

A comprehensive review on ocean energy and state-of-the-art conversion technology in the bay of bengal region

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ABSTRACT

Rapid population growth is driving higher energy demand, increasing fossil-fuel dependence and CO₂ emissions. Thereby, great interest is found in the blue energy source of the ocean. The existing state of ocean energy in the nations bordering the Bay of Bengal (BOB) is investigated in this study. This study explores the wave, tidal, and global resources for the BOB. The various energy conversion technologies have also been systematically investigated. The BOB currently exhibits relatively high wave heights, signifying substantial wave energy potential available for efficient extraction. Among marine energy technologies, point absorbers and oscillating water columns are preferred for wave energy, while horizontal-axis tidal turbines and barrage or fence systems are deemed most effective for tidal energy in South Asia. The proposed Mini Hydroelectric Power Plant (MHPP) for Saint Martin's Island demonstrates effective wave-driven water pumping and modular reservoir storage, ensuring reliable and scalable island electrification. Site-specific assessment of tidal energy technologies indicates that a modular horizontal-axis tidal stream turbine array is the most technically and environmentally suitable solution for Cox's Bazar. The results confirm the feasibility of location-optimized marine renewable energy systems for sustainable power. The proposed model has become effective for energy generation from the ocean, along with being environmentally friendly.

1. Introduction

Due to population expansion, the world's energy consumption is rising and creating significant challenges for low-income and developing countries to meet rising consumption while transitioning to clean and sustainable energy systems. By 2050, there will be around 9.6 billion people on this world, ensuring access to modern energy services for billions of people has become a critical issue Khan et al. [1]. Global energy consumption (GEC) is predicted to increase by almost 30% between 2010 and 2040 [2]. This statistic insists on finding alternative energy sources as the conventional energy resources have many negative impacts on the environment, such as petroleum-based fuels Khan et al. [1]. Burning fossil fuels causes serious environmental and social problems and is the main source of greenhouse gas emissions. Therefore, renewable energy is increasingly preferred over conventional sources, as it provides reliable power, improves energy security, reduces carbon emissions, and decreases dependence on imported fuels.

Fig. 1(a) shows a rapid rise in global CO₂ emissions from 1965 to 2023, with the Middle East and Asia-Pacific regions experiencing the highest growth, recording increases of 1610.83% and 1213.55%, respectively (Fig. 1(b)). Together, these regions account for more than half of global CO₂ emissions, and human activities are responsible for about 97% of global warming throughout the past century [3]. This highlights the urgent need to transition to renewable energy sources; while PV and WT have a significant impact, ocean energy is emerging as a promising alternative. Wave and tidal energy are the main forms of ocean energy, with wave energy historically used as early as the 13th century in China and formally patented in France in 1799 by Girard and his son [2,3]. In 1910, the French Praceique-Bochaux system was among the earliest wave energy applications, supplying power to homes in Royan using a concept similar to oscillating water columns (OWCs) [4]. Yoshio Masuda created a drifting OWC apparatus, which is a wave-generating navigating buoy incorporating an air turbine [5,6], Masuda [7], Masuda [8]. Although the concept of ocean-based renewable energy

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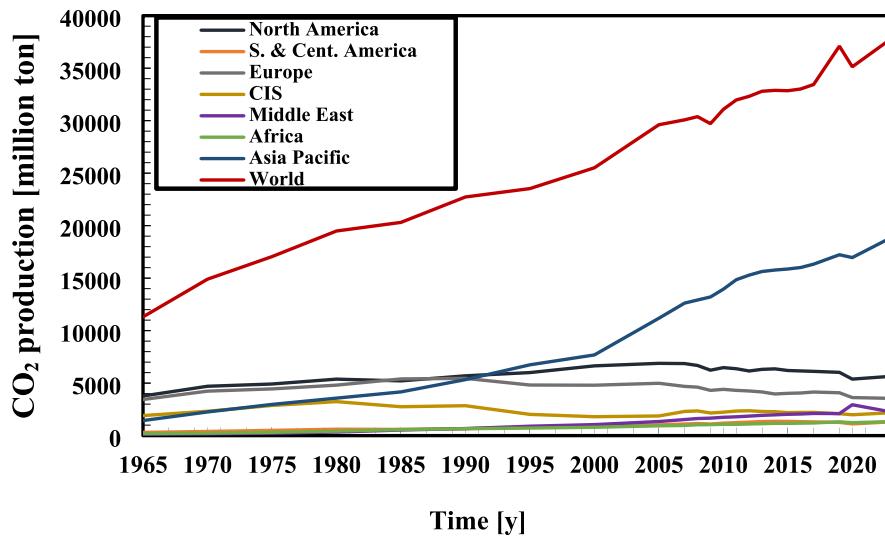
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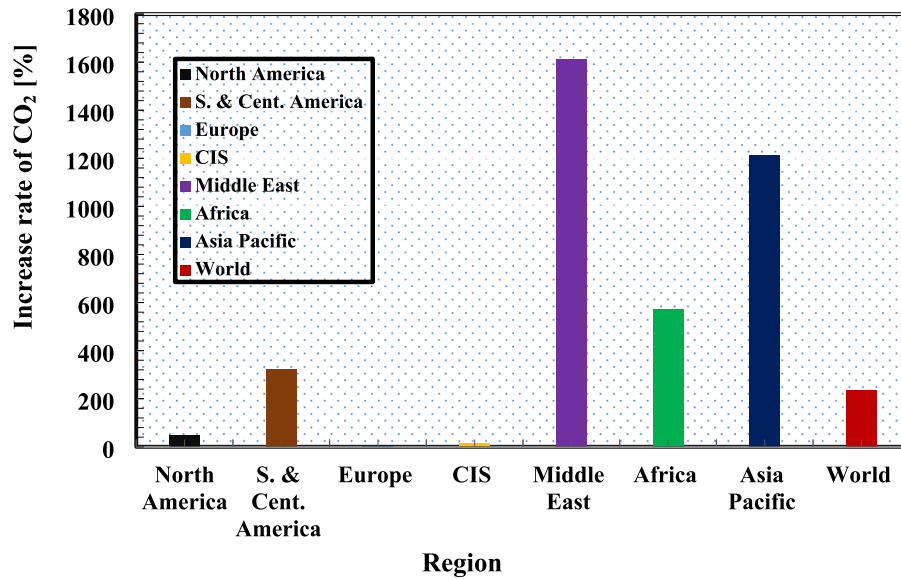
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(a)



(b)

Fig. 1. (a) CO₂ production and (b) % increasing in emission levels since 1965 to 2023 by region.[12–14].

dates back centuries [9,10], Haces-Fernandez et al. [11], and the first tidal barrage was built in France in 1966, progress remained slow until development began to accelerate significantly after the 2000 s. Fig. 2 shows the renewable energy market.

Marine renewable energy harnesses power from ocean sources such as tides, waves, currents, and thermal gradients using technologies including OTEC systems, tidal turbines, and wave energy converters, offering a vast yet underutilized clean energy resource. Despite obstacles such as expensive rates, consequences for the environment, and technical advancement, current research advances. Global ocean energy capacity is projected to reach 350 GW by 2050, playing a key role in decarbonization and supplying reliable electricity to coastal and island regions, with the European Commission targeting a fivefold increase by 2030 and a twenty-fivefold increase by 2050, highlighting major opportunities for innovation and investment [15]. Wave-energy, also

known as unidirectional or gross wave power, refers to the wave power passing through a one-meter-wide wave front [16]. It has a kinetic energy concentration nearly 1000 times greater than that of wind energy and is generated using about 1% of the solar heat reaching the Earth (Ocean Energy [17]. Long-period waves carry significantly more energy than short-period waves, which are smaller and weaker Rony [18]. Table 1 shows the comparison of wave energy.

Ocean waves are generated by wind-driven motion on the water surface, with wave size increasing with wind speed, and about 95% of wave energy concentrated within one-quarter of the wavelength from the surface Rony [18]. Favorable wave energy conditions occur in deep waters (>40 m) under moderate to strong winds, where power density reaches 60–70 kW/m [21]. Wave growth results from wind-induced surface tension, turbulent airflow, and resonance with existing waves [22], and wave energy is influenced by wave height, wavelength, speed,

Marine Renewable Energy Market

Size, By Type, 2022–2032 (USD million)

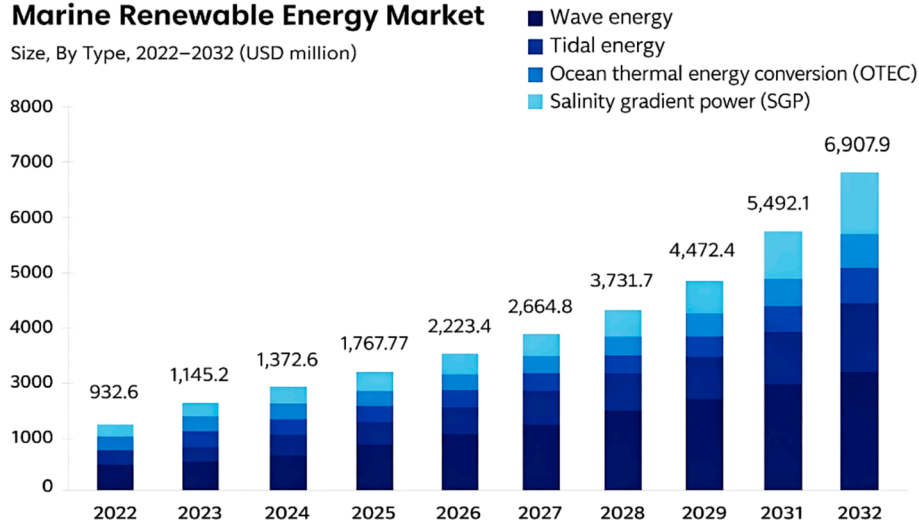


Fig. 2. Marine renewable energy market over the world from 2022 to 2032 (MarketResearch.biz, n.d.).

Table 1

Comparison of wave energy with other renewable energies Khan et al. [1,19,20].

Name of renewable energy	Wind	Wave	Hydroelectric	Geothermal	Solar
Technology Status	Commercially Mature	Pre-commercial	Commercially mature	Commercially mature	Commercially mature
Energy Source	Wind	Ocean/Tide	Flowing Water	Earth geothermal	Solar radiation
Density	low	Low to Moderate	Low to Moderate	low	low
Resource Variability	High	Medium	Low	Low	High
Predictability	Uncertain outside of just a handful of locations	Predictable in most sites	High	High	low
Geographically Available Sites	Site dependent	Extensive coastal potential	River/reservoir dependent	Geologically restricted	Widely available
Environmental Issues	Noise & Visual Pollution	None [virtually no environmental impact]	No pollution.	Water quality & use, air emission, and land use.	Visual pollution
Estimated cost (pence/kWh)	8.3 on land, 16.9 offshore	29.3	6.9	15.9	Varies by technology and region
Average power Output per Plant	Scalable to 30 MW	Scalable to 100 + MW	Large scale (MW to GW range)	Typically, 5 to 100 MW	scalable to Several MW

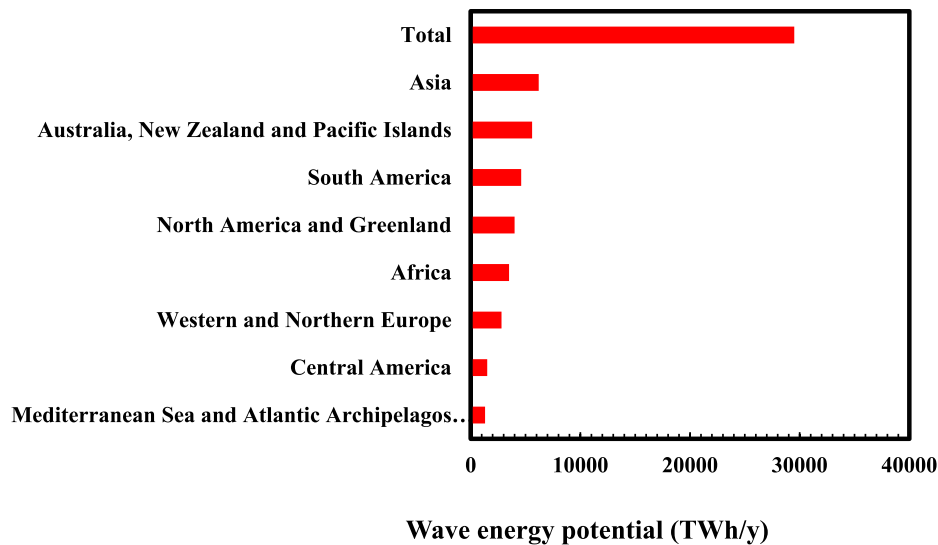


Fig. 3. Wave energy reserves in various parts of the world [21].

water density, and depth [23]. Wave energy is significantly more concentrated than wind and solar energy ($2 \sim 3 \text{ kW/m}^2$ compared to

$0.4 \sim 0.6 \text{ kW/m}^2$ and $0.1 \sim 0.2 \text{ kW/m}^2$, respectively), can travel long distances with minimal loss, and serves as a wind-charged energy

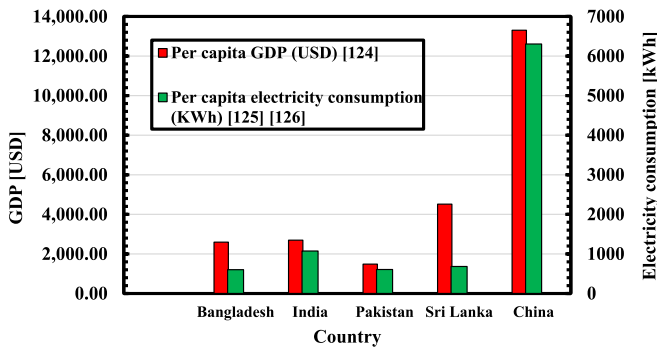


Fig. 4. Comparison of per capita GDP and energy consumption for some countries in Asia 2024(World Bank, 2018; [35], WorldData [36]; Data Commons, n.d.).

reservoir, though only a small portion is currently utilized for power generation [2,24,25]. Countries around the Bay of Bengal (BOB) have strong ocean energy potential, driven by renewable energy policies, with India leading through tidal and OTEC initiatives that support investment and research [26]. Fig. 3 shows the wave energy reserves. Globally, the highest wave energy potentials typically range between 401 and 601, with the Southern Hemisphere showing higher mean annual wave power and lower seasonal variability than the Northern Hemisphere [27–29].

The South Indian Ocean near New Zealand, South Africa, Chile, Southern Australia, and East of Kerguelen Island exhibits exceptional resources exceeding 120 kW/m [28–30], while in the Northern Hemisphere the North Atlantic reaches 80–90 kW/m along the west coasts of Iceland and Greenland, decreasing toward lower latitudes [29]. Significant potential also exists in the Pacific Northwest and Alaska (USA), as well as the UK and Scotland [3]. Among particularly strongly potential RES, wave energy and numerous studies have assessed its potential across different regions worldwide, with conceptual estimates summarized [31]. In Bangladesh, to maintain economic growth, a stable energy sector must be ensured. By the year 2041, Bangladesh will need 82 GWh of electricity. The goals were set to produce 5% to 10% power from REs by the government in the year 2020 [32–34]. The government is also seeking to privatize the power sector to promote investment from home and abroad. Besides nuclear power plants, there are some small-scale renewable power plants, but not yet any investment in ocean energy. Fig. 4 represents the comparison of GDP.

In India, energy policy focuses on its rapid increase, which is now mainly met by nuclear, wind, and solar power. India's energy strategy from 1950 to 1970 was primarily concerned with developing the gas and oil industries and supplying power. The Planning Commission of India established several initiatives, such as privatization, the beginning of foreign investment in energy markets, and a plan to implement the decentralized structure of the power sector [37]. The solar power of 22

GW will be grid-connected by 2022, which is currently 100 GW of RES [38]. In Pakistan, before the 1990 s, the energy-related strategies in Pakistan were nonexistent due to a lack of consistency, reliability, and implementation. In 1994, the government finally focused on development and formation of strategies to achieve energy stability [39,40]. Now Pakistan has a mostly stable energy sector with 64% fossil fuels, 27% hydropower, 5% nuclear power, and 4% renewables. The recently announced plan is for 20% of Pakistan's installed power capacity to come from renewable sources by 2025 and 30% by 2030 [39]. There are no plans at all for investing in ocean energy. The Sri Lankan government aims to achieve energy self-sufficiency by 2030. The target is to raise the nation's electricity production from the current 4043 MW to 6900 MW by 2025, with a significant increase in RE. Sri Lanka has already achieved 98% of its grid connection, which is rather good by South Asian standards International Trade Administration [41]. The National Energy Policy of Sri Lanka, 2019 states that “a developing resources strategy will implement a full-fledged tendering mechanism for REs to produce an inventory of ‘ready to invest’ developments by the middle of 2020 by the SEA, achieving 20% of the electricity generated with a combined generation of approximately 1,600 MW by 2023 [42,43]. Additionally, all types of renewable energy are actively promoted by the Sri Lanka Sustainable Energy Authority (SLSEA).

Though there are some establishments, still south Asian countries are far behind in comparison to European countries. The main drawbacks may be the energy distribution structure, lack of privatization, and others.

This paper aims to demonstrate the potential of ocean energy resources in the BOB to strengthen the power sectors of South Asian countries, Bangladesh, India, and Sri Lanka, and mitigate persistent energy shortages. That means, firstly, review the global technologies, then assess the regional resources in terms of the techno-economic aspect, and finally come to a suggestion for the Bay of Bengal. It provides a comprehensive review of wave and tidal energy technologies, outlining the fundamental concepts required for a holistic understanding of marine energy systems. The study examines the hydrodynamic characteristics of the BOB, compares wave energy potential with other renewable sources, evaluates environmental implications, and presents approximate cost assessments of various technologies. Furthermore, it discusses the global distribution of ocean energy resources, identifies high-potential locations, classifies major extraction technologies, and analyzes the sequential energy conversion stages necessary to deliver grid-compatible electrical output.

2.0. Methodology

This is the review paper, so the literature survey is crucial here. Firstly, data and information are collected in terms of the global context of ocean energy. Then the regional area in terms of BOB, like India, Sri Lanka, and Myanmar, is also discussed and investigated in comparison in terms of technology. According to the suitability of the regional

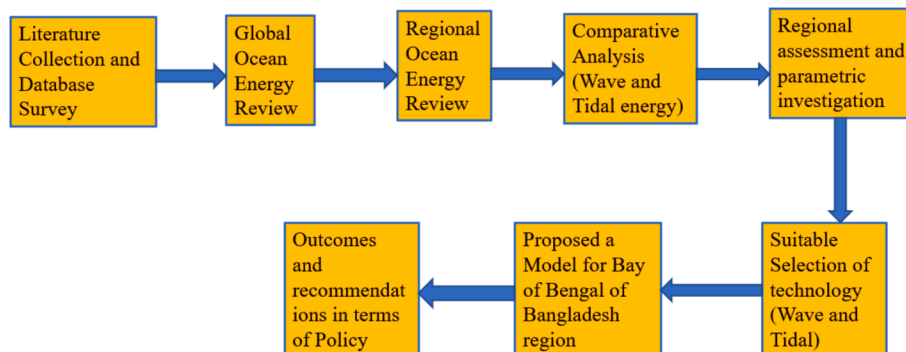


Fig. 5. Schematic block diagram of the methodology.

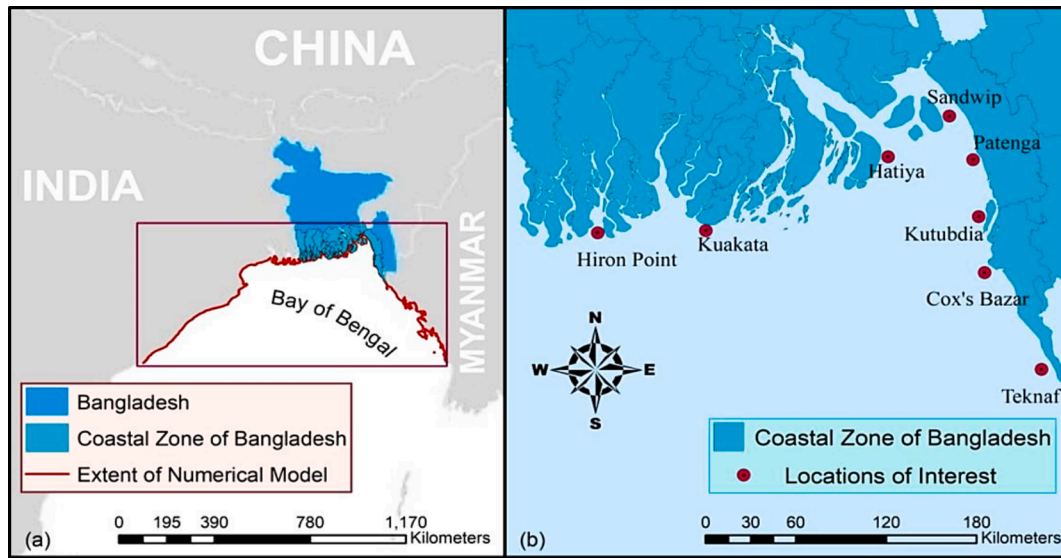


Fig. 6. (a) Countries surrounding BOB [49] and (b) coastal zones of Bangladesh [49].

assessment, the wave and tidal technology are selected for application in the BOB for Bangladesh. The schematic block diagram is shown in Fig. 5.

3. Regional ocean energy in BOB

3.1. Wave energy resources

3.1.1. Wave characteristics in South Asia

The developing wave energy resources require a clear understanding of wave climate and power estimation, as demonstrated by several studies that present global wave power assessments [2,27]. The socio-economic growth of coastlines in countries that are developing or underdeveloped may be greatly aided by wave energy [44]. Wave energy is now a good source for the countries that border the BOB, which includes nations such as India, Bangladesh, and Sri Lanka. The BOB runs along Bangladesh's coast for 580 km [45,46]. Wave energy may assist in addressing the energy crisis, especially for small coastal communities and island settlements. The best way to get power to the three secluded Bangladeshi island nations of Sandwip, Kutubdia, and Saint Martin is to use wave energy [3].

3.1.2. Bangladesh

Studies at Cox's Bazar and Chittagong show favorable wave energy resources, with above-average wave power from April to October and particularly from November to March, indicating strong potential for wave farm installation to meet local power demand [20]. In 2011, a Malaysian company proposed a wave power plant in north Chittagong with an annual output of about 900 M kWh, potentially reducing electricity production costs by half (The Daily [47]). Additionally, estimates suggest that a 30 MW sea wave farm could be developed with an investment of approximately USD 4 M and relatively low maintenance costs [48]. Fig. 6 is a representation of BOB.

3.1.3. India

Wave power in Indian shelf seas shows strong seasonal variation, with the smallest mean value (2.6 kW/m) during the post-monsoon period (October–January) and a peak of 25.9 kW/m during the southwest monsoon (June–September) [12]. The eastern coast exhibits lower annual wave power (2.6–9.9 kW/m) compared to the western coast (7.9–11.3 kW/m), while the southern region shows the least seasonal variability and the highest annual mean wave power (11.3 kW/m), making it highly suitable for wave energy development [12,50]. Reports also indicate higher wave power along the west coast due to strong

Table 2

Optimal locations for wave energy converter technology in India [52].

Location	Wave power (kW/m)
Kudal	21.95
Trivandrum	21.95
Kanyakumari	21.95
Puducherry	21.95
Kaviti	21.95

southwest monsoon waves, with maximum potential at the southern tip of India (Kanyakumari, Nagercoil, and Kudankulam), where five promising sites for wave energy devices have been identified and summarized in Table 2 (Indian Renewable Energy Development Agency [51]).

3.1.4. Sri Lanka

Sri Lanka is a prime candidate to produce nearly all of its power from REs since it is an island nation in the BOB with plenty of hot days and abundant wind and wave assets in numerous locations [53]. With a maximum wave height of less than 6 m and a power density of 20 kW/m, the nation has economic energy potential [54]. Wave energy generators with a 10 MW capacity have been determined to be electrically viable for the region [23]. By taking the required steps and implementing energy policies to assist investors and researchers, the government of Sri Lanka has taken a significant lead role in achieving this goal [3].

3.2. Wave characteristics in the BOB

3.2.1. Wave height (Wh), seasonal variation & energy density

Accurate estimation of wave energy and extractable power requires determining key parameters, particularly wave height and wave period, which must be recorded throughout the year. For the BOB, multi-year wave data have been analyzed to assess regional wave energy potential, revealing significant seasonal fluctuations in significant wave height over the year.

Fig. 7 shows significant wave heights for 2005, including larger waves in March (approximately 2 m) and significantly larger waves from March to September (above 1.5 m). From October to February, and the month of April, the wave had a moderate height, fluctuating between 0.5 and 1.5 m. Table 3 shows the maximum wave height of the BOB.

Fig. 8 shows the wh combination. The above graphs provide data

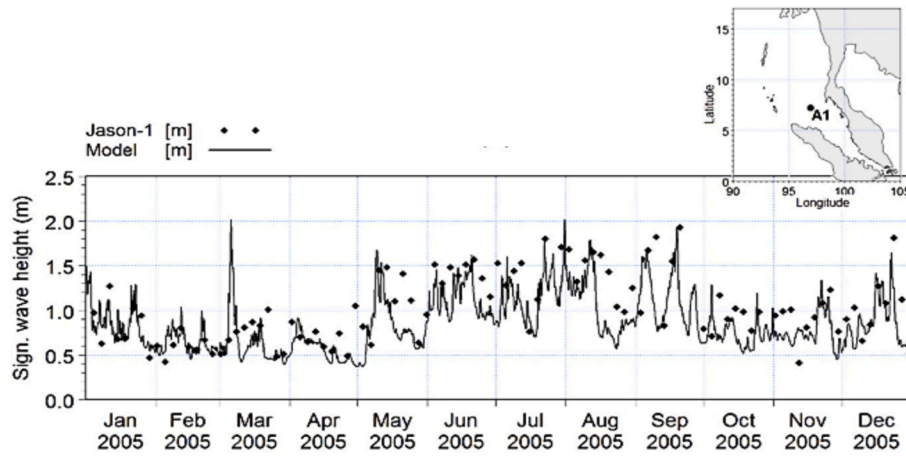


Fig. 7. Characteristics wave height (Wh) merged (m) in the year 2005 at eastern BOB (Andaman Sea – Malacca Strait interface) [23].

Table 3

Maximum Wh of BOB at different years.

Year	Maximum Wh (m)	Month
2005	2 m	March, July
2010	3.35 m	July
2011	4 m	June
2012	3.4 m	June
2013	3.8 m	July, October
2017	1.7 m	July
2018	2.9 m	June
2019	1.2 m	June, August
2020	1.55 m (Hiron point)	June
(Bangladesh)	1.8 m (Kuakata)	May
	1.45 m (Hatiya)	May
	1.24 m (Sandwip)	May
	1.8 m (Patenga)	May
	2.2 m (Kutubdia)	May
	3.6 m (Cox's Bazar)	May
	4.2 m (Teknaf)	May

maximum height of 4 m, and fluctuates within 0.5 to 1.2 m from November to December and January to March. Fig. 9 and Fig. 10 are for wh at (a) Hiron Point (b) Kuakata and (a) Hatiya (b) Sandwip respectively.

Fig. 11 illustrates significant wave heights at Hiron Point, Kutubdia, Hatia, Sandwip, Patenga, Kuakata, Cox's Bazar, and Teknaf in Bangladesh during 2020. Higher wave heights (up to ~ 1.55 m) were observed at Hiron Point and Kuakata from April to October, while Hatia and Sandwip showed moderate values (1 ~ 1.5 m) during the same period. Based on wave trends, Patenga, Kutubdia, Cox's Bazar, and Teknaf were identified as the most suitable locations. Patenga experienced peak wave heights of around 1 m from May to August (Fig. 11(a)), Kutubdia showed increasing wave heights up to ~ 1.5 m from June to mid-September with lower values during the dry season (Fig. 11(b)), and Cox's Bazar recorded very high waves with a peak of 3.60 m in May, remaining elevated until mid-September (Fig. 11(c)). Teknaf exhibited the highest waves among all sites, reaching 4.29 m in May and maintaining high values year-round, including during the dry season (Fig. 11(d)). The southeast coast of Bangladesh is characterized by a comparatively narrow continental shelf, influencing these wave conditions Finkl et al. [55]. Fig. 12 represents (a) Peak wave period (b) Mean wavelength at Cox's Bazar. Also, Fig. 13 shows wave characteristics.

While weaker northeastern winds and waves prevail from December to February, strong south-west winds and waves pour onto the Bay from June to September [57]. The conversion of the wave energy to electric power and the amount of energy stored within the wave must be calculated. To calculate the extractable energy and power from the wave, the following equations (Eq.01 to Eq.04) are usable.

$$E = E_K + E_P = \frac{E}{2} = \frac{\rho_w g H^2 L}{8} (Jm - 2) \quad (1)$$

$$L = \frac{gT}{2\pi} (m) \quad (2)$$

$$V_g(T) = \frac{gT}{4\pi} (ms - 1) \quad (3)$$

$$P_w = EV_g = \frac{gT}{8\pi} \times E = \frac{\rho_w g^2}{64\pi} \times H_m^2 T (W.m - 1) \quad (4)$$

According to Khan et al. (2017) (a); Islam et al. [20], Fowze et al. [48] and Sandro et al. [58], Energy of wave [E], length of the wave [L], Velocity of wave front [V_g], the period of the sinusoidal wave [T], extractable power from wave [P_w].

The equation is called the Equation of K. Huls. It is valid only for the condition of deep water, that is, water depth is larger than half of the wavelength (depth > $\frac{L}{2}$) [20].

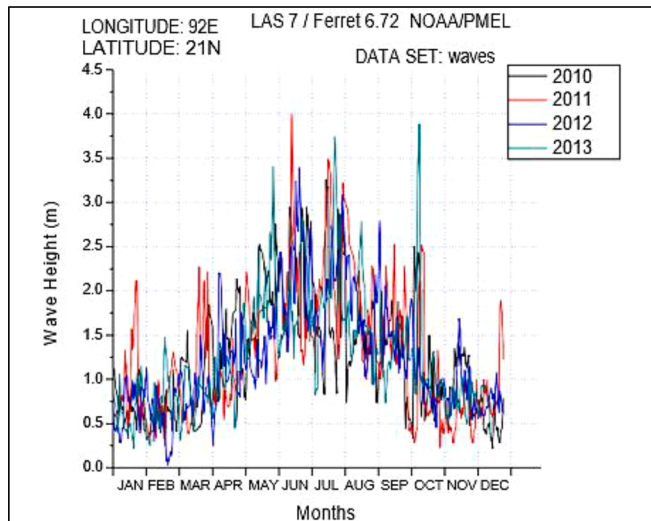


Fig. 8. Highest wh combination [20].

about the impact of wave height for the BOB over the period 2010–2013. The higher wave heights are observed in July 2010, June 2011, 2012, and Jun and October 2013. So, we can conclude that the maximum wave height can be found around May to July of a year at the BOB. The importance of wave heights is higher from April to October, with a

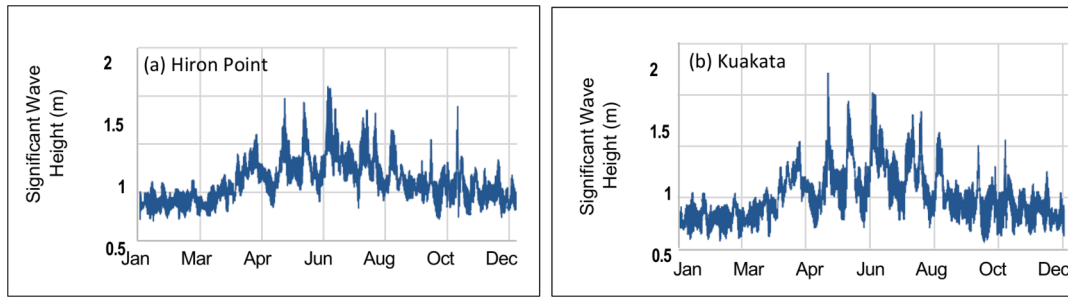


Fig. 9. Characteristics of wh at (a) Hiron Point (b) Kuakata [49].

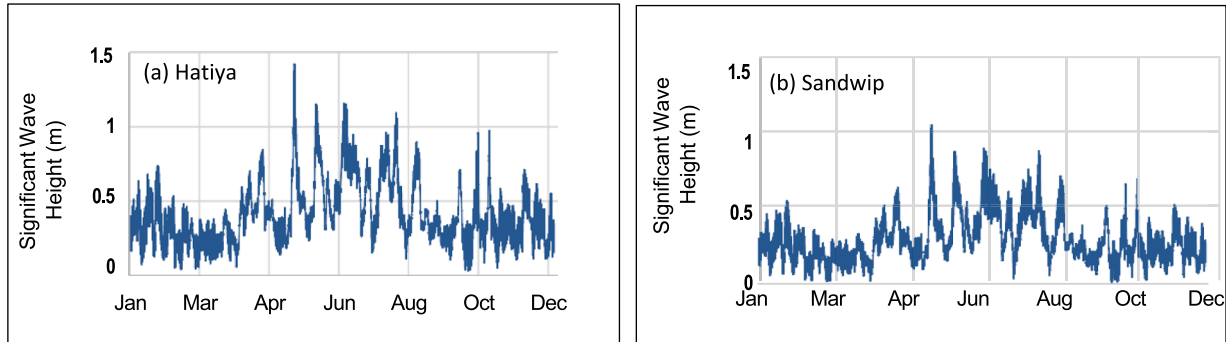


Fig. 10. Characteristics of wh at (a) Hatiya (b) Sandwip [49].

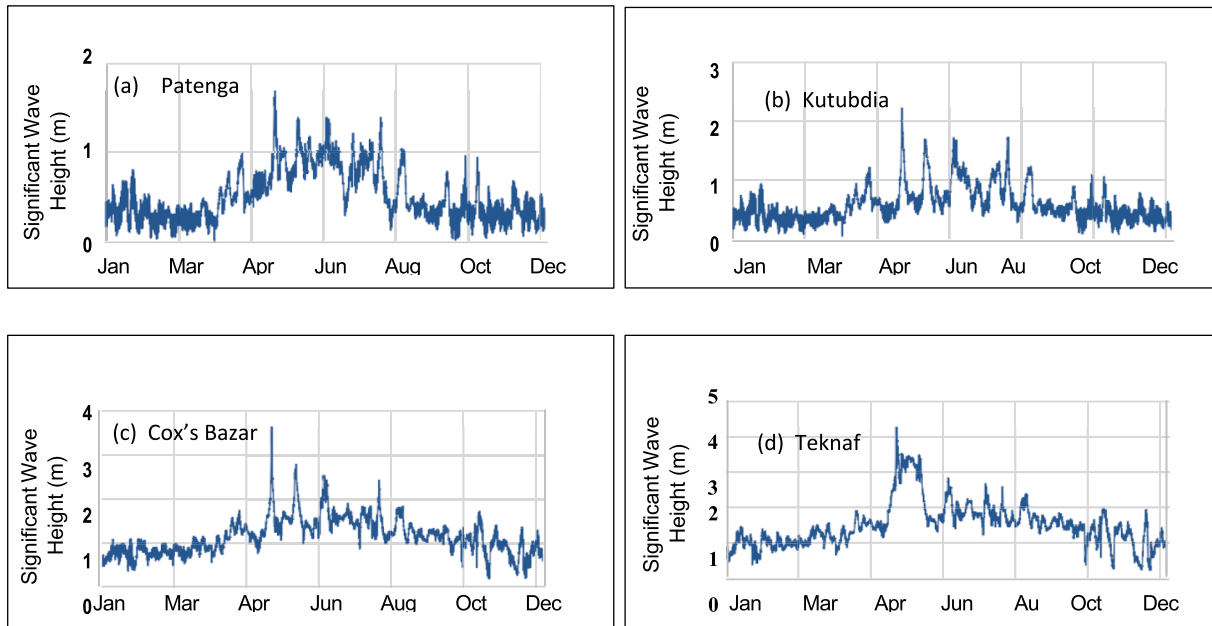


Fig. 11. Characteristics of wh at (a) Potenga (b) Kutubdia (c) Cox's Bazar (d) Teknaf [49].

According to Matin et al. [49], which presents the monthly average wave energy of the BOB for the years 2010–2013, showing minimal variation from January to April (and up to May in 2012), followed by a significant increase from May to October. The highest extractable wave energy occurs between May and July, with peak values of about 15.35 kW/m in July 2011, 20 kW/m in July 2012, and 13.90 kW/m in July 2013. Comparative results for 2011–2013 in Fig. 17 further indicate that July consistently exhibits the highest wave energy, while September and October show higher values than November and December, and overall wave energy levels remain relatively consistent across the years.

Fig. 14 shows the wave power of 12 years marged at one graph. Almost the same condition can be seen for the years 2000–2012 at BOB. From January to April, there is no discernible variation in wave energy throughout the first four months of a given year. While the most wave energy could be recovered in May and July, the substantial wave energy is recorded from May to August.

Fig. 15 shows the wave height, period, and average power per meter at Saint Martin Island of Bangladesh. Maximum extractable power is 6.787 KW/m at year 2017. We can decide from the above data sets that there remains most high wave height from May to October at BOB,

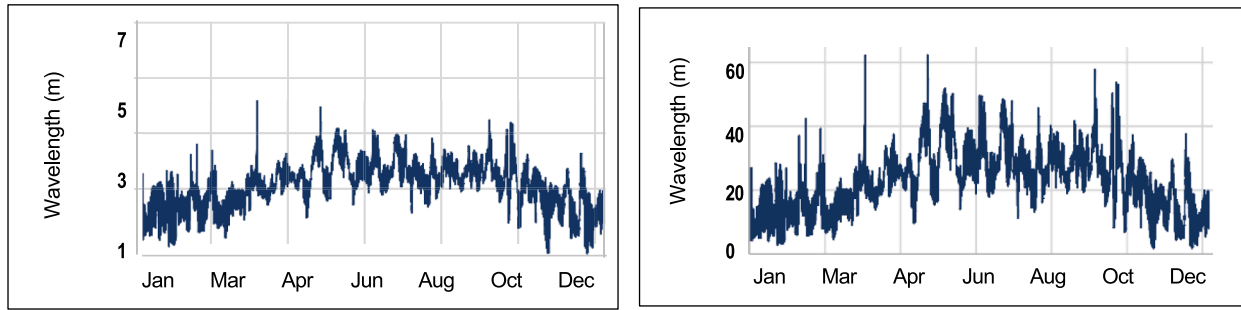


Fig. 12. (a) Peak wave period (b) Mean wavelength at Cox's Bazar [49].

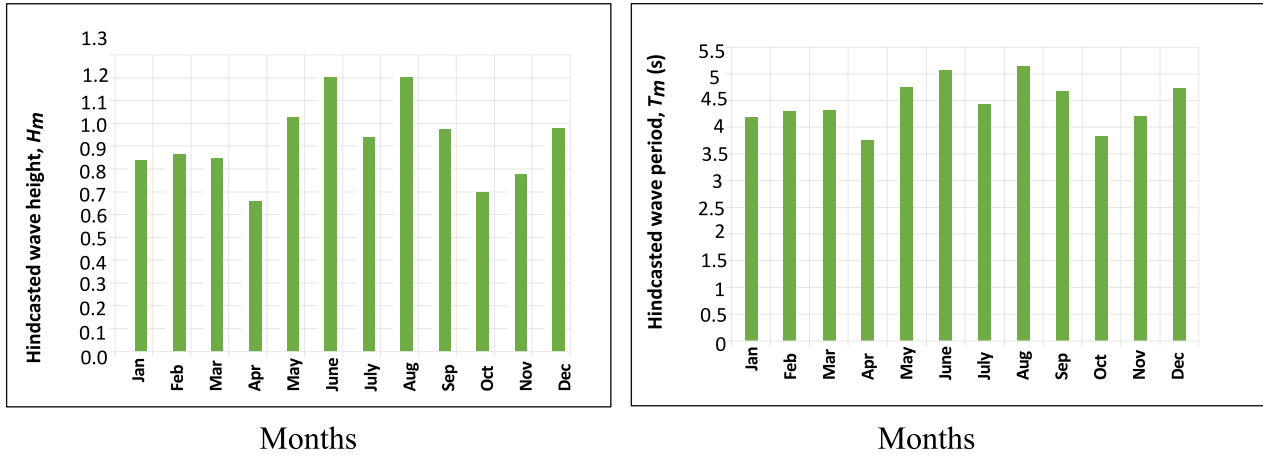


Fig. 13. Wave characteristics at 25 m assumed depth (a) wave height, (b) wave period, 2019 [56].

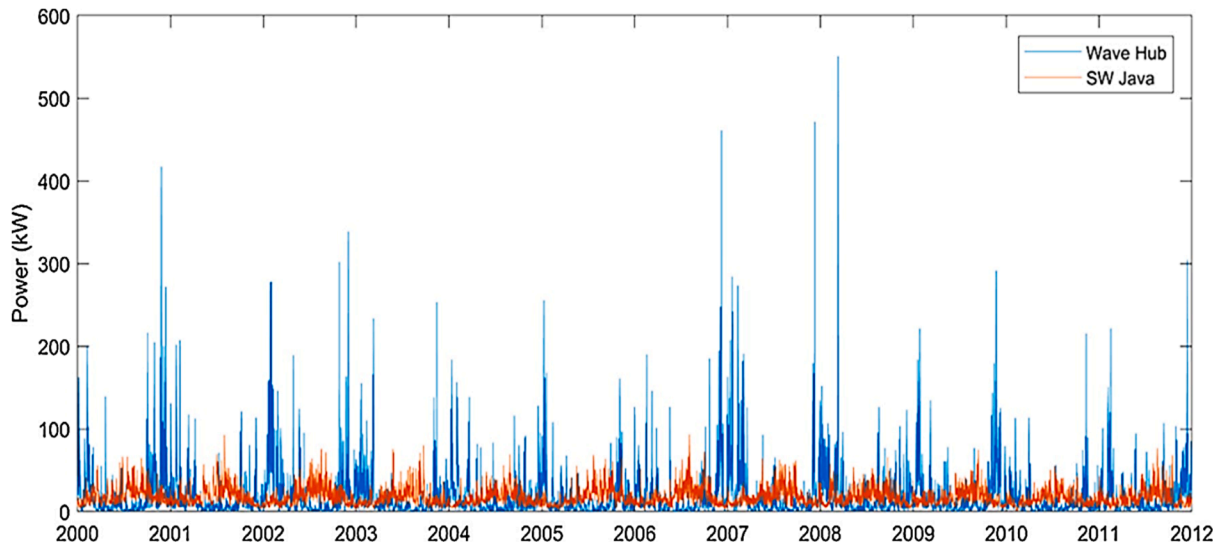


Fig. 14. Significant wave power showed in the years 2000–2012 of BOB [59].

which contains the largest amount of wave power to extract at this time.

3.3. Tidal energy

The gravitational as well as centrifugal forces between the Earth, moon, and sun provide tidal energy, a sustainable energy source [61,62]. Ocean water is drawn to the sun and moon by their gravitational pull, and the Earth's centrifugal force is also to blame [63]. The tides, or regular fluctuation in the level of the ocean's surface water, are

an outcome of these effects. Because of its smaller distance from Earth than the sun, the moon produces a gravitational pull that is roughly 2.2 times greater than that of the sun [64]. Two tidal phenomena occur every 24 h, 50 min, and 28 s as a result of the Earth's rotation with respect to the sun and moon [65].

Ocean tides arise from the combined effects of the Moon's gravitational attraction and the centrifugal force associated with the Earth–Moon system's rotation about their common center of mass. The Moon's gravity causes a redistribution of ocean water, creating a tidal

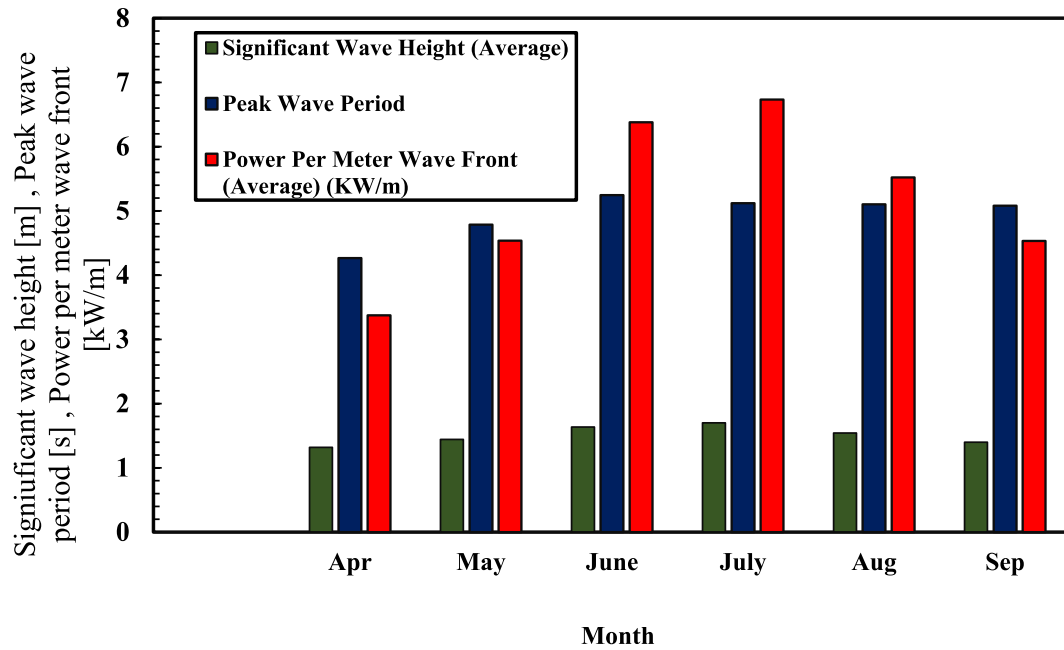


Fig. 15. Significant wave height, peak wave period, and average power per meter of St. Martine Island, 2017 [60].

bulge on the side of the Earth facing the Moon due to the stronger gravitational pull at shorter distances. Simultaneously, the rotation of the Earth–Moon system generates a centrifugal effect that produces a second tidal bulge on the opposite side of the Earth. The interaction of these forces leads to two opposing high tides and corresponding low tides as the Earth rotates, forming the fundamental mechanism of lunar tidal motion [66,67].

Two “bulges” in the Earth's envelope, one on the side facing the

moon and the other on the opposite side, create tidal waves due to gravity. Depending on the position in relation to the Earth's rotational axis, the greatest of the two waves can be witnessed [68]. tidal ranges that are categorized as neap tide and spring tide. When the earth, moon, and sun were all closely aligned on the same line during the new and full moons, the spring tide took place. This explains why, during spring tide, tidal ranges are larger than usual [69]. The neap tide, on the other hand, happened when the Earth's moon was at an angle to the sun's

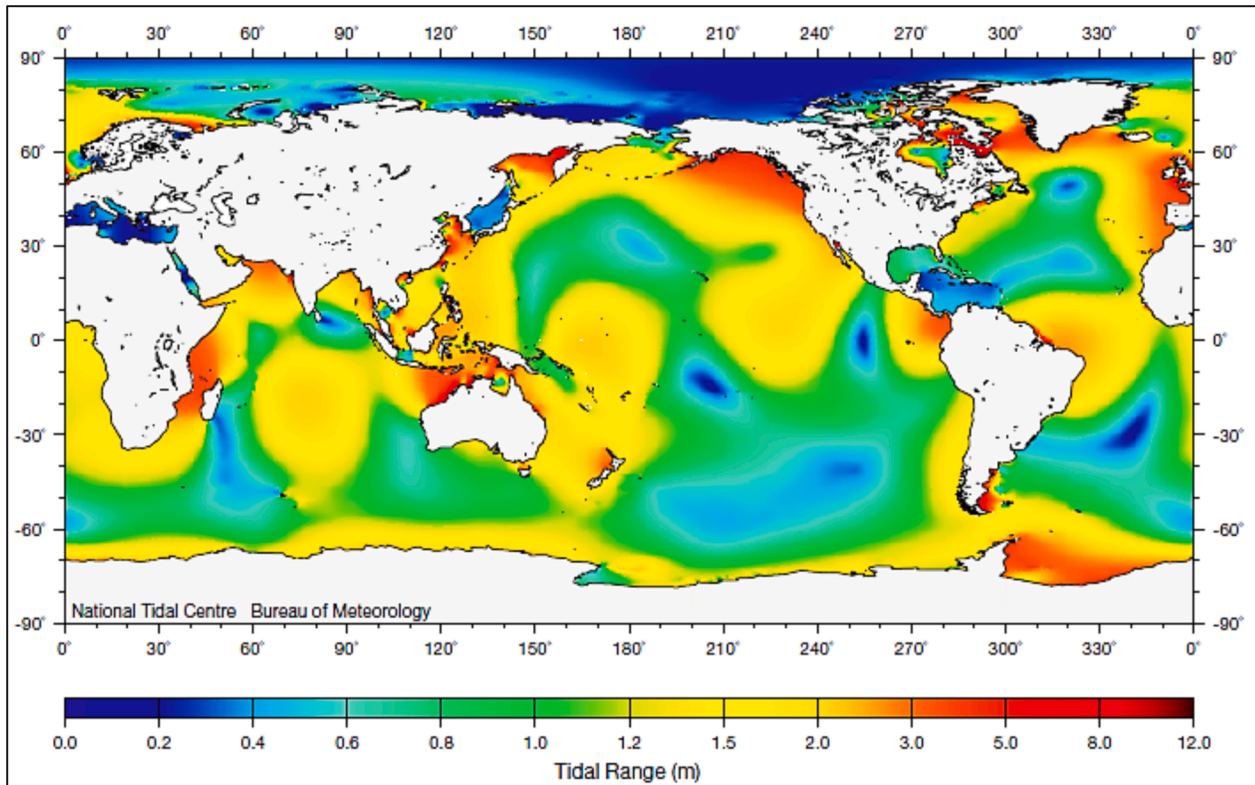


Fig. 16. Map of tidal range [10].

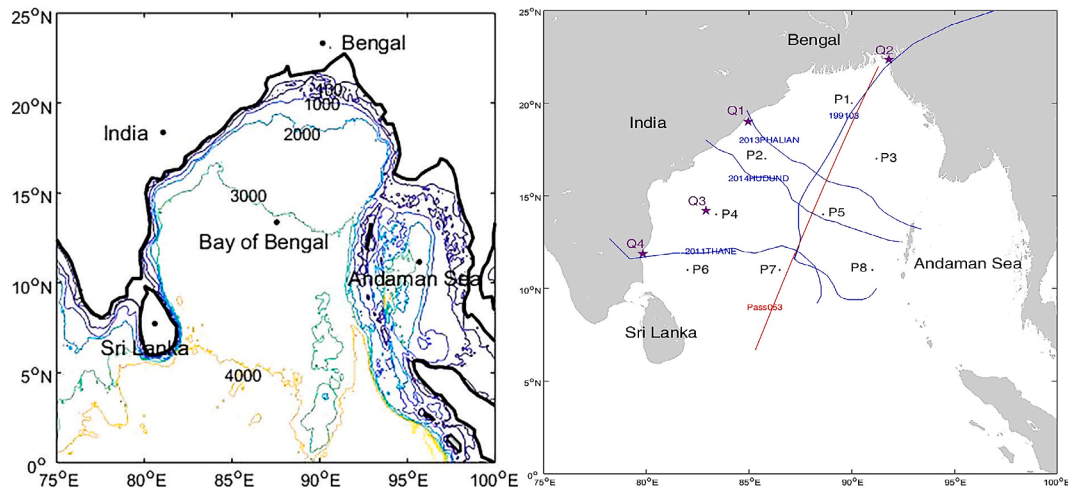


Fig. 17. Topography and depth of BOB [76].

gravitational pull. Tidal ranges are smaller than usual during the period of neap tide [70]. High tide and low tide are the two types of tide. The ocean's water rushes toward and then retreats from the coast throughout these processes. We obtain tidal currents if the coastal region is largely encircled by land. Tidal streams have zero mean velocity with a duration of roughly half a day plus a day, but ocean currents are defined as those that produce a mean velocity varying from zero over an amount of time of at least a year. Both kinds of streams are typically included in the broadest definition of the term "tidal" found in literature. There is a clear definition for the term "river stream." Tidal currents can be found next to headlands or in between land masses [71]. Semi-diurnal tides, diurnal tides, and mixed tides are the three primary forms of tide phenomena that are influenced by various locations on Earth Khan et al. [72]. The semi-diurnal tides' period corresponds to the moon's basic period, which is 12 h and 25 min. The ocean typically experiences two high tides every day throughout the months of May and June. As previously stated, the tidal range is largest during the lunar month when the tide's amplitude fluctuates the most. The diurnal tides have a duration of 24 h and 50 min, which is equivalent to a full moon rotation with respect to the Earth. There is a single high tide every day for this kind of tide. It is susceptible to changes brought on by the Earth's rotational axis being tilted with respect to the Moon's and the Earth's orbits around the Sun.

The properties of both diurnal and semi-diurnal tides are combined to form the mixed tide. Both monthly and bimonthly variations may be displayed. A good coastal range is required to operate a tidal barrage setup. The projected potential of neap and spring tide along the sea-shores is 1–10 MW/km, with a range of 4–12 m. Water springs can range in elevation from 11.4 m in Penzhinsk, Russia, to 12.4 m in Cobequid, Canada [73]. Tidal current energy collectors, however, require discharge. These work best in narrow coastal areas. Nowadays, one form of renewable energy that can be obtained from normal tidal activity is tidal energy. Since the tide interval & water height during flow are largely known and consistent, this type of renewable energy is highly predictable. Tidal energy extraction & tidal activity prediction are easily accessible, in contrast to other renewable energy sources [74]. NOAA Current Predictions provides online forecasts for the next 48 h, one week, and one year.

3.3.1. Tidal energy resources

Energy resources from tidal currents have been evaluated for a lot of years. Direct measurements have frequently been taken on location. A few years ago, current velocities were modeled using 2D and 3D modeling approaches to evaluate tidal current energy resources. The hydrodynamic impacts of power extraction are also evaluated in more

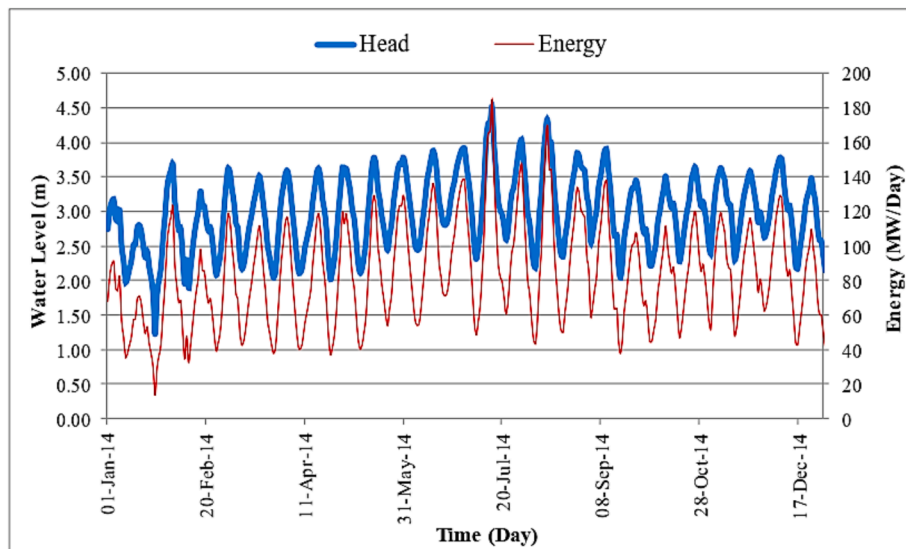


Fig. 18. Predicted energy and daily tide water level [78].

Table 4

Tidal potential along BOB coastline [66,79].

Coastal region	Tidal range (m)	Typical tidal current (m/s)	Average available PE per square kilometer (MW)	Average available KE per square meter (W)
Khambhat	5–11	2.5	10.9	2604.3
Kutch	4–9	3.0	7.2	4500.2
South Gujarat	2–4	2.0	1.5	1333.4
Maharashtra	2–4	1.5	1.5	562.5
Karnataka	1–1.5	1.5	0.2	562.5
Kerala	1–1.5	1.5	0.2	562.5
Tamil Nadu coast	1	0.8	0.1	85.3
Andhra coast	1–2	1	0.2	166.7
Orissa coast	2–4	1.5	1.5	562.5
Sundarbans/Hooghly	4–7	2–3	7.2	2604.3
Sandwip		2.83	0.45	
Petenga		3.5	0.841	
Kutubdia		2.0578	0.17	
Cox's-Bazar		2.0578	0.17	
Elephant Point	1	1.0289	0.02	
Mongla		2.0578	0.17	
Hiron Point	3	2.0578	0.17	

recent works, which take into account factors like flow field changes, elevation changes at the water's surface, or disruptions in tidal motion [69,75]. The primary determinants of the energy extraction are tidal range and current flow. The most important factors in a tidal barrage are water head and water volume. In contrast, tidal wave energy collectors rely on the current's flow rate rather than the water head. That is tidal energy's future. Fig. 16 shows the Map of tidal range.

The northeastern portion of the Indian Ocean, known as the BOB, is around 839,000 square miles (2,173,000 square kilometers) in size. It shares borders with Bangladesh to the north, Myanmar (Burma) and the northern portion of the Malay Peninsula to the east, and Sri Lanka and India to the west. The International Association Hydrographic Bureau defines the southern limit as extending from the northern extremity of the Indonesian continent of Sumatra in the east to Dondra Head at the southernmost point of Sri Lanka in the west. The bay has an average depth of around 8,500 feet (2,600 m) and a width of over 1,000 miles (1,600 km). 15,400 feet (4,694 m) is the greatest depth. Fig. 17 shows

the topography and depth of BOB.

The BOB receives water from several major rivers, including the Ganges (Ganga) and Brahmaputra in the north and the Mahanadi, Godavari, Krishna, and Kaveri (Cauvery) in the west. The bay is divided from the Andaman Sea by the Andaman and Nicobar groups, which are the only islands [77].

Bangladesh has a long coastline of 710 km with an average tidal variation of 2 m to 5 m. The Sundarbans location is close to Hiron Point, Khepupara, and Charchanga, which are encircled by several tidal rivers and creeks. Hiron Point is situated close to the Passur River's mouth. Khepupara is situated in the shallow area to the west of Pokhkhair Char and Dimer Char. On the western end of Hatia Island, at the entrance of the Meghna River, Charchanga is encircled by a number of smaller islands. Jahaizzer Char is a recently constructed island with two separate channels on its east and west sides that is close to Sandwip. Saint Martin sits on Bangladesh's southernmost point, and the tide station at Cox's Bazar is about ten kilometers offshore from the Maheshkhali Channel. The typical tidal range in these places' ranges from 5 m during the monsoon to 2 m during the dry season. These seven locations were chosen because they have small mouths, deep channels, and modest basin areas, which make it simpler to build tidal barrages [78]. Fig. 18 shows the predicted energy and daily tide water level. Table 4 represents Tidal potential along BOB coastline.

These are the potential locations to construct TEC according to demand.

3.3.2. Energy conversion equations

To calculate the extractable energy and power from wave, the following equations (Eq. 05 to Eq.07) are usable: [73].

$$E = \rho g \int_{h=0}^{h=R} h A dh \quad (5)$$

$$E = \frac{1}{2} \rho g A R^2 \quad (6)$$

Taking $P = E/t$, the average power (in kW) comes out to be [73],

$$\bar{P} = \frac{\frac{1}{2} \rho g A R^2}{T} = 1025 \times 9.81 \times A \times \frac{R^2}{44700} = 225 A R^2 \quad (7)$$

The tide station at Cox's Bazar is around ten kilometers offshore from the Maheshkhali Channel, while Saint Martin is situated on the

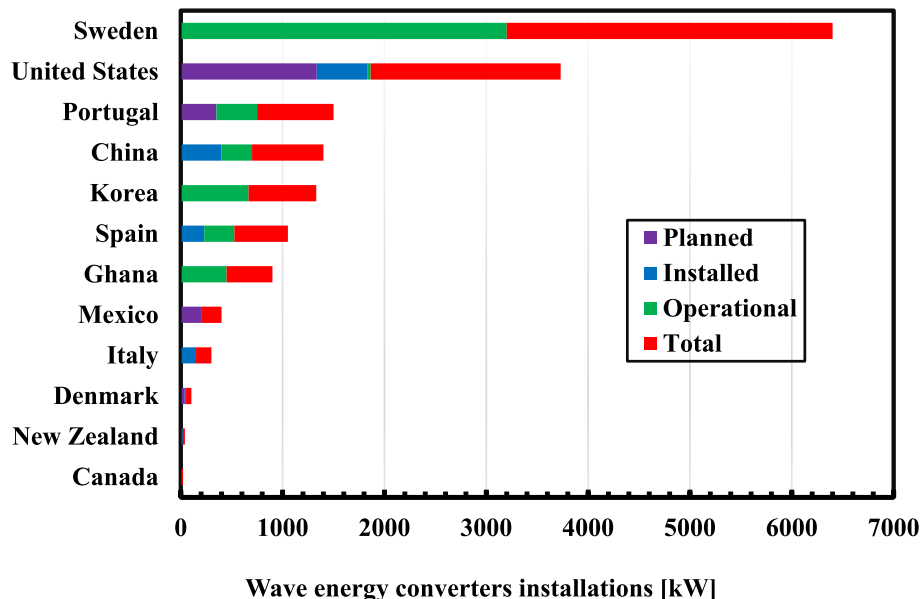


Fig. 19. WECs Installations (kW) around the World [27].

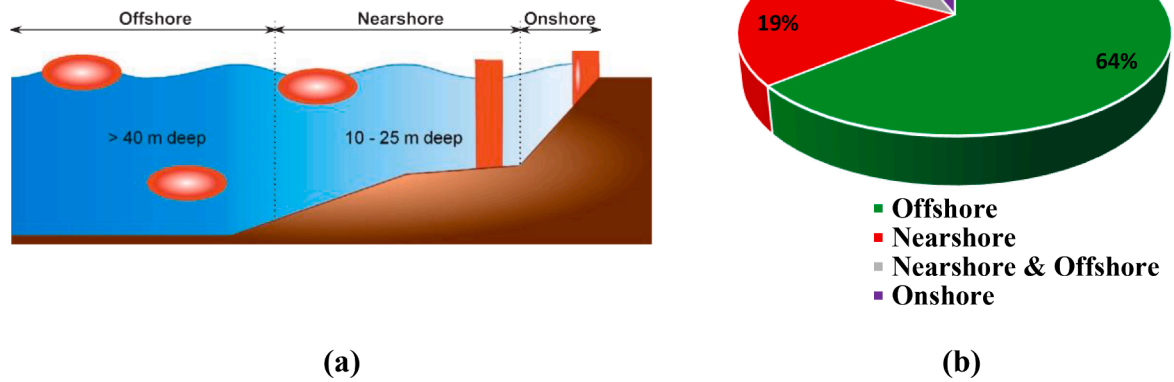


Fig. 20. (a) Location and dimensions of the wave energy converters [2] and (b) WEC designed available based on Location [22].

southernmost tip of Bangladesh. In these locations, the average tidal range is 2 m during the dry season and 5 m during the monsoon. These seven sites were picked because they had moderate basin sizes, deep channels, and tiny mouths that make it easier to construct tidal barrages ($Q = AH/t$) through the turbine the work done by falling water through h height is given by (Eq.08)

$$P = \rho Q h \quad (8)$$

Power generation potential for 705 tidal cycles by a η efficiency turbine in a year is equating by Eq. 09 [73],

$$P_{year} = \int_0^t P dt = \int_0^t \frac{\rho \eta Q h}{75} \times 0.736 \times 705 dt P_{year} = 7092.3 \eta \int_0^t Q h dt \quad (9)$$

Tidal power generation capacity increases with tidal range [80]. According to [73], Tidal current power is computed as an expression of peak springtime velocity, velocity accessibility coefficient, neap/spring coefficient, and saltwater density movement. Yet, because of Betz's law and mechanical degradation in the turbines, all tidal current energy cannot be converted. The power coefficient is used to account for these restrictions.

4. Global ocean energy conversion technologies

4.1. WEC technology

A WEC is designed to transform the kinetic and potential energy of ocean waves into electrical power [22], and recent assessments indicate that more than 50 wave energy devices are currently at various stages of development [81,82]. Fig. 19 shows WEC installations. A typical WEC comprises a wave energy capture structure and prime mover, a foundation or mooring system, a power take-off mechanism to convert mechanical energy into electricity, control systems for performance optimization and protection under varying conditions, and an electrical connection to transmit power to the grid [22].

Wave energy may be extracted from the ocean using a number of technologies with a broad range of structures, extraction mechanisms, and uses [22]. More than one thousand prototypes have been developed worldwide [2,83]. Therefore, these WECs are classified into several groups according to some characteristics: location, size, working principle, etc. [2].

4.1.1. Onshore device

Those types of converters are located at the coastline in shallow water and consist of a dam. They don't have the mooring system, which allows them to be installed with lower cost comparing to other devices. Because these devices are located on the shore, they don't need a long

Table 5

The offshore available energy test sites [2,86–89].

Name	Location	Start Date	Wave Resource
Amets	Belmullet (Ireland)	2012	—
Wave hub	Cornwall (England)	2011	>20 kW/m
Plocan	Canary island (Spain)	2011	—
Runde	Runde (Norway)	2009	40–50 kW/m
Danwec	Hanstholm (Denmark)	2009	16.3 kW/m
SEM-REV	Pays de la loire (France)	2008	14.4 kW/m
Pilot zone	North sao pedro de Moel (Portugal)	2007	32 kW/m
Wave power	Lysekil (Sweden)	2006	3 kW/m
Emec	Orkney Island (Scotland)	2004	40 kW/m
Hinnmrec	Kaneohe (Hawaii)	2003	12 kW/m

sea cable to transmit power to the grid and provide easy maintenance. This is the main advantage of this type of device. Also, there are some disadvantages too. Because waves have less energy due to their impact with the seafloor, onshore devices convert less energy. Installing these kinds of devices is also made more difficult by the lack of land that is an appropriate site [2,22].

4.1.2. Nearshore device

These devices are typically positioned a few hundred meters from the coast, roughly 10 to 15 km [22] away, with water depths ranging from 10 to 25 m [2]. Since they lack moorings, the structure is subject to the stress created when waves pass over it. Usually, this device is found on the ocean floor. However, floating structures also exist in certain situations [4,84,85].

4.1.3. Offshore device

Offshore devices are located in the deep water, far away from shore, with a depth of more than 40 m. They have floating and submerged structures moored to the seabed. Those devices can harvest more energy than onshore and nearshore devices, as deep-water waves contain more power. But these are not easy to construct and have expensive maintenance. They should be strong enough to withstand the water pressure and wave thrust. Furthermore, long, expensive sea cables are needed to transmit power to the grid. Currently, about 64% of WEC devices are designed as offshore devices [2,4,84,85] (Fig. 20). Table 5 represents the offshore energy test.

Based on López et al. [2], which presents a category of offshore wave energy conversion technologies based on their working procedures, including OWC, pressure differential, floating structures, overtopping, and oscillating wave surge impact systems. It further categorizes devices

Table 6

Principal developers of the Attenuator type of WEC and their technologies Haces-Fernandez et al. [11].

Technology	Country Base
Rock n Roll	India
FFWEC	India
WAG Buoy	Japan
Ocean Star ocean power system	USA
Floating Wave Generator	USA
Wave berg	USA
Salter Duck, Sloped IPS	UK
Pelamis	UK
Wave Turbine	UK
Hybrid Float	UK
DEXA WAVE Converter	Denmark
Wave Piston	Denmark
Poseidon's Organ	Denmark
Wave Energy Propulsion	France
PSE-MAR	Spain
Vortex oscillation	Russia
Vigor Wave Energy Converter	Sweden
The B1 Buoy	Norway
Sea Power Platform	Ireland

according to installation location (onshore, nearshore, and offshore) and highlights representative commercial or pilot projects implemented in different countries. This comparative framework provides a systematic understanding of technological diversity, deployment environments, and global development trends in marine renewable energy systems. Table 6 demonstrates the principal developers of Attenuator. Fig. 21 shows the offshore wave energy sites.

4.1.4. Technologies according to the wave

4.1.5. Attenuator

Attenuator wave energy converters are long, segmented devices aligned parallel to incoming wave direction, where they reduce wave amplitude by riding the waves, as shown in Fig. 22(a)(b) [2]. These devices generate power through relative motion between connected segments, where hydraulic pistons compress oil to drive a hydraulic motor and generator, utilizing heave, sway, and surge motions [2,4,84,85]. A well-known example is the Pelamis device (Fig. 22(c)), developed by Pelamis Wave Power, which consists of multiple cylindrical steel floating sections linked by hydraulic hinges; each hinge contains hydraulic rams, accumulators, motors, and generators to extract energy from pitching motions during wave activity [2,4,84,85].

4.1.6. Point absorber

Point absorbers are the simplest wave energy converters, characterized by their small size relative to the incident wavelength and a floating body that moves vertically with incoming waves from all directions, making wave direction insignificant. They operate mainly on heaving motion using an internal hydraulic system to drive a generator, with the entire power take-off mechanism housed within the device. Although individual units have relatively low power ratings (a few hundred kW) and limited resistance to extreme storm waves, they can efficiently extract energy at optimal wave frequencies and heights, be deployed in large arrays, and are best suited for offshore deep-water locations [2,22]. Table 7 shows the technology for the point absorber.

Fig. 23 shows the concept of a point absorber. The Power Buoy with 150 kW of power technology [21], created by Ocean Energy Technologies, a US-based company [2], is one of the strongest absorption devices that is currently in use worldwide. As seen in Fig. 24, the Power Buoy is made up of a float, spar, and heave plate. As the waves pass, the

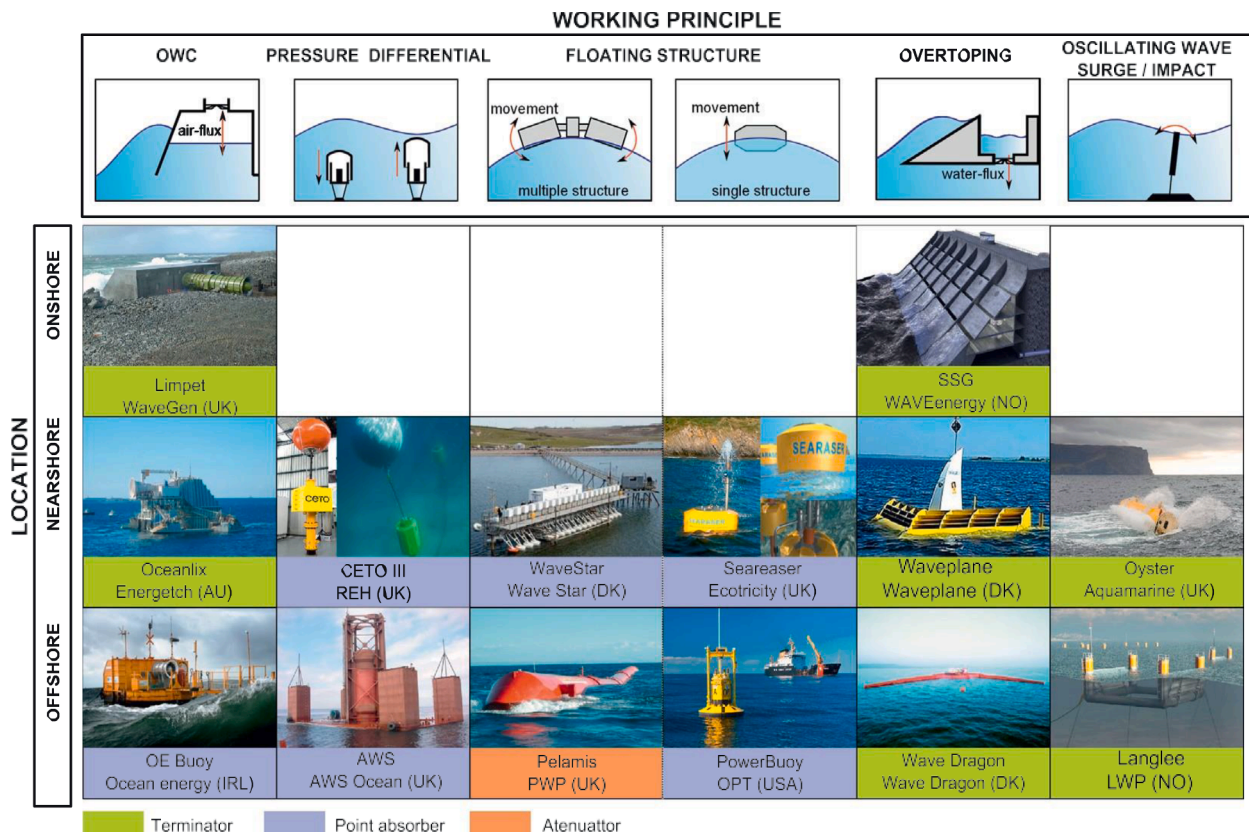


Fig. 21. Offshore wave energy test sites [2].

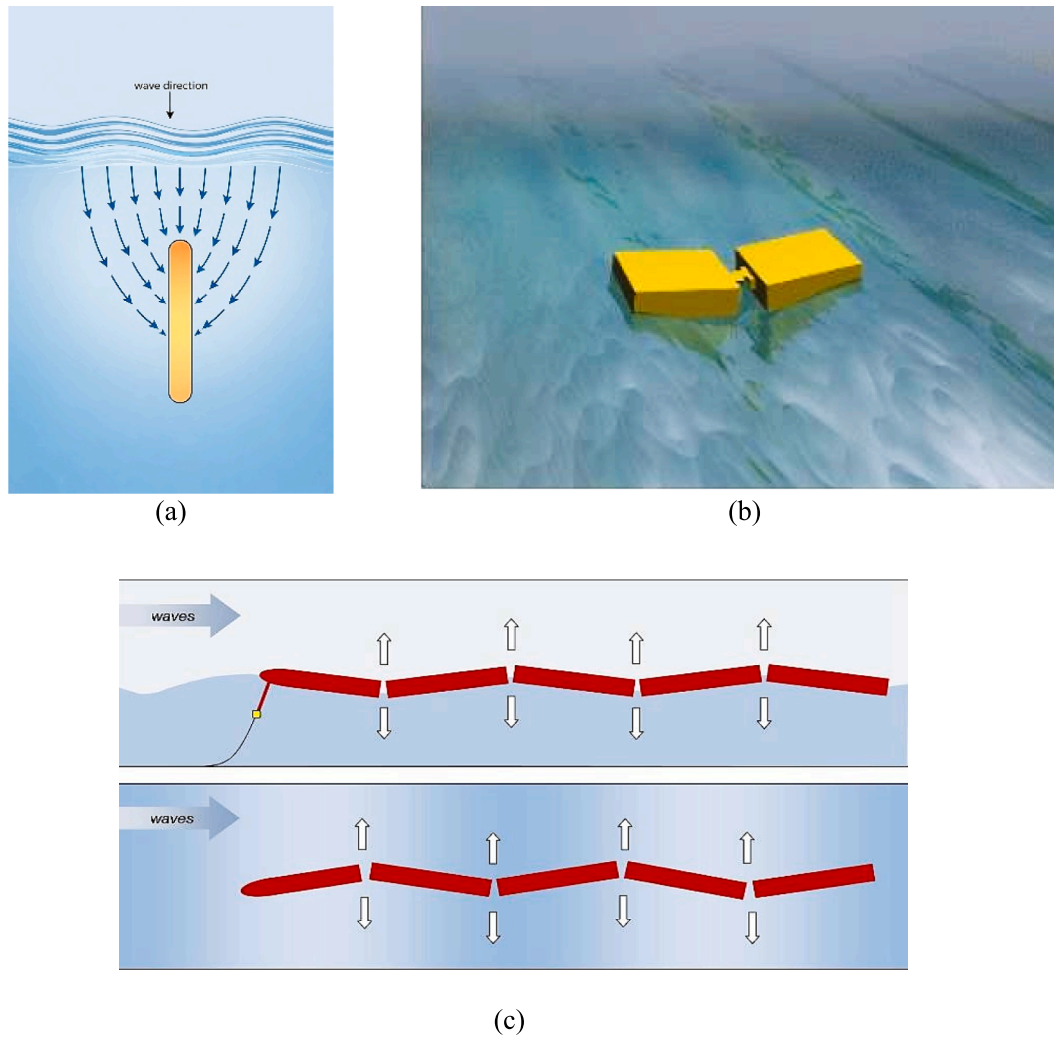


Fig. 22. (a) Schematic Diagram of Attenuator (b) Basic Concept of Attenuator Device (c) Concept of Pelamis WEC [22].

Table 7

Technology available for Point absorber lopers Haces-Fernandez et al. [11].

Company	Technology	Country Base
Indian Wave Energy Device	IWAVE	India
Able Technologies L.L.C	Electric Generating USA Wave Pipe	USA
AeroVironment Inc	eel Grass	USA
Aqua-Magnetics Inc	Electric Buoy	USA
Independent natural resources	SEADOG	USA
Applied Technologies Company Ltd	Float Wave Electric Power Station	Russia
Arlas Invest	TUVALU	Spain
AWS Ocean Energy	Archimedes Wave Swing	UK
Ecotricity	Searaser	UK
Embley Energy	Sperboy	UK
Brandl Motor	Bran dl Generator	Germany
Fred Olsen & Co.	SEEWEC	Norway/EU
Hann-Ocean	Drakoo	Singapore
Hydrocap Energy	Seacap	France
Lancaster University	PS Frog	England
Manchester Bobber	Manchester Bobber	UK

Float moves up and down like a piston. The spar is kept comparatively stationary by the heave plate. The mechanical system is driven by the angle of movement of the float in relation to the spar. The float's linear motion is transformed into rotary motion, which propels the generator

to generate more power. The device's entire power take-off system is sealed inside. The structure can move freely up and down because it is only loosely moored to the seabed. Ultimately, a transmission cable is used to deliver the generated electricity to the shore. Under the most difficult maritime conditions, its energy transformation and maintenance provide constant power. Additionally, the spar has more room for a battery that supplies power during prolonged periods without waves [22]. Fig. 25 demonstrates an inverter pendulum.

4.1.7. Terminator

These devices are also long structures similar to Attenuators. They essentially “terminate” the wave activity since they are positioned orthogonal to the primary path of the wave's spread [2]. Sometimes it is also positioned at a slight angle to improve the performance. Salter's Duck Device is a terminator-style device that was created at the University of Edinburgh in the United Kingdom. In 1973, Stephen Salter, an Emeritus Professor at the University of Edinburgh, created this apparatus. In this device, the Duck rotates in a nodding motion as waves pass by. The movement is used to compress air or pump hydraulic fluid, which powers the hydraulic motor or as turbine that powers the generator. Table 8 shows OWC technology. Fig. 26 shows schematic diagram of Functioning of Duck.

Although this device's effectiveness was 90% in theory, it only reached 50% in testing in laboratories Production [90]. This program was disbanded in 1980. Another example of Terminator is the Wave Plane converterProduction [90]. Table 8 shows the principal developers

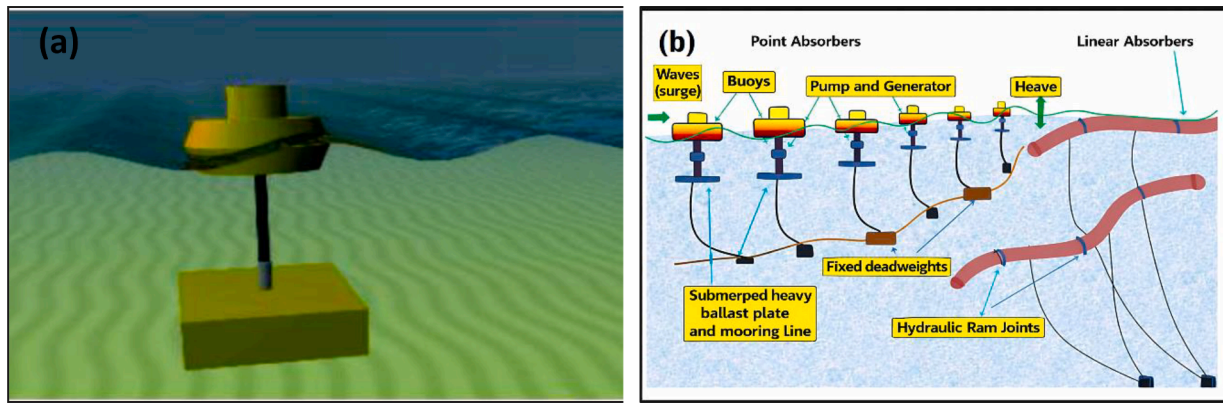


Fig. 23. (a) Basic concept of Point Absorber device [23],(b) combined unit of point absorber (Khan et al., 2017).

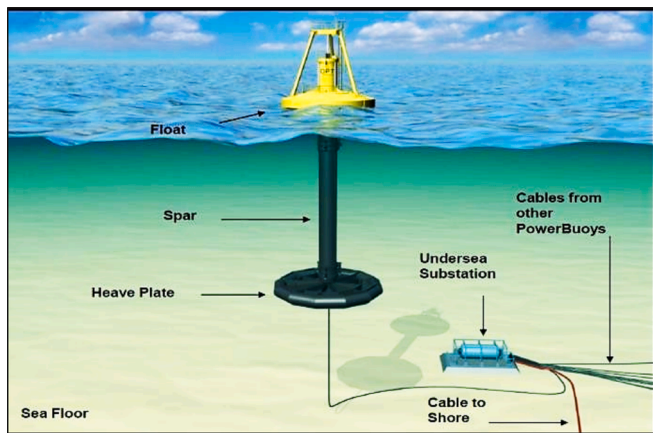


Fig. 24. Internal details of power buoy [22].

of Overtopping.

4.1.8. OWC

Fig. 27 shows a device with an oscillating water column. There is a round chamber that is partly underwater and has one end open to the sea. To make it work better, it is sometimes put at an angle. The top of the container is completely closed off. A column of air stays trapped under the structure that is underwater. Because of the waves, seawater comes in and out of this chamber from time to time. When water goes into the chamber, the air above it gets compressed. When the water leaves the chamber, the air above it gets less compressed. During the process, air over the water chamber is put under pressure. This high-pressure air can turn a turbine, which makes electricity. The turbine must only turn in one direction, even though the air can flow in both directions. The Wells turbine, a unique kind of turbine installed atop the chamber, is used to extract energy. Narrowing the air chamber increases efficiency and speeds up air currents. It is possible to install this device offshore or in shallow water. Compared to the traditional one, U-OWC performs better Khan et al. [1,22,46,91]. A U-OWC device is depicted in Fig. 28. Table 9 shows the available OWC technology.

4.1.9. Based on the working principle

Below is another grouping of devices according to their operation [4]; Masuda, 1986; [31].

4.1.10. Pressure differential

The Archimedes impact converters and OWCs are the two sub-categories of devices that fall under the pressure differential type. The first type is a floating-point absorber that is typically fixed to the seafloor

and found close to shore. It utilizes the pressure differential created by the wave crests and troughs across the apparatus. The pressure of water compresses the trapped air in the device, causing it to move downward when the wave's crest passes over it. The pressure of water will drop, and the device will rise if a wave passes through it [2]. The 250 kW Archimedes Wave Swing (AWS) [92], which is categorized based on its characteristics in Fig. 29, is an example of this kind of converter. The OWC is typically found close to or on the shore. Utilizing a partially submerged chamber that is open at the bottom to move the internal air volume, the waves' reciprocating movement raises and lowers the water level. Despite being bidirectional, this air flow powers a turbine known as a Wells turbine, which rotates consistently in the same direction. The Ocean Lix 500 kW development ([93]) (Fig. 30), as a near-shore structure, and the Limpet 500 kW power station [94] as a shore straight fixed structure are examples of this technology.

4.1.11. Floating structure

These kinds of devices are reliant on the flotation of the body, and that is shifted by the waves. Pitch, vertical, or any combination of these oscillatory movements can be used. Additionally, the movement can be generated on more than one body, or it is found as absolute movement between the body that is floating and another fixed reference. The Searaser WEC [95] is an example of a single floating structure, while Wave Star[96,97] is an example of a multiple floating structure (Fig. 30).

4.1.12. Overtopping device

By raising the water level of a reservoir above sea level, the overtopping wave power device, depicted in Fig. 31, is an onshore to near-shore for capturing wave movement and transforms it into potential energy. Either a floating structure attached to the seafloor or a fixed one can be used. The waves enter a raised lake to fill it after striking the structure and flowing through a ramp. This produces a low head, which is subsequently taken out by gravity via a small head Kaplan turbine that is mounted at the device's base to produce electricity. They are only appropriate for deep water shorelines and have relatively low power output because of their low head. Table 10 represents the Comparison of different types of WEC.

A Wave Dragon is a practical use of an overtopping-type device. It is a sizable floating structure made up of a reservoir and two wave reflector arms. The waves are guided by the reflector arms into a ramp that leads to an overhanging reservoir where the water is collected and momentarily stored. Through a series of small Kaplan turbines, the water leaves the reservoir. It is among the most substantial structures for harnessing wave energy to produce electricityKhan et al. [1,2,22].

Based on Table 10 and the previous discussion, it can be understood that Point Absorber and Oscillating Water Column (OWC) technologies can be relatively viable options for the Bay of Bengal (BOB) region.

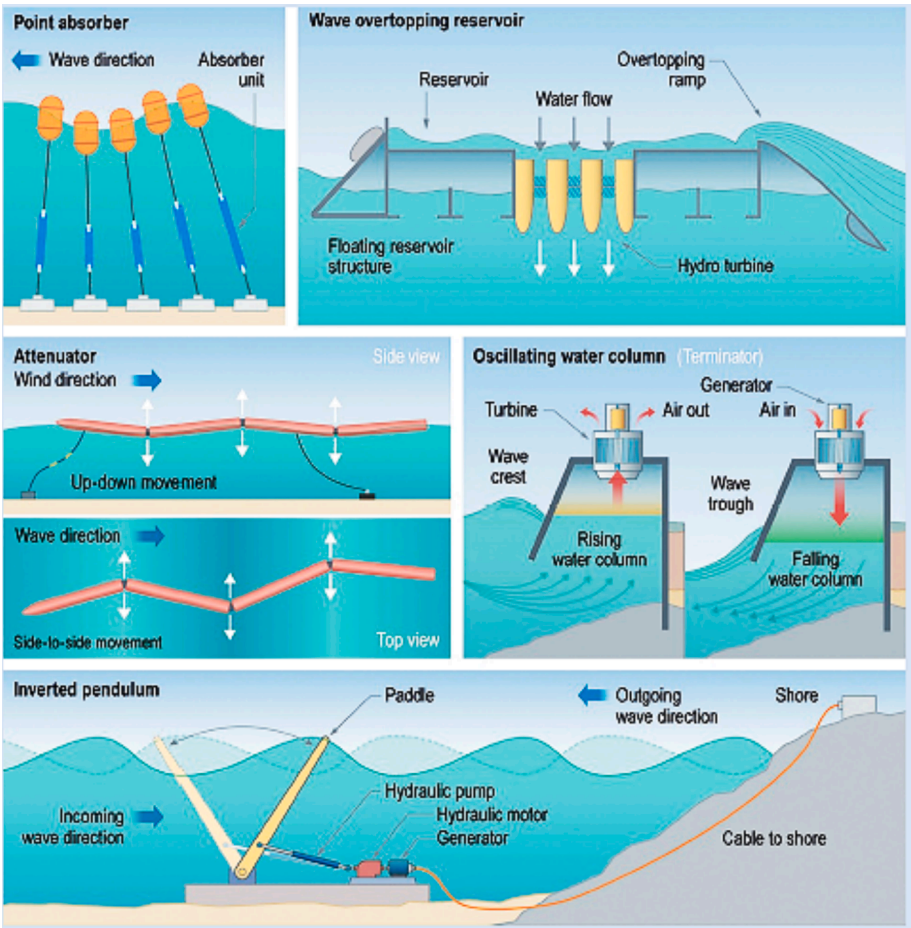


Fig. 25. Point absorber, wave overtopping reservoir, attenuator, OWC, inverter pendulum [10].

Table 8
Principal developers of Overtopping/ Terminator Devices [2].

Company	Technology	Country Base
JAMSTEC	Mighty Whale	Japan
Wave Dragon	Wave Dragon	Denmark
Wave Energy AS	Seawave Slot-Cone Generator	Norway
WaveTORK	WaveTORK	USA
Portsmouth Innovation Ltd	Wavestore	UK

However, the suitability of a wave energy converter cannot be determined solely on the basis of structural simplicity or small size. In addition to the structural characteristics of the device, factors such as the regional wave climate type, ability to survive extreme monsoon and cyclone conditions, installation and logistical convenience, local operation and maintenance capabilities, and potential environmental impact risks need to be considered. Fig. 32 shows the percentage of wave energy converter development.

The Bay of Bengal is characterized by moderate to highly seasonal wave conditions, where relatively high wave energy is generally available during the monsoon season. At the same time, severe sea conditions

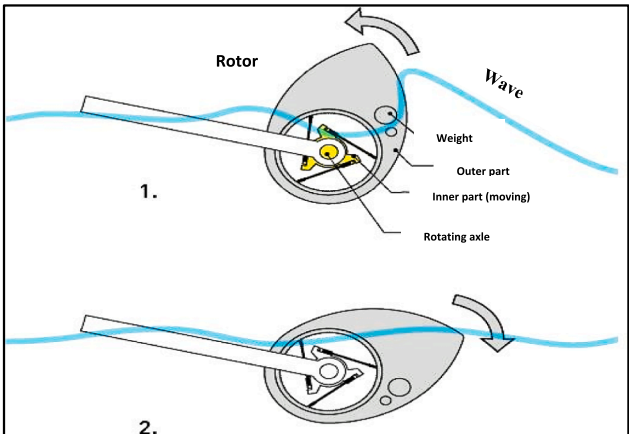
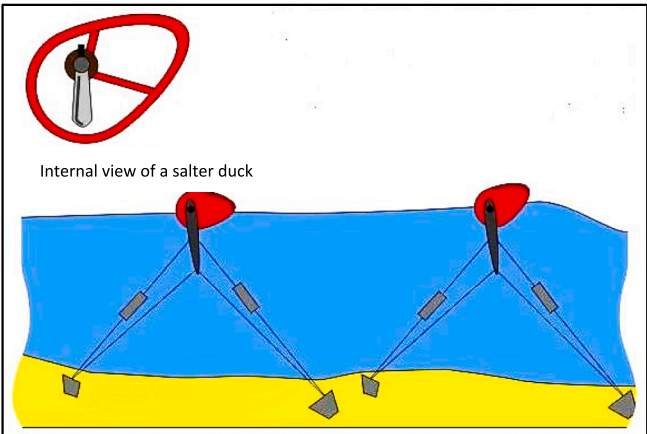


Fig. 26. Schematic Diagram and Details of Functioning of Duck [22]; WavePlane Production, n.d.).

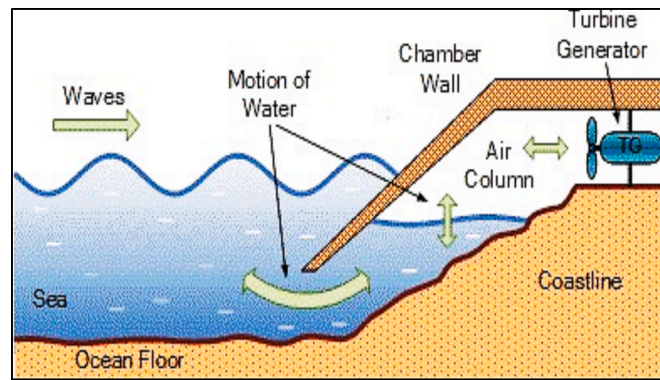


Fig. 27. Concept of OWC [19,22].

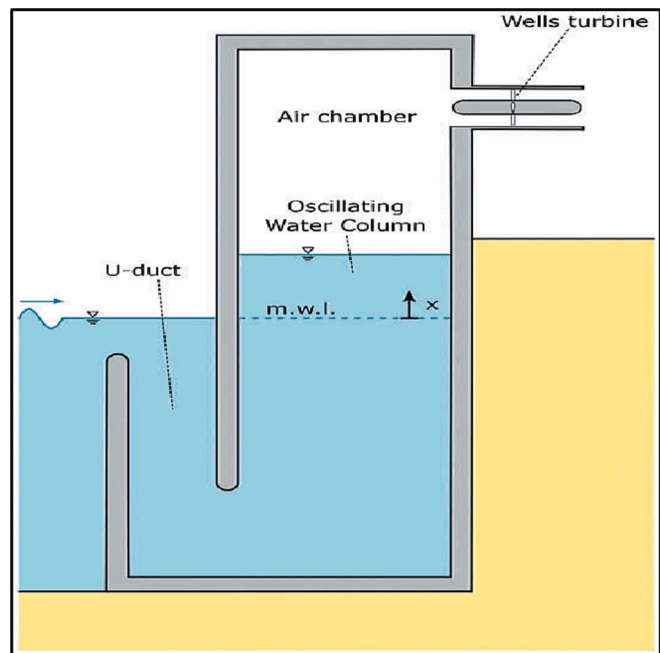


Fig. 28. Schematic of U-OWC [19,22].

Table 9
Available OWC technology [2].

Company	Technology	Country
Grays Harbor Ocean	Titan Platform	USA
Dresser-Rand	Hydro Air	USA
New Energy Solutions LLC	Oscillating Cascade	USA
Fobox AS	FO ₃	Norway
Hydro Gen	Hydro Gen 10	France
Instituto Superior Tecnico	Pico OWC	Portugal
Voith Hydro Wavegen	Limpet	UK
Union Electrica Fenosa of Spain	OWC	Spain
RWE Power Renewables Ocean Energy Ltd.	Ocean Energy Buoy	Germany
Oceanlinx	Green WAVE / Blue WAVE	Australia

during cyclones can have a significant impact on the stability and long-term performance of offshore wave energy systems. Considering these regional constraints, point absorber and OWC technologies appear to be relatively suitable, as they are relatively simple in design, have moderate installation requirements, and are more adaptable to changing wave conditions compared to large attenuator systems. However, further

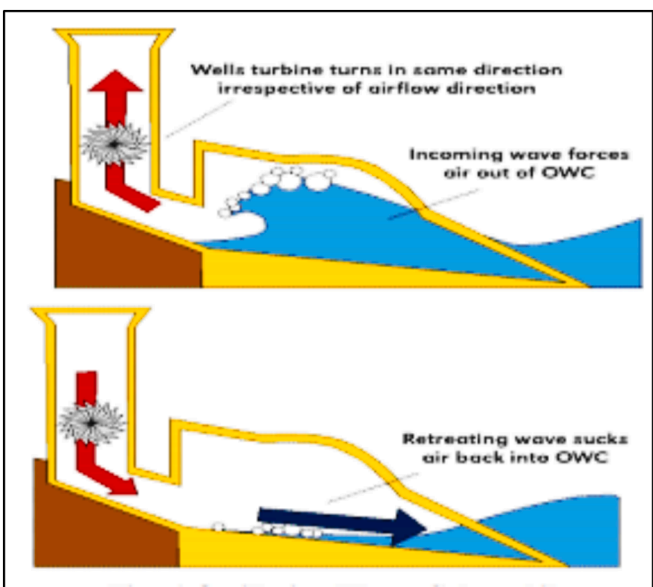


Fig. 29. Working of Well Turbine during Nearshore Incoming OWC Plant [19,22].



Fig. 30. Ocean Linx 1 MW and Retreating Waves [22,81].

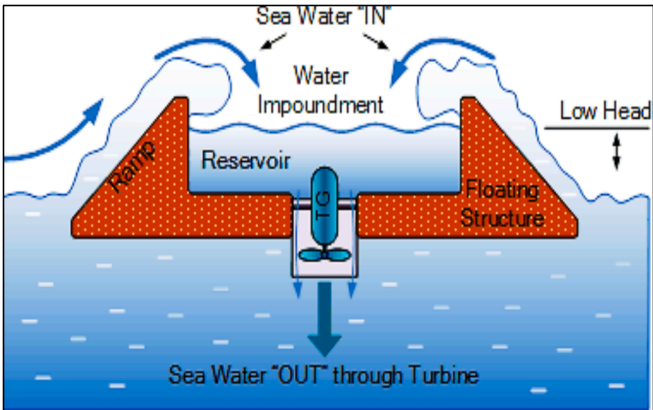


Fig. 31. Schematic Diagram of Overtopping Device [22].

Table 10

Comparison of different types of Wave energy converters technology Khan et al. [1].

Topics	Point Absorber	Overtopping	Wave Attenuator	Oscillating Water Column
Cents/KW	12–20	8–12	10–15	10–17
Leadership	Europe	Europe	Europe	Australia
Rated Power	500 kW–1 MW	4–7 MW	750 kW	500 kW
Power Conversion Rate	<14%	18%	<14%	<14%
Mooring	Slack	Slack	Fixed Bottom	Four Legs Slab
Wave Energy Utilization	Vertical only	Vertical only	Vertical only	Vertical only

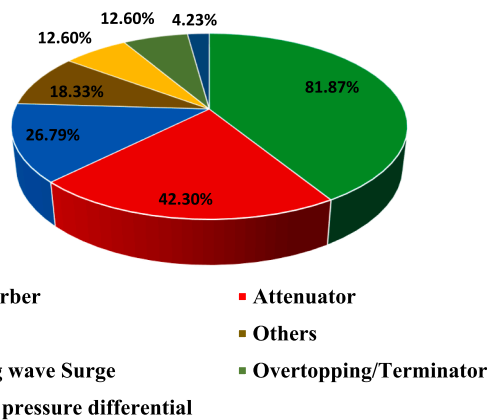


Fig. 32. Percentage of wave energy converter development [2].

experimental verification, hydrodynamic analysis, and techno-economic evaluation are required before large-scale practical application in the Bay of Bengal region can be confirmed. Table 11 shows the performance of different types of WEC and Table 12 for Wave Energy resources, projects, and plans of different countries.

4.2. Tidal energy technology

Tidal energy exploitation may be done in two essentially distinct ways. The initial is to use barrages, which draw energy from a potential head of water in a manner akin to the production of hydropower, to take advantage of the cyclical fluctuation of sea levels. Utilizing regional tidal currents in a way that is somewhat similar to hydroelectric power is the

next step. This technique uses tidal electricity conversion devices, such as tidal turbines, to harvest the kinetic energy of the flowing water [73].

4.2.1. Tidal energy barrage

This is an old way to harness tidal energy by building a barrage or dam-type structure across a designated coastal area to utilize the elevation of water between high tide and low tide. Tidal barrages operate in a similar principle to hydropower plants. Though America and Canada started developing tidal barrages in the 1930 s, the first tidal barrage was built in 1966, the La Rance tidal barrage in France.

4.2.2. Tidal current converter

These types of converters extract energy (Figs. 33–38) from current or a stream of water that moves with tidal activities. The working principle is similar to a windmill. It needs less infrastructure to begin with, which reduces the installation cost significantly. Tidal waves, river waterways, and ocean waves are often used with TEC designed for marine movements. To address the key technological ideas behind how devices work, a number of categories have been developed. According to the international nomenclature, the first categorization is determined by the type of equipment [99]. Five different categories exist [67,100]:

- ° Horizontal Axis (HA) Devices use the lift produced by blades to rotate a rotor. The spin is then transformed into electricity using a power source. Though they are smaller and function underwater, these devices share a principle with the conventional axial rotor machines used for the wind sector. These devices fall under one category: open rotor devices [101,102] and turbine-type devices [103].
- ° Vertical Axis (VA) devices use the lift produced by the blades to rotate the rotor situated on a vertical axis. The blades may be helical or vertical. Additionally, the blades may have an oscillating shaft while they are upright. A generator is used to transform the spinning into electrical energy. These devices' energy conversion components are often situated outside of the water [67].
- ° HA Perpendicular Axis: Their actions resemble those of the vertical axis devices quite a bit. These gadgets work best in shallow environments.
- ° Oscillating Hydrofoil: It functions similarly to a fish's tail fin. To produce an oscillating motion, the control system modifies the foil's pitch. The movement in question powers hydraulic cylinders, which in turn power a motor responsible for energy transformation.
- ° Helical Screw: As the water rises over the rotating part, these devices capture electricity from the wave movementHaces-Fernandez et al. [11].

Table 11

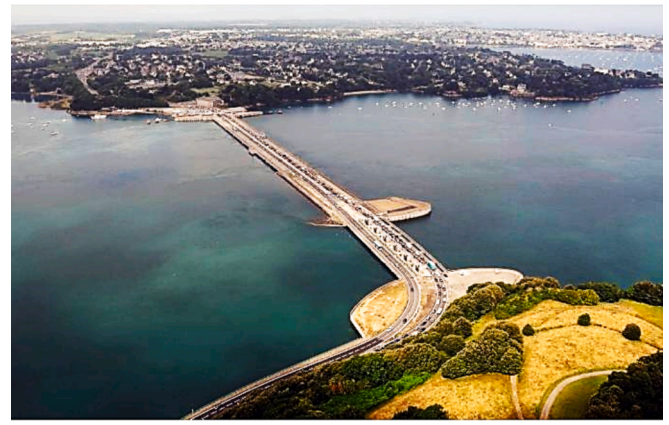
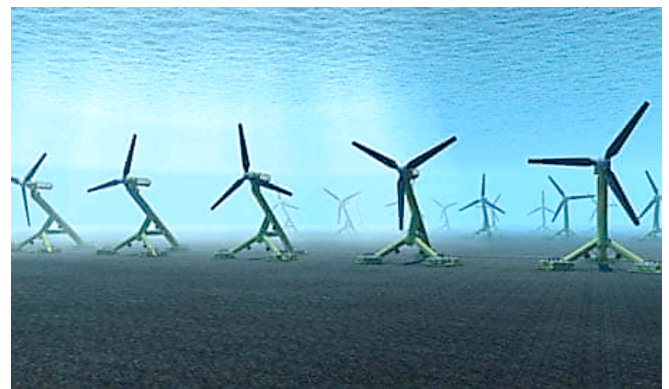
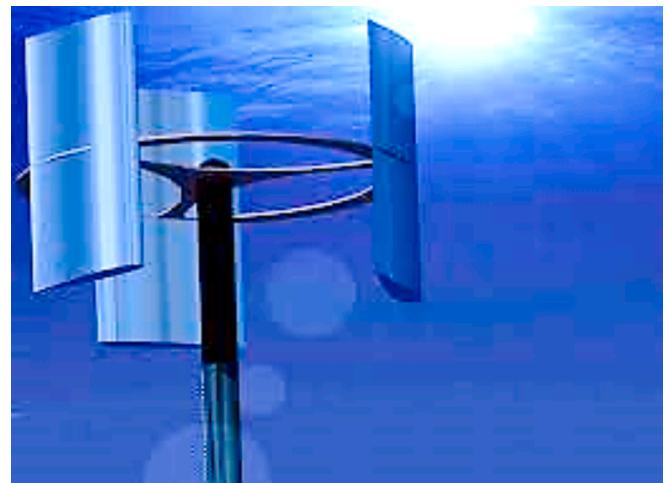
Comprising list of the hydrodynamic performance of different types of WEC [98].

Category	Sub-category	Average hydrodynamic performance	Min.	Max.	Typical Size	Reference dimension
OWC		33%	20%	45%	30 m	Width
Overtopping system		13%	4%	235	300 m	Width
System driven by waves	Small heaving buoy	9%	3%	14%	5 m	Width
	Large heaving buoy	29%	19%	42%	20 m	Width
	Bottom fixed oscillating flaps system	41%	25%	65%	20 m	Width
	Floating oscillating flaps system	20%	14%	36%	25 m	Width
	Floating system combining surge/heave/ pitch	17%	6%	27%	30 m	Width

Table 12

Wave Energy resources, projects, and plans of different countries around the world Khan et al. [1].

Country	Coastline	Wave resource	Wave energy projects	Present and plans
China	14,500 Km		The Guangzhou Institute of Energy Conversion has constructed onshore oscillating water columns with capacities of 3 kW, 20 kW, and 100 kW, as well as a 5 kW backward bent duct buoy oscillating water column. Two 8 kW and 30 kW pendulum wave energy converters are located onshore. A floating duck device with a 10 kW capacity was installed at the end of 2009.	The project cost is too high. However, projects are undertaken to construct WECs in islands where fossil fuels are expensive.
France	4,853 Km	28 GW	Research on creating wave-absorbing pads for wave basin equipment has been going on since 1995.	In 2013, an agreement was signed for developing a 1.5-megawatt wave power demonstration project in Bretagne. In a subsequent stage, nine more buoys with a 125 kW capacity will be added to the pilot plant on the Santona coast. The electricity produced by the plant will be enough to power 2,500 households.
Spain	4,964 Km		A commercial OWC wave power plant opened in Mutriku, which will produce about 300 kW of electricity. A 40 kW power buoy was installed four kilometres from the coast of Santoña as the first phase of the development of a pilot plant.	The construction of a 10 MW power plant has been announced. Ten more plants will be built after this one, which has a 10 MW initial capacity.
Srilanka	1,340 Km		The Ministry of Science & Technology funded the development of a 150 kW demonstration OWC device. This comes after successful testing of a prototype in 2000.	Discussions are ongoing to initially construct a 10 MW wave power station in Gujarat and expand it across India in the long run.
India	7,000 Km	40,000 MW per annum	Along with the development of additional WECs, such as the OWC and the OD, a 100 kW illustration plant.	By FY2050, 12.03 M kW of wave power and 1.92 M kW of tidal power are anticipated by the Ministry of the Environment's Central Environment Council.
Japan	29,751 Km	87 TWh per annum	A prototype OWC of 60 kW capacity was constructed on the port of Sakata in 1990.	

**Fig. 33.** Available Tidal barrage [104].**Fig. 34.** Available horizontal axis turbine (array) [105].**Fig. 35.** Available vertical axis turbine [106].

⁶ Tidal Kite: These items are made up of a turbine connected to a wing that travels in loops over the ocean and is connected to the seafloor by a moving cable, much like a kiteHaces-Fernandez et al. [11].

The wide range of tidewater energy methods and equipment that transform tidal power into mechanical energy is demonstrated by the prior analysis. The efficiency assessments depend on standard hydrodynamic concepts and have a reasonably wide range. The larger density of energy, yet, is found at altitudes above 80 m when we take into

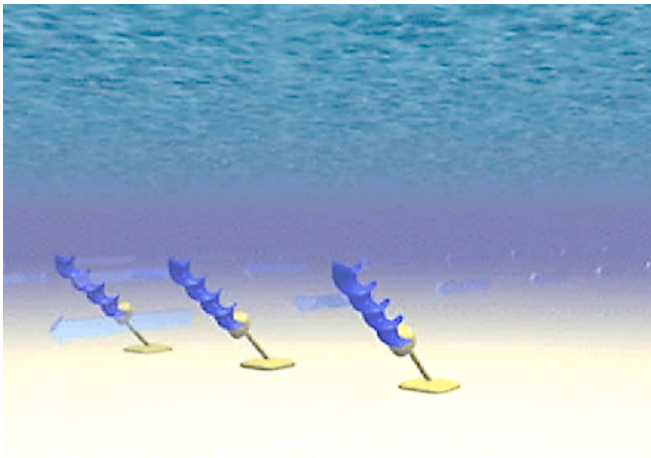


Fig. 36. Available helical screwHaces-Fernandez et al. [11].

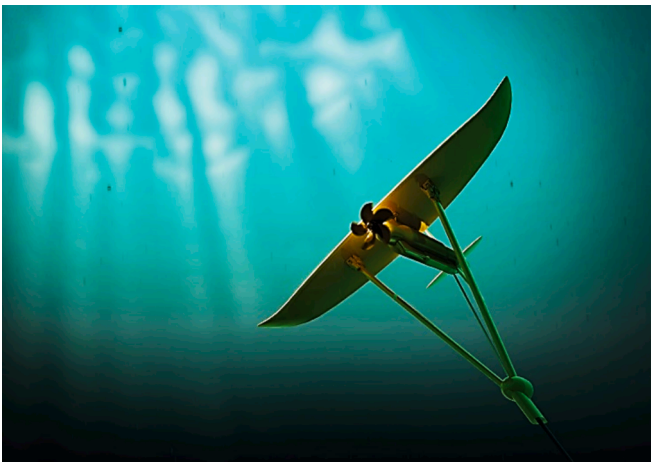


Fig. 37. Available tidal kite [107].



Fig. 38. Available oscillating hydrofoil [108].

account the levels at which such kinds of devices may be put. As a result, a second categorization of apparatus based on the water column's depth may be carried out [67]. Fig. 39 shows TEC foundation type.

⁶ Devices that are tethered to the sea floor are considered first-generation devices. They may function up to 40 m below the surface. The TEC can be fixed to the sea floor using the following

methods. Monopile: The TEC is installed atop a tubular steel tower that is buried in the ocean floor. This design can only be used in water up to 30 m deep. Piloted: Small-hole foundations support the structure responsible for maintaining the TEC on the sea floor. Gravity: A significant mass supports the structure responsible for maintaining the TEC on the ocean floor. Second-generation devices: They may be attached to the seafloor using mooring or anchoring lines and have the ability to float. These floating gadgets engage with the water–air interface, or free surface. Because they may be positioned at the appropriate depth using buoys and wires, other devices that function entirely underwater with mooring lines are an excellent idea for harvesting energy from extreme depths.

⁶ Devices capable of harnessing energy from modest velocity streams are classified as third-generation devices. The authors believe that the international community has not given this third group enough attention [67].

4.3. Modern tidal energy conversion technologies

The conventional tidal energy conversion technologies are base of the modern concept He et al. [109]. The recent development is a more focused, flow-induced system. The emerging and modern technology focuses on increasing the performance under varying conditions like hydrodynamic variations, flapping foil systems, etc.

4.3.1. Oscillating hydrofoil

Hydrodynamic foils are responsible for generating oscillation and utilizing the periodic motion, such as pitching and heaving. This oscillation is converted through the technology. This technology converts the oscillation into mechanical energy or electrical energy or electrochemical transmission Sheng et al. [110]. But compared to the conventional tidal energy conversion system, this system converts based on the foil geometry, oscillation height, pitching frequency, fluid interactions, etc. This emerging technology has shown moderate efficiency in terms of lower to medium oscillation with medium to higher efficiency Mo et al. [111].

4.3.2. Flapping and Biomimetic system

This is the modern and nature-inspired model. This is developed based on the swimming mechanism of the fish and marine mammals Mo et al. [112]. The Technology utilized the combined pitching and plunging motion to produce a lift force and a vortex in the energy harvesting phenomena Ai et al. [113]. The more the interaction, the more the vortex generation with increasing energy extraction efficiency. The technology with optimization can be most emerging technologies with higher efficiency He et al. [114].

4.3.3. Vortex-induced Vibration system

In this technology, around the bluff bodies, an alternating vortex is generated, and a periodic oscillation is found. The induced oscillation is responsible for the conversion of tidal energy to power or electromagnetic. Compared to the conventional, it is mostly significant technology with amazing marine environmental and control effect Badhurshah et al. [115].

4.3.4. Cross-flow oscillatory system

This is the combination of hydrofoil and cross-flow configurations. Where the interaction between structure and fluid becomes flexible for the system Sheng et al. [110]. This technology has advantages in adaptability in multidirectional flow and enables harnessing the energy. The overall conversion technology is crucial here for higher efficiency and operational configuration Yang et al. [116].

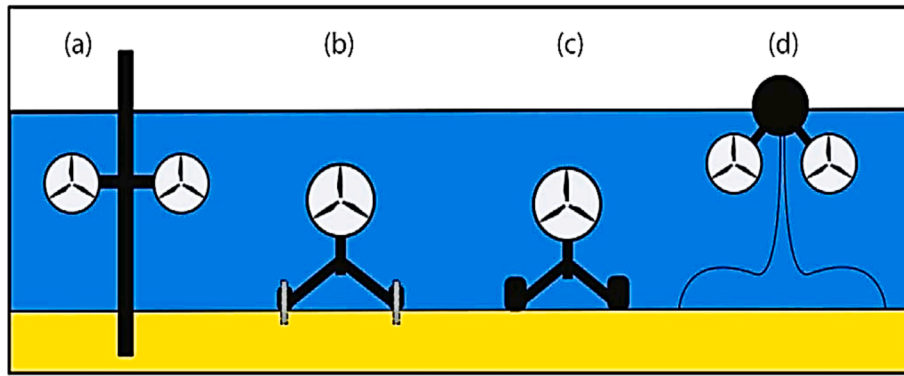


Fig. 39. TEC foundation type (a) Monopile; (b) Piloted; (c) Gravity, and (d) Pile Foundation. [67].

Table 13

Economic model of a particular wave energy device Khan et al. [1].

Comparison topic	Cost of device parts	Unit	Cost (dollar)
Structure	Cost of the main structure	USD (K)	6552
Foundations/Moorings	Expenditure of all foundations, anchors, or moorings	USD (K)	2184
Control/instrument	Cost and monitoring instruments	USD (K)	1092
Power takes off	Power Take-Off costs, including all mechanical and electrical components.	USD (K)	2184
Grid connection	Grid connection	USD (K)	1092
Installation surveys	Surveys	USD (K)	546
Installation of the structure	Installation of the structure (including hire of vessels).	USD (K)	5460
Installation of the mooring	Installation of the mooring (including hire of vessels).	USD (K)	2730
Installation of the grid connection	Installation of the grid connection from farm to shore and onshore work.	USD (K)	1365
Commissioning	Commissioning of the farm	USD (K)	1365
Management and other	Management, insurance, and other costs.	USD (K)	2730
Capital cost: Total installed	–	USD (K)	27,300
Planned maintenance	Planned maintenance and inspection.	USD (K)	2520
Monitoring/control	Monitoring/Control of energy production and condition monitoring.	USD (K)	630
Unscheduled repair	Unscheduled repair	USD (K)	630
Rent	Rent, both land and sea.	USD (K)	210
Insurance	Insurance	USD (K)	210
Operating cost: total annual	–	USD (K)	4200
Total decommissioning costs	Incurred after the project life has ended.	USD (K)	4200

5. Comparative assessment of technologies

5.1. Based on cost estimation

WE Technology is currently more affluent than other renewables such as wind and tidal power due to limited commercial experience; however, costs can be reduced through device upscaling, larger deployments, improved equipment utilization, standardization, and bulk

Table 14

Total Cost of an Attenuator Device (University of Strathclyde, n.d.).

Capital Costs	USD
Structure	35,02,932.3
Power Take Off	15,27,557.85
Moorings	4,09,256.4
Transmission	41,049.75
Installation	5,48,576.7
Project Management	18,78,348.15
O & M	4,05,300
Decommissioning	2,10,000
Total	79,07,721.15

component procurement. Ongoing research is expected to optimize manufacturing, installation, and operation strategies, further lowering costs over time [22]. Table 12 shows Wave Energy resources, and Table 13 for Cost model.

5.1.1. Attenuator device

The cost assessment for the attenuator device (Pelamis power plant) is based on the EPRI in San Francisco, USA. The comprehensive evaluation of all the costs required in a wave project of a single Pelamis is made by EPRI. The total capital cost is approximately 5.5 M USD. It is estimated that a probable practical cost for a single attenuator device with a capacity of 750 kW is around 78, 75,000 USD, with the cost distribution shown in Table 14.

Considering the working lifetime of an attenuator device is 20 years. So, the annual cost for setting up each unit of this device = (Capital cost + Decommissioning/ Expected lifetime + annual operating & maintenance cost) = (79, 07,721.15 + 2, 10,000)/20 + 4, 05,300 = 8, 11,186.0575 USD.

The annual energy production of each unit. If each unit of this device runs for 8760 h in a year, the total output from all of the units is equal to 750 x 8760 = 6,570,000 kWh. The annual cost divided by the annual energy output, or 8, 11,186.0575/6,570,000 = 0.123 = 0.123 × 78.67 [1 USD = 78.67 BDT] = 9.71 BDT Khan et al. [1], is the cost per kWh.

5.1.2. Point absorber

Considering the working lifetime of an attenuator device is 20 years. So, the annual cost for setting up each unit of this device = (Capital cost + Decommissioning/ Expected lifetime + annual operating & maintenance cost) = (1,525,033.125 + 415,918.65)/20 + 76,252.05 = 1, 73,299.6 USD. The total annual production from every instance of this device is 250 x 8760 = 2,190,000 kWh if each unit operates for 8760 h in a year. The price per kWh is calculated as follows: 73,299.6 /2,190,000 = 0.079 USD = 0.079 × 78.67 [1 USD = 78.67 BDT] = 6.2 BDT Khan et al. [1]. Table 15 shows the total cost of a point absorber. Fig. 40 shows Capital and operational cost.

Table 15

Total Cost of a point absorber device (University of Strathclyde, n.d.).

Capital Costs	USD
Structure	3,96,112.5
Moorings	39,611.25
Transmission & Grid Connection	4,15,918.125
Installation	4,95,140.625
Project Management	1,78,250.625
O & M	76,252.05
Decommissioning	4,15,918.65
Total	1,525,033.125

5.1.3. Oscillating water column (OWC)

The analysis of the cost for the commercial project of OWC is shown above. The cost of the electricity per kWh is USD 0.111, which is equivalent to 8.764 BDT. Comparing the above three wave energy devices, the minimum cost of electricity per kWh is 6.2 BDT for the point absorber device, followed by OWC of 8.764 BDT and the attenuator device of 9.71 BDT Khan et al. [1]. Table 16 shows the cost estimation of OWC.

5.2. Energy conversion stages

Wave energy conversion employs numerous technologies with different power take-off systems, though only a few are standardized, while others are modified or upgraded versions of these systems Khan et al. [1,2]. The main goal of WECs is to efficiently transform WE into usable electrical power for grid integration, while some studies also focus on small- to medium-scale devices designed for local energy use with minimal transmission and storage requirements Khan et al. [1,2]. Table 17 shows the example of WEC,

Device-to-device and site-specific variations exist in the energy conversion process. Normally, a turbine is necessary to handle the fluid, such as an air turbine or a hydraulic turbine, and is coupled with the generator to produce electricity. A primary interface device is used before using the turbines to convert the horizontal wave motion to the body motion of a mechanical system Khan et al. [1,2].

The many steps involved in converting wave energy into electrical energy are depicted in Fig. 41. An interface between WEC & the electrical generator is necessary, and issues like heaving & nodding devices are inappropriate for rotational electrical machines [84].

5.2.1. Power transmission system

HVAC and HVDC transmission systems are the two types of transmission systems used to transport offshore energy from the WECs to the grid (Fig. 42). There are two possible topologies for HVDC transmission: HVDC-VSC (HVDC Voltage Source Converter) and HVDC-LCC (HVDC Line Commutated Converter). The HVDC-LCC architecture is inferior to the HVAC-VSC transmission system [2]. The most popular offshore transmission system is HVAC. The technology is established, reliable, and well-known. When the voltage level at the grid input point and the transmission line is the same, a transformer is not required [119,120]. Table 18 shows a comparison of HVAC.

Small farms, where the offshore farm grid's voltage level is normally

Table 16

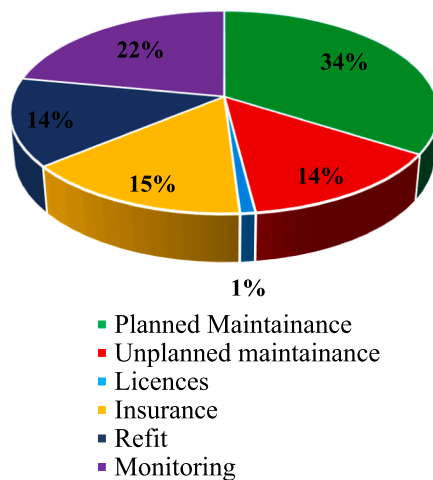
Cost estimation of OWC commercial project [117].

Oscillating Water Column (OWC) commercial project cost analysis	
Capital cost (1 device)	\$5,352,000
Capital cost of project (152 devices)	\$238,038,000
operation and maintenance cost	\$10,631,000
10-year Refit cost	\$14,712,000
Estimated Project cost for a non-utility generator	\$239,432,000
IRR for a non-utility generator (29.8% of estimated project cost)	\$71,350,736
Industrial price of electricity for a non-utility generator	10.8 cents/kWh
Price of electricity for a utility generator	11.1 cents/kWh

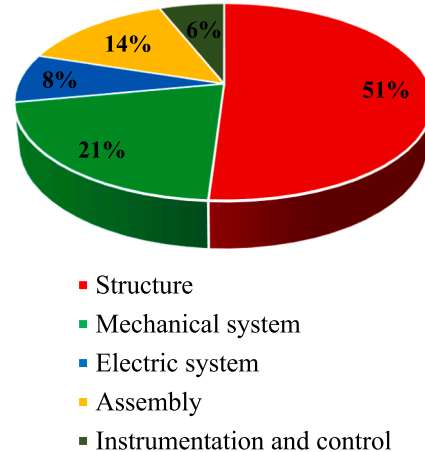
Table 17

Examples of some wave energy converters with their power take-off (PTO) systems [118].

WEC name	WEC type	Power take-off
Pico	OWC	Wells turbine(WT)
LIMPET	OWC	WT
REWEC3	OWC	WT
Mutriku	OWC	WT
Mighty Whale	OWC	WT
Sakata	OWC	WT
IPS buoy	Heaving body	Hydraulic oil system & linear generator
Aqua-Buoy	Heaving system	Impulse turbine
Wave-bob	Heaving body	Hydraulic System
SEAREV	Pitching system	Hydraulic System
Pelamis	Pitching system	Hydraulic System
Oyster	Pitching/quasi surge system	Hydraulic System



(a)



(b)

Fig. 40. (a) Capital cost of a wave energy device, (b) operation & management cost of a wave energy device (by parts)Khan et al. [1].

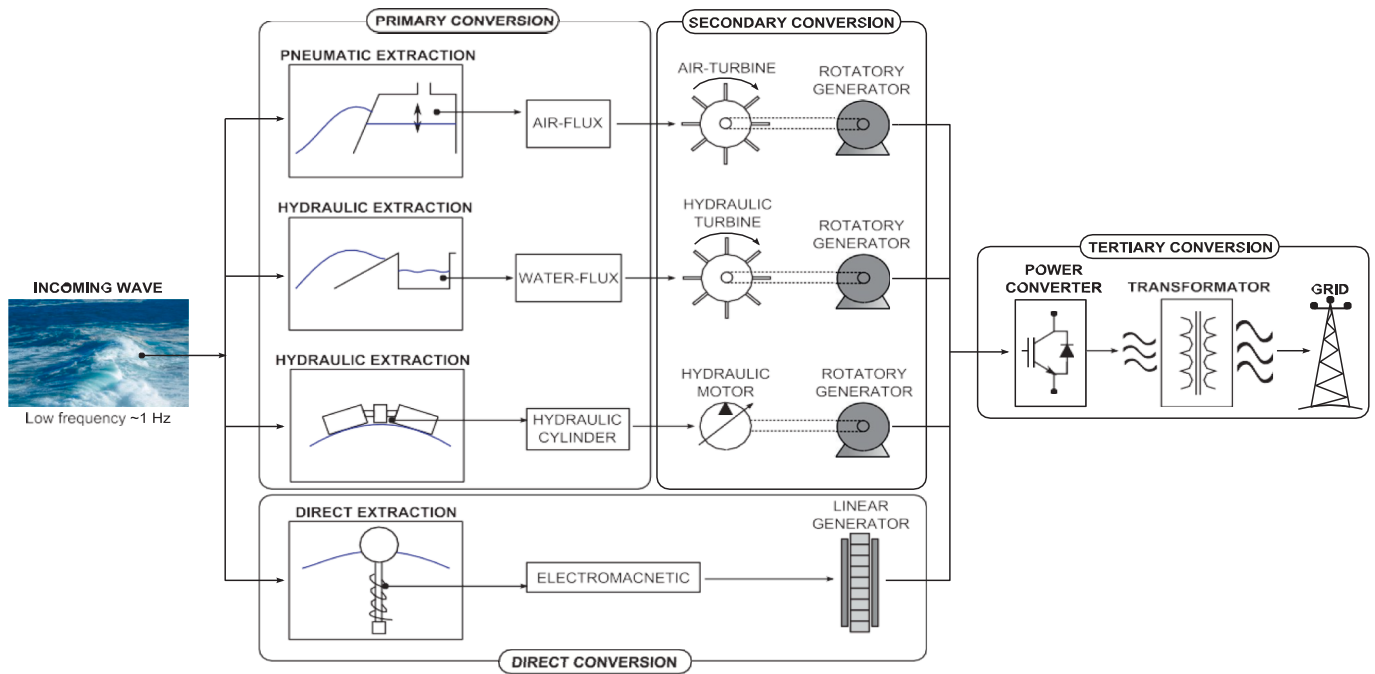


Fig. 41. Some energy conversion stages Khan et al. [1,2].

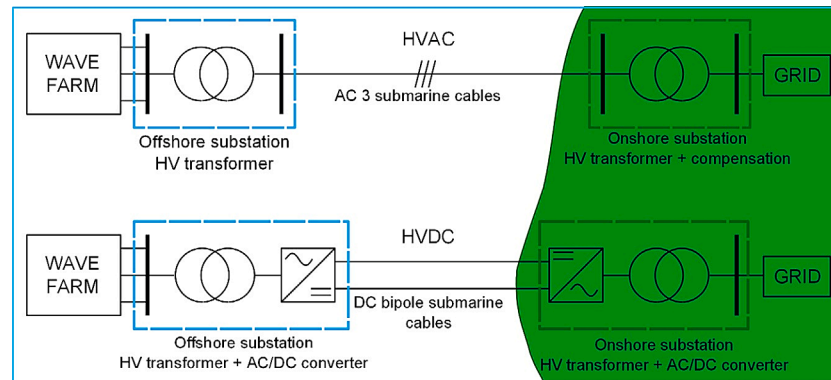


Fig. 42. Offshore transmission systems [2].

between 30 and 36 kV, are where this phenomenon is seen [121]. However, in order to send energy to the beach, huge offshore farms that are distant from the shore require an offshore substation to bring up the electrical voltage level to 132 kV or 220 kV [125]. HDAC is utilized to carry energy over long distances, while HVAC is appropriate for medium to short distances. Fig. 43 shows the single-line diagram of the Wave Hub.

Table 19 shows the techno economic assessment of the technologies Chen et al. [126], Astariz and Iglesias [127].

6. Prospect & challenges among the RES

6.1. Environmental impact

Renewable energy is a source that is considered endless and has huge potential for power development, especially for electrical power. Moreover, it does not need time to have the sources. On the other hand, fossil fuels require thousands of years of formation, with the huge prospect of renewable energy sources. Still, there are some negative impacts on the environment, as pointed out in Table 20.

WE are regarded as a RES that doesn't pollute because, while

operating normally, WEC devices don't emit any harmful CO₂, NO₂, or other pollutants. The influence on the environment is not well understood because the bulk of WEC systems are still in the early stages of development and deployment [22]. The environmental effect is shown in Table 21.

Tidal barrages have the same environmental issues as dams in the rivers. The GBM delta (Ganga, Brahmaputra, and Meghna) carries a large amount of silt deposits into the BOB. Tidal plants may disturb the silt flow pattern. Additionally, estuaries provide a unique and valuable environment for estuarine creatures as well as a nursery for numerous marine organisms. Therefore, it is best to avoid altering this ecosystem by building huge tidal plants. The estuary was completely cut off from the ocean for two to three years while the tidal plant at La Rance was being built, and it took a while for the estuary to achieve a new natural balance. The marine community there changed as a result of the barrage's effects, which included decreased intertidal area, slower currents, a narrower range of salinities, and altered bottom water properties [128]). Tidal barrage construction should proceed with a full report of the environmental impact on marine ecology. Tidal fences and tidal turbines are likely to be more environmentally benign [129]. Since tidal barriers obstruct waterways, making it harder for fish and wildlife to

Table 18

Comparison of HVAC-HVDC transmission system [121], Gasch et al. [122–124].

Comparison topic	HVAC	HVDC LCC	HVDC VSC
Maximum capacity	800 MW at 400 kV 380 MW at 220 kV 220 MW at 132 kV All up to 100 km	Up to 600 MW (submarine transmission)	Up to 350 MW installed 500 MW announced (1080 MW proposed)
Voltage level	132 kV installed 220 and 400 kV under development	Up to ± 500 kV	Up to ± 150 kV (± 300 kV proposed)
Offshore installed projects	Many small installations	Not installed yet	Only test project (oil platform in Norway)
Black start capability	Yes	No	Yes
Technical capability for network support	No	No	Yes
Offshore station in operation	Yes	No	On an oil platform
Decoupling of connected networks	No	Yes	Yes
Cable model	Resistances, capacitance, and induction	Resistance	Resistance
Requirements for ancillary service	Not necessary	Yes, for low wind speeds conditions	Yes, for low wind speed conditions
Space requirements for the offshore substation	Smallest size	Biggest size	Medium size
Installation costs	Small for the station High cost for cable	High cost for the station Low costs for cable	Station 30–40% more expensive than LCC

travel across them, they may have some detrimental effects on the ecosystem. In the case of GBM delta, migration is very important for this ecology to sustain, and also for the Sundarbans. But according to Blue the Environment, the stationary turbines have little influence on sediment movement and let liquid and animals pass past the buildings. Blue Energy's forerunner, Nova Energy, constructed a 20 kW prototype in the St. Lawrence Seaway in 1983 and discovered no fish kills [83]. Longer-term scenarios would inevitably result in some fish mortality, fences might be designed to allow fish to pass through the openings between the caisson wall and the rotor foil, and the turbines could be geared down to low speeds (25–50 rpm) to minimize fish kill [83]. A barrier that would keep larger creatures from entering the building and a sonar sensor auto-braking systems that would turn off the system when it spotted underwater creatures would safeguard marine life [130]. The time and amplitude of the tides would remain unchanged by the tidal barriers. The most ecologically benign tidal power solution could be tidal turbines. They do not disrupt fish movement, obstruct waterways or estuary outlets, or change hydrology [129]. While tidal barrages are likely to do too much harm to the marine ecology, tidal turbines and tidal gates may provide significant production capacity without having a significant influence on the ocean. Turbines, fences, and related technologies should be the main emphasis of tidal energy research. Major migratory pathways should be left open during the construction and placement of these projects. Turbines should rotate slowly enough to prevent fish death while generally unaffected the movement of nutrients and sediment. Tidal walls shouldn't completely obstruct a bay or corridor; instead, they should be constructed across small channels. The environmental impact of marine renewable energy systems in the Bay of Bengal (BOB) needs to be assessed very carefully, as coastal and island ecosystems are environmentally sensitive. In particular, Saint Martin's

Island, which is known to be the only coral-rich island in Bangladesh, is home to ecologically vulnerable coral reefs, seagrass beds, benthic organisms and important fish breeding grounds. Therefore, it is very important to consider the potential environmental disruption and long-term environmental sustainability when installing Wave Energy Converter (WEC) in coastal areas. Point absorber array and Oscillating Water Column (OWC) devices can cause local environmental impacts through seabed anchorage, mooring systems and noise from underwater activities. The installation of mooring foundations can disrupt benthic habitats and sediment transport processes, which can negatively impact coral-associated organisms and seabed animals. In addition, underwater noise from hydraulic systems and turbine operations can affect fish migration routes, breeding grounds, and behavioral patterns of marine animals. The coastal waters around Saint Martin's Island are important habitats for a variety of marine species, including reef fish, sea turtles, and commercially important fish species. Excessive underwater noise and construction activities can temporarily alter the feeding, breeding, and migratory behaviors of these animals. However, wave energy technologies generally emit much lower greenhouse gas emissions than fossil fuel-based power generation systems and have limited chemical pollution. Therefore, proper Environmental Impact Assessment (EIA), careful site selection, environmentally friendly mooring design, and continuous environmental monitoring are essential before large-scale marine energy systems are deployed in the Bay of Bengal region. These remedial measures can help reduce environmental disruption and promote sustainable and environmentally responsible marine energy development.

7. Conceptual proposed technology for BOB

7.1. Mini Hydroelectric power plant (MHPP) for BOB

The BOB is losing its appeal to tourists and becoming uninhabitable due to a shortage of energy. To address the need for electricity in the island's tourist resorts, a decentralized MHPP has been suggested and designed.

The design of the proposed Searaser-based power plant on the islands of Saint Martin is depicted in Fig. 44. Searaser pumps water into the Mega-reservoir. It is made up of multiple chambers that can store a specific amount of water for all of the generating units (turbine-generator) that are connected to it. Any unit's water-chamber capacity and the water flow rate needed by the turbine are determined by its water-head acquired, power rating, and operating time. In the event of an emergency, water can be transferred between the water chambers thanks to connecting valves. The water chambers' capacity can be readily expanded if necessary to accommodate future unit size expansions. Rainwater is collected via a detachable reservoir roof equipped with a filtering net. Various parts of searaser's are shown in Fig. 45.

Searaser, which is schematically depicted in Fig. 38, is primarily a wave-driven water pump for producing hydroelectric power. The suction stroke and the working stroke are the two actions that make up the Searaser's working cycle. When the wave crest approaches Searaser during a suction stroke, the Weighted Surface Buoy (WSB) and the elongated member (piston) are compelled to heave upward. As a result, water from the surroundings begins to enter the cylindrical pumping chamber, creating a vacuum inside. When the wave goes to sea during its working stroke, gravity causes the WSB to heave downward, pressurizing the water that has accumulated in the chamber. After that, a reservoir is used to store the pressurized water. Before eventually returning to the ocean, the held water can be discharged via a hydraulic turbine that generates power.

7.2. Conceptual selection and Consideration of suitable technologies for BOB

According to the location of choice, the preference for models varies

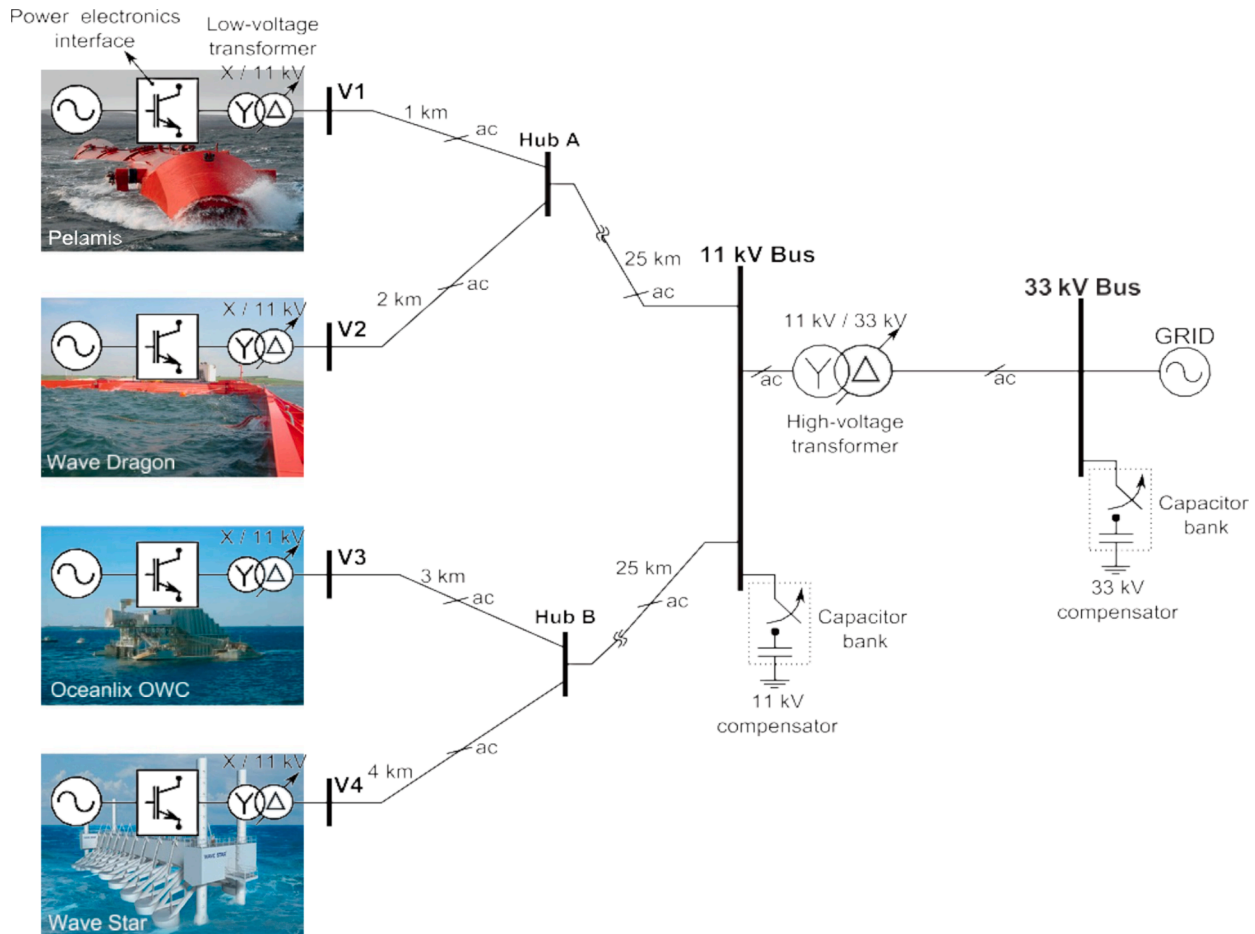


Fig. 43. Single-line diagram of the Wave Hub [2].

Table 19

Techno economic status for among the effective technologies.

Technology	Status	CAPEX	OPEX	LCOE
OWC	Moderate to higher	Moderate	Medium	Moderate to higher
Point absorber	Moderate	Medium to higher	Medium	Medium to higher
Attenuator Overtopping	Moderate	Higher	Higher	Higher
Tidal barrage	Higher	Very Higher	Lower to Medium	Medium
Tidal steam Turbine	higher	Higher	Medium to higher	Medium to higher

greatly. With the change of underwater terrain and depth of water, the model preference also changes. Those locations with a narrow entry point or enclosed mostly by land are suitable for tidal barrages. On the other hand, those places with open waters, estuaries, and narrow channels can utilize tidal current technologies. There are some locations where TEC is most suitable with appropriate technologies. Table 22 shows the proposed locations and technologies.

7.2.1. Conceptual selection of technology

Some important parameters, like properties are crucial for selecting technology. The technical considerations are found as climate compatibility, water depth, conversion efficiency, unavoidable situations, fluctuating expenditure etc, From the qualitative comparison, OWC found as best in terms of Technology, maintenance, and water availability He et al. [132]. On the other hand, the point absorber also

Table 20

Potential negative impacts of different renewable energies on the environment (Khan et al. 2017(a)).

Energy Source	Potential Negative Impacts on the Environment
Solar Energy	Solar panels can cause visual hindrance. Nitrogen trifluoride and Sulphur hexafluoride emitted from the production of solar panels have a thousand times the negative impact on global warming compared to carbon dioxide. Can result in soil erosion.
Wind Energy	Causes noise pollution and soil erosion. Threat to birds and other flying creatures.
Hydroelectric Energy	Disturbs the local ecosystem. Can change weather conditions. Large dams destroy the aquatic creatures and plants around them.
Wave Energy	Affects the marine ecosystem, disrupting the movement of commercial and private vessels. The onshore wave power plant can damage the beauty of the sea.
Geo Thermal	The stability of the soil may be impacted by the emissions of sulfur dioxide and silica from geothermal power plants, as well as the presence of harmful heavy metals, including boron, arsenic, and mercury, in the reservoirs. As part of the development of enhanced geothermal system (EGS) power plants, hydraulic fracturing has the potential to cause earthquakes.
Biomass	Emits global warming gases like methane during the production of biofuels. The usage of waste products spreads odor. It can spread bacteria and infection.

becomes more preferable for the BOB in terms of adaptability, hydrodynamic modelling, structural analysis, and economic assessment basis He et al. [133], He et al. [132]. The conceptual finding based on the

Table 21
The environmental impacts of WECs [61].

Environmental Effects	Shore line	Near shore	Offshore
Land use	Weak	—	—
Construction	Weak	—	—
Recreation	Weak	Weak	—
Coastal erosion	Weak	Weak to Medium	Weak to Medium
Sedimentary flow patterns	—	Weak	Weak
Navigation hazard	—	Weak	Weak
Fish & marine biota	Weak	Weak	Weak
Acoustic noise	Weak	—	—
Working fluid losses	—	Weak	Weak
Endangered species	Weak	Weak	—
Device/mooring damage	—	Weak to Medium	Weak to Medium

literature is shown and described as OWC systems for Cox’s Bazar under

all relevant favorable conditions.
OWC is suitable for nearshore with good hydrodynamic behavior and

Table 22
List of proposed locations and technologies [66,79], Atlantis Energy [13,131].

locations	Technologies	Reason
Sandwip	Horizontal-axis tidal turbine	Narrow channel
kutubdia	Horizontal-axis tidal turbine	Narrow channel
Gulf of Kutch	Barrage or fence	Mostly surrounded by land
Gulf of Khambhat	Barrage or fence	Mostly surrounded by land
Port Blair	Horizontal axis tidal turbine (array)	Heavy current with reasonable depth
Sundarbans	Fence or turbine	Low depth and heavy tidal activity

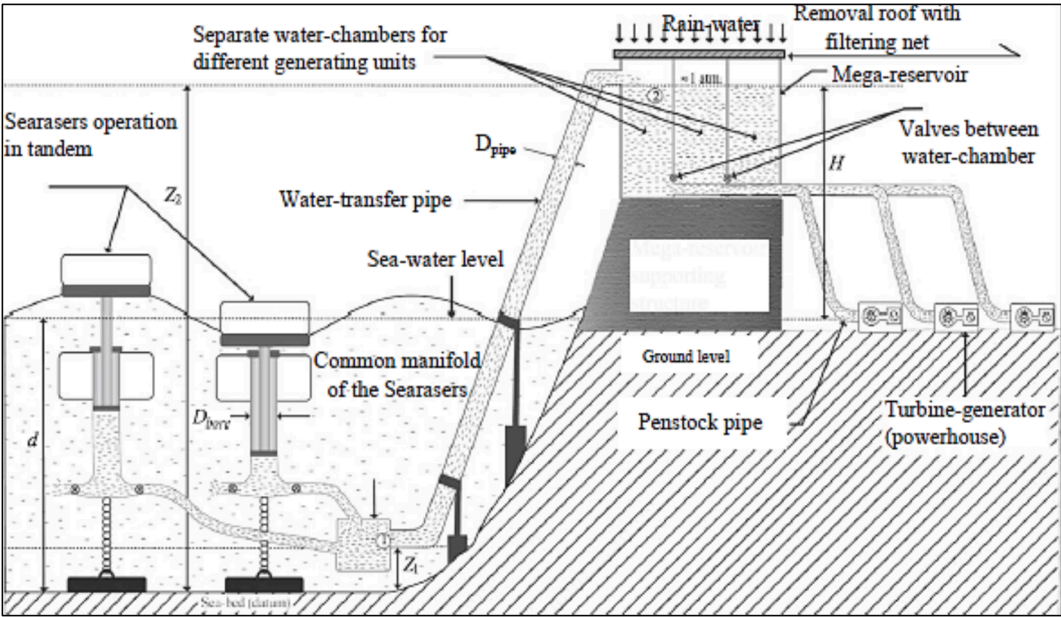


Fig. 44. The layout of the proposed MHPP run by Searaser [56].

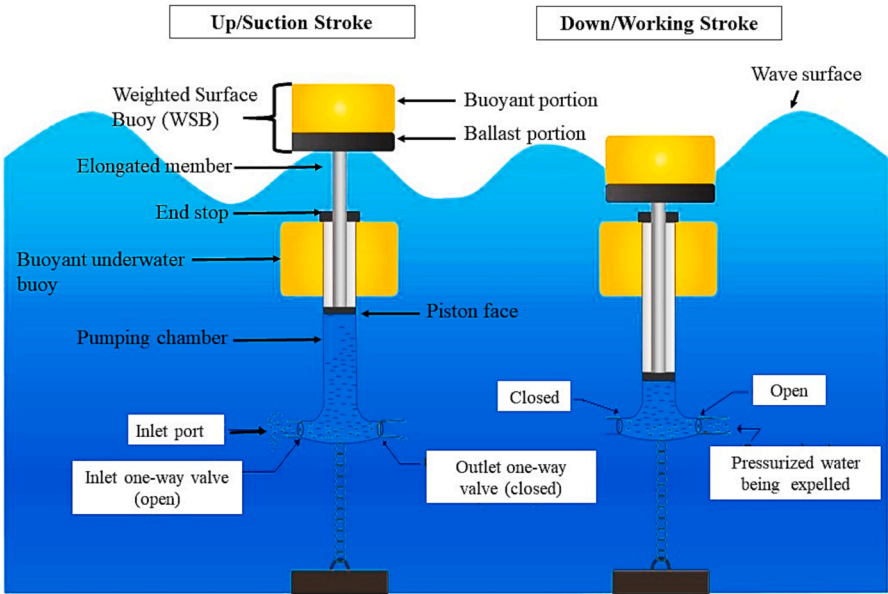


Fig. 45. Various parts of a Searaser's operation cycle [56].

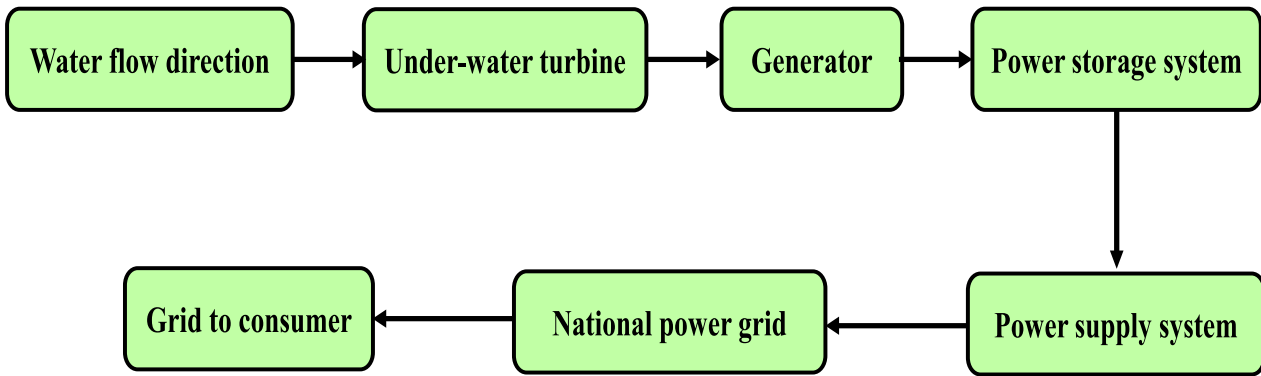


Fig. 46. Proposed model's flow chart of TEC.

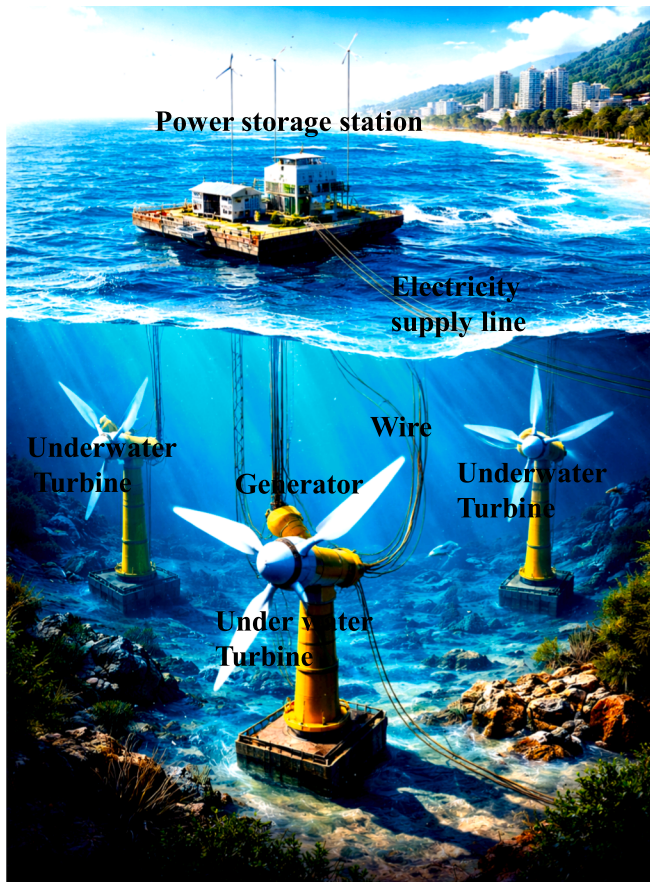


Fig. 47. Suitable Proposed Model of TEC for Cox's Bazar.

nearshore compatibility in the higher stage He et al. [133]. The point absorber shows hybrid and medium hydrodynamic suitability and medium maintenance complexity. Attenuators are available for the offshore application and require stable wave directions with higher maintenance compatibility He et al. [134]. On the other hand, the Tidal system requires higher hydrodynamic stability and medium to higher compatibility of maintenance He et al. [135].

7.2.2. Conceptual recommendation of TEC configuration for BOB

Based on the comparative assessment of previously implemented tidal energy projects (Table 21), the selection of technology is strongly governed by site-specific hydrodynamic and geographical characteristics such as tidal range, channel width, current velocity, and seabed condition. For example, narrow channels like Sandwip and Kutubdia

Table 23

Characteristics of selection criteria of BOB.

Selection criteria	BOB at region of Cox's Bazar	BOB at region of Saint Martin
Climate	Medium	Medium to higher
Water requirement	Medium	Medium
Unavoidable climate exposure	Higher	Higher
Preference	Nearshore	Nearshore and offshore hybrid

favor horizontal-axis tidal turbines due to accelerated flow velocity, whereas regions such as the Gulf of Kutch and Gulf of Khambhat adopt barrage or fence systems because they are semi-enclosed and suitable for impoundment structures. In contrast, areas with moderate depth and strong tidal currents, such as Port Blair, utilize turbine arrays for efficient kinetic energy extraction.

Considering the coastal morphology and moderate tidal range, a large barrage system may not be economically or environmentally optimal. Therefore, the proposed TEC model (Fig. 46) adopts a modular horizontal-axis tidal stream turbine array system. This configuration is more suitable for open coastal environments with steady bidirectional tidal currents, minimal obstruction to marine navigation, and lower ecological disturbance. The modular design allows phased installation, scalability, and easier maintenance, making it technically feasible and economically sustainable for Bangladesh's coastal energy development strategy. Fig. 47 shows the suitable proposed model.

7.3. Technology selection criteria for the BOB region

Table 23 shows the properties for which selections are conducted. The main parameters for finding and selecting are like climate, water requirements, seasonal effect, and preferences Luan et al. [136], He et al. [137].

Furthermore, the reason of choosing OWC as found as easy maintenance, lower mooring difficulties, nearshore capabilities. On the other hand, findings of choosing the point absorber like adaptability, modular technology, medium wave requirements Luan et al. [136], He, G. et al., 2022) Finally, other technologies are not suitable due to survival concern, structural length and offshore difficulties.

8. Conclusion

In this paper, a deep study of ocean (wave & tidal) energy in the region of BOB has been presented. The most suitable time for extracting wave energy has been found from May to October around the year. Wave height remains at this period of the year, providing the most amount of wave power to extract.

- The maximum wave height is 4.2 m at Teknaf, Bangladesh, and 2nd highest height is 3.6 m at Cox's Bazar, Bangladesh, in May 2020. In June 2011, the maximum wave height was 4 m. Maximum extractable power at 2011 is near 15.35 kW/m, 20 kW/m at 2012, and 13.90 kW/m at 2013.
- From this study, it is also found that about 15 kW/m to 20 kW/m power can be extracted from the regions of Bangladesh. Sandwip, Kutubdia, Gulf of Kutch, Khambhat, Port of Blair, and Sundarbans are proposed for extracting tidal energy, and for wave energy, Cox's Bazar, and Teknaf are suggested.
- The point absorber, OWC of wave technology, is suitable because of its simplest design, having small dimensions, and being independent of wave direction.
- For a horizontal-axis tidal turbine, a barrage or fence is suggested for a narrow channel and a low-depth channel. A cost analysis for the electricity cost per unit of three wave devices, point absorber (6.2 BDT), OWC (8.764 BDT), and attenuator device (9.71 BDT) has also been done. From several studies, it is found that point absorber technology can provide relatively low-cost power generation potential compared to attenuator and oscillating water column (OWC) technologies. However, this comparison is based on data collected from different studies, where the power ratings used, operational assumptions and economic conditions were different from each other.
- Therefore, the present comparison should be considered as a preliminary assessment and not as a final decision. A more detailed techno-economic assessment using a standardized Levelized Cost of Energy (LCOE) framework based on similar assumptions and criteria is required for a reliable and accurate comparative analysis of wave energy technologies in the Bay of Bengal region.
- The two-wave technology model (Mini Hydroelectric Power Plant for Saint Martin Island, Hybrid Model for any sea) has been described. Finally, different energy transmission alternatives have been shown. Nowadays, the majority of wave parks in operation have an HVAC (High-Voltage Alternating Current) transmission system, because the most economical option for short and medium waves. HVDC (High-Voltage Direct Current) system is more suitable for long distances.

The proposed conceptual models demonstrate the potential for future ocean-based renewable energy generation in the Bay of Bengal. However, further experimental validation and techno-economic assessment are required to determine their practical feasibility and environmental impact. Such a system not only supports sustainable development but also contributes to meeting the growing energy demand while minimizing environmental impacts. In this study, the governments of countries near the Bay of Bengal could benefit from the proposed model implemented at the ocean and meet their energy demand at a low cost, and energy supply-based industries and companies could also benefit from the proposed model of electric energy from the ocean.

8.1. Comparison with Existing Literature and Study Limitations

This study has several limitations. The data on wave and tidal energy have been collected from secondary sources, which may lead to some uncertainties in the accuracy and consistency of the data. In addition, the proposed ocean-based energy models are at the conceptual stage and have not yet been experimentally validated at the laboratory or field scale. Detailed environmental impact assessment and full techno-economic analysis were also beyond the scope of this study. Therefore, future studies should focus on experimental validation, CFD analysis, environmental assessment, and pilot-scale implementation of the proposed systems in the real operating environment of the Bay of Bengal. This study also mentioned further limitation like field measurement, satellite observation with implementation of numerous methodologies. The direct quantitative comparison with similar studies is not available

in the study.

CRedit authorship contribution statement

Md.Rasel Ahmed: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Kazi Md. Mehedi Hasan:** Writing – original draft, Visualization, Data curation. **Ammara Al Jabin:** Methodology, Conceptualization. **Saurav Sarker:** Methodology, Conceptualization. **Md Mahabur Hossain:** Writing – review & editing. **Md Alamgir Hossain:** Writing – review & editing. **Md. Sanowar Hossain:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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