Heliyon 10 (2024) e27477

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Greening the grid: A comprehensive review of renewable energy in Bangladesh

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A R T I C L E I N F O

Keywords:
Renewable energy technologies
Bangladesh
SDG-7
Energy policy
Environmental impact

A B S T R A C T

The escalating global demand for energy has coincided with economic development, while Bangladesh's reliance on renewable energy remains modest at 4.59%. Investigating economically viable solutions such as solar, biomass, and other renewable sources, the research underscores the pivotal role of sound policies and a strategic plan in transforming the current energy landscape. Despite facing various challenges, particularly in technology, the implementation of sound policies and a strategic plan can substantially alter the current landscape. By reviewing the Renewable Energy Policy of 2008 and incorporating recommendations from United States Agency for International Development (USAID) in 2023, this paper not only delves into challenges and future prospects but also aligns with the Sustainable Development Goal (SDG) aimed at achieving affordable and clean energy. This study contributes valuable insights by proposing methodologies to generate renewable energy by offering a comprehensive overview of the present energy scenario in Bangladesh, with a focus on strategic policy recommendations, thus surpassing previous efforts in the literature. The paper, in its entirety, strives to foster the adoption of renewable energy while concurrently mitigating reliance on conventional fossil fuels.

1. Introduction

In the contemporary era, energy stands as a fundamental requirement for industrialization and sustainable economic growth [1,2]. Nevertheless, the escalating global energy demand and consumption present an increasing concern on a global scale. Predictions indicate a 33% rise in global energy demand by 2030 [3,4], with estimates revealing an increase of 45 billion Megawatts (MW) in global energy usage during 2007. Furthermore, the demand escalation is anticipated to climb by 49% by 2035, reaching around 218 billion MW [5]. The growing energy consumption rate among various Asian countries are depicted in Fig. 1, with China, Malaysia, and Iran exhibiting approximately 6% while on the other hand, Japan displays a notably lower growth rate. Characterized by moderate energy growth, the country deals with energy security issues amid striving for necessities [6]. The rapid expansion of renewable energy sources is crucial to achieving net-zero carbon goals, with the share of renewables projected to reach 60% of electricity generation by 2030 and 90% by 2050 [7]. The transport sector is a critical area of focus for the EU in its efforts to reduce greenhouse gas emissions by

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https://doi.org/10.1016/j.heliyon.2024.e27477
Received 6 October 2023; Received in revised form 11 January 2024; Accepted 29 February 2024
Available online 6 March 2024

Nomenclature

BPDB	Bangladesh Power Development Board
BWDB	Bangladesh Water Development Board
CMEC	China Machinery Engineering Corporation
CO_2	Carbon dioxide
FIT	Feed-in tariffs
GoB	Government of Bangladesh
IDCOL	Infrastructure Development Company Limited
LGED	Local Government Engineering Department
Mtoe	Metric Tons of Oil Equivalent
MW	Megawatts
NEM	Net energy meter
PV	Photovoltaic
RE	Renewable energy
REB	Rural Electrification Board
SDG	Sustainable Development Goal
SHS	Solar Home Systems
SREDA	Sustainable and Renewable Energy Development Authority
USAID	United States Agency for International Development
GWh	Gigawatt hour
GW	Gigawatt
UK	United Kingdom
MJ	Mega Joule
USD	US Dollar
Tcf	Trillion cubic feet
GoB	Government of Bangladesh
RET	Renewable Energy Technology
RETs	Renewable Energy Technologies
SDGs	Sustainable Development Goals
SDG-7	Sustainable Development Goal Seven
kWh	Kilowatt-hour
IPPs	Independent Power Producers

55% by 2030 [8]. The EU is committed to phasing out fossil fuels in road transport, aiming for all new cars and vans to be powered by electricity and emit no net greenhouse gases by 2035 [9].

In contrast, Bangladesh stands as one of the lowest renewable energies in Asia and South Asia, with a per-capita energy use of 146.5 Kilowatt-hours (kWh). This pales compared to India and Pakistan with 480.5 kWh and 456.2 kWh respectively [11]. As illustrated in Fig. 2 Bangladesh predominantly relies on conventional energy sources for electricity generation where natural gas accounts for the most significant proportion of energy, followed by furnace oil and other essential sources [12]. However, natural gas and coal reserves

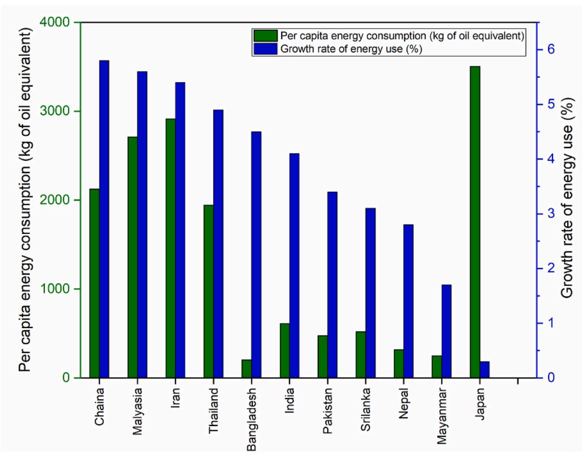

Fig. 1. Energy consumption per capita and the variation in energy usage growth rates among various nations [10].

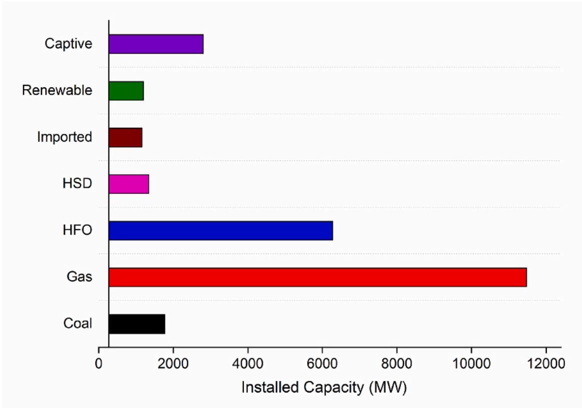

Fig. 2. Capacity of current energy generation mix installed in Bangladesh [14].

are limited in the country and unfortunately, the remaining recoverable reserve of gas, which is 10.42 trillion cubic feet (Tcf) will be deplete by the next decade [13]. An optimal energy generation mix for the country is crucial to deal with these upcoming possible energy crises. Fig. 2 shows the installed capacity of the current energy generation mix of the country.

Several studies address fossil fuel pollution concerns due to global energy demand. Policies push renewable integration and micro grids, facing challenges of converters, regulations, grids, and communication [15,16]. Globalization, including economic, political,

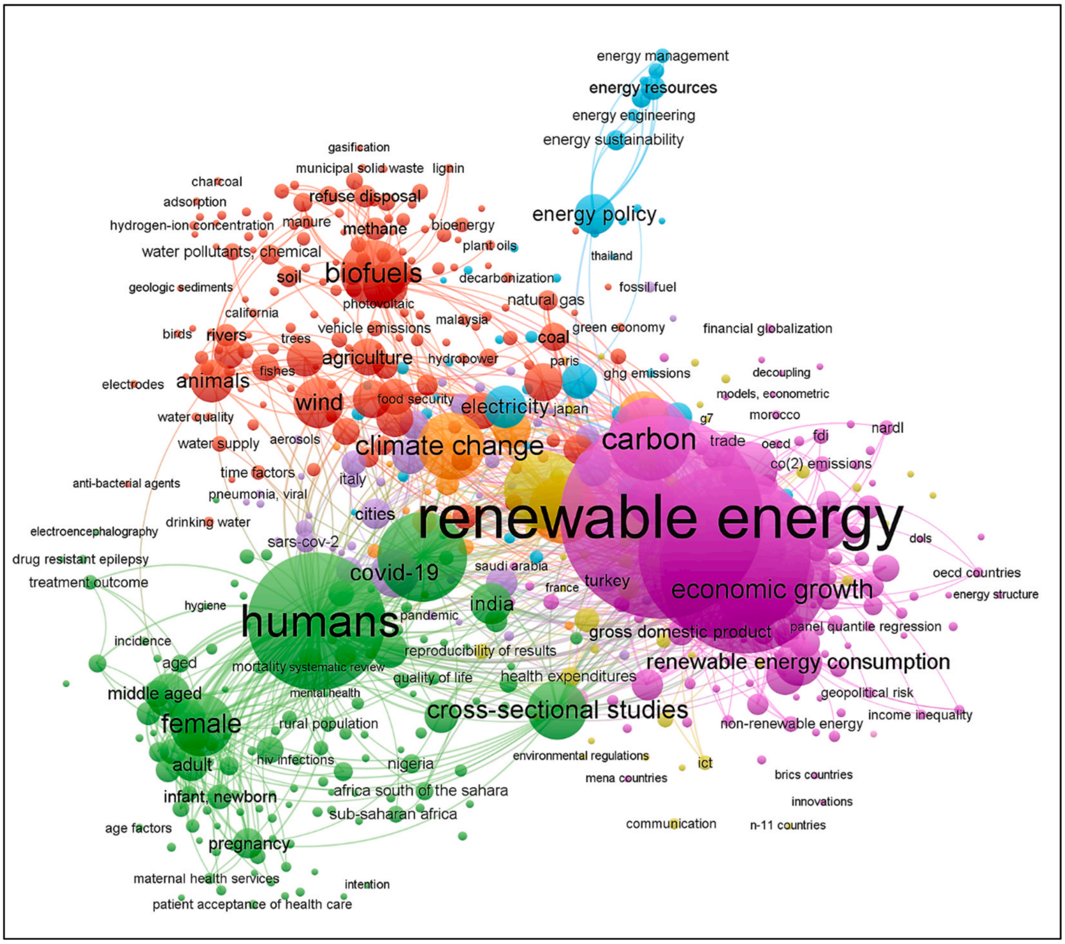

Fig. 3. Network of renewable energy and its technologies (Figure created based on 923 papers of search of keywords published between 2019 and 2023 from pubmed).

and social aspects, can have adverse effects on climate change and ecological balance, as well as on environmental pollution [17]. Another study has examined the socio-economic effects on energy use, emphasizing renewables. Focusing on Bangladesh (1990–2019) with Autoregressive distributed lag (ARDL) analysis, results highlight income's varied impact, foreign and domestic investments' benefits, and urbanization's nuanced role in consumption trends. Simulations reveal predictor shock effects [18].

The per capita energy use of Bangladesh is 608.76 kWh, which is among the lowest in the worldwide scenario [13]. From 667 MW installed capacity in 1974, the capacity grew to 14782 MW by 2022 where 1160 MW including 600 MW of imported power from India [13,19]. The private sector and independent power producers (IPPs) contribute 46% of the total power generation [20]. Moreover, the strategy encompasses the integration of power stations with outputs of 2650 MW, 2027 MW, 2763 MW, 2811 MW, and 3812 MW into the national grid by 2017, 2018, 2019, 2020, and 2021, correspondingly. Most of this additional capacity will be generated by coal-based power stations [21]. Globally, the adoption of renewable energy instead of gas, coal, and oil has commenced, proving imperative for sustainable progress and environmental protection through the mitigation of carbon emissions [22]. Numerous nations worldwide, including China, China Sweden, Germany, and the USA, presently rely on renewable energy as a substantial component of their energy requirements [23]. Bangladesh is also using renewable energy, but it is less than necessary. The government has taken various steps to increase the use of renewable energy projects like solar home system (SHS), solar irrigation system, Ruppur nuclear project [24].

The purpose of this paper is to review the current energy scenario and renewable energy sources with its challenges and future opportunity in Bangladesh. The discussion covers the description of the renewable energy policy 2008, as well as the recommendation by USAID. Additionally, the paper explores the SDG on the point of affordability and clean energy by renewable energy and reduction of carbon footprint with renewable energy utilization [25,26]. This review will provide insight into the possible approaches for generating renewable energy and support a long-term strategy for increasing renewable energy over conventional fossil fuels.

Fig. 3 depicts the renewable energy network, where the purple section signifies the upcoming research in renewable energy, encompassing its consumption and expansion. The red region represents the previous works on biofuels and diverse energy sources, while the green area symbolizes the current progress made in public acceptance of these renewable energies. The conclusion aims to support the contemplation of energy-sector researchers and streamline the decision-making processes for pertinent authorities, policymakers, planners, and entrepreneurs.

2. Overview of energy in Bangladesh

Bangladesh draws upon a diverse range of established commercial energy resources [27]. These encompass indigenous natural gas, coal, imported oil, LPG, imported LNG, imported electricity, and hydroelectricity [28]. The nation's energy landscape showcases a calculated balance: biomass constitutes approximately 25% of the primary energy, while the remaining 75% is judiciously supplied through commercial channels [13]. Indigenous natural gas takes the lead in contributing around 51% to the nation's commercial energy, with an additional 13% addressing from imported LNG [13,29]. The primary share of the remaining energy profile is attributed to imported oil. Presently, Bangladesh has recorded an import of roughly 9.56 million metric tons of crude and refined petroleum products in 2021-22 [13]. Beyond the scope of natural gas and crude oil, coal plays a pivotal role as the chief fuel source in brick fields and Thermal Power Plants.

Within wider energy strategies, the nation employs diverse methods to enhance electricity production. This includes SHS for cooking and on/off-grid power, yielding around 0.69 MW, and biomass gasification generating 0.4 MW [13]. Regarding energy consumption, Bangladesh envisions an ultimate trajectory of approximately 57.20 million metric tons of oil equivalent (Mtoe) and this projection is underpinned by an average annual growth in energy demand of approximately 6% [13]. On a per capita basis, the nation's energy consumption averages around 346 kg (Kilogram Oil Equivalent), with each individual contributing to per capita electricity generation of 608.76 kWh [13]. Remarkably, universal access to electricity is achieved at an impressive 100% [19]. However, it is

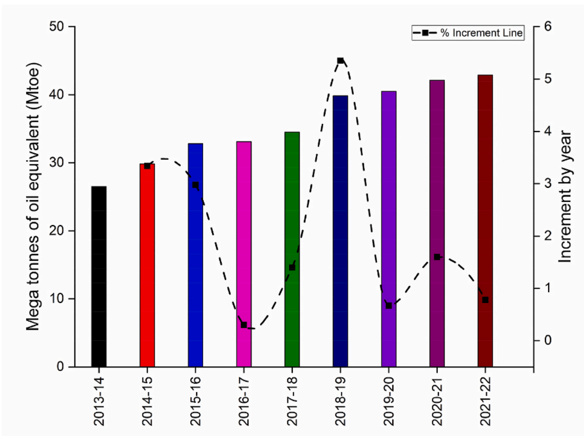

Fig. 4. Year-wise (2008–20) Commercial Energy in Mtoe and increment rate [13].

noteworthy that substantial remain comparatively lower compared to the energy metrics observed in neighboring South Asian countries. Figs. 4 and 5 shown the Energy calculation for 2021-22 in Mtoe and Year-wise (2008–20) Commercial Energy in Mtoe with increment rate. Where the analysis found that the primary driver of the commercial energy sector is natural gas, accounting for a significant 44.11% share. Following closely, oil contributes 24.1%, while LNG holds a respectable 13%, and LPG maintains a 4% portion [14]. Local coal stands at a modest 0.31%, whereas coal imports reach the percentage figure of 3.88. Regarding renewable sources, hydroelectricity makes up 0.39%, while solar and wind collectively amounts to 0.53%. Biomass holds a substantial share, constituting 27% of the energy landscape, equivalent to 57.20 Mtoe [29].

The future of electricity generation in Bangladesh appears bright, as the nation is well-positioned to harness the potential of wind and mini-hydro resources. Notably, a recent advancement involves the widespread adoption of solar-powered irrigation pumps across multiple regions. This innovative approach not only demonstrates the nation's commitment but also carries the potential to reduce dependence on traditional diesel and electricity sources, thereby easing the accompanying pressures.

3. Assessment of renewable energy sources in Bangladesh

Renewable energy offers many benefits that extend across environmental, economic, and social dimensions. Environmentally, it significantly reduces greenhouse gas emissions, which is crucial in mitigating climate change [30]. Solar, wind, and hydropower improve air and water quality, fostering a healthier environment [31]. The renewable energy sector economically stimulates job creation, promotes economic growth, and enhances energy security by diversifying energy sources [32]. The inexhaustible nature of renewable resources ensures long-term sustainability and reduces dependence on finite fossil fuel reserves [33]. Additionally, community engagement and ownership in renewable energy projects empower local populations, fostering a sense of pride and shared responsibility [34]. The ongoing technological innovation in the renewable energy sector further positions it as a catalyst for positive change, driving efficiency and grid management advancements [35]. In essence, adopting renewable energy is a critical step towards a cleaner planet and a driver of economic prosperity and social well-being [36].

The integration of renewable energy sources has the potential to amplify the energy security of Bangladesh and mitigate its dependence on natural gas. This is especially significant in regions with limited access to conventional electric grids and natural gas. Biomass plays a pivotal role in such areas, serving as a fundamental element for cooking purposes [37]. Solar power and wind energy are also harnessed not only to electrifying the household machineries but also to dry agricultural produce and clothing [38]. Among the array of renewable energy sources, biomass is the predominant contributor, constituting a substantial portion of the nation's energy consumption, primarily in the domains of cooking and heating. At present, biomass accounts for 27% of the primary energy consumption in the country [29]. Abundant solar potential aligns with global renewable energy trends amid depleting fossil fuels. Renewables appeal stems from eco-friendliness. The energy landscape of Bangladesh benefits from this resource diversity, shaping its dynamic outlook.

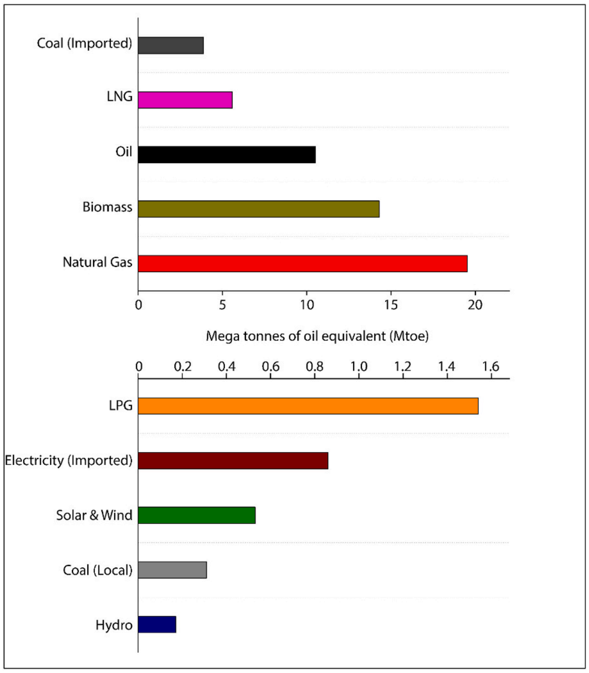

Fig. 5. Energy calculation for 2021-22 in Mtoe [13].

3.1. Solar energy landscape

Reiterating the aforementioned point, Bangladesh's strategically favorable geographical position positions solar power as a pivotal renewable energy asset. The diurnal average solar radiation fluctuates from 4 to 6.5 kWh/m^2, underscoring the noteworthy variation in solar energy availability [10]. The Asian Development Bank's calculations suggest a potential solar energy generation capacity of nearly 50,463 MW [39]. This estimation is derived from the diverse location of the country, with the monthly average of daily solar

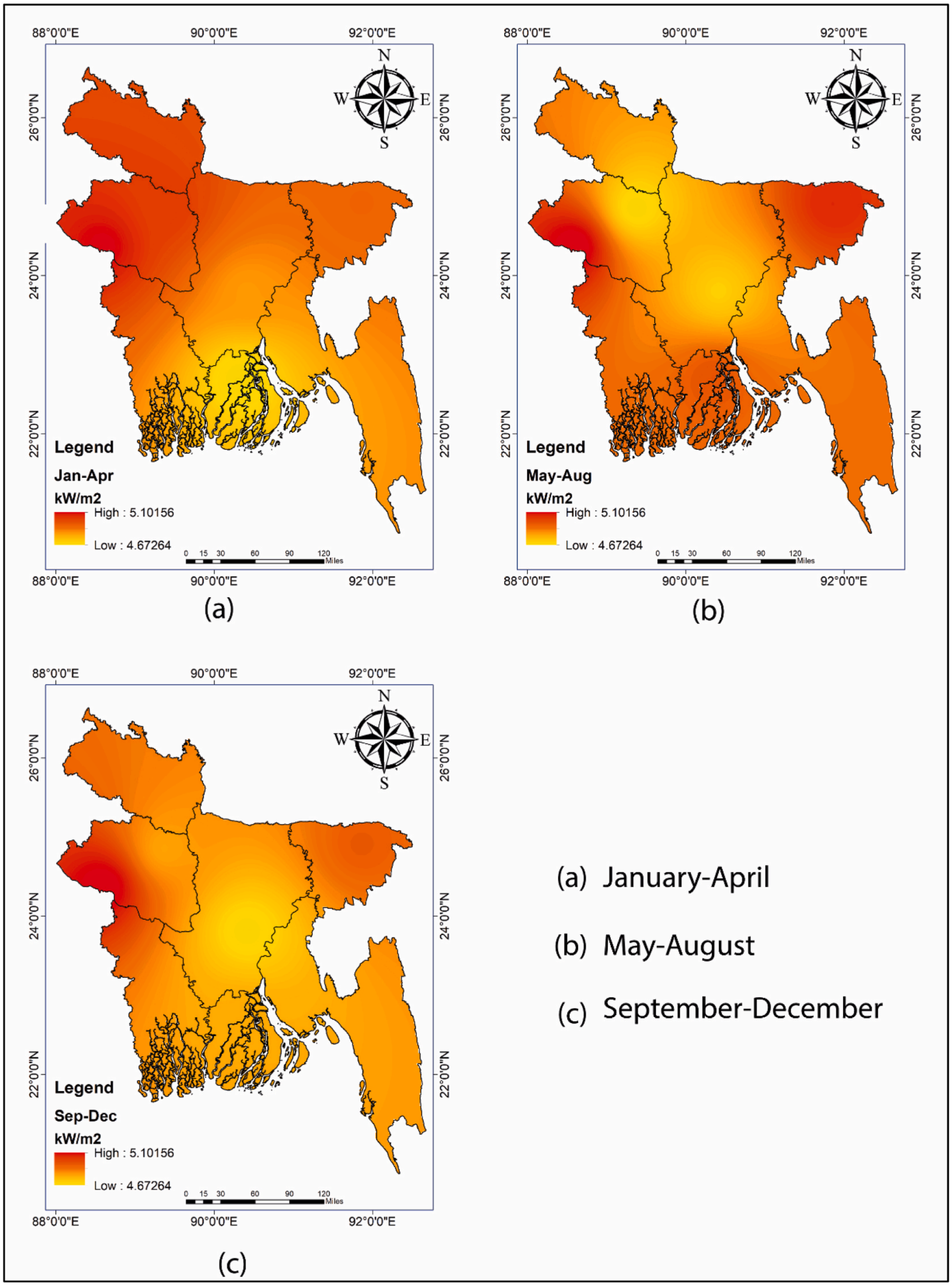

Fig. 6. Annual radiation across Bangladesh, extrapolated from its five major cities: Dhaka, Bogura, Rajshahi, Sylhet, and Barishal [45].

irradiation levels being documented within the available literature [40]. A substantial portion of the primary energy demand is fulfilled through solar power, as indicated [41]. The Rajshahi district, in particular, has significant potential for solar energy extraction where the yearly average of direct natural insulation in Rajshahi measures 1900 kWh/m^2, a value sufficient for deploying concentrating solar power technology [42]. Employing this technology over a 2 m^2 area with an annual average radiation of 2000 kWh/m^2 could yield the generation of 100 MW of electricity [43].

Bangladesh has achieved the deployment of 6 million SHS, marking the world's most extensive SHS program to date [44]. This

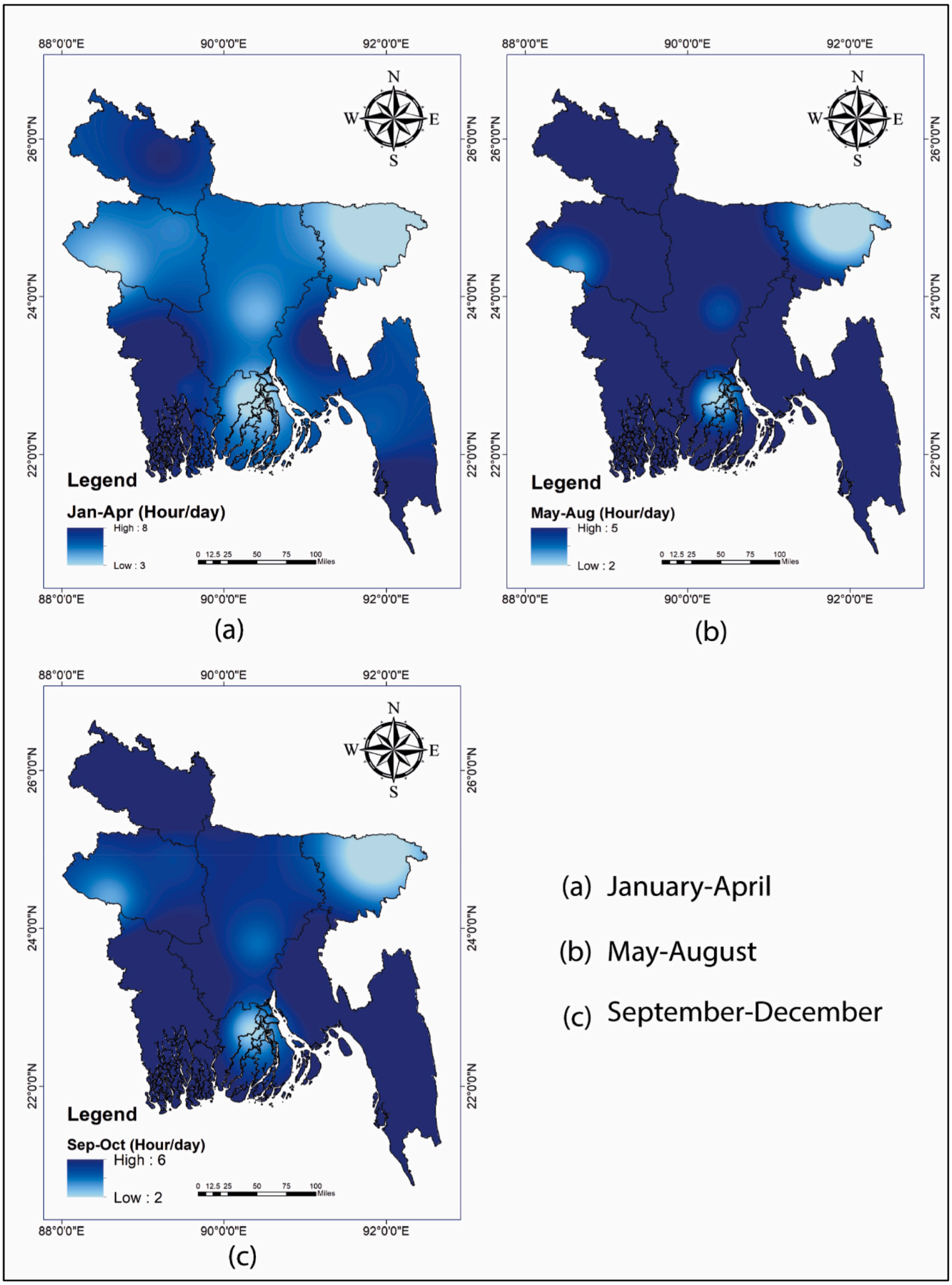

Fig. 7. Sunlight hours in Bangladesh [48].

initiative has engendered the creation of over 100,000 new employment opportunities, directly benefiting more than 30 million individuals through solar energy [40]. Fig. 6 illustrates the annual radiation across Bangladesh, extrapolated from its five major cities: Dhaka, Bogura, Rajshahi, Sylhet, and Barishal.

Solar radiation is crucial in determining the potential for solar energy generation in a particular area [46]. It represents the amount of sunlight received by a location and directly impacts the efficiency and output of solar panels. Higher solar radiation generally leads to greater energy generation from solar panels [47]. Rajshahi consistently leads in solar radiation, followed by Sylhet, Barishal, and Bogura. May to August records peak radiation due to the intense summer sun. Dhaka shows a decline, likely due to local factors. Rajshahi stands out as a consistent solar energy candidate, joined by Sylhet, Barishal, and Bogura. Besides solar radiation, another significant factor for solar energy generation is the availability of sunlight hours. Fig. 7 shows the average number of sunlight hours of Bangladesh.

The analysis of sunlight hours across different districts presents their suitability for solar energy generation [49]. Sylhet, Barishal, and Cumilla maintain high sunlight values year-round, showing potential for solar projects. Chittagong, despite monsoons, has notable sunlight, supporting solar initiatives during clouds. May to August sees reduced sunlight due to monsoons and clouds. Adaptive strategies are vital for well-informed solar planning in these areas. As technology continues to evolve, its role in enhancing the feasibility of solar projects becomes increasingly significant. Districts like Sylhet, Barishal, Comilla, Chittagong, Rajshahi, and Rangpur possess favorable conditions for solar energy generation. Mymensingh's largest solar power facility has been successfully linked to the national fluctuations with a capacity to generate 73 MW of electricity, this plant plays a pivotal role in achieving the government's aim of producing 10% of the nation's total electricity from renewable sources by 2021 [50]. Featuring an array of 173,000 solar panels and 332 inverters, the solar power installation was fully equipped with Huawei's intelligent photovoltaic (PV) solution for seamless integration into the national grid [13]. The Rural Electrification Board (REB), a governmental organization, has been actively involved in advancing the commercial adoption of solar power for domestic, commercial, and irrigation purposes in rural areas [51]. Infrastructure Development Company Limited (IDCOL), a government-owned entity, has partnered with NGOs to distribute SHS. Although the relatively high production costs pose a challenge, the technology has gathered increasing popularity in remote regions of the country. The government has taken significant steps to provide subsidies and support for this endeavor [52]. Furthermore, the government is in the process of implementing solar panel installations ranging from 5 to 10 MW in capacity, demonstrating a commitment to expanding solar energy usage and diversifying the country's energy landscape [13].

Fig. 8 represents the evolution of solar energy adoption in Bangladesh from 2007 to 08 to 2021–22. It highlights a consistent annual increase in installed capacity, reaching 250 MW in recent years [13,45]. The data reported in the Energy scenario report of the Hydrocarbon Unit, Energy and mineral resources department of Bangladesh reveals a consistent upward trajectory in the cumulative installed capacity of these systems [13].

Bangladesh's strategic geographical positioning and substantial solar radiation potential make solar energy a vital renewable asset for the country. The Asian Development Bank's projections highlight an impressive solar energy generation capacity, reflecting the nation's ability to harness this resource [53]. SHS implementation and the solar power success of Rajshahi highlight the advantages, including jobs and grid use. Variable sunlight hours require tech and weather considerations. Solar growth, like expanded capacity and irrigation integration, showcases sustainable commitment, affirming solar transformative impact in the country.

3.2. *Traditional biomass fuels*

Biomass is crucial for renewable energy in Asia, including Bangladesh. Agriculture waste, foliage, manure, charcoal, and timber are used industrially and domestically. Beyond heat, biomass generates power and steam for industries [54]. The biomass energy capacity

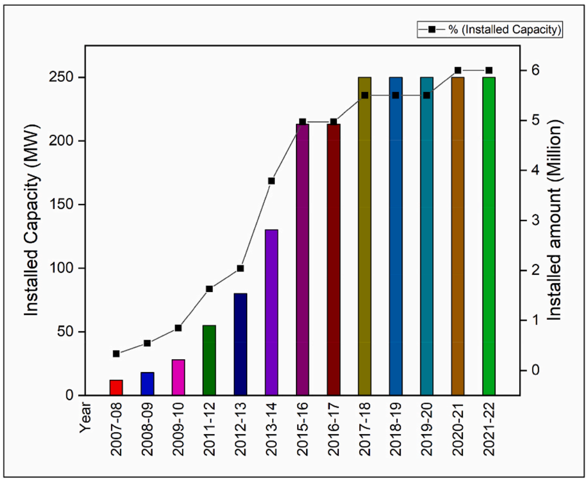

Fig. 8. Increasing numbers of SMS in Bangladesh [13,45].

of certain Asian countries, including but not limited to India, China, Thailand, and Sri Lanka, has been subjected to comprehensive evaluation [45]. The country needs to assess its biomass energy potential. Key sources include agriculture waste, municipal solid waste, excrement, forest residue, and organic waste. Fig. 9 depicts methods for converting these into power sources.

In Bangladesh, three main types of biomass fuel resources are used: wood fuels, agricultural leftovers, and animal manure [56]. Wood fuels derive from rural forest sources. Bangladesh primarily uses agricultural residues and animal dung as biomass fuel. A portion of crop residues and cattle manure serves as fuel. Converting biomass improves rural energy consumption. Biogas suits cooking, lighting, and small power generation. About 80,000 households use biogas systems, with IDCOL supporting around 50,000 facilities [13]. For producing biogas from this biomass the agricultural remnants directly gathered from the terrain, which are called field residues, while residues arising after crop processing are denominated as process residues [45]. Within Bangladesh, possible bioenergy sources include jute, rice husk, straw, and sugarcane bagasse. Fig. 10 shows the energy potential of agricultural residue in Bangladesh.

Fig. 10 provides crucial insights into the potential of diverse crop residues for bioenergy generation, revealing their dry residue recovery in thousands of tons and their associated lower calorific values. For instance, rice straws exhibit an impressive dry residue recovery of 17,831.55 thousand tons and a lower calorific value of 16.3 GJ/ton, emphasizing their significant energy content [45]. Sugarcane bagasse offers 1079.67 thousand tons dry residue and 18.1 GJ/ton calorific value. Rice husk has 8052.9 thousand tons residue and 16.3 GJ/ton value. These figures show potential for sustainable bioenergy, waste management, and renewables in Bangladesh. These biomass sources are key for biogas production. Table 1 lists bio-electricity projects with capacities, locations, agencies, and statuses.

In the off-grid sector, Oasis Services (Agro) Ltd and Phenix Agro Ltd. have capacities of 0.3 MWp and 0.4 MWp, respectively, using biogas for electricity in Bhaluka and Gazipur. These completed projects showcase successful decentralized biogas energy. Other

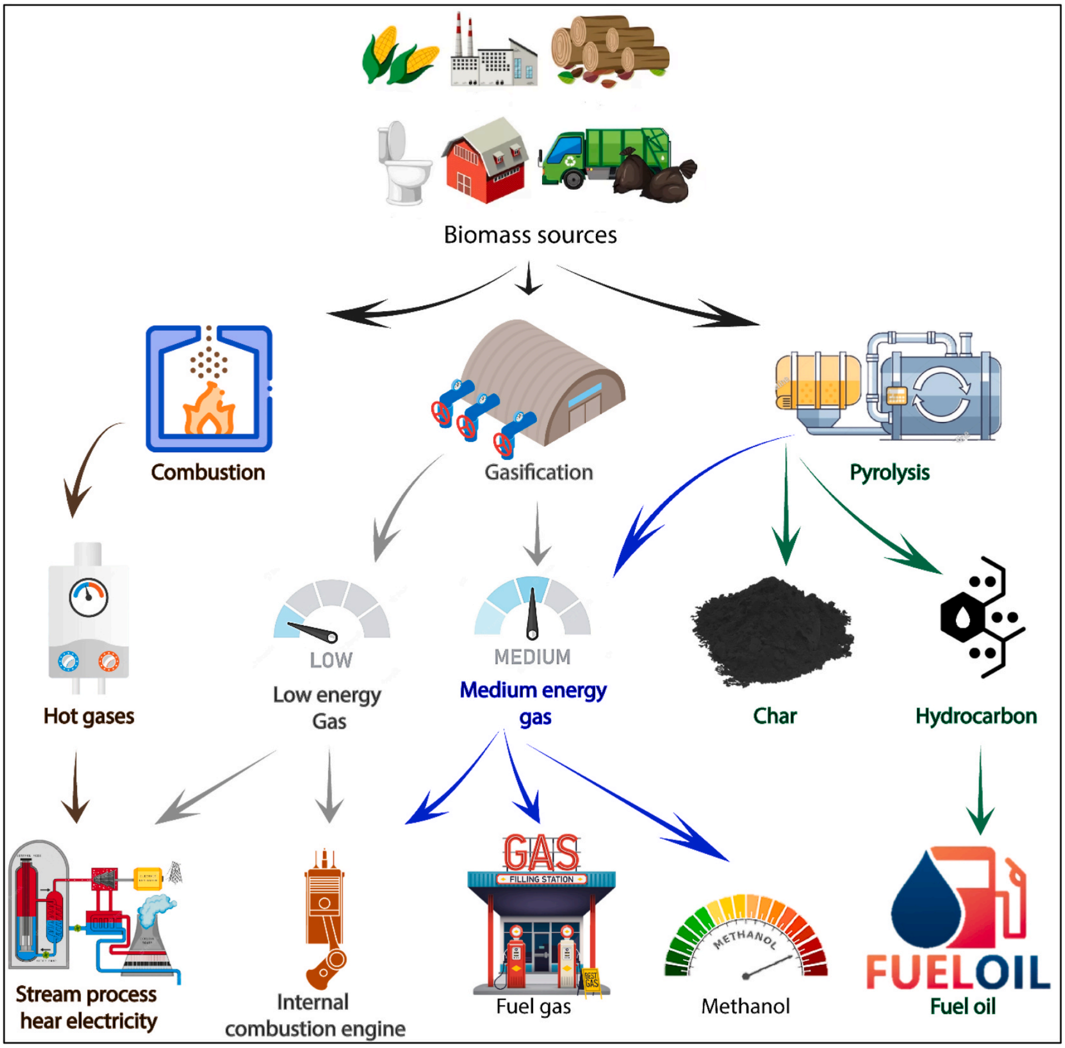

Fig. 9. Transformation of biomass resources into potential power sources [55].

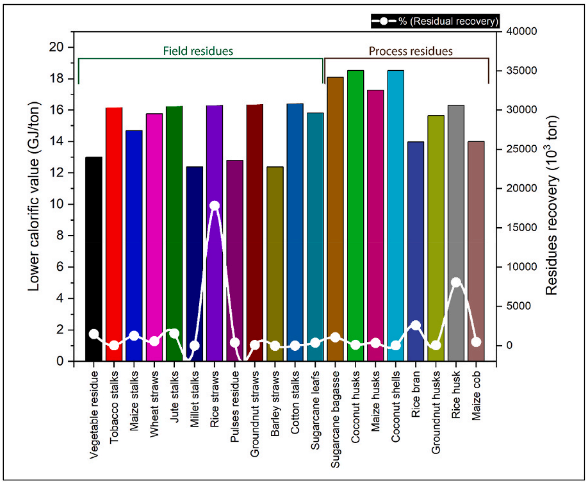

Fig. 10. Energy potential of agricultural residue in Bangladesh [45].

Table 1
Large Biogas projects of Bangladesh [57].

Grid (Present Condition)	Project Name	Location	Capacity (MWp)	Agency
Off Grid (Completed & Running)	Oasis Services (Agro) Ltd	Mymensingh	0.3	IDCOL
	Phenix Agro Ltd. at Member Bari, Gazipur	Gazipur	0.4	
	UAL Bio - Electricity Project	Gazipur	0.06	
	KKT Bio - Electricity Project	Panchagarh	0.1	
	ZPL Bio - Electricity Project	Chuadanga	0.03	
	UKAL Bio - Electricity Project	Tangail	0.03	
	Seed Bangla Foundation Bio Electricity Project	Gazipur	0.02	
	RKKL Bio - Electricity Project	Mymensingh	0.05	
	Dutch Dairy Ltd. (Ongoing)	Munshiganj	0.4	
On Grid (Under Planning)	Narayanganj 6 MW Power Plant by Consortium of UD Environmental Equipment Technology Co. Ltd, Everbright Environmental Protection Technical Equipment (Changzhou) Limited and SABS Syndicate	Narayanganj	6	BPDB
	42.5 MW Municipal Solid Waste based Power Plant at Dhaka North City Corporation by China Machinery Engineering Corporation (CMEC)	Dhaka	42.5	
	1 MW Grid Connected Power Plant Based on Municipal Solid Waste under Pilot Project at Keraniganj on Turnkey Basis	Keraniganj	1	

initiatives like UAL, KKT, and ZPL Bio-Electricity Projects highlight biogas potential in diverse locations. On the on-grid side, the Narayanganj 6 MW Power Plant and the 42.5 MW Municipal Solid Waste-based Power Plant in Dhaka North City Corporation, led by consortium and CMEC, respectively, with capacities of 6 MWp and 42.5 MWp, are in planning stages. These reflect the commitment of Bangladesh to grid-integrated biogas, aiding energy and waste solutions. The 1 MW Keraniganj Pilot Project underscores waste-to-energy efforts. These combined endeavors illustrate progress in innovative bio-electricity projects for stronger energy infrastructure.

3.3. Hydro energy scenario

The initial hydroelectric power plant in country possessed a capacity of 230 MW and was situated at the Kaptai Dam, situated along the Karnaphuli River within the Chittagong district [58]. This facility contributed around 5% of the electricity generated [59]. Following this, the Bangladesh Power Development Board (BPDB) augmented the capacity of the plant by 100 MW, enhancing energy generation in the rainy season. Another project proposes an encompassing hydroelectric initiative in Mahamaya Chara to provide power, irrigation, and flood control at minimized expenses. The key goals encompass furnishing irrigation water during dry season and safeguarding around 10.5 km^2 of land from monsoon flooding [60]. Concerning hydropower production, the Bangladesh Power Development Board (BPDB) has pinpointed two favorable locations, the Sangu and Matamuhuri rivers with the potentiality of generating an estimated annual average energy of 300 Gigawatt hour (GWh) and 200 GWh respectively [49]. Furthermore, collaborative studies involving government and private organizations such as Khoin and Local Government Engineering Department (LGED) have pinpointed eight potential locations for small-scale hydroelectric power generation in the southern hilly regions of the country [61]. Recent advancements involve the submission of proposals for two additional minor hydropower initiatives to the BPDB which encompass a 25 kW facility at the Teesta Barrage and a 10 kW facility at Barkal in the Rangamati district [62]. Several initiatives have assessed micro hydropower viability. BPDB and BWDB collaborated to assess 19 potential sites. Chinese experts also evaluated opportunities.

Table 2 reveals energy forecasts from micro hydropower across diverse areas. Projections, from 3 kW to 616 kW, highlight varied potential. Rangapani Gung, Sylhet, promises high energy, reflecting regional hydro potential. Yet, practicality requires water flow assessment, eco-concerns, community engagement, and infrastructure. While data is promising, successful projects hinge on thorough studies, eco-friendly planning, and community welfare.

However, hydropower also presents some environmental challenges. The construction of dams for hydropower projects can disrupt habitats, alter water flow, and impact aquatic ecosystems [63]. Sedimentation, changes in water quality, and the potential for methane emissions are environmental concerns associated with hydropower [64]. Despite these challenges, ongoing technological advancements and the exploration of alternative hydropower approaches aim to minimize the environmental impacts and make this renewable energy source more sustainable [65].

3.4. Wind energy outlook

The dynamic energy of the airflow is transformed into the mechanical force of the turbine shaft, subsequently translated into electrical energy by a generator [66]. The provided equation (1) can approximate the theoretical quantity of electrical power generation. However, in practice, only about 30–35% of this power is realistically accessible for practical utilization [55].

$$P = \frac{1}{2} \times \rho \times A \times V^3 \tag{1}$$

Where the power generated (P) is calculated in watts (W), with ρ representing the air density in kilograms per cubic meter (kg/m^3), A denoting the swept area of the turbine blade in square meters (m^2), and V indicating the wind speed in meters per second (m/s). Wind speed is a pivotal factor in power generation, directly influencing its effectiveness. Higher wind speeds result in greater kinetic energy transfer to turbine blades, leading to increased mechanical rotation and, subsequently, higher electricity production [67]. Optimal wind speeds ensure consistent and reliable energy output, making it crucial for maximizing the efficiency of wind turbines [68]. Precise evaluation of wind speed patterns informs effective turbine design, amplifying renewable energy production for sustainable, eco-friendly power. Fig. 11 depicts annual wind speeds using data of the Bangladesh Meteorological Department, aiding strategic energy planning [48].

Fig. 11 depicts annual wind speed variations across different locations. Coastal zones like Chittagong, Cox's Bazar, and Kutubdia exhibit higher speeds (5.37 ms^{-1}, 4.48 ms^{-1}, and 3.43 ms^{-1}), indicating significant wind energy potential due to proximity to water bodies and consistent coastal winds. Inland areas like Dhaka and Rajshahi have lower speeds. Coastal influence correlates with higher speeds, highlighting coastal wind energy potential. Various governmental and organizational projects consider this parameter for wind power initiatives.

A comprehensive glimpse into the state of wind power projects in the country, highlighting completed, ongoing, and planned initiatives in Table 3 from the National Database of Renewable Energy by SERDA. Wind energy presents a promising possibility for sustainable power generation. Coastal regions exhibit higher wind speeds, harboring significant potential. The wind energy landscape in Bangladesh, as showcased in Table 3, demonstrates ongoing initiatives and future projects, indicating the country's commitment to diversify its energy mix. Successful integration, collaboration, and meticulous planning will be essential in fully harnessing wind power's potential for a greener energy future.

3.5. Wave and tidal energy prospects

The Government of Bangladesh (GoB) has yet to initiate efforts to evaluate the potential for harnessing energy from sea waves in the

Table 2
Details micro hydropower potential in Bangladesh via BPDB, BWDB, and LGED's SRE project [55].

River/Chara/Stream/site	Districts	Expected energy generation from micro hydro plant (kW)
Nunchari Tholipara	Khagrachari	3
Chang-oo-Para	Bandarban	30
Bangchari		25
Monjaipara		7.5
Liragaon		20
Bandarban	Rangamati	20
Thang Khrue		30
Foy's lake	Chittagong	4
Choto Kumira		15
Choto Kumira		12
Sealock		81
Lungichara		10
Budiachara		10
Nikhari Chara	Sylhet	26
Rangapani Gung		616
Buri Khora Chikli at Nizbari	Rangpur	322

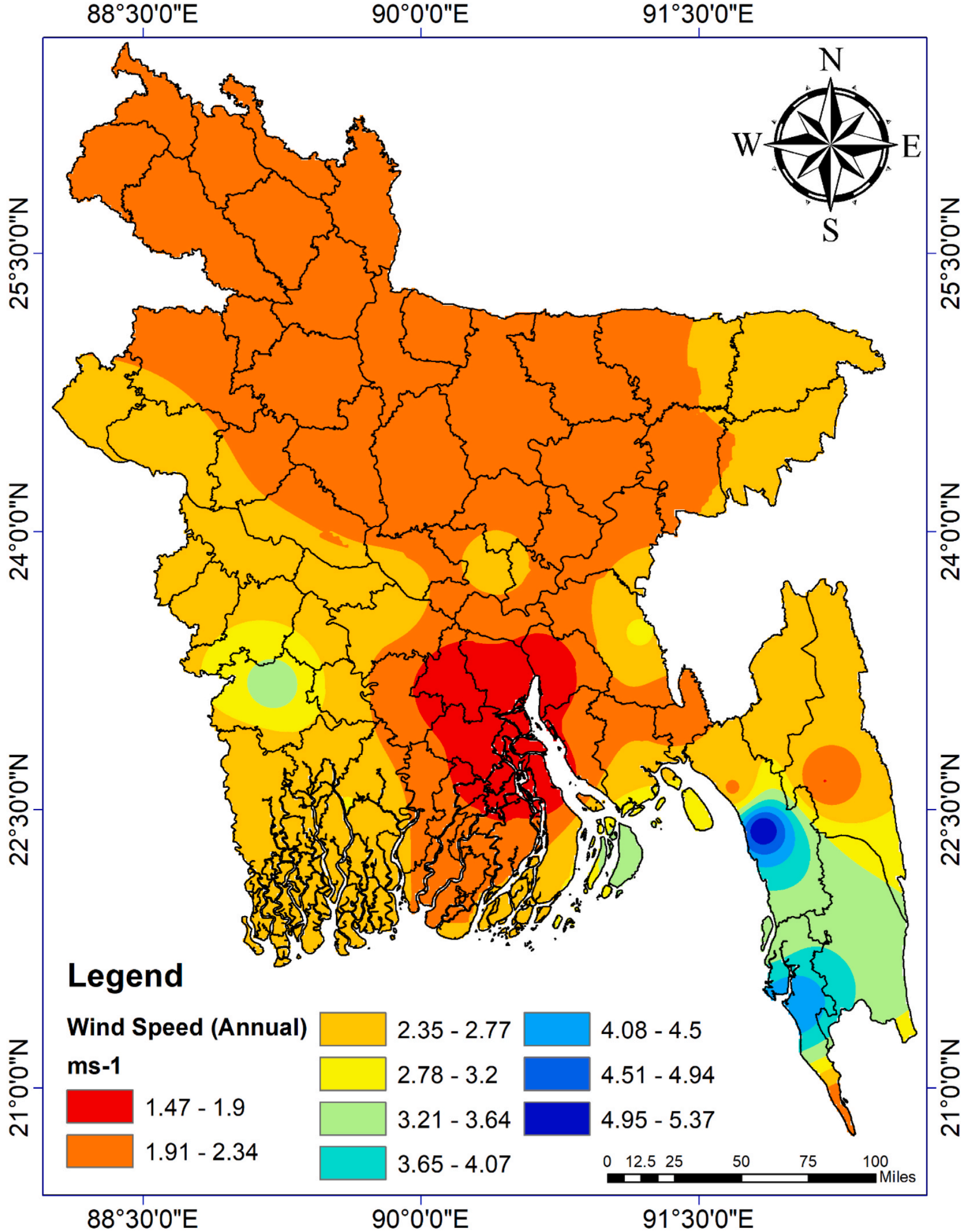

Fig. 11. The average annual wind speed distribution over Bangladesh.

Bay of Bengal. Nonetheless, wave power is a substantial and untapped alternative energy source within the country. Favorable wave conditions, which are most prevalent from late March to early October, serve to highlight this potential. The occurrence of these waves is intricately linked to wind patterns, primarily originating from the southwestern direction in the Bay of Bengal [70]. Significant wave heights have been discovered through an analysis of wave data collected using a wave rider buoy. The greatest wave heights have exceeded 2 m, with a peak of 2.4 m being recorded on July 29th [13]. The time intervals between waves also demonstrate diversity, ranging from 3 to 4 s that are waves of about 0.5 m in height and approximately 6 s for waves attaining a height of 2 m [13]. Historical wind speeds have attained remarkable magnitudes, with documented readings reaching as high as 650 km/h, 221 km/h and 416 km/h in the years 1969, 1970, and 1989, respectively in the country [71]. The region has faced severe cyclonic storms along with storm

Table 3
Large wind energy projects of Bangladesh [69].

Project Status/Off or On Grid	Location	Project Name	Capacity (MWp)	Agency
Completed & Running/ Off- Grid	Kutubdia Upazila, Cox's Bazar	1000 kW Capacity Wind Battery Hybrid Power Plant	1	BPDB
Completed & Running/ On- Grid	Sonagazi, Feni	0.9 MW Grid Connected Wind Turbine Power Plant at Mahuri Dam, Feni	0.9	BPDB
Implementation Ongoing/On- Grid	Sirajganj Sadar Upazila, Sirajgonj	Design, Supply, Installation, Testing and Commissioning of 2 MW Capacity Wind Power Plant on turnkey basis at the bank of the River Jamuna adjacent to the existing Sirajganj 150 MW Power Plant, Sirajganj, Bangladesh	2	BPDB
	Chakaria Upazila, Cox's Bazar	60 MW Wind Power Project at Coxs Bazar by US-DK Green Energy (BD) Ltd	60	BPDB
Under Planning/On- Grid	Maheshkhali Upazila, Cox's Bazar	Matarbari 100 MW Wind Power Plant Project	100	CPGCBL
	Sonagazi, Feni	30 MW Wind Power Plant by Consortium of Bhagwati products ltd (India), Regen Powertech Provate Ltd (India) and Siddhant Wind Energy Pvt. Ltd	30	BPDB
	Mongla Upazila, Bagerhat	Mongla 55 MW Wind Power Plant by Consortium of Envision Energy (Jiangsu) Co. Ltd., SQ Trading and Engineering & Envision Renewable Energy Bangladesh Limited	55	BPDB
	Cox's Bazar Sadar Upazila, Cox's Bazar	50 MW Grid-tied Wind Power Plant	50	BPDB
	Chandpur Sadar, Chandpur	50 MW Grid-tied Wind Power Plant	50	BPDB
	Kalapara Upazila, Patuakhali	10 MW Wind Power Plant	10	RPCL
	Maheshkhali Upazila, Cox's Bazar	Feasibility Study for Installation of Wind Firm in Matarbari Island	0	CPGCBL

surges reaching heights of up to 15 m. As a result, any potential wave energy facility must be meticulously designed to endure such exceptional occurrences, including extremely high waves during storm conditions. Table 4 have shown the Costal tidal levels of Bangladesh.

Table 4 offers tidal measurements, detailing the complex coastal tide fluctuations across the country. Ranging from the Lowest Astronomical Tide to the Highest Astronomical Tide, this data is crucial for evaluating tidal energy potential. Places like Mongla, Sadarghat, and Sandwip display significant tidal ranges, indicating strong energy prospects. This information forms the basis for identifying suitable tidal energy project locations. However, unlocking tidal energy's potential mandates comprehensive strategies encompassing technology, ecology, and sustainable infrastructure. The tides in Chittagong, southeastern Bangladesh, follow a mostly semidiurnal pattern with varying ranges corresponding to seasons [72], peaking during the southwest monsoon. Diurnal influences because daytime tides to be smaller than nighttime tides. Despite favorable conditions from March to October, Bangladesh has yet to tap its wave power potential. Prominent wave heights and wind speeds underscore feasibility. To effectively harness wave energy, robust planning is essential, ensuring resilience against extremes for coastal energy integration. As tidal energy exploration progresses, a balance between innovation and ecological preservation is vital for successful coastal renewable integration.

4. Economic evaluation of key renewable energy sources in Bangladesh

Renewable energy generation has evolved from an alternative to a vital choice to meet growing energy demands [73]. For limited non-renewable resources as well as considering the environmental concerns, renewables should be prioritized. Bangladesh largely relies on non-renewables and energy imports, which could be more cost-efficient and secure but it draws a greater carbon foot prints to the environment [74]. Shifting to renewables is imperative for long-term energy security. Cost analysis of prominent renewable

Table 4
Costal tidal levels of Bangladesh [55].

Area	Lowest Astronomical Tide	Mean Low Water Spring	Mean Low Water Neap	Mean Level	Mean High Water Neap	Mean High Water Spring	Highest Astronomical Tide	Astronomical Tide
Hiron Points	−0.256	0.225	0.905	1.700	2.495	3.175	3.656	3.912
Mongla	−0.261	0.325	1.194	2.310	3.427	4.296	4.882	5.143
Galachipa	−0.159	0.283	0.937	1.764	2.592	3.245	3.689	3.848
Sandwip	−0.583	0.238	1.634	3.243	4.851	6.248	7.070	7.653
Khepupara	−0.323	0.195	1.025	2.060	3.096	3.925	4.445	4.768
Barisal	+0.134	0.434	0.692	1.539	2.386	2.644	2.944	2.810
Chandpur	+0.019	0.256	0.493	2.172	3.852	4.088	4.326	4.307
Narayanganj	+0.458	0.585	0.697	2.770	4.844	4.956	5.083	4.625
Cox's Bazar	−0.339	0.205	1.023	1.995	2.967	3.785	4.329	4.668
Patuakhali	−0.143	0.242	0.740	1.575	2.409	2.907	3.293	3.436
Sadarghat	−0.423	0.239	1.100	2.481	3.861	4.722	5.385	5.808

sources in Bangladesh is crucial as it aids in informed energy policy decisions. Policymakers can determine the most economically viable options by evaluating the expenses associated with solar, wind, and hydropower projects. This analysis ensures the optimal allocation of resources, effective budgeting, and the selection of sustainable energy solutions that align with the nation's economic goals. Moreover, understanding costs facilitate attracting investments, fostering technological innovation, and promoting a greener energy mix, ultimately contributing to Bangladesh's energy security, environmental sustainability, and long-term economic growth. The financial portion of this Renewable Energy Technologies (RETs) installation is more important than all other factors. Table 5 discusses cost analysis of different renewable energy sources.

Table 5 provides cost insights for different power plant types: solar, tidal, biomass, and wind. These figures compare investment needs, revealing the economic facets of renewables. Renewables prove more financially favorable than conventional sources. The country acknowledges the role of renewable sources in energy security, considering the limitations and profitability needs of non-renewable sources. The nation holds substantial solar, biomass, and hydro potential, ensuring secure energy where the complexity of geothermal hinders its suitability.

5. Renewable energy policy of Bangladesh (2008) and USAID's recommendations (2023)

The Renewable Energy Policy, established by the GoB, underscores the need for advancing renewable energy technology in the country [78]. Despite substantial emissions (96.4%) from energy-related sectors and a policy framework lacking gender and social inclusivity, Bangladesh recognizes the potential of renewable energy to enhance energy security and sustainability and reduce greenhouse gas emissions [79]. At COP26, Bangladesh's commitment to achieving 40% renewable energy by 2041 was announced [80]. While the 2008 renewable energy policy aimed for a 10% contribution to total demand by 2020 (achieving 1.24% including hydro), challenges that require policy incorporation and recommendations drawn from stakeholder engagement and global best practices persist [81]. The Renewable Energy Policy of 2008 outlines several intended policy actions to promote the efficient and environmentally friendly use of renewable energy in Bangladesh [49]. These actions include harnessing the potential of renewable energy sources, creating an enabling legal framework, establishing financing mechanisms using grants, subsidies, and carbon/clean development mechanism (CDM) funds for public and private sector investments, offering corporate income tax exemptions for renewable energy project investors, incentivizing electricity tariffs for renewable energy sources, and exempting renewable energy equipment and raw materials from VAT [82].

Despite initial challenges and a decade-long delay in execution, renewable energy's contribution to power generation still needs to be higher. The revised policy should address these challenges and be promptly enacted to facilitate the substantial scaling of renewable energy adoption. A white paper under the USAID-SURE project highlights challenges in developing variable renewable energy in Bangladesh. It identifies critical obstacles to grid-connected renewable energy and proposes resolutions for stakeholders to stimulate growth in this sector. The forthcoming recommendations in the subsequent chapter will aid in updating the renewable energy policy and furthering its objectives [79]. A visual representation of USAID's recommendation is shown in Fig. 12.

To ensure a successful transition to renewable energy, governments should establish ambitious yet practical targets in line with these guidelines [83]. Firstly, these targets should span short (5 years), medium (10–15 years), and long-term (up to 2050) periods; secondly, government should incorporate all sectors including electricity, heating, cooling, and transport; thirdly, embedding these targets in primary legislature can enhance their certainty; fourthly, the purpose of renewable targets such as reduce carbon footprint, air pollution, or ensuring energy security should bring into line with wider strategic policy goals to prevent unintended concerns; Finally, objectives must encompass energy requirements inclusively, catering to men, women, children, and marginalized social groups. Such renewable energy targets have now become a defining global energy trend, with 164 countries adopting them by mid-2015, a significant increase from 43 countries in 2005 [84]. After that USAID recommended establishing strategies and an integrated action plan. This is essential for advancing renewable energy generation. These approaches should incorporate resource assessments, align with national plans, and be periodically revised. Social impacts can be tackled via price-based or multi-criteria auctions. Solar park guidelines, and net-metering frameworks have been introduced in Bangladesh's Renewable Energy Policy [82]. However, the Power System Master Plan 2016's targets are limited compared to demand. SREDA's five-year plan based on these targets misaligns with generation and transmission plans. Bangladesh's current renewable capacity stands at 787.3 MW, including 434.36 MW on-grid and 230 MW hydro sources [85].

Comprehensive foundations should underlie effective strategies and action plans for renewable energy, long-term scenarios that outline a clear path to achieving set targets [86,87]. These plans should identify existing barriers and propose viable solutions to overcome them. These strategies must be tightly integrated into the national energy plan, ensuring a cohesive approach to fulfilling strategic goals such as bolstering energy security and reducing CO_2 emissions. For inclusivity and success, these plans must actively engage all relevant governance levels, spanning from national authorities to local stakeholders [79]. Renewable Purchase Obligations

Table 5
Cost analysis of different renewable energy sources.

Energy type	Plant cost in million US Dollar (USD)	Power Plant cost per MW (10^3) USD	Ref.
Solar	7636.21	1469	[75]
Tidal	250.39	486	[76]
Biomass	768.62	995	[77]
Wind	246.37	1146	[74]

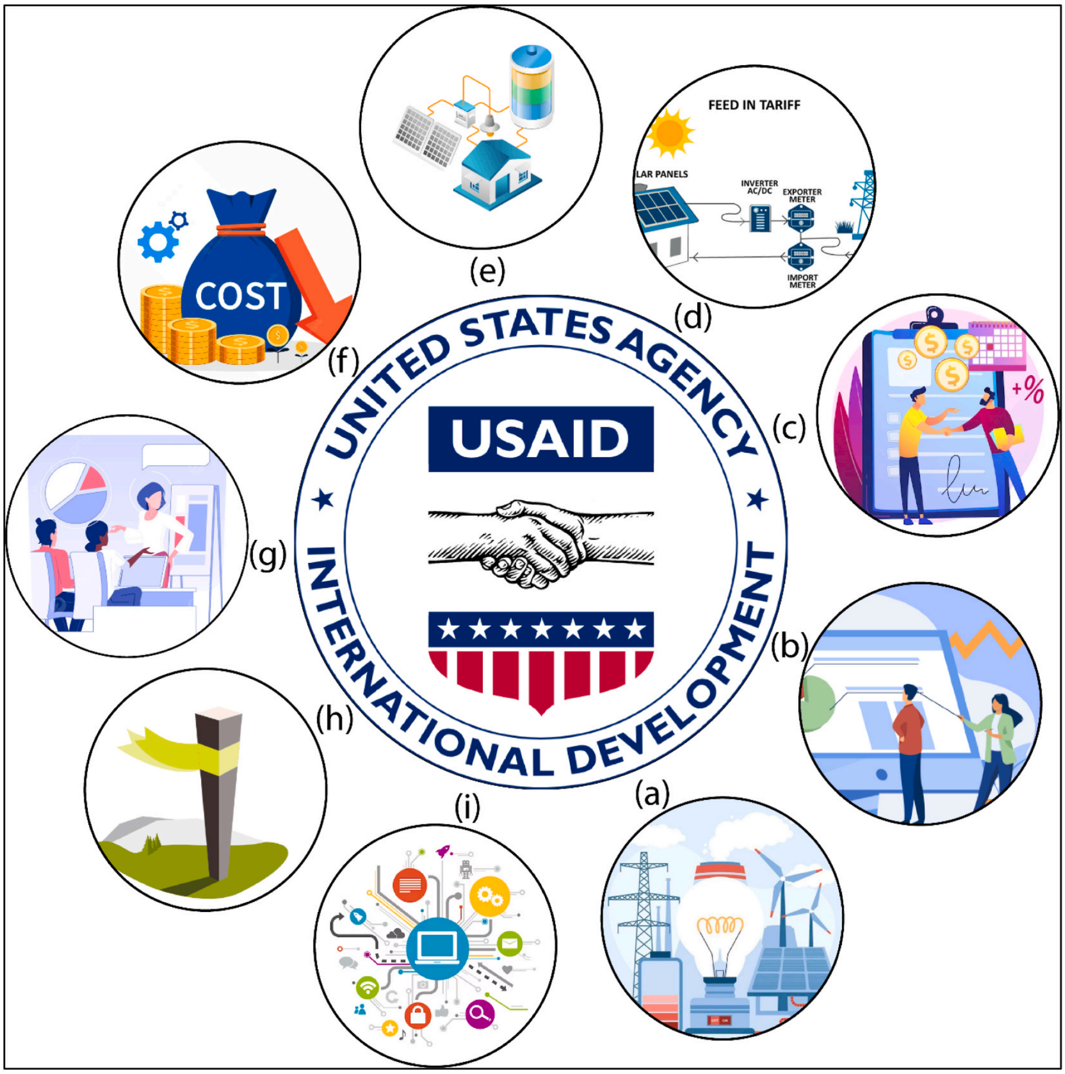

Fig. 12. A visual representation of USAID's recommendation [79]. Where (a) Goal for Developing Renewable Energy (b) Approaches and Comprehensive Action Plan (c) Mandates for Renewable Energy Procurement (d) Feed-In Tariff (FIT) Mechanism (e) Net Metering System (f) Policies to Lower Costs (g) Organizational Structure and Enhanced Collaboration Among Stakeholders (h) Guidelines for Land Procurement (i) Renewable Energy Sources, Technology, and Capacity.

(RPOs) require power generation and distribution entities and significant electricity consumers to obtain or produce a designated portion of their power from renewable sources. Despite Bangladesh's total generation capacity reaching approximately 25 Gigawatt (GW) in early 2022, only 787.3 MW originates from renewables [71]. Only some establishments have ventured into renewables, often newcomers to the sector. All power producers must generate a set proportion from renewable sources to achieve ambitious renewable targets. To maximize available land, rooftop space utilization is crucial. Mandatory rooftop solar systems were introduced in 2010 for new electricity connections, yet adjustments are needed to increase existing consumer contributions. Distribution companies can enforce renewable obligations and introduce renewable energy certificates to stimulate growth, as seen in the United Kingdom (UK), where renewable obligations led to significant renewable energy expansion [79].

Among USAID's recommendation, Feed-in tariffs (FITs) have emerged as a widely adopted policy to accelerate renewable energy (RE) adoption, superior other policies driving RE expansion [88]. FITs have propelled countries effectively implementing them to the forefront of the global RE market. In the European Union (EU), FIT regulations led to over 15 GW of solar PV electricity and 55 GW of wind power deployment between 2000 and 2009 [89]. Feed-In Tariffs (FITs) account for more than 75 percent of worldwide photovoltaic (PV) installation and 45 percent of global wind energy deployment [88]. Notably, countries like Germany have demonstrated the effectiveness of FITs in advancing RE deployment, aligning with energy security and emission reduction goals [90]. Several European countries, the United Kingdom, the United States, and over 26 developing nations have implemented various forms of Feed-In Tariff (FIT) policies to support the advancement of renewable energy [91]. FIT structure primarily supports small-scale generation in the UK, while various US states have applied FITs to promote residential and commercial rooftop solar projects [92]. Japan introduced a new FIT with high PV tariff rates post-Fukushima [93]. ASEAN member countries have embraced FITs to reach a 23 percentage share of renewable energy in their energy generation mix by 2025 [94]. Distinct investment-based incentives, FITs are performance-based, resembling production tax credits and renewable energy credits. They are often used alongside other incentives. FITs operate similarly to net-metering programs, but the generated power is compensated at the FIT rate instead of the retail rate. FIT rates, higher than retail electricity costs, can be determined by program goals, such as achieving capacity targets, renewable energy credit quotas, or fostering a domestic renewable energy industry [95]. Net energy meter (NEM) policy mechanism is another recommendation of USAID. By 2017, 55 countries, such as Australia, Canada, China, the European Union, Japan, and the United States, had embraced the Net Energy Metering (NEM) policy approach to promote decentralized renewable energy production with solar photovoltaics (PV) emerging as the predominant technology [96]. Net-metered solar PV systems have gained significant traction globally, and it is projected that installations will increase substantially, doubling from 2019 to 530 GW by 2024 [97]. Bangladesh has significant potential for integrating rooftop solar into its industrial hubs, such as economic and export processing zones, to achieve ambitious renewable energy targets [98]. In 2018, the country introduced a net-metering policy targeted at the industrial sector, although its generic nature could improve its effectiveness [99]. Challenges include financing gaps, tariff cross-subsidization, quality control, and installation limitations. The program must also address utility concerns over economic implications. Only a limited number of rooftop solar projects have been integrated into the net-metering system. To overcome these obstacles, recommendations involve tailored tariff structures, incentives for utilities, embracing the CAPEX and OPEX/ESCO financing models, and extending benefits to third-party financing [79]. Over the past decade, cost reduction policies have played a significant role in driving down the investment expenses associated with renewable energy. Improved technology, economies of scale, supply chain competitiveness, and government support have substantially dropped installation costs [100]. For example, global weighted-average installation costs for utility-scale solar PV decreased by 81% between 2010 and 2020 [101]. Various policies globally aim to decrease renewable energy costs by offering subsidies, tax relief, production tax credits, concessional loans, and economies of scale [102]. In Bangladesh, the government has introduced incentive programs to encourage electricity generation from renewable sources [103]. However, inconsistencies in policies have led to challenges in benefit realization. Investment costs for utility-scale solar facilities in Bangladesh remain comparatively high due to land scarcity, approval processes, and infrastructure requirements [104]. To address these challenges, the government can refine project solicitation processes, establish competitive renewable energy zones, create a streamlined online platform for documentation submission, and collaborate with agencies for land acquisition and infrastructure development. These measures could lower initial investment costs and attract domestic and international investors to participate in renewable energy projects [105].

Institutional arrangements and enhanced stakeholder cooperation are crucial for advancing renewable energy development [106]. The Sustainable and Renewable Energy Development Authority (SREDA) was established as a nodal agency under the Ministry of Power's Power Division to promote sustainable energy encompassing renewable sources and energy efficiency [107]. However, limited human resources challenges fulfilling the mandates outlined in the renewable energy policy. To meet ambitious targets, there is a need to bolster SREDA's capacity and consider a dedicated renewable energy ministry. Collaboration gaps among public and private entities and a lack of experience have hindered Bangladesh's renewable energy progress. SREDA should devise a plan to enhance institutional expertise, close coordination gaps, and create a streamlined platform for private sector engagement. Harmonizing laws, business models, financing tools, and incentives requires collaboration among government bodies, industry players, finance agencies, and stakeholders, with regular working group meetings to formulate and improve frameworks across technical, regulatory, market, and business aspects. This collaborative effort is essential to achieve the ambitious renewable energy targets the Prime Minister sets [79]. The primary obstacle to establishing utility-scale renewable energy plants and integrating them into the national grid in Bangladesh is the scarcity and suitability of land [108]. The country's high population density, with a majority residing in rural areas heavily dependent on agriculture, has led to the classification of land as either agricultural or non-agricultural. Non-agricultural land is essential for renewable energy projects, but finding suitable plots poses a challenge due to their size requirements and remote locations. This issue is not unique to Bangladesh; it is a global challenge. A comprehensive land study is recommended to identify feasible land options, including public lands, less agriculturally valuable areas, and potential zones designated for renewable projects [79]. Uncertainties in defining agricultural land further complicate the matter, causing uncertainty in identifying land for renewable projects. The revised policy should provide clear criteria for acceptable land use. Land acquisition, whether through purchase or lease, is intricate and time-consuming, often involving numerous landowners and complex legal documents. Additionally, the availability of suitable land often coincides with floodplains and coastal areas, necessitating backfilling and erosion control measures that increase costs and timelines [109]. Community engagement and social implications are vital to consider in renewable energy development, particularly in rural areas with abundant resources. Engagement must include sidelined groups, such as women, to ensure their voices are heard and their interests are protected. The government's approach should prioritize the social well-being of affected communities, offering them security and employment opportunities as part of the renewable energy projects' social feasibility. These challenges must be effectively addressed to facilitate the successful implementation of renewable energy projects in Bangladesh and ensure equitable benefits for all stakeholders [79]. The ambition of achieving middle-income status by 2021 necessitated industrialization, a task that relied heavily on a robust power industry [110]. Recognizing this, the GoB prioritized expanding the power sector to meet the nation's needs. However, the focus was primarily on conventional energy sources due to the perceived high costs and limitations of renewable energy. The scarcity of domestic natural gas and the unpredictable international fuel market, particularly driven by geopolitical tensions, led to electricity shortages and load shedding. In response, the GoB aims to revise the Renewable Energy Policy 2008 to create an enabling environment that attracts investment and mitigates risks associated with renewable energy projects. Despite this intention, the pace of renewable energy development has been hindered by unaddressed challenges within the existing policy framework. The proposed recommendations aim to tackle these constraints, support the GoB in crafting a comprehensive new renewable energy policy, fulfil its commitments under the Paris Agreement, and enhance energy security across Bangladesh.

6. Current challenges of renewable energy technology

For densely populated nations like China, India and Bangladesh, it is crucial to gain comprehensive insight into global trends in adoption of renewable energy. These countries, grappling with substantial energy demands amid rapid growth, can benefit from understanding the scalability and challenges of such strategies. India has set an ambitious goal of installing 175 GW of renewable energy capacity by 2022 [111]. This goal is part of the country's Intended Nationally Determined Contribution (INDC) to the Paris Agreement on climate change [112].As of 2023, India has an installed renewable energy capacity of 167 GW, which is the fourth largest in the world [113]. As of 2023, China has an installed renewable energy capacity of 850 GW, which is the largest in the world [114]. Both India and China are committed to continuing to develop renewable energy sources. India has set a goal of installing 500 GW of renewable energy capacity by 2030 [115]. China has set a goal of having renewable energy account for 20% of its energy mix by 2030 [116]. This approach ensures the research contributes not only to addressing regional energy challenges but also to the broader global imperative of transitioning towards sustainable, low-carbon energy systems in highly populated settings.

Like India and China Bangladesh also holds immense untapped potential for harnessing renewable energy. However, the global advancement of RETs faces numerous challenges. Various barriers impede progress, as outlined below. Refer to Fig. 13 for an overview of these challenges in renewable energy.

Bangladesh faces various challenges in its pursuit of renewable energy adoption. Transparent, consistent, and long-term policies are needed to integrate RETs effectively into the national energy plan, but policy shifts and weak foundations impede progress [49]. Renewable Energy Technology (RET) initiatives are often constrained by budget reliance, causing delays and uncertainty amidst competing priorities like healthcare and education [117]. Indirect subsidies to conventional energy sources hinder the competitiveness of RETs, necessitating legislative backing and financial incentives. High initial costs present barriers to RET adoption in Bangladesh, demanding subsidies for viability [118]. Although RETs offer feasible lifecycles, their upfront expenses hinder returns, while market interest rates further limit their implementation [118]. As demonstrated by Grameen Shakti, micro-credit supports RET affordability [117]. Bangladesh's higher transmission and distribution losses than developed countries hinder RET feasibility [118].

Quality control and standards for RETs need development domestically, as bulk procurement is restricted by a small market for modern energy services [49]. Lack of past research has led to inadequate technical support, affecting RET growth [49]. Custom-made technology development and increased technology transfer are required for local needs, while seasonal factors influence RETs like wind energy [45,119]. The need for more awareness and information across industries, institutions, and the public hampers RET implementation and access [45]. Inadequate access to renewable energy information demands a centralized hub, and gaps in public awareness hinder RET information collection [49]. Limited knowledge about renewable energy potential, resources, and technologies persists, requiring comprehensive investigation [117]. In Bangladesh, Information Technology's role in the power sector is limited due to the country's lower-income status and reliance on conventional resources. Managing RETs involves balancing human resources and finances across institutions, while complex approval processes hinder implementation [49]. Skilled labor scarcity due to inadequate awareness, knowledge, and information is a considerable obstacle to RET advancement [117]. To overcome these multifaceted challenges, Bangladesh must prioritize transparent policies, financial incentives, information dissemination, and skill development to drive its renewable energy journey forward.

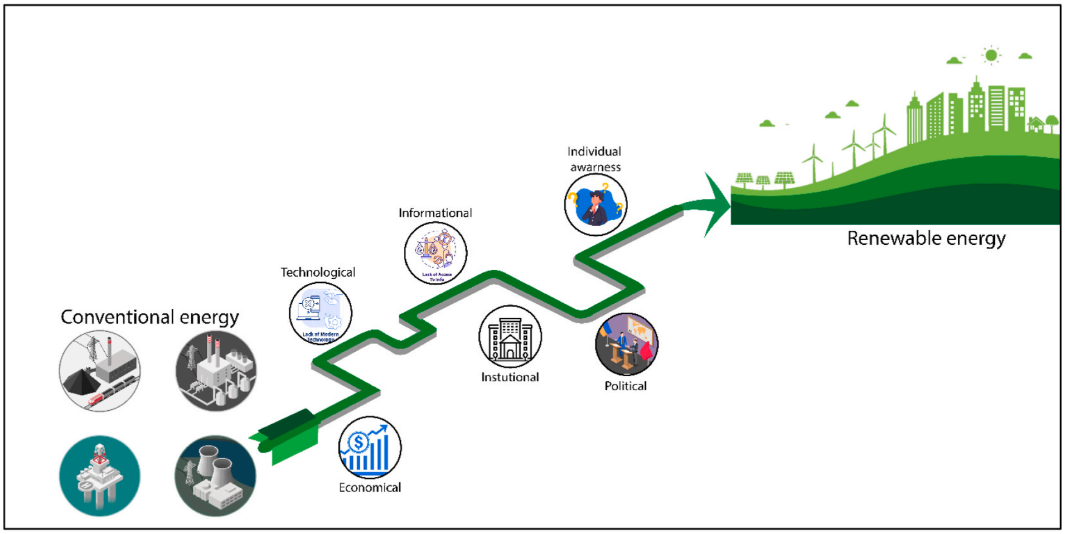

Fig. 13. An overview of challenges in renewable energy.

Bangladesh has showcased ambitious intentions for renewable energy integration, especially evident in its commitment during COP26. The NDC aims to achieve 4100 MW of renewable energy by 2030 [29]. While these aspirations are commendable, translating them into action from a private sector standpoint requires significant grid enhancements and regulatory overhauls. To truly unleash the potential of renewable energy, the nation must foster an environment conducive to private sector engagement through comprehensive changes to its infrastructure and regulatory framework.

7. Sustainable development goal Seven (SDG-7) and Bangladesh's progress

SDG-7 forms a part of the 17 worldwide objectives established by the United Nations within the framework of the 2030 Agenda for Sustainable Development [120]. The objectives urge global action to eradicate poverty, safeguard the environment, and secure universal prosperity. SDG-7 centers on affordable, reliable, and sustainable energy access for fairness and a greener future [121]. According to a current study, three billion people currently rely on polluting energy sources like wood and coal for cooking and heating. The generation of energy significantly contributes to climate change, being accountable for 60% of the total emissions of greenhouse gases on a global scale [122]. CO_2 emissions surged 46% since 1990. Hydropower tops renewables (16% global power), with bioenergy leading renewable energy (10% global primary energy). SDGs prioritize 2030 global energy progress [123]. Target 7.1 focuses on widespread access to affordable, reliable, modern energy services. Target 7.2 aims to significantly boost the proportion of renewable energy within the global energy blend. Additionally, Target 7.3 seeks to double the worldwide pace of enhancing energy efficiency, fostering more sustainable energy consumption patterns [124].

According to the SDG Tracker report 2021 [125], Bangladesh has made commendable progress in achieving SDG-7 targets. The nation has achieved universal access to electricity, reaching 99% population coverage from just 48% in 2010 [126]. Additionally, Bangladesh has integrated renewable energy sources, contributing to 28% of its Total Final Energy Consumption [29]. While these achievements are noteworthy, there is room for growth in energy efficiency, as the country's score stands at 2 MJ per USD 2017 PPP compared to the global average of 4.6. Moreover, with a 3.4 Watts per capita renewable capacity, Bangladesh is committed to promoting sustainable energy practices, even as it continues to work towards greater energy efficiency and renewable adoption. Table 6 shows some Asian country's SDG tracker report data.

In the context of energy-related indicators, Bangladesh demonstrates notable progress with 100% access to electricity, surpassing some neighboring countries like Myanmar and Pakistan [19]. However, challenges persist, as clean cooking access stands at 27%, indicating room for improvement. Bangladesh's commitment to renewable energy is evident, with 28% of its final energy consumption being renewable, comparatively higher than India and Indonesia. The nation's energy efficiency ratio is commendably low at 2 Megajoule (MJ) per USD 2017 PPP, showcasing efficient energy use. Although Bangladesh's renewable capacity per capita is relatively modest at 3.4 Watts, it is steadily advancing towards sustainable energy integration. International financial flows for energy development are substantial at 305.9 million USD in 2019 PPP, affirming the nation's proactive stance towards energy sector growth. These comparisons underscore Bangladesh's progress and ongoing efforts to enhance energy access, efficiency, and renewable energy adoption within its unique socio-economic context. To achieve SDG-7 in Bangladesh, several challenges need attention. Firstly, rural electricity access must be expanded, as about 10% lack power [127]. Secondly, enhancing energy efficiency in agriculture is vital due to its high energy consumption. Finally, given Bangladesh's vulnerability, adapting the energy sector to climate change impacts is essential. Furthermore, integrating more renewable sources like solar and wind is crucial. This requires improved infrastructure, policies, and public awareness. Balancing economic growth with sustainable energy demand is also key. Collaborative efforts are needed for reliable and affordable energy for all.

8. Discussion on future direction of RE technologies

In the context of Bangladesh's renewable energy landscape, the assessment offers valuable insights into the feasibility and potential of different energy sources is critical [128]. Solar energy is a standout option with its affordability, high sustainability, and positive overall assessment [129]. Given Bangladesh's abundant sunlight, solar power can be pivotal in addressing the nation's energy needs

Table 6
SDG Tracker record of some south Asian countries.

Country	Access to Electricity (%)	Access to Clean Cooking (%)	Renewable Energy (% of Total Final Energy Consumption)	Energy Efficiency (MJ per USD 2017 PPP)	Renewable Capacity per Capita (Watts)	International Financial Flows (USD million, 2019 PPP)
Bangladesh	99	27	28	2	3.4	305.9
India	100	71	36	4.3	104.5	1275.1
Pakistan	95	51	47	4	55.7	786.2
Myanmar	72	44	60	3.6	64	11
Maldives	100	100	1	3.4	62.3	25.8
Sri Lanka	100	33	49	1.7	116.9	0.5
Nepal	90	35	75	5.7	69.6	97.1
Bhutan	100	87	88	8.3	3003.7	0.8
Malaysia	100	944	6	4.5	265	0
Indonesia	99	87	22	3.1	40.8	350.5

while aligning with its sustainable development goals [130]. The medium adequacy and reliability ratings suggest that while solar energy is promising, efforts should be made to enhance storage solutions and grid integration to ensure a consistent power supply [131]. On the other hand, wind power receives a low overall assessment due to its low affordability, adequacy, and reliability. This highlights the challenges Bangladesh may face in harnessing wind energy effectively, potentially due to geographic constraints or technological limitations [78]. However, exploring offshore wind energy possibilities in coastal areas could be an avenue for enhancing the adequacy and reliability of this resource [132]. Biogas and hydropower, both assessed as having medium overall potential, can complement the renewable energy mix in Bangladesh [133]. With its medium affordability and adequacy, Biogas offers a sustainable option for organic waste management and localized energy generation [134]. Similarly, hydro power's medium sustainability and high reliability, particularly in hilly regions, provide opportunities for expanding the nation's renewable energy portfolio [49]. However, attention must be given to potential environmental impacts and effective management of water resources. Geothermal power receives a low assessment across all criteria, indicating that it might not be feasible within Bangladesh's geographical context.

This assessment underscores the need for a diversified approach to renewable energy in Bangladesh. While solar energy shines as a strong contender, careful consideration should be given to wind, biogas, hydro, and other sources to create a well-rounded and reliable renewable energy mix. Policymakers and stakeholders can utilize these insights to tailor strategies that harness the strengths of each energy source while addressing their limitations, ultimately driving the nation towards a sustainable and resilient energy future.

9. Renewable energy's mitigation of carbon footprint

Renewable energy systems have gathered significant economic, environmental, and technical interest over the past decade, with some being present in the market for nearly a century [135]. Nevertheless, it is important to note that even renewable energy can have adverse environmental effects, although generally less severe than those associated with fossil energy resources. Reducing the gap between carbon emissions and economic growth is an important solution for achieving sustainable development goals (SDGs) [136]. The significance of renewable energy in restoring balance between the environment and the economy is a major topic now-a-day. Therefore, to ensure a sustainable and stable society, the necessity for clean, environmentally friendly, and efficient energy sources has grown [137]. Fossil fuels and conventional processes for energy production, such as coal, crude oil, and natural gas, maintain their dominance, making up more than 80 percent of primary energy sources in 2018 [138]. Burning fuels releases CO_2, causing global warming, rising sea levels, ocean acidification, extreme weather, ecosystem disruption, health risks, and economic losses [139,140]. Carbon footprint refers to the total amount of greenhouse gases, specifically CO_2 and other equivalent gases like methane and nitrous oxide, emitted directly or indirectly as a result of human activities [141]. It measures the environmental impact of an individual, organization, product, event, or process regarding its contribution to global warming and climate change. Over the decades, this amount of CO_2 emission has increased by a great number. Fig. 14 shows some Asian countries' last decades' CO_2 emissions per capita.

Fig. 14 portrays CO_2 emissions per capita (metric tons) across countries from 1971 to 2021. Bangladesh increased from 0.0527 (1971) to 0.5502 (2021), India from 0.3368 to 1.9251. Nepal and Bhutan grew gradually: Nepal, 0.0155 to 0.4719; Bhutan, 0.0119 to 1.9577. Pakistan moderately increased, 0.3193 to 0.9918. Indonesia (2.2622) and Malaysia (7.6264) surged by 2021. The Maldives spiked from 0.0288 to 4.0619, highlighting small nations' vulnerability. The data showcases the intricate link between economic growth, environment, and the need for sustainable policies and climate initiatives [143]. Renewable energy can significantly mitigates carbon footprints by curbing greenhouse gas emissions linked to energy production and consumption [144]. Renewables like solar, wind, hydro, and geothermal emit few greenhouse gases, unlike fossil fuels. Shifting to clean energy reduces carbon reliance, mitigating global warming's harmful effects through lowered CO_2 emissions. Using renewable energy is not a choice; it is an option obvious now.

10. Conclusion

In conclusion, this study provides a comprehensive overview of Bangladesh's current energy landscape, particularly focusing on its renewable energy mix. Despite having a substantial reserve of natural gas estimated at around 34 Tcf, a significant portion of which currently fuels power generation, renewable energy sources for electricity production only contribute a mere 4.59%. This disparity highlights the pressing need for sustainable energy solutions. Recognizing the importance of diversifying its energy sources, the government has outlined various projects and policies. Policies established in 2008, supplemented by recommendations from USAID, serve as a strategic framework for the country's future electricity generation endeavors. This strategic blueprint emphasizes the maximization of natural resource potential and underscores the integration of innovative international technologies and local intellectual expertise to ensure energy sustainability. Addressing the Sustainable Development Goal (SDG) 7, which focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all, the study emphasizes the necessity for strategic and consistent multiphase planning. Implementation becomes pivotal in achieving this goal and elevating the percentage of renewable energy use. Such efforts are crucial not only for reducing the carbon footprint but also for diminishing dependence on fossil fuels, thereby fostering a more sustainable and environmentally friendly energy landscape in Bangladesh.

Additional information

No additional data and information are available for this paper.

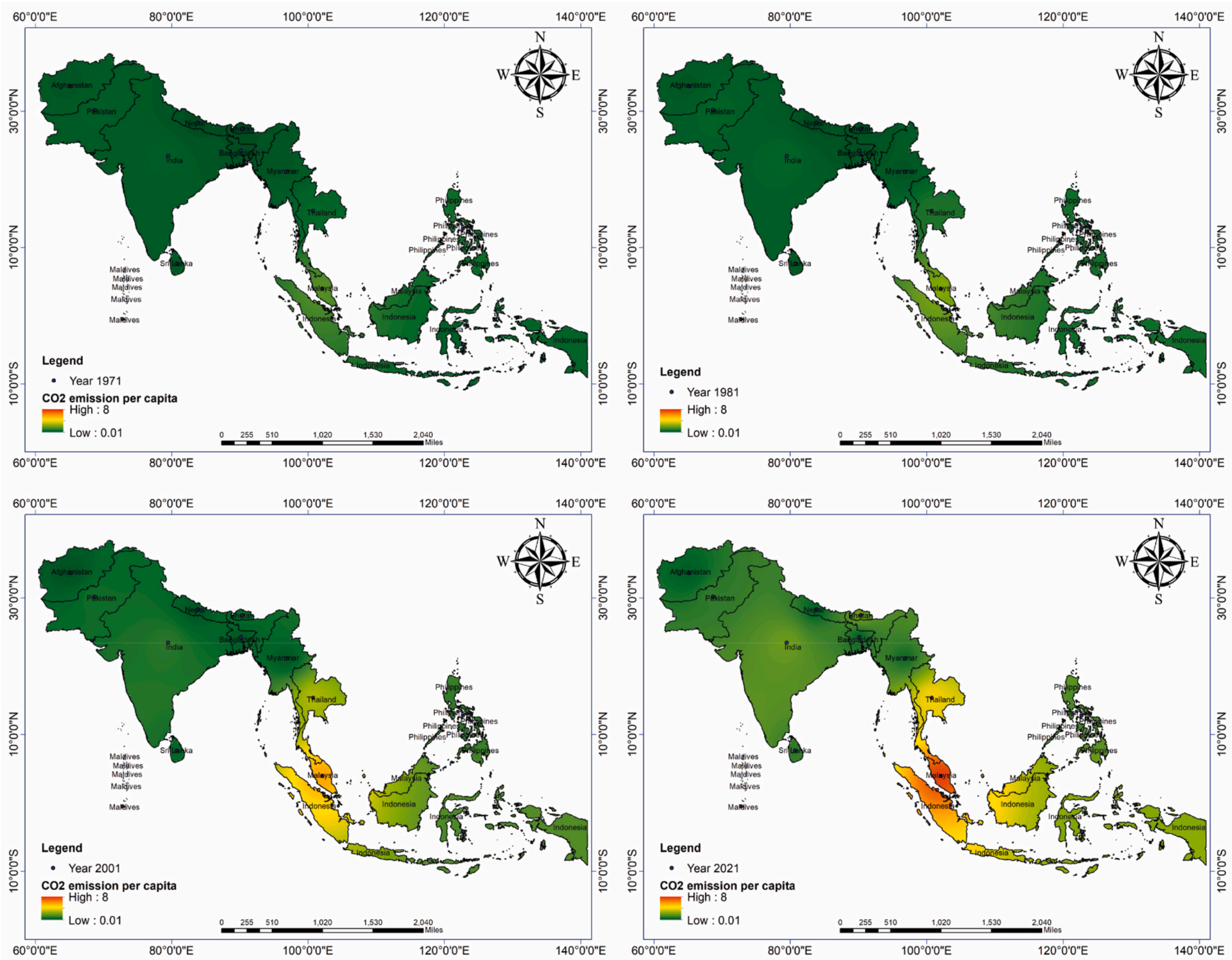

Fig. 14. CO_2 emissions per capita(in ton) in various south Asian countries from 1971 to 2021 [142].

Data availability statement

The authors declare that the data is included in the article and no additional data is available.

CRediT authorship contribution statement

Faysal Ahamed Akash: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shaik Muntasir Shovon:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wahida Rahman:** Writing – original draft, Methodology, Formal analysis. **Md Abdur Rahman:** Writing – original draft, Formal analysis, Data curation. **Prosenjeet Chakraborty:** Writing – original draft, Formal analysis, Data curation. **Minhaj Uddin Monir:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Acknowledgements

The authors would like to express their gratitude to the Energy Conversion Laboratory, which is located within the Department of Petroleum and Mining Engineering at Jashore University of Science and Technology in Jashore, Bangladesh. This laboratory has been of great assistance to the authors in doing this review work.

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