electricity demand. Currently, renewable energy constitutes about 2-3% of total electricity generation, with sources including solar, wind, biomass, and hydropower. **Table 2** illustrates the progress in renewable energy, highlighting that solar power leads with an installed capacity of 960.01 MW. Hydropower follows with 230 MW, while wind energy contributes a mere 2.9 MW. Biogas and biomass to electricity have capacities of 0.69 MW and 0.4 MW, respectively. **Table 2**



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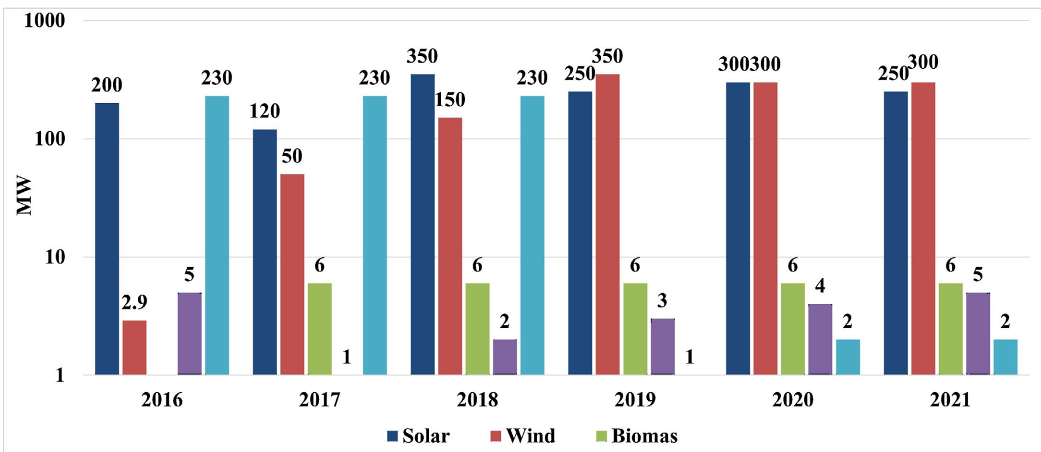

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Figure 1. (a) Percentage share of renewable energy to the country's total energy; (b) Year-wise targeted plan of Renewable Energy from 2016 to 2021 [25].

Table 2. Renewable energy generation [19].

Technology	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	365.68	594.33	960.01
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.69	0	0.69
Biomass to Electricity	0.4	0	0.4
Total	368.77	825.23	1194

underscores the need for further investment to decrease dependence on non-renewable sources [19].

2.2. Policies and Regulation to Promote the Use of Renewable Energy

The government of Bangladesh has implemented several initiatives and policies to promote the use of renewable energy and reduce dependence on fossil fuels. The Renewable Energy Policy 2008 is the primary policy framework promoting renewable energy in Bangladesh [20]. The policy aims to increase the share of renewable energy in the country's energy mix, reduce dependence on imported energy, and promote sustainable development. The policy framework includes provisions such as tax exemptions, low-interest rate loans, and other incentives to attract private sector investment in renewable energy. Major features of the policy can be concluded as follows:

- The policy aims to promote and develop renewable energy sources such as solar, wind, biomass, and hydroelectric power to encourage the use of these sources for electricity generation, heating, and cooling purposes.
- The policy provides various incentives and financial support mechanisms to encourage investment in renewable energy projects.
- The policy emphasizes the integration of renewable energy into the national grid system. It encourages the establishment of grid-connected renewable energy projects to ensure a reliable and sustainable electricity supply.
- The policy promotes research and development activities in the field of renewable energy technologies.
- The policy focuses on capacity-building initiatives to enhance skills and knowledge related to renewable energy technologies among stakeholders.

Bangladesh's solar energy policy promotes solar PV installations and offers incentives such as import duty waivers, equipment tax exemptions, and a 15-year tax holiday [21]. The government has initiated projects like the Solar Home Systems (SHS) program, which has provided solar-powered electricity to over 7 million rural households and reached 21 million people by 2023 [22]. The impact of these policies has been significant, with a 200% increase in renewable energy installations from 2019-2020, primarily driven by solar and wind energy [23].

Government initiatives have facilitated the country's transition to a low-carbon economy by promoting renewable energy technologies [24]. Figure 1(b) presents a year-wise targeted plan for renewable energy (MW) from 2016 to 2021, highlighting solar, wind, biomass, biogas, and hydro technologies. In 2016, the targeted solar plan was 200 MW, wind 2.9 MW, biomass 0 MW, biogas 5 MW, and hydro 230 MW [25]. Solar and biogas targets consistently increased, while wind saw a significant rise in 2017, and biomass remained constant. As the sector grows, policy updates may be needed to address the evolving energy landscape.

2.3. Renewable Energy Capacity Modelling

In this study, we present a comprehensive methodological framework for assessing the renewable energy potential in Bangladesh, focusing on solar, wind, and biomass energy sources. The framework is structured around four pillars: Policy analysis, resource assessment, technological viability, and economic feasibility (Figure 2). Policy analysis evaluates current renewable energy policies, identifying implementation barriers and examining government initiatives and international commitments in fostering renewable energy adoption. Resource assessment evaluates the potential of solar, wind, and biomass energy by considering geographic and environmental factors, particularly solar radiation levels, wind patterns, and biomass availability.

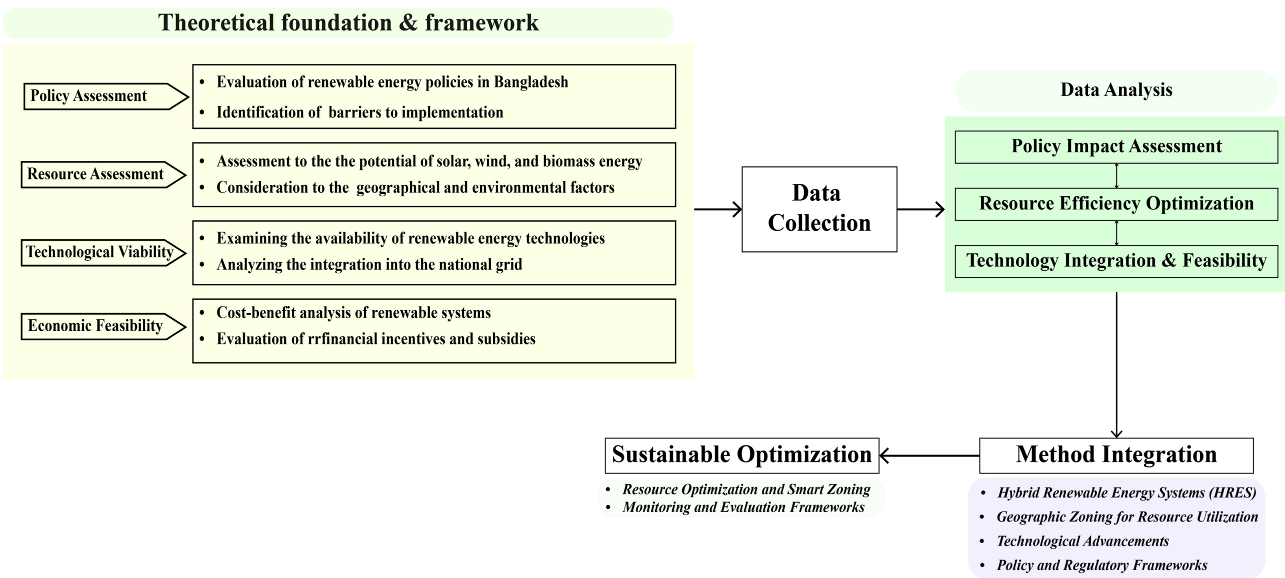


Figure 2. Integrated framework for evaluating renewable energy resources.

For solar energy, a structured approach focuses on data collection, analysis, and model-based assumptions. The methodology integrates empirical data from government reports, energy resource databases, and peer-reviewed literature. Solar radiation data, ranging from 4.5 to 6.5 kWh per square meter per day, has been validated using satellite and ground-based measurements, while data on installed solar capacity of 416 MW (as of 2018) has been obtained from audits and publications. The potential capacity for grid-connected solar photovoltaic (PV) systems, estimated at 50,174 MW, is derived from feasibility studies and technical reports. This solar energy output potential is calculated using Equation (1), incorporating geographic and meteorological factors to enhance prediction accuracy.

Technological viability examines the availability of renewable energy technologies and their capacity to integrate into the national grid, including the feasibility of hybrid renewable energy systems (HRES) that combine solar, wind, and biomass energy for maximum efficiency. Economic feasibility is explored through cost-benefit analyses of renewable systems, including financial incentives and subsidies offered by the government. The data analysis phase includes policy impact assessment, resource efficiency optimization, and technology integration. Method integration involves deploying HRES to synergize the generation potential of solar, wind, and biomass energy, while geographic zoning optimizes resource utilization by aligning renewable technologies with suitable areas. Technological advancements and regulatory frameworks are critical in supporting this integration, ensuring the scalability and sustainability of renewable energy solutions. Finally, the framework emphasizes sustainable optimization through smart zoning and continuous monitoring and evaluation (M&E) frameworks, providing an adaptable roadmap for maximizing renewable energy potential in Bangladesh.

$$E = A \times G \times \eta \tag{1}$$

where, E is the estimated energy output (kWh), A is the area available for solar installation (m^2), G is the average solar radiation ($kWh/m^2/day$), η is the efficiency of the solar photovoltaic (PV) system (dimensionless). Equation (1) has been applied to various regions of Bangladesh, using estimates of land suitable for solar installations. The efficiency (η) of solar panels has been assumed to range from 15% - 20%, based on available commercial technologies. Estimates of rooftop solar potential in urban areas have been derived from average building sizes and available rooftop space. A similar efficiency range has been used to estimate current and future solar energy output. For large-scale solar potential, it has been assumed that rural and semi-urban land can be allocated for solar farms. The analysis has also considered rooftop availability for small-scale solar PV installations. Government policies are assumed to support solar expansion with subsidies, loans, and financial mechanisms for large-scale projects and household-level Solar Home Systems (SHS). Infrastructure improvements have been assumed to facilitate renewable energy integration into the grid as Bangladesh modernizes its energy networks. This study has utilized a theoretical approach to estimate the hydropower potential in wetlands across Bangladesh, focusing on the available catchment areas, rainfall data, and water storage capacities. Key parameters, such as the catchment area of major wetlands, average rainfall, and water flow rates, have been sourced from reliable research studies such as those from Uddin & Park (2021) [26] and national hydrological records. To estimate the hydropower potential, the following Equation (2) has been used:

$$P = Q \times 9.8 \times H_{net} \times N \quad (2)$$

where, P is power produced in MW; Q is the total volume of water stored in the Catchment area in m3 per sec; H is the gross head in m; N is the efficiency; To simplify our calculations and based on the geographical condition, a gross head of 2.25 meters and an efficiency rate of 75%. Total volume of water stored in the catchment area can be calculated using Equation (3).

$$Q = A_c \times RF_{avg} \times 0.7 \times 1.15 \times 10^{-5} \quad (3)$$

where A_c is the catchment area in m^2; RF_{avg} is the average rainfall in the wetland in m; 0.7 is co-efficient of run-off. The runoff coefficient is a factor that relates the amount of rainfall runoff to the total amount of precipitation received on the catchment area. Gross head of the wetland site in Bangladesh is relatively low: 2.5 m. For simple calculation, we assume 10% of head loss. Therefore, net head can be calculated by using Equation 4.

$$H_{net} = H_{gross} \times 0.9 \quad (4)$$

The net head has been estimated by accounting for a 10% head loss due to system inefficiencies, calculated using Equation (3). A gross head of 2.25 meters has been assumed, which is typical for the flat terrain of Bangladesh. A hydropower system efficiency of 75% has been applied. Large wetlands with consistent water supplies throughout the year have been considered, with an average depth of 2 - 3 meters. Runoff coefficient of 0.7 has been assumed to account for water loss in the catchment area. In order to evaluate the potentials of wind energy in Bangladesh, a simple calculation has been performed. To calculate the energy from wind, E_{wind}, Equation (5) is used.

$$E_{wind} = 0.5 \times \rho \times A_{awept} \times V^3 \quad (5)$$

where, ρ is the density of air in kg/m^3; A_{awept} is the area over which the wind turbine blades rotate in m^2; V is the speed of the wind in m/s. Equation (6) calculates the amount of power that can be harnessed from the wind by a wind turbine.

$$P_{wind} = E_{wind} \times C_p \quad (6)$$

where C_p is the coefficient of performance, which indicates the efficiency of the wind turbine in converting the energy in the wind to electricity. The value of C_p varies with the design and manufacturer of the wind turbine. Hossain & Ahmed [27] specify some contemporary turbine model that is highly compatible with the prevailing wind conditions in Bangladesh. Our calculations consider their specific recommendations, incorporating C_p value of 0.45 and a blade diameter of 80 meters.

In order to calculate the amount of residue and the energy content of the residue in PJ (petajoules) using the lower calorific value (LCV), Equations (7) and (8). have used.

$$NR = CP \times RY \times RRF \quad (7)$$

Where, NR is the net amount of residue in tons; CP is the net production of crops in ton; RY is the residue yield factor; RRF is the residue recovery factor. Here, net amount of residue refers to the total amount of biomass residue available after deductions for losses during processing, transportation, and storage. LCV represents the amount of heat that is released when the biomass is burned and includes the energy released through the combustion of the volatile matter. There are several factors that can affect the calorific value of biomass residue, including its moisture content, ash content, and chemical composition [28].

$$EP = NR \times FDM \times RVS \times LCV \tag{8}$$

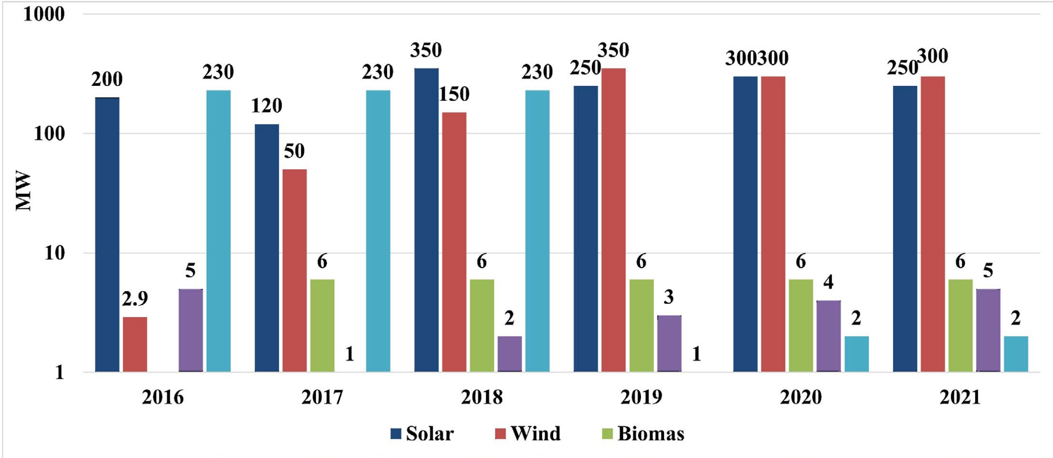
EP is the energy potential in PJ; FDM is the fraction of dry matter to corresponding crops; RVS is the ratio of amount of solid to dry matter, LCV is the lower calorific value in PJ per ton. Our study involves using Equations (7) and (8) to estimate the theoretical net amount of residue generated and associated energy content from major crops produced in Bangladesh during 2020.

3. Results

Renewable energy has significant potential in Bangladesh. The country has abundant solar radiation, hydropower, wind energy, and biomass resources, which can be harnessed to reduce dependence on non-renewable energy sources. Assessing the renewable energy potential in Bangladesh requires a thorough understanding of the available resources such as solar, wind, hydro, and biomass energy. Each of these energy sources and potential that may contribute to the country's clean energy ambition are described in the following section.

3.1. Solar Energy Resources and Potentials

Solar energy is abundant in Bangladesh, as the country lies in a tropical region with sunshine throughout the year. The total annual average solar radiation in Bangladesh ranges from 4.5 to 6.5 kWh per square meter per day [29]. This high solar radiation level presents a significant opportunity for solar PV system development. Bangladesh has significant solar energy potential, with estimates in 2018 suggesting a potential of 240,000 MW assuming current technologies [30]. There is also potential for renewable energy in remote areas through off-grid solar capacity. The country's current installed solar capacity is 416 MW, while the total potential for grid-connected solar PV is 50,174 MW [19]. Bangladesh has developed a master plan aiming for 600 MW of solar capacity by 2021. There is optimism that with the right policies and investment, Bangladesh can continue to increase solar capacity and reduce reliance on non-renewable energy. **Figure 3(a)** illustrates the distribution of solar technology installations in Bangladesh [19], showing progress in diversifying solar power sources and expanding access. **Figure 3(b)** highlights the focus on solar parks and Solar Home Systems (SHS), which have been effective in rural areas without grid electricity [31]. By May 2017, over four million SHS were installed, benefiting more than 12% of Bangladesh's population [32]. The SHS program, the largest domestic off-grid solar



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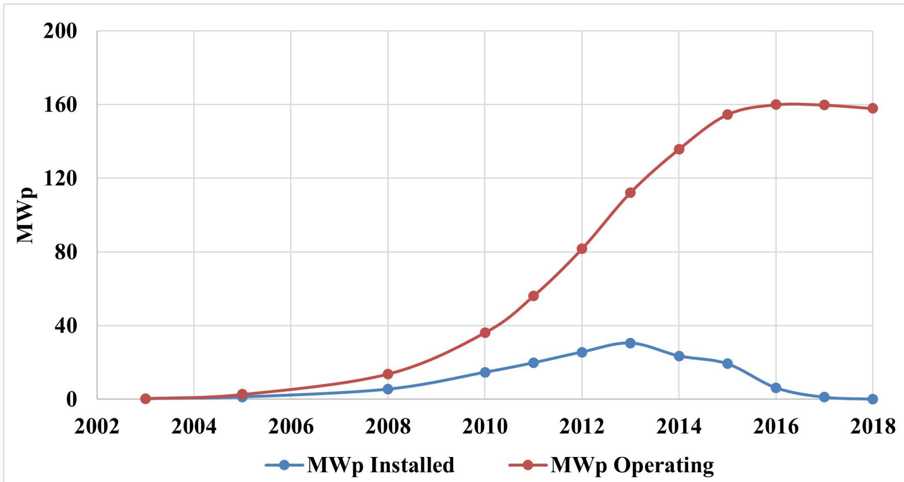


(b)

Figure 3. (a) Distribution of solar technology installations in Bangladesh; (b) SHS installation and cumulative operating in MWp.

electrification initiative, has gained international attention for expanding access to affordable electricity in rural areas [33]. It has thrived due to support from the World Bank and the Bangladesh government, fostering a robust off-grid solar market. **Figure 3** details SHS installations and MWp operations in Bangladesh from 2003 to 2018 [32]. In 2003, 9075 SHS were installed with 0.45 MWp operating. By 2018, cumulative MWp reached 157.93, reflecting significant growth despite some fluctuations in annual installations. **Table 3** reflects Solar Power Plant Development and potential in Bangladesh [19], showing that 461 MW of solar power projects are operational. There are also 350 MW of projects under implementation, demonstrating Bangladesh's ongoing efforts and commitment to increasing renewable energy capacity.

It is also worth noting from **Table 3** that there are 1374 MW of solar power projects still under planning. This suggests exploring opportunities to expand its renewable energy capacity and reduce dependence on fossil fuels. Despite these efforts, there are still some challenges that need to be addressed for the widespread adoption of solar energy in Bangladesh. These include high upfront costs, lack of financing options, and inadequate infrastructure.

Table 3. Solar power plant development and potentials in Bangladesh [19].

Project	Capacity	Technology
Active project	461	Solar photovoltaic (PV) technology
Implementation Ongoing	350	Solar photovoltaic (PV) technology
Under Planning	1374.34	Solar photovoltaic (PV) technology

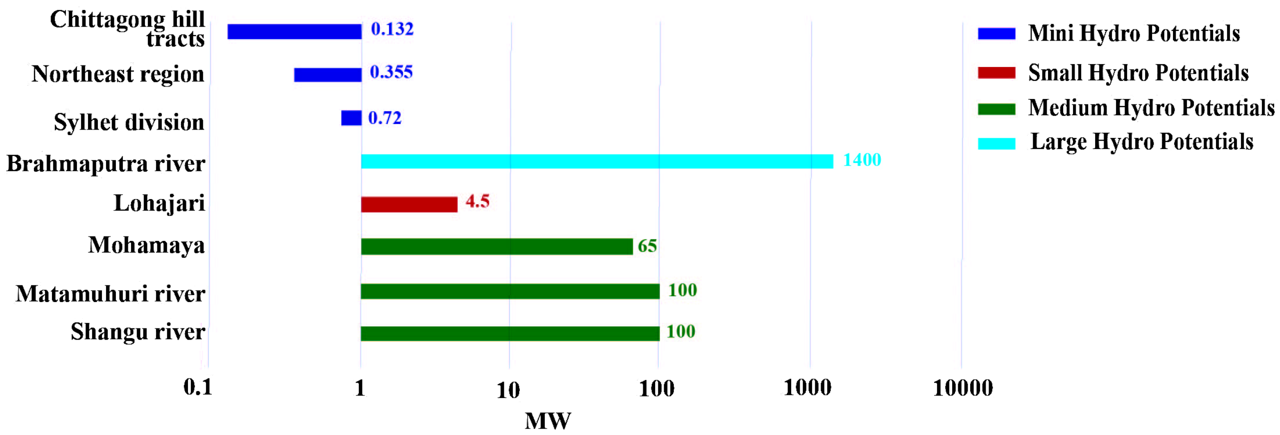
3.2. Hydro Energy Resources and Potentials

Hydroenergy is one of the major renewable energy sources in Bangladesh. The country has several rivers and waterfalls that can be harnessed for hydroelectric power generation. As of now, there is only one large Hydro Power Station located in Kaptai, Bangladesh. Specification of this project is summarized in **Table 4** [19]. The status of hydro energy in the development of Bangladesh is not very satisfactory due to flat terrain of the country and potential social and environmental impact, small area with large population [34]. In addition, the potential of medium, small and micro hydro power plants across the country shows that the future of hydro power generation project is bright. Uddin & Park, 2021 [26] provides valuable information of potential sites for hydropower generation. **Figure 4(a)** represents graphical analysis of the potentials of hydropower project based on the information of Uddin & Park, 2021 [26].

According to **Figure 4(a)**, small and mini hydropower has been identified as having significant potential in Bangladesh, particularly in hilly areas and in the northeast and southeast regions of the country. The Brahmaputra, Shangu and Matamuhuri rivers have good possibility for hydropower development, along with several other rivers such as Mohamaya, Lahajari. Brahmaputra River has large hydropower potentials with more than 1000 MW [35]. Despite of these

Table 4. Kaptai hydroelectric project [19].

Name	Specification
Capacity	230 MW
Turbine type	Kaplan turbine
Number of unit	5 (2 × 40 MW; 3 × 50 MW)
Type of dam	Embankment
Dam volume	69,800,000 cu ft
Spillway type	Controlled with 16 gates
Spillway capacity	16,000 m^3/ sec
Catchment area	11,000 km^2



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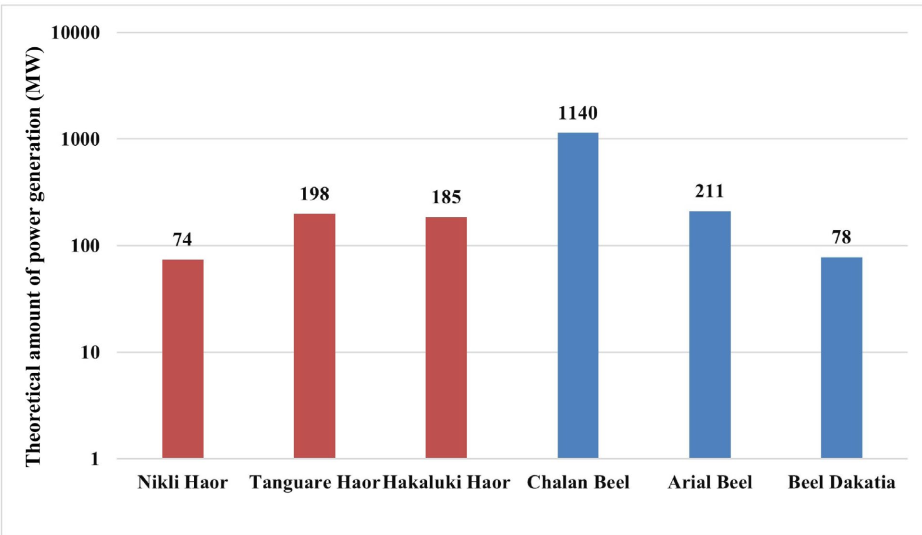


(b)

Figure 4. (a) Potential site for hydropower generation project, (b) Potentials of hydropower generation in wetland.

development of hydropower in Bangladesh faces numerous challenges, including regulatory and environmental hurdles, as well as a lack of public support. Bangladesh possesses a significant area of wetlands, including rivers and streams, freshwater lakes and marshes, haors, beels. The wetlands of Bangladesh are mainly distributed in Haor basin of the northeastern region and the lowlands, locally known as beel [36]. The wetlands of Bangladesh are highly important for a range of ecosystem services, including fisheries, agriculture, and biodiversity conservation [37]. While wetlands are valuable ecosystems, they may not necessarily be suitable for hydropower generation due to their ecological importance and the potential social and environmental impacts of hydropower development [38]. This study is focused on generating a theoretical evaluation of the amount of power that can be harnessed from wetlands located in Bangladesh, including Haor and Beel. Not all wetlands in Bangladesh are suitable for hydropower generation. The focus of this study is on the largest wetlands with an average depth of 2 to 3 meters and a consistent water supply throughout the year. The calculated potential of hydroenergy indicates that a substantial amount of energy can be produced, meaning that these wetlands have significant hydropower potential. However, it must consider the severe negative impact that implementing hydropower technology can have on local ecosystems, the environment, and the populace residing in the area. Table 5 shows the results potential of hydro energy in the wetland calculated using Equations (2)-(4).

Table 5. Theoretical evaluation of hydropower generation in wetland.

Wetland	Catchment area, m ^{2}	Average rainfall, mm	Theoretical the amount of power (MW)	Type of hydro power
Tanguare Haor	100,000,000	5413	198	Large
Nikli Haor	89,257,465	2250	74	Medium
Hakaluki Haor	181,150,000	2780	185	Large
Chalan Beel	1,424,000,000	2180	1140	Large
Arial Beel	136,000,000	4239	211	Large
Beel Dakatia	121,400,000	1750	78	Medium

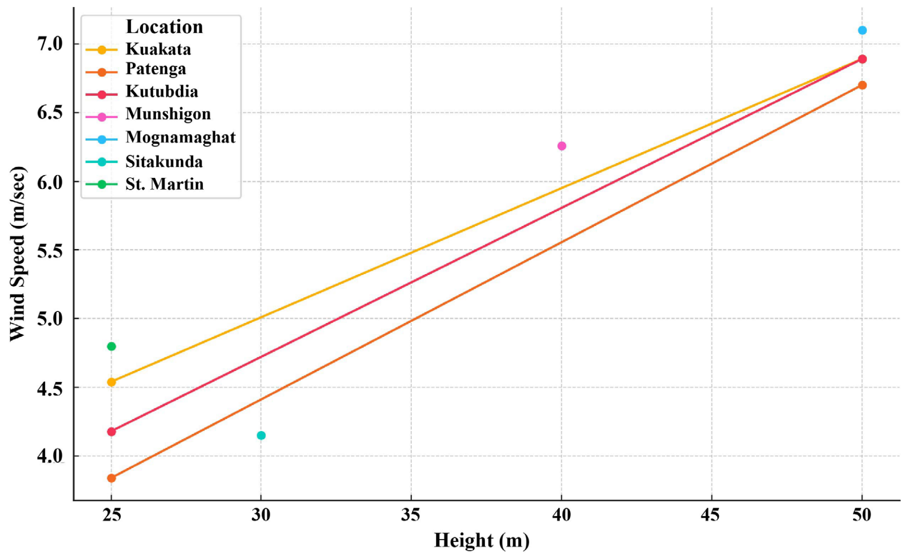
The catchment area indicates the total water-containing area of the wetland. The larger the catchment area, the more water can be stored for power generation. The average rainfall of the wetland has also been included because it plays a vital role in hydropower generation. Higher rainfall rates imply more water availability, which means that higher amounts of power can theoretically be generated. The average rainfall received by these wetlands varies from 1750 mm to 5413 mm. Chalan Beel can generate up to 1140 MW of power due to its larger containment area and a higher average rainfall received (**Figure 4(b)**). Despite having the smallest containment area and lower average rainfall compared to other sites, Tanguare Haor is expected to generate 198 MW of power.

3.3. Wind Energy Resource and Potentials

Wind energy is also a potential renewable energy source in Bangladesh, particularly in the coastal regions of the country. Wind speed in Bangladesh varies from 1 to 8 meters per second. In the past, it was assumed that Bangladesh did not have significant potential for wind energy as several studies were conducted at lower height from sea level. But recent studies confirm that at higher heights, *i.e.*, 40 - 50 m from sea level, average wind speed is greater than 5 m/s which is suitable for producing energy from wind. Wind energy projects in the country have already been initiated and there are additional opportunities to increase power generation using this method. **Table 6** presents significant wind energy projects that are presently in different phases, including active projects, projects under construction, and those that are still in the planning stages [19], [12]. **Figure 5(a)** shows the potential sites for wind energy project [39]. **Figure 5(a)** provides that there is

Table 6. Significant wind energy projects in Bangladesh [19].

Wind Energy Project	Location	Capacity	Status
1000 kW Capacity Wind Battery Hybrid Power Plant	Kutubdia Upazila, Cox's Bazar	1 MW	Functioning
0.9 MW Wind Turbine Power Plant	Sonagazi, Feni	900 kW	Functioning
2 MW Wind Power Plant	Sirajganj Sadar Upazila, Sirajgonj	2 MW	Implementation in process
60 MW Wind Power	Chakaria Upazila, Cox's Bazar	60 MW	Implementation in process
Matarbari 100 MW Wind Power Plant Project	Maheshkhali Upazila, Cox's Bazar	100 MW	In the planning stages
Mongla 55 MW Wind Power Plant	Mongla Upazila, Bagerhat	55 MW	In the planning stages
50 MW Grid-tied Wind Power Plant	Cox's Bazar Sadar Upazila, Cox's Bazar	50 MW	In the planning stages



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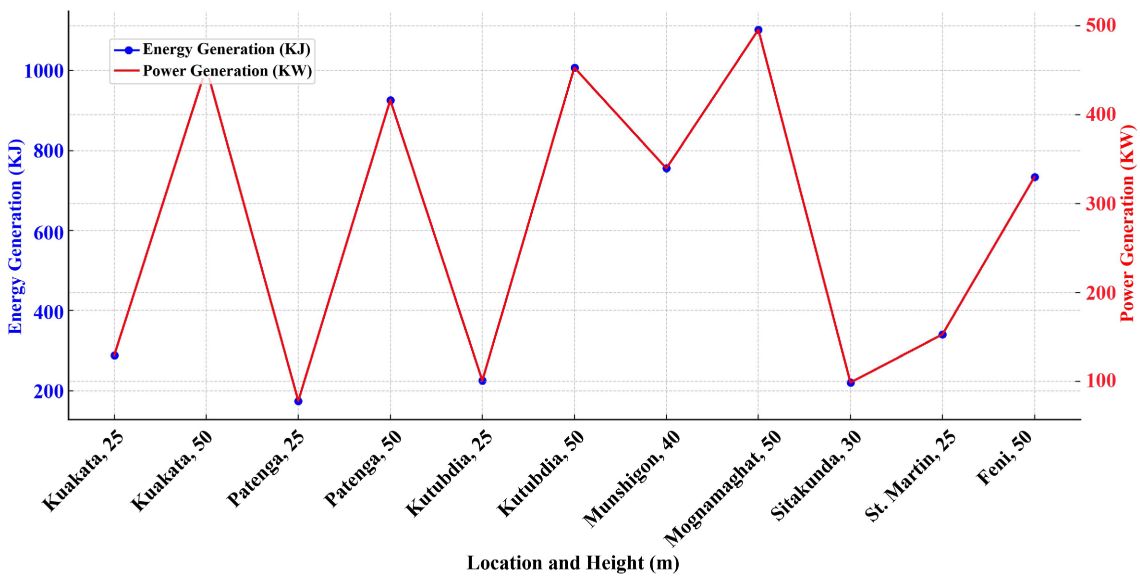


(b)

Figure 5. (a) Potential sites for wind energy project. (b) Calculated energy and power at different potential sites.

a significant variation in the average wind speeds across the different locations and heights. For instance, Mognamaghat has the highest average wind speed of 7.1 m/s, while Patenga has the lowest average wind speed of 3.84 m/s at a height of 25 meters. Also, the wind speed generally increases with height, as is evident from the higher values recorded at 50 meters for most locations. Hence it can be concluded that costal area such as Kuakata, Kutubdia, Patenga has potential of energy generation from wind. Along with the coastal area, Munshigon, Feni can be a suitable site for utilizing wind energy.

It appears from **Figure 5(b)** that Mognamaghat at 50 meters in height has the highest energy output of approximately 1100 KJ and power output of 496 KW, indicating a favorable wind power potential in this region. Similarly, the locations of Kuakata, Patenga, Feni and Kutubdia also show promising wind power potential, with power outputs ranging from 330 KW to 453 KW. However, the energy and power output values measured at each location can vary due to changes in wind speed, turbine height, and other factors.

3.4. Biomass Energy Resources and Potential

Biomass and biogas are both considered renewable energy sources. Biomass is a solid, organic material that can be burned to produce energy, while biogas is a gaseous fuel produced from biomass through anaerobic digestion. Both are carbon-neutral biofuels, as they do not contribute to greenhouse gas emissions when burned. The development and utilization of renewable energy resources like biomass and biogas are increasingly important in promoting sustainable energy practices [35]. Biogas and biomass energy have been identified as promising areas for sustainable energy development in Bangladesh. The country has an abundant supply of biomass feedstock, including agricultural residues, animal waste, and forestry waste. Biogas plants can convert these materials into electricity and biogas, which is a promising energy source in rural areas. Biogas is mainly composed of 50% - 70% methane and 30% - 40% carbon dioxide [40]. Currently, there are 25,000 biogas plants and over 0.20 million ameliorate ovens installed throughout the country to save biomass fuel [41]. The current electricity generation capacity for biomass-based power plants in Bangladesh is 42.5 MW [41]. The potential of biomass energy from livestock residues is presented in **Table 7** and **Figure 6** & **Figure 7**. From **Figure 6**, it is observed that rice residue has the highest energy content at 575.02 PJ. This is consistent, as rice is one of the major crops produced in Bangladesh. Maize and vegetable residues also have relatively high energy content, at 90.36 and 35.85 PJ, respectively. Jute, sugarcane, and wheat residues have lower energy content compared to rice residues. We estimated the theoretical net residue and energy content generated from livestock, municipal solid waste (MSW), and forest resources in 2020. The calculations of MSW potential for 2020 were based on the previous year's data from Islam *et al.*, 2021 [40] while forest data were obtained from Halder *et al.*, 2015 [35]. Residue generation of livestock potential are provided in **Table 8**, **Table 9**. **Figure 7(a)** highlights the substantial

Table 7. Total amount of residue and energy content from agriculture in Bangladesh.

Crops	Production in 2020 (Million Tons) [42]	Residue Type	Residue Yield [43]	Recovery Factor [43]	Residue Million Tons	Energy Content, PJ	Electricity Generation KWh
Rice	37.4	Straw	1.695	0.35	22.187	575.02	159.73
		Husk	0.267	1	9.9858		
		Bran	0.083	1	3.1042		
Maize	4.7	Straw	2	0.654	6.147	90.36	25.103
Wheat	1.18	Stalks	1.75	0.35	0.723	11.39	3.164
Jute	1.15	Jute stalks	2	0.35	0.805	13.61	3.781
Sugarcane	3.33	Sugarcane tops	0.3	0.35	0.349	5.53	1.535
Mustard		Straw	0.3	0.75	0.618	13.54	3.761
		Husk	0.3	0.31	0.255		
Vegetable	19.7	-	0.4	0.35	2.78	35.854	9.959

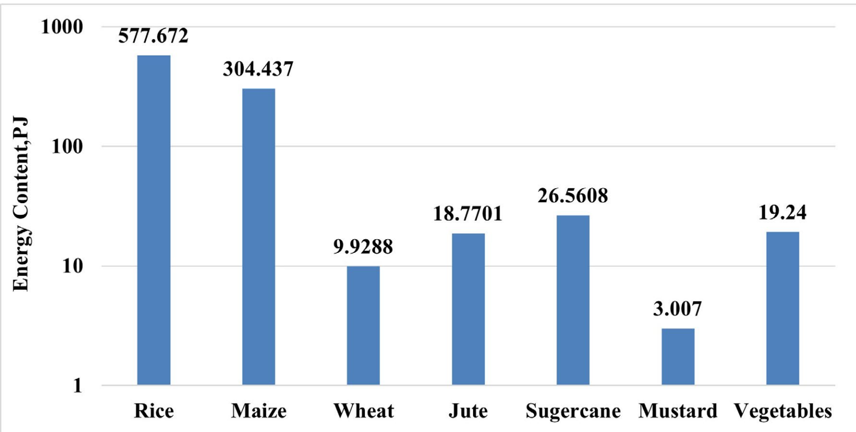


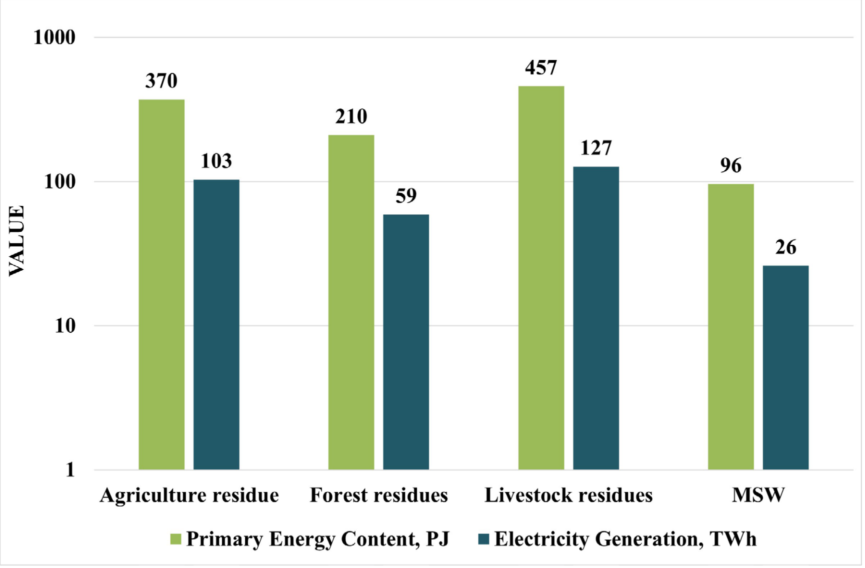
Figure 6. Energy contents of major agricultural cops of Bangladesh as bio energy.

Table 8. Residue generation of livestock in 2020.

Livestock	Head (million)	Dung Yield (kg/head/day) [28]	RRF	LCV (GJ/ton)	Residue generation (ton)
Cattle	24.7	7.5	1.67	13.86	6,761,6250
Goat	26.7	0.375			3,654,562.5
Sheep	3.6	0.375			492,750
Buffalo		10			5,110,000
Total animal					7,687,362.5
Chicken	304.1	0.1	2	13.5	11,099,650
Duck	61.7	0.1			2,252,050
Total poultry					13,351,700
Total					90,225,262.5

Table 9. Energy content and electricity generation from livestock residue.

Sector	Residue (million tons)	Energy content PJ	Electricity generation KWh
Agriculture	46.93	745.3	207
Forest	17.44	210.6	58.5
Livestock	90.22	463.6	128.8
MSW	13.325	95.2	26.4



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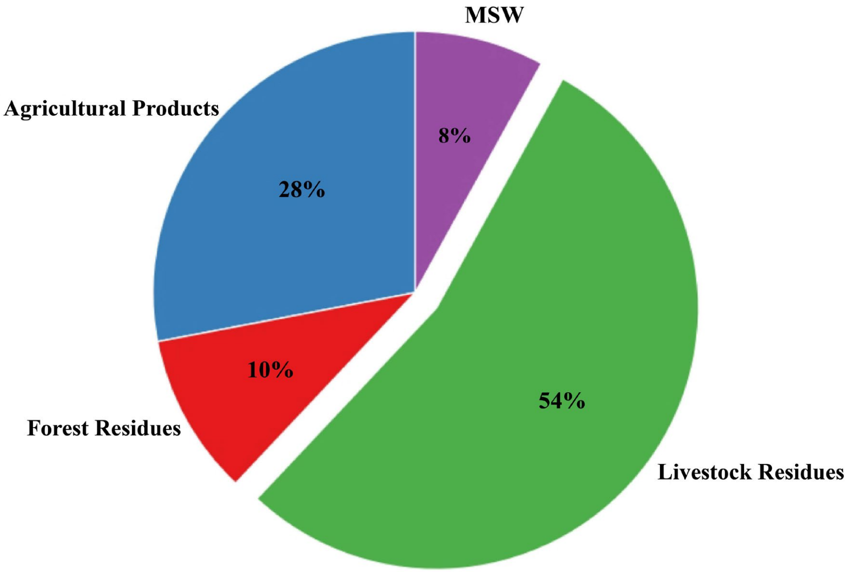


(b)

Figure 7. (a) Potentials of energy content in PJ and associated electricity generation in TWh from different source of biomass; (b) Contribution of different source of residue to biomass energy.

bioenergy potential in Bangladesh from various sectors. Livestock residues stand out with a primary energy content of 457 PJ and an electricity generation potential of 127 TWh, reflecting the country's robust livestock farming industry. Agricultural residues and forest residues also present significant opportunities. These resources can greatly enhance energy supply in rural areas while promoting job creation in biomass energy conversion technologies. Although municipal solid waste (MSW) shows lower figures, it offers potential for urban energy generation and waste management.

From **Figure 7(b)**, agriculture and livestock are the biggest contributors to annual residue generation in Bangladesh, accounting for 28% and 54% of the total residue generation, respectively. It is worth noting that forest waste and MSW also contribute to annual residue generation in Bangladesh. Proper management of forest waste through sustainable forest management practices can help to reduce the waste generated, while MSW can be managed through effective waste management strategies such as waste reduction, reuse, and recycling. Although biogas and biomass energy have great potential in the country, there are still some obstacles that need to be overcome. Some of the main challenges that affect the growth of biogas and biomass energy in Bangladesh include, a lack of awareness and technical knowledge among the rural population, the high cost of biogas plants and other equipment, inadequate financing, and insufficient government support.

3.5. Hybrid Renewable Energy System (HRES) and Its Potentials

A hybrid renewable energy system combines multiple sources of renewable energy, such as solar, wind, and biomass, with conventional power generation methods. This system offers a viable alternative to traditional fossil fuel-based generation and promotes sustainable development. This integration allows for a more reliable and efficient energy supply that meets the diverse needs of Bangladesh's population. These systems have significant potential to provide energy access in rural areas and reduce the carbon footprint while ensuring reliable power generation. A block diagram of a simple hybrid energy system is shown in **Figure 8**. One key advantage of a hybrid renewable energy system is its ability to overcome the intermittent nature of renewable sources. Bangladesh experiences abundant sunlight year-round, making solar power an ideal component. By combining solar panels with wind turbines and biomass generators, the system can generate electricity consistently, even during periods of low sunlight or calm winds. Bangladesh's geographical location offers immense potential for harnessing wind power, particularly in coastal regions favorable for turbine installations. Incorporating wind energy can diversify the energy mix. Another advantage is utilizing biomass as an energy source. Bangladesh, being agricultural, generates vast amounts of agricultural residues and organic waste daily. These materials can be converted into biogas or used directly as fuel in biomass power plants, reducing waste while generating clean electricity. The implementation of hybrid renewable energy systems

(HRES) is supported by various initiatives. Table 10 provides an overview of HRES projects in Bangladesh.

Figure 9 represents a framework for assessing, planning, and integrating renewable energy systems, focusing on technological, environmental, and strategic aspects. The first step involves assessing Bangladesh's energy needs and identifying potential renewable resources such as solar, wind, biomass, and hydropower. This aligns with the national goal of reducing dependence on fossil fuels and addressing power shortages. Through technological analysis and integration planning, the feasibility and compatibility of these resources with existing systems are evaluated.

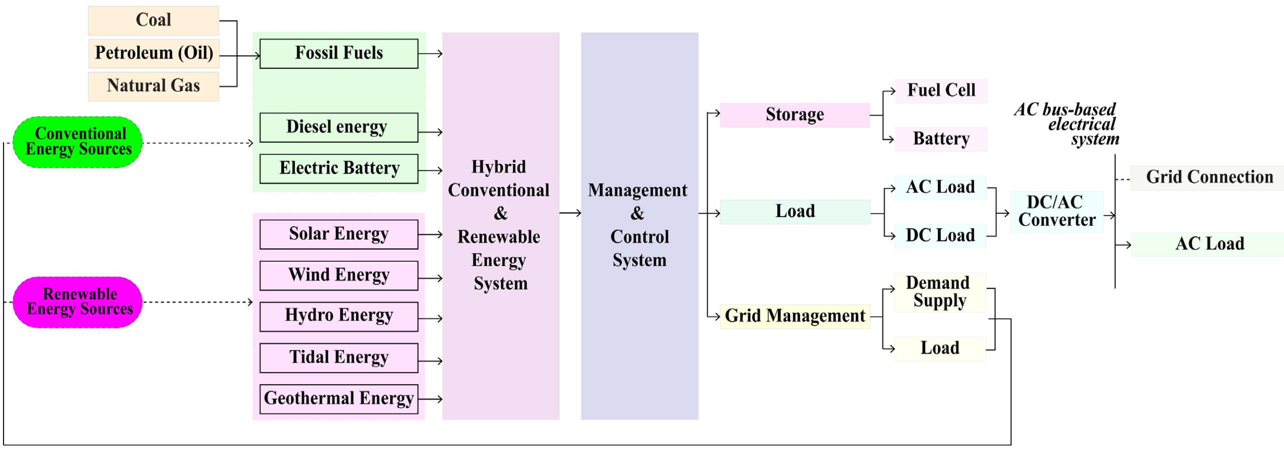


Figure 8. Block diagram of hybrid renewable energy systems.

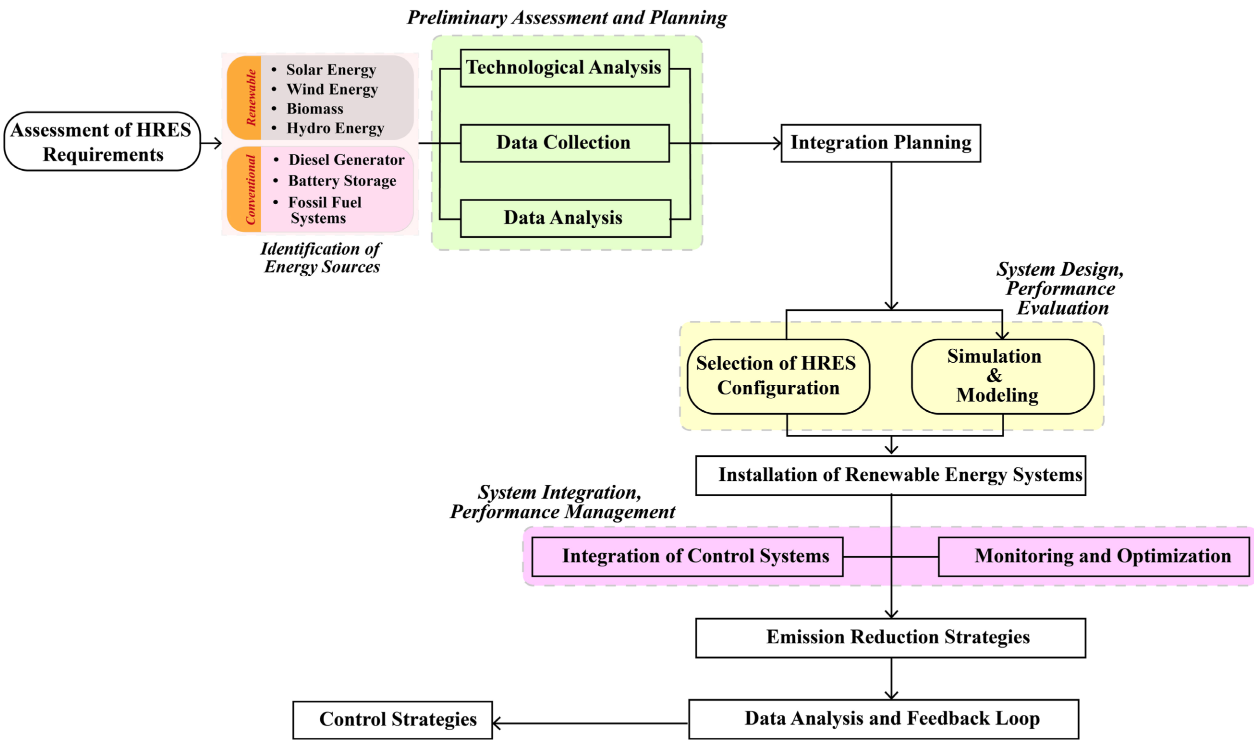


Figure 9. Framework for planning, integration, and optimization of renewable energy systems.

Table 10. HRES project in Bangladesh.

Name	Capacity, MW	Location	Type	Status
Wind-solar hybrid power plant	3.15	Kutubdia	Wind-solar hybrid system	Active
Wind-solar hybrid system with HFO/diesel based engine driven generator	7.5 [44]	Hatiya Island, Noakhali	Wind-solar hybrid System	Active
Floating solar PV	50 [45]	Kaptai, Chittagong	Solar-hydro hybrid system	Proposed
Solar-diesel based hybrid power plan	1 [44]	Kutubdia Island	Solar-diesel hybrid system	Under planning

Selecting HRES configurations, along with simulation and modeling, is essential for optimizing the energy mix across diverse geographical areas. Coastal regions could integrate solar and wind energy, while rural zones might focus on biomass. Proper modeling ensures renewable sources can meet local demands while maintaining grid stability. Once systems are installed, integrating control systems for performance monitoring is crucial to tracking energy output and grid integration efficiency. This monitoring would benefit Bangladesh's energy policy, reducing power outages and dependency on imported fuels. Additionally, Bangladesh's emission reduction targets can be supported by monitoring and optimizing these systems, leading to cuts in greenhouse gas emissions. Investment in renewable energy, supported by policy incentives, can be strengthened by implementing data analysis and feedback loops, ensuring that policies adapt to technological advancements and performance outcomes.

4. Discussion

Bangladesh has abundant potential for renewable energy, particularly solar and hydroenergy. The country's tropical climate makes it favorable for solar power generation, and its numerous rivers present significant potential for hydroelectric power generation. **Figure 10** highlights the potential for renewable energy in Bangladesh and the necessity for the country to invest in these sources to meet its energy demand sustainably. After analyzing the renewable energy potentials discussed above, we can compare them to the current energy demand. Our findings indicate that renewable energy can cover almost 86.36% of the energy demand in 2015-16 and 47.50% in 2020-21. The highest potential for renewable energy in Bangladesh is in solar power, followed by hydroenergy. Wind power, biomass energy, and hybrid energy have lower potential but can effectively contribute to rural and coastal areas. It is important to note that while Bangladesh has great potential for renewable energy, actual production from these sources is still limited. The country has been investing in renewable energy in recent years, but more effort is needed to reduce reliance on traditional non-renewable energy sources such as fossil fuels. Based on the analysis of the resources and potentials of various renewable sources discussed above, leads to recommend the implementation of three hybrid renewable energy systems, as detailed in **Table 11** and

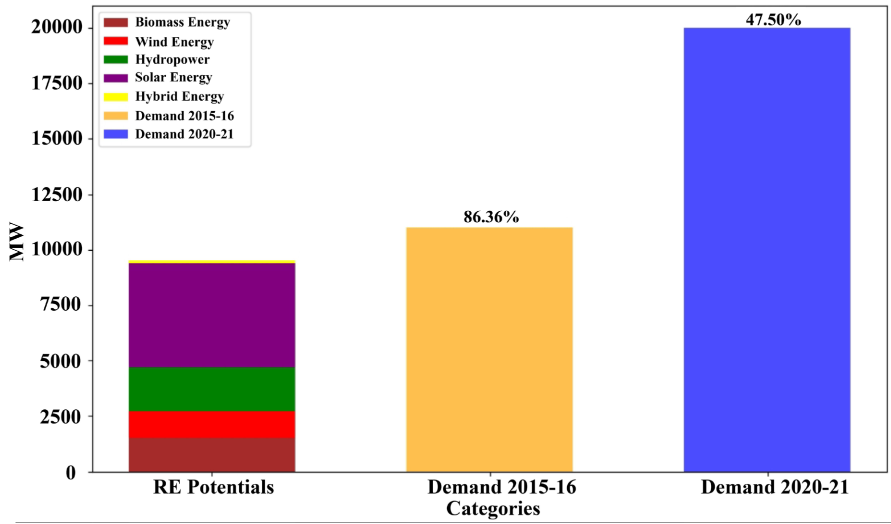


Figure 10. Comparison of renewable energy potentials and energy demand in Bangladesh.

Table 11. Proposed hybrid renewable energy system in Bangladesh.

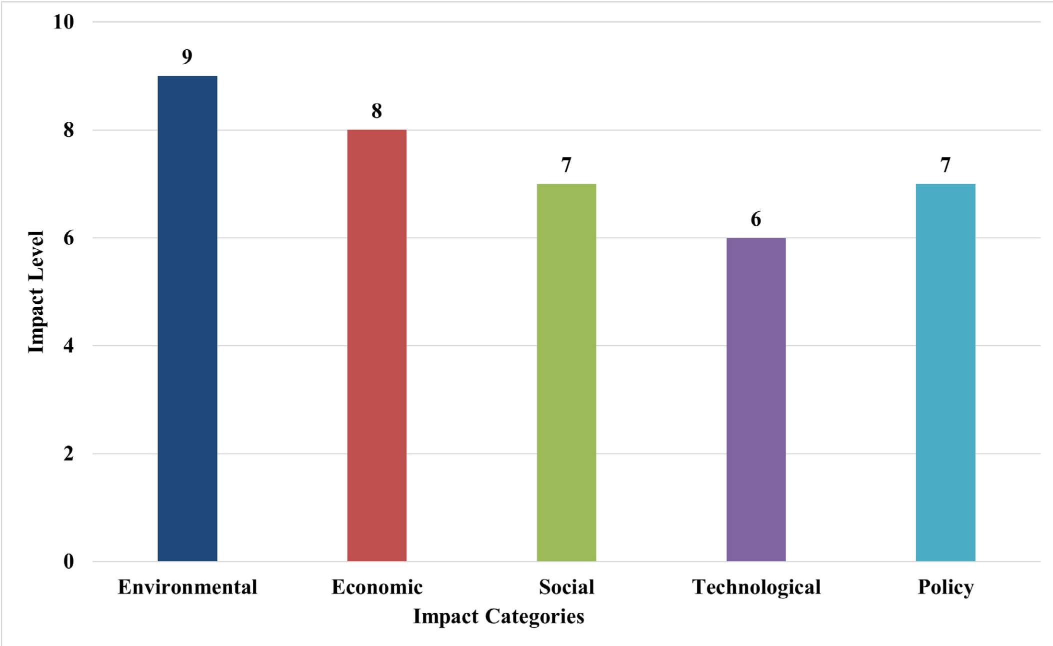
Hybrid renewable energy system	Potential site
Solar-wind hybrid energy system	Coastal area, island
Solar-battery-based hybrid system	Rural area, irrigation sector
Wind-battery based hybrid system	Island
Solar biomass hybrid energy system	Rural area
Solar hydro hybrid energy system	Inland, wetland, river basin

We can draw the following conclusions:

- Solar energy has enormous potential in Bangladesh and is suitable for efficient use across the country. The progress in this sector can be considered satisfactory.
- Hydroenergy has abundant potential in Bangladesh, especially in the hilly areas and river basins. However, the progress in this sector is not up to the mark.
- While biomass energy is a promising source of energy in rural areas of Bangladesh, its progress in this sector has not been up to the mark, despite the sufficient potential it presents. Biomass energy is cost-effective and an easily accessible source of energy in remote areas, but significant improvements are needed to fully tap into its potential.
- Wind energy has adequate potential in the coastal areas of Bangladesh, but the progress in this sector is also not satisfactory as main challenges in the wind energy sector include high installation and maintenance costs, lack of suitable infrastructure, technical complexities and difficulty in finding suitable land.

4.1. Evaluating the Technological and Environmental Impacts of Renewable Energy Initiatives

The assessment of the technological impact of renewable energy initiatives has been conducted using key metrics, including grid modernization, technology transfer, and the integration of renewable energy technologies (Figure 11(a)). Evaluations indicated significant advancements in grid capabilities, with projections suggesting improvements in efficiency and reliability. For example, integrating renewable energy technologies could enhance overall grid performance by about 15%. Furthermore, the evaluation of technology transfer from developed



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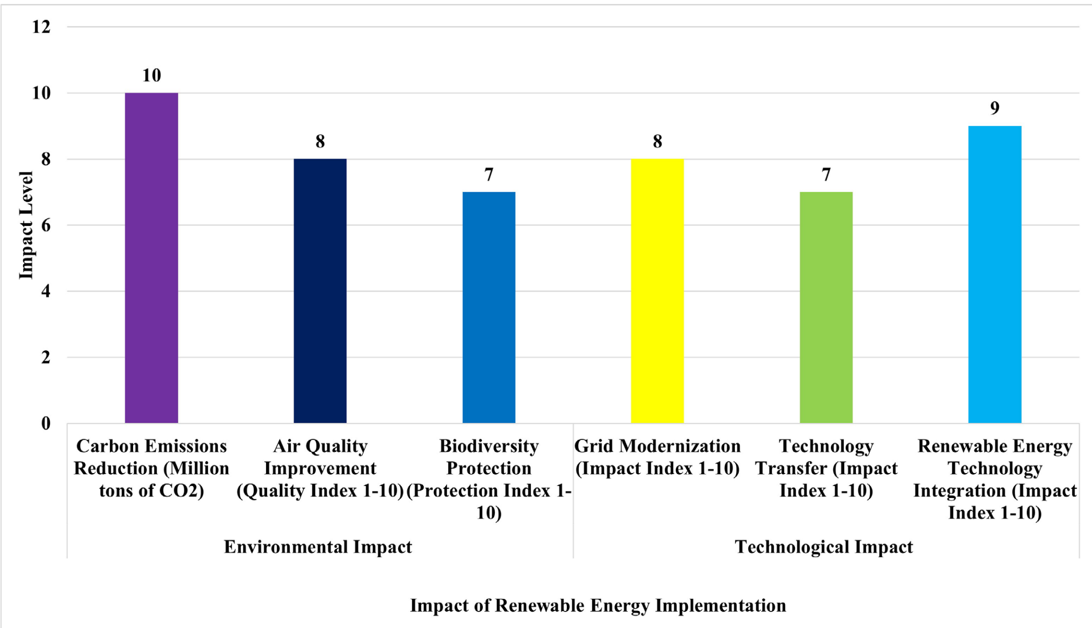

(b)

Figure 11. (a) Impact assessment of renewable energy initiatives; (b) Environmental and technological impact of renewable energy implementation.

to developing regions highlighted its potential to stimulate local innovation and build capacity. These factors culminated in a score of approximately 6, reflecting a positive yet moderate technological impact, primarily due to existing barriers and the need for further advancements in infrastructure and skill development. Figure 11(b) illustrates the Technological Impact of renewable energy implementation in Bangladesh, focusing on three critical dimensions: Grid Modernization, Technology Transfer, and Renewable Energy Technology Integration. The scores for each category were derived through systematic calculations. Grid Modernization received a score of 8, based on an estimated economic benefit of around $924.57 million from reduced energy losses due to infrastructure upgrades, projected to enhance grid efficiency by 10%. Technology Transfer scored 7, reflecting a 15% anticipated increase in renewable energy efficiency, augmenting energy production capacity to approximately 2462.08 GWh. Renewable Energy Technology Integration received the highest score of 9, as successful integration is projected to elevate renewables to 40% of total energy consumption, enhancing energy security and sustainability. Collectively, these metrics underscore the anticipated technological advancements associated with renewable energy adoption, which are expected to transform Bangladesh's energy landscape. Figure 11(b) also delineates the environmental impact of renewable energy implementation. Each aspect's values were derived through a rigorous analytical framework. Carbon Emissions Reduction was quantified at 10 million tons of CO_2, based on projected declines in emissions from the transition to renewable energy, substantially mitigating dependence on fossil fuels. Air Quality Improvement was evaluated through a qualitative Quality Index, reflecting anticipated enhancements in air quality from decreased pollutant emissions. Biodiversity Protection received a score of 7, based on qualitative assessments indicating expected positive effects on ecosystems and wildlife due to reduced habitat degradation and pollution from fossil fuels.

Impact analysis conveys the expected environmental benefits associated with renewable energy adoption, supported by both quantitative and qualitative metrics. The estimated potential energy for certain renewable energy sources, including hydropower in wetlands, wind energy, and biomass energy, may differ based on various technical factors. Turbine height, wind speed, and other variables may impact wind energy values, while feedstock quality and conversion efficiency can influence biomass energy generation. Thus, to draw precise conclusions, a detailed analysis of the potential for these energy sources is recommended, considering all technical factors for accurate assessments.

4.2. Challenges of Renewable Energy Adaptation in Bangladesh

The transition to renewable energy in Bangladesh is essential for energy security, reducing carbon emissions, and meeting growing energy demands. Despite significant potential in solar, wind, and biomass resources, widespread adoption of renewable energy technologies faces numerous challenges. These barriers, classified into technical, economic, social, and environmental categories, are illustrated in Figure 12. Overcoming these challenges is crucial for unlocking Bangladesh's renewable energy potential and achieving sustainable energy development. Major barriers include:

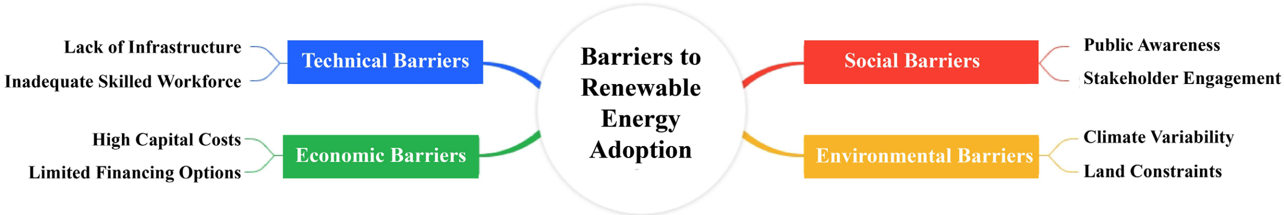

Figure 12. Factors impeding renewable energy growth in Bangladesh.

Social Challenges—Social challenges include inadequate awareness and understanding of renewable energy technologies among the public and stakeholders. Furthermore, a lack of community participation in renewable energy projects and insufficient local governance can hinder the successful implementation of renewable energy projects.

Economic Challenges—Economic challenges include the high capital cost of renewable energy technologies and the lack of access to financing options. In Bangladesh, many financial institutions still lack the expertise and resources needed to finance renewable energy projects. This can hinder the growth of the renewable energy sector and discourage private sector investment in renewable energy.

Technical Challenges—The technical challenges of renewable energy in Bangladesh include the lack of adequate infrastructure, skilled workforce, and research and development capabilities. These factors can hinder the effective and consistent operation of renewable energy projects, making them less reliable than traditional energy sources.

Environmental Challenges—The environmental challenges of renewable energy in Bangladesh include climate variability, natural disasters, and land constraints. Bangladesh is vulnerable to climate change due to its geographical location, which can impact renewable energy infrastructure and operations.

Carbon capture and storage (CCS) is a vital technology that complements renewable energy efforts by reducing emissions from fossil fuel-based energy sources [46]. By capturing carbon dioxide before its release, CCS can aid Bangladesh's transition to a low-carbon energy system while still relying on conventional sources during the shift to renewables. This makes it a key tool for lowering emissions in the short and medium term. Addressing challenges and barriers through innovative strategies and policies will be crucial for the growth of the renewable energy sector in Bangladesh. Increased investment in research and development, better access to financing, and raising public awareness can significantly help overcome these obstacles. A comprehensive plan is essential for addressing these challenges alongside the implementation of hybrid renewable energy systems.

5. Conclusions

The study highlights the immense potential for sustainable energy development in the country. The analysis has shed light on the current energy scenario, emphasizing the need for a shift towards renewable sources to address the challenges posed by climate change and limited fossil fuel resources. Bangladesh, being heavy reliance on fossil fuels, particularly natural gas and coal, has led to environmental degradation and increased greenhouse gas emissions. This evaluation recognizes that renewable energy can provide a viable solution to these issues while also promoting economic growth and social development.

The assessment of renewable energy prospects reveals that Bangladesh possesses abundant resources such as solar, wind, biomass, and hydroelectric power. Solar energy stands out as one of the most promising sources due to its availability throughout the year. The country's geographical location also offers favorable conditions for wind power generation in coastal areas. Additionally, biomass and hydroelectric power have significant potential for electricity production and rural electrification. Despite these positive developments, several challenges persist. Limited financial resources, inadequate infrastructure, bureaucratic hurdles, and lack of public awareness hinder the widespread adoption of renewable energy technologies. The study emphasizes the importance of addressing these barriers through targeted policy interventions that prioritize investment in research and development, infrastructure improvement, skill enhancement programs, and awareness campaigns.

This study underscores the significance of transitioning towards a sustainable energy future in Bangladesh. By harnessing its abundant renewable resources effectively and implementing supportive policies, Bangladesh can reduce its dependence on fossil fuels while simultaneously mitigating climate change impacts and improving energy access for all. The findings of this study provide valuable insights for policymakers, stakeholders, and international partners to collaborate and work towards a greener and more resilient energy sector in Bangladesh.

Conflicts of Interest

The authors declare no conflicts of interest.

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