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Analysis of the power sector in Bangladesh: current trends, challenges, and future perspectives

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ABSTRACT

Bangladesh's economic development is largely dependent on the power sector, which promotes sustainability and growth. The country's future energy security, however, is seriously threatened by the natural gas reserves running out by 2028. As a result, the current energy mix has to be modified right away to ensure Bangladesh's sustained economic growth. This research paper offers a thorough analysis of Bangladesh's power sector's current state. With a focus on important metrics like installed capacity, electricity generation, and distribution infrastructure, the study seeks to provide insights into the sector's opportunities, challenges, and strengths. The research highlighting the importance of energy security and forecasting the projected energy demand in Bangladesh. The study also looks at current projects and advancements that have shaped Bangladesh's power industry. This research also provides an ideal energy option that supports Bangladesh's sustainable growth. This analysis offers significant insights into the dynamics of the power industry in Bangladesh, elucidating it is present trajectory, the challenges it encounters, and the potential avenues for achieving a more sustainable and resilient energy future.

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1. INTRODUCTION

The annual increase in gross domestic product (GDP) serves as an indicator of a country's socio-economic progress. This growth rate is closely linked to the long-term energy security and stability of the country's energy market. The energy market encompasses various aspects such as electricity generation, power plants, transmission and distribution infrastructure, utilities maintenance, and an effective energy strategy to regulate the market. The fuels used for electricity generation play a crucial role as they determine the associated costs [1]. Electricity, a secondary form of energy, is produced through the conversion of different energy sources, including fossil fuels (coal, oil, natural gas) and renewable sources (hydro, wind, tidal, solar, nuclear energy). However, fossil fuel-based generation poses environmental challenges due to greenhouse gas emissions. In contrast, renewable energy sources offer clean alternatives, but their conversion to electricity presents it is own set of challenges [2]. Bangladesh, known for it is high population density and lower-middle-income status, aims to become a high-income nation by 2041. To achieve this, the country forecasts a net electricity demand of 61 GW by 2041 [3]. Figure 1 shown the generation capacity expansion

plans from 2021 to 2041. Currently, renewable energy sources contribute around 3% to Bangladesh's total electricity generation, with solar energy showing significant potential [4]. The country's economic growth rate has consistently remained above 6.5% since 2002, and the vision is to sustain this growth momentum [5].

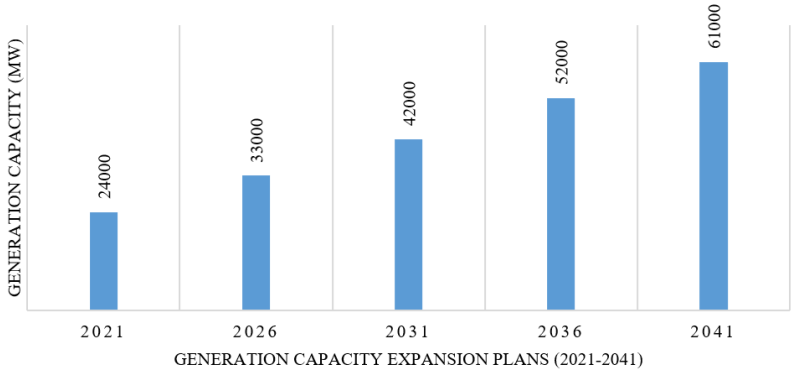

Figure 1. Generation capacity expansion plans (2021-2041)

Currently, Bangladesh has a power generation capacity of approximately 25,700 megawatts (MW). However, the per capita electricity generation stands at 440 kWh, which is relatively low compared to developed nations [6]. The country heavily relies on fossil fuels, particularly natural gas, which accounts for about 65% of the total power generation. The remaining portion comes from coal, imported liquid fuel, and hydropower. Despite a high electricity connectivity rate of over 97% of the population, the availability of continuous power supply remains a challenge, resulting in load shedding for consumers. This situation is attributed to insufficient power plants, limited energy fuel sources, inadequate hybrid power plant operations, and a lack of effective planning to regulate the local energy market [7]. Moreover, the depletion of fossil fuel reserves within the next decade necessitates the development of a sustainable energy policy in Bangladesh. This policy aims to reduce dependency on domestic natural gas and various imported fuels such as coal, liquefied natural gas (LNG), and imported hydro power.

This study provides a comprehensive analysis of the energy sector in Bangladesh and presents an optimal energy solution to facilitate the country's long-term socio-economic development. It also looks at installed capacity and the main energy sources in the present energy mix of the market for electricity. Along with an analysis of the developments in the global energy industry, a variety of energy sources, including fossil fuels (coal, natural gas) and renewable energy sources (hydropower, solar, wind, biomass, and nuclear energy), are examined [8]. A hybrid energy system (energy mix) is recommended as the most acceptable energy solution for Bangladesh's demands based on an analysis of the performance metrics of the available energy resources [9]. We are confident that our analysis and suggested energy mix scenario will pave the way for ensuring long-term energy security in Bangladesh.

The remaining portion of the paper is structured as follows, Effects of uninterrupted energy supplies for the sustainable development is described in section 2. Sections 3 and 4 deliver the estimated energy demand in Bangladesh and renewable energy resources of Bangladesh, respectively. In sections 5 and 6 are discribed the nuclear energy in Bangladesh and development challenges in power sector of Bangladesh, respectively. Future prospects for the power sector in Bangladesh is shown in section 7. Final thoughts and recommendations for further work are offered in section 8.

2. EFFECTS OF UNINTERRUPTED ENERGY SUPPLIES FOR THE SUSTAINABLE DEVELOPMENT

Access to uninterrupted energy supplies is fundamental for achieving sustainable development, as recognized by the United Nations Sustainable Development Goal 7 (SDG 7). Reliable energy sources are crucial for powering economic activities, improving living standards, ensuring equitable access to basic services, and mitigating environmental impacts. Uninterrupted energy supplies contribute to energy security and resilience. Diversification of energy sources, along with robust transmission and distribution systems, reduces vulnerability to supply disruptions. This becomes especially important in the face of natural disasters, geopolitical uncertainties, and global energy market fluctuations. The concept of "energy security" refers to the availability of uninterrupted and affordable energy supplies to consumers [9]. It encompasses both

short-term and long-term aspects. Short-term energy security focuses on the ability to quickly respond to sudden changes in energy supply and demand, ensuring a reliable energy system [1]. Long-term energy security involves making timely investments to meet the growing energy demand in a sustainable manner, considering economic and environmental factors. Energy transmission and distribution play a crucial role in maintaining energy security, requiring significant investments in infrastructure and human resources [10].

Insufficient energy security can negatively impact socio-economic development [11]. While achieving complete energy self-sufficiency is rare, countries strive for a balance between domestic production and imports to enhance energy security. However, reliance on imported fuels and geopolitical uncertainties pose risks to global energy security. Therefore, a combination of domestic and imported energy sources is essential to ensure robust energy security for sustainable economic growth [12]. Figure 2 illustrates the key elements of energy security for clarity. Governments and policymakers play a pivotal role in ensuring uninterrupted energy supplies for sustainable development. Comprehensive energy policies that prioritize investments in infrastructure, promote renewable energy adoption, and improve energy efficiency can pave the way for long-term benefits [13]. Cross-sectoral coordination, regulatory frameworks, and partnerships with the private sector are essential for effective policy implementation.

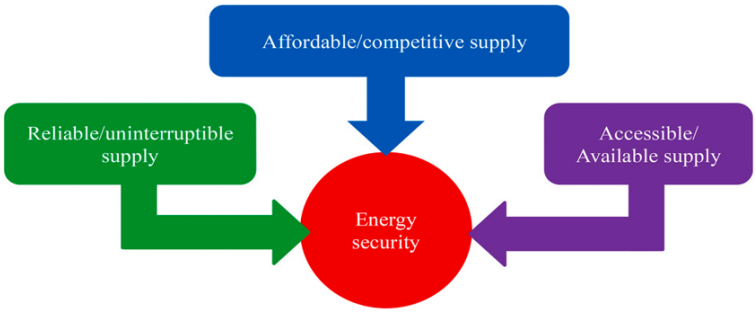

Figure 2. Energy security at a glance [8]

Continuous energy sources are essential to industrial operations. When they can count on a steady and uninterrupted power supply, industries of all sizes enjoy higher productivity and operational efficiency. Adoption of cutting-edge technologies and innovation are fostered by a stable energy infrastructure. This in turn encourages the emergence of new businesses and services, which boosts economic growth. The growth of electric transportation networks, which include electric cars and effective public transit systems, is facilitated by uninterrupted energy. This lessens the impact on the environment and helps us rely less on fossil fuels.

In order to achieve sustainable development, intelligent technologies must be incorporated into infrastructure [14]. Powering digital communication systems, smart grids, and other technological advancements that improve the overall efficiency of infrastructure requires uninterrupted energy. For healthcare facilities to maintain the continuous operation of medical equipment, vaccine and medication refrigeration, and overall healthcare delivery, reliable energy is crucial [15]. Continued power supply leads to better public health results. Consistent energy supplies help improve education by supporting e-learning environments, supplying energy to colleges and universities, and allowing students to regularly access learning materials.

Switching to cleaner energy sources is a necessary step towards sustainable development. Continuous energy makes it easier to incorporate renewable energy sources, like wind and solar energy, which lowers greenhouse gas emissions and improves the environment [16]. Uninterrupted energy supplies have far-reaching effects on sustainable development, spanning economic growth, social well-being, environmental sustainability, and technological progress. By recognizing the critical role of energy access and investing in reliable and clean energy sources, countries can propel themselves towards achieving their sustainable development goals while fostering a more resilient and inclusive society.

3. OVERVIEW OF THE ENERGY DEMAND IN BANGLADESH

Bangladesh, a country in South Asia that is developing quickly, is at a crossroads between social advancement and economic growth [17]. The indispensible need for energy, a vital facilitator of growth across sectors, powers this revolutionary journey. Understanding and precisely projecting the country's energy demand is critical as it moves forward, acting as a compass for stakeholders, industry leaders, and policymakers as they work towards a resilient and sustainable future.

Bangladesh's energy demand has been steadily increasing due to population growth, urbanization, and industrialization [18]. The growing need to understand the complexities of the country's energy needs is highlighted by the increasing demand for electricity to power homes, businesses, and public infrastructure. The foundation of strategic energy planning is thus a thorough examination of the demand-influencing variables, current trends, and future projections. The energy demand primarily consists of electricity, natural gas, petroleum products, and biomass. The power sector is a major driver of energy demand, accounting for a significant portion of the country's energy consumption [19]. Electricity demand in Bangladesh has been growing rapidly, driven by increased urbanization and industrialization. The demand for electricity is influenced by factors such as economic growth, population expansion, and lifestyle changes. The government has been making efforts to increase electrification rates, particularly in rural areas. In pursuit of its long-term goal to become a high-income country by 2041, Bangladesh has formulated the power system master plan (PSMP-2016) to guide it is power sector development [2]. The Bangladesh power development board (BPDB) and other relevant agencies regularly publish energy demand forecasts and projections. These projections take into account factors such as economic growth, population growth, technological advancements, and policy initiatives. The government has been working to diversify it is energy mix by increasing the share of renewable energy sources like solar and wind to meet the growing energy demand and reduce dependency on fossil fuels [20].

The plan takes into account the projected electricity demand and growth rate, which have a direct correlation with the country's GDP growth rate. Table 1 presents the projected electricity demand and growth rate, indicating a robust real GDP growth rate exceeding 8.27% until the 2020s [21]. Beyond that, the GDP growth rate is expected to stabilize as the economy approaches a certain level of maturity. The key sectors driving the economy of Bangladesh include the ready-made garments (RMG) industry, agriculture, manufacturing, and commercial building sectors [22]. The performance of these sectors heavily relies on the availability of a reliable and uninterrupted supply of electricity. To sustain a high GDP growth rate, it becomes imperative to ensure a surplus of electricity by increasing the overall production capacity [23]. The projected electricity demand has been calculated based on the latest data from the BPDB and the power cell, utilizing (1) as the basis for estimation:

$$P_t = (1 + rt)P_0 \quad (1)$$

where P_t represents the value of the installed capacity of the present year, P_o represents the value of the installed capacity of the previous year, t is the time interval between the previous and present year, and r is the growth rate. An important factor in guiding Bangladesh towards a future of resilience, inclusivity, and sustainable growth is the country's estimated energy consumption. Bangladesh can create a path that not only satisfies it is present energy needs but also guarantees a stable and sustainable energy landscape for future generations by thoroughly comprehending and addressing these energy dynamics.

Table 1. The projected electricity demand and growth rate

Fiscal year	2016	2021	2026	2031	2036	2041
GDP growth rate (p.a)	6.70%	7.70%	7.72%	6.70%	5.70%	4.75%
Projected demand of electricity (MW)	13100	17200	24347	34005	45314	61330

3.1. Primary energy mix for power generation in Bangladesh

As of June 2022, the combined power generation capacity of the public and private sectors in Bangladesh reached 25,700 MW [24]. To account for maintenance and forced outages, approximately 20% of the capacity was allocated, resulting in an available generation capacity of around 22,482 MW without any fuel constraints. However, the maximum generation achieved by June 30, 2022, was only 14,782 MW, which fell short of the available capacity. This discrepancy could be attributed to limitations in fuel supply. The distribution of the total generation capacity shows that the public sector accounts for 45.5% while the private sector entities contribute 49%, and the remaining 5% is obtained through imports [6]. Bangladesh's power sector: At a glance is shown in Table 2.

It is important to note that the energy mix can change due to evolving policies, advancements in technology, and shifts in global energy trends. The Bangladesh government has been working on various initiatives to improve energy security, promote energy efficiency, and increase the share of renewable energy in the power generation mix. In Bangladesh's past, natural gas has been the primary energy source used to generate electricity. The majority of the electricity produced in the nation comes from gas-fired power plants, on which the nation is heavily dependent [25]. Bangladesh has a wealth of natural gas resources, which makes it an essential part of the country's energy mix. Bangladesh has been reducing its reliance on a single energy source by progressively adding coal to its energy mix. The rampal power station and other coal-fired

power facilities seek to improve energy security and diversify the nation's energy supply. In contrast to natural gas, coal still makes up a smaller portion of the energy mix. The importance of raising the proportion of renewable energy in Bangladesh's electricity generation has grown in recent years [26]. To take advantage of its plentiful solar resources, Bangladesh has been investing in solar energy projects, such as rooftop solar installations and solar parks [27]. Despite it is relative lack of prominence compared to other power sources, efforts have been made to investigate and harness wind energy for the production of electricity. Bangladesh's energy mix includes a small number of hydroelectric power plants, but their contribution is less than that of other energy sources [28]. Figures 3 and 4 are representing the power production capacity (technology wise) and sector wise power consumption pattern, respectively.

Table 2. Bangladesh's power sector: at a glance (2022-2023)

Types	Amount
Electricity growth	8.27%
Number of power plants	153
Installed capacity (MW)	25,700
Maximum generation (MW)	14,782
Total consumers (in Millions)	43.10
Transmission lines (km)	13,889
Distribution lines (km)	629,000
Grid substation capacity (MVA)	56,882
Per capita generation (including captive)	608.76 kWh
Access to electricity (including off-grid renewable)	100%
Overall system loss (%)	10.41

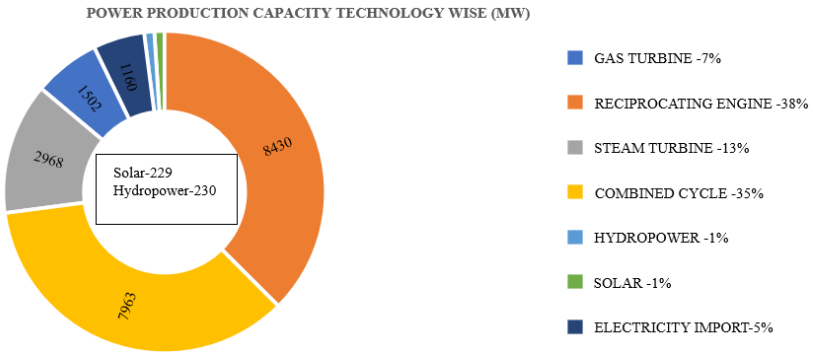

Figure 3. Power production capacity (technology wise) (2022-23)

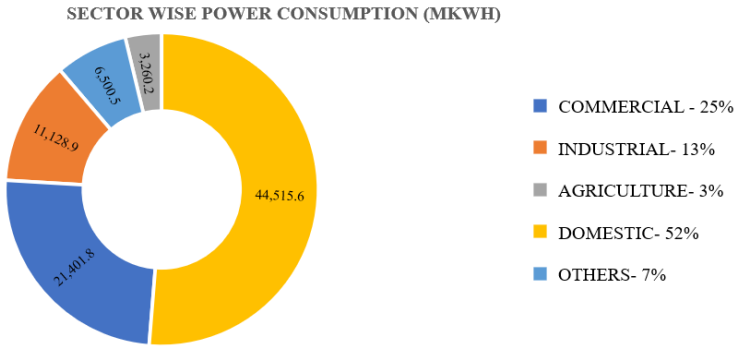

Figure 4. Sector wise power consumption pattern (2022-23)

Figure 5 displays the levelized cost of energy (LCoE) for solar photovoltaic (PV) systems. By the end of 2020, the global weighted average total installed cost of solar PV systems had significantly decreased from USD 4,602/kWp in 2015 to USD 895/kWp. There was also a discernible decrease in the Bangladeshi situation. Technological developments that decreased the cost of solar PV components, decreased the cost of operation and maintenance, and raised higher capacity factors (C.F.) made this advancement possible [29].

The expansion of solar PV power penetration in Bangladesh has been aided by the more affordable mass production of PV modules and accessories in China as well as faster imports from that country. The cost of C.F. was steadily declining due to a number of factors, including increased use of tracking facilities in large-scale projects, deployment in regions with relatively higher radiation, and a decrease in system losses. Thus, in 2022, the utility-scale solar PV projects' global weighted average LCoE is expected to be US $69/MWh. This amount represents an 85% decrease from 2015.

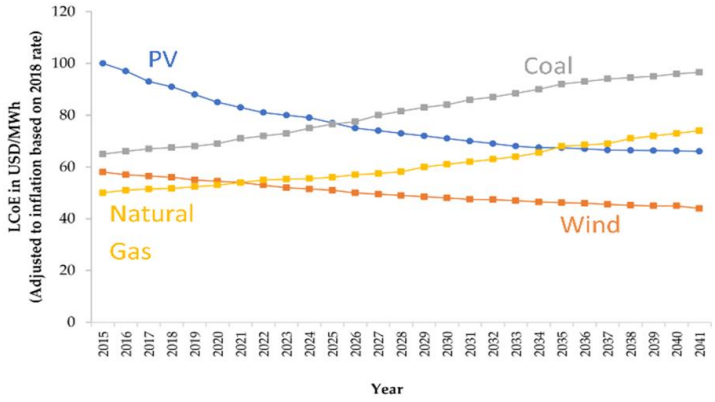

Figure 5. Previous and predictable future of worldwide LCoE from different sources

3.2. Electricity import scenario of Bangladesh

Bangladesh is part of the South Asian Association for Regional Cooperation (SAARC), which aims to enhance regional cooperation in various sectors, including energy. Cross-border electricity trading and cooperation have been discussed as a means to ensure energy security and optimize energy resources within the region. Since October 2013, Bangladesh has been importing 500 MW of energy from India, with an additional 100 MW added in March 2016 and an extra 560 MW in December 2018 [21]. The amount of power generated in Bangladesh as a whole thanks to these imports is about 10%. The scenario for power imports in the fiscal year 2022-2023 is shown in Table 3.

Table 3. Electricity import scenario 2022-2023

Import location	Power transmission capacity	Imported electricity amount (MW)
Bheramara, Kustia (from Baharampur, India)	400 KVA	1000
Cumilla (From Tripura)		160
Total Import from India		1160

About 62% of the power produced at this time was produced domestically utilizing fuels including natural gas, coal, and hydro. Diesel and furnace oil were among the petroleum fuels imported, which made up 28.44% of the power generated [21]. Additionally, through international energy commerce, 5% of the electricity was imported from India. There are plans to dramatically boost the 1,160 MW of power that Bangladesh now imports from India in the foreseeable future [30]. Various projects and proposals were being explored to facilitate electricity trade between the two countries. These projects include the Bangladesh-India Grid Interconnection, which aimed to establish transmission links between the two countries to facilitate cross-border electricity exchange. Discussions were also underway regarding potential electricity cooperation between Nepal and Bangladesh. Nepal has significant hydropower potential, and exporting surplus electricity to neighboring countries like Bangladesh was being explored as a means of mutual benefit [31].

4. RENEWABLE ENERGY RESOURCES OF BANGLADESH

Renewable energy sources have the potential to improve Bangladesh's energy security and lessen its reliance on gas. Biomass is used for cooking in regions of the nation where access to the electric grid or natural gas supplies are few, while solar and wind energy are used to dry different types of cereals and clothing. Currently, biomass is used extensively in the production of renewable energy, particularly for heating and cooking. It makes for 27% of Bangladesh's overall primary energy consumption [32]. The nation also has excellent solar energy production potential. Due to its reputation for being environmentally friendly,

renewable energy is becoming more and more popular on a global scale as non-renewable fossil fuel stocks are depleted [33]. Traditional biomass fuels, conventional hydropower, and novel renewable resources including solar PV, wind, and biogas are the three primary categories of renewable energy sources used in Bangladesh.

4.1. Traditional biomass fuels in Bangladesh

Traditional biomass fuels in Bangladesh include wood, agricultural residues, animal dung, and crop waste. These resources are often readily available in rural areas and have been used for generations to meet basic energy needs. The different woods and trees that may be found in rural locations provide a source of wood fuel. The country's biomass fuel is also mostly composed of agricultural waste and animal excrement [34]. A fraction of the available agricultural wastes and a portion of the overall amount of animal dung generated are used as fuel during crop harvesting. These materials' suitability as fuel relies on the environment and the socioeconomic status of the owners. The chance to enhance the rural energy consumption pattern is presented by the conversion of biomass into more energy-efficient fuel. Cooking, lighting (Mantel/Hazak), and using tiny generators to produce energy are all excellent uses for biogas. In Bangladesh, there are already over 80,000 homes and village-level biogas plants, with Infrastructure Development Company Limited (IDCOL) installing about 50,000 residential biogas plants [21]. Expanding basic biogas technology through village-level biogas production, rural electrification, and power generation using internal combustion engines or micro turbines has tremendous potential. The biomass potential of Bangladesh is seen in Figure 6.

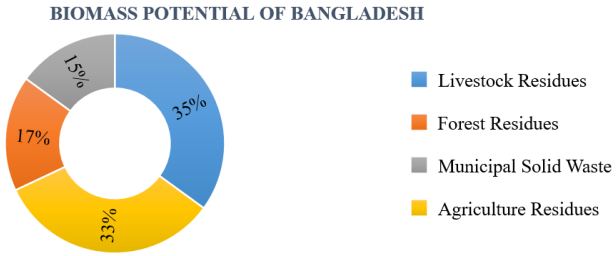

Figure 6. Biomass potential of Bangladesh

The power generation in Bangladesh heavily relies on non-renewable energy sources, particularly natural gas, which is causing a rapid depletion of these finite resources. It is therefore essential to reduce the dependence on non-renewable energy sources and instead harness the available renewable resources to meet the country's substantial energy demand. Many people residing in rural, remote, coastal, and isolated areas of Bangladesh still lack access to electricity. However, renewable energy resources, especially biomass, have the potential to play a crucial role in electrifying these underserved regions. Humanity has been using biomass as an energy source for thousands of years. The potential for bio-energy in Bangladesh, as well as its use and application of renewable energy technologies (RETs), are examined in research by Paul *et al.* [32]. Improved cooking stoves, biogas facilities, and biomass briquetting are examples of RETs that are often used. The assessment takes into account the potential of animal dung, agricultural leftovers, and forest residue. Bangladesh's predicted total biomass resource for energy in 2021-2022, with an annual energy potential comparable to 124.70 million tons of coal, was 249.40 million tons. The quantity of recoverable biomass at that time was 249.40 million tons, or 2670 MW of energy.

4.2. Conventional hydropower in Bangladesh

According to a 1996 assessment, the nation's total hydropower potential was 1,500 MkWh/year, with Kaptai (1,000 MkWh/year), Matamuhury (300 MkWh/year), and Sangu (200 MkWh/year) having particularly high potential. Five units totaling 230 MW were the installed hydroelectric capacity at Kaptai as of 2018–19, producing 8934 MkWh of electricity. Depending on rainfall, hydroelectric facilities have an annual ability to produce between 700 MkWh and 1,000 MkWh [21].

In order to investigate the possibility of building two further hydropower units at Kaptai with a combined generating capacity of 100 MW, units 6 and 7, a feasibility study was carried out in 1998. Hydropower stations might be built in the Sangu and Matamuhury rivers in the Chittagong Hill Tracts. In addition, the option of building a second dam for hydroelectric purposes six kilometers downstream of the current Kaptai dam exists. The Chittagong Hill Tracts community is already aware of the drawbacks of the

Kaptai hydropower facilities that are now in operation, but appropriate rehabilitation initiatives should be put in place. Given the lack of energy in the nation, it is crucial to investigate the viability of generating extra electricity using both conventional and mini/micro hydropower methods in order to partially satisfy future energy demands [35].

There is also a good chance that Bangladesh's northeastern area will support the country's hydroelectric industry. For this reason, a preliminary assessment was carried out by the Northeast Regional Water Management Project (FAP-6) under the flood action plan (FAP) to identify possible sites and rivers for hydro energy production. The primary goal of the project was to identify the most viable locations for runoff-based, low-head hydropower plants [29]. Based on the average monthly discharges and 5 metres of head for these ten sites, they calculated an overall potential of 161 MW and 1,410 gigawatt hours of energy production annually. From this study, nine rivers were also determined to be appropriate. Rivers typically have high water discharge during the rainy season and nearly dry out during the winter. Thus, during the winter, there will be a considerable drop in power generation. The annual production of these nine rivers is predicted to be 307 GWh, with an estimated 35 MW of power output [29]. Table 4 displays the possible small hydropower sites district wise capacity acknowledged by BPDB and Bangladesh water development board (BWDB). Figure 7 is shown the electricity generation in percentage from hydropower sources in Bangladesh from 2010 to 2023.

Table 4. Possible small hydropower sites acknowledged by BPDB and BWDB

SL	District	Potential of electrical energy (kW)
1	Chittagong	132
2	Sylhet	720
3	Jamalpur	95
4	Dinajpur	171
5	Rangpur	80

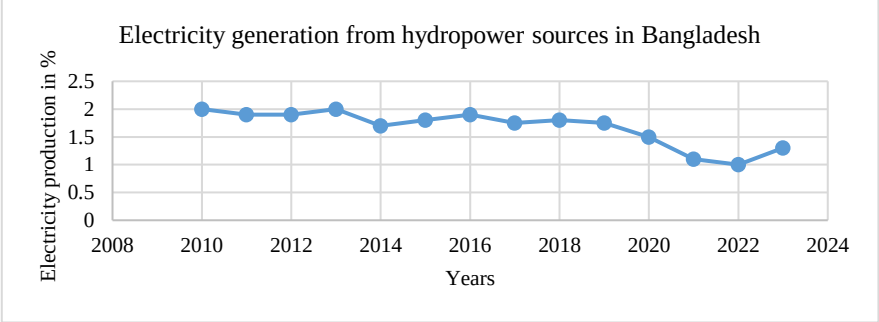

Figure 7. Electricity generation in percentage from hydropower sources in Bangladesh from 2010 to 2023

4.3. New-renewable energy resource of Bangladesh

By 2015 and 2020, respectively, 5% and 10% of all power were to be produced using renewable energy sources, according the renewable energy policy 2008 [36]. Under the sustainable and renewable energy development authority (SREDA) Act of 2012, the SREDA was created to advance renewable and efficient energy technologies. Currently, institutionalization is taking place inside the authority. As of June 2019, 368 MW of power were produced entirely from renewable energy sources, such as solar PV, biomass, and biogas. The entire generation of renewable energy, including off-grid, renewable energy, and captive sources, is 765.62 MW when hydropower generation (230 MW) is included. This represents around 3.035% of the nation's total electricity generation capacity of 25,235 MW in the FY 2021-22 [21]. The government has already started a number of initiatives in the development of renewable energy, with some projects/programs already finished and others still in progress.

4.3.1. Solar energy in Bangladesh

Solar energy has gained substantial popularity in Bangladesh, especially for off-grid and remote areas. The government's "solar home system (SHS)" program has provided millions of households with solar panels, enabling access to electricity in areas without grid connectivity [37]. Additionally, grid-connected solar power projects, including solar parks and rooftop solar installations, have been developed to contribute to the country's electricity generation [38]. Bangladesh enjoys a privileged geographic location that receives

adequate sunshine for the most of the year, with the exception of the time when it rains heavily from June to August, which is located within 20034' to 26038' north latitude. The nation has a lot of solar energy, ranging from 4 to 7 kWh/m^2/day, which is enough to meet the country's energy needs. The solar power potential in Bangladesh is represented in Figure 8.

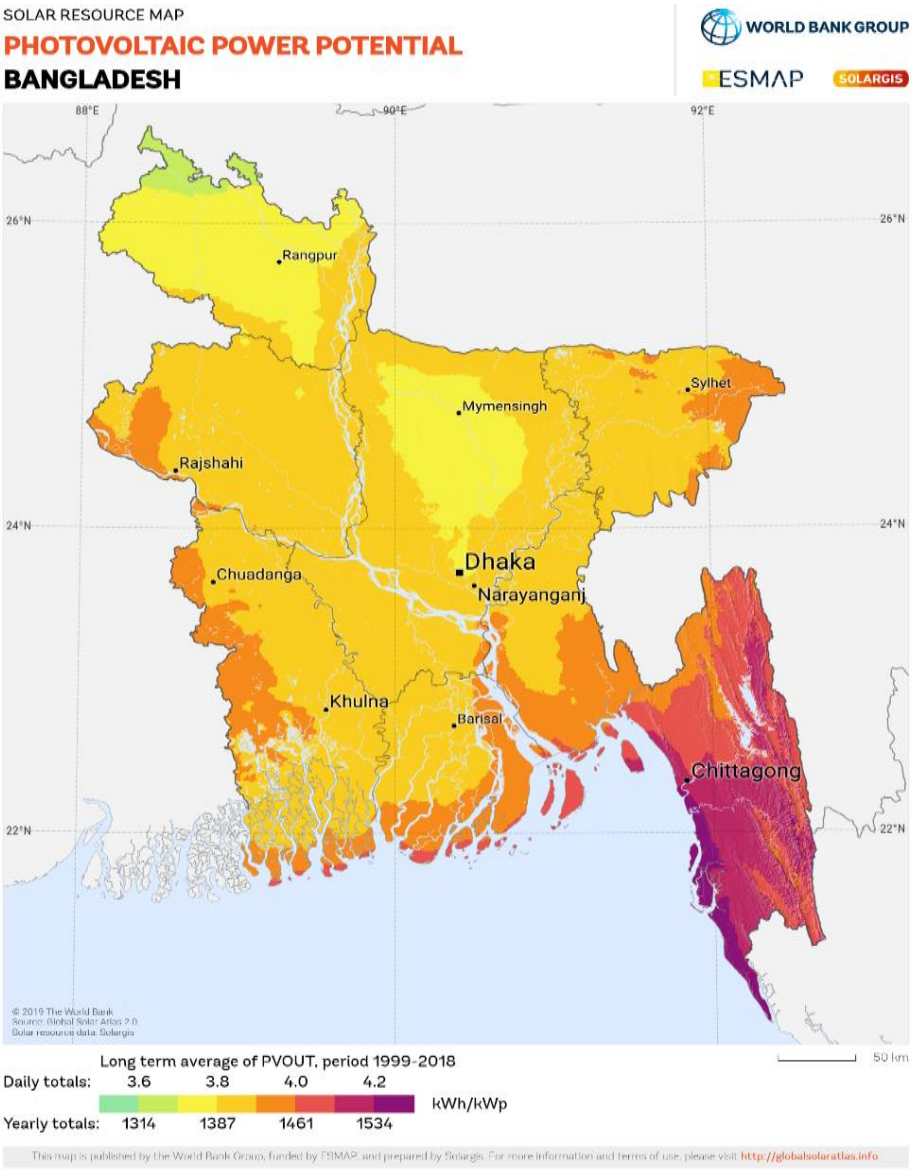

Figure 8. PV solar power potential in Bangladesh

Cities in the northern area that receive a lot of solar radiation all year round are Rajshahi, Rangpur, and Dinajpur [39]. The region's flat terrain and comparatively lower humidity levels support ideal solar conditions. The central region includes the capital city of Bangladesh, Dhaka, and the surrounding areas. During the dry season in particular, these areas receive comparatively high levels of solar radiation. The availability of solar energy is facilitated by the level terrain and reduced cloud cover. Significant solar radiation benefits the southern cities, such as Barisal, Khulna, and Jessore. The climate is influenced by the Bay of Bengal's proximity, with high humidity during the rainy season. The eastern states of Sylhet and Comilla enjoy good solar radiation, particularly in the dry season. The availability of solar energy is influenced by topography and regional weather patterns. In general, the western region-which includes cities like Khulna and Jessore-has favourable solar conditions. Solar irradiance patterns are influenced by both climatic variations and geographic features. Due to terrain and elevation variations, hilly areas, like those in the Chittagong Hill Tracts (e.g., Bandarban, Rangamati), may display variations in solar irradiance [39].

During the dry season, clear skies maximise solar exposure, even though the hilly terrain can introduce shading effects. The proximity of the Bay of Bengal and its associated weather patterns can cause variations in solar irradiance in coastal areas, like Cox's Bazar.

Bangladesh has clearer skies and less cloud cover from November to March, which is known as the dry season. Because of the increased sunshine exposure and longer daylight hours during these months, solar PV systems typically produce higher output. The dry and wet seasons change between April and October. Even though solar PV output is still comparatively high, weather patterns can cause some variability [40]. Monsoon rains and increased cloud cover are hallmarks of the wet season, which runs from April to September. Because of the frequent cloud cover that reduces sunlight exposure, solar PV output may decrease during these months.

The local meteorological patterns can have an impact on the PV power output distribution. Higher solar energy production is typically found in areas with more sunshine and fewer cloudy days. The amount of sunlight that PV panels receive can be influenced by the topography of the area. Solar power generation can be increased and is more consistent in flat terrain with little shading. A major factor is the distribution of installed PV capacity, which takes into account both distributed solar installations and utility-scale solar farms [41]. The total PV power output will be higher in areas where solar installations are more concentrated. Level 0: Realistic potential that ignores any restrictions on land use level 1: practical potential up to level 0, excluding land where utility-scale PV plants are physically prevented from operating. Level 2: practical potential at level 1, excluding land that might be subject to land use restrictions because of environmental concerns and cropland preservation. The distribution of PV power output in Bangladesh is shown in Figure 9.

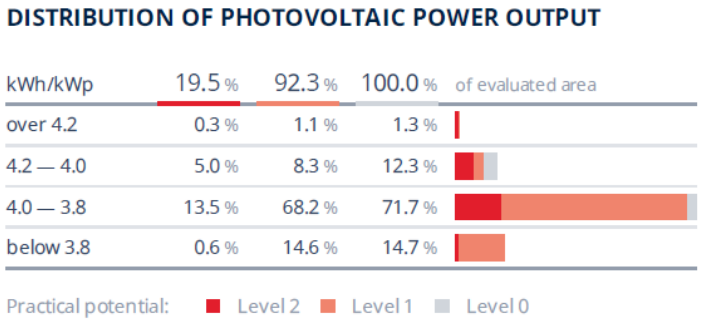

Figure 9. Distribution of PV power output in Bangladesh

Rural populations in Bangladesh are using solar PV systems to power homes and small enterprises in off-grid rural regions, demonstrating a growing acceptance of these technologies [42]-[45]. A significant milestone in the country's solar energy development is the establishment of the largest solar power plant in Sundarganj Upazila of Gaibandha, which has been integrated into the national grid. With a capacity to generate 200 MW of electricity, this solar power plant contributes to the government's target of achieving 10% of the total electricity generation from renewable energy sources by 2022 [6]. The power project has been implemented at the cost of around Tk1,800 crore on a land of around 700 acres in the char areas of Khodda and Lathshala at Tarapur Union. Located near the Teesta River, it has already become a tourist attraction in the area. The solar power plant at Gaibandha has been fully equipped with 520,000 solar panels. Table 5 is shown an overview of some notable solar power plants in Bangladesh.

Bangladesh is blessed with an abundance of sunlight all year round due to its tropical location. Because of it is close proximity to the equator, the country has a high theoretical potential and consistently high levels of solar irradiance [46]. Bangladesh has between 2,300 and 3,000 hours of sunshine on average annually, which offers a sizable theoretical potential for the production of solar energy. Large tracts of open land, including rooftops and vacant areas, exist in Bangladesh and have the potential to support a sizable number of solar PV installations. Bangladesh's larger plan to use solar energy and lessen reliance on fossil fuels includes these solar power plants. The development of solar energy projects across the nation has been greatly aided by government initiatives, including laws and subsidies. As Bangladesh continues to develop its solar energy infrastructure, it is imperative to monitor new and ongoing projects. Summery statistics of the theoretical and practical potential of PV system in Bangladesh is shown is Figure 10.

The rural electrification board (REB), a government organization, has been actively involved in commercializing solar power solutions for home, commercial, and irrigation applications in order to promote solar

power electrification in rural regions [47]. The government-owned company IDCOL has distributed SHS in conjunction with partner NGOs. Despite solar energy's relatively high production costs, attempts are being undertaken to increase its commercial viability. Solar energy is becoming more and more popular in Bangladesh, especially in the country's outlying areas, and the government has put in place a number of programs to subsidize its use. Additionally, the government intends to install solar panels with a 5 to 10 MW capacity [21].

Table 5. Overview of some notable solar power plants in Bangladesh

SL	Name	Location	Capacity (MW)	Description
1	Teesta solar power plant	Sundarganj, Gaibandha	200	Teesta Solar Limited, a sister concern of BEXIMCO Group. This is the largest capacity solar power plant in Bangladesh.
1	Shapla solar power plant	Khulna	20	Shapla Solar Power Plant, which has been in operation since 2016, is one of Bangladesh's first solar projects and contributes to the country's grid.
2	Bangladesh-South Korea Friendship solar power plant	Tentulia, Panchagarh	28	This solar power plant was the result of cooperation between South Korea and Bangladesh and was put into service in 2018.
3	Sirajganj 150 MW solar power park	Sirajganj	150	The Sirajganj Solar Power Park, one of Bangladesh's biggest solar power initiatives, was put into service to increase the nation's capacity for renewable energy.
4	Mymensingh solar power plant	Mymensingh	10	This solar power plant has been in operation since 2018 and helps meet the region's increasing energy demand while also contributing to the national grid.
5	Teknaf solar power plant	Teknaf, Cox's Bazar	50	The goal of this solar power plant in Bangladesh's southeast is to take advantage of the area's abundant solar energy.
6	Jamalpur solar power plant	Jamalpur	20	The Jamalpur solar power plant, which has been in operation since 2019, is a component of Bangladesh's initiatives to diversify its energy mix and lessen its dependency on conventional sources.
7	Sutiakhali solar power plant	Sutiakhali, Cox's Bazar	50	The Sutiakhali solar power plant, another solar project in Cox's Bazar, supports the nation's effort to boost its capacity for renewable energy.

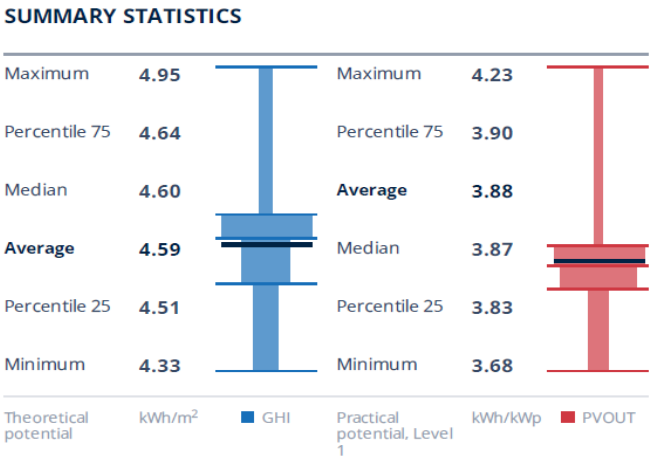

Figure 10. Summery statistics of the theoretical and practical potential of PV system in Bangladesh

- SHS in Bangladesh

SHS are dependable power sources that deliver electricity for lighting and running tiny electric fans, radios, and televisions. They can also charge mobile phone batteries and power direct current (DC)-driven devices like drills and soldering irons. Larger SHS systems are capable of powering several equipment, including computers, freezers, and pumps [48]. SHS are being distributed to those who live off the grid by IDCOL and BREB. While BREB has dispersed around 30,000 SHS units across the country, IDCOL has already distributed over 6 million SHS units (with an installed capacity of 250 MW) through a number of partner organizations. Bangladesh's SHS program has received international recognition for its innovative approach to rural electrification. It has been showcased as a model for other countries looking to provide clean and affordable energy solutions to underserved populations.

- Solar ırrigation system in Bangladesh

Bangladesh is an agriculture-based country, and irrigation is crucial for crop production. Solar irrigation systems can provide reliable water supply for fields, even in remote areas with limited access to

electricity. Solar irrigation systems reduce dependence on grid electricity or diesel generators, which can be expensive and unreliable. An innovative technique that addresses the energy issues encountered by economies with an agricultural foundation is solar-powered irrigation. It provides an inventive and green solution for irrigation systems, which at the moment rely on incredibly inefficient electric and diesel pumps [47]. Solar water pumps can eventually replace electric and diesel pumps in irrigation systems, saving huge amounts of power and money [49], [50]. A total of 2,125 solar irrigation pumps with a 44 MW capacity have been installed as of June 2021. The IDCOL, a government-owned financial institution, has been implementing solar irrigation projects across Bangladesh. This initiative aims to promote sustainable energy use in agriculture.

4.3.2. Bio fuel in Bangladesh

The SREDA has been working to promote and facilitate the development of renewable energy projects, including biofuel initiatives. Biofuels can be derived from various plant sources such as rapeseed, mustard, corn, sunflower, canola, algae, soybean, pulses, sugarcane, wheat, maize, and palm. Among these options, non-edible oilseed bearing trees are the most popular choice for biofuel production. Two highly suitable tree species for this purpose are Jatropha curcas (locally known as Jamal gota) and Ricinus communis (known as Verenda). These trees can thrive in diverse soil and climatic conditions across Bangladesh. The use of biofuels is not a new concept in the country [51], [52]. In the early 20th century, biofuels were commonly used for lighting lamps or lanterns. Given that Bangladesh is primarily an agriculture-based nation, biofuels can serve as a promising alternative. It is possible to blend biofuels with diesel or petrol at a ratio of 30%, making it an excellent fuel for lighting lamps in rural areas [21]. In addition to liquid biofuels like biodiesel, Bangladesh has been actively promoting biogas production from organic waste and animal manure. Biogas can be used for cooking, heating, and electricity generation. The utilization of biofuels is on the rise in many European countries. Germany, for instance, has numerous fuel stations that offer biofuels at a lower cost compared to petrol or diesel. The German government has set a target that by 2020, 5%of every liter of fuel must consist of biofuel.

4.3.3. Wind energy in Bangladesh

Bangladesh has some potential for onshore wind energy generation, primarily in coastal areas and certain hilly regions. Bangladesh is actively investigating the viability of harnessing wind power as an alternative energy source. Currently, there are operational windmills with a capacity of 2.9 MW in the coastal regions of the country. However, to become more competitive with traditional commercial energy sources, Bangladesh has been waiting for advancements in wind power technology [53]. As part of it is efforts, the government has devised a pilot project to install windmills along the seashore, with a planned capacity of 20 MW. This initiative aims to further explore the potential of wind power in Bangladesh.

One excellent source of free renewable energy is wind. Bangladesh has just begun studying wind energy. The study's conclusions indicate that Bangladesh's coastal areas have a great deal of potential for capturing wind energy. The centre for wind energy technology (CWET) in India claims that the wind speed in Bangladesh, with the exception of the coastal region, is insufficient (4 m/s) for the production of electricity throughout the nation [54]. Another important component of wind flow is altitude. At different heights, different wind speeds are noticed. Table 6 shows the wind speed at six different places in Bnagladesh. This table shows that Chittagong, Kuakata, Charfassion, and Cox's Bazar, which are coastal areas, have excellent annual wind speeds that are ideal for producing electricity.

Table 6. The wind speed at six different places in Bangladesh

Location	Height (ft)	Avg. speed (m/s)
Sitakundu	65.62	3.02
Sitakundu	98.43	3.56
Kuakata	65.62	3.14
Kuakata	98.43	4.15
Kutubdia	65.62	3.65
Charfassion	82.02	4.44
Chittagong	82.02	4.37
Cox's Bazar	82.02	3.8

The 22 turbines in Cox's Bazar wind power project generate 60 MW, which is fed into the national grid. China's State Power Investment Corp. (SPIC) subsidiary Wuling Power Corporation is investing in and Power China Chengdu Engineering Corporation is building the wind power project. Bangladesh has the potential to develop a massive renewable energy generation capacity in the future. because one of the main

goals in creating a developed nation is electricity. The findings of the pilot project indicate that there is a potential to generate an additional 200 MW of power through wind energy.

As fossil fuel prices and CO_2 emissions continue to rise, along with technological advancements and the scaling up of renewable energy systems, it is expected that renewable-based systems will become more cost-competitive in the future (IEA 2011). The EU has been focusing on promoting renewable energy and energy efficiency through this package, which includes regulations and directives aimed at advancing microgrids and distributed energy resources [55]. This directive sets binding targets for renewable energy use and encourages member states to facilitate the integration of renewables through mechanisms like microgrids. The government of Bangladesh has expressed interest in diversifying its energy mix and reducing dependence on fossil fuels. The renewable energy policy, formulated in 2008, includes wind energy as one of the priority areas for development. One of the main challenges for wind energy in Bangladesh is the relatively low and inconsistent wind speeds in many parts of the country [56]. Wind energy projects require consistent and sufficient wind speeds to be economically viable.

5. NUCLEAR ENERGY IN BANGLADESH

Nuclear power is known for its substantial initial investments, technical intricacies, and inherent risks related to technology, market dynamics, and regulations. However, it boasts low operational costs and has the capacity to generate significant amounts of baseload electricity while emitting minimal CO_2 [57]. Nuclear power is considered a low-carbon energy source, which can help Bangladesh in its efforts to mitigate climate change. Typical construction durations range from five to eight years, starting from the first concrete pouring. The Government of Bangladesh entered into a comprehensive agreement with Russia on December 25, 2015, to construct and establish the nation's first nuclear power plant in Rooppur, Pabna. The Rooppur Nuclear Power Plant is expected to contribute significantly to Bangladesh's energy diversification efforts, reducing dependence on fossil fuels and enhancing energy security. The Rooppur Nuclear Power Plant features two VVER-1200 pressurized water reactors, each with a capacity of about 1,200 MW, is estimated to cost $12.65 billion [21]. Rosatom is responsible for supplying all the fuel required for the Rooppur nuclear power plant, and as per the standard practice followed by Russia in such cases, all used fuel will be returned to Russia. In March 2017, a preliminary agreement was signed regarding the used fuel, specifying an annual quantity of approximately 22.5 tons from each reactor (consisting of 42 fuel assemblies, with each assembly containing 534 kg of fuel). Subsequently, in August 2017, an additional agreement was signed for the repatriation and reprocessing of the used fuel.

To address the future electricity demands of the country, the Bangladesh Atomic Energy Commission (BAEC) has initiated a survey in eight char areas of the southern region. The purpose of this survey is to identify one or two suitable sites for the construction of Bangladesh's second nuclear power plant. The survey will encompass various aspects such as demographic analysis within a 5-km radius, assessment of seismic stability, geological considerations, and evaluation of power infrastructure and communication systems.

6. DEVELOPMENT CHALLENGES IN POWER SECTOR OF BANGLADESH

Bangladesh has been struggling to bridge the gap between electricity demand and supply [20]. The demand for electricity was consistently increasing due to population growth, urbanization, and industrialization, putting pressure on the power generation capacity. Inefficient distribution systems, technical losses, and electricity theft were prevalent issues in the power sector. Resistance and inefficiencies in the equipment and power lines during the transmission and distribution process result in technical losses. Technical losses are a result of ageing infrastructure and low grid modernization investments. A sizable portion of T&D losses in Bangladesh are commercial losses, which are frequently linked to theft, inefficient billing, and non-payment. Reducing commercial losses requires concerted efforts to enhance billing and collection procedures and fight electricity theft [20]. Reducing losses can be aided by the use of smart grid technologies, which allow for real-time monitoring and management of the electrical distribution system. Smart grids lower technical losses and enable better energy flow management. These factors contributed to transmission and distribution losses, which further strained the sector's financial sustainability. Bangladesh heavily relied on natural gas for power generation, and there were concerns about the availability and sustainability of this fuel source. Frequent gas shortages led to reduced power generation capacity, causing electricity shortages. State-owned utilities, such as BPDB and REB, faced financial challenges due to a combination of factors including inadequate tariff structures, inefficient operations, and a high level of non-performing loans. Insufficient investments in the power sector hindered the development of new generation capacity and the modernization of infrastructure. This lack of funding affected the sector's ability to keep up

with growing demand. Bangladesh's heavy reliance on fossil fuels for power generation raised environmental concerns, contributing to air pollution and greenhouse gas emissions [58]. There was a growing need to transition towards cleaner and more sustainable energy sources [59]. Inconsistent policies and regulatory frameworks posed challenges for investors and stakeholders in the power sector. Clear and stable policies are essential to attract investments and foster sector growth. While Bangladesh was making efforts to diversify its energy mix by incorporating renewable energy sources like solar and wind, integrating these sources effectively into the grid and addressing technical challenges remained a hurdle. The power sector required skilled manpower to manage operations, maintenance, and technological advancements [59]. Ensuring a well-trained workforce was vital for the sector's growth and sustainability. Political instability and social unrest could impact the implementation of long-term plans and policies in the power sector. Consensus-building and stakeholder engagement were essential to overcome these challenges.

7. FUTURE PROSPECTS FOR THE POWER SECTOR IN BANGLADESH

Bangladesh is probably going to keep concentrating on increasing the amount of renewable energy available, especially solar and wind power. Wind farms and large-scale solar projects are anticipated to make major contributions to the nation's energy mix [54]. It is probable that the government will impose additional regulations on energy efficiency in a number of industries. In order to lower overall energy consumption, this may entail implementing energy-efficient building codes, practices, and technologies. Bangladesh's reliance on natural gas for electricity production suggests that efforts to effectively explore and utilise the country's natural gas resources may continue. This entails using ethical extraction methods and making technological investments to increase recovery rates. Bangladesh might investigate additional prospects for transnational power trading in order to augment energy security, foster interregional collaboration, and tackle fluctuations in supply and demand.

Because they offer better grid management, lower transmission losses, and increased reliability, smart grid technologies are expected to become more widely used. Demand-side management and improved integration of renewable energy sources are made possible by smart grids. Continuous investments in power infrastructure are necessary to meet the rising demand for electricity. These investments include building new power plants, transmission lines, and distribution networks. Bangladesh might keep pushing for private industry involvement in the electricity industry. In order to finance and carry out new projects, foreign investments and public-private partnerships (PPPs) may be important factors. It is likely that efforts to increase rural and remote areas' access to electricity will continue. To combat energy poverty, this might entail putting off-grid and micro-grid solutions into place, such as systems based on renewable energy. In order to address the intermittent nature of renewable energy sources and increase overall system efficiency, research and development on energy storage technologies, grid management systems, and other innovations should continue. Bangladesh might strengthen its commitment to cutting carbon emissions from the power sector in line with international initiatives. To lessen the effects of climate change, this may entail implementing greener technologies and practices.

With the world's energy ecosystem being so dynamic and interconnected, adopting cutting-edge technologies has come to be associated with advancement. Energy storage technologies, which include everything from state-of-the-art battery systems to creative thermal storage solutions, have the potential to completely transform how we store and use energy. Concurrently, the adoption of smart grid systems, which are distinguished by advanced communication networks and real-time data analytics, signifies a fundamental change in the way power grid management and optimisation are conducted. For Bangladesh, a country grappling with the intricacies of swift economic expansion and increasing energy requirements, implementing these cutting-edge technologies is not just a matter of preference but also a tactical imperative. Energy storage solutions present the prospect of reducing the intermittent nature of renewable energy sources, offering grid stability, and guaranteeing a steady supply of electricity as the nation works to ensure a resilient and sustainable energy future [60]. In a similar vein, integrating smart grid systems could improve grid management, lower transmission losses, and give customers more control over how much energy they use. Conceiving of a fully integrated smart grid network that combines real-time data analytics, communication technologies, and cutting-edge sensors. Predictive maintenance, adaptive management, and efficient resource use would all be possible with this intelligent grid system. Establishing research and development hubs to create a thriving innovation ecosystem and to encourage cooperation between government, business, and academia. putting money into cutting-edge technologies like artificial intelligence and quantum computing to keep pushing the envelope of what's feasible in the power industry.

8. CONCLUSION

Electricity is in high demand globally and is essential for a country's technical, economic, and social advancement. The analysis of the power industry in Bangladesh highlights the substantial significance of

tackling existing obstacles while embracing forthcoming prospects in order to guarantee a sustainable and resilient energy future for the country. In recent years, Bangladesh's power sector has achieved great progress despite encountering obstacles such as insufficient infrastructure, transmission losses, and budgetary limitations. This progress is evident via the growth in capacity and the diversity of energy sources. Nevertheless, in order to maintain this progress and satisfy the increasing requirement for power, together endeavours are required to surmount the mentioned obstacles. This calls for a comprehensive strategy that encompasses various aspects, such as allocating resources towards the development of infrastructure, strengthening regulatory frameworks, advocating for the utilisation of renewable energy sources, and implementing energy efficiency measures. Furthermore, it is crucial to promote cooperation among the government, corporate sector, and foreign partners in order to secure resources and expertise for the sector's goals.

Looking forward, the power sector in Bangladesh holds significant potential for growth, namely in harnessing renewable energy sources like solar and wind power, while also investigating novel technologies and business models. Seizing these prospects will not only bolster energy security and environmental sustainability, but also foster economic expansion and improve the overall welfare of the population. The opportunity for Bangladesh to convert its power industry into a powerful, inclusive, and sustainable engine of growth and development lies in its ability to address present difficulties and embrace future prospects. Through collaborative endeavours and calculated financial commitments, the country may establish a path towards a more promising energy future, guaranteeing dependable and cost-effective electricity availability for its entire population, while also making a valuable contribution to worldwide initiatives aimed at reducing the impact of climate change.

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