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Renewable Energy in Bangladesh: Challenges, Sustainable Power Generation, and Future Prospects

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ABSTRACT

This review examines the potential of renewable energy sources to meet Bangladesh's expanding energy needs and critically examines their role in the country's power industry. The study highlights the critical contributions of solar, wind, hydro, biomass, biogas, geothermal, and nuclear resources, each of which uniquely reduces dependence on fossil fuels. Visual aids, including charts and maps, illustrate the distribution and capacity of renewable energy, highlighting the urgent need for integration to meet future demand. The review also analyses financial requirements, cost-effectiveness, and potential for reduction of greenhouse gas emissions. Critical barriers to rural electrification include land availability, funding constraints, and weak network infrastructure. The study argues that technological advancements, green finance, and policy reforms are crucial to overcoming these challenges. Proposed solutions include infrastructure modernization, international cooperation, and adopting climate-resilient technologies. Hydropower and solar energy are the most promising energy sources, contributing significantly to the current energy balance. The findings demonstrate a cooperative strategy for utilizing Bangladesh's renewable energy resources for a robust and sustainable energy transition.

Keywords: Renewable Energy; Bangladesh Energy Scenario; Fossil Fuels; Electricity Generation; Sustainable Solution.

1. Introduction

Today, energy is closely linked to development and is a foundation and essential component of modern national development. It is essential for sustaining and improving human life [1]. Population growth and economic development have increased Bangladesh's energy demand recently. Renewable energy has significant potential for sustainable growth in the energy sector [2]. Renewable energy sources such as solar, wind, hydro, and biomass meet energy demands while contributing to worldwide social development and environmental protection [3]. Wind energy is considered one of the most promising renewable sources due to its high efficiency and minimal pollution [4]. Bangladesh's energy needs are highly dependent on natural gas, furnace oil, coal, and imports. This source contributes about 96.78% of the whole electricity supply for the country, while the contribution of renewable energy is 3.22% [5]. Figure 1 displays the installed capacity of BPDB power plants as of September 2024. Coal, natural gas, and petroleum are commonly called fossil fuels [6]. The reliance on fossil fuels negatively impacts the environment by emitting greenhouse gases, which significantly contribute to global warming; when fossil fuels like coal, oil, and natural gas are burned for energy, they release carbon dioxide and other harmful gases into the atmosphere [7]. It is estimated that conventional electricity generation from fossil fuels has contributed to about one-third of global greenhouse gas emissions [8]. In Bangladesh, the existing reserves of this fuel will run out within the coming decades, and there are no significant oil reserves to meet demand solely through imports [9]. Bangladesh has been facing numerous challenges in ramping up the electricity supply due to its acute shortage of fossil fuels [10]. To keep stable foreign reserves, the import of these fuels is discouraged by the growing prices in the global energy market brought on by war scenarios and natural disasters [10].

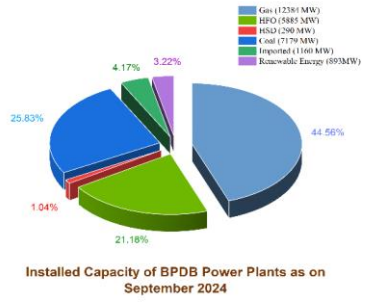

FIG.1. Installed Capacity of BPDB Power Plant as of September 2024

On the other hand, Bangladesh's first nuclear power plant is located in Rooppur, which is expected to inspire the generation of 2.4 GW of electricity in the future and is anticipated to become operational in 2029 [11]. This project requires a significant initial investment and challenges integrating advanced technology [11]. As a result, one national priority for further development is to identify a sustainable source of electricity generation. Therefore, the government is focusing on establishing renewable energy plants as a priority. Wind energy, in particular, has one of the highest potentials for boosting the country's renewable

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energy capacity. It offers the advantage of producing electricity without emitting pollutants [12]. In late July 1887, Professor James Blyth of Anderson's College in Glasgow constructed the first wind turbine for electricity production, setting up a small windmill in the garden of his vacation home in Mary Kirk, Kincardineshire, to provide electric lighting through storage cells [13]. In 1888, Charles Francis Brush equipped his mansion with the world's first self-powered wind turbine, capable of charging 12 household batteries. It made it the first house in Cleveland to have electricity [14]. In response to the energy crisis in 1973, Western countries began seeking their own clean and renewable energy (RE) sources, such as wind, solar, and biomass. While these alternatives are effective, they must inevitably compete with conventional energy sources.

A distinctive feature of this review is its thorough examination of Bangladesh's renewable energy landscape. It highlights the current progress in energy efficiency and the urgent need for change in the sector. The study provides new insights into the country's progress and challenges in creating a greener energy future. It focuses on the interplay between growth rates, environmental sustainability, and renewable resource optimization. It also highlights the importance of these reforms.

2. Methodology

To conduct thorough research, important data has been gathered from academic journals, annual reports, or government websites. Choosing the right buzzwords is a crucial step in writing reviews on any topic. Two hundred academic publications were found using the selected criteria. The main prerequisite for conducting a thorough investigation is a carefully considered approach. The initial planning, evaluation, and outcome phases are the three primary components of the research approach, as seen in Figure. They are described in more detail in the sections that follow. The graphic depicts how the review task is carried out. The review process is shown in Figure 2, including source identification, screening, and data analysis to combine study findings.

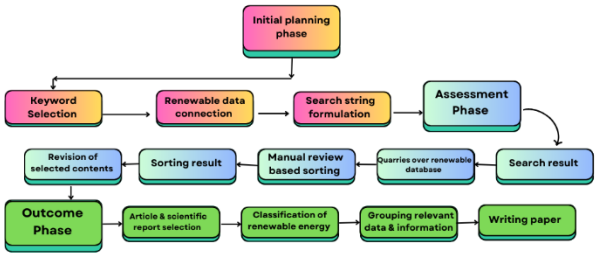

FIG.2. Review Methodology

Initial planning phase: The thorough study process begins with the first planning stage. The development of the research objectives is the focus of this phase. A set of crucial phrases chosen based on the primary objectives was then used to perform an investigation to achieve the goal. The primary resources utilized to search for research articles include MDPI, IEEE, Springer, Elsevier, Taylor & Francis, and Sage. Government publications about renewable energy and power are also taken into consideration. Additionally, energy statistics from other websites about power are examined.

Assessment phase: During the assessment, specific research questions and targeted buzzwords are used to analyze annual data, review articles, and research papers. Each site is carefully reviewed against predetermined criteria to ensure that learning opportunities are met. The retention of only a methodical screening process guaranteed trustworthy and relevant sources for further study, which was guaranteed by off-course or obstructed study goals, which were meticulously eliminated to maintain Arch's precision and integrity.

Outcome phase: At this stage, data is collected from the chosen study locations and divided into several important sections. When pertinent information and insights have been obtained, the article is then produced using this systematic technique.

3. Renewable energy generation scenario in Bangladesh

Bangladesh's goal is to become a developed country, and one of its main priorities is to enhance the electricity sector through several government master plans. The nation now meets many of its electricity needs from fossil fuels. The continuous energy issue is being addressed by the quest for new energy sources, albeit due to the resources' rapid depletion [4]. The reliance on electricity across all sectors is steadily growing, and in today's modern world, access to electricity has become a fundamental right for individuals. The government has already implemented several initiatives to extend electrification to the broader population and regions [15]. The government has already met its goal by providing energy to 100% of the population, and it intends to raise power generation capacity to 40,000 MW by 2030 and 60,000 MW by 2041 [16]. In 2024, Bangladesh's installed power generation capacity is 27791 megawatts (MW) against the maximum demand of 17,200MW [17]. Bangladesh is projected to require 57,000 MW of electricity generation by 2040 to meet its demand [18]. Bangladesh has 144 electricity-generating units with an installed capacity of 27,791 MW and a current output of 27,086 MW. More than 55.56% of these plants are privately owned, 1.38% are joint ventures with foreign countries, and 43.06% are managed by the public sector [19]. Bangladesh's current energy mix as of September 2024: Coal (25.83%), Natural Gas (44.56%), HFO (21.18%), HSD (1.04%), Power Import (4.17%), Hydro (0.83%), Solar (2.17%) & Wind (0.22%) [19].

3.1 Solar

Solar energy is the cleanest, greenest, and healthiest renewable energy source. Additionally, it may significantly strengthen the nation's power position. The sun is the energy source, from photovoltaic power generation to fertilization. The sun produces enough electricity every second to meet the needs of the Earth's crust for the entire season [20]. The solar system is expected to release around 450 EJ of electricity, 7500 times more than what is now consumed worldwide [21]. Solar parks, solar roofs, solar irrigation, solar grids (mini- and nano-grids), solar charging stations, solar-powered telecom BTS, solar home systems, and solar street lights are some of the various configurations in Bangladesh that use solar energy [22]. Bangladesh produces 893 MW of power from renewable sources, with installed solar photovoltaic systems producing around 603 MW [18]. According to Bangladesh's average long-term sunshine statistics, bright sunlight varies from four to eleven hours per day throughout the year, excluding the rainy and winter seasons. The country's solar insolation ranges from 4 to 6

kWh/m^2/day, with the summer months seeing the highest values [22]. Figure 3 illustrates the diversity of solar energy practices in Bangladesh.

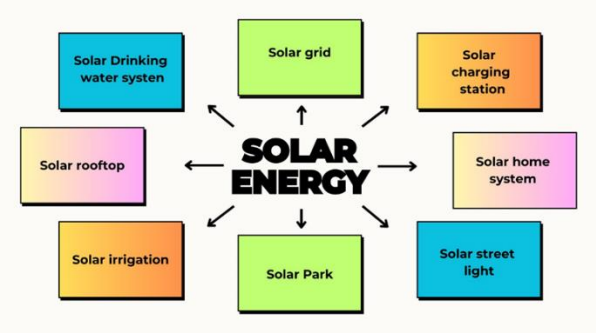

FIG.3. Diversity of solar energy practice in Bangladesh.

Bangladesh is a viable renewable energy source because of its location, which permits it to produce more than 250 trillion kWh of pure solar energy yearly. Large-scale systems with a capacity of about 1 GW are now being developed by utilities in the public and commercial sectors [23-25]. Bangladesh's largest solar photovoltaic power plant is the Rays Power Infra 275-MW solar facility in Sundarganj, Gaibandha [26]. Some solar projects in Bangladesh are shown in Table 1 [27].

Table 1: Present solar projects in Bangladesh.

Location	Capacity (MWp)	Present Status
Barisal Sadar Upazila, Barisal	1	
Sonagazi, Feni	75	
Sundarganj, Gaibandha	200	
Gangachara, Rangpur	30	
Mongla Upazila, Bagerhat	100	
Sirajganj Sadar Upazila, Sirajgonj	7.6	Completed
Shibalaya Upazila, Manikganj	35	& Running
Gauripur, Mymensingh	50	
Kaptai Upazila, Rangamati	7.4	
Panchagarh Sadar, Panchagarh	8	
Teknaf Upazila, Cox's Bazar	20	
Sarishabari Upazila, Jamalpur	3	

3.2 Hydropower

Hydropower is the most notable renewable energy source on Earth. It may have been the world's first renewable energy source, and it continues to provide the most renewable electricity produced worldwide since its inception. Typically, a dam is constructed over a sizable river, and the water is then routed through a hydroelectric power plant, which produces energy and is placed into power lines [28]. The country's quest for renewable electricity heavily relies on hydropower because of its inherent smoothness and environmental friendliness [29]. Bangladesh's Kaptai plant, commissioned in 1962, generates 180 MW of electricity daily. The government plans to increase its capacity by establishing two additional 50 MW units, aiming to increase total production to 230 MW for optimal performance during the rainy season [22]. Potential locations for small-scale hydropower installations include Foy's Lake, Choto Kumira, Sealock, Nikhari Chara, Madhab Char, Moulavibazar, Ranga Poni Gung, Bhugai Kangsha, Marisi, Punarbhaba, Talma, and Pathraj [4]. From micro to large-scale capacity, hydroelectric power flexibility offers a variety of straightforward power options. Micro hydroelectric power plants have capacities up to 100 kW, and small-scale plants with a 1–30 MW capacity are just two instances of how this environmentally beneficial system may be readily incorporated into water supply networks and small river flows, enhancing the environment and the economy [30]. Hydropower makes up 25.75% of Bangladesh's renewable energy mix. Bangladesh has two micro-hydropower plants: a 50-kW facility in Rangamati and a 10-kW unit in Bandarban. Potential locations in the Chittagong district have an estimated capacity of 135.5 MW. However, the Sangu and Matamuhuri basins can produce 300 GWh. 1,400 MW is the large-scale potential of the Brahmaputra basin [31].

3.3 Wind energy

Renewable energy sources such as wind, solar, hydroelectric, and geothermal have played an important role in solving energy problems and mitigating climate change. Among these, wind energy is considered to be one of the cleanest, safest, and most reliable natural energy sources [32]. Wind energy is one of the fastest-growing renewable sources [33]. Wind energy is attractive because it takes up less space and can be easily integrated into agriculture [34]. Analyzed the wind potential in Bangladesh and developed a model to evaluate electricity production based on climate change [35]. Wind research in Bangladesh began only a few years ago and has shown that many southern regions, especially the coast, have great potential for wind generation. These areas benefit from seasonal trade winds across the country for eight months each year from March to October [36]. Bangladesh, consisting of numerous small islands and a 724 km coastline along the Bengal coast, experiences southwesterly, moderate northeasterly, tropical cyclones and summer storms [37]. When the trade wind enters the V-shaped coastal area of Bangladesh, the wind becomes very heavy because the trade wind gains a significant amount of kinetic energy when it hits the coastal area [38]. The Renewable Energy Laboratory of the US Department of Homeland Security estimates that Bangladesh could generate more than 30,000 megawatts of wind energy. This estimate reflects the country's size but is incapable of generating strong winds [39].

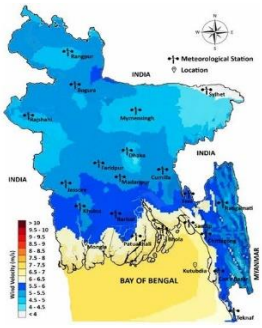

FIG.4. Geographical distribution of wind power potential [10, 39]

Figure 4 shows the geographical distribution of wind power potential. However, due to the great difficulties, progress may be faster [10]. Bangladesh's first wind energy production was at Muhuri Dam in Feni, which had a capacity of 0.9 MW (including 4 turbines of 225 kW). There is also another field on Kutubdia Island with a capacity of 1 MW

(50 turbines of 20 kW) [40]. The United Nations Framework Convention on Climate Change (UNFCCC) was signed by Bangladesh on 21 September 2016 and the Paris Agreement and ratified on 4 November. Unlike the Kyoto Protocol, which mainly reduces carbon emissions for developing countries, the Paris Agreement is a bottom-up approach that requires all countries to reduce carbon emissions and protect and secure the environment [10]. To meet this commitment, the Bangladesh government has announced policies and targets to increase renewable energy production to 10% of total electricity production by 2020, and 20% by 2035 [41]. However, by 2020, only 3% of the target has been achieved, which is below the target of meeting energy demand and sustaining all connected resources [42]. Existing energy solutions need to shift to reliable, cheap, and non-polluting renewable energy sources such as wind energy and make them popular again [43].

3.4 Biomass

Reusable waste products derived from plants and animals are called biomass [44]. All organic material from plants or animals that may be converted into various forms for burning or used directly as fuel is essentially considered biomass. Numerous biological elements are covered by it, such as wood, fallen branches, plant remains, crops, agricultural leftovers, animal dung, grain husks, and other kinds of aquatic life [45]. Wood fuels, agricultural waste, and cow dung are the primary cooking and heating sources for low-income, rural, and isolated populations in Bangladesh. Wealthy and urban people use LP gas for cooking and heating.

FIG.5. Available biomass sources in Bangladesh.

Figure 5 illustrates the available biomass sources in Bangladesh. More than 94% of rural residents use traditional solid biomass to generate harmful carbon oxide and particulate matter that can cause respiratory ailments. Children and women are more vulnerable to emphysema, chronic bronchitis, and indoor smoke, and using coal increases the risk of lung illness, especially in women [7, 46]. Bangladesh currently generates 0.40 MW of electricity from biomass in the Thakurgaon district [47].

3.5 Biogas

The primary components of biogas are CH_4 (40–70%) and CO_2 (30–60%), with trace amounts of NH_3 and CO as well as H_2O condensate (1%–5%) and N_2 (0%–5%) also present [1, 48, 49]. Biogas production uses anaerobic bacteria to break down organic waste, producing methane-rich biogas. This clean-burning fuel reduces fossil fuel use and greenhouse gas emissions while also providing nutrient-rich fertilizer Shown in Figure 6.

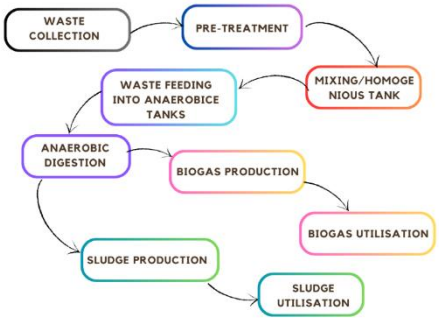

FIG. 6. Diversity of Biogas practice in Bangladesh.

3.6 Geothermal

Geothermal energy (GE) has emerged as a promising way to decarbonize the energy industry and achieve net-zero carbon emissions. Compared to fossil fuel energy sources, it provides a competitively priced, dependable power supply for baseload demand [50]. Geothermal field production may be increased over the long term, reservoir deterioration can be decreased, and environmental effects can be reduced by hybridizing GE with solar or biomass [51]. According to assessments worldwide, geothermal energy potential is roughly 50,000 times larger than the known reserves of gas and oil combined with its substantial power generation dominance [52]. Bangladesh has several possible geothermal energy locations, but the northwest area offers the most promise because of its temperature gradient. With a 200 MW capacity, the first geothermal plant was started in Thakurgaon by Anglo MGH [50].

4. Future Prospects and Challenges of Renewable Energy in Bangladesh

4.1 Prospects and Challenges of Wind Energy in Bangladesh

Air's adoption of a low-carbon, more sustainable energy system worldwide depends on wind energy. As technology has developed and economies of scale have been realized, wind power is expected to become more popular and reasonably priced to meet the world's growing energy needs [53]. Wind energy's inherent availability, readiness for on-grid integration, and low land usage are essential for future applications [54]. Based on National Renewable Energy Laboratory estimates of the U.S. Department of Energy, Bangladesh has the potential to produce over 30,000 MW of wind energy [39]. Per kWh, a massive wind turbine may produce as much energy as thousands of solar panels [55]. Bangladesh will generate 5000 MW of wind-powered electricity by 2030 using onshore and offshore farm facilities [56]. Its tropical climate and seasonal variability limit Bangladesh's wind energy potential. The average wind speed in the coastal and island areas is 3-5 m/s, which is considered pretty low for efficient production [57].

4.2 Prospects and challenges of Geothermal energy in Bangladesh

Geothermal energy, with its significant dominance in power generation, has a vast potential estimated to be about 50,000 times more than the known reserves of gas and oil [52]. At depths of 304 kilometers, the geothermal gradient in Bangladesh varies between 19.8 and 48.7°C/km, with temperatures between 110 and 153°C. Rangpur Saddle,

Madhupur Clay, Kuchma, Bogra, and the Thakurgaon warm water region are critical geothermal hotspots. Anglo MGH and the government intend to build a 200 MW geothermal power plant near Thakurgaon [58]. Geothermal energy can greatly aid energy security and source diversification, especially in the northern areas. It could help meet the increasing demand for electricity in cities and rural areas, thereby reducing our dependence on fossil fuels [59]. Although promising, issues such as budgeting, lack of awareness, and environmental impact must be addressed before the investigation.

4.3 Prospects and challenges of nuclear energy in Bangladesh

For many industrialized and emerging nations, nuclear power can significantly contribute to supplying energy needs and maintaining global development in the twenty-first century [60]. According to the study, an equivalent amount of coal can yield almost 20,000 times less energy than one kilogram of organic uranium [61]. Atomic energy can benefit Bangladesh greatly as it seeks to diversify its energy sources and guarantee long-term energy security. The Rooppur Nuclear Power Plant, now under construction with Russian help and will generate 2,400 MW of electricity, demonstrates nuclear energy's ability to provide a large-scale, dependable power supply [62]. Manufacturers and investors from domestic and international markets will undoubtedly establish factories and facilities in Bangladesh if the country moves on with its nuclear power program [42]. Capital cost is the most crucial factor influencing nuclear energy's capacity to compete economically. Uranium is a costly substance to use as nuclear fuel [63].

4.4 Prospects and challenges of solar energy in Bangladesh

Bangladesh is between 20.30 – 26.38 degrees North latitude and 88.04 – 92.44 degrees East, a perfect location for solar energy utilization and storage [43]. Bangladesh in South Asia is ideal for solar energy utilization and storage due to its favorable geographical position [64]. There is much sunshine in the nation all year round, with extreme solar emission from March to April and minimum radiation in December and January [65]. With significant solar energy available, Bangladesh has a bright future for solar power, as the government has initiated various projects .The weather and the quantity of sunshine affect solar energy. Energy output may drop at night or on cloudy days. Developing affordable, high-capacity energy storage devices is challenging because current technologies can be expensive and have limited lifespans [66].

4.5 Prospects and challenges of bioenergy in Bangladesh

Bioethanol and biodiesel production is complex in Bangladesh because of its dense population, lack of land, and outdated equipment. Algae technology could be an alternative, but a comprehensive site survey is needed [7]. Biomass, mainly trees, is a traditional fuel source for rural, low-income people in Bangladesh. Biogas can improve combustion competence, reduce harmful substances, and save time and money. Biogas farms can generate biogas for self-consumption and sell the remaining gas to neighboring families. Bangladesh's average temperature ranges from 21.2°C to 30.4°C, indicating high potential for biogas or bioenergy production [67].

4.6 Prospects and challenges of hydro energy in Bangladesh

Hydropower is the most promising energy source because it is environmentally clean and regenerative [68]. Bangladesh needs more hydroelectric potential because of its flat topography, unlike the Himalayan countries [69]. The only sizable hydroelectric facility is in the Chittagong district's Karnafuli River, Kaptai. The power station has a 230 MW generating capacity [22]. Furthermore, the Northeast's ten largest hydro potential rivers have an approximate yearly generation capacity of 1410 GWh [70]. Notwithstanding these opportunities, issues like high upfront infrastructure expenditures, adverse environmental effects, community dislocation, and seasonal fluctuations in water flow must be resolved [71].

5. Strategic Solutions for Renewable Energy Challenges

Figure 7 illustrates the following usual topics to cover in a research paper on how Bangladesh may enhance renewable energy development and solve related obstacles:

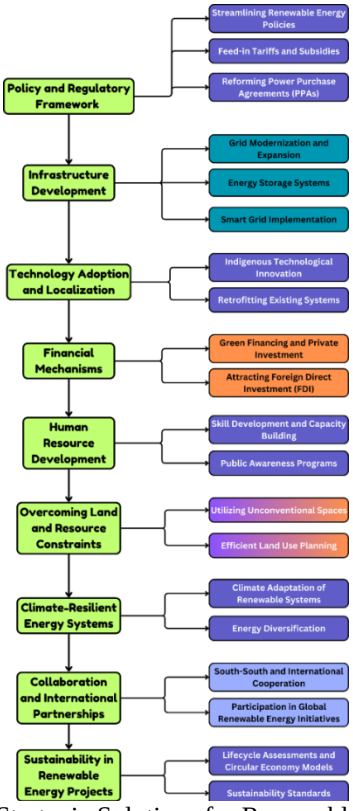

FIG.7. Strategic Solutions for Renewable Energy Challenges.

The Bangladeshi government's efforts focus on the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy). By 2025, 10% of its power generation mix will come from renewable sources. Reducing carbon emissions, guaranteeing energy security, increasing solar and wind power, and providing electricity to rural regions are all crucial strategies to meet SDG 13 (Climate Action).

6. Conclusion

In conclusion, this review highlights the promising developments and current challenges of renewable energy in Bangladesh, focusing mainly on the contribution, leadership, and environmental impact of various renewable resources.

I. Contribution of Renewable Energy: The analysis shows that renewable energy sources contribute to Bangladesh's national power grid, reflecting efforts to reduce dependence on fossil fuels and improve energy security.

II. Leadership in Solar and Hydropower: Solar and hydropower have become primary energy sources. The growth of solar infrastructure, supported by significant government initiatives, is consistent with Bangladesh's unique geographical advantages. Additionally, although limited by geographical constraints, hydropower potential provides a reliable renewable energy source, mainly through the Kaptai Dam.

III. Reduce Greenhouse Gas Emissions: The transition to renewable energy sources can significantly reduce greenhouse gas emissions. Bangladesh is an active participant in global efforts to mitigate climate change. Challenges and Solutions: Challenges remain, including limited funding, technology barriers, and policy gaps. However, initiatives such as international partnerships, regulatory reform, and capacity-building efforts represent viable solutions to improve the deployment of renewable energy sources.

IV. The Way Forward: Continued efforts to expand renewable energy infrastructure, foster innovation, and strengthen policy frameworks are essential for Bangladesh to realize its total renewable energy potential and contribute to a sustainable, low-carbon future.

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