



## Review Article

## Renewable energy resources for green development in Bangladesh: Perspectives, challenges, and opportunities

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## ABSTRACT

Energy is a substantial element in the sustainable development of nations, as global energy consumption increases along with population growth. Fossil fuel combustion results in the atmospheric dispersion of greenhouse gases, which leads to global warming and climate change. Integrating renewable energy sources into electricity generation can help tackle climate issues. This study aims to provide an overview of Bangladesh's current renewable energy capacity and predict its future potential. This review focuses on Bangladesh's ability to harness solar, wind, and bioenergy resources, reducing reliance on hydropower. Bangladesh's current renewable electricity generation capacity is 950 MW, which has the potential to meet the electricity demands of off-grid regions in the country. This study explores the challenges encountered in the establishment of renewable energy technology in Bangladesh and provides recommendations for overcoming them. This article proposes policies and strategies to increase funding for renewable energy production, energy efficiency, and green technology innovation to encourage wider adoption of renewable energy. This study provides investors, shareholders, researchers, and public and private sector decision-makers with valuable insights into renewable energy in Bangladesh to improve their understanding of renewable energy possibilities and guide sustainable and green development.

## 1. Introduction

Increased fossil fuel use driven by energy demand leads to greenhouse gas (GHG) emissions and contributes to global climate change, a major challenge (Begum et al., 2025; Saleh et al., 2024; Wang & Azam, 2024). Addressing these issues requires major changes in the energy sector. Switching to renewable energy reduces climate change effects, lowers GHG emissions, ensures efficient and affordable energy delivery, boosts energy security, and creates jobs (Kelly & Radler, 2024; Salam et al., 2024; Yolcan, 2023). Different sources of renewable energy, like hydro, geothermal, wind, solar, and biomass, are recognized for their emission-free qualities. Renewable energy resources are continuously replenished and generate electricity for residential, commercial, and

industrial use (Idroes et al., 2024; Raihan et al., 2023).

Bangladesh, a rapidly developing South Asian country, possesses significant potential in the field of renewable energy production (Mitra et al., 2023). Uddin et al. (2019) found that biomass and biofuel are the key drivers of the creation of green energy in Bangladesh. Power from solar cells is widely used in Bangladesh, particularly in rural, mountainous, and coastal areas, where solar photovoltaic (PV) cells are commonly employed (Islam et al., 2024). Bangladesh has a significant historical background in hydroelectricity generation, with the successful implementation of micro-hydro and tiny hydropower initiatives within its borders (Munjer et al., 2023). The power of wind is a prominent renewable resource in Bangladesh, with suitable locations for small-scale and micro-wind generation for electricity production (Akter

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et al., 2022; Debanth et al., 2023). Renewable energy sources offer a viable solution for Bangladesh to address energy scarcity, ensure energy security, and develop sustainable long-term energy strategies (Abdulrazak et al., 2021). They also contribute to reducing GHG pollution and supporting climate change objectives (Gulagi et al., 2020).

However, Bangladesh's clean energy capacity plays a growing but relatively modest role in the global context of energy production and consumption. As a developing nation, Bangladesh has made strides in expanding its renewable energy portfolio, particularly in solar power, which has been instrumental in providing electricity to off-grid rural areas through initiatives like solar home systems (SHS). However, its contribution to global clean energy production remains small compared to larger economies. Despite this, the country's efforts are significant in addressing local energy demands sustainably and reducing dependence on fossil fuels. Bangladesh's progress also demonstrates how nations with limited resources can leverage innovation and policy support to transition toward cleaner energy systems, contributing to global climate goals and serving as a model for other developing nations seeking sustainable energy solutions. Bangladesh is a noteworthy case study for emerging nations due to its compelling justifications. The country is categorized as a developing nation and heavily depends on fossil fuels for its electricity generation. Additionally, the country's future energy strategy indicates a tendency to rely on the importation of fossil fuels (Das et al., 2020). Moreover, the region's location is marked by a notable solar potential, suggesting that a considerable proportion of its forthcoming energy supply will be obtained from solar PV sources. Additionally, the rainy season and limited options for electricity production, apart from solar power, pose considerable obstacles to the establishment of a fully sustainable energy system.

Understanding the relationship between energy structures and sustainable growth is crucial to the global trend toward affordable, eco-friendly, and efficient energy systems. The research question of the present study is: What are the perspectives, challenges, and opportunities of renewable energy resources in advancing green development in Bangladesh? To address the research question, this study explored the renewable energy resources of Bangladesh, their recent status, obstacles, and upcoming possibilities while proposing a strategic framework for developing renewable energy policies. The motive of the study is to highlight the feasibility of extra sources of green power in Bangladesh, attracting attention from authorities and potential investment from both local and foreign sectors. The investigation also focuses on the policies and legislation pertaining to the generation of renewable energy in Bangladesh. The review also covered the major challenges and solutions to current global breakthroughs in addressing core issues. The country's ongoing energy crisis has been addressed through various suggestions, including the use of renewable energy resources.

This study makes a marginal but significant contribution to the existing body of literature by providing a focused, context-specific analysis of renewable energy development within the socio-economic and environmental landscape of Bangladesh. While global and regional studies have broadly addressed renewable energy transitions (Bhattarai et al., 2022; Cheikh & Zaided, 2024; Hoicka et al., 2021; Ige-land et al., 2024; Li et al., 2020; Werner & Lazaro, 2023; Yang & Dodge, 2024; York & Bell, 2019), this research uniquely contextualizes the challenges and opportunities specific to Bangladesh—a densely populated, climate-vulnerable, and energy-deficient nation. Unlike existing studies that primarily emphasize the technical and economic feasibility of renewable energy integration (Masud et al., 2020; Chowdhury et al., 2020; Das et al., 2021; Mojumder et al., 2022; Ali et al., 2023; Miskat et al., 2023; Bijoy et al., 2023; Hossain et al., 2024), this work broadens the analytical lens by incorporating socio-economic, environmental, policy, and institutional dimensions. It synthesizes national policies, local energy demands, technological feasibility, and geographic potentials into a single comprehensive framework, offering a holistic view tailored to Bangladesh's developmental trajectory. In contrast to studies such as Yousuf et al. (2022), which examined the prospects and

challenges of renewable energy, this study distinguishes itself by providing a comprehensive theoretical framework and detailed methodology. It evaluates both technical potential and policy and regulatory environments, highlighting institutional bottlenecks and governance gaps that hinder effective implementation. The study critiques the current energy framework while assessing renewable energy capacity targets through 2030, supported by geographical maps and sectoral breakdowns of solar, wind, biomass, hydro, geothermal, and tidal resources. Importantly, the research also delves into the socio-political and infrastructural constraints limiting renewable energy expansion in rural and underserved areas. It identifies practical barriers such as financing limitations, public awareness gaps, and coordination challenges among government entities. In doing so, it extends the discourse beyond technical feasibility to include governance and capacity-building considerations critical for successful energy transitions.

The novelty of this work lies in its integrated and multidimensional approach. By examining local constraints—such as grid infrastructure limitations, political challenges, and financial bottlenecks—the study underscores the need to embed renewable energy within Bangladesh's broader sustainable development goals (SDGs). This is especially relevant given the country's heightened vulnerability to climate change impacts. Furthermore, the study offers strategic policy recommendations aimed at fostering the growth of a green energy industry in Bangladesh. These include guidance on institutional reforms, cross-sectoral collaboration, investment mobilization, and public-private partnerships. The research aligns with SDG-7, emphasizing energy security, emission reduction, and inclusive economic development. In a nutshell, this review contributes significantly to both academic and practical realms. It provides a comprehensive understanding of the current status, potential, and challenges of renewable energy in Bangladesh. By identifying key renewable energy sources and evaluating their economic and environmental benefits, the study supports efforts to reduce fossil fuel dependency, mitigate climate change, and promote energy security. It also serves as a practical guide for policy-makers, private investors, development organizations, and communities aiming to realize Bangladesh's green development goals and contribute to a sustainable future.

## 2. Methodology

### 2.1. Theoretical frameworks

The theoretical framework of the study is grounded in the inter-connection between sustainable development theory, energy transition theory, and socio-technical systems theory. These frameworks provide a structured lens through which the development, integration, and expansion of renewable energy in Bangladesh can be analyzed and understood.

Sustainable development theory serves as the foundational basis, emphasizing the balance between economic growth, environmental protection, and social equity. This theory posits that energy development must meet present needs without compromising the ability of future generations to meet their own. In the context of Bangladesh, where rapid urbanization, population growth, and industrial development are intensifying energy demands, the role of renewable energy becomes critical in supporting long-term sustainability. This theory helps in understanding the imperative for transitioning from fossil fuel dependency to cleaner energy alternatives to ensure environmental conservation and socio-economic well-being.

Energy transition theory further supports this framework by focusing on the systemic shift from conventional energy systems to more sustainable and decentralized models. This theoretical approach is particularly relevant for Bangladesh as it explores the pathways, drivers, and barriers associated with the adoption of renewable technologies such as solar, wind, biomass, and hydropower. The theory also considers the role of institutions, policy instruments, and technological innovation in

facilitating this transition. It provides a lens to evaluate government policies, private sector participation, and community involvement in shaping a resilient and inclusive energy future.

Additionally, the socio-technical systems theory enriches the analysis by highlighting the co-evolution of technology, society, and infrastructure. In Bangladesh, renewable energy development is not just a technical challenge but also a socio-political and economic process. This theory underscores the interplay between technological advancements and the social context in which they are embedded, including governance structures, cultural practices, economic conditions, and public acceptance. By incorporating this perspective, the study can better identify the multifaceted challenges hindering renewable energy uptake, such as lack of awareness, insufficient financing mechanisms, and regulatory bottlenecks, while also recognizing the opportunities for systemic change through coordinated efforts across stakeholders.

Together, these theoretical foundations provide a comprehensive framework to critically examine the current landscape of renewable energy in Bangladesh. They guide the exploration of the perspectives of various actors, the challenges that persist in scaling up renewable energy initiatives, and the potential strategies and opportunities that can be leveraged to achieve a more sustainable and energy-secure future for the country.

## 2.2. Systematic review method

This investigation adopts a systematic literature review approach to ensure a comprehensive, objective, and replicable analysis of the existing body of knowledge related to renewable energy development in Bangladesh. The methodological framework was designed to identify, evaluate, and synthesize relevant scholarly and gray literature that explores various dimensions of renewable energy, including technological innovations, policy frameworks, economic implications, environmental benefits, and socio-political challenges in the context of Bangladesh.

The literature search was conducted using multiple academic databases to ensure the breadth and depth of the review. These databases included Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, Google Scholar, and PubMed. Additionally, official reports and policy documents from recognized organizations such as the International Renewable Energy Agency (IRENA), the Bangladesh Power Development Board (BPDB), the Ministry of Power, Energy and Mineral Resources (MoPEMR), and the World Bank were also reviewed to incorporate current and practical perspectives.

The search for relevant literature was performed using a combination of keywords connected with Boolean operators to refine and expand the search results. The primary search string included the following terms: ("renewable energy" OR "green energy" OR "sustainable energy") AND ("Bangladesh") AND ("development" OR "economic development" OR "green development") AND ("challenges" OR "barriers" OR "opportunities" OR "policy" OR "technology"). The search covered literature published in English between 2000 and 2024, ensuring both contemporary relevance and historical context in the evolution of renewable energy in Bangladesh.

To ensure the quality and relevance of the included studies, clear inclusion and exclusion criteria were established. The inclusion criteria consisted of peer-reviewed journal articles, review papers, conference proceedings, book chapters, policy papers, and institutional reports that specifically addressed renewable energy in the context of Bangladesh. Only documents that provided empirical data, theoretical analysis, or comprehensive policy discussions were included. In contrast, the exclusion criteria eliminated studies focused solely on renewable energy development outside the context of Bangladesh, documents lacking academic rigor (e.g., non-peer-reviewed opinion pieces or promotional content), and sources with insufficient methodological clarity or incomplete data.

Following the application of these criteria, an initial pool of approximately 450 documents was identified. After screening for

relevance based on titles and abstracts, and subsequently reviewing the full texts, 148 documents were deemed relevant and included in the final review. These documents provided the foundational basis for analyzing the current status, barriers, and future potential of renewable energy resources in Bangladesh, with a particular focus on how these can support the country's transition toward sustainable and green development. The methodology employed in this review thus ensures a holistic and evidence-based analysis that contributes meaningfully to academic and policy-oriented discussions on renewable energy in Bangladesh.

## 3. Results and discussion

### 3.1. Renewable energy scenario

#### 3.1.1. Global renewable energy scenario

Energy demand has been increasing day by day in both developed and developing countries, mostly using fossil fuels (Aryal et al., 2021; Sher et al., 2024). Fossil fuels currently constitute around 80 % of the world's primary energy supply (Karakurt & Aydin, 2023). The projected world energy consumption from 2002 to 2030 indicates a major upsurge in power demand, with a growth rate of approximately 1.6 % per year, resulting in a total increase of nearly 60 % (IEA, 2024a). Efforts to find alternative energy sources and meet the growing global energy demand, driven by population growth and developing countries, have been ongoing (Majeed et al., 2023). Renewable energy sources significantly mitigate dependency on fossil fuels and extend energy security (Khan et al., 2023). Green power resources might be utilized for transportation, electricity production, and heat generation (Algarni et al., 2023). Additionally, renewable energy sources decrease dependency on fossil fuels and energy imports, leading to enhanced economic growth (Carfora et al., 2022). Moreover, renewable energy sources, including solar grid electrification, have gained popularity in several countries, including Kenya, China, India, Indonesia, and South Africa, due to technological advancements (Babayomi et al., 2022; Cantarero, 2020; Harish et al., 2022; Ibrahim et al., 2023; Tetteh et al., 2024). The global share of renewable energy in the electricity sector is projected to increase from 30 % in 2023 to 46 % by 2030 (IEA, 2024b).

Fig. 1 presents the annual trend of global renewable electricity generation. In 2022, renewable energy sources constituted 29.1 % of global power generation, amounting to 8440 TWh (IRENA, 2024). Since 2011, total electricity generation from renewable sources has risen by 6.1 % per annum. In 2022, renewable electricity increased by 7.2 % compared to 2021. In recent decades, the profile of renewable energy sources has markedly varied. Although hydropower remains the predominant source of electricity generation, variable renewables have consistently augmented their proportion in the global electricity mix, rising from 1.1 % of renewable generation in 2000 to 40.2 % in 2022

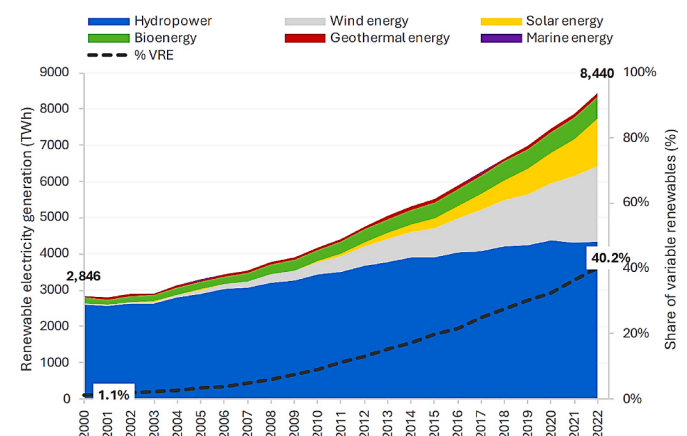


Fig. 1. Annual trend of global renewable electricity generation (IRENA, 2024).

(IRENA, 2024). In 2022, hydropower continued to be the predominant source of renewable electricity, producing 4330 TWh, reflecting a 0.8 % rise compared to 2021. Wind energy generated 2098 TWh, reflecting a 14.0 % increase relative to 2021. Solar energy, the most rapidly expanding renewable energy source in recent years, produced 1294 TWh, reflecting a year-on-year rise exceeding 25.6 %. Bioenergy generated 619 TWh, reflecting a growth of 1.5 %, while geothermal energy accounted for 97 TWh, and marine or tidal energy approached 1 TWh.

The global demand and consumption of energy are rising due to accelerated population expansion (Rehman et al., 2023). The global community's commitment to achieving the SDGs by 2030, coupled with global commercial progress and population growth, is expected to result in a 30 % increase in energy consumption. Renewable energies are crucial in addressing this situation (Peng et al., 2023). Fig. 2 displays the cumulative capacity of renewable electricity in the main, accelerated, and net zero emissions (NZE) scenarios. The Global Stocktake statement, agreed upon by 198 states at COP28, included several initiatives by the International Energy Agency (IEA), including the objective to triple renewable energy sources. Increasing global renewable capacity three-fold from 2022 levels by 2030 would elevate it to 11,000 GW, consistent with the IEA net zero emissions by 2050 scenario (IEA, 2023). According to current regulations and market conditions, worldwide renewable capacity is projected to attain 7300 GW by 2028 under the primary scenario. Despite this trend indicating that renewables constitute nearly all newly added electricity capacity globally, the projected trajectory is that global capacity would rise to two and a half times its current level by 2030, hence failing to meet the tripling objective. In the expedited scenario, worldwide cumulative capacity more than doubles, exceeding 8130 GW by 2028, positioning the world close to fulfilling the global tripling commitment (IEA, 2023).

### 3.1.2. Renewable energy scenario in Bangladesh

Table 1 displays the data on electricity generation in Bangladesh, including the sources of energy utilized and the corresponding proportions of reliance on these sources. The electricity production capacity utilizing gas as fuel amounts to 11,476 MW, representing approximately 44.53 % of the total production capacity. Renewable energy is a significant energy source, comprising 3.59 % of the total expansion capacity, with approximately 950 MW of capacity (SREDA, 2023).

Furthermore, a complete overview of Bangladesh's existing potential for renewable energy from some streams is presented in Table 2. Solar energy accounts for approximately 75 % (716 MW) of the total renewable energy capacity in Bangladesh, with hydropower contributing 24 % (230 MW). The solar energy capacity is divided into two categories: off-grid production, which accounts for 356.35 MW, and on-grid

**Table 1**

Bangladesh's energy production capacity (Adapted from SREDA, 2023).

| Fuel/Resource           | Installed capacity (MW) | Share (%) |
|-------------------------|-------------------------|-----------|
| Gas                     | 11476                   | 44.53     |
| Coal                    | 1768                    | 6.86      |
| Heavy fuel oil (HFO)    | 6278                    | 24.36     |
| High-Speed Diesel (HSD) | 1341                    | 5.2       |
| Captive                 | 2800                    | 10.86     |
| Renewables              | 950                     | 3.69      |
| Imported                | 1160                    | 4.5       |

**Table 2**

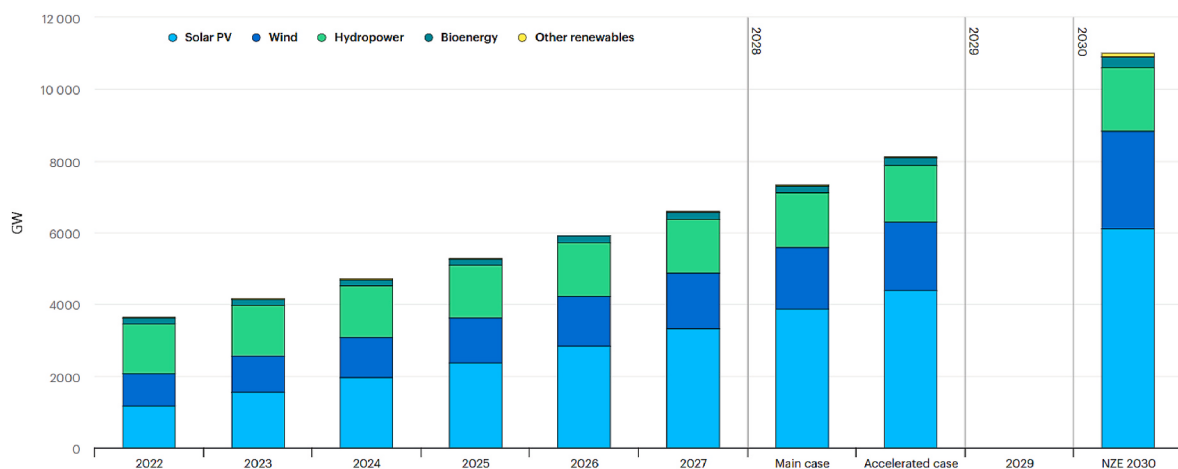
Bangladesh's renewable energy capacity from various sources (Adapted from Miskat et al., 2023).

| Technology         | On-grid (MW) | Off-grid (MW) | Total (MW) |
|--------------------|--------------|---------------|------------|
| Solar              | 359.16       | 356.35        | 715.51     |
| Hydro              | 230          | –             | 230        |
| Wind               | 0.9          | 2             | 2.9        |
| Biogas and biomass | –            | 1.09          | 1.09       |
| Total              | 590.06       | 359.44        | 949.5      |

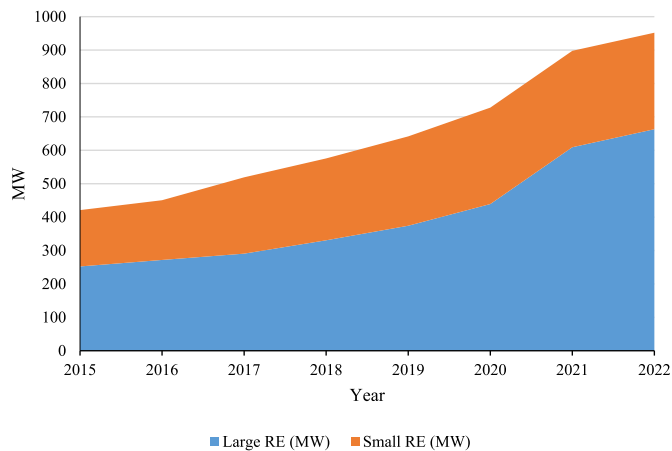
production, which accounts for 359.16 MW (Miskat et al., 2023). Renewable energy sources like wind and biomass only contribute 1 % of the overall electricity generated from renewable resources.

The Sustainable and Renewable Energy Development Authority (SREDA) in Bangladesh categorizes clean energy projects into two categories: small renewable energy and large renewable energy. The small project initiatives included a solar water heater, a biogas plant, a SHS, and a solar streetlight. In addition, solar parks, solar irrigation, solar microgrid, solar mini-grid, and solar net metering are among the production activities classified as large-scale projects in the domains of hydro, wind, biogas, solar, and biomass (Munjer et al., 2023). Fig. 3 illustrates the consistent growth of Bangladesh's renewable energy production capacity from 2015 onwards.

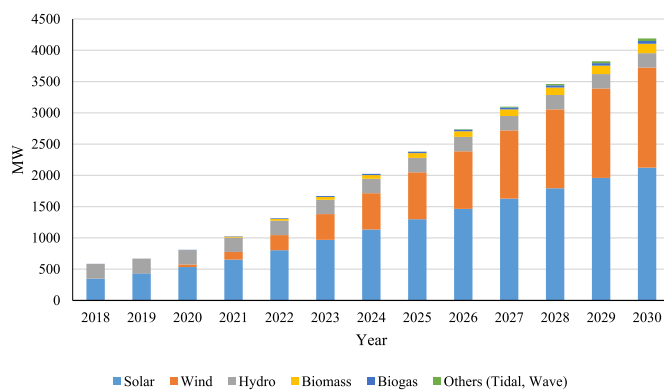
The government of Bangladesh intends to produce 4190 MW of electricity from green power sources by 2030. Fig. 4 shows the government's annual targets for producing electricity from different renewable energy sources. SREDA intends to enhance electricity generation from solar and wind sources to 2124 MW and 1601 MW, respectively, by 2030. These figures surpass Bangladesh's current electricity generation from all renewable sources, which stands at 950 MW. However, SREDA does not have plans to increase hydropower electricity production; thus, it is expected to remain constant at 230 MW by 2030. Furthermore, the projected electricity production targets for biomass and biogas in the year 2030 are 150 MW and 45 MW, respectively.



**Fig. 2.** Cumulative capacity of renewable electricity in the main, accelerated, and NZE scenarios (IEA, 2023).



**Fig. 3.** Bangladesh's large- and small-scale renewable energy production capacity (Adapted from Munjer et al., 2023).



**Fig. 4.** Bangladesh's annual target of electricity generation from various renewable energy sources (Adapted from SREDA, 2023).

Furthermore, there is a specific goal to achieve a tidal and wave electricity production capacity of 40 MW by the year 2030.

### 3.1.3. SDG-7 progress in Bangladesh

The energy sector plays a major role in climate change, responsible

for 75 % of global GHG emissions. SDG-7 focuses on ensuring that energy access is affordable, reliable, and sustainable, promoting equity and a more environmentally friendly future. Bangladesh has made significant strides in meeting the targets of SDG-7. The country has successfully attained universal electricity access, increasing coverage from 48 % in 2010 to an impressive 99 % of the population. Furthermore, Bangladesh has incorporated renewable energy sources, accounting for 25 % of its overall final energy consumption. Although these accomplishments are significant, there remains potential for improvement in energy efficiency, with the nation's score at 1.9 MJ per USD, in contrast to the global average of 4.6. Furthermore, with a renewable capacity of 4.7 Watts per capita, Bangladesh demonstrates a strong commitment to advancing sustainable energy practices while simultaneously striving for improved energy efficiency and increased adoption of renewable sources. Table 3 presents data from the SDG-7 Tracking of several Asian countries. Bangladesh shows significant advancement in energy-related indicators, achieving 99 % access to electricity and outpacing some neighboring countries such as Myanmar, Nepal, Pakistan, Afghanistan, Cambodia, and the Philippines. Nonetheless, obstacles remain, with clean cooking access currently at 28 %, highlighting the potential for advancement. Bangladesh demonstrates a strong commitment to renewable energy, with 25 % of its final energy consumption sourced from renewables, which is notably higher than that of China, Japan, South Korea, Afghanistan, Thailand, Malaysia, Indonesia, Vietnam, and Singapore. The energy efficiency ratio of the nation stands impressively at 1.9 MJ (MJ) per USD, highlighting effective energy utilization.

Despite Bangladesh's renewable capacity per capita being a modest 4.7 Watts, the country is making consistent progress towards the integration of sustainable energy. However, in comparison to neighboring countries like India and Nepal, Bangladesh lags behind in terms of total renewable energy capacity and diversification. India, for example, has a much more advanced renewable energy sector, with over 125 GW of installed capacity as of 2024, and a focus on solar, wind, and hydropower. India's geographic size and economic resources give it a distinct advantage in developing large-scale renewable projects. Nepal, on the other hand, leverages its mountainous terrain to generate significant amounts of electricity through hydropower, which makes up about 90 % of its total energy production. Bangladesh, lacking such geographical advantages, relies more on solar and smaller-scale wind projects due to its flat, low-lying topography and vulnerability to climate change. When compared to countries with similar geographic and economic characteristics, such as Vietnam and Myanmar, Bangladesh's renewable energy

**Table 3**  
Record of SDG-7 for Asian nations.

| Country     | Electricity access (%) | Clean cooking access (%) | Usage of renewable energy (%) | Energy efficiency (MJ per USD) | Renewable energy capacity (Watts per capita) | International financial flows |
|-------------|------------------------|--------------------------|-------------------------------|--------------------------------|----------------------------------------------|-------------------------------|
| Bangladesh  | 99                     | 28                       | 25                            | 1.9                            | 4.7                                          | 112.1                         |
| India       | 99                     | 75                       | 35                            | 4.2                            | 115                                          | 627.3                         |
| Myanmar     | 74                     | 51                       | 63                            | 4.2                            | 64                                           | 18.3                          |
| Nepal       | 91                     | 40                       | 74                            | 5.6                            | 77                                           | 28.5                          |
| Pakistan    | 95                     | 53                       | 42                            | 4.2                            | 59                                           | 103.1                         |
| Sri Lanka   | 100                    | 36                       | 49                            | 1.7                            | 131                                          | 18.5                          |
| Bhutan      | 100                    | 88                       | 82                            | 9.7                            | 2985                                         | 19.9                          |
| Maldives    | 100                    | 100                      | 1                             | 2.9                            | 72                                           | 0.7                           |
| Afganistan  | 85                     | 36                       | 20                            | 2.9                            | 12                                           | 64.4                          |
| Thailand    | 100                    | 86                       | 19                            | 4.4                            | 170                                          | 33.8                          |
| Vietnam     | 100                    | 98                       | 24                            | 4.6                            | 462                                          | 186.4                         |
| Malaysia    | 100                    | 84                       | 8                             | 4.5                            | 266                                          | 0                             |
| Singapore   | 100                    | 100                      | 1                             | 2.5                            | 142                                          | 0                             |
| Laos        | 100                    | 10                       | 52                            | 4.3                            | 1278                                         | 156                           |
| Cambodia    | 92                     | 54                       | 52                            | 5                              | 110                                          | 13.5                          |
| Philippines | 95                     | 59                       | 28                            | 2.8                            | 66                                           | 9.7                           |
| Indonesia   | 100                    | 89                       | 20                            | 3                              | 46                                           | 355.8                         |
| China       | 100                    | 88                       | 15                            | 6.3                            | 814                                          | 54.8                          |
| Japan       | 100                    | 100                      | 9                             | 3.3                            | 980                                          | 0                             |
| South Korea | 100                    | 100                      | 4                             | 5.3                            | 601                                          | 0                             |

development is relatively slower. Vietnam has rapidly expanded its solar and wind energy sectors, driven by favorable government policies and foreign investments, achieving over 30 GW of renewable capacity. Myanmar, like Bangladesh, has focused on rural electrification, but its

renewable energy efforts have been hampered by political instability. Bangladesh's progress, while slower than Vietnam's, has been more stable and inclusive, with a strong emphasis on off-grid solutions for underserved populations. The international financial flows for

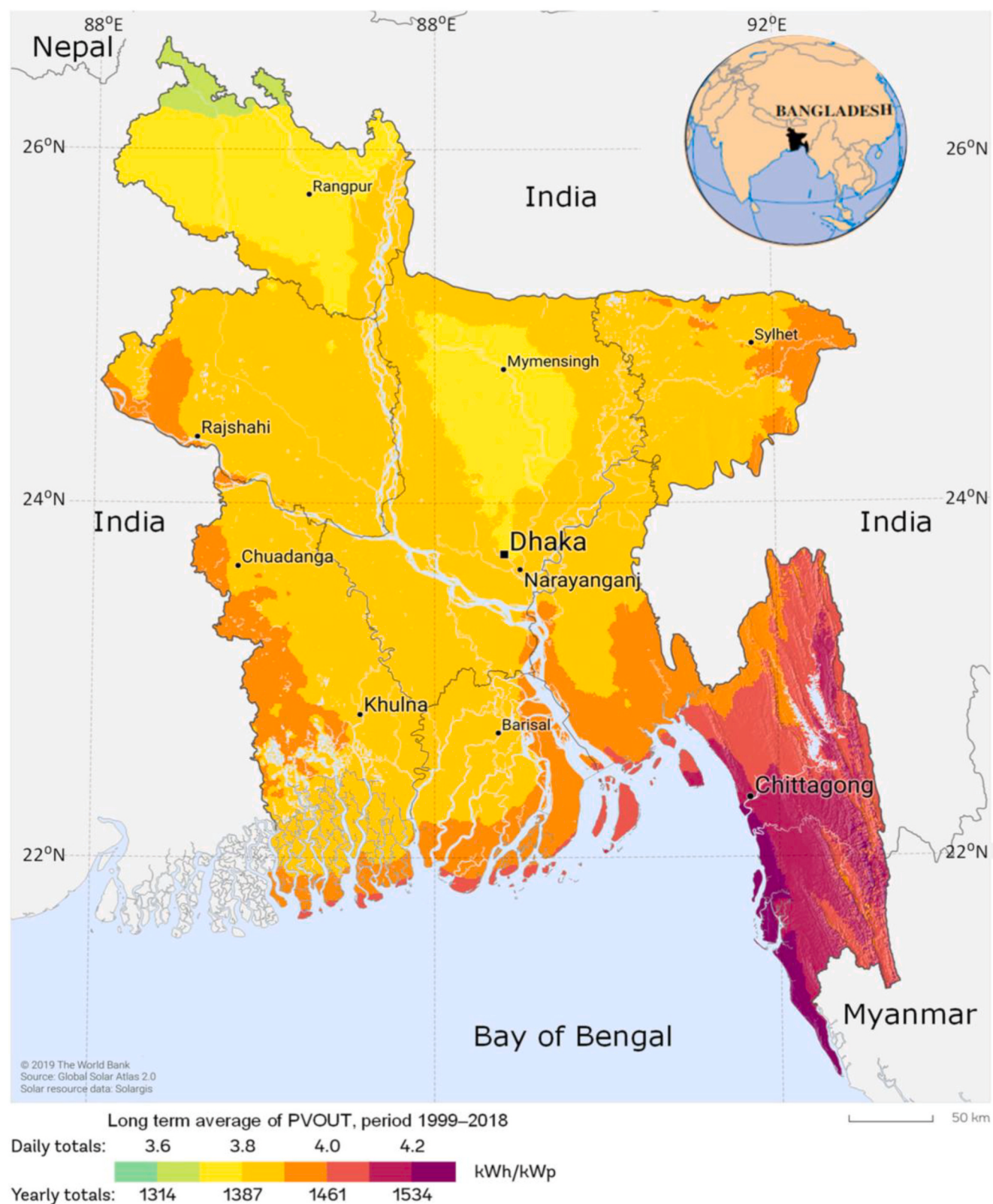


Fig. 5. Bangladesh solar energy potential map (GSA, 2023).

renewable energy development in Bangladesh were 112.1 million USD in 2022, which is higher than those of other Asian countries except India, Indonesia, and Vietnam. This highlights Bangladesh's proactive approach to advancing its renewable energy sector. The comparisons highlight the advancements made by Bangladesh and its continuous initiatives to improve energy access, efficiency, and the integration of renewable energy, all within its distinct socio-economic framework.

Bangladesh has made notable strides in renewable energy development, especially given its geographic constraints and economic status. The country's focus has primarily been on solar power, with the SHS initiative being a globally recognized success. Over 6 million SHS have been installed in off-grid rural areas, providing electricity access to millions of people. The government has set a target to achieve 40 % of energy from renewables by 2041, but challenges such as limited land availability, funding, and technical expertise hinder rapid progress. While Bangladesh faces significant geographic and economic limitations, its achievements in renewable energy, particularly in rural electrification, are commendable. Achieving SDG-7 in Bangladesh requires addressing several challenges. Initially, it is essential to enhance electricity access in rural areas. Secondly, improving energy efficiency in agriculture is crucial because of its significant energy usage. Ultimately, considering Bangladesh's susceptibility, it is crucial to modify the energy sector in response to the effects of climate change. Moreover, the incorporation of additional renewable sources such as solar and wind is essential. This necessitates enhanced infrastructure, refined policies, and increased public awareness. It is essential to find a balance between economic growth and the demand for sustainable energy. Joint initiatives are essential for ensuring dependable and cost-effective energy access for everyone. To keep pace with regional leaders and countries with similar challenges, Bangladesh must accelerate investment in renewable technologies, improve policy frameworks, and explore innovative solutions like floating solar and offshore wind projects.

### 3.2. Solar energy

Solar radiation is huge and easily accessible as Earth's energy source. The solar irradiance received by the Earth's surface in 1 h exceeds the global energy demands for a whole year. Solar energy is the radiant energy emitted by the sun, including electromagnetic radiation and thermal energy (Osigbeme et al., 2023). The solar PV industry witnessed a significant increase in electricity production worldwide, with a noteworthy rise of 270 TW-hours (TWh) in 2022. This indicates a substantial growth rate of 26 % when compared to the preceding year. Solar PV technology, accounting for 4.5 % of global electricity generation, is the third most significant renewable energy source globally and is increasingly popular in Bangladesh.

Bangladesh benefits from ample sunshine, leading to an increasing adoption of solar energy as the cost of solar equipment decreases. Fig. 5 displays Bangladesh's geographical location and photovoltaic power potential. Bangladesh benefits from a favorable geographical location that provides ample sunlight throughout the majority of the year, making it conducive to the utilization of solar energy. According to Abdullah-Al-Mahbub and Islam (2023), there is a period of intense solar emission occurring from March to April, while minimal radiation is observed from December to January. The power availability ranges from 4.0 to 6.5 kWh/m<sup>2</sup>/day, with sunny daylight hours varying from 6 to 9 h per day for approximately 300 days per year. This duration is sufficient to fulfill the sunlight requirement for solar energy, disregarding cloud cover, rainfall, and fog. This has the potential to generate a total energy output of  $1018 \times 1018$  J. According to Baky et al. (2017), approximately 0.11 % of this country's energy is sufficient to meet its primary energy consumption.

In rural off-grid areas of Bangladesh, solar PV systems have been widely embraced due to their ability to provide convenient electricity access to households and small businesses. Abdullah-Al-Mahbub et al. (2022) found that solar power benefits both rural off-grid and

grid-attached consumers, including commercial and industrial sectors. Solar energy can be harnessed by individuals by installing various types of solar cells on their rooftops. Solar energy has given 20 million rural Bangladeshis the availability of electricity during the night, enabling them to meet their energy needs and potentially sell surplus electricity to national grids (Abdullah-Al-Mahbub et al., 2022). Bangladesh generates solar energy through various methods, including solar parks, irrigation, rooftops, grids, home systems, charging stations, streetlights, and drinking water (Abdullah-Al-Mahbub et al., 2022).

Bangladesh's solar projects are divided into three phases: completed and operational, ongoing implementation, and currently in the planning stage. The nation initiated a 500 MW solar power initiative to reduce reliance on fossil fuels and attain a target of 10 % sustainable power generation by 2020. The Infrastructure Development Company Limited (IDCOL), in collaboration with the Bangladesh Power Development Board (BPDB), aims to implement multiple projects, such as the installation of 50 mini-grids by 2025. IDCOL aims to reduce reliance on diesel generators in the agricultural industry by installing 50,000 pumps by 2025. IDCOL has approved a total of 1429 pumps, out of which 1186 are currently operational, collectively providing a capacity of 26.59 MW. IDCOL has provided funding for two photovoltaic assembly plants with a combined capacity of 10 MW in order to achieve self-sufficiency in PV manufacturing within the country. In addition, BPDB has prioritized the development of grid-connected solar power plants. In the districts of Jamalpur and Rangamati, two power plants with capacities of 3 MW and 8 MW, respectively, are presently under construction. IDCOL intends to build a rooftop solar plant in Gazipur, Dhaka, that will produce 1000 MW of electricity. The textile industry can produce 400 MW of power on its rooftops, whereas commercial and industrial rooftops can produce 4000 MW.

Furthermore, the government of Bangladesh is collaborating with development organizations such as the World Bank and the private sector to facilitate the production of solar energy. Bangladesh hosts a significant domestic solar power initiative, with around 125 stakeholder companies involved in the renewable energy sector. Several organizations in Bangladesh, including IDCOL, BPDB, Bangladesh Rural Electrification Board (BREB), Ministry of Disaster Management and Relief (MoDMR), Rural Development and Co-operatives Division (RDCD), and Electricity Generation Company of Bangladesh (EGCB), have been involved in the commercialization of solar power in rural irrigation, domestic, and commercial sectors (Abdullah-Al-Mahbub et al., 2022).

### 3.3. Hydropower

Hydropower is widely acknowledged as a prominent and well-established low-carbon energy source on a global level. Large-scale hydroelectric power has a history spanning over a century, establishing it as the leading renewable energy source. The construction of a dam allows for the creation of a large reservoir, which can be used to control water flow and generate electricity through the activation of a turbine. Hydropower outperforms nuclear energy globally by 55 % and constituted 17 % of global electricity generation in 2020, ranking it as the third most prominent energy source after coal and natural gas. In 2021, global hydropower electricity capacity exceeded 1400 GW, solidifying its status as the leading renewable energy technology.

Hydroelectricity is highly significant in the expansion of territories like Bangladesh. Bangladesh has numerous rivers characterized by strong currents, while waterfalls are relatively scarce in the country. Large rivers such as the Jamuna, Meghna, Padma, and Surma have made noteworthy contributions to national development. On the other hand, small rivers, canals, and falls can serve as sources of hydropower for electrifying a country's rural areas. This can be achieved through the utilization of crossflow turbines and Francis turbine-based technology. The northeastern region of Bangladesh holds significant potential for the country's hydro-energy industry (Amin et al., 2023). According to Sen et al. (2022), the rivers in Bangladesh have the potential to generate

hydroelectricity through the utilization of their flowing water. Bangladesh has a single hydropower plant called Kaptai Hydropower Plant, with a capacity of 230 MW per day. This plant contributes 24 % of the total renewable energy generated in the country (Akter et al., 2022). About 140 families and a temple in Rangamati receive electricity from the Barkal mini-hydropower plant, which adds 50 kW to the country's power-producing capability (Miskat et al., 2021). In addition to large-scale hydropower plants, smaller hydroelectric plants with a capacity of less than 1000 kW could be installed, making use of the existing drainage system. The Bangladesh Power Board (BPDB) and Bangladesh Water Development Board (BWDB) have recognized the regional potential for small hydropower plants, as shown in Fig. 6. The Sylhet district ranked first with a potential of 642 kW, followed by Jamalpur (172 kW), Dinajpur (171 kW), Chittagong (132 kW), and Rangpur (80 kW).

Bangladesh is located adjacent to the Bay of Bengal, which causes the rivers and canals in the southern regions of the country to experience tidal fluctuations with a range of approximately 2–5 m. Miskat et al. (2021) suggest that installing a micro-hydropower plant on a canal can generate sufficient energy from tidal water sources. Ali et al. (2021) conducted a case study in Dhaka, Bangladesh, examining drainage flow rates and head levels at four locations. The study found that the flow rates ranged from 10 to 30 m<sup>3</sup>/s, while the head levels ranged from 1 to 5 m. Based on these findings, it was estimated that an average power generation of 100 kW–500 kW is possible. LGED has identified potential locations in the remote hill tract area of Bangladesh, specifically in Bandarban, Khagrachari, and Rangamati (Miskat et al., 2021). A hybrid power system, combining hydro, PV, wind, and other renewable energy sources, is more efficient in remote areas due to low electricity rates. Azimov and Avezova (2022) demonstrated that micro-hydroelectric plants can achieve a 90 percent increase in conversion efficiency by utilizing solar hybrid technology.

### 3.4. Wind energy

Wind energy is a plentiful and eco-friendly type of renewable energy. Electricity is produced from wind energy using wind turbines. These turbines propel generators, which then supply electrical power to the National Grid (Rahman et al., 2022). Wind farms are increasingly common in many countries as wind power plays a larger role in supplying electricity to the national grid. Wind energy is widely recognized as the leading non-hydro renewable technology globally, with a significant production of over 2100 TWh in 2022. The global power generation from wind energy saw a notable rise in 2022, reaching about 7.33 %, up from 6.6 % the previous year.

Fig. 7 illustrates yearly wind speeds based on data from the Bangladesh Meteorological Department, supporting informed energy planning. The map illustrates the annual fluctuations in wind speed

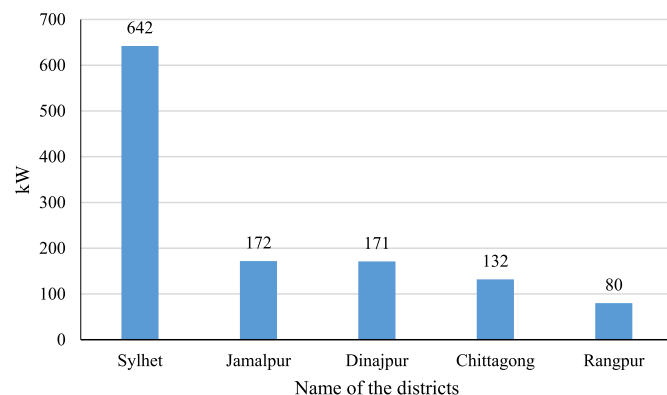


Fig. 6. Hydropower potential in Bangladesh by district (Adapted from Yousuf et al., 2022).

across various locations. Coastal areas such as Chittagong, Cox's Bazar, and Kutubdia demonstrate elevated wind speeds (5.37 ms<sup>-1</sup>, 4.48 ms<sup>-1</sup>, and 3.43 ms<sup>-1</sup>), highlighting substantial wind energy potential attributed to their closeness to water bodies and steady coastal winds. Inland regions such as Dhaka and Rajshahi exhibit reduced speeds. The correlation between coastal influence and increased speeds underscores the potential for harnessing wind energy in coastal regions. Numerous governmental and organizational projects take this parameter into account for wind power initiatives. Coastal areas in Bangladesh employ tidal power technologies such as Swiss Gates and barrages to harness the energy generated by tidal heights ranging from 2 to 8 m in the Bay of Bengal. These technologies serve the dual purpose of disaster prevention and renewable energy generation. In addition, Bosch et al. (2018) reported that onshore wind production costs are projected to decrease by 15 % by 2021.

Bangladesh's wind power generation is currently falling behind that of other developing nations. At the moment, wind turbines in Bangladesh produce 3 MW of power, mostly from the Feni Wind Power Plant and the Kutubdia Hybrid Power Plant. Bangladesh has an estimated wind power potential of over 20,000 MW. With a number of initiatives led by the Bangladesh Power Development Board (BPDB), Bangladesh hopes to boost its wind power capacity (Irfan et al., 2019). Bangladesh has many potential areas that could be used for wind energy, such as a 200 km hilly coastline, a 724 km coastal belt, and more than 50 islands in the Bay of Bengal (Babu et al., 2022). Bangladesh's regions, such as Chittagong, Cox's Bazar, Jessore, Khepupara, Hatiya, Kuakata, Kutubdia, and Patenga, have significant potential for wind energy generation.

### 3.5. Biomass energy

Biomass is a sustainable and green material obtained from living organisms, including plants and animals. Biomass is the stored chemical energy produced by plants through photosynthesis using solar radiation. Biomass presents a cost-effective and environmentally sustainable approach to power generation through the utilization of agricultural, industrial, and household waste for the generation of solid, liquid, and fuels (Sudalai et al., 2024). Fig. 8 illustrates various forms of biomass energy sources. Biomass can be used for heat generation through direct combustion or can be converted into liquid and gaseous fuels. The thermochemical conversion of biomass involves different processes like pyrolysis, hydrothermal processes, and gasification. In 2020, the global electricity generation from biomass reached 685 TWh. Solid biomass sources comprised 69 % of the overall biopower generation, with municipal and industrial waste contributing 17 % to the total biopower production. Asia accounted for 39 % of global biopower generation in 2019, producing 255 TWh. Europe contributed 35 % of the total global biopower generation.

Bangladesh generates biomass energy from sources like agricultural, municipal, animal, human, organic, and forest residue (Akram et al., 2022). The substance might be used as a solid fuel or converted into bioenergy by thermochemical and biochemical processes. Bangladesh's economy is primarily reliant on the agricultural sector. Bangladesh's agricultural output comprises diverse crops like groundnuts, rice, cotton, sugar cane, millet, maize, coconuts, legumes, jute, and vegetables. Bangladesh generates a significant amount of agricultural residue from its crops (Akram et al., 2022). Forest residue in Bangladesh is a significant source of biomass energy despite its smaller forest land area compared to arable land. The agricultural and forest residues have significant potential as sources of bioenergy for industrial and agricultural applications. Biomass exhibits a significantly higher primary energy capacity relative to alternative energy sources within the context of Bangladesh. Bangladesh's annual energy consumption is 71 % biomass energy, with conventional fuels consumed at 210 PJ/year and biomass energy accounting for 504 PJ/year.

Bangladesh, being an agricultural nation, possesses significant

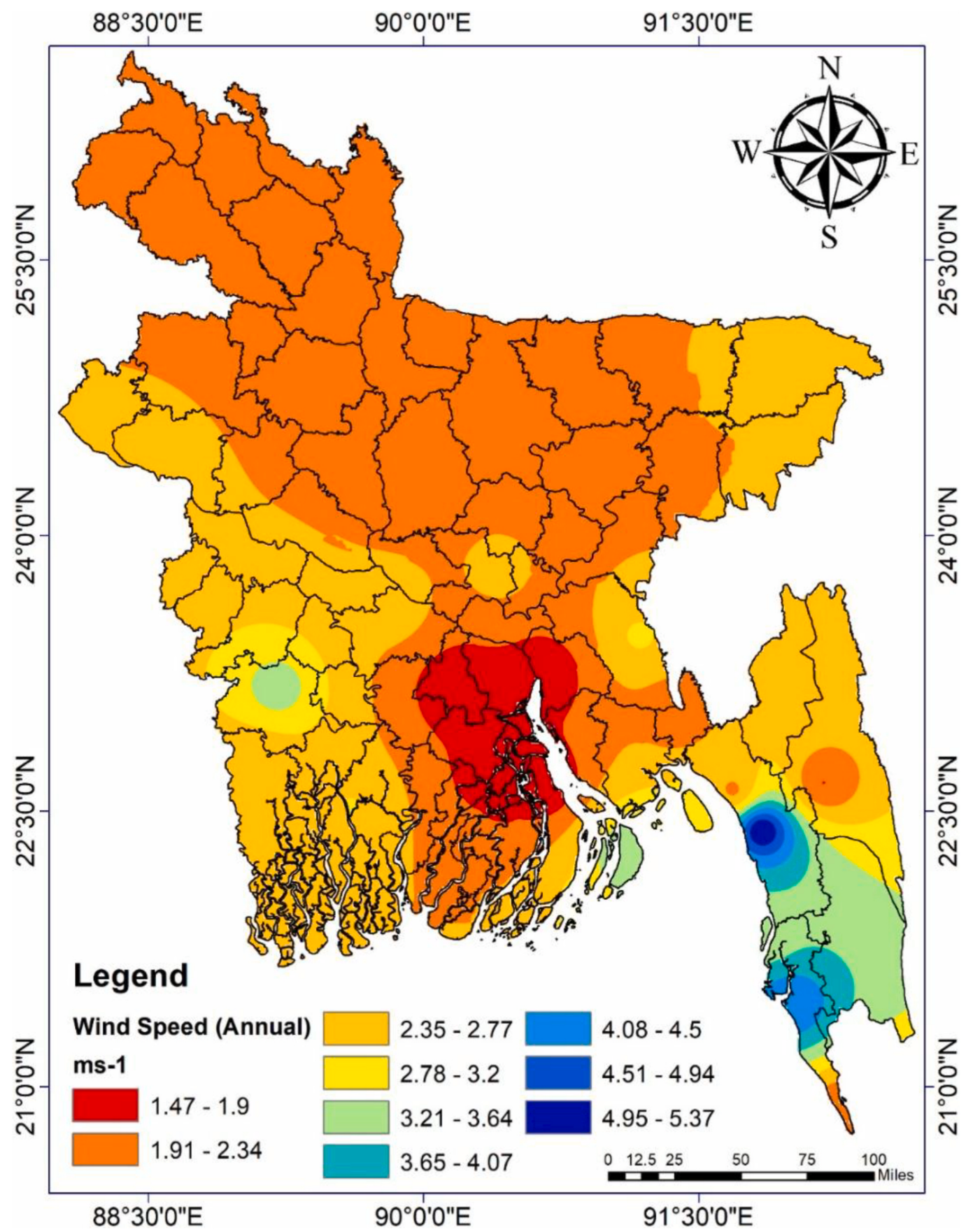


Fig. 7. The map of yearly average wind speeds across Bangladesh (Akash et al., 2024).

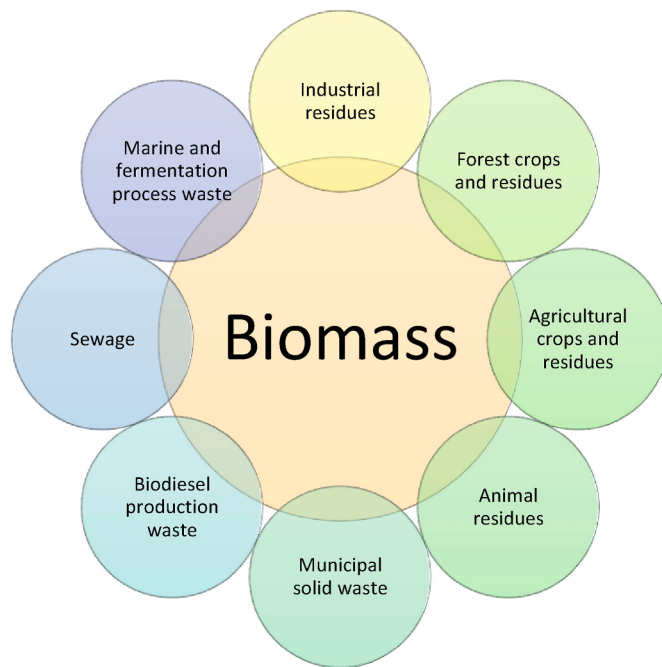


Fig. 8. Available sources of biomass energy in Bangladesh (Adapted from Uddin et al., 2019).

potential for harnessing animal waste as a source of bioenergy, specifically biogas production (Hossain et al., 2023). Animal dung is primarily sourced from cattle, goats, sheep, and buffalo. In contrast, the poultry population is steadily growing and is expected to reach 263 million (Baky et al., 2017). The recovery rates for poultry and animal waste droppings are 50 % and 60 %, respectively. The combined population of cattle and buffalo is approximately 24.48 million, resulting in a daily production of animal dung of nearly 186,000 tons. One kilogram of dung can yield approximately 0.037 cubic meters of biogas. The current dung supply has the potential to generate approximately 2.5 billion cubic meters of gas daily. This amount is comparable to 2.56 million metric tons of coal or 1.28 million metric tons of kerosene (Hasan et al., 2022). Bangladesh's daily human waste production is estimated to be 0.09 kg. The annual rate of human waste generation is estimated to be 4.54 million tons of dry matter. The daily creation of municipal solid waste (MSW) is 0.4–0.5 kg. Bangladesh has a large amount of biomass from MSW and human waste, which makes it a promising place to produce biogas. Specifically, the total biomass available from these sources is estimated to be 14.793 million tons per year. According to Akram et al. (2022), MSW in Bangladesh has the potential to generate 95.61 PJ (PJ) of energy. Moreover, organic solid waste serves as a significant biomass energy resource in Bangladesh's industrial regions. The food and wood product industries of Bangladesh generate a substantial amount of organic solid waste, which comprises vegetables, plastic products, food, cotton, jute, and paper (Soni et al., 2022).

Fig. 9 displays the yearly availability of biomass potentials in six divisions of Bangladesh due to limited data availability, despite the country having eight divisions. Rajshahi, Dhaka, and Chittagong divisions exhibit higher biomass production than other divisions due to their larger geographical size, as these divisions rank among the top three in terms of land area. Bangladesh primarily sources biomass energy from agricultural residues and animal waste. Rajshahi, Chittagong, and Khulna are the primary sources of agricultural and forestry residues. In contrast, Rajshahi, Dhaka, and Khulna exhibit higher levels of animal waste production in comparison to other biomass resources. Rajshahi city in Bangladesh generates the highest quantities of agricultural, animal, and poultry waste compared to other cities in the country. Dhaka City generates significantly more MSW and human excrement than other

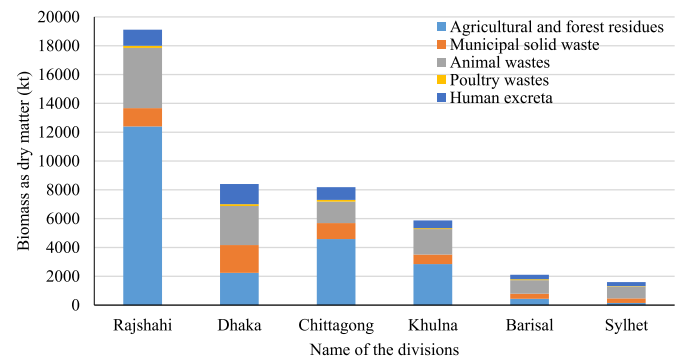


Fig. 9. Annual availability of biomass in various divisions of Bangladesh (Adapted from Hossain & Badr, 2007).

divisions in Bangladesh. The total biomass production and recoverable rate have been estimated to be 213.81 and 108 million tons/year, respectively, taking into account all biomass energy generation sources. However, the recovered biomass amounts to 90.21 million tons annually. According to Akram et al. (2022), biomass has been harnessed to produce a total energy amount of 1345 PJ. The energy generation is equivalent to 45.91 million tons of coal, 34.01 billion cubic meters of gas, and 373.71 trillion watt-hours of electricity generation.

### 3.6. Geothermal energy

Geothermal power is recognized as a sustainable and renewable form of energy. Geothermal energy is thermal energy sourced from geological reservoirs on Earth. Geothermal energy relies on the geothermal gradient, which is determined by the temperature disparity between the planet's interior and surface. Radioactive decay generates the internal heat of the planet. Geothermal energy is an easily accessible, economical, dependable, sustainable, and eco-friendly energy source. Geothermal sources contribute around 6.5 % to global energy production. Geothermal energy has a smaller environmental impact compared to conventional fossil fuel sources. Geothermal energy is fuel-free from an economic standpoint. Heat dissipation is facilitated by fluid circulation, which occurs through various mechanisms, including magma conduits, hot springs, and hydrothermal circulation. Despite the high initial capital investment, the subsequent operational expenses are relatively low. Although the power source beneath our feet exists, its overall significance is limited. Geothermal energy only accounts for 0.5 % of the global installed capacity for electricity generation, heating, and cooling systems.

Possible sites for geothermal energy in Bangladesh's northwest and southeast are shown in Fig. 10. The possible places are divided into six groups, and the most promising regions within each group are indicated by highlighted areas. Shallow geothermal reservoirs may exist in the northwest due to geological factors such as hydrogeological settings, seismic activity, basement faults, and surface thermal anomalies. This location has a geothermal gradient that varies from 20.8 to 48.7 °C/km (Islam et al., 2022). Thakurgaon district exhibits potential for geothermal energy because of thermal manifestations and signs of shallow aquifers (Islam et al., 2022). Additionally, the Singra-Kuchma-Bogra region exhibits promising potential. According to Das et al. (2021), the Singra well has the highest bottom hole temperature of over 150 °C, making it the most significant among the three areas. Possible locations for geothermal energy include the Madhyapara hard rock mine area and the Barapukuria coal basin. The Madhyapara region, with temperature variations ranging from 67 to 153 °C, indicates the existence of a low-temperature geothermal reservoir. Additionally, research indicates that the temperature in the northwestern region of Bangladesh, specifically near the Salbanhat-1 well, reaches 79 °C at a depth of 2500 m below the Earth's surface. Furthermore, at a depth of

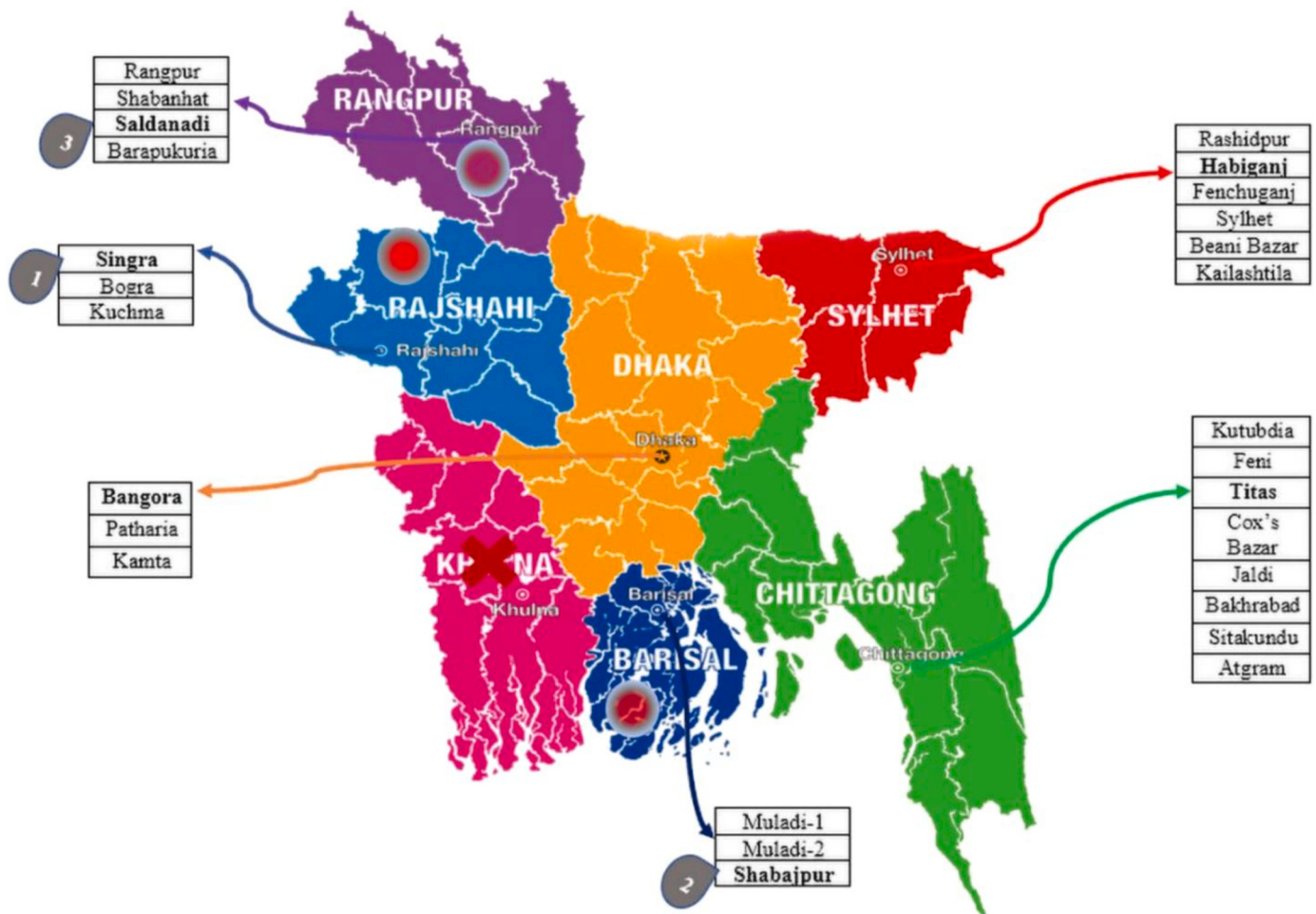


Fig. 10. Geothermal energy zones on a map of possible sites in Bangladesh (Islam et al., 2022).

4000 m, the temperature rises to 110 °C. The GDH-65/11 well in Thakurgaon district reached a temperature of 47 °C at a depth of 587m (Islam et al., 2022).

Moreover, Fig. 11 displays the geothermal gradients in the northwest and southeast territories, allowing for a comparison between these areas. In the southeast, the geothermal gradient varies from 19.8 to 27 °C/km. The Sitakund hilly area has gained popularity due to the presence of thermal springs. The Semutang-1 well in Khagrachari has the highest gradient in the southeast, measuring 27 °C/km. The northwest generally has more favorable geothermal gradients than the southeast. The highest temperature gradients are seen in the Thakurgaon and Barapukuria wells, which measure 34.2 °C/km and 48.7 °C/km, respectively. (Islam et al., 2022). However, operational barriers exist to establishing a geothermal power plant in Bangladesh, including institutional, regulatory, technical, and financial obstacles.

### 3.7. Tidal energy

Tidal energy is a well-established hydropower method that converts energy from ocean tides into electricity. The ocean's natural currents are used to generate tidal energy. Tidal stream utilization involves converting the kinetic power of water movement into electricity using turbines. The reliance on fossil fuels for electricity generation could be replaced by tidal energy. According to the Tidal Energy Development Report of 2020, wave and tidal energy account for 1.5 % of installed electricity worldwide, 7.5 % of hydropower capacity, and 4.5 % of renewable energy capacity.

Bangladesh is a riverine country with consistent tidal patterns

throughout the year. Bangladesh exhibits significant potential for harnessing tidal energy for electricity generation. The coastal area is conducive to harnessing tidal energy. Tidal energy is the sole energy source derived directly from the relative motion of the Moon and Earth. Tidal energy is currently generated through the use of stream generators or barrage generation methods. The primary requirements for generating tidal power are the presence of tidal waves with a minimum height of 3 m and a suitable embankment. When selecting a tidal power station, it is important to consider several factors, including the presence of a consistent tidal wave, minimal risk of natural disasters, distance from populated areas, and an efficient transmission system. Coastal areas of Bangladesh offer tides ranging from 3 to 5 m in height. Tidal power can be generated consistently throughout the year and around the clock, achieving an efficiency rate of 80 %.

The average tidal range in the southeastern coastal area of Bangladesh is between 4 and 5 m, with the spring tide reaching amplitudes exceeding 6 m. Suitable sites in the southeastern coastal region and other locations are expected to be available for the construction of permanent basins with pumping arrangements. These basins would be designed to operate in a dual capacity. In Bangladesh, 19 districts are located in the coastal zone, with 12 of them directly adjacent to the sea and deemed suitable for tidal power initiatives. Tidal power can be swiftly deactivated and reactivated with minimal damage. Researchers have identified several locations in southern Bangladesh as potential sources of significant tidal energy for power generation (Ali et al., 2012; Haque & Khatun, 2017). Fig. 12 presents various locations that exhibit tidal range and desired power output potential. Nine potential stations in Bangladesh have the potential to generate a major power output of

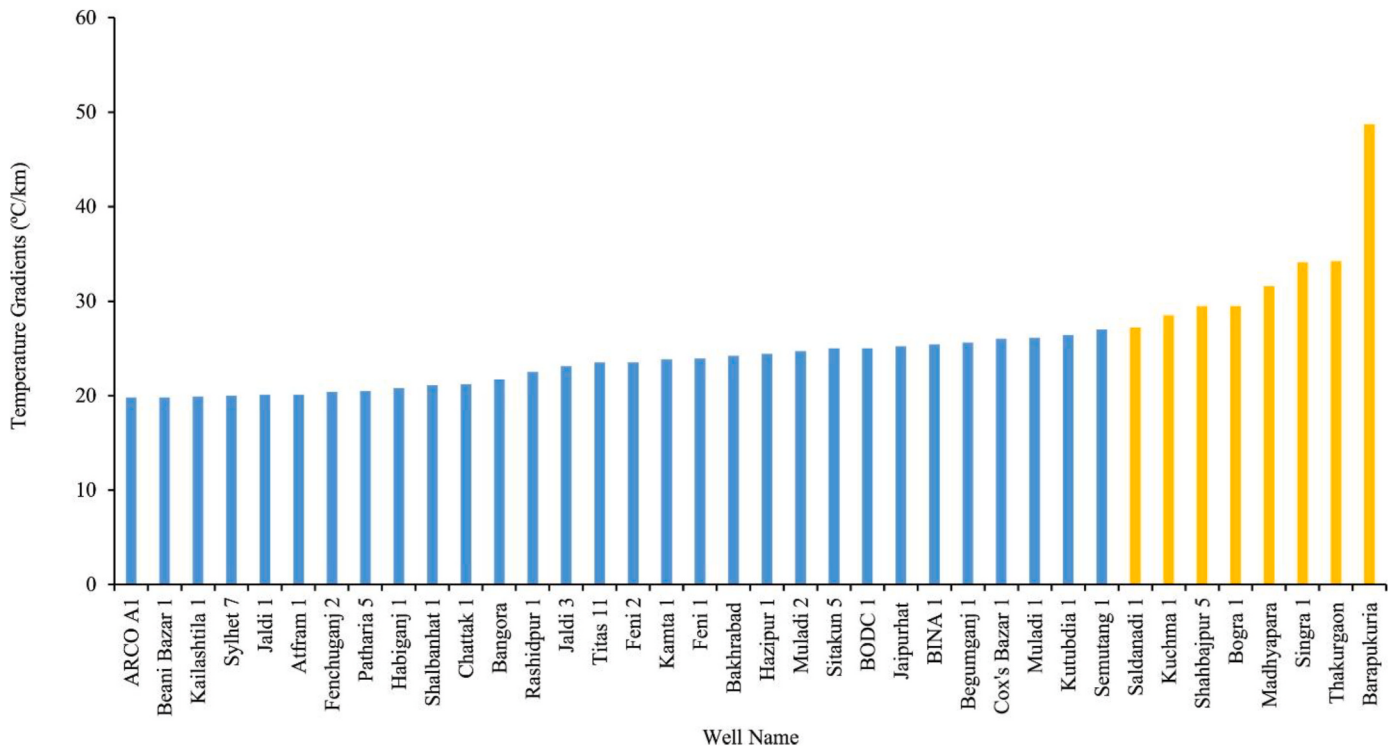


Fig. 11. Geothermal gradients in southeast (blue) and northwest (yellow) Bangladesh (Islam et al., 2022).

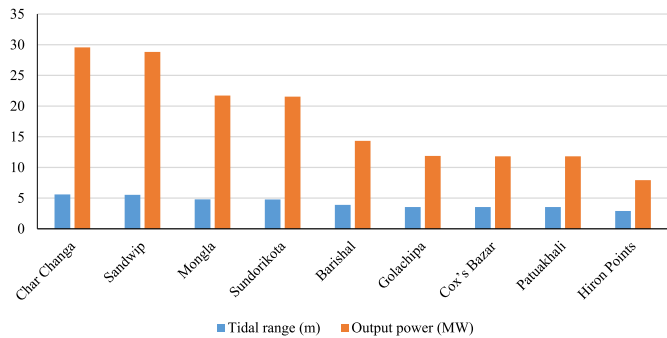


Fig. 12. Estimated tidal energy installations and output (Adapted from Haque & Khatun, 2017).

176.64 MW. Because of its favorable geographic features, Sandwip is considered the best place to generate barrage-type tidal power. A proposal has been made to construct a tidal energy harvesting system in Sandwip. The system would consist of a 75 kW micro-hydro turbine and have the potential to generate approximately 1380 kWh of energy per day.

3.8. Economic appraisal of renewable energy

The evolution of renewable energy production has transitioned from being an alternative option to becoming an essential solution for addressing increasing energy demands. Given the constraints of finite non-renewable resources and the pressing environmental issues, it is essential to prioritize renewable alternatives. Bangladesh predominantly depends on non-renewable energy sources and imports, which may offer enhanced cost-efficiency and security; however, this reliance contributes significantly to the carbon footprint impacting the environment. Transitioning to renewable energy sources is essential for ensuring energy security in the long run. An analysis of the costs associated with major sources of renewable power in Bangladesh is essential

for facilitating informed decisions regarding energy policy. Decision-makers can identify the most financially feasible alternatives by assessing the costs linked to solar, wind, and hydropower initiatives. This analysis guarantees the best use of resources, efficient budgeting, and the choice of sustainable energy solutions that correspond with Bangladesh's economic objectives (Akash et al., 2024).

Furthermore, comprehending costs aids in drawing investments, encouraging technological advancements, and supporting a more sustainable energy mix, which ultimately enhances Bangladesh's energy security, environmental sustainability, and long-term economic development (Raihan et al., 2022). The financial aspect of the installation of renewable energy technologies holds greater significance than any other considerations. Table 4 presents a detailed analysis of the costs associated with various types of power plants, including solar, tidal, biomass, and wind. The data illustrates the investment requirements, highlighting the economic aspects of renewable energy sources. Renewable energy sources demonstrate greater financial advantages compared to traditional options. Bangladesh recognizes the significance of renewable energy sources in ensuring energy security, while also taking into account the constraints and economic viability of non-renewable sources. The country possesses significant potential in solar, biomass, and hydro energy, providing a reliable energy source, while the intricacies of geothermal energy limit its applicability.

Table 4  
Costs associated with various renewable energy.

| Type of renewable energy | Plant cost (million USD) | Power plant cost per MW (million USD) | Source                |
|--------------------------|--------------------------|---------------------------------------|-----------------------|
| Solar                    | 7636                     | 1.47                                  | Saim and Khan (2021)  |
| Wind                     | 246                      | 1.15                                  | Alam et al. (2021)    |
| Biomass                  | 769                      | 1.00                                  | Liu and Li (2016)     |
| Tidal                    | 250                      | 0.49                                  | Hossain et al. (2014) |

### 3.9. Policies relating to renewable energy

Over time, there has been a consistent rise in both the GDP and population of Bangladesh. By 2030, the projected electricity requirement is expected to reach 34,000 MW. To address the increasing electricity demand, the government has implemented various measures, including policymaking, regulation, and investments in the sector. The government of Bangladesh has committed to spending USD 70 billion over the next 15 years to advance environmentally friendly and sustainable energy.

The Bangladesh Environment Conservation Act of 1995 (amended 2010) is the main law that ensures a sustainable ecosystem. The ordinance was introduced to replace the 1992 environmental pollution control ordinance. The goal of the National Energy Policy (NEP) of 1996 is to encourage the effective use of renewable energy sources, such as solar energy, biogas, and biomass fuels. Furthermore, the policy motivates the implementation of sustainable energy development programs that prioritize environmental preservation. The National Energy Policy (NEP) has proposed the establishment of the Renewable Energy Development Agency (REDA) to expedite the development of renewable energy infrastructure in Bangladesh. A thorough set of regulations is provided by the Environment Conservation Rules, 1997 (Amended 2002) to ensure that the Environment Conservation Act, 1995, is implemented in an efficient manner. In order to ensure environmental cleanliness and ambient standards, this law document offers a categorized list of projects, which are named Green, Orange-A, Orange-B, and Red. The projects tackle water, noise, and air pollution, utilizing renewable energy technologies as a sustainable solution.

The Renewable Energy Policy of Bangladesh, 2002, provides a comprehensive overview of the roles and funding of agencies responsible for renewable energy development. It also emphasizes the importance of implementing tariffs on oil. The plan will provide financial incentives to international investors in the renewable energy sector, enabling up to 50 % remittance of foreign employees' salaries in Bangladesh. The energy tariff for companies with a renewable energy production capacity of 5 MW or more is approved by the Bangladesh Energy Regulatory Commission Act, 2003 (BERC Act 2003), in line with the Power Division of the Ministry of Power, Electricity, and Mineral Resources. The policy permits the government to undertake projects aimed at developing renewable energy infrastructure.

The Government of Bangladesh initially implemented the Bangladesh Renewable Energy Policy 2008 to encourage the growth and exploitation of renewable energy sources within the country. Bangladesh set a specific objective in its 'Renewable Energy Policy, 2008', although the progress in developing renewable energy sources in the country has been inadequate. The objective was to fulfill a minimum of 5 % of the overall electricity requirement by 2010 and 10 % by 2020 through the utilization of renewable energy sources. Currently, renewables account for around 3.49 percent of Bangladesh's energy mix, which includes off-grid installations. The successful execution of a specific strategy to encourage the use of renewable energy relies on the policy tools it possesses. A policy instrument serves as a connection between the process of creating policies and the process of putting those policies into action. The Renewable Energy Policy 2008 did not include strategic planning, renewable energy financing, and net metering. However, it did include renewable portfolio standards, feed-in-tariffs, and grants and subsidies to a small extent. Only the tax incentives were given proper consideration in the policy statement. The 'Renewable Energy Policy, 2008' includes policy measures such as tax holidays and VAT exemptions. However, those measures were insufficient to expedite the process of transitioning to renewable energy in Bangladesh. The inadequate implementation of renewable energy in Bangladesh can be attributed to several factors, including the absence of policy instruments, limited availability of resources, minimal institutional support, and unfavorable attitudes towards renewable energy sources. The Renewable Energy Policy of 2008 addresses concerns related to the

accessibility of fuel, the release of emissions, and the assurance of energy stability. The 2008 policy promoted and supported investments from both the public and private sectors. Nevertheless, it lacked the incentive to uphold global obligations for climate objectives. Furthermore, the 2008 policy lacked any particular regulatory measures.

The Power Sector Master Plan (PSMP) 2010 aims to achieve a 7.3 % GDP growth rate by combining renewable and conventional energy sources for the national energy grid. During the period from 2011 to 2015, Bangladesh experienced a 6.3 % increase in its GDP. The Sustainable and Renewable Energy Development Authority Act, 2012 (Act No. 48 of 2012) establishes the Sustainable and Renewable Energy Development Authority (SREDA). SREDA is the principal regulatory authority in charge of supervising all projects and activities pertaining to sustainable and renewable energy resources. The Energy Efficiency and Conservation Rules, issued in March 2015, set forth a goal for Bangladesh to achieve 15 % of its total consumable energy from renewable sources by 2021 and 20 % by 2030. The government of Bangladesh has committed to making a substantial investment to accomplish this objective. The 7th Five-Year Plan, December 2015, aims to expand the reach of renewable energy by implementing and funding projects related to ocean, tidal, and geothermal energy. As part of the 7th Five-Year Plan, the government of Bangladesh has actively promoted R&D in the fields of ocean, tidal, and geothermal energy.

In 2014, the National Centre for Atmospheric Research (NCAR) partnered with NREL and the Government of Bangladesh (GOB), funded by the US Agency for International Development, to assess Bangladesh's wind resources. Despite a goal to generate 10 % of national electricity from renewable sources by 2021, no utility-scale wind farms have been established. The NREL research team used NCAR's dataset to estimate wind speed potential across nine meteorological stations, and the data is now available for harnessing wind energy. Additionally, the UNDP-funded Sustainable Renewable Energy Power Generation (SREPGen) Project conducted a biomass resource mapping survey to assess the country's biomass energy potential.

The 2016 Power Sector Master Plan (PSMP) laid out a comprehensive energy and power development plan up to 2041, focusing on renewable energy, energy balance, and tariff strategies. It introduced feed-in tariffs, a roadmap for nuclear energy, and set targets of 2,470 MW of domestic renewable energy by 2021 and 3,864 MW by 2041. The Energy Efficiency and Conservation Master Plan up to 2030 outlines SREDA's goals and allocates a revised budget for renewable energy projects. The plan also recommends using energy-efficient building equipment and includes significant financial incentives like low-interest loans for solar PV systems, ongoing financial support for end users, and tax breaks.

The Climate Prosperity Plan 2022–2041 aims to provide 100 % energy access to Bangladesh's people through efficient energy wealth utilization. At COP26, Bangladesh aims to achieve 40 % renewable energy by 2041 and 100 % by 2050, fostering resilience and energy independence to become a net energy exporter and global green economy participant. Bangladesh plans to replace outdated technology to enhance trade balance, reduce inflation, and enhance cost competitiveness in the sector. Reducing or eliminating imports of coal, oil, diesel, and gas can protect the economy from volatile commodity markets, ensuring price stability and promoting trade balance. Bangladesh plans to leverage record-low solar power tariffs through renewable energy auctions across the region, aiming to enhance price stability, cost competitiveness, and power sector resilience. Bangladesh Delta Plan 2100 aims to ensure domestic energy security through investment in solar, including reclaimed land, rooftop, ground, and floating. The government plans to generate 2000 MW of solar power in addition to offshore wind and domestic storage capacity. Alternative power generation in the Bay of Bengal can be achieved through predictable tidal power and the conversion of ocean thermal energy.

As of May 2025, Bangladesh's most recent renewable energy policy is the Draft Renewable Energy Policy 2025. This policy aims to increase

renewable energy capacity to 6,145 MW (20 % of total capacity) by 2030 and 17,470 MW (30 %) by 2041. However, these targets are based on installed capacity rather than actual energy generation, raising concerns about their effectiveness in driving a genuine energy transition. The policy has faced criticism for lacking a clear roadmap and coherent direction to meet its renewable energy goals, with stakeholders noting limited public consultation and insufficient inclusion of civil society and experts in the formulation process. Previously, the Draft Renewable Energy Policy 2022 had set more ambitious targets, aiming for 40 % of electricity generation from renewables by 2041, and included plans for a Renewable Energy Master Plan, integration of technologies like solar, wind, and bioenergy, and fiscal incentives such as VAT and import duty waivers. Despite these efforts, Bangladesh's renewable energy share remains low, with only 3.5 % of its 25,528 MW installed electricity capacity sourced from renewables as of June 2022. The country's renewable energy transition continues to face challenges, including policy implementation gaps, limited investment, and infrastructural constraints.

### 3.10. Challenges in renewable energy

Bangladesh, along with other nations, is making significant strides in the renewable energy sector. In 2041, total electricity demand for the high- and low-case scenarios will be about 82292 MW and 72000 MW, respectively. For the former case, the required renewable capacity will be 9400 MW, and for the latter case, it will be 7950 MW in 2041, considering there is a 10 % renewable capacity in the generation fuel mix of the Bangladesh Power System Master Plan (PSPMP). The UN's SDGs are the primary challenge to Bangladesh's aim to expand its power generation. These goals include: first, ensuring energy access for the total population of the country; second, introducing a considerable share of green power into the generation fuel mix; third, importing power from neighboring countries; and finally, related policymaking for the energy sector. Bangladesh has significant potential for utilizing renewable energy sources, but numerous challenges hinder the advancement of these technologies. Fig. 13 presents a detailed overview of the challenges associated with renewable energy.

#### 3.10.1. Political

Bangladesh faces a significant issue due to the absence of clear, consistent, and sustainable policies regarding renewable energy technology (Joarder et al., 2024). The maximum number of renewable

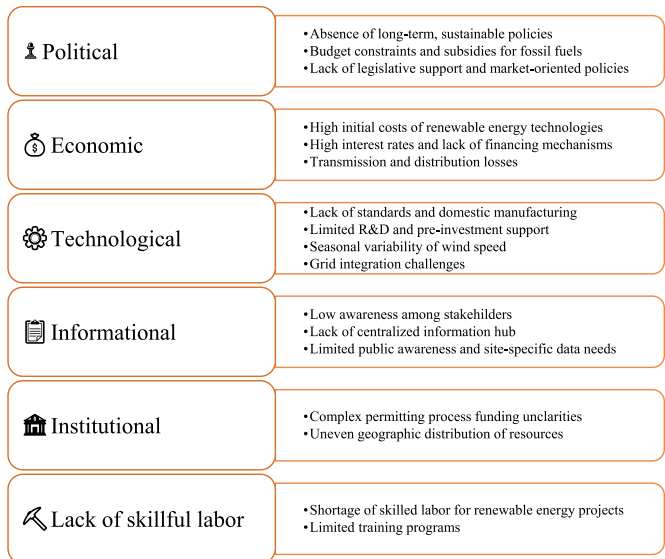


Fig. 13. Challenges in renewable energy development in Bangladesh.

energy technology initiatives is intermittent and lacks strong policy support, which hinders their integration into government-level energy planning (Mahmud & Roy, 2021). Renewable energy technology policies lack budgetary guidelines and legislative support (Yan et al., 2023). The national budget has an influence on the adoption of renewable energy technology, which causes delays in decision-making and uncertainty in the distribution of funding. The Bangladeshi government's budget for subsidizing renewable energy projects is restricted due to prioritizing health, education, and disaster management over renewable energy projects (Mahbub, 2024). Direct and indirect subsidies to traditional energy sources reduce the competitiveness of renewable energy technologies (Lin & Xie, 2023). Bangladesh currently lacks adequate legislative support for the implementation of renewable energy technologies (Abdullah-Al-Mahbub & Islam, 2023). Insufficient financial incentive policies impede the progress of renewable energy development. Market-oriented renewable energy initiatives face obstacles, such as a lack of the needed policy, legal, and regulatory framework (Akram et al., 2022).

#### 3.10.2. Economic

The high initial cost of renewable energy technologies poses a significant challenge to emerging nations like Bangladesh (Akash et al., 2024). Subsidies are crucial in order to make renewable energy technologies economically viable for users (Ahmed et al., 2024). In the absence of effective targeting, it serves as an obstacle. While renewable energy technologies have a feasible lifespan, their cost makes returns smaller. Additionally, the elevated market interest rate constrains the adoption and implementation of renewable energy technologies. The deficiency of appropriate financing mechanisms, such as micro-credit, poses a significant challenge to the accessibility of renewable energy technologies (Akram et al., 2022). Currently, Grameen Shakti is implementing a project that seeks to expand the accessibility of renewable energy technologies in both rural and urban areas through the use of microcredit mechanisms (Hellqvist & Heubaum, 2023). System loss is a significant performance indicator in all renewable energy technologies. Both transmission and distribution losses exhibit a significant percentage in Bangladesh. Transmission and distribution losses in developed countries typically range from 2 % to 8 %. These factors render renewable energy technologies unfeasible in Bangladesh (Mojumder et al., 2022).

#### 3.10.3. Technological

Bangladesh is criticized for its lack of quality control measures and standards for renewable energy technologies (Mahmud & Roy, 2021). There prevails a significant deficit in the domestic generation of green power technologies. Despite the presence of expertise, facilities, knowledge, and skills, the absence of adequate technical support hinders the growth of renewable energy technologies in this country (Mahmud & Roy, 2021). The primary concern in this situation is the absence of prior research endeavors in the pertinent field. The limited accessibility of modern energy services and renewable energy technologies is prevailing due to their inadequate technical capability for their development, implementation, management, and maintenance (Barman et al., 2023). The evidence indicates that there is a lack of technology transfer and pre-investment support for demonstration and performance testing (Akram et al., 2022). In addition to seasonal factors, the fluctuation of wind speed presents technological constraints for wind turbine operation (Eladl et al., 2024). A large percentage of wind power innovations in Bangladesh are located in coastal areas, which makes it difficult to connect to the national grid and raises the cost of transporting electricity (Akram et al., 2022).

#### 3.10.4. Informational

The primary challenges to the widespread utilization of clean energy include a lack of awareness and commitment among industry, the general public, utility companies, policymakers, and financial organizations

(Akram et al., 2022). The current availability and accessibility of information on renewable energy resources and technologies are insufficient. Bangladesh lacks a centralized information point for renewable energy, resulting in the dispersion of relevant information across multiple sectors, including academia, research and development centers, development assistance organizations, and the public sector (Hussain et al., 2024; Ullah et al., 2024). A significant barrier to obtaining accurate information on renewable energy technologies is limited public awareness (Saraji et al., 2023). Additionally, there is a lack of deep knowledge regarding the possibility, resources, technologies, and usage of renewable energy. The information on renewable energy technologies and resources is often specific to specific sites, requiring thorough investigation (Akram et al., 2022). The relationship between information technology and the power sector in Bangladesh is minimal due to the country's lower economic status. The contribution of renewable energy to the production of electricity is rather minimal due to the limited availability of technological information. The power sector's use of information technology is currently limited (Sarker et al., 2024).

### 3.10.5. Institutional

The management of green power technologies, resources, and cutting-edge energy services is overseen by various institutions, agencies, and ministries to establish a suitable connection between human resources and limited finances, thereby ensuring efficient utilization of these technologies (Chen et al., 2024). The process of obtaining permits and provisions for the application of renewable energy technologies is complex and time-consuming (Siddique et al., 2021). The reliance on the national budget for decision-making creates uncertainty in the use of renewable energy technologies and project financing (Akram et al., 2022). The uneven geographical distribution of renewable energy technologies limits their implementation and access (Hussain et al., 2024).

### 3.10.6. Lack of skillful labor

The development of skilled labor is hindered by the absence of awareness, expertise, and information regarding renewable energy resources (Akram et al., 2022). Skilled labor is needed for the construction of renewable energy infrastructure projects. The successful implementation of renewable energy projects heavily relies on the availability of skilled labor (Pouresmaeili et al., 2023). The growth of renewable energy innovation in Bangladesh is severely hindered by a lack of skilled manpower (Mahmud & Roy, 2021).

## 4. Conclusions and recommendations

### 4.1. Conclusions

The depletion of finite resources and the environmental consequences of emissions have rendered traditional fossil fuel-based power generation unsustainable in the long run. Utilizing renewable energy sources to generate power has advantages for the environment by lowering GHG emissions, in addition to economic benefits that outweigh associated costs. This paper provides a comprehensive overview of the primary renewable energy resources available in Bangladesh, along with an examination of their advantages, expansion, financial support, implementation, and obstacles. Bangladesh's 4–5 kWh/m<sup>2</sup> average solar radiation has the potential to generate substantial electricity and bridge the gap between demand and supply. Summer winds in coastal regions are vital for generating regional electricity through wind energy. The future energy demand in Bangladesh is anticipated to be influenced by increased investment in this sector. The amount of energy produced by hydropower is still restricted, even with the presence of small-scale working hydropower facilities and continuous research into possible locations. Bangladesh has the capacity to utilize sustainable energy resources such as geothermal, wave, nuclear, and tidal energy; however, additional investigation is required. By 2050, renewable energy is

projected to account for almost 57 % of all energy demand. Future energy security can be ensured through the integration of renewable energy sources into the smart grid system. This article suggests that in order to achieve sustainable and carbon-free energy, Bangladeshi officials should implement appropriate measures to promote the use of renewable resources.

### 4.2. Recommendations

This review presents the following guidelines for ensuring energy security and promoting development and welfare in Bangladesh through renewable energy sources:

- The Bangladeshi government should implement strategies to enhance the utilization of renewable resources.
- Promoting renewable energy development through technological advancements.
- An effective generation expansion plan must consider the increasing demands from various sectors.
- The private sector should be encouraged and supported to invest in renewable energy initiatives.
- Coordination is essential for the expansion plan of generation, transmission, and distribution.
- To effectively manage peak demands and optimize network infrastructure, it is essential to prioritize demand-side management, energy efficiency, and conservation measures.
- Encouraging increased contributions to renewable energy resources for electricity generation should be promoted.
- To increase the production of electricity, more renewable energy plants should be installed in rural regions.
- To reduce the cost of generating renewable power and enhance market competitiveness.
- Government and non-government organizations should have a role in influencing waste recycling and management.
- Establishing a robust policy, legal, and regulatory framework
- Enhancing strategic public relations efforts to promote public awareness.
- Fostering the growth of an integrated energy sector in Bangladesh as a catalyst for sustainable economic development.
- Rural communities should receive awareness and training on how to effectively utilize these energy sources.
- The promotion of indigenous technologies in the renewable energy sector is crucial.
- The utilization of renewable energy sources should be increased, as suggested by various sources.
- The government should provide assistance for enhancing technological capabilities in order to improve electricity generation from renewable sources.
- Tax exemption should be granted for the importation of machinery related to renewable and sustainable energy.
- Increased collaboration with technologically progressive countries.
- Import renewable energy machinery from the developed nations.
- Tax reduction for the industries using renewable energy resources.
- To enhance the use of nearby green power sources, there should be more collaboration between academics, scientists, researchers, the government, and non-governmental groups.

### 4.3. Limitations and future research

The present study investigating the perspectives, challenges, and opportunities of renewable energy resources for green development in Bangladesh has several limitations. First, data availability and reliability can be a significant constraint, as comprehensive and up-to-date information on renewable energy projects, policies, and infrastructure in Bangladesh is limited and inconsistent. Additionally, the study relied on secondary data sources, expert opinions, or case studies, which could

introduce biases or limit the generalizability of the findings. Another potential limitation is the scope of stakeholder perspectives. If the study does not incorporate insights from all relevant groups, such as policy-makers, industry experts, local communities, and investors, it may not fully capture the diverse challenges and opportunities within the sector. Furthermore, the study may not account for rapid technological advancements or shifting policy landscapes, which could affect the long-term feasibility of proposed renewable energy solutions. Lastly, financial and socio-political constraints, including funding limitations, bureaucratic barriers, and public acceptance, may not be fully explored, potentially underestimating the complexities of implementing large-scale renewable energy projects in Bangladesh.

Future research into the utilization of renewable energies for green development in Bangladesh is essential due to the country's increasing energy demand, environmental concerns, and vulnerability to climate change. As a nation with significant agricultural and industrial sectors, Bangladesh requires sustainable energy solutions to support economic growth while reducing its carbon footprint. Investigating renewable energy sources such as solar, wind, and biomass could help diversify the energy mix, ensuring energy security and minimizing dependence on fossil fuels. Moreover, future research can lead to the development of more efficient technologies, enhancing the affordability and accessibility of renewable energy for rural and underserved communities. The potential impact includes the reduction of GHG emissions, improved public health through cleaner air, job creation in green industries, and strengthened resilience to climate change, positioning Bangladesh as a leader in sustainable development in the region. Future research on utilizing renewable energy for green development in Bangladesh could focus on several critical areas. First, studies could explore the integration of diverse renewable energy sources, such as solar, wind, biogas, and hydropower, into the national grid to reduce dependence on fossil fuels. Research could also address the optimization of renewable energy storage systems to manage intermittency and ensure a reliable energy supply. Another important direction could involve assessing the socio-economic impacts of renewable energy projects, especially in rural and underprivileged areas, to promote inclusive green development. Additionally, investigating policy frameworks and financial models, such as public-private partnerships and green financing, could help scale up investments in renewable energy infrastructure. Research could further delve into innovative technologies, such as floating solar farms and offshore wind turbines, considering Bangladesh's geographical characteristics. Finally, studies could evaluate the environmental benefits of renewable energy adoption, focusing on carbon emissions reduction and its alignment with Bangladesh's climate goals under international agreements.

#### CRedit authorship contribution statement

**Asif Raihan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Md Sadman Anjum Joarder:** Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Syed Masiur Rahman:** Writing – review & editing, Supervision, Investigation. **ABM Mainul Bari:** Writing – review & editing, Validation, Investigation, Conceptualization. **Mohammad Ridwan:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **Tapan Sarker:** Writing – review & editing, Validation, Supervision.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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