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Review article

Marine renewable energy harnessing for sustainable development in Bangladesh: A technological review

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ABSTRACT

A strategy for promoting ethical use of ocean resources while preserving the marine environment is known as the blue economy. The Blue Econ- omy's foundational element, marine renewable energy (MRE), has enormous potential to generate clean energy, spur economic growth, and slow global warming. Bangladesh has a lot of potential for the development of MRE due to its wide coastline and maritime resources. From a Blue Economy viewpoint, this review article offers a thorough examination of the present trends, opportunities, and difficulties associated with MRE implementation in Bangladesh's coastal region. The potential of MRE technologies, such as tidal energy, wave energy, wind energy, and ocean thermal energy conversion (OTEC), to deliver clean, dependable, and affordable energy while generat- ing new business opportunities for coastal towns has been examined in this article. The paper also evaluates Bangladesh's legal and policy frameworks for MRE develop- ment, as well as the funding alternatives, investment op- portunities, and socioeconomic and environmental effects of MRE projects. The paper emphasizes the importance of employing sustainable and ethical development methods to guarantee that MRE development adheres to the objectives of the Blue Economy. Overall, this review paper offers a road map for Bangladesh's MRE sector's sustainable and inclusive growth, addressing several Sustainable Development Goals (SDGs) in Bangladesh, ranging from clean energy access to climate action, economic growth, and environmental sustainability. It is hoped that it will add to the ongoing discussion on the nation's sustainable energy development.

1. Introduction

Bangladesh is a young developing nation with a fast-growing population and economy, having approximately 7% annual GDP growth and its energy consumption rate is also expanding quickly (Shaikh et al., 2017). Energy is crucial to the na- tion's economic and social growth. Recently, the Bangladesh government launched a program called "Hundred Percent Electrification" to increase the availability of power (Babu et al., 2022). With the help of this program, Bangladesh achieved 97% power access in 2023 and generated 4100 MW of electricity using inter- nal and renewable resources (Babu et al., 2022). Worrisomely, just 715 MW of energy, or around 3% of total power generation, is produced using renewable resources (Shaikh et al., 2017). The government has thus set a goal to increase the use of renewable resources by up to 10% in the future (Zaman). Currently, the main renewable re- sources frequently employed in Bangladesh are solar radiation, wind speed, and biomass. The percentage of renewable energy (RE) sources excluding large hydropower facilities was only 1.9% (Babu et al., 2022).

The Blue Economy is a strategy for promoting sustainable economic. growth and job opportunities while ensuring the conservation and sustainable use of marine resources. MRE is a foundational element of the Blue Econ- omy, as it has enormous potential to generate clean energy, spur economic growth, and slow global warming. In Bangladesh's coastal region, MRE tech- nologies such as tidal energy, wave energy, wind energy, and OTEC (Fig. 1) provide clean, reliable, and cost-effective energy solutions, creating new business opportunities for coastal cities. Utilising these resources can boost energy security, cut greenhouse gas emissions, and open up new employment opportunities in the nation's coastal regions.

However, the nation must overcome a number of challenges,

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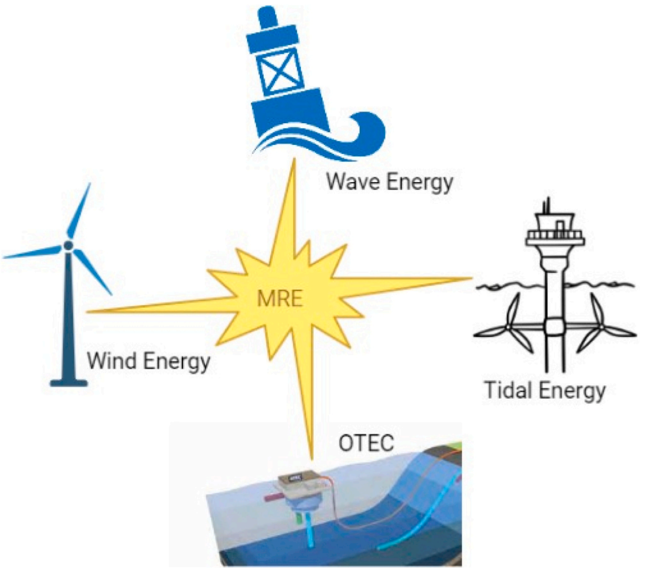

Fig. 1. Viable technologies to harness RE from the ocean (Hossain et al., 2014; Sarker et al., 2009; Azad and Alam, 2012; Masud et al., 2020; Shakil and Hoque, 2013).

including insufficient technical capability, financial limitations, a lack of regulatory frameworks, frequent natural disasters, rising sea levels, and saline intrusion. All of which have a negative impact on the lives and livelihoods of coastal residents. In recent years, both developed and developing nations are adopting MRE, and the viable technologies are being utilized to harness ocean energy with minimum environmental effects (Rony; Astariz and Iglesias, 2015; McCombie and Jefferson, 2016; Langhamer et al., 2010).

Fig. 2 shows the percentage of installed generation capacity in 2018 in Bangladesh from various sources. Bangladesh will be needing to produce 20,000 MW of electricity by 2021 and 34,000 MW by 2030 to reach the goal of economic growth (Hasan et al., 2018; Chowdhury et al., 2018). Gas usage for electricity generation increased as a result of the construction of a natural gas-dependent power plant (66.82%) and the shutdown of other fuel-dependent facilities. Only 3.56% of all electricity is produced by renewable sources of energy. Fossil fuels, which produce 96.44% of all energy, harm the environment and release CO_2 into the environment, increasing the risk of climate change and natural catastrophes (Hossain et al., 2014; Masud et al., 2020; Hossain et al., 2017). As fossil fuel supplies decline, RE becomes crucial for energy security and sustainable development (Authority, 1999). Bangladesh can meet its energy needs through sustainable energy sources like solar, nuclear, wind, tidal, and OTEC, while fossil fuels may still be necessary in the short term (Hossain et al., 2014; Sarker et al., 2009; Azad and Alam, 2012; Masud et al., 2020; Shakil and Hoque, 2013). Bangladesh's Renewable Energy Policy (REP-2008) intends for RE to make up 10% of all energy generation by 2030, according to the Sustainable and Renewable Energy Development Authority (SREDA) (Rahman et al., 2022). The country has currently implemented programs promoting domestic biogas, solar irrigation, and biogas/biomass-based power.

Fig. 3 represents hydro and solar power presently account for 99% of all RE produced in Bangladesh, but wave, OTEC, and wind energy should also be taken into account for future policy due to their predictability and potential. The nation expanded its maritime limit also offers opportunities to investigate oceanic natural resources (Hossain et al., 2014; Azad and Alam, 2012). When fossil fuels are used, they release greenhouse gases (GHG), whereas sources of RE, such as solar, wind, hydropower, biomass, and geothermal energy, emit far less (see Table 1).

In contrast to solar power's 28 g CO_2/kWh, wind power's 12 g CO_2/kWh, hydropower's 24 g CO_2/kWh, biomass's 220 g CO_2/kWh, and geothermal energy's 400 g CO_2/kWh (Hossain et al., 2014), coal and gas plants produce about 1180 g CO_2/kWh and 530 g CO_2/kWh, respectively, during operation. Deep ocean temperature fluctuations must also be taken into account in order to effectively anticipate changes in OTEC power potential under global warming (Wind Projects). Although solar energy systems don't produce greenhouse gases, their development and use raise environmental issues (Shakil and Hoque, 2013; Wind Projects). This review has been intended to advance the ongoing national conversation on the development of sustainable energy systems and encourage Bangladesh to develop its MRE resources using a Blue Economy strategy.

2. Literature review

Abu hasan Rony et. al., (2017) (Rony) concentrated solely on Bangladesh's potential for wave energy and might not offer a thorough examination of all available alternative energy sources or the nation's overall energy situation. Astariz and Iglesias (2015) conducted a review work on economics of wave energy. Their is based on a theoretical model and may not fully capture. the complexities and uncertainties associated with real-world wave energy projects. Additionally, the paper does not provide a detailed analysis of the environmental impacts of wave energy projects, which is an important consideration for the development of any RE technology. Also, Charles McCombie et. al., (2016) (McCombie and Jefferson, 2016) performed a review work on the environmental effects of nuclear and renewable electricity. The authors did not examine the economic feasibility of the different methods, which is an important factor in energy decision-making. With a focus on linear wave energy converters, the article conducted by Olivia Langhamer et. al., (2010) (Langhamer et al., 2010) examined wave power as a sustainable energy source. They focused primarily on the

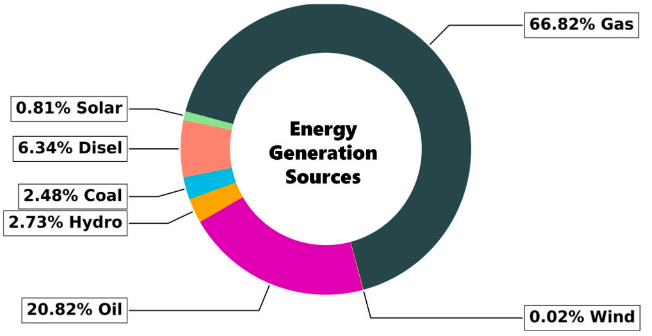

Fig. 2. Power generation in Bangladesh from various sources (Hossain et al., 2014; Masud et al., 2020; Hasan et al., 2018; Chowdhury et al., 2018; Hossain et al., 2017).

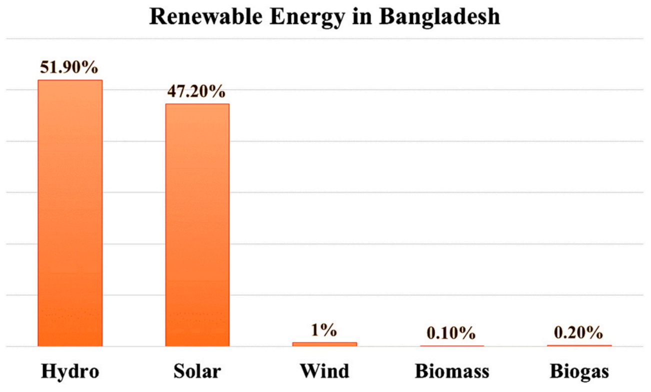

Fig. 3. Energy Production from renewable source in Bangladesh (Hossain et al., 2014; Azad and Alam, 2012).

Table 1
Emission of different gas per unit energy generation (Hossain et al., 2014; Azad and Alam, 2012).

Source	Emission Factor (Kg/KWh)			
	CO2	SO2	NOx	CO
Natural Gas	0.53	0.0005	0.00009	0.0005
Furnace Oil	0.85	0.0164	0.0025	0.0002
Hydro	0.024	0	0	0
Coal	1.18	0.0139	0.0052	0.0002
Wind	0.012	0	0	0
Hybrid OTEC	0.0117	0	0	0
Solar	0.028	0	0	0
Biomass	0.220	0.0023	0	0.0045

Lysekil project and may not be representative of all wave power projects. Additionally, the paper does not provide a comprehensive analysis of the economic feasibility of wave power as a sustainable energy source. Sarker et al. (2009) prepared a report on wave energy prospect in Bangladesh. The potential for utilising tides and ocean waves as a source of energy has been covered in the study conducted by Mirko Previsic et. al., (2005) (Herrera et al., 2021).

A. Roberts et. al. (2016) (Previsic, 2005) reviewed various tidal energy conversion systems for shallow near-shore sites. The assessment of the suitability of each technology for small-scale electricity generation is based on theoretical analysis and not on empirical data from actual installations. To demonstrate that Bangladesh has the capacity to produce electricity from tidal sources, Amit Kumar Sikder et. al., (2014) (Roberts et al., 2016) offered tidal data from six different places in Bangladesh. But they did not provide a detailed cost-benefit anal- ysis of tidal energy projects in Bangladesh. Nahidul Hoque Samrat et. al., (2013) (Sikder et al., 2014) suggested tidal energy in Bangladesh, which has a lengthy coast- line along the Bay of Bengal (BoB), as a dependable energy source. They did not provide a detailed economic analysis of the proposed tidal energy site, which could be important for decision-making. Mohammad Asadul Haque et. al., (2017) (Samrat et al., 2013) examined tidal data from three potential sites in Bangladesh and came to the conclusion that the country has a promising future for tidal power. The paper did not discuss the economic feasibility of implementing tidal power projects in Bangladesh In specifically, Md. Alamgir Hossain et. al., (2014) (Hossain et al., 2014) discussed the remote region of Sandwip in the paper's discussion of tidal power's potential as a new RE source in Bangladesh. They did not discuss the potential environmental impacts of tidal power plants in Sandwip or other locations in Bangladesh.

Olayinka S. Ohunakin et. al., (2012) (Haque and Khatun, 2017) used wind speed data of 37 years to examine the possibilities for wind energy in Nigeria. The paper did not consider other factors that may affect wind energy generation, such as turbulence intensity and wind direction. To produce accurate mapping findings for the commercially viable wind resource, Khandaker Dahirul Islam et. al., (2021) (Ohunakin and Akinnawonu, 2012) included mesoscale and microscale modelling. Their results were based on modeling and estimation techniques, and may not fully reflect the actual wind potential and energy generation capacity of the study area. Md. Alamgir Hossain et. al., (2017) (Chowdhury et al., 2018) analysed the possibilities for using massive wind turbines and emphasised the need for RE sources given the nation's energy constraint. The research on wind energy in Bangladesh was included by A. K. Azad et. al., (2012) (Azad and Alam, 2012), along with studies on wind speed and the creation of a RE policy. In order to address the country's energy crisis, A.Z.A. Saifullah et. al., (2016) (Islam et al., 2021) evaluated wind energy's potential in Bangladesh.

In order to address Bangladesh's electricity problems, Shifur Rahman Shakil et. al., (2013) (2014) (Shakil and Hoque, 2013; Saifullah et al., 2016) suggested OTEC technology. Utilizing the inherent temperature gradient of the ocean, OTEC is a RE system that converts solar energy into electrical energy. Jorge Herrera et. al., (2021) (Wind Projects) offered an overview of global OTEC technology advancements and applications. These papers did not provide a detailed analysis of the economic, social, and environmental impacts of OTEC technology in Bangladesh.

To address the challenges emerges from the past studies shown in Table 2, we will try to concentrate simply on the potential of MRE technologies, such as tidal energy, wave energy, wind energy, and OTEC, to deliver clean, dependable, and affordable energy while generating new business opportu- nities for coastal towns. The paper also evaluates Bangladesh's legal and policy frameworks for MRE development, as well as the funding alternatives, investment opportunities, and socioeconomic and environmental effects of MRE projects. The contributions of this paper are:

- It offers a thorough analysis of the present trends, opportunities, and difficulties associated with capturing MRE from Bangladesh's coastal region from the perspective of the Blue Economy.
- It evaluates the legal and policy frameworks, funding alternatives, in- vestment opportunities, and socioeconomic and environmental effects of MRE projects in Bangladesh.
- It highlights a roadmap of the potential of MRE technologies to deliver clean, dependable, and affordable energy while generating new business

opportunities for coastal towns.

3. Study area

This review article's study area is Bangladesh's coastal region. Bangladesh is a small, deltaic nation in South Asia that shares borders with Myanmar, India, and the BoB. The nation's 710 km coastline stretches from the Sundar- bans mangrove area in the southwest to the Teknaf peninsula in the south. A sizeable chunk of Bangladesh's population resides in the coastal region, which also supports millions of people's livelihoods through fishing, aquacul- ture, and tourism. The region has the potential to significantly contribute to the nation's energy security while fostering sustainable economic growth and environmental sustainability due to its abundance of RE resources, notably MRE.

4. Review process

Fig. 4 shows the review process of the work. After selecting the study area, the research articles related to the sites have been searched and down- loaded. The papers covering MRE have been considered for further review by a research team consisting of four members. During the review of the articles, the technical aspects, economic viability, environmental impacts, prospects, and challenges of MRE have been noted to draw a summary by which future research and steps can easily be identified.

4.1. Methodical search approach

Using a methodical search approach, the papers for this review article were chosen. Numerous academic databases, including PubMed, Web of Sci- ence, Scopus, and Google Scholar, were thoroughly searched. The following search phrases were used: "marine renewable energy," "tidal energy," "wave energy," "ocean thermal energy conversion," "Bangladesh," "coastal area," "blue economy," "sustainability," "economic growth," "policy," "regulation," and "investment."

Peer-reviewed articles released in English between 2000 and 2023 were the only articles that could be found. Applying inclusion and exclusion criteria helped to further refine the search results. Papers focusing on the present state, opportunities, and difficulties of capturing MRE in Bangladesh's coastal.

region from a Blue Economy perspective met the criteria for inclusion. Pa- pers that weren't peer-reviewed, weren't published in English,

Table 2
Novelty of the proposed review work.

Authors	Energy Types	Overcomin challenges and barriers	gAnalysis of environment impacts	Analysis of economic feasibility	Analysis of Technical aspects
Abu Hasan Rony et. al. (2017) (Rony)	Wave	No	No	No	No
S. Astariz et. al. (2015) (Astariz and Iglesias, 2015)	Wave	No	No	Yes	Yes
Charles McCombie et. al. (2016) (McCombie and Jefferson, 2016)	Nuclear, Hydro, Wind, Solar, and Biomass	Yes	No	No	No
Olivia Langhamer et. al. (2020) (Shakil et al., 2014)	Wave	No	Yes	No	No
Md. Junayed Sarker et. al. (2009) (Sarker et al., 2009)	Wave	No	Yes	No	Yes
Mirko Previsic et. al. (2005) (Herrera et al., 2021)	Wave	Yes	No	Yes	Yes
A. Roberts et. al. (2016) (Previsic, 2005)	Tidal	Yes	No	No	No
Amit Kumar Sikder et. al. (2014) (Roberts et al., 2016)	Tidal	Yes	No	No	No
Nahidul Hoque Samrat et. al. (2013) (Sikder et al., 2014)	Tidal	Yes	No	No	Yes
Mohammad Asadul Haque et. al. (2017) (Samrat et al., 2013)	Tidal	No	No	No	Yes
Md. Alamgir Hossain et. al. (2014) (Hossain et al., 2014)	Tidal	No	No	Yes	Yes
Olayinka S. Ohunakin et. al. (2012) (Haque and Khatun, 2017)	Wind	No	Yes	Yes	Yes
Khandaker Dahirul Islam et. al. (2021) (Ohunakin and Akinnawonu, 2012)	Wind	Yes	No	Yes	Yes
Md. Alamgir Hossain et. al. (2013) (Langer et al., 2020)	Wind	Yes	No	No	No
A. K. Azad et. al. (2012) (Azad and Alam, 2012)	Wind	No	No	No	No
A.Z.A. Saifullah et. al. (2016) (Islam et al., 2021)	Wind	No	No	Yes	Yes
Shifur Rahman Shakil et. al. (2014) (Saifullah et al., 2016)	OTEC	No	No	No	No
Jorge Herrera et. al. (2021) (Wind Projects)	OTEC	No	No	No	No
This Paper	Wave, Tidal, Wind, OTEC	Yes 9	Yes	Yes	Yes

or weren't relevant to the research topic were all excluded.

The full-text publications were downloaded and examined once the titles and abstracts had been checked. The chosen papers were then examined and synthesised to offer a thorough analysis of the prospects and difficulties facing the development of MRE in Bangladesh today. The review process is graphically represented in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram shown in Fig. 5, which gives an overview of the study selection process. The steps in the PRISMA flow diagram for this review article would be as follows:

The database search technique led to the discovery of 113 articles in total. 67 articles' titles and abstracts were examined after duplicates were eliminated. 61 of these articles were chosen for full-text analysis. 55 papers were considered eligible for inclusion in the review after the inclusion and exclusion criteria were applied. From a Blue Economy viewpoint, the 48 papers that were chosen were carefully read and analysed to offer a thorough analysis of the present trends, opportunities, and difficulties associated with capturing MRE in Bangladesh's coastal region. The review article provided justifications for excluding the remaining 65 articles (Fig. 5). The PRISMA flow diagram aids readers in assessing the reliability of the review findings by providing transparency and clarity on the selection process.

5. Wave energy

5.1. Current status of wave energy in Bangladesh

A RE source that may be obtained from the motion of the sea waves is wave energy. The conditions for wave energy are favorable in Bangladesh, especially from late March to early October (Hossain et al., 2017). The waves in the BoB are produced by southwest wind (Hossain and Ahmed, 2013). According to research, the BoB may experience waves up to 2.9 m high (Shahid, 2010). The typical wave height is 2.6 m. And the wave duration is around 8 to 9 s (Ashik-Ur-Rahman and Gain, 2023). Where we may simply acquire 27 kw from a single unit using energy calculations (Langhamer et al., 2010). In Bangladesh, wave power has the potential to be a significant alternative energy source (Shakil and Hoque, 2013; Ashik-Ur-Rahman and Gain, 2023; Sarker et al., 2009).

5.1.1. Wave energy conversion and power estimation of coastline in Bangladesh

The greatest and most geographically extensive collection of wave data is comprised of wave energy calculations using a variety of techniques, at first visual wave measurements from passing maritime vessels (Sarker et al., 2009). Wave data were calculated using a Hindcast technique using 20 years of data, and the results were recognized more representative of the real wave climatology than visual projections from ships (see Table 3). These data are part of a series called Summary of

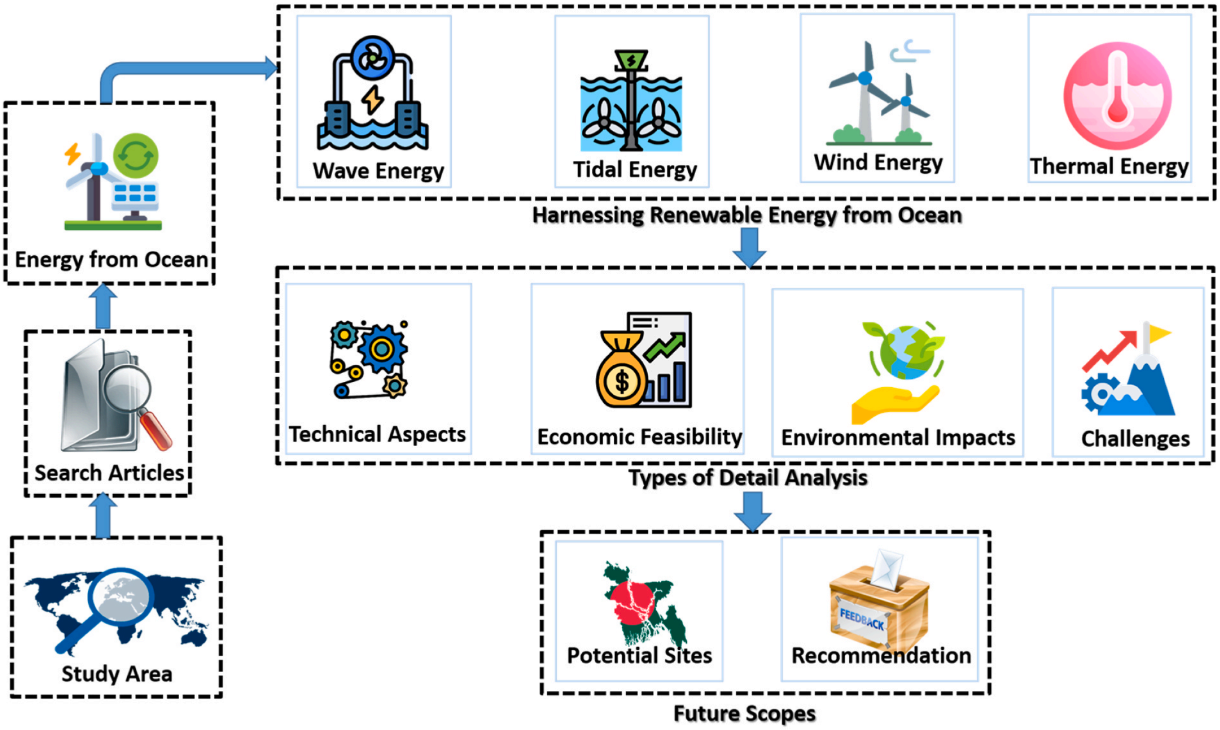

Fig. 4. Process of Review.

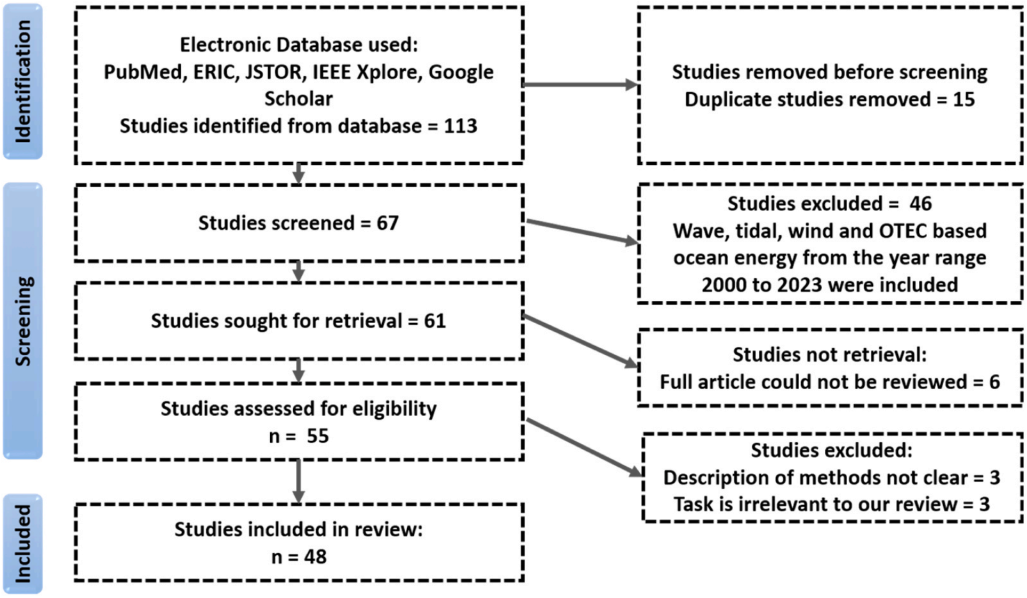

Fig. 5. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the review process.

Synoptic Meteorological Observations (SSMO), and they include monthly and annual wave vs. period (Herrera et al., 2021).

Potential energy is related to the form or elevation of the wave, whereas kinetic energy is related to the motion or velocity of the water particles inside the wave. For sinusoidal waves, the overall energy is defined in Eq. 1 (Sarker et al., 2009).

$$\mathbf{E} = \rho \mathbf{g}\mathbf{H}^2 /\mathbf{8} \tag{1}$$

Where, E = the overall energy per unit of surface water, ρ = ocean water's mass density, g = gravitational acceleration, H = based on the crest, the wave height.

And the relationship between wave period (T) and wave length (L), is shown in Eq. (2) (Herrera et al., 2021).

$$\mathbf{L} = \mathbf{g}^2/\mathbf{2}\pi \tag{2}$$

For small aptitude waves in deep water (water depth > L/2), power per unit of wave is defined in Eq. (3) (Langhamer et al., 2010).

$$\mathbf{P} = \mathbf{E}(\mathbf{c}/2) = \mathbf{E}(\mathbf{L}/\mathbf{2\ T}) = \mathbf{pg}^2\mathbf{H}^2\mathbf{T}/\mathbf{32I} \sim \mathbf{H}^2\mathbf{T} \tag{3}$$

Where c = wave speed or phase velocity. The wave height and period for Bangladesh have already been stated as being 2 m and 6 s, respectively (Langhamer et al., 2010). The wave energy will thus be 24KW/m,

Table 3
Contrasts the SSMO and Hind cast casting techniques (Hossain et al., 2014; Sarker et al., 2009; Azad and Alam, 2012; Masud et al., 2020; Shakil and Hoque, 2013; Rony; Astariz and Iglesias, 2015; McCombie and Jefferson, 2016; Langhamer et al., 2010; Hasan et al., 2018; Chowdhury et al., 2018; Hossain et al., 2017; Authority, 1999; Rahman et al., 2022; Wind Projects).

SSMO		Hindcast	
Height (m)	Period (s)	Height (m)	Period (s)
0.25	5.50	0.25	7.91
0.50	6.50	0.59	8.73
1.00	8.50	1.28	10.38
2.00	10.50	2.66	12.03
3.00	12.50	4.04	13.68
6.25	18.00	8.40	18.22

but for random seas the relevant relation is $\mathbf{P \sim 0.5\ H^2T}$, so we obtain 12KW/m (Masud et al., 2020). If we take into account the hindcast technique, the hindcast height and period will be 2.66 m and 8.41 s, respectively (Haldar, 2023), and the energy will then be defined by Eq. 4 (Haldar, 2023).

$$P \sim 0\cdot 5x2\cdot 662x8\cdot 41 = 29\cdot 75KW/m \quad (4)$$

As the waves are erratic, accurate equalization is difficult, yet the coast- line of the BoB generates about 15KW/m, there is a significant difference between these two results (Shahid, 2010). Bangladesh has around 580 kilometers of coastline, hence (580 × 1000 × 15) = 8700000Kw = 8700Mw of electricity is produced along the coast (Hossain and Ahmed, 2013). The following information indicates that if we are able to manage 20% of the coastline, then around 1740Mw of energy may be harvested, which is equal to 30% of the current energy demands of Bangladesh (Ashik-Ur-Rahman and Gain, 2023).

5.1.2. Wave energy sites in Bangladesh

Despite the significant wave-power potential in several of the country's islands and coastal regions (Kuakata, Sandwip, and St. Martin's Island shown in Fig. 14), the utilization of this potential requires careful considera- tion with the suitable Wave Energy Converter (WEC) technology. However, WEC research is still in its infancy phases in Bangladesh (Washim Akram et al., 2022; Masud et al., 2020). This analysis shows that Bangladesh's wave-energy use status quo may improve with the promise of the state-of-the-art nearshore WEC dubbed Searaser. It is the perfect WEC for low-budget conditions and can be implemented in distant islands because to its straightforward concept and environmentally benefi- cial design elements (Wind Projects). In the years 1969, 1970, and 1989, respectively, wind speeds of up to 650 km/h, 221 km/h, and 416 km/h were reported in Bangladesh (Shahid, 2010). Storm surges of up to 15 m and severe cyclonic storms have been observed (Hossain and Ahmed, 2013). Also, the plant must be able to withstand the rare occurrence of extremely high waves during a storm. In addition, Cox's Bazar, one of the 120 km-long natural sea beaches in the world, Kuakata, another well-known beach, is 30 kilometers long, and Bangladesh's whole coastline is 710 kilometers long (Masud et al., 2020; McCombie and Jefferson, 2016; Chowdhury et al., 2018; Washim Akram et al., 2022),].

The wave heights for Cox's Bazar and Saint Martin Island, respectively, range between 2.6 and 2.9 m and 1.5 and 2 m, according to Figs. 6 and 7. Moreover, the greatest wave period in Cox's Bazar was 9 s, whereas the maximum wave period for Saint Martin island was determined to be 7 s. Most crucially, the power generated by wave energy is directly influenced by wave height and period (Masud et al., 2020).

5.1.3. Cost estimation of wave farm

The following are the key expenses for a wave energy facility:

Pre-operating cost: As it greatly varies on the type of installation, location, and specifics of the project at hand, it is sometimes regarded as 10% of the capital cost (CAPEX) (Masud et al., 2020; Astariz and Iglesias, 2015). According to the Association of Renewable Energy Suppliers, it spans between 650,000 and 2600,000 dollars (Herrera et al., 2021). Next, charges for obtaining licenses and approvals must be included; they are expected to be 2% of the Wave Energy Converters' initial cost (Sarker et al., 2009). (The GBP to USD conversion rate was $1.30 = £1, The ratio is more like 1.30 as of the time of writing, although it fluctuates a lot (Astariz and Iglesias, 2015; Shahriar et al., 2019; Allan et al., 2011).).

Construction Costs: The cost of the WEC includes both the device's cost and the expense of installing it. It may be estimated after evaluating and contrasting many research and sources that the price of equipment and installation ranges between 2.5 = $3.25 and 6.0 = $ 7.8 million per installed Megawatt (Haldar, 2023). Reference figures for the cost of the converter per MW of installed electricity are shown in Table 4.Also, the cost of installation must be taken into account, particularly for the underwater cable. In comparison, the price of the necessary vessel is around 2.431 $/m, or 2.86 $/m (Sarker et al., 2009). In addition to the cost of the cable, one must consider the price of the electrical substation, which changes depending on the increase in tension needed to supply energy to the network. For instance, a substation would cost 1443,000 $ to raise the voltage to 33 kV, and 1729000$ to raise it to 66 kV (Sarker et al., 2009; Astariz and Iglesias, 2015; Shahriar et al., 2019; Allan et al.,

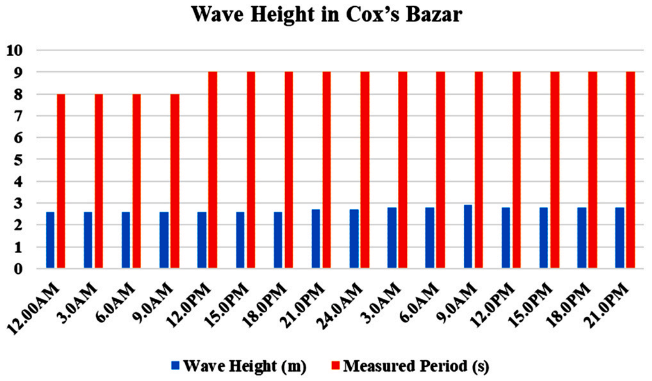

Fig. 6. Statistics on the wave height (m) in Cox's Bazar, Bangladesh (Masud et al., 2020).

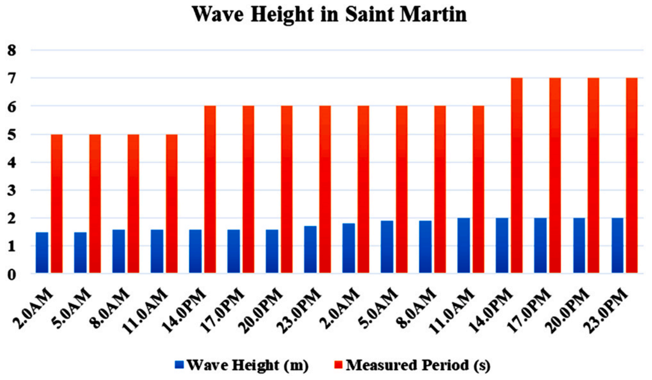

Fig. 7. Wave height (m) information of Saint Martin Island, Bangladesh (Masud et al., 2020).

Table 4
Wave Energy Converter cost per Megawatt (Sarker et al., 2009).

Converter Power (MW)	Cost Per MW
0.25	6500,000
0.5	5200,000
1	3900,000

2011). Fig. 7.

Operational and Maintenance Expenditure: Some of these expenses are listed in Table 5 as $ /MW or as a proportion of CAPEX or Operational Expenditure (OPEX) (Masud et al., 2020; Haldar, 2023; Herrera et al., 2021; Langhamer et al., 2010). The document presents a thorough technique to calculate the cost of both normal maintenance and emergency repairs.

Decommissioning Costs: Also, it must be remembered that 10 years after their initial installation, the WECs must be taken out of the water for an overhaul, which includes repainting and replacing various components, such as hydraulic cylinders. The expected expense is approx. 4.2% of the initial expenditure. Also, the entire facility is planned to be decommissioned 20 years from now at a cost of 0.5% to 1% of the initial expenditure (Masud et al., 2020). Ac- cording to a different analysis, the average decommissioning expense would be about 65,000 dollars per megawatt. The total capital cost comes to ap- proximately $7.0 million per megawatt (Sarker et al., 2009; Astariz and Iglesias, 2015; Shahriar et al., 2019; Allan et al., 2011; Dalton et al., 2010).

In fact, much like with other RE sources (including solar PV, solar, and thermal), wave energy currently has higher capital costs than traditional generating methods (such gas and coal) (Sarker et al., 2009). Similar to a facility in the water, there are also substantial operating and maintenance expenses. The selling of the electricity produced by a wave farm is obviously the major source of income. In this regard, current converters perform poorly, and increasing their performance will significantly increase the economic feasibility of wave energy. using Table 6, where useful capacity is ignored, it will take almost 20 years to reach profit margin.

5.2. *Prospects and challenges of wave energy*

Because wave energy has a higher density (2–3 kW/m^2) than solar and wind energy (0.4–0.6 kW/m^2 and 0.1–0.2 kW/m^2, respectively) (Sarker et al., 2009), it is much larger and more dependable. Other advantages are given below:

- Waves have a low energy loss and can travel long distances (Langhamer et al., 2010).
- Wave energy converters have a 90% efficiency rate (20–30% for wind and solar devices) and compared to the wind, it has a far higher pre- dictive capacity (Haldar, 2023).
- As 37% of the world's population lives within 90 kilometers of the coastline, there is a direct relationship between supply and demand. Because of its many sites, it is a readily accessible energy source (from coast to deep seas) (Sarker et al., 2009).
- The nearly minimal environmental impact because low greenhouse gas emissions (Herrera et al., 2021).

On the other hand, it is important to remember the difficulties that this technology must overcome in order to be commercially viable in the world energy market:

- The transformation of wave motion from its slow (0.1 Hz), random, and oscillatory forms into a usable (50 Hz) motion that may be used to link a generator and deliver a suitable output to the grid (Haldar, 2023).

Table 5
Yearly operating and maintenance expenses (Masud et al., 2020; Haldar, 2023; Herrera et al., 2021; Langhamer et al., 2010).

Expenditure	CAPEX	OPEX
Operation & Maintenance Tasks	1.5-5.0%	57%
Revision & Time off	10%	
Spares	90%	
Public Services		3.5%
Renting	2.5%	
Insurance	0.8-2%	13-14%

Table 6
Approximate Revenue Calculation of 35 MW Wave Energy plant (Sarker et al., 2009; Astariz and Iglesias, 2015; Shahriar et al., 2019; Allan et al., 2011; Dalton et al., 2010).

Total Capacity	35 MW
Life Time	More than 50 years
Annual Production	306,600 MWh/year.
Total Installation Cost	$ 245 million
Pre operating Cost	650,000 *and*2600, 000 per MW
Maintenance and Operation Cost	$ 4.2 million
Minimum Cost of KWh in Bangladesh	$ 0.053
Yearly income	$ 16.25 million
Yearly revenue	$ 12.05 million

- The power level of waves fluctuates along with their height and duration. A smooth electrical signal must be created from this energy vector (Masud et al., 2020).
- Offshore converters provide another difficulty. At these places, the de- vice must also withstand strong wave conditions, which presents chal- lenging structural engineering problems. It is apparent that the main- tenance operations get exceedingly challenging (Sarker et al., 2009).
- The investment in these technologies becomes increasingly challenging in the context of the financial downturn. The scientific community should collaborate to make this technology more practical, effective, and inexpensive (Rezaei et al., 2023).
- Debris from ship collisions, coastal deposits, and absorbing wave energy on inshore currents can create negative environmental impacts. A more important potential problem is the effect on navigation, particularly the dangers when a device runs away from its anchors in a storm (Ahmed et al., 2013).

Wave energy has a substantial potential in Bangladesh's 710 km of BoB coastline, with an estimated 1.8 GW of potential and peak power densities of 10–30 kW/m (Hossain et al., 2017; Masud et al., 2020). Due to the stronger waves, the southern coastal areas have the most promise. Wave energy can be captured by devices like oscillating water columns, point absorbers, OWSCs, surface attenuators, and overtopping devices (Dalton et al., 2010; López et al., 2013; Xu et al., 2023; Liang et al., 2023). In order to utilize the surplus energy generated by waves along its coastline, Bangladesh should investigate these technologies.

5.2.1. *Oscillating water column (OWC) devices*

OWC devices harness wave energy by using the rise and fall of waves to drive a turbine via the compression and decompression of air in a chamber. The OWC system illustrated in Fig. 8(a) typically consists of a partially submerged chamber with a small opening in the roof for airflow in and out. As waves enter the chamber, the air is compressed, which then drives a tur- bine to generate electricity. When the waves subside, the air is drawn back into the chamber through the opening, and the cycle repeats. Compared to other wave energy sources, OWC devices have a minimal influence on the environment because they don't make a lot of noise or emit any toxic gases (López et al., 2013). They are suitable for isolated either onshore or offshore places where maintenance may be challenging because they are straightforward and de- pendable with few moving parts (Liang et al., 2023). Direct connection with the coastline for onshore installations, with the chamber, placed below high tide; for offshore installations, a floating platform anchored to the ocean floor in offshore areas (Dalton et al., 2010; Xu et al., 2023). However, their sensitivity to variations in wave height and frequency, they may perform less effectively (López et al., 2013).

5.2.2. *Point absorbers*

Another kind of device used to capture wave energy is called a point

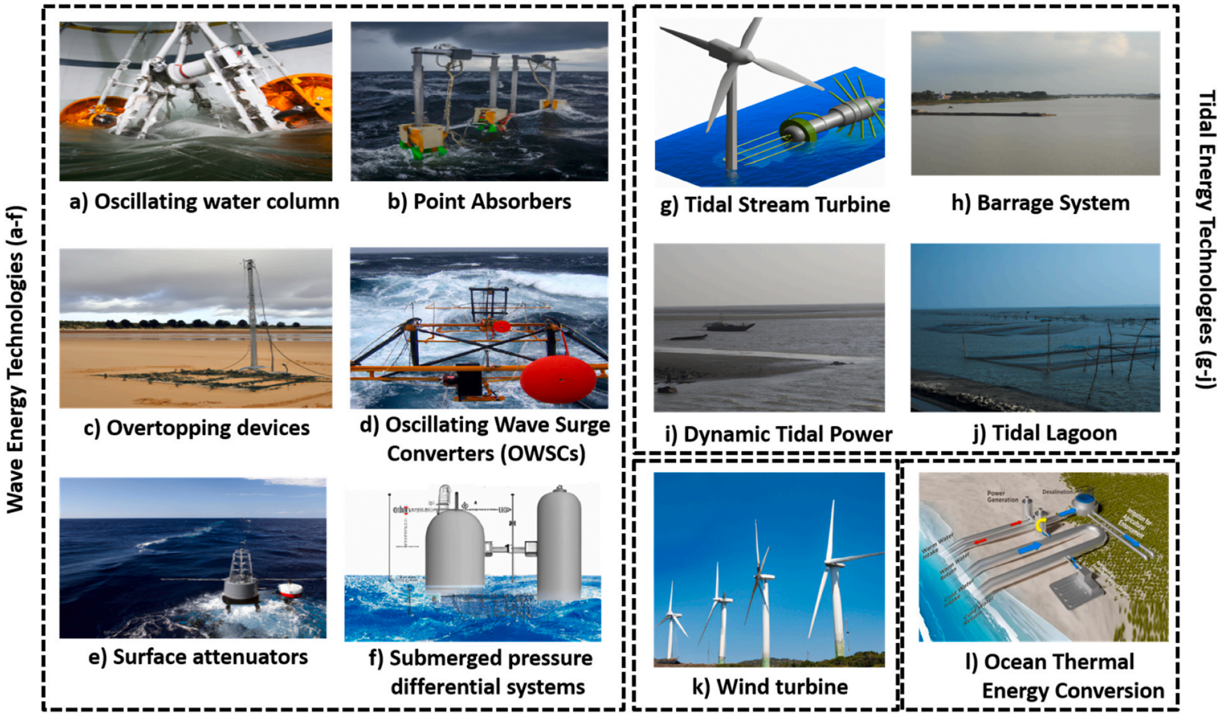

Fig. 8. Different types of MRE technologies.

absorber (Fig. 8(b)). A power take-off (PTO) system is housed inside the buoy or connected to the mooring system and as the buoy rises and falls, it produces electricity. The deployment and design of point absorbers faced difficulties that require careful positioning to prevent damage from severe weather or collisions with other waterborne items. Additionally, to make sure the mooring system and other components are working properly, they also need routine maintenance (Ĺopez et al., 2013; Liang et al., 2023; Molla et al., 2023; El hou et al., 2023).

5.2.3. *Overtopping devices*

Another wave energy converter is an overtopping device (Fig. 8(c)), which takes advantage of the water's increased potential energy. Overtopping de- vices have the ability to produce comparatively constant energy. However, the functioning and design of overtopping devices can present certain diffi- culties. They need to be placed carefully to prevent damage from extreme weather conditions or tidal changes and need to be carefully designed in the PTO system to capture the maximum amount of wave energy (Nasrollahi et al., 2023; Dalton et al., 2010; Ĺopez et al., 2013).

5.2.4. *Oscillating wave surge converters (OWSCs)*

An example of a wave energy converter (Fig. 8(d)) is an oscillating wave surge converter (OWSC), which uses the surge motion of waves to power a piston or other mechanical devices that then produce electricity (El hou et al., 2023). A piston or mechanical system is often housed inside a chamber that is partially submerged in the water, while OWSCs typically consist of a floating device that is attached to the seabed. The water level inside the chamber rises and falls as waves pass over the device, producing a surge action that powers the piston or mechanical system. A power take-off system is then used to create electricity using this motion (Sarker et al., 2009; Langhamer et al., 2010; Nasrollahi et al., 2023). The design and construction of OWSCs are straightforward and can be made using common materials and manufacturing techniques. However, they need to be installed carefully to prevent damage from severe weather conditions and collisions with other vessels and ships.

5.2.5. *Surface attenuators*

Surface attenuators consist of a long, floating structure that is anchored to the seafloor shown in Fig. 8(e). The structure often has a sequence of floats or other buoyancy components attached to it, and it is oriented perpendicular to the direction of wave propagation. The floats move up and down as waves approach the gadget, creating a relative motion between two sections of the device. A hydraulic or pneumatic system that produces electricity is driven by this motion (Ĺopez et al., 2013; Molla et al., 2023; El hou et al., 2023). Surface attenuators are easily designed and constructed using common materials and procedures and they are very scalable to generate more energy with larger devices (El hou et al., 2023). Research and development efforts are still being made with the goal of enhancing the effectiveness and dependability of surface attenuators while also lowering their price and environmental impact (Ĺopez et al., 2013).

5.2.6. *Submerged pressure differential systems*

A type of wave energy converter known as a submerged pressure differ- ential system (Fig. 8(f)) uses the pressure difference between the top and bottom of a submerged structure to produce electricity when waves pass by. This system consists of a vertical or slanted structure with an air-filled cham- ber at the top that is partially immersed in the water. The water level in the chamber fluctuates as waves pass over the structure, creating a pressure difference between the top and bottom of the chamber. In order to gen- erate energy, a turbine or other PTO is driven by this pressure differential (El hou et al., 2023; Nasrollahi et al., 2023; Hosseinzadeh et al., 2023). The ability to be constructed to function in a range of wave situations, from small, regular waves to enormous, irregular swells, is one advantage of submerged pressure differential systems. They require careful positioning to maximize their ability to catch the energy, and they are more difficult to design and construct than certain other wave energy devices. Sys- tems with submerged pressure differentials have the potential to be crucial in the growth of wave energy as a clean, RE source.

Wave energy growth in Bangladesh can bring benefits like diversifying the energy mix, reducing fossil fuel reliance, promoting sustainable indus- tries, and improving energy access in rural/off-grid areas.

However, the de- velopment of wave energy in Bangladesh has been impeded by factors such as high initial prices, cautious site selection, adverse environmental effects, and legal frameworks. However, wave energy is a topic that the government is interested in and has been incorporated into the national energy strat- egy. Ongoing research aims to improve the effectiveness, dependability, and cost-effectiveness, and also reduce the environmental negative effect of wave energy systems.

6. Tidal energy

6.1. *Current status*

Bangladesh's electricity usage per capita is just 154 KW/hr, which is much lower than that of any developed nation (Ashik-Ur-Rahman and Gain, 2023). The country's vast coastal territory, with tidal height ranges of 2 to 8 m, an average tidal range of 2 to 5 m, and tidal stream speeds of more than 2 m/s, offers a highly attractive promise for tidal power (Samrat et al., 2013). Tidal energy is easily produced by the fluctuating water levels and is more predictable than wind and sunshine. Within 98% accuracy, tidal currents can be accurately predicted decades in the future (Roberts et al., 2016). A coastal bay with significant variances between low and high tides can be used to generate power using changing tides (Hossain and Ahmed, 2013). The power gen- eration from tides is quite similar to hydroelectricity production apart from that water may flow in both directions and electricity is created by employing two-way turbines (Li and Zhu, 2023). Tidal power technology is fairly straightforward and has an estimated lifespan of more than 40 years (Roberts et al., 2016).

6.1.1. *Prospective tidal energy sites*

Bangladesh's coastline (Fig. 14) is suitable for the construction of tidal power plants. Several deltaic islands have huge tidal sites and numerous.

canals with low tidal ranges, where barrages and sluice gates are already in place. As a result, the increased building costs may be kept to a minimum because some of the necessary infrastructure already exists. Bangladesh has a lengthy (710 km) coastline region with 2 to 8 m head rise and fall (Shahid, 2010). Bangladesh has a tidal current with an average speed of 2–4 m (Ashik-Ur-Rahman and Gain, 2023). The Sandwip island generates a maximum of 16.49 MW per day and a minimum of 2.90 MW at Hiron Point with five turbines (Rashid et al., 2017). Fig. 9 depicts the daily tidal range for several coastal areas in Bangladesh with computed output power where five turbines are utilized, and the basin area is $4 \times 10^6\ m^2$ (Ali et al., 2012).

Six locations in Bangladesh's coastal region are chosen for our study after.

considering the viability of electricity generating (see in Fig. 14). These locations were chosen because they have acceptable tidal ranges for power generation—between 2 and 8 m. Sandwip (22.4937° N and 91.5015° E), a 50-kilometer island, located along Bangladesh's south-eastern coast at the entrance of the Meghna River on the Bay of Bengal, stands out as the ideal location for barrage-type tidal power production due to its geographical advantages (Rahman et al., 2013; Alam et al., 2012; Bhuyan, 2010; Ahmad et al., 2018).

6.1.2. *Tidal energy calculation*

The amount of water in a barrage determines how much energy is accessi- ble (Samrat et al., 2013). In a volume of water, the one-way potential system's average power is calculated by the Eq. 5 (Roberts et al., 2016).

$$E = 0{\cdot}5A\rho g h^2 \tag{5}$$

Where, A = total surface area of basin (m^2), ρ = water density (kg/m^3), g = acceleration of Earth's gravitation and h = tidal range (the difference between high tide & low tide) (m).

We have 2 high tides and 2 low tides every day. At low tide the potential energy is zero. Therefore the total energy potential per day = E × 2.

Now Output Power can be calculated by Eq. 6 (Roy et al., 2015).

$$P = (E * \eta * 2)\,/86400(\,W) \tag{6}$$

The power conversion efficiency of tidal energy projects is often poor, ranging from 20 to 40%, with an average of 33% frequently utilized (Li and Zhu, 2023).

6.1.3. *Cost management and revenue prediction for establishment of a tidal plant*

Bangladesh was chosen as one of the most vulnerable nations at the COP15 meeting because it is a developing nation that is most affected by climate change (Bhuyan, 2010). So, the generation of tidal power project will benefit this nation and will receive the financial backing it needs from various financial institutions (Yadav et al., 2023; Sarker et al., 2009; Johnstone et al., 2013). The Tidal project is mostly broken down into 4 areas.

1. The overall capital cost of the plant, which consists of civil, electrical, and mechanical, constructional work and includes the installation of necessary equipment.
2. Operational and maintenance cost (15%) which entails hiring supervi- sors, engineers, and workers while providing enough food, lodging, and other necessities.
3. Moreover, from the executable research conclusion, several tendering processes will be used.
4. The operation and upkeep of the whole project take into account administrative expenditures like license fee.

The capital and installation costs of tidal turbines vary depending on the manufacturer. Between 2010 and 2020, a significant decrease in

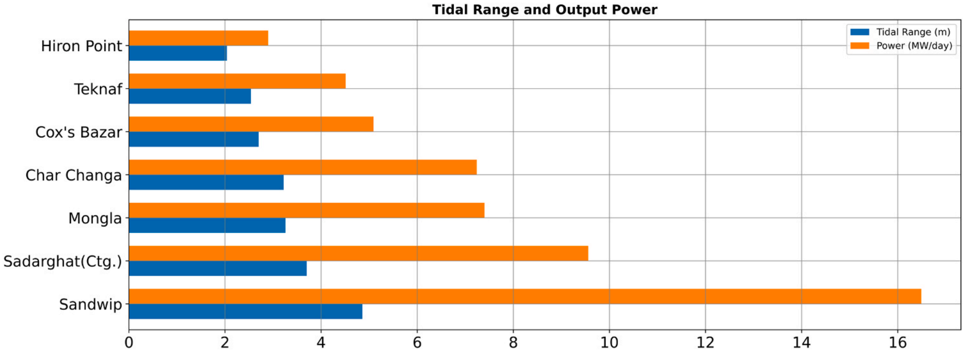

Fig. 9. Tidal power estimation from different coastal area in Bangladesh (Rahman et al., 2013; Alam et al., 2012; Bhuyan, 2010; Ahmad et al., 2018). The unit of tidal range is m and output power is MW/day.

those costs was seen, with capital costs falling from 10,000 $/kW to 5000 $/kW as a result of technological advancements in the manufacture and installation of these turbines (Previsic, 2005; Khan et al., 2012). With a 254 MW installed capacity, the Sihwa tidal power plant in South Korea is the largest and most costly tidal energy facility in the world (Rashid et al., 2017). It cost $298 million in capital to be built in 2011 and.

approximately $117 per kWh (Ahmad et al., 2018). Tidal energy generally costs two to nine.

times more to produce power than wind energy at its highest peak pricing (Bhuyan, 2010). An efficient design with either a vertical or horizontal orientation is anticipated to have high economic potential, according to the power density of tidal turbines (Previsic, 2005).

The following mechanisms influence the revenue of tidal plants: the tariff system, the bank rate, govt. renewable policy, tax breaks or exemptions, financial incentives, and investment grants. We include all costs associated with maintaining and operating a plant once it has been fully installed in our research to facilitate calculation. Accordings to Table 7, Tidal power's unit cost is around $0 six years after installation and it does not release CO_2 in the environment. Tidal power is produced continuously, 365 days a year, with an efficiency that is competitive with other power sources (80%) (Hossain et al., 2014). By the use of tidal power, coastal residents may irrigate their land and improve the economic stability of their lives. Tidal energy plants have substantial setup costs, but their maintenance expenses are quite cheap. When the capital ex- penses have been recovered, it may be assumed that the cost of power is close to $0. Hence, tidal power technology can be profitable (Rezaei et al., 2023; Rashid et al., 2017; Rahman et al., 2013; Bhuyan, 2010; Bae et al., 2010).

6.2. *Prospects*

Bangladesh has a lot of potential for tidal current energy, especially around the coast where the BoB meets the mouths of several big rivers (Shahid, 2010).

Tidal currents are powerful and predictable due to the nation's extensive coastline and intricate network of rivers and estuaries (Ashik-Ur-Rahman and Gain, 2023). By the use of tidal power, coastal residents may irrigate their land, lessen reliance on imported fossil fuels, generate job opportunities in the RE industry, and improve the economic stability of their lives. Tidal energy plants have substantial setup costs, but their maintenance expenses are quite cheap. When the capital expenses have been recovered, it may be assumed that the cost of power is close to $0. Hence, tidal power technology can be profitable (Previsic, 2005; Haque and Khatun, 2017; Rahman et al., 2013; Bhuyan, 2010). Bangladesh has the ability to produce up to 10 GW of tidal current energy from the BoB, according to research by the International Finance Corpora- tion (IFC) (Hossain and Ahmed, 2013). This accounts for a sizeable amount of the nation's overall energy consumption, which is now mostly satisfied by fossil fuel imports. However, careful planning and consideration of the environmental and social implications are necessary for the development of tidal current generation in Bangladesh. Finding appropriate sites for tidal energy projects is crucial, keeping in mind the potential effects on local residents and marine habitats.

Table 7
Revenue Calculation of 254 MW tidal plant (Hossain et al., 2014).

Total Capacity	50 MW/day
Life Time	More than 75 years
Useable Capacity	40 MW (most turbine operate at 80% of their maximum capacity)
Tidal Range (Sandwip)	4.86 m/s
Capital cost	$117 per kWh
Maintenance and Operation Cost (15% approx.)	$ 2.38 million
Minimum Cost of KWh in Bangladesh	$ 0.053
Yearly income (approx.)	$ 5.95million
Yearly revenue (approx.)	$ 3.50 million

6.2.1. *Tidal stream turbines*

In Bangladesh's coastal regions, particularly in regions with high tidal currents, tidal stream turbines may be an appropriate technology shown in Fig. 8(g). Tidal stream turbines are used to capture tidal current energy by rotating with the current while submerged in water. The turbines produce power that is then transmitted through cables to the coast. The effect of the turbines on marine habitats and the potential for sediment to accumulate around the turbine structures, however, may raise some concerns (Hosseinzadeh et al., 2023; Noman et al., 2022).

6.2.2. *Barrage systems*

Given Bangladesh's wide river network and the possible effects on water flow and sediment transport, barrage systems, which entail building dams across estuaries or tidal rivers, may not be as ideal for Bangladesh (Fig. 8(h)). Smaller-scale barrage systems might be possible in some places, though (Ma et al., 2023; Wang et al., 2023).

6.2.3. *Dynamic tidal power*

Due to Bangladesh's limited offshore space and the potential effects on marine ecosystems, dynamic tidal power (Fig. 8(i)), which entails the con- struction of sizable offshore structures to harvest tidal energy, may not be practical (Hosseinzadeh et al., 2023; Noman et al., 2022).

6.2.4. *Tidal lagoons*

For Bangladesh's coastal regions, tidal lagoons (Fig. 8(j)), which entail building impoundment structures in shallow coastal areas, might be a feasible method. However, there might be issues with how the structures affect fish and other marine life, as well as the potential for the lagoon to get clogged with sediment (Rashid et al., 2017). Bangladesh is now looking into a number of tidal energy projects, one of which would involve 100 MW of power in the Meghna River estuary. Tidal stream turbines would be used in the project to produce power, which would then be sent via cables to the shore.

6.3. *Challenges for tidal energy harnessing*

Tidal power is produced continuously, 365 days a year, with an efficiency that is competitive with other power sources (80%). The following environ- mental and cost concerns must be taken into account when tidal power is deployed (Johnstone et al., 2013).

1. Because coastal areas are more prone to experience change, hydroelec- tricity often has significant capital expenditures and may require much more engineering (Alam et al., 2012).
2. Tidal turbines must be significantly stronger and heavier since water is nearly 800 times denser than air, which raises the cost of construction (Previsic, 2005).
3. Regarding fisheries, the construction and cabling may have an impact on fish stocks and their habitats (Ali et al., 2023).
4. Through hydraulic oil leaks, hydraulic tidal energy devices can disrupt the ecosystem of the ocean (Samrat et al., 2013).
5. Due to a lack of site evaluation before the installation of the device, underwater archaeology might be harmed (Li and Zhu, 2023).
6. Tidal energy systems need parts that are extremely robust, dependable, and proven safe due to the increased water density, the harsh corrosive climate of the sea, and worries about oil seeping from components and damaging marine life (Ali et al., 2023).

7. Wind energy

7.1. *Current status*

Bangladesh's energy needs might be significantly met by wind energy, particularly in the coastal areas of the nation where strong and steady winds are frequently prevalent. A study by the International Renewable Energy Agency (IRENA) determined that Bangladesh's coastline region has an es- timated 20 GW of wind energy potential, which is about equal to half of the nation's existing installed power-producing capacity (Masud et al., 2020). Offshore wind turbines can be built in shallow waters close to the coast, while onshore wind turbines can be installed in places with strong wind speeds, including hill- tops and broad plains shown in Fig. 8(k). The growth of wind energy in Bangladesh has a number of obstacles, though, including a lack of techni- cal knowledge and infrastructure, a lack of readily available financing, and complicated legal frameworks. A 50 MW wind farm in Bangladesh's coastal region is one of the biggest wind energy projects currently under develop- ment in the country (Bonar et al., 2015). It is anticipated that the project, which is being developed by a group of businesses led by the US-based GE RE, will produce clean and renewable electricity for the nation. Several smaller wind energy projects are also being constructed by private enterprises in Bangladesh, in addition to the 50 MW wind farm. These initiatives are anticipated to assist the nation achieve its targets for RE and lessen its reliance on fossil fuels (Ohunakin and Akinnawonu, 2012; Islam et al., 2021).

7.1.1. *Potential wind power sites*

In Bangladesh, there are now just three operational wind power plants. By 2026, the government plans to build nine additional wind power facilities around the country, including six along the country's coast (see Table 8) (Azad and Alam, 2012; Ohunakin and Akinnawonu, 2012; Islam et al., 2021). Bangladesh's BoB coastline stretches over 724 kilometers (Shahid, 2010). Additionally, there lies some island in the BoB (Fig. 14) where wind speed is high enough to produce significant power (Islam et al., 2021). In Table 8, ten sites on the coastline of Bangladesh are listed along with their yearly average wind speed and measured power at various heights, including Sandwip, Kutubdia, Cox's Bazar, Parky Saikat in Chittagong, and Kuakata. The annual average wind speed of these ten sites are varied from 1.84 m/s to 6.90 m/s at different elevations (Shaikh et al., 2017). The annual average wind speed of most of the sites is more than.

4.0 m/s (Zaman). the highest amount of wind speed (6.90 m/s) and derived power (78.84 w/m^2) is found in cox's Bazar at 50 m altitude while the minimum is obtained from Mongla which are 1.84 m/s and 1.50 w/m^2. Various national and international organizations, including the PDB, BCAS, LGED, BCSIR, BUET, and UNDP, conducted sophisticated wind mapping at 50 m heights in Bangladesh across diverse time periods and coastal locations (Babu et al., 2022).

Table 8
Average annual wind speed at various altitudes and coastal areas (Azad and Alam, 2012; Ohunakin and Akinnawonu, 2012; Islam et al., 2021; Shaikh et al., 2017; Zaman; Babu et al., 2022).

Coastal Area	Yearly Average Wind Speed (m/s)	Altitude (m)	Power density (W/m2)
Sandwip	3.56	50	11.82
Kutubdia	6.73	50	73.16
Mognamaghat, Cox's Bazar	6.90	50	78.84
Parki Saikat, Chittagong	6.73	50	73.16
Saint Martin	4.84	30	27.21
Kuakata	6.89	50	78.50
Shaporir Deep, Teknaf	4.66	18.3	24.29
Chor Fession, Bhola	4.433	25	20.91
Hatiya	3.74	20	12.55
Mongla	1.84	20	1.50

7.1.2. *Wind power plant capacity and energy generation in Bangladesh*

According to a widely acknowledged rule, that suitable location (Table 9) having an annual average wind speed above 4.0 m/s is feasible for small turbines and 6.0 m/s or higher is feasible for harnessing wind electricity for utility-scale and commercial scale (Zaman; Azad and Alam, 2012; Islam et al., 2021).

7.1.3. *Study of wind energy in some coastal Areas at 50 m height*

The year-round variation in wind speed and extracted power density at five different coastal locations are depicted in Fig. 10, where four sites have wind speeds that are higher than the approved value which is 6 m/s for commercially harnessing electric power (Azad and Alam, 2012). The greatest average (8.40 m/s) is recorded in September at Mognamaghat, Cox's Bazar, where the power is 142.25 KW/m^2 at altitude 50 m. Wind speed is found to be more than the allowed limit at all sites from March to October, with the exception of Sandwip Island locations (Ohunakin and Akinnawonu, 2012). The lowest average wind speed and power density are 2.1 m/s and 2.22 KW in October at Sandwip Island (Ohunakin and Akinnawonu, 2012).

Based on Fig. 10 done at 50 m height onshore, it can be inferred from the above analysis that various coastal areas of Bangladesh, including Mog- namaghat Cox's Bazar, Kuakata, Kutubdia, and Parky Saikat Chittagong, are appropriate for harnessing wind energy when wind speeds exceed 6 m/s. it is expected that the wind average speed value will surely exceed more than 7 m/s at 80–100 m elevation, these height ranges modern wind turbines are available nowadays (Hossain and Ahmed, 2013; Shaikh et al., 2017). Also, it is expected that the wind speed would rise if the performed data were offshore (Shaikh et al., 2017; Babu et al., 2022; Zaman; Azad and Alam, 2012; Ohunakin and Akinnawonu, 2012).

7.1.4. *Potential wind projects*

Bangladesh Power Development Board (BPDB) has several upcoming projects listed in Table 10, as well as a project that is currently in the imple- mentation phase. BPDB has an ongoing plan to set up a wind power project in the Chakaria Upazila region of Cox's Bazar (Fig. 14) with a capacity of 60 MW (Shaikh et al., 2017). This project is expected to reduce 619,000 tonnes of CO_2 emissions during its lifetime. Additionally, Power Division and BPDB have identified four other potential sites in the coastal regions of Bangladesh for harvesting wind energy. Together, these sites have a total power generation capacity of 225 MW and are expected to reduce 2.237 million tonnes of CO_2 emissions (Azad and Alam, 2012; Ohunakin and Akinnawonu, 2012).

Fig. 11 illustrates the structure of BPDB's wind power projects, which aim to increase the supply of energy to the national power grid to combine wind power with other existing sources. In Patenga, BCAS has set up a wind pump with a 40-foot tower and 12-blade rotor that can

Table 9
Wind Power plant capacity and energy generation in Bangladesh (Rahman et al., 2022).

Name	Capacity (MW)	Expected Energy Gen- eration and CO2 Emis- sion reduction during System Life	Latitude, Longitude
FeniWind Power Plant	0.99	20 GWh, 9 kt CO2	23.073005, 91.484633
Kutubdia Power Plant	1.00 * 2 = 2	22 GWh, 10 k tCO2	21.8122, 91.846291

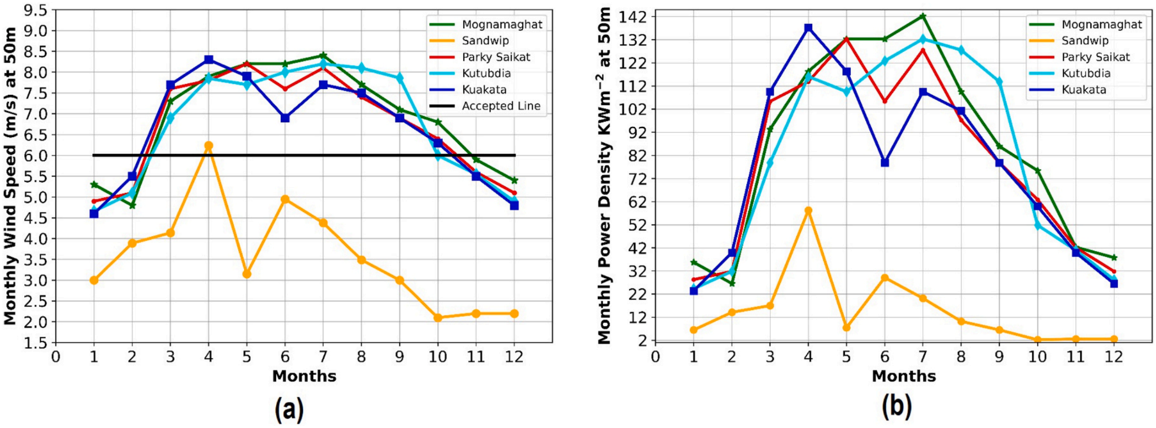

Fig. 10. Monthly (a) average wind speed and (b) power density at different coastal places in Bangladesh (Rashid et al., 2017; Babu et al., 2022; Zaman).

Table 10
Future wind energy projects of BPDP at Coastline of Bangladesh (Rahman et al., 2022).

Site	Capacity	Estimated Energy Production & De- crease CO2 Emission in System Life- time
Chakaria Upazila, Cox's Bazar	60 MW	1 TWh, 619 k tCO2
Matarbari, Maheshkhali, Cox's Bazar	100 MW	2 TWh 1 M tCO2
Mongla Upazila, Bagerhat	55 MW	1 TWh 567 k tCO2
Cox's Bazar Sadar Upazila, Cox's Bazar	50 MW	1 TWh 516 k tCO2
Kalapara Upazila, Patuakhali	10 MW	218 GWh 103 k tCO2

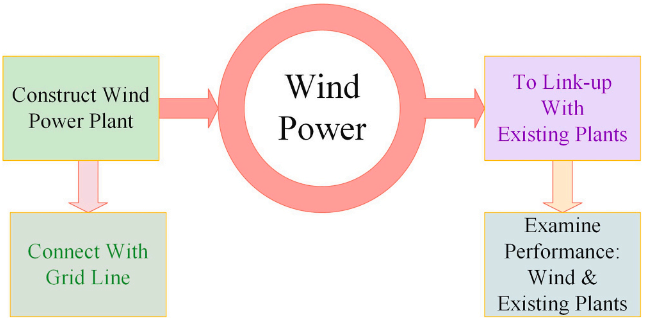

Fig. 11. Structure of wind power plants of BPDB.

generate up to 8,000 litres of water per day between November and January (Ohunakin and Akinnawonu, 2012). Local Government Engineering Department (LGED) has also installed 27-foot wind pumps in Cox's Bazar (Babu et al., 2022). The government sector is researching to explore the use of wind energy in coastal areas where energy distribution is lacking. Furthermore, Bangladesh Banking Company (BBC) has installed four hybrid wind power stations, which combine wind turbines with diesel generators (Islam et al., 2021).

7.1.5. Wind energy estimation procedure

Wind energy may be considered as the kinetic energy of the moving air mass. The extracted power (P) depends on wind velocity (V) and the density of air (ρ) and the Eq. (7) expresses the power (Stromp et al., 2023).

$$P = 1/2\rho V^3 A \tag{7}$$

Where A is the area covered by the rotating blades of the wind turbine (m^2), V is the velocity of wind (m/s), ρ is air density (kg/m^3).

Under ambient temperature (25°C) and pressure (760 mm of Hg), the density of air is considered as 1.2 kg/m^3. According to the Betz limit the ideal efficiency of the wind turbine is only 59% of the wind power can be converted into useful power. In practice, the real efficiency of wind turbines is less and it is normally referred to as the coefficient of performance, C_p. Assuming the coefficient of performance, C_p for two or three-blade propeller type wind turbine as 0.4, the wind power per unit area is $P/A = 0.24\ V^3$ in watt /m^2, without considering generator loss and transmission loss. The highest monthly average extractable wind energy in Watt-hr /m^2 at Mogna- maghat Cox's Bazar, Parkysaikat Chittagong, Sandwip, Kuakata and Ku- tubdia are 142.25, 132.33, 58.31, 137.29 and 132.33 respectively at 50 m. altitudes (Shaikh et al., 2017; Babu et al., 2022; Zaman) (see Fig. 14).

Now the modern commercially available wind turbines are rated between 500KV and 8.0 MW having rotor diameters from 30 m to more than 100 m and hub height from 50 m to more than 100 m (Ohunakin and Akinnawonu, 2012). Table 11 indicates modern wind turbine specifications.

The whole coastline of Bangladesh spans 710 kilometers (710000 m) (Ohunakin and Akinnawonu, 2012). We have set aside 50% of the coastline zone (287000 m) for wind turbines and are contemplating using an additional 30% of the land for operational flexibility, office space, responsible personnel's homes, and other amenities. According to observations, the average wind speed rises with height. The consequence is an increase in extractable power (Azad and Alam, 2012). At 25 m above sea level at Kuakata, the average wind speed is around 4.463 m/s (Bhuyan, 2010). The average wind speed increases to 6.89 m/s when height is increased to 50 m (Hossain and Ahmed, 2013). Undoubtedly, there will be greater wind power generation at higher altitudes. In order to produce the complete power of 1455.85 MW from

Table 11
Wind Turbine specifications (Azad and Alam, 2012; Islam et al., 2021; Ohunakin and Akinnawonu, 2012).

Manufacturer & Model	Height (m)	Capacity (MW)	Swept Area (m^2)
Enercon, E-126	135	7.58	12668
Simens Wind Power, SWT-6.0-154	Site-specific	6	18600
Gamesa, G 128	80-94	5	12868
Siemens Wind Power, SWT-3.0-113	79.5-142.5	3	10000
Goldwind, GW 100	100	2.5	7823
Ming Yang, MY 1.5 s	65.70-75.50	1.5	5320

wind energy at H = 50 m, swept area = 12668 m^2, and V = 6.89 m/sec in 4 rows of the near-shore wind farm, a total of 576 turbines would be needed (Haldar, 2023). This is 3.36% of the 40,000 Megawatt total anticipated in 2030 (Haldar, 2023).

7.1.6. Cost and revenue estimation of a wind power plant

Capital expenses for wind energy have been continually falling. Onshore wind farms typically cost approximately $1000 kW^{-1} of installed rated ca- pacity, and offshore wind farms typically cost around $1600 kW^{-1}. Due to changes in wind speed, geographic location, and institutional frameworks in various nations, the accompanying power costs change (Haldar, 2023). The follow- ing assumptions were employed to analyze the costs per MWh of electricity generated at the site by the turbines-

1. Investment and capital costs
2. Cost of operation and maintenance
3. The span
4. Bangladesh’s current interest rate and inflation rate
5. Expenses for power utilized in standby mode and royalties paid to landowners

A lack of knowledge of both the technology and economics involved might make studies of the cost of wind energy and other RE sources incorrect. Due to shipping expenses, varying tower heights, rotor diameters, generator capacity, and grid connection costs, wind turbine prices may vary. The cost of a wind turbine on a per MW basis is 1.3 million USD at the time of 2021 (Salehin et al., 2016).

According to the estimate above, the price of a wind farm with 16.50 MW of power would be around $21.65 million (Azad and Alam, 2012). Further expenditures will be expended, such as those for maintenance, the construction of a substation, an 11KV transmission line, and some distribution lines (Salehin et al., 2016). According to studies on the operating costs of wind turbines, operation and maintenance cost an additional $ 42,000–$ 48000 per MW annually for the first 10 years of installation (Wind Turbine Cost, 2022). However, the majority of the expense is required for turbine installation. After the wind turbines are installed, maintenance is quite inexpensive (Haque and Khatun, 2017).

It was formerly thought that using wind energy to reduce carbon emis- sions was unprofitable. These technologies’ costs are now reducing quickly, increasing the potential for RE worldwide (Babu et al., 2022). The cost of installing a wind turbine varies from nation to country owing to a variety of factors, including the location of an appropriate site, energy policies, loan rates, tariff rates, lo- cal infrastructure, and operating and maintenance expenses (Babu et al., 2022). The amount of energy produced relies on the wind’s direction, and because the wind frequently changes directions, the efficiency of the turbine is considerably re- duced (Ohunakin and Akinnawonu, 2012). In this scenario, we deduct maintenance and operation costs from revenue in order to compute revenue and other costs once turbine installa- tion is taken into account as maintenance and operation cost. According to revenue study (see Table 12) it is evident that, wind energy will be cost-free after roughly 7 years, with only operating and maintenance expenses.

Table 12
Revenue estimation of a 16.5 MW wind plants (Ohunakin and Akinnawonu, 2012).

Total Capacity	16.5 MW
Life Time	20-25 years
Useable Capacity	8.25 MW (most turbine operate at 35-65% of their maximum ca- pacity)
Velocity of Wind	6.89 m/s
Total Installation Cost	$ 21.45 million
Maintenance and Operation Cost (approx.)	42000 $– 48000 $ per MW
Minimum Cost of KWh in Bangladesh	$ 0.053
Yearly income (approx.)	$ 3.83 million
Yearly revenue (approx.)	$ 3.038 million

7.2. Challenges for wind energy harnessing

The wind is cost-free, clean, native, and unlimited; it doesn’t need fuel, so there are no direct environmental hazards or contamination from the explo- ration, extraction, transport, shipment, handling, or movement of fossil fuels. However, wind power harnessing has some challenges, mentioned below:

- Natural catastrophes like cyclones, tornadoes, and other similar events might pose the biggest challenge to building a modern wind turbine (Hosseinzadeh et al., 2023).
- The unpredictability of wind speed affects the reliability and consistency of energy production (Wang et al., 2023).
- The initial capital investment cost makes it challenging for some com- munities or companies to finance the development and implementation of wind energy projects (Samrat et al., 2013).
- Wind turbine blades made of fiberglass are vulnerable to lightning, wind gusts, fatigue, and moisture absorption. Even minor damage can cause the spinning mass to unbalance, which may harm the wind turbine system and lead to tower collapse (US wind OampM costs estimated, 2023).
- Accurate information on wind speed at higher altitudes is required.
- The fatality of birds and bats due to direct collisions with a turbine, habitat disruption, and relocation. Also, noise caused by wind turbines is the most serious ecological consequence (Liu et al., 2010).
- Radar, cell phones, and microwave transmission can all be affected by the electromagnetic interference emitted by wind turbines (Wang et al., 2015).

8. Ocean thermal energy conversion (OTEC)

OTEC is a technique that makes use of the temperature differential be- tween warm surface water and cold deep water (Saifullah et al., 2016). The temperature dif- ference between the surface and the subsurface needs to be more than 20 °C for it to be deployed successfully. The efficiency of the Rankine cycle in this system was only around 3–5%, with the surface temperature being approximately 25 °C and the deep cold water being 5 °C (Adeyeye et al., 2020). Due to ammo- nia’s low boiling point, which enables it to change into liquid and gas phases with only a slight temperature difference, it was chosen as the working fluid.

OTEC has the highest theoretical potential of all ocean energy sources and provides a continuous power source due to its constant temperature gradient. A commercial-scale OTEC power plant must have a minimum temperature differential of 20 °C, with an annual average difference between 20 °C and 24 °C (Vega, 2002). In addition, the system needs around 30% of the gross energy produced to keep running, particularly the pumping system (Zulqarnain et al., 2023). Little islands that require both electricity and fresh water are where OTECs are most in de- mand, but the cost per unit is still the biggest barrier to making OTECs commercially viable (Shakil and Hoque, 2013; Saifullah et al., 2016).

8.1. Prospects of OTEC

Bangladesh has a substantial OTEC potential due to the BoB’s temperature differential of up to 20 degrees Celsius encircling the country’s 19 coastal districts (Masud et al., 2020). Through the use of OTEC technology, this temper- ature differential may be used to produce clean, renewable electricity (see Fig. 8(l)). There are many advantages to introducing OTEC technology to Bangladesh’s energy industry. It will primarily offer a clean and renewable source of electricity that can aid in lessening the nation's reliance on fossil fuels and addressing the nation's problems with climate change, energy secu- rity, and sustainable development. Additionally, OTEC technology has the potential to boost economic development across the nation, particularly in the coastal regions where it can be used (Saifullah et al., 2016; Shakil and Hoque, 2013). We fervently urge the admin- istration to take this idea under consideration and implement the required measures to bring OTEC technology to the nation. We have discussed a number of prospective locations in Bangladesh for the deployment of OTEC after completing a preliminary analysis.

- The BoB, especially the region near the Sundarbans, is where there is a substantial temperature differential between the surface and deep waters (Shakil and Hoque, 2013).
- The deployment of OTEC equipment might be made easier along the Chittagong coast because of a deep-water trench that is near the coast- line (Saifullah et al., 2016).
- The Cox's Bazar coast, with its extensive coastline, tall waves, and powerful ocean currents, might offer the best environment for OTEC systems (Shakil and Hoque, 2013).
- The BoB's Saint Martin's Island coast, where there is a big temperature differential between the surface and deep waters (Saifullah et al., 2016).

Warm surface and cold deep water, strong ocean currents, and grid prox- imity are advantages of the proposed OTEC locations. However, before installing OTEC systems, site-specific analysis of temperature variations, currents, and other factors is required for practicality. Once viability has been confirmed, OTEC technology deployment in Bangladesh needs to be governed by a legislative framework in order to promote private investment while reducing the adverse environmental impact.

8.1.1. OTEC working and efficiency calculation

The OTEC cycle's components and procedure are depicted in Fig. 12. Fundamentally, the heat exchanger, working fluid, turbine generator, and pumps make up an OTEC system (Dezhdar et al., 2023). The working fluid (ammonia), which is heated by the warm seawater that flows through the evaporator, subse- quently transforms into gas phases (Rehman et al., 2023). The vaporized pumped ammonia drives the generator's turbine, which generates energy (Majumdar et al., 2023). After that, uti- lizing cold water pumped from the deep sea, low-pressure working fluid will be condensed into liquid form. The liquid ammonia will be fed back to the evaporator to keep the cycle going. Continuously, this cycle is repeated (Adeyeye et al., 2020; Zulqarnain et al., 2023; Stutzmann and Csoklich, 2023; Dezhdar et al., 2023).

We can use Eq. 8 (Carnot's equation) to get an idea about the efficiency of OTEC:

$$W = \frac{T - To}{T}.Q \tag{8}$$

Here, W = Work function (energy), T = Surface water temperature (K), T_o = The deep water temperature (K), Q = Thermal value for practical conversion purposes, Q should be in the order of 0.5, thus the efficiency is little over 3%. OTEC may not be as competitive as other RE sources despite what could appear like its poor efficiency (Vega, 2002). For instance, it just requires a hydroelectric plant, and OTEC has enough resources available; its capacity is 300 times more than the total power usage of humanity at now (Rehman et al., 2023; Majumdar et al., 2023).

The fundamental benefit of an OTEC system is that it not only generates energy but also produces fresh water as a byproduct, making it a feasible op- tion for usage on islands with a limited supply of fresh water (Adeyeye et al., 2020). OTEC is significantly more favorable than other RE systems since it is a base load source that can be constantly used day and night (Stutzmann and Csoklich, 2023). As the water orig- inates from a deeper part of the ocean, it has a distinct salinity level and includes nutrients (Dezhdar et al., 2023). The OTEC system includes extracting highly min- eralized water from the depths of the ocean. When poured over the ocean's surface, this mineral-rich water aids in fostering the development of photo- synthetic phytoplankton (Rehman et al., 2023) restricted to a single, sizable operating portion that mostly consists of a generator. As the output is directly linked to the main power grid, distribution is simple (Majumdar et al., 2023; Vega, 2002; Stutzmann and Csoklich, 2023; Dezhdar et al., 2023; Rehman et al., 2023).

8.1.2. Potential OTEC sites

The optimum areas for OTEC are those where it is possible to see a considerable difference in ocean water temperature (Adeyeye et al., 2020). Since the difference between the higher and lower temperatures involved determines the system's efficiency. Less than 18 degrees Celsius to more than 24 degrees Celsius may be found as the temperature difference between the ocean surface and the water at a depth of 1000 m (Dezhdar et al., 2023). In theory, OTEC can be located practically anywhere in the tropical ocean, typically between the Tropics of Cancer and Capricorn (Zulqarnain et al., 2023). Here, there is typically a temperature differential of more than 22 degrees Celsius between the surface and 1000 m below the surface (Rehman et al., 2023). The difference in temperature in the BoB (Fig. 14) between the surface and subsurface (1000 m deep) seawater is between 20 and 22 degrees Celsius

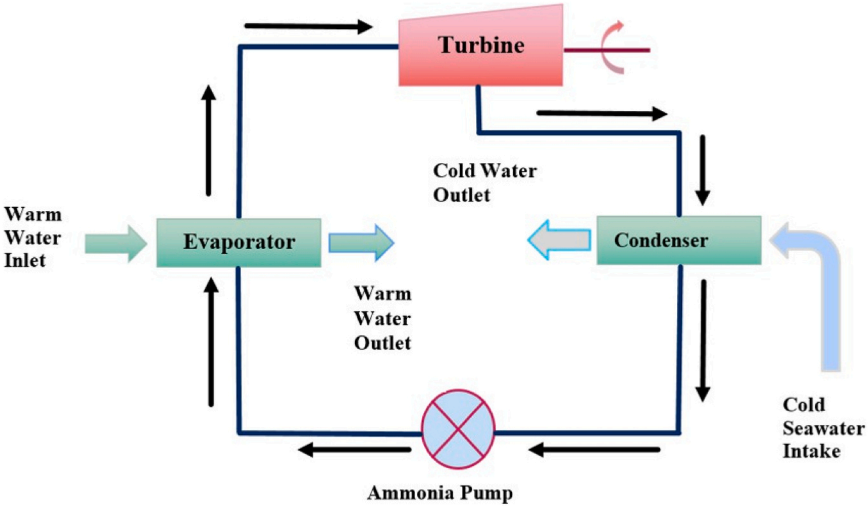

Fig. 12. The fundamental process of OTEC cycle (Dezhdar et al., 2023; Majumdar et al., 2023).

(Majumdar et al., 2023). OTEC project is therefore likely to be possible in this area (Adeyeye et al., 2020).

The difference in temperature in the BoB between the surface and sub- surface (1000 m deep) seawater is between 20 and 22 degrees Celsius (Adeyeye et al., 2020). OTEC project is therefore likely to be possible in this area. The following locations are included in Table 13 as potential OTEC plants located near the BoB (Fig. 14): Cox's Bazar Beach, Saint Martin Island, Patenga Beach, Parki Beach, Nijhum Island, and Kuakata (Shakil and Hoque, 2013; Saifullah et al., 2016; Rehman et al., 2023).

8.1.3. Power Generation Economics of OTEC Plants

The following two features of OTEC schemes must be used to evaluate the OTEC economy, which includes all three types of OTEC systems. They are:

- Evaluated using a widely known economic metric, such as the cost per kWh of energy production.
- Range of the byproducts from OTEC schemes that are only available with OTEC systems and do not produce power.

In this article, we solely cover cost management for the production of electricity. It is significant to highlight that, similar to all other ocean energy projects, the effective implementation of an OTEC plant requires an enor- mous initial capital investment. However, it takes a long time for the plant to begin turning a profit. Thus, until it starts to turn a profit, it is necessary to bear in mind the declining value of money invested. The following rela- tionship (Eq. 9) may be used to determine the cost of electricity using the Net Present Value (NPV) concept (Zhang et al., 2023)(just the generation cost is taken into account, eliminating the cost of insurance, local taxes, profit margin, etc.):

$$\text{Thecostofelectricityproduction}/\text{kWh} = \left(Cc + \sum_{0} 0.01x * \frac{Cc}{(1+r)t}\right) / \left(\sum_{0} \frac{E}{(1+r)t}\right) \#per\text{KWh} \tag{9}$$

where C_c stands for capital cost, E for yearly energy output, t stands for life, r for assumed discount rate, and operational cost is equal to x% of C_c.

for capital cost. It should be emphasized that NPV estimates of cost per kWh would fluctuate as t and r changed. Using Eq. 9, the economic indicators based on the aforementioned fundamental data have a 30 year life. So the total Capital cost C_c = 128,776,000 = $167,408,800 (The GBP to.

Table 13
OTEC sites in Bangladesh with energy scenario (Shakil and Hoque, 2013; Saifullah et al., 2016; Rehman et al., 2023).

Site	Area Cover (Sq.Km)	Population	Energy Demand (MW)	Famous For
Cox's Bazar Beach	2491.86	51,918	45	Tourist destination
St. Martin Island	8	3700	3.0	Tourist destination
Patenga &Parki beach	168	2579,107	2000-2500	sea-port,major national industrial activity
Nijhum Island	56	200,000	10	uprising tourist destination
Kuakata	3205	1557137	65	Tourist spot, jute mills, ice mills and fish farms

USD conversion rate was $1.30 = 1, The ratio is more like 1.30 as of the time of writing, although it fluctuates a lot.). Vega (1992) estimated that. the operating and maintenance cost (C_o) accounted for 1.5% of the capital cost annually. Annual OM cost (Com)= 2511,132 and Annual Production of electricity (E) = 455,520,000 kWh (Banerjee et al., 2015; Zhang et al., 2023). OTEC power will be economically viable if its unit cost is compared to that of other power sources like wave, hydro, and diesel. To evaluate the various technologies fairly, it is crucial to take into account all startup expenses as well as continuing maintenance and support costs. Table 14 compares the price of building plants of around 1 MW in size using various technologies (Shakil and Hoque, 2013; Adeyeye et al., 2020; Vega, 2002; Banerjee et al., 2015).

Table 15 makes it evident that, if the cost of insurance and local taxes are ignored, it will take 8 years to reach a profit margin. Efficiency drastically drops when the offshore distance is more than 200 m (Shakil and Hoque, 2013) and efficiency fluction is no considered. This highlights the need to keep the travel time between the water wells and the power plant to a minimum. According to the economic study, OTEC plants need to maintain a plant factor of at least 0.9 and have a capacity of at least 25 MW in order to generate more electricity than other non-renewable energy sources (Shakil et al., 2014).

8.1.4. Challenges for OTEC in energy harnessing

OTEC technology provides a source of clean energy. Contrarily, compared to fossil fuel plants, open-cycle OTECs produce a very little quantity of carbon dioxide into the ocean. Here are some challenges of OTEC that can hinder to capitalization of the endless supply of energy (Majumdar et al., 2023).

- Enormous infrastructure expenses, particularly for cables that would connect the sea to the mainland (Dezhdar et al., 2023).
- Heat exchanger materials that can withstand corrosive sea conditions are very limited, and their robustness is yet unknown (Rehman et al., 2023).
- Regarding the OTEC system, the periodic release and redistribution of a significant volume of water will result in certain natural changes in the local geological stratification, ocean salinity, oxygen, and nutrient levels. Several creatures' native habitats may be impacted (Adeyeye et al., 2020).
- The possibility of lubricants and anti-biofouling substances entering the water and noise from the plant could obstruct animal communication (Shakil and Hoque, 2013; Wind Projects).
- OTEC systems require specialized equipment and skilled employees, which makes them challenging to create, operate, and maintain (Adeyeye et al., 2020).

9. Future research directions

Fig. 13 represents the future research directions for the development of MRE contributing Blue Economy.

To integrate MRE sources, a supportive regulatory framework is needed, to ensure national grid security. Incentives and a RE fund, supported by gov- ernment grants, govt. private collaboration projects,

Table 14
Energy cost per KW of various power production techniques (Shakil and Hoque, 2013; Adeyeye et al., 2020; Vega, 2002; Banerjee et al., 2015).

Plant	Plant Capacity (MW)	AnnualCapacity (GW)	Cost (US $/kW)
Wave	1.5	9	0.062-0.072
Hydro	1.2	5	0.113
Diesel	0.9	5	0.126
OTEC	1.256	8.8	0.149

Table 15
Approximate revenue prediction for 100 mw OTEC plant for power generation (Shakil and Hoque, 2013).

Total Capacity	16.5 MW
Life Time	20-25 years
Useable Capacity	8.25 MW (most turbine operate at 35-65% of their maximum ca- pacity)
Velocity of Wind	6.89 m/s
Total Installation Cost	$ 21.45 million
Maintenance and Operation Cost (approx.)	42000 – 48000 per MW
Minimum Cost of KWh in Bangladesh	$ 0.053
Yearly income (approx.)	$ 3.83 million
Yearly revenue (approx.)	$ 3.038 million

green credit guarantee programs, de-risking on the financial programs, and foreign aid, can en- courage MRE investment. Strict environmental regulations, monitoring, and cutting-edge technology like GIS, and remote sensing help reduce pollution and identify ideal coastal renewable sites. Carbon credits improve finances, while public awareness and collaboration alleviate conflicts and emphasize RE benefits.

9.1. Advanced materials

In order to increase the effectiveness, endurance, and lower the cost of MRE technologies, researchers are looking into new designs, controls, and materials for WECs, wind turbines, OTEC systems, and tidal turbines that can endure the harsh ocean wind environment and transfer more of the energy in ocean waves into electricity. Advanced composites, polymers, and ceramics are a few materials that show promise for use in WECs. In terms of wind turbines, advanced composites, plastics, and lightweight metals like titanium are among the materials that can boost toughness and decrease weight, enabling larger areas and making them more energy-effective. To improve the efficiency and lessen the environmental impact of tidal turbines sophisticated alloys and composite materials that can survive the corrosive effects of seawater are one of the new materials being investigated for tidal turbines. Finally, in the area of OTEC energy, researchers have started to utilize new intriguing materials such as advanced polymers and ceramics that can endure the high pressures and temperatures seen in OTEC.

9.2. New MRE techniques

In terms of efficiency, affordability, and sustainability, new-wave energy conversion concepts and designs have the potential to make significant strides. For instance, oscillating water column devices, point absorbers, and overtop- ping devices are a few new wave energy concepts. In the field of wave and tidal energy, researchers try to implement new techniques that can boost performance, lower the cost, reduce the environmental negative impact as low as possible, and compete with fossil fuels. It's also crucial to have rec- ognized standards for wave and tidal energy systems in order to guarantee safety and dependability. A variety of topics, such as device design, pro- duction, installation, operation, and decommissioning, should be covered by these standards.

9.3. Environmental impacts

Beyond just reducing greenhouse gas emissions, the projects utilizing MRE have the potential to cause serious environmental issues, particularly when it comes to the possible effects on the nearby fishing industry, wildlife, tourism industry, cultural resources, and marine ecosystems. As a result, it is essential to carry out exhaustive environmental impact assessments (EIAs) and interact with the local community at every stage of the project's con- ception, development, and operation. EIAs, for instance, can evaluate how wind, wave, and tidal energy devices will affect fish populations, seabird pop- ulations, and other marine species, in addition to the physical and chemical properties of the water column. Additional study is required to comprehend the potential environmental effects of OTEC systems. OTEC systems use salt water to extract heat, which may have an impact on the water's quality and marine ecosystems. Therefore, it is crucial to carry out comprehensive EIAs and keep an eye on how OTEC systems affect the environment. These effects can be evaluated and avoided by stakeholder involvement and com- munity outreach, ensuring that MRE projects are advantageous to nearby communities and the environment.

9.4. GIS and remote sensing

Advanced technologies like remote sensing and Geographic Information Systems (GIS) aid in identifying suitable locations for producing coastal RE sources such as wind, wave, tidal, or OTEC by:

- Providing detailed information about the physical characteristics of the coastal environment, such as water depth, wave height, and wind speed, which are critical factors in determining the feasibility of MRE projects.

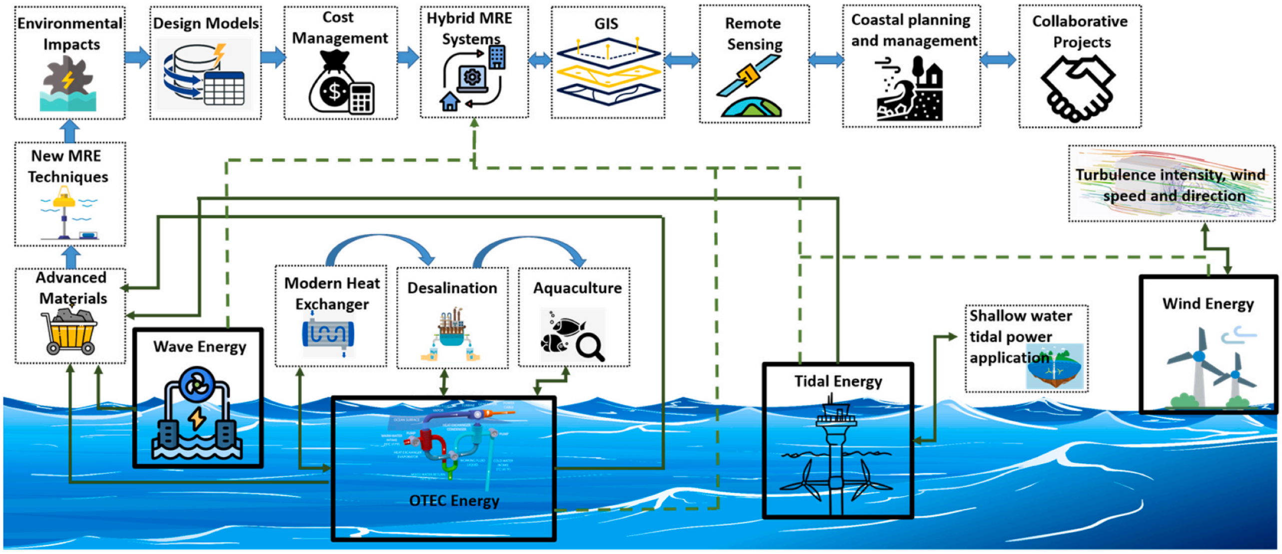

Fig. 13. Future Research Directions.

- Allowing for the analysis of large amounts of data from multiple sources, including satellite imagery, oceanographic data, and meteorological data, to identify areas with the highest potential for MRE develop- ment.
- Making precise coastal maps and models helps in visualizing the distri- bution of MRE resources and determining the best locations for various MRE technologies.
- Integrating various types of data (environmental, socioeconomic, and cultural) supports informed decision-making for MRE development.

9.5. Coastal planning and management

The development of a regulatory framework is necessary for Bangladesh to successfully implement MRE technology. To do this, policies and rules must be developed that encourage the growth of wave, wind, OTEC, and tidal energy and guarantee that these technologies are used in an environ- mentally friendly way. Setting requirements for environmental impact evalu- ations, creating protected regions where RE development is prohibited, and ensuring that RE projects are incorporated into more comprehensive coastal management plans are some examples of how to accomplish this. Regula- tory frameworks to assist the integration of MRE into the national power system could be included, as well as financial incentives for developers like tax credits or subsidies.

9.6. Hybrid MRE systems

The reliability and stability of RE output can be improved by integrating MRE sources with other RE sources such as solar, biomass, and hydro to build hybrid systems. Also, investigating OTEC's potential for use in con- junction with other RE sources can contribute to the development of more varied and dependable energy systems. For instance, OTEC can be utilized to produce power from the differential in temperature between deep and sur- face seawater, while wind or solar energy can be used as a backup energy source when OTEC is not producing enough energy.

9.7. Design models

Making wise decisions about the economics and feasibility of MRE energy projects requires the development of more precise models for cost estimation. We can make better choices about project funding, risk management, and timeframes by improving cost estimations. Furthermore, the efficiency and effectiveness of the MRE system can be increased by researching alternative turbine and equipment models that might be more appropriate for the lo- cation. A variety of elements, including energy output, cost-effectiveness,

environmental effects, and technical viability, should be taken into account in this analysis. Comparing the proposed system with other RE systems is important in order to establish the most practical and cost-effective way to meet the energy demand in remote coastal islands such as Saint Martin's and Kuakata. Energy storage devices can also increase the planned system's stability and dependability. By storing extra energy produced during times of high production for use later during times of low production or high de- mand, energy storage devices increase the overall efficiency and stability of the energy system.

9.8. Collaborative projects

The MRE industry or Govt. of Bangladesh may gain a lot from cooperation with international organizations like World Bank and IRENA and other developed nations to get technological information, access to funding opportunities as well as partnerships for joint research, technical assistance for capacity building, minimizing hazards, selecting suitable sites and pol- icy and project development. Working closely with various stakeholders can also aid in resolving any potential conflicts of interest between the produc- tion of RE and other coastal activities like fishing and tourism. In order to reduce credit risks for RE projects and to address concerns about green investments, the government may also explore creating regulatory de-risking, green credit guarantee systems, and fund subsidies to encourage research and infrastructure development. Adopting the Clean Development Mechanism, which offers a framework for calculating and verifying reductions in green- house gas emissions and encouraging sustainable development, can ensure proper management of RE projects.

9.9. Cost management

Due to the large initial investment required and the absence of a finan- cial framework for RE investors, it is challenging to attract investors and secure financing for MRE ventures in emerging economies like Bangladesh. It could be required to provide financial incentives like grants to make these projects financially viable. Economic models must take into account all ex- penses and prospective revenue sources, including the price of power, equip- ment/installation costs, maintenance/operations costs, and revenue from in- centives like carbon credits, in order to determine the profitability of MRE projects. Comprehensive financial feasibility analysis can assist in identi- fying the most affordable solutions for generating sufficient energy to meet Bangladesh's energy needs.

9.10. Modern heat exchanger

Improved energy extraction from OTEC can be achieved by doing research into the development of more effective heat exchangers. Investigating alternate heat transfer fluids with higher thermal conductivities and the use of cutting-edge materials, such as nanomaterials, to increase the heat transfer efficiency of the heat exchangers is crucial. Improvements in energy extrac- tion can also be made by optimizing the layout and arrangement of the heat exchangers. Therefore, additional study and development in this field can greatly boost OTEC systems' effectiveness and make them a more attractive option for the production of RE.

9.11. Desalination and aquaculture

OTEC systems may be employed in aquaculture and desalination. The economic viability of OTEC systems can be improved overall by integrat- ing OTEC technology with various applications because these systems can generate not just RE but also valuable byproducts like freshwater and fish. To optimize OTEC systems for these applications and to address potential technical and financial difficulties, additional study and development are nec- essary.

9.12. Turbulence intensity, wind speed, and direction

To correctly calculate the wind energy potential, a thorough review of the wind resource assessment such as wind speed, wind direction, altitude, and distance at the chosen location. The height of the wind turbine towers can be optimized using this assessment information, and the best wind turbine mod- els can be chosen for the location. The possible effects of neighboring wind turbines on the neighborhood, including any noise and visual effects, must also be taken into account. These issues can be addressed and the effective execution of wind energy projects ensured by carrying out an environmental impact assessment and interacting with regional people and stakeholders.

9.13. Shallow water tidal power applications

Utilizing energy from tidal currents in locations with relatively shallow water depths—typically less than 30 m—is referred to as shallow water tidal power. Compared to deep water systems, this kind of tidal energy conversion provides a number of benefits, including lower construction and maintenance costs, fewer negative environmental effects, and greater accessibility to the energy source.

10. Legal, policy framework and master plan for marine renewable energy in Bangladesh

Bangladesh's increasing GDP and population have increased power consumption to 34,000 MW by 2030 (Adiputra et al., 2020). To close the capacity gap, the government will invest USD 70 billion over the next 15 years in sustainable and green energy initiatives, focusing on policy, strict regulation, and considerable investments to alleviate poverty and stimulate socioeconomic development (Masud et al., 2020; &x99F;&x9C7;&x995, 2023). In accordance with Article 16 of the Constitution, Bangladesh aims to address urban-rural discrepancies in living conditions through electrification and development. In pursuit of this objective, the government has established a variety of policies, legal frameworks, and master plans over the course of decades shown in Table 16.

In order to attain the power systems master plan-2016, the government encourages collaboration between the corporate and public sectors. As a result, many government institutions and Public-private organizations, including the Ministry, SREDA, BERC, BPDB, REB, the Bangladesh Council of Scientific and Industrial Research, Local NGO, and the Local Government Engineering Department, began carrying out a variety of RE-related initiatives (Masud et al., 2020; Karim et al., 2019). Various key institutions oversee energy policy and regulation in Bangladesh, as illustrated in Fig. 15, delineating their responsibilities and interconnections.

11. Marine Renewable Energy (MRE) for achieving sustainable development goals (SDGs) in Bangladesh

Marine Renewable Energy (MRE) can significantly advance Bangladesh's SDGs by providing clean energy (SDG 7), utilizing innovative technologies (SDG 9), reducing greenhouse gas emissions (SDG 13), and ensuring sustainable practices to protect marine ecosystems (SDG 14). MRE projects create jobs (SDG 8), promote affordable clean energy access (SDG 1), and require strategic planning to minimize water quality impact (SDG 6). They also support education in renewable energy (SDG 4) and contribute to resilient urban infrastructure (SDG 11). Successful MRE implementation hinges on collaboration among government, private sector, and international partners (SDG 17), offering a comprehensive approach to environmental sustainability, climate action, economic growth, and poverty reduction in Bangladesh.

12. Limitations

This review work "Current Trends, prospects and Challenges of MRE Harnessing from the Coastal Area of Bangladesh" faced several difficulties in conducting this work are given below:

- Obtaining adequate pricing data for the turbine and essential equipment for MRE is the main issue. Due to the rarity of pricing data from sources, so exact estimation of the cost and revenue is difficult.
- Bangladesh's RE policies and regulations are unclear and change frequently, making it challenging to stay up-to-date and include the latest information.
- For wind energy, the data of the wind velocity is not uniform for the height of the turbine, different altitude is considered for different locations.
- Yet Bangladesh has no OTEC, Tidal, and Wave energy plant, so environmental impact information is based on foreign research.
- Because of the variation of MRE plant locations, equipment manufacturers, and operation and maintenance techniques, it might be challenging to decide on precise MRE plant models for the coastal area that is the best fit for Bangladesh.
- Most of the wave, OTEC, and Tidal turbines and essential devices are in the research stage, so predicting the suitability for specific plant sites is difficult.

Table 16

Regulatory framework, policy, and master plan for renewable energy development issued and adopted by the various Governmental Organizations of Bangladesh (Masud et al., 2020; &x99F;&x9C7;&x995, 2023; Karim et al., 2019; Abdulrazak et al., 2021; Adiputra et al., 2020).

Name of policy/ Framework/ Regulations/ Master Plan	Targets
Bangladesh Environment Conservation Act (1995, Amended 2010)	Focusing on clean power generation, particularly RE
National Energy Policy (NEP)– 1996	Establishment of Renewable Energy Development Agency (REDA) to accelerate infrastructure development.
Private Sector Power Generation Policy-1996	Supports private power enterprises, especially RE producers.
Energy Regulatory Commission Act-2003	All operators in energy generation, transmission, distribution, marketing, supply, or storage must be licensed by the BERC, which also determines electricity tariffs and Producing RE is 5 MW or more
RE Policy of Bangladesh, 2008	Mandates 10% of electricity to come from renewables by 2020
Policy Guidelines for Commercial IPP – 2008 (Amended 2010)	Promoting private sector participation, competition, efficient use of natural gas, and the development and revitalization of power plants through PPPs
Bangladesh Climate Change Strategy & Action Plan (BCCSAP)- 2009	Mitigation & low carbon development
Quick Enhancement of Electricity and Energy Supply (Special Provisions) Act- 2010	Allows for individual negotiation of tariffs for Renewable Energy Technologies (RETs)
Sustainable and Renewable Energy Development Authority Act- 2012	Establishment of SREDA to regulate all activities and projects related to renewable and sustainable energy resources
Energy Efficiency and Conservation Rules - 2015	RE generation target of 15% of Bangladesh's total consumable energy by 2021 and 20% by 2030.
Power Systems Master Plan-2016	A comprehensive plan addressing the development of the power industry until 2041, with the goal of maximizing green energy (RE at least 10%) consumption.
Net Metering Guidelines, 2018	Up to 3 MW may be exported to the grid.
International Cooperation	Member of International Renewable Energy Agency (IRENA), Founding Member of International Solar Alliance (ISA), Joint Crediting Mechanism (JCM) with Japan in 2013, and adoption of UN regulations
Specialized funding	Bangladesh Bank's revolving fund of Taka 2 (Two) Billion, BCCTF has allocated Tk.3500 Crore during FY10-FY 19, Bangladesh Infrastructure Finance Fund Limited (BIFFL)

13. Conclusion

Bangladesh is facing an energy crisis, with 68% of its electricity dependent on reserved natural gas supplies, which will not last long. Around 30% of the population lacks access to power, increasing the demand for energy and making RE adoption essential to long-term solutions. Harnessing wind power in any coastlines of Bangladesh, including Mognamaghat, Cox's Bazar, Kuakata, Kutubdia, and Parky Saikat Chittagong, with 576 turbines at 50 m height, generates 1455.85 MW, which amounts to 3.36% of the 2030 target, and becomes cost-free after approximately 7 years, covering only operating and

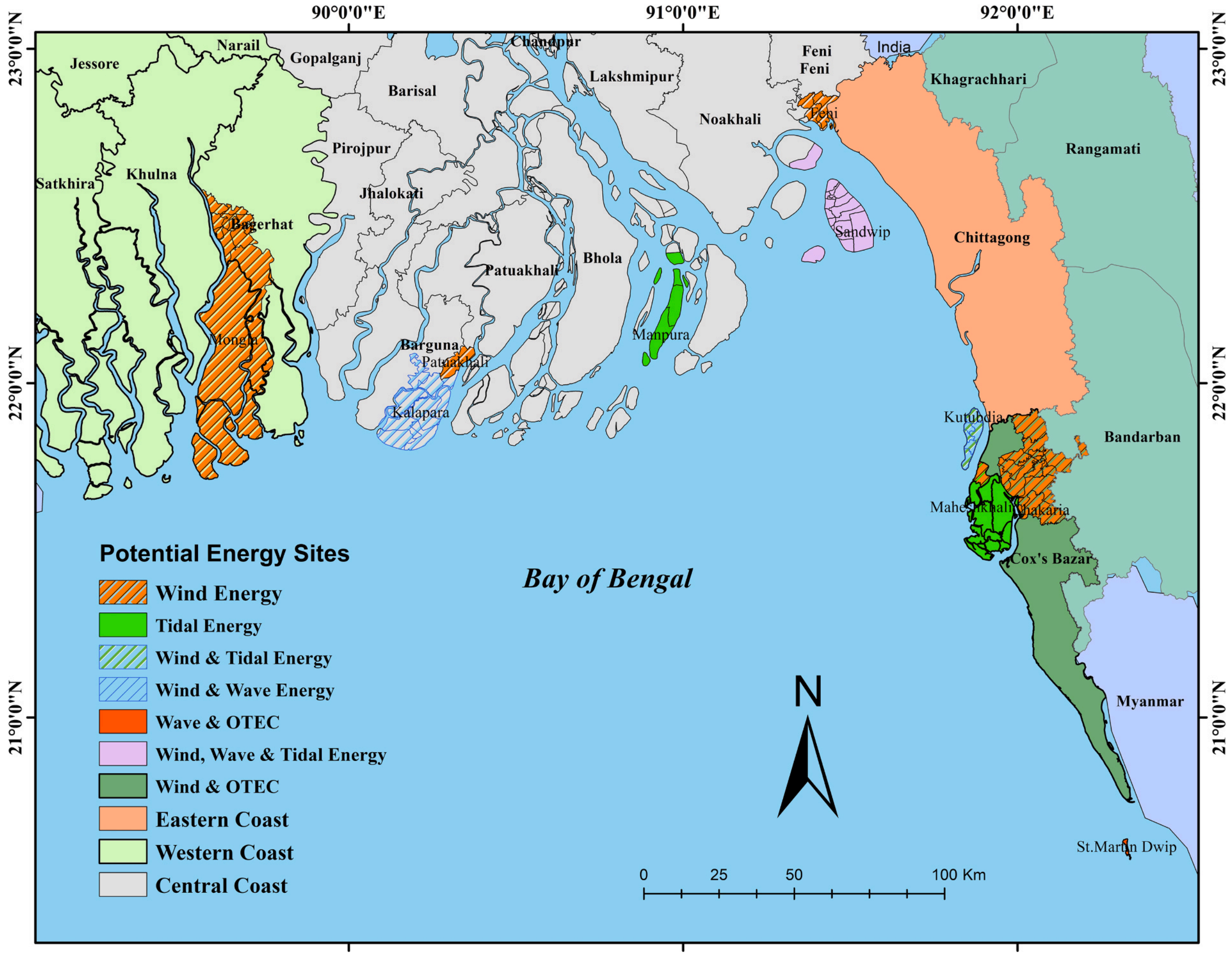

Fig. 14. Potential sites of MRE.

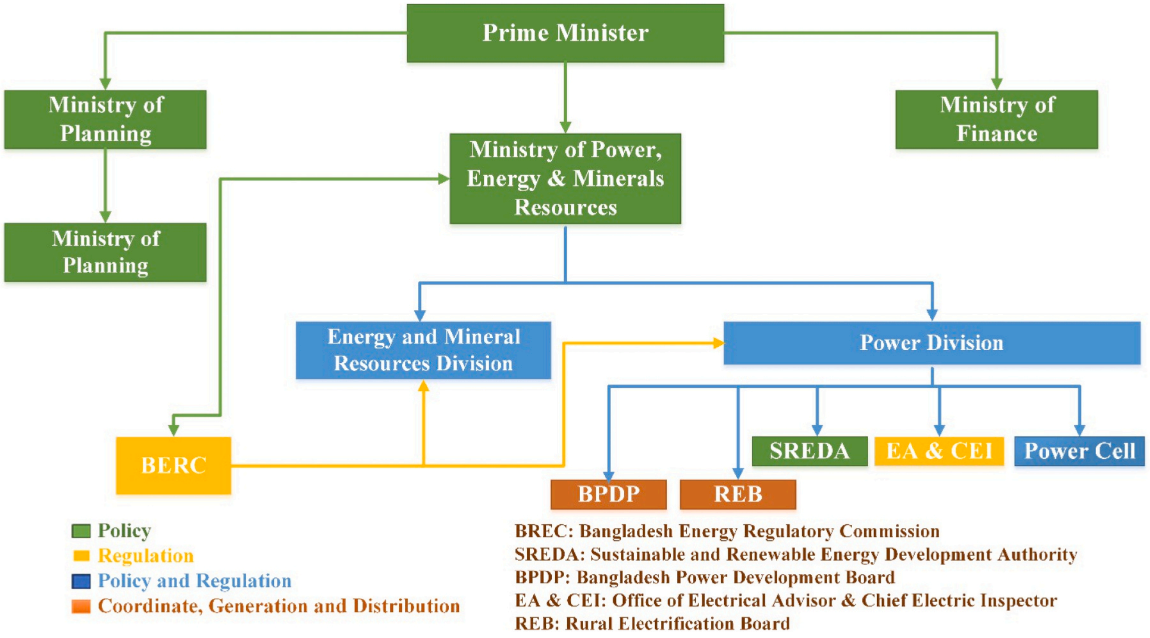

Fig. 15. Bangladesh's Energy Policy and Regulatory Authorities (Adiputra et al., 2020).

maintenance costs. Despite the need for specialized equipment and skilled employees, OTEC systems offer tremendous potential in Bangladesh, because of the BoB's 20-degree Celsius temperature differential. Economic studies propose an 8-year period for profitability, enabling Bangladesh to meet 1% of total power consumption through OTEC while ignoring insur- ance and local taxes. According to the IFC, Bangladesh's 710 km coastline, with tidal height changes of 2 to 8 m, has the potential to generate up to 10 GW of tidal energy. Tidal plants have substantial setup costs but min- imal maintenance costs. The power cost is expected to be close to zero once capital expenses are recovered. Southern coastal areas with stronger waves show promise for wave energy, with an estimated 1.8 GW potential. Given its higher density (2–3 kW/m^2), it outperforms solar and wind energy (0.4–0.6 kW/m^2 and 0.1–0.2 kW/m^2, respectively). In terms of revenue, wave energy.

could take approximately 20 years to generate a profit margin. More In- vestment in the MRE sector has the potential to satisfy Bangladesh's future energy needs. While solar, biomass & biogas, and nuclear energy all show promise, further research is required to explore more sources. The Govt. of Bangladesh needs to create local, low-cost technology to make MRE more cost-effective for its people. Collaboration between the government, corpo- rate sector, and international organizations is critical for economic support and long-term prosperity. Prioritizing MRE technologies such as tidal, wave, wind, and OTEC can offer sustainable energy while also promoting coastal development and job creation. Concurrently, awareness programs and initia- tives to prevent electricity loss are required for a reliable power supply.

CRediT authorship contribution statement

Shampa Mosa. Tania Alim: Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Majumder Md. Ziaul Hasan:** Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Deowan Shamim Ahmed:** Supervision, Project administration, Investigation. **Islam Md. Ariful:** Writing – review & editing, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Hafiz Farhana:** Project administration, Investigation.

Declaration of Competing Interest

None.

Data Availability

Data will be made available on request.

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