Oceanic perspectives on renewable energy conversion: A comprehensive review in the Indian context

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ABSTRACT

The demand for energy exploitation by natural means has currently become popular, which poses several issues related to global warming. The extraction of the abundance of energy from the marine environment that can cope with the ever-increasing demand is exciting and challenging for its sustainable aspects. The prominent forms of energy available in the sea are due to waves, tides, wind, and thermal gradients. Several existing research has focused on these challenging tasks for renewable energy conversion. This paper discusses the modern, innovative, renewable hybrid marine energy converters that are proposed and attempted globally, and also illustrates the relevance of these technologies in the Indian context. Further, the projects that have been explored on the Indian coast and the future potential that could be explored are also discussed.

Keywords: Energy, Global warming, Sustainability, Renewable energy, Hybrid marine energy converters

INTRODUCTION

It is widely accepted that there is an increase in the demand for electricity consumption globally. ElA (2013) has predicted that an increase in global consumption will reach about 40% by 2020 to 2040. This is due to technological advancement and population. Many developed and developing countries focus on excess power generation to meet every individual's demand for the present and future.

India is the world’s second-largest coal producer to the tune of 762 million tons, with its consumption to the extent of about 967 million tons as per Ahmed et al. (2023). India’s annual electricity use crossed 1300 billion kWh in 2022, a nearly 70% jump over 2012. Industrial and domestic fields hold the maximum total energy consumption for the year 2012-2022, which is likely to increase exponentially over the next decade. India is the third-largest country in the world in terms of electricity generation, as per the findings of the Energy Information Administration (EIA) in 2023. The thermal power plants supply over 65% of the electricity consumed, followed by hydroelectric power plants (22%), nuclear power plants (3%), and other energy sources (10%) like solar and biomass. Thermal power plants are, therefore, the primary source. However, this emits an excess amount of CO_2, which is a significant factor in global warming. The contribution of renewable sources for power generation is very low in India. This paper focused on electricity energy conversion using marine renewable energy. Among several other sources of renewable energy, marine energy is a clean and renewable source of energy. Since the sea waves always exist, wave power is more consistent and available for electricity generation compared to other renewable energy sources like wind, tide, and solar. They can be a good source of energy generation for off-grid coastal areas and islands.

According to IRENA (International Renewable Energy Agency), India has the potential to generate more than 4500 MW of electricity by 2022 through renewable hydropower. Moreover, they have brought out a comparison of renewable energy jobs by different technologies for India (Figure 1), showing that the employment and technology for marine renewable energy are still under development.

The availability of energy from the marine environment is huge, and its extraction for energy conversion worldwide is still in progress. Several developed countries have demonstrated successful techniques and employment opportunities for converting energy from the ocean to electricity. Hence, introducing this technology in India not only produces clean energy, but also enhances employment and economic growth. China is expected to contribute significantly to the global increase in renewable electricity, followed by the United States, the European Union, and India. Norway, known for hydroelectric power, consumed hydro energy equivalent to 45% of its total energy supply in 2021.

Gielen et al. (2019) reported that, according to the International Renewable Energy Agency (IRENA), renewable energy's contribution to the global energy mix must increase sixfold in order to reduce the rise in average world temperatures below 2.0 °C over pre-industrial levels. The goal by 2040 is for renewable energy to match coal and natural gas electricity generation globally, aiming for zero CO_2 emissions. Some jurisdictions, including Denmark, Germany, South Australia, and certain US states, have achieved high integration of variable renewables. Examples include Denmark, where wind power met 42% of electricity demand in 2015, and Portugal and Uruguay, with significant contributions from wind power as well.

Interconnectors play a crucial role in balancing electricity systems by facilitating the import and export of renewable energy. Innovative hybrid systems have emerged between countries and regions to optimize the use of renewable resources. Considering the geographical location of the Indian sub-continent, there is ample scope for marine energy to meet the present and future energy demands. Wave energy potential in India may be limited compared to other regions due to its proximity to the equator. There is a need to explore hybrid technologies for utilizing marine energy potential in India. In summary, there is a global shift towards renewable energy, highlighting successful examples and the paper emphasizing India's unique challenges and opportunities, particularly in the context of marine energy. It underscores the importance of innovation and a diversified approach to achieving sustainable energy goals.

DIFFERENT FORMS OF MARINE ENERGY

Different forms of marine renewable energy are available globally, such as wave, tidal, wind, thermal, salinity, etc. (Figure 2). The tidal energy by means of current is due to the gravitational attraction between celestial bodies that have its significant flux occasionally in a year. Offshore wind energy is associated with the mass movement of wind at high speed at sea. This has more potential than the onshore wind. Harvesting energy by means of temperature between different seawater levels is called Ocean Thermal Energy Conversion (OTEC). The temperature varies as a function of water depth. Repeated weather changes also influence the temperature gradient in the deep ocean along the Indian border. Salinity gradient energy conversion indicates the extraction of energy through salinity gradient at different regions of seawater. Penetration of fresh water from land into the sea through rivers plays a major factor in salinity gradient. Further, several research organizations and industries have focused on the most prominent forms of energy from the ocean, such as wind and waves. It is essential to know that the marine wind and wave energy are interrelated. The magnitude of wave energy transferring from deep to shallow waters also directly depends on the intensity of the offshore wind. Nevertheless, one should keep in mind that India lies near the equator, so the wave energy potential is not that much compared to the other regions (Figure 3). This paper reviews mostly wave, wind, and tidal energy, which are the most promising from extraction point of view.

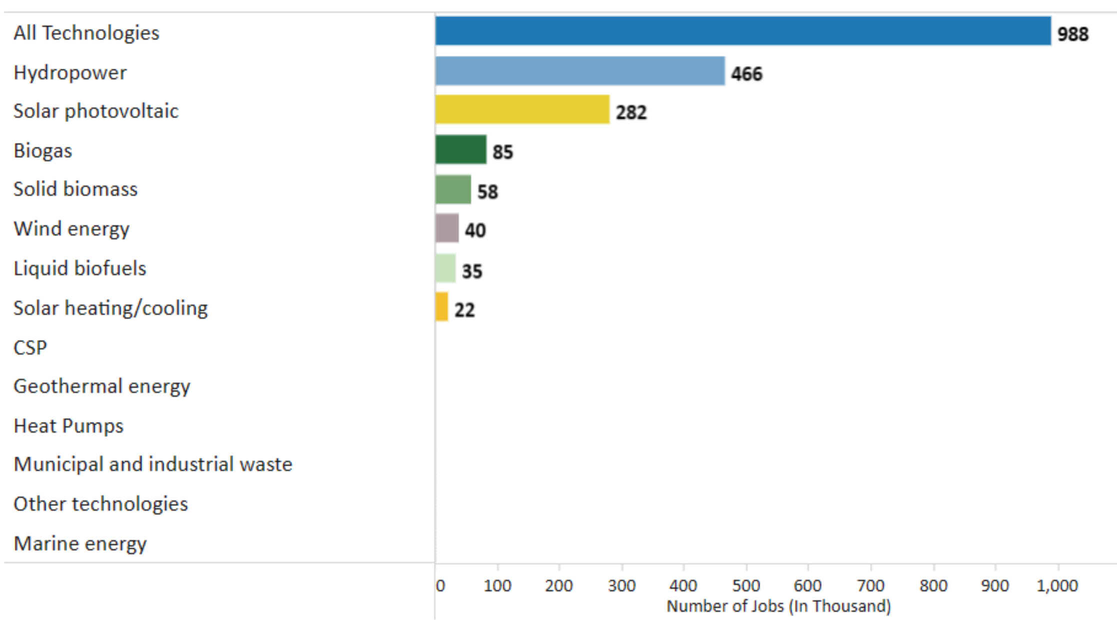


Figure 1. Renewable energy employment by technology in India in 2022 (source IRENA)

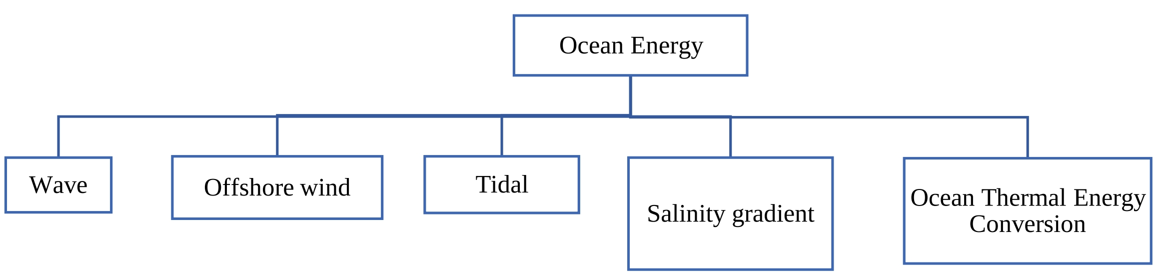


Figure 2. Different forms of Ocean energy at the global level

Figure 3. Average wave power in kW/m of Wave Front (Thorpe, 1999). The shaded region corresponds to the equator.

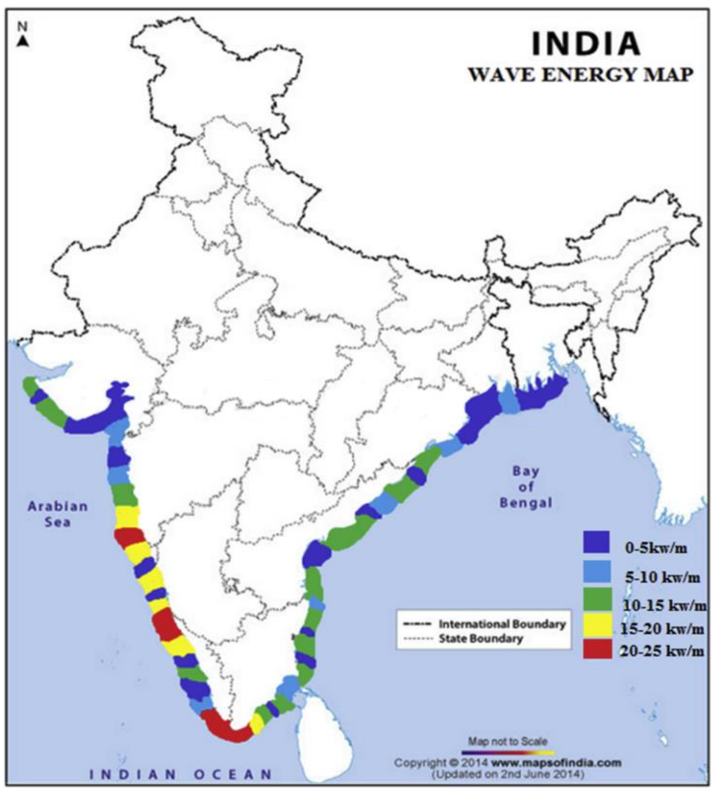


Figure 4. Wave energy map for India (Sannasiraj and Sundar, 2016)

Wave energy

Wave power is enormous and more reliable than the other renewable resources such as solar and wind energy because its density (wave:2–3 kW/m^2) is more significant (wind 0.4–0.6 kW/m^2; solar 0.1– 0.2 kW/m^2) (Wimalaratna et al., 2022; Kumar et al., 2022). The energy of a sea wave is determined by its height and period. Early evidence was discovered in China in the thirteenth century, where the waves were already employed to drive mills (Lopez et al., 2013). A preliminary study conducted by the Energy Technology Division (UK) indicated that large-scale wave power exploitation was theoretically feasible but that the cost of electricity produced would be almost double that of nuclear power (Leishman and Scobie, 1976).

India has a wave power potential of 40-60 GW with the coastline of 7500 Km. Primary estimates of wave energy potential along the Indian coast range from 5 to 15 kW/m, implying a theoretical capacity of 8000 to 80,000 TW/year of wave energy in the entire Ocean (Sannasiraj and Sundar, 2016). According to a study conducted by IIT Madras and Credit Rating Information Services of India Ltd (CRISIL), the western coast has more significant wind power potential than the eastern coast (Miyan and Shukla, 2018). Potential locations along the west coast of India are Maharashtra, Goa, Karnataka, and Kerala. Due to the effects of refraction and strong winds, Kanyakumari, located near the southern tip of the Indian peninsula, has the most power along the Southeast coast. Figure 4 shows the wave energy map for India's coast (Sannasiraj and Sundar, 2016). The quantity of power generated by wave energy using currently accessible methods is substantially less than the theoretically predicted potential. In India, the capacity utilization factor for wave energy is 15-20% (Sannasiraj and Sundar, 2016). There are several devices available to harvest wave energy across the world. Three significant classifications are Attenuator, Point absorber, and Terminator (Lopez et al., 2013). Subsequent classifications are discussed in the following sections.

Wind energy

Wind, the airflow across the Earth's and ocean's surface, is driven by pressure differentials resulting from unequal heating. This pressure variance creates gradients that cause air to move from areas of high pressure to low pressure, especially due to temperature variations between the tropics and high-latitude regions. Offshore wind farms and turbines have gained popularity as devices to harness wind energy. While they are more expensive and challenging to construct compared to onshore wind farms, offshore installations offer the advantage of maximizing energy extraction due to lower surface roughness. Additionally, offshore wind projects have reduced visual impact and noise compared to their onshore counterparts. Germany is actively pursuing the generation of 7700 MW of renewable electricity along its coast through wind energy resources.

Despite India having a coastline three times larger than Germany's, it has struggled to achieve comparable targets in harnessing wind energy from the marine environment. The limited success in India is attributed to various factors, including the wind climate, foundation requirements, costs, and installation distances from the shore. Foundations for offshore wind farms are categorized into fixed and floating types, drawing on experiences from the offshore oil and gas industry. Fixed wind farms, commonly supported by monopile and jacket templates anchored to the seabed, have been prevalent in Western countries. Selecting offshore locations based on wind intensity and stable ground is crucial for the successful installation of fixed wind farms. In India, these considerations are essential for implementing sustainable wind farm concepts, but challenges persist, particularly along the Indian border. India, being a developing country, has many constraints, such as cost, shortage of materials, and others that can affect the installation of windmills along the coast. Despite these challenges, ongoing research is focused on the development of floating wind farms and turbines. These floating structures can be deployed at greater depths in regions with higher wind potential. In this innovative approach, multiple devices form an array connected to underwater substations, with each substation linked to a common port leading to the land station. This strategy aims to overcome the limitations posed by traditional fixed wind farms and enhance India's capacity for harnessing wind energy from its extensive coastline

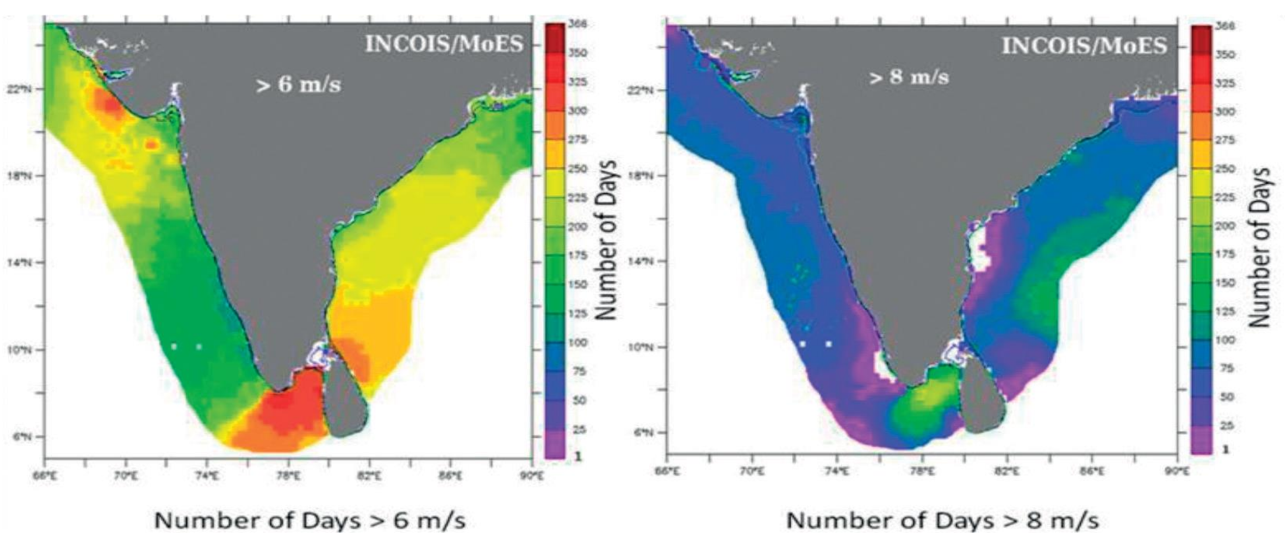


Figure 5. Offshore wind potential maps for the Indian coast (8˚4′ N to 37˚6′ N and 68˚7′E to 97˚25′E) by Earth System Science Organization (ESSO)-INCOIS (Alluri et al., 2018).

Office for National Statistics UK reported that wind energy generation accounted for 24% of total electricity generation, including renewables and non-renewables in 2020; offshore wind accounted for 13%, and onshore wind accounted for 11%. Hence, offshore wind farms dominate the onshore wind farms. A research center for offshore windmill installation at Dhanushkodi, South India coast, with a cost estimated at Rs. 350 crores, was planned for 2022 by the Indian government, along with the government initiative to invite international bids to install offshore wind turbines in Tamil Nadu and Gujarat. As the average wind speed is higher in offshore than in onshore, offshore wind turbines can generate higher power than onshore (Nikitas et al., 2019).

Wind potential maps produced by India's National Centre for Ocean Information Services (INCOIS) and National Institute of Ocean Technology (NIOT) show tremendous potential around the shores of Tamil Nadu and Gujarat, as shown in Figure 5 (Alluri et al., 2018). The authors explained that winds of 6 m/s or higher have remained for more than 300 days, and winds of 8 m/s or higher have been observed to persist for around 200 days along Tamil Nadu's southern coastlines. Both organizations' wind potential maps identify Rameshwaram and Kanyakumari in Tamil Nadu, as appropriate locations for offshore wind farms.

Tidal energy

Tides are characterized by periodic changes in the ocean surface height due to the gravitational forces exerted by celestial bodies and the Earth's rotational inertia. Tidal energy encompasses the potential energy stored in water due to the contrast between high and low tides, or the kinetic energy within the moving water during tidal ebbs and flows. Unlike stochastic resources such as wind, solar radiation, and ocean waves, tidal energy follows a predictable, non-stochastic periodic cycle. Consequently, global research efforts in this field have been relatively limited.

Nonetheless, there is potential to expand research and explore the installation of tidal energy converters along the Indian Coast. Tidal energy converters can be strategically placed at suitable sites to harness this reliable and periodic energy source. Furthermore, an innovative approach involves the integration of tidal energy converters with other energy converters, coastal structures, or offshore structures, forming a hybrid system. This emerging concept aims to enhance overall energy conversion capacity and presents an avenue for sustainable energy solutions along coastal regions. Murali and Sundar (2017) and Pal et al. (2017) reported that the Indian coast's maximum tidal range of 11m is in the Gulf of Khambat with the potential of 7000 MW, a maximum tidal range of 8 m at the Gulf of Kutch with the potential of 1200MW and a maximum tidal range of 5m at the Sunderbans delta with the potential of 100 MW. The distribution of tidal range along the Indian coast is shown in Figure 6. The authors reported fewer tidal ranges observed on the southern coast of India. Hence, the Gujarat and West Bengal coasts are suitable places to install Tidal energy converters.

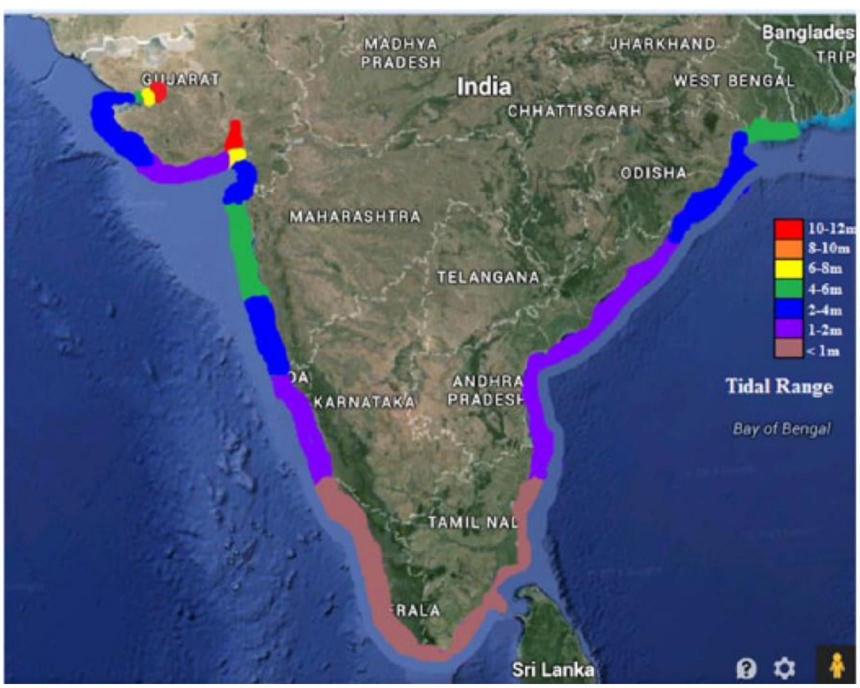


Figure 6. Potential tidal energy sites in India (Murali and Sundar, 2017)

CONCEPTS OF FIXED AND FLOATING DEVICE

Energy converters can be installed as fixed as well as floating devices in the marine environment, depending on the requirement. The fixed concept indicates that the device is attached to the sea bed by means of any supporting structure or integrated with any fixed structure. In contrast, the floating device remains on the free surface and is attached to the seabed/other structure using mooring. This device responds with respect to the wave characteristics such as wave amplitude, period, and direction. The maximum amount of wave energy is located on the free surface, especially in the case of deep and intermediate water. However, the bottom interaction in shallow waters can lead to wave energy dissipation. Clement et al. (2002) described the effect of the installation of energy converter devices on the different water depth conditions. Considering the above conditions, installing the WEC device in a higher water depth is beneficial. Hence, the floating WEC device will be suitable for installation in deep-water conditions to capture a higher amount of wave energy. However, it has some drawbacks, as the floating devices are held with mooring lines. In case of extreme weather/survival conditions, waves with maximum energy may cause failure to the mooring line and its support. The other aspect is the cost of transfer of the converted energy from deep water to the coastal region. Under these circumstances, the fixed WEC device can be advantageous and can be designed to withstand extreme wave climates.

POPULAR MARINE ENERGY CONVERTERS

Different Forms

There is no specific classification of ocean renewable energy converters, as many ideas, inventions, and patents are filed. Some of the most common energy converters used worldwide are discussed here. The classification is based on the energy source discussed above and illustrated in Figure 7.

Wave energy converters

A variety of wave energy converters are present in the current scenario, including point absorbers, attenuators, and terminators, as outlined by Sundar and Sannasiraj (2021). In this discourse, we will narrow our focus to a specific category within this diverse range of converters. Terminators are devices oriented parallel to the wave front and perpendicular to the wave directions. Positioned along the principal wave directions, attenuators mitigate the impact of the wave as it propagates from offshore to the coast.

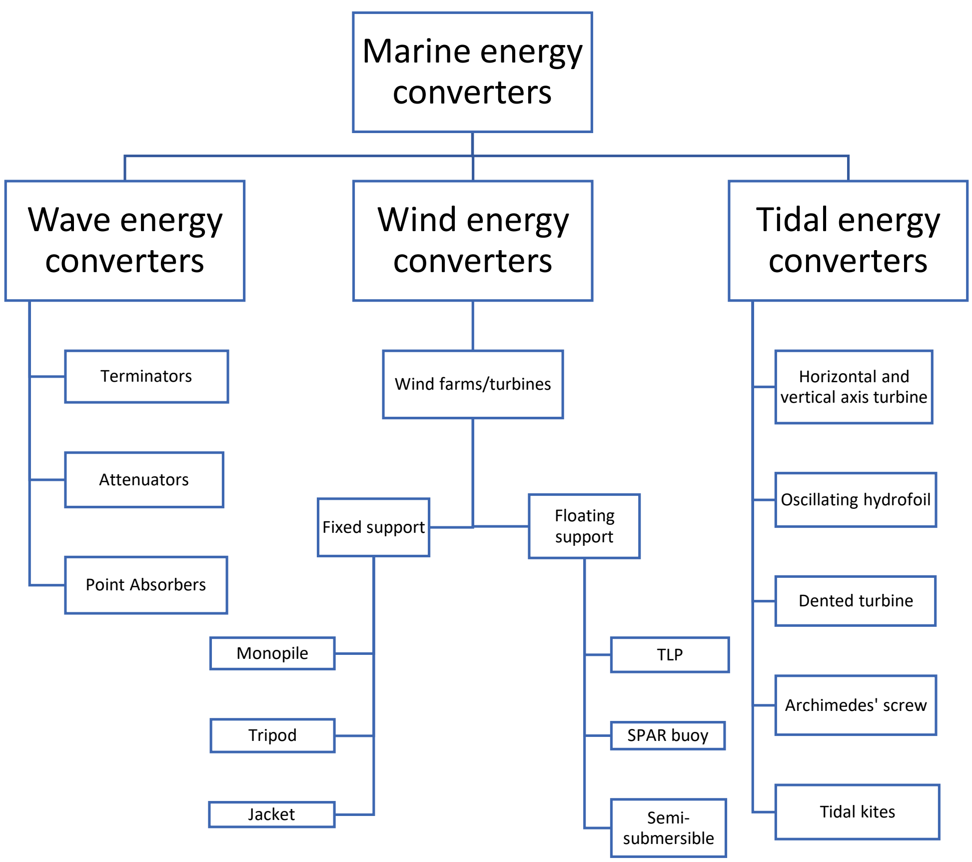


Figure7. Flow chart on different marine energy converters

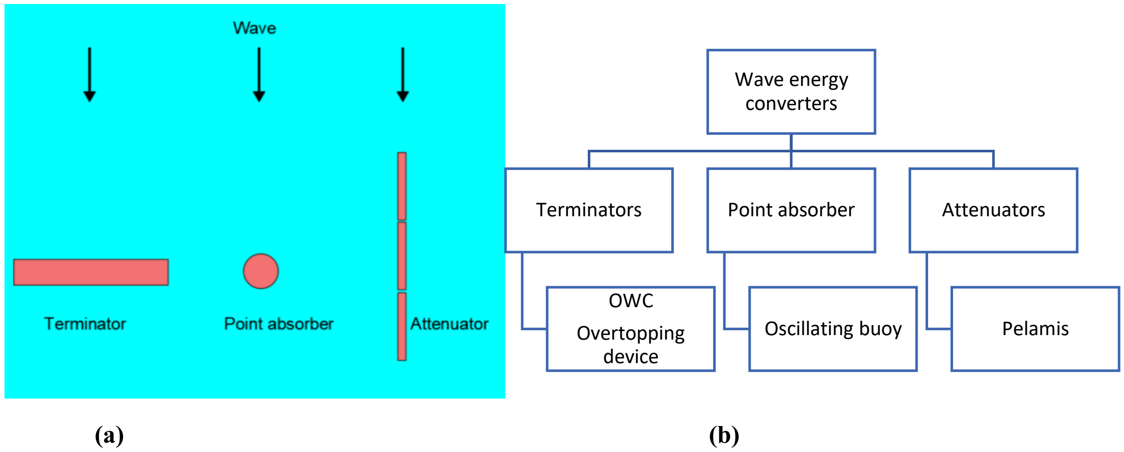


Figure 8. **(a)** Schematic representation of the Terminator, Point absorber, and Attenuator. **(b)** Typical classification of WEC according to its function (Sundar and Sannasiraj, 2021)

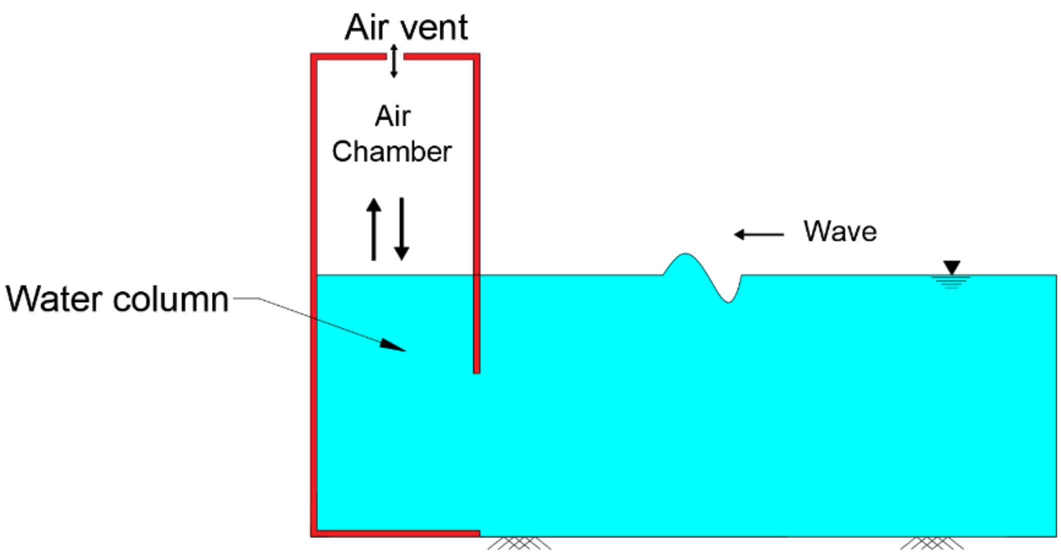


Figure 9. Principle of working of Oscillating Water Column device (OWC)

On the other hand, point absorbers distinguish themselves through floating structures equipped with components that undergo relative movement in response to wave action. Consider the concept of a floating buoy enclosed within a fixed cylinder, for example. Figure 8 presents a schematic representation that elucidates the alignment of these wave energy converters in relation to the direction of the waves. To elaborate further, an oscillating body or a buoy falls into the category of point absorber wave energy converters, exemplified by Pelamis, which signifies the wave attenuator. The overtopping device and Oscillating Water Column (OWC) signify the wave terminators in this context.

Oscillating water column (OWC)

This constitutes a partially submerged hollow apparatus featuring both an air and water chamber. The front lip wall, including the draft, is oriented towards the seaside, while the rear wall remains completely enclosed. The upper lid wall is equipped with an air vent. When sea waves impact the front lip wall, the water chamber within experiences oscillation, facilitating the exchange of air through its vent. Figure 9 provides comprehensive information about the Oscillating Water Column (OWC). The generation of electricity can be achieved by positioning a bi-directional turbine above the vent. Widely employed in both isolated and integrated applications, this device finds application in various developed and developing countries situated along coastal regions. This technology can be employed either as a fixed or floating device, adapting to specific requirements as discussed by Evan (1978) and Sarmento and Falcao (1985). Figure 10 illustrates key field installations of Oscillating Water Columns (OWCs) in various countries.

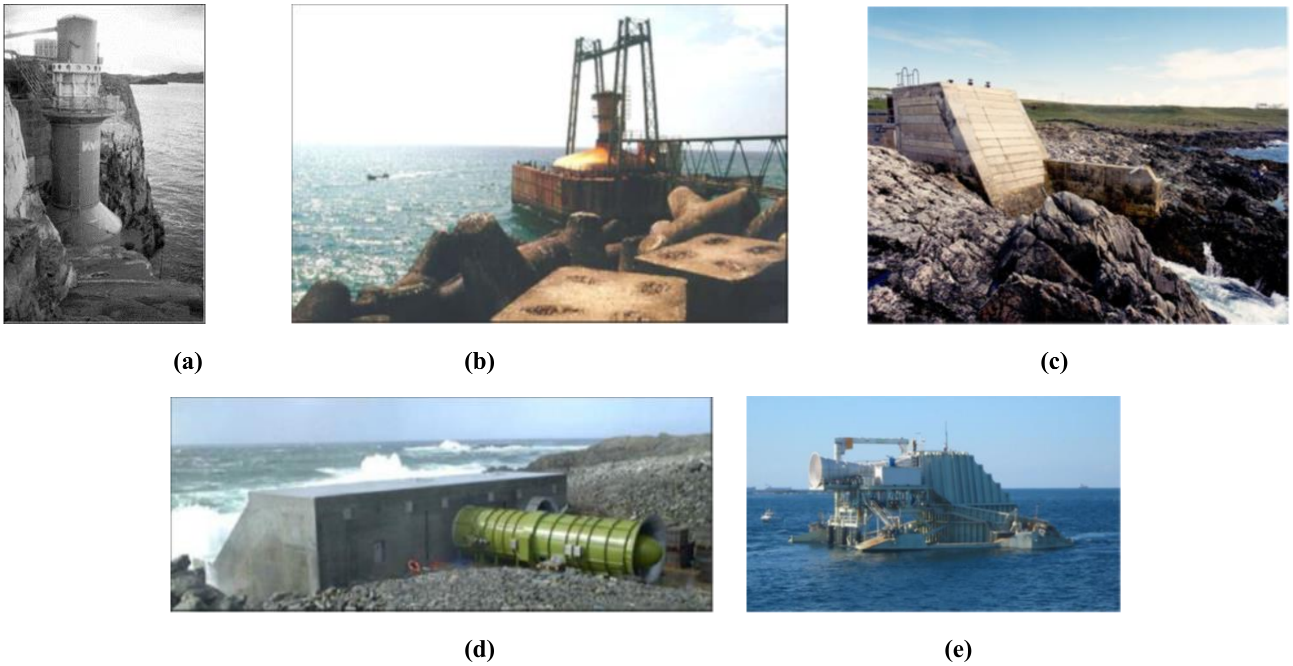


Figure 10. Different OWC at the different sites (Bray et al., 2014; Falcao and Henriques, 2016; Zhang et al., 2021). **(a)** Shoreline OWC, Norway, 1985, Attached with the cliff. **(b)** Bottom-standing OWC 1990 at Vizhinjam, India, Rated power 125 kW. **(c)** Shoreline OWC on the island of Islay, Scotland, rated 75 kW, commissioned in 1991. **(d)** LIMPET OWC plant, 2000 Scotland, UK, Rated power 500 kW. **(e)** Oceanlinx greenWAVE, Australia, 2014, rated power 1MW

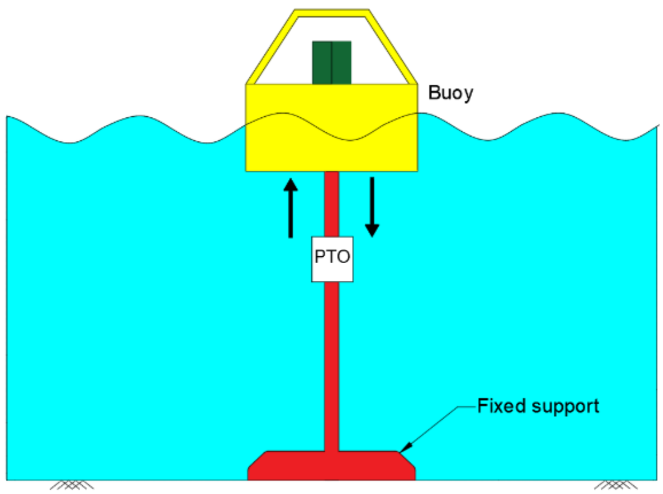
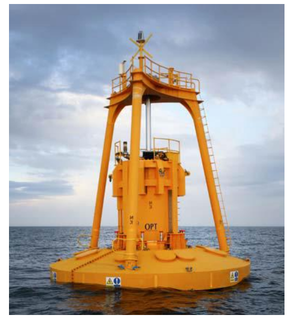


Figure 11. Point absorber/oscillating buoy

Oscillating buoy

The oscillating buoy/point absorber is a floating device situated on the sea surface, extracting wave energy through its relative motion in response to sea waves. It may be affixed to the seabed or other structures using mooring techniques (Figure 11). To harness electricity, either a linear or rotary generator can be employed. Lopez et al. (2013) reported that point absorber-type energy converters contributed to being the most highly produced energy device by companies compared to other energy converters. This can be used for multifunctional aspects such as navigational purposes and other integrated applications. Figure 12 (a) indicates some of the oscillating buoys successfully installed in the field. According to Bray et al. (2014), the point absorber was deployed to the Oregon coast in 2012 with a capacity of 1.5 MW. The point absorber in Figure 12 (b) was designed with a peak-rated power potential of 15 kW (Artal-Sevil et al., 2018). This can also be a good option for energy devices along the Indian coast other than OWC, as this can be installed and operated successfully. Kumar et al. (2022) reported that research on this device had been carried out at IIT Madras, India, to implement this device along the Indian coast.



(a) **(b)**

Figure 12. Case study on Point Absorber WEC. **(a)** Point absorber by OPT (US coast) (Bray et al., 2014; Zhang et al., 2021). **(b)** Power Buoy (PTO) (UK) (Artal-Sevil et al., 2018).

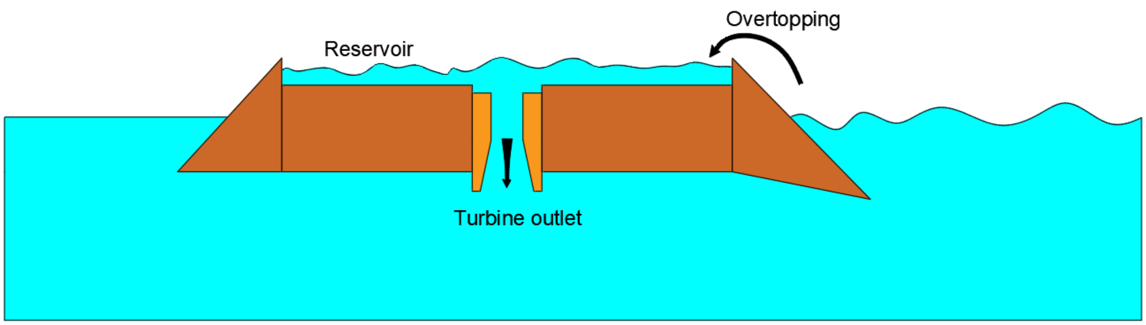
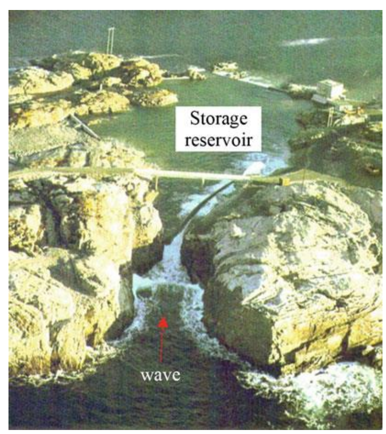


Figure 13. Overtopping device



(a) **(b)**

Figure 14. Case study on overtopping WEC in the field. **(a)** Wave Dragon (overtopping device), (UK) (Bevilacqua and Zanuttigh, 2011). **(b)** TAPCHAN wave energy plant (Sheng, 2022; Zhang et al., 2021)

Overtopping device

Operating on the principle of a hydroelectric turbine system, this device transforms the kinetic energy of waves into the potential energy of water within a reservoir. Waves ascend an inclined structure and overflow into the reservoir. It results in water flux in the reservoir and helps in electricity generation by the turbine outlet, as shown in Figure 13 (Lopez et al., 2013; Zhang et al., 2021; Sundar and Sannasiraj, 2021). This device can be of fixed or floating structure, depending on the requirements. The best examples are TAPCHAN (350kW) and Wave Dragon (4- 10 MW) (Figure 14). This overtopping device can be applied as a hybrid system by integrating with other devices. In addition, this device can be more effective in energy conversion, particularly during extreme weather conditions. Hence, this device may be an option in the southeastern portion of India because of the monsoon.

Pelamis

The Pelamis Wave Energy Converter has been deployed in various locations to test and demonstrate its effectiveness in converting wave energy into electricity. According to Lopez et al. (2013) and Bray et al. (2014), this was considered a promising technology for harnessing wave energy due to its innovative design and potential to capture energy over a wide range of wave characteristics. It's important to highlight that while Pelamis technology initially showed promise, it encountered challenges associated with cost, maintenance, and reliability. The Pelamis device is engineered to float on the ocean's surface, and it is comprised of a series of cylindrical sections interconnected by hinged joints, forming a segmented snake-like structure, as depicted in Figure 15. Each section moves autonomously in response to passing waves. As waves traverse these segments, the joints flex and bend, causing the motion to pump hydraulic fluid through power take-off systems. This process converts the mechanical energy of the waves into hydraulic pressure. The generated hydraulic pressure is then utilized to drive hydraulic motors, subsequently powering generators to produce electricity. The electricity is transported to the shore via undersea cables (Lopez et al., 2013; Bray et al., 2014; Zhang et al., 2021). Figure 16 shows that the Pelamis devices installed on the site with a rated power potential of 750 kW

Case study of WEC in India

A higher number of these energy converters have been installed in European countries and the southern coast of Australia owing to higher wave power potential concentrated in the northern and southern hemispheres (Lopez et al., 2013). Table 1 shows the information on India's marine energy converters in the field. Wave energy converter (OWC) at Vizhinjam, Kerala, was the first pilot power plant in India, installed in 1990. It was later decommissioned due to maintenance issues in 1991. Ismail et al. (2020) and Nagata et al. (2011) reported that the Backward bend duct buoy (BBDB) has a significant potential for generating Ocean energy in India from field tests in real sea conditions. In addition, IIT Madras has also carried out research activities on various wave energy converters, particularly numerical and physical model studies. Some of these concepts are also being patented.

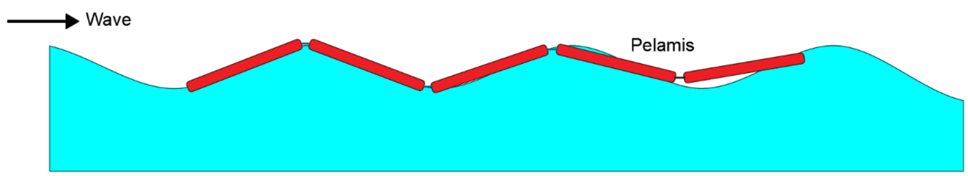


Figure 15. Pictorial view of the series of Pelamis wave energy converters on the sea surface

(a) **(b)**

Figure 16. Case study on Pelamis WEC. **(a)** Pelamis (UK) (Bray et al., 2014). (**b**) Pelamis (UK) (Artal-Sevil et al., 2018; Zhang et al., 2021)

Table 1. Detailed information on marine energy converters along the Indian coast

Location	Capacity (MW)	Wave height	Tidal	Technology	Cap Ex.	Status
Vizhinjam	0.15	2-4 m	0.6 m, 0.5 m/s	OWC, Horizontal axis turbine	Euro 2 million / MW	Decommissioned
BBDB	0.05	3 m	-	Floating OWC, BD turbine	-	Demonstrated
OWC integrated with coastal structures	IIT Madras has carried out several physical model studies as well as filed patents for the hybrid concept					

Wind energy converter

Numerous countries are directing their attention to offshore wind technology as a source of clean energy. Offshore locations boast higher wind speeds compared to onshore areas, resulting in greater power production per installed capacity, as highlighted by Bray et al. (2014). Figure 17 illustrates a schematic representation of a wind turbine affixed to the seabed using a monopile, and an alternative configuration involving a floating platform tethered to the seabed through mooring, as explored by Arshad and Kelly (2013) and Breton and Moe (2009). Fixed concepts of wind farms with different foundation supports are standard, as well as established methods. However, floating wind farms with the potential to equal the performance of fixed wind farms have not yet been attained. Many research groups are exploring different ways to eliminate the complications in floating concepts. The vibration induced by wave loading to the wind blades in floating conditions may affect the function of the energy conversion system. Linking it with some other integrated application as a hybrid system can reduce such vibration. Some of the wind farms installed in the field are shown in Figure 18. Breton and Moe (2009) reported that the offshore field in Denmark (Figure 18b) consists of 80 turbines with a 2 MW capacity that can supply 150000 Danish homes.

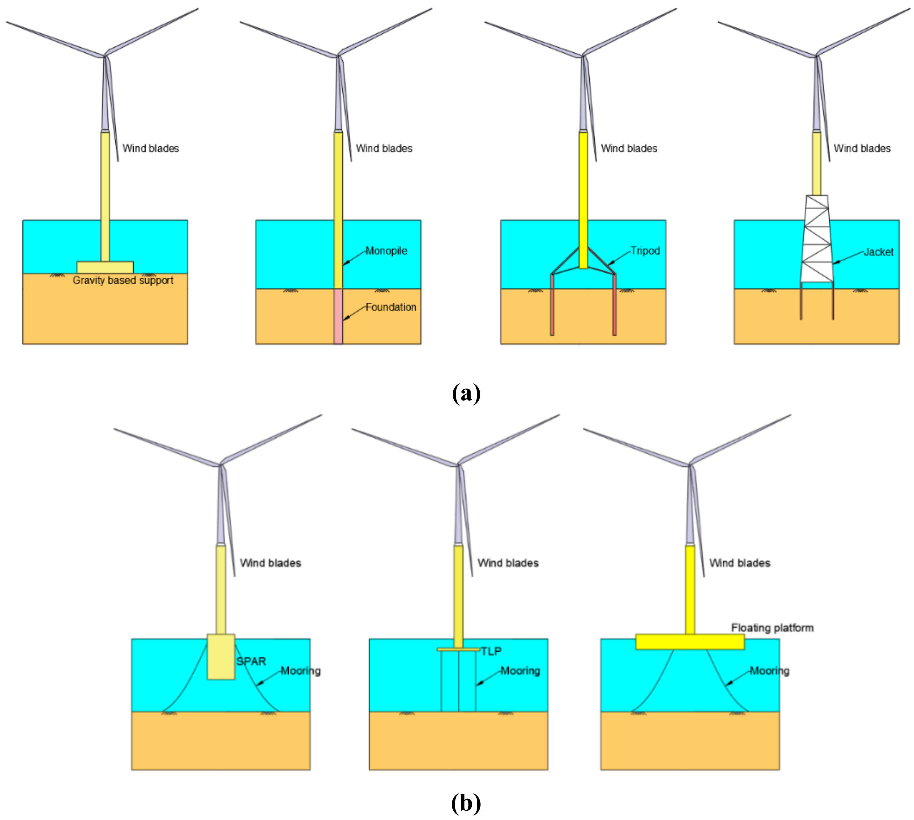


Figure 17. Wind turbine **(a)** Fixed support, and **(b)** Floating support (Arshad and Kelly, 2013; Breton and Moe, 2009)

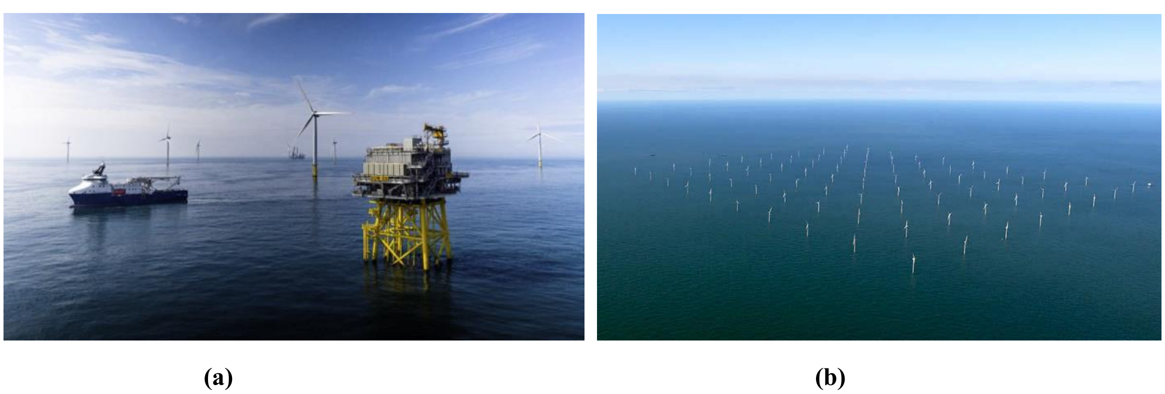


Figure 18. Visualization of offshore wind farms in the field. **(a)** Drone view of the Dudgeon wind farm, UK (Nikitas et al., 2019). **(b)** Horns Rev offshore wind farm, Denmark (Breton and Moe, 2009)

Table 2. Global offshore wind power capacity and number of turbines installed (Diaz and Soares, 2020)

Continent	Europe								Asia					America
Country	Belgium	Finland	Denmark	Germany	Ireland	Netherland	Sweden	UK	China	Japan	South Korea	Taiwan	Vietnam	US
Installed capacity (MW)	871.2	84.4	1273.1	5342.3	25.2	1117.8	191.2	7347.8	2409.9	41.3	35	8	183.2	30
No. of turbines	231	18	510	1167	7	365	79	1796	676	22	15	2	102	5

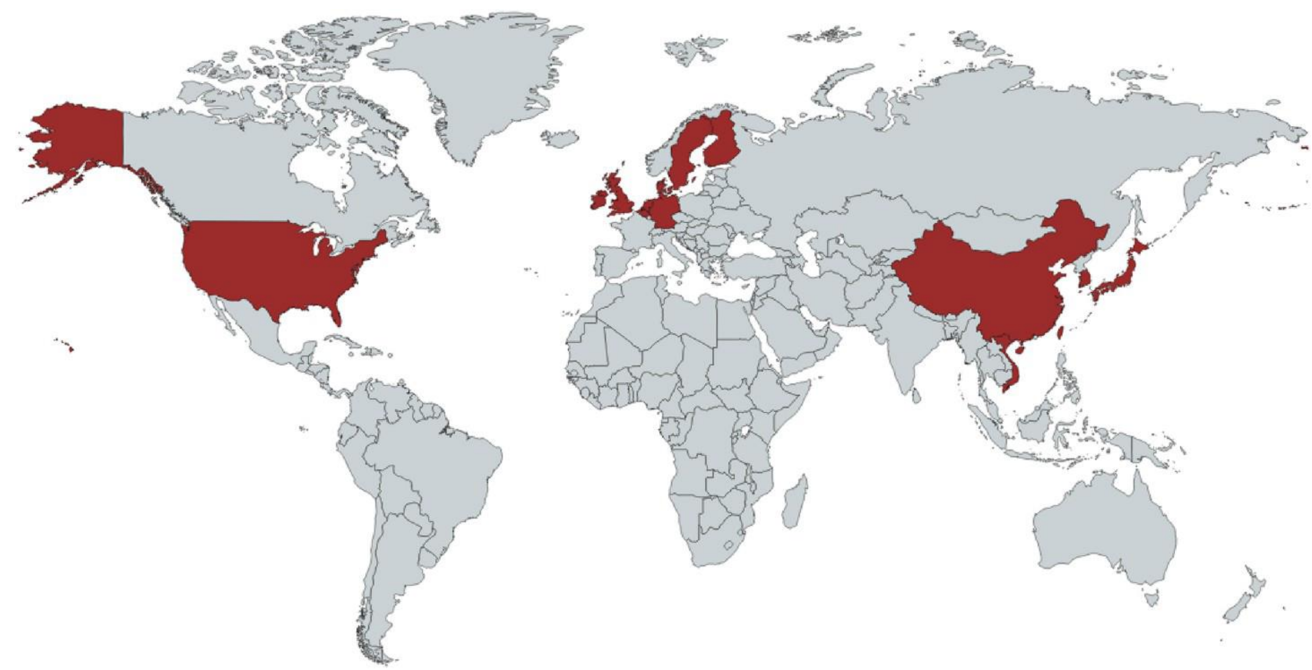


Figure 19. Global distribution of offshore wind farms by countries (Diaz and Soares, 2020)

Case study on wind farms worldwide

The global wind farm usage for harvesting marine energy is shown in Table 2. Diaz and Soares (2020) depicted the global distribution of offshore wind farms in Figure 19, which shows that Europe, Asia, and the American continents are focused on offshore wind energy conversion. Being a smaller coastline, Europe dominates the others in the maximum number of offshore wind turbines with maximum power capacity. The UK, with 1796 turbines, and Germany, with 1167 turbines, hold the maximum number of installations globally. However, for India, there is still a long way to go, although studies are being pursued vigorously.

Tidal energy converter

The extraction of tidal current energy can be achieved through three primary methods: tidal stream generators, tidal barrages, and tidal lagoons. Tidal stream generation closely resembles conventional wind turbines, utilizing the kinetic energy of the fluid to generate power. As the name suggests, a tidal stream generator involves the deployment of a tidal turbine or similar technology within a tidal flow or moving water stream. The mass of flowing water imparts energy to the harvesting system. Tidal stream generators stand out as one of the most widely adopted techniques for harnessing tidal energy in the ocean, particularly when compared to the other two methods. Figure 20 shows the global classification of tidal turbine designers as per Nachtane et al. (2020). Kaufmann et al. (2019) explained that the tidal turbines can be installed at the seabed and fixed to any of the vessels, as mentioned in Figure 21. The depths of the turbine blades are chosen based on the tidal stream characteristics existing at the site. The different available tidal current energy converter devices, according to their classification, which were executed in the field, are discussed here. Pacheco and Ferreira (2016) and Nachtane et al. (2020) have explained some of the large-scale tidal energy converters in the site (Figure 22).

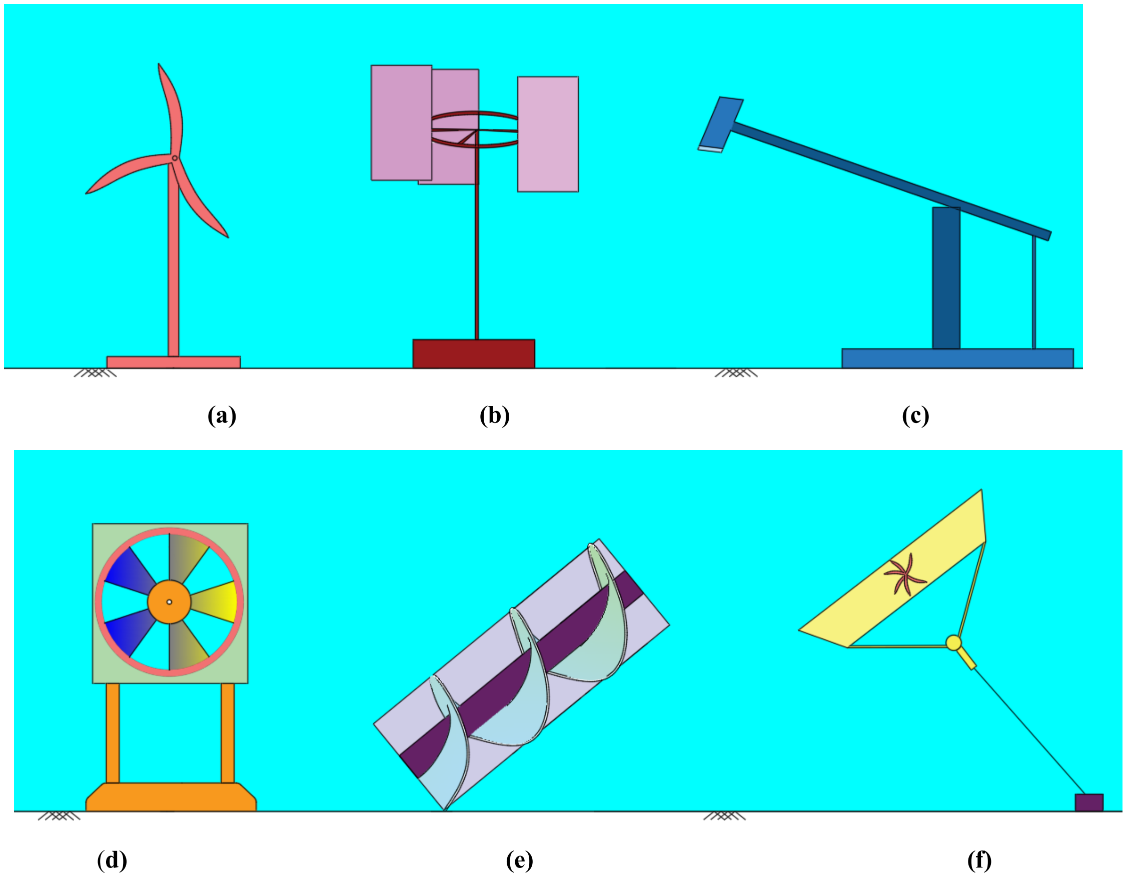


Figure 20. Different classifications of turbine energy converters (Nachtane et al., 2020). **(a)** Horizontal axis turbine, **(b)** Vertical axis turbine, **(c)** Oscillating hydrofoil, **(d)** Ducted turbine, **(e)** Archimedes' screw, and **(f)** Tidal Kite

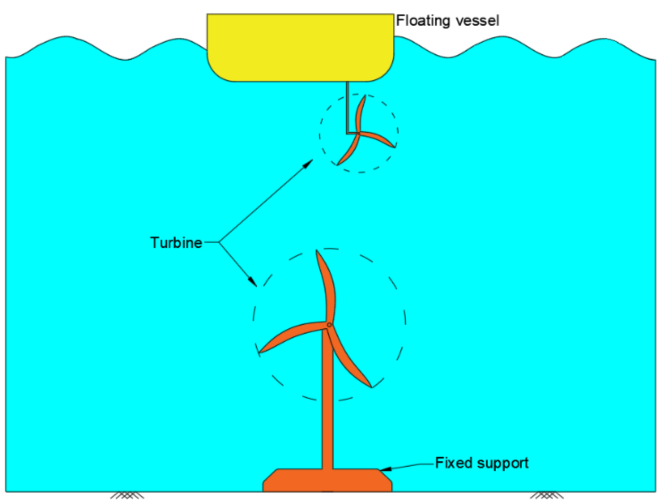


Figure 21. Seabed and surface platform-mounted turbines (Kaufmann et al., 2019)

Case studies

Case studies in the UK showcase a 400-kW capacity (Figure 22a), while China has implemented a system with a 450-kW capacity (Figure 22b). Additionally, Scotland has a rated output of 35 kW (Figure 22c). These regions have experienced significant technological progress in tidal current energy conversion over the past decade. WES (Wave Energy Scotland) clarifies that they initially employed vertical axis turbines until 2010 and subsequently integrated horizontal axis turbines along with other types.


(a) **(b)**

(c)

Figure 22. Large-scale horizontal axis turbine. **(a)** UK and **(b)** China (Harrold and Ouro, 2019; Si et al., 2022). **(c)** Tidal energy device deployed by Oceanflow in Scotland (Pacheco and Ferreira, 2016)

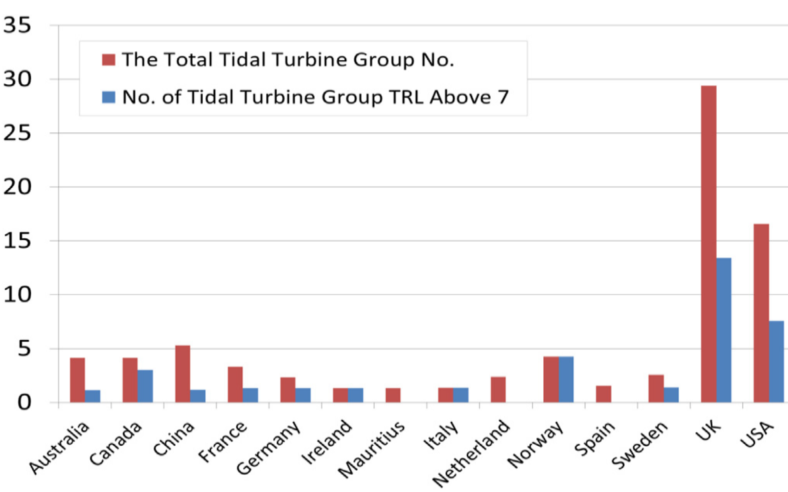


Figure 23. Technology readiness levels of the TCTs technology (Nachtane et al., 2020)

The UK and the US lead the design of tidal turbines (Figure 23). Existing research by several authors reported that the horizontal axis turbine is a commonly used device compared to other types, as it is more beneficial. However, Nachtane et al. (2020) explained that the hydrofoil type of turbine current energy converter plays a significant role in terms of optimal design and successful implementations on site.

STAGES OF ENERGY TRANSFER MECHANISM INVOLVED IN ENERGY DEVICES

It is crucial to examine the energy transfer process from its source to the grid and acknowledge associated energy losses. The subsequent section underscores the significance of energy transfer mechanisms, focusing on WEC-type OWC as an illustrative example. This principle applies to all the energy converters as discussed earlier. The diagram in Figure 24 outlines the phases of energy transfer from sea waves to the grid electricity supply via the energy device OWC and turbine/motor. As sea waves interact with the OWC in the initial stage, input energy is introduced into the OWC chamber through the front draft. This marks the primary energy conversion. Consequently, the turbine rotates under the influence of this air pressure, facilitating the generation of mechanical energy and signifying secondary energy conversion. Ultimately, utilizing a generator, the electricity produced in the secondary conversion is transferred to the land, constituting the tertiary energy conversion. This sequential process is consistent across various energy converters in marine environments, although the specifics of its operation may vary depending on the nature of the converters.

It is impossible to convert sea energy to land without losses in the stages of energy conversion. The energy loss encountered in these stages is shown in Figure 25. It is essential to investigate these losses as they affect the efficiency of the energy conversion system and sometimes may lead to its malfunction. Hence, much research and efforts are being focused on the reduction in the losses, thereby increasing the efficiency of the devices.

HYBRID ENERGY CONVERTERS

Hybrid and synergistic energy systems have gained popularity in recent decades, addressing challenges associated with marine energy converters operating in isolated conditions. Standalone energy devices necessitate a dedicated supporting structure or foundation to ensure stability and resilience against the forces of sea waves and wind.

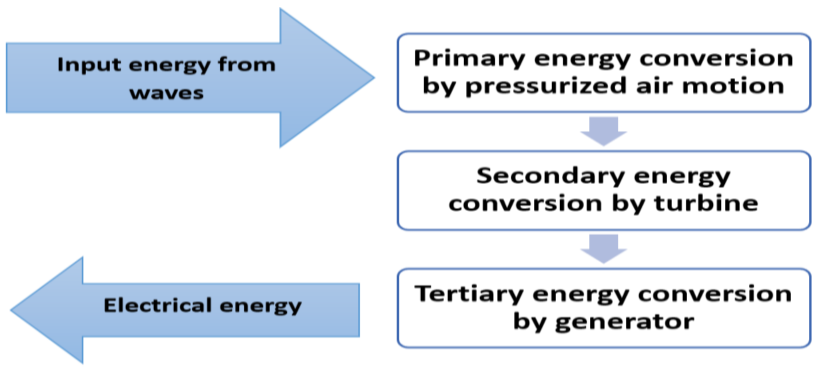


Figure 24. Stages of energy transfer from sea waves to the grid through the OWC energy converter

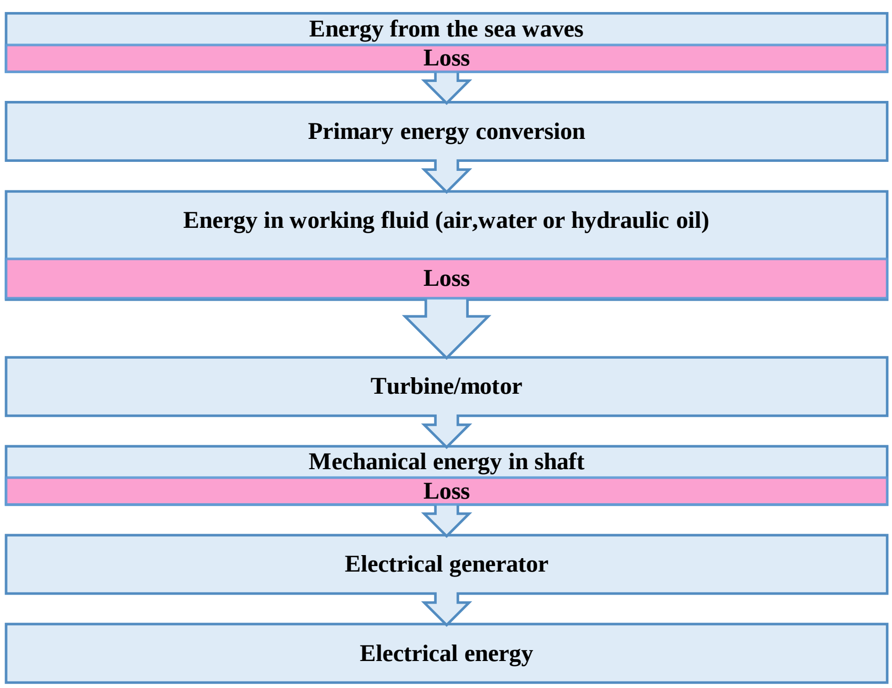


Figure 25. Flowchart for loss associated with energy transfer mechanism in OWC (Sundar and Sannasiraj, 2021)

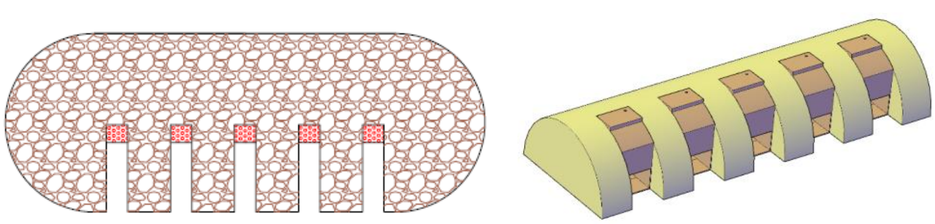
Conversely, when integrated with other structures like breakwaters or wind turbines, the need for additional support diminishes, transforming the system into a multipurpose structure. For example, integrating an OWC with a breakwater not only serves as an energy converter but also functions as a coastal protection measure. In this scenario, a section of the breakwater is repurposed for the installation of the OWC, making the approach cost-effective. Additionally, the OWC's stability is enhanced by its connection to a substantial supporting structure. The same principle applies to other hybrid concepts like OWC with wind turbines, overtopping reservoir devices with a breakwater, and OWC with SPAR. Particularly from the Indian perspective, this is the best approach due to the limited availability of wave energy potential. Further, the high costs associated with the slow commercialization progress of WECs, lead to sharing the substructure. The main criterion for this integration is the availability of wave power and the local demand for the power. The device selection strategy should be combined with the requirements such as, (i) in erosion-prone regions, where WEC can be integrated with coastal protection systems, (ii) in wind dominated regions, where combined offshore wind and wave power units can be applied in a single platform, and (iii) in islands, where multiple energy devices can be integrated with desalination plants, solar panels and so on. Several studies explained that the hybrid system of energy converters would be more beneficial because of its functional aspects and cost-effectiveness (Sundar et al., 2010; Zhao et al., 2019; Doyle and Aggidis, 2020; Sundar and Sannasiraj, 2021; Fenu et al., 2023). Hence, these concepts of hybrid/synergies energy systems have been very familiar in recent trends. Some popular hybrid energy converters installed on the site are described below.

Numerous researchers are directing their efforts toward integrating energy devices with various breakwater applications. Given that India boasts 13 major and 205 minor ports, incorporating energy converters into port and harbor breakwaters emerges as a promising solution for clean energy. At the very least, this approach can cater to the energy needs of port operations, navigation lights, or other low-power consumption applications. In the context of floating wind turbines, hybrid concepts hold the potential to provide additional support and optimize maximum power output.

WEC with breakwater

The integrated concept of combining breakwaters with wave energy converters (WECs) stands as a crucial global hybrid application, renowned for its stability compared to other hybrid energy converter devices. In this configuration, the fundamental structure is a breakwater, a widely employed coastal structure with versatile applications. WECs such as OWC and overtopping devices, can be seamlessly incorporated or attached to breakwaters, serving as energy converter devices and coastal protection or berthing structures. This hybrid approach yields benefits for both the WEC and the breakwater, as outlined by Sundar et al. (2010) and Sundar and Sannasiraj (2021).

Hybrid WECs, in this context, eliminate the need for additional support foundations required in isolated conditions. Moreover, the construction of the breakwater requires less material as WECs occupy partial spaces, resulting in potential cost savings. Over the past decade, researchers at IIT Madras, India, conducted extensive research on this hybrid application, particularly in the integration of OWC with rubble mound breakwater (Ashlin et al., 2018). Their findings revealed that the performance of OWC improved in integrated applications, contributing to more tranquil conditions on the lee side of the breakwater. Additionally, the impact of inclined harbor walls on enhancing WEC performance was explored by Raj et al. (2019). Currently, IIT Madras is focusing on this hybrid application with semi-circular breakwater (SCBW)(Socrates et al., 2024; 2025) Existing numerical and experimental studies have found that the SCBW has several benefits, compared to other types in terms of energy dissipation and stability of the structures. Figure 26 shows the integrated concepts of rubble mound and semicircular breakwater. The semi-circular breakwater with OWC (Figure 26b) was patented by IIT Madras in 2023 (Indian Patent No. 461144). Some other important hybrid wave energy devices are shown in Figure 27. These are installed in different parts of the world, such as Japan, Spain, South Korea, and Italy. For example, Figure 27(e) shows the breakwater integrated with an overtopping energy device in the field with a nominal power of 1.5 kW at 3 m head and a flow rate of 0.045 m^3/s (Contestabile et al., 2016).



(a) **(b)**

Figure 26. Array of OWC integrated with (**a**) Rubble mound breakwater (Ashlin et al., 2018), and **(b)** Semi-circular breakwater with OWC (Indian Patent No. 46114)

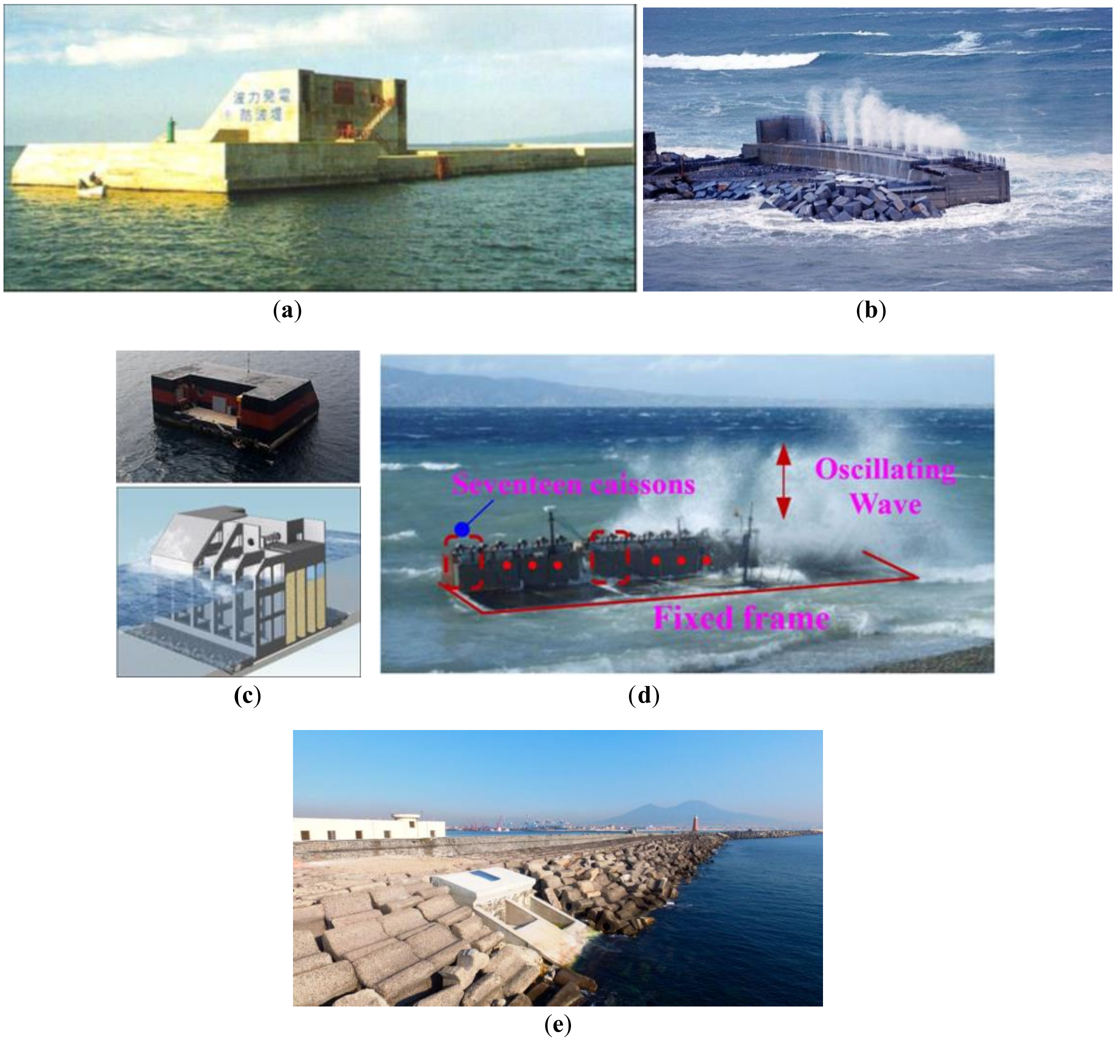


Figure 27. WEC integrated with breakwater (Falcao and Henriques, 2016; Contestabile et al., 2016; Zhang et al., 2021). **(a)** OWC plant integrated into a breakwater at Sakata harbour, Japan, 1990. First OWC combined with breakwater concept with rated power of 60 kW. (**b**) Multi-chamber OWC plant integrated into a breakwater, Mutriku harbour, Spain, 2008, with 16 OWC chambers rated 18.5 kW each. (**c**) 500 kW bottom-standing plant in South Korea, 2015. **(d)** U-shaped OWC in a REWEC3 caisson breakwater for Civitavecchia harbour, Italy, with total installed power of 2.5MW. **(e)** Overtopping breakwater for wave energy conversion OBREC prototype at the Port of Naples (Italy).

WEC with wind turbine

Doyle and Aggidis (2020) explored various hybrid Oscillating Water Column (OWC) applications in their review. Floating structures can be seamlessly integrated with Wave Energy Converters (WECs) to provide support in offshore environments. For example, a wind turbine can be combined with interconnected OWCs, as depicted in Figure 28. This integration offers increased stability to offshore wind turbine platforms, while concurrently reducing costs. Wind turbines situated on floating platforms are more susceptible to oscillations caused by sea waves, potentially leading to issues with the turbine's periodic vibrations. Consequently, integrating wave absorption and energy conversion devices, such as OWCs, can mitigate the movement of wind turbines.

Similarly, Fenu et al. (2023) conducted an experimental investigation on a multi-OWC wind turbine floating platform, where the authors concluded that there is no significant reduction in vertical and angular motions of the floating platform with the variation of OWC power take-off (PTO) damping ratio. This is due to the sloshing of the water column in OWC. Sloshing hinders the maximum wave energy absorption capacity. Still, many researchers are finding a better solution for this problem that will benefit both the wind turbine and OWC performances. This will be an excellent integrated application for wind energy conversion in remote areas from the shore. Even in the offshore region, the wave energy is concentrated more on the sea surface; hence, maximum absorption of the energy capacity of OWC is possible. Some of the field visualizations of wind turbines with wave energy converters, according to McTiernan and Sharman (2020), are shown in Figure 29. It was reported that different WECs, such as Oscillating body and OWC, are used in these projects. The W2Power hybrid system is designed with a total power potential of 10MW, which includes 7.2 MW from wind turbines and 2- 3 MW from the Oscillating body. Poseidon hybrid energy system has a power potential of 2.6 MW from OWC and 2.3-5 MW from wind turbines.

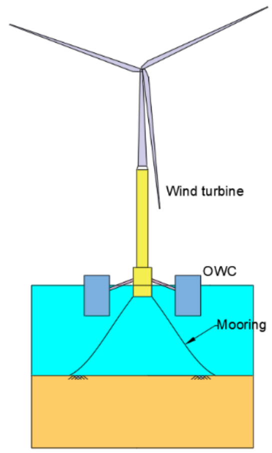


Figure 28. Multiple OWC integrated with floating wind turbine (Doyle and Aggidis, 2020; Fenu et al., 2023)

(a) **(b)**

Figure 29. Case study on wind-wave hybrid energy system (McTiernan and Sharman, 2020). **(a)** W2Power Hybrid Wind Wave System by Pelagic Power (Norway). **(b)** Poseidon Hybrid Wind Wave System by Floating Power Plant in Denmark

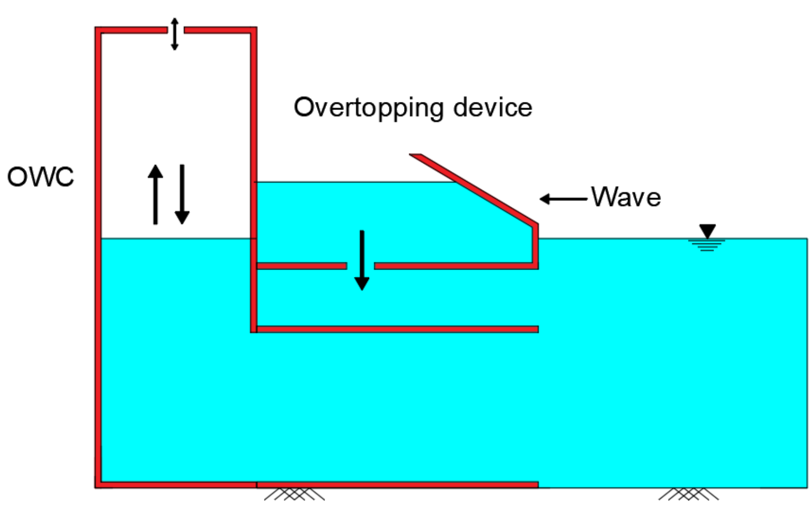


Figure 30. Overtopping device attached with OWC (Doyle and Aggidis, 2020)

OWC with overtopping device

The overtopping concept integrated with OWC can be adopted to some near-shore applications. Besides the OWC, the energy conversion concept can be included by having turbines upstream or downstream of the hybrid OWC structure (Doyle and Aggidis, 2020). Overtopping device energy converters work on a principle similar to hydropower generation. Figure 30 shows a schematic representation of this hybrid energy device, which consists of an overtopping device in front of an OWC towards the seaside. The periodic incident of waves on the overtopping device aids in power generation through the turbine at the required place. The OWC behind the Overtopping device can also generate power by its working principle. By this integrated application, the wave forces acting on the front lip wall of OWC, can be reduced as the overtopping devices absorb the energy. The implementation/case study of this hybrid energy system in the field has not yet been explored. This can be a suitable option for survival/extreme weather conditions.

Wave-solar hybrid concept

While applying solar panels for energy conversion on land is widespread globally, implementing this concept in marine environments presents a unique set of challenges. Addressing this complexity, Cranfield University has pioneered an innovative and sustainable approach to utilizing solar panels for renewable energy conversion in marine settings, as detailed by Wei et al. (2023) and Huo et al. (2022). The plan layout of the solar and wave energy hybrid system is shown in Figure 31. This pioneering concept has been proposed for countries such as Indonesia, particularly in connection with various small islands where establishing grid connections for electricity supply proves impractical. Hence, it was recommended to have solar panels on the sea surface as the space to install them on land is insufficient. Existing floating solar panels are established to work on the lakes. This is the first concept in marine environments. As surface waves can affect the flat rigid panels, the design can be made at a height above sea level with flexible membranes below that can deform according to incident wave conditions and also dissipate energy acting on them. This entire structure is proposed as floating panels with catenary mooring attached to the seabed. In addition, the integration of the offshore breakwater with the floating solar panels adds more stability, as explained earlier. It reduces the wave forces and increases the stability in case of extreme events. As mentioned above, OWC can be integrated into the breakwater, and this would be a multi-functional aspect with three different energy converters coupled to a single structure. Clemente et al. (2021) introduced the hybrid concept of solar panels with potentials of 10 W to 70 W/panels, integrated with aquaculture buoys to feed aquatic living organisms, as shown in Figure 32 (b). This buoy can support floating wind turbines, according to the authors. Zhang et al. (2021) reported the field visualization of the buoy with solar panels (Figure 32a).

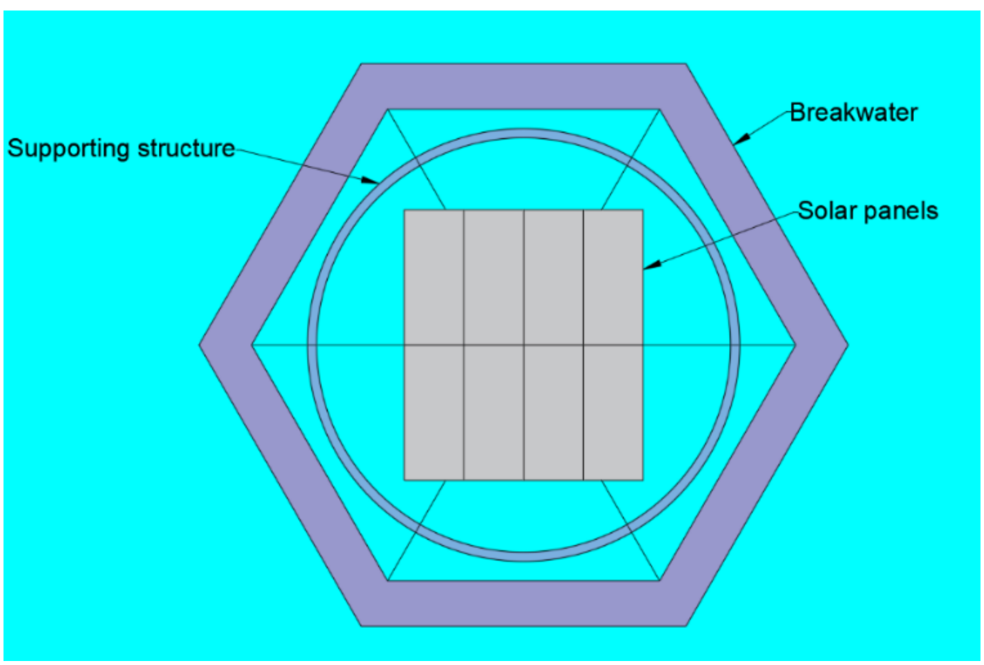
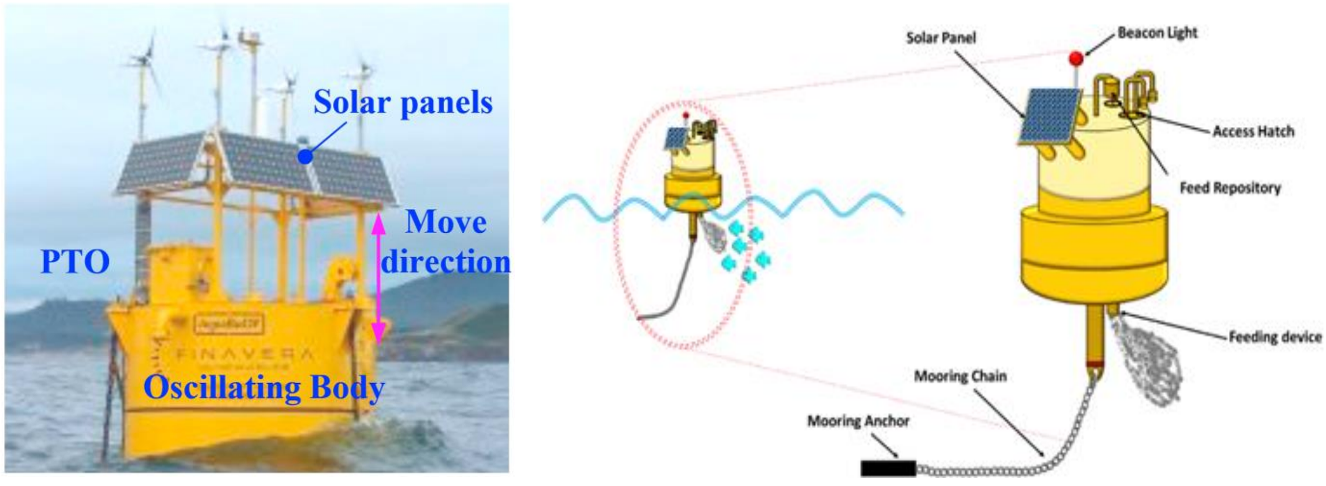


Figure 31. Top view of Solar2 Wave hybrid system (Wei et al., 2023)



(a) (b)

Figure32. Visualization of Wave solar hybrid energy device. **(a)** AquaBuoy WEC, Canada (Zhang et al., 2021). **(b)** Schematic of an aquaculture feed buoy (Clemente et al., 2021)

Even though not installed as hybrid concept, a Cirata Floating solar farm is one such example **(**Sukmawan et al., 2021; Sibuea et al., 2022**)**. It was completed in November 2023 with an energy conversion capacity of 145 MW. Solar panels float on seawater/lake. Indonesia is a country with around 17000 islands. No wind is possible on these islands; hence, installing wind farms on land is challenging. As there was no flat land, they used their terrain for agriculture. Client MASDAR (UAE) designed a new type of stronger solar panels (350000) that won't sink and move with waves. This is as big as 14 football fields. It is in the reservoir. The water doesn't evaporate, saves water, and generates electricity simultaneously. All these panels are interconnected and moored to the lakebed/seabed at a depth of 100 m. The project aimed to supply power to Indonesia's nearly 50000 homes with zero carbon emissions.

WEC integrated with AUV docking station

Due to the difficulty in extracting power requirements in the grid connection from WEC, it can be alternatively used for some offshore applications as a standalone device. One such application of the WEC is to power the Autonomous Underwater Vehicle (AUV). AUV is an underwater device that can serve multiple functions, such as for the Navy, hydrographic surveying, mine countermeasures, homeland security, and so on (Driscoll et al., 2019; Wallen et al., 2019). It works on the stored battery devices in it. Hence, it needs to be recharged manually onshore or/a ship after being utilized for any of its purposes. Normal endurance is 4 to 5 hours. Hence, recharging AUVs on the land station frequently was found difficult as it requires excessive time, cost, and human resources. Therefore, an underwater charging system can be developed, especially with the help of floating WEC at offshore. This is also a hybrid concept where WEC is integrated into an underwater AUV docking station. This energy is a clean, renewable source as the wave induced heave motion, regulates the PTO on the SPAR. Figure 33 shows the schematic representation of the WEC with the AUV docking system, which has been conceptualized by IIT, Madras. A typical AUV docking station laboratory setup at the University of Hawaii is shown in Figure 34b (Wallen et al., 2019).

Tidal energy converter with WEC and wind turbine

It has been reported by many studies that hybrid energy shows an increase in energy conversion compared to isolated energy conversion. Silva et al. (2023) explained that the tidal energy converter can be integrated with a wave energy converter. The authors reported that the horizontal axis turbine, attached to the vertical support of the point absorber below the sea level (Figure 35) can be one option. Hence, it behaves as a hybrid energy device, and the authors reported that this hybrid system, could yield a 30% increase in power production compared to individual energy devices. As several existing studies show that the horizontal axis turbine gave higher power than many other tidal energy harvesting devices, Silva et al. (2023) reported this concept in their work. Similarly, the hybrid concept of integrating tidal turbines with wind turbines has also become popular. Rahman and Shirai (2008), Da and Khaligh (2009) and Ashglaf et al. (2017) explained that this hybrid energy system could be feasible with fixed support wind turbines, as shown in Figure 36. They reported that this hybrid energy system could be proposed with 2 MW power potential from wind turbine and 1 MW rated tidal turbine in the field.

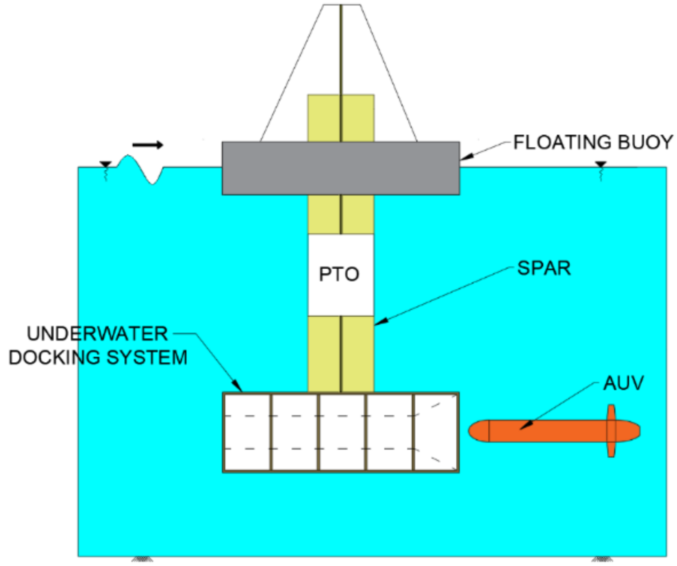
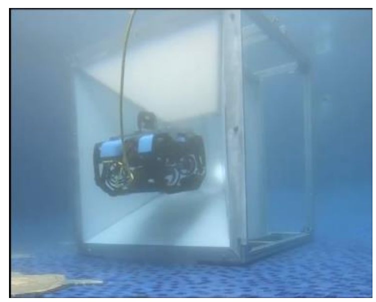


Figure 33. Integrated wave energy converter with AUV docking station



(a) **(b)**

Figure 34. (**a**) Floating spar point absorber WEC. **(b)** Docking station for AUV (Wallen et al., 2019)

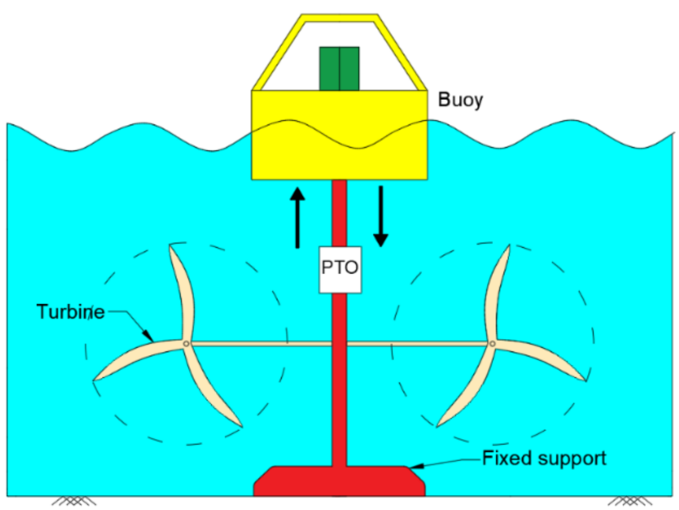


Figure 35. Horizontal axis turbine integrated with point absorber (Silva et al., 2023)

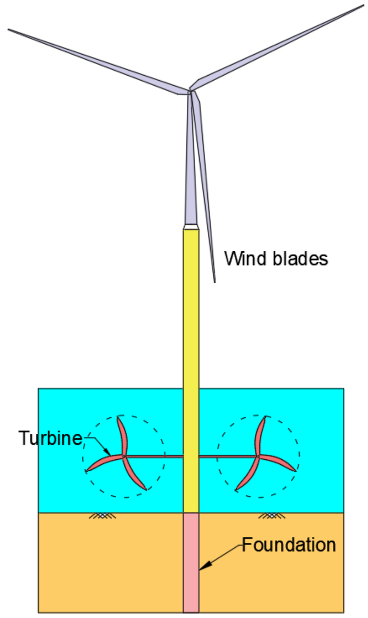


Figure 36. Tidal turbine attached to the support of wind farm (Rahman and Shirai, 2008; Da and Khaligh, 2009; Ashglaf et al., 2017)

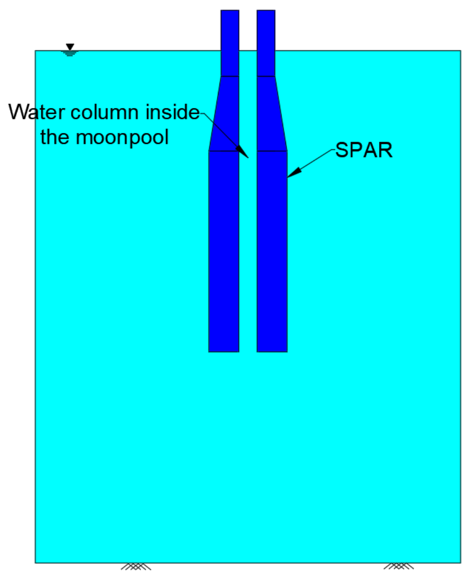


Figure 37. SPAR type offshore wind turbine with moonpool (Pham and Shin, 2019)

Moonpool to OWC

In Figure 37, a SPAR-type platform is illustrated, capable of providing support to offshore floating wind turbines and featuring a moonpool at its center, as elucidated by Pham and Shin (2019). The water column within the moonpool, exhibits oscillations in response to waves, making it conducive to serving as a floating Oscillating Water Column (OWC), a widely adopted wave energy converter in offshore. However, the implementation of a large-scale prototype for this hybrid energy device on-site remains unexplored. This endeavor presents considerable challenges, particularly due to the potential impact of the internal sloshing within the water column on maintaining the stability of the turbine and the SPAR platform.

PROPOSED IDEAS ON THE INDIAN COASTLINE

Isolated energy converters

This section presents an analysis of wave, wind, and tidal power potential along the Indian coast, outlining potential locations for installing energy devices in isolated and hybrid configurations. Figure 38 illustrates the proposed site locations for isolated wave, wind, and tidal energy converters. For isolated Wave Energy Converters (WECs), the coastal areas of Tamil Nadu, Kerala, and Karnataka are identified as suitable locations due to the 15-25 kW/m wave power potential (Sannasiraj and Sundar, 2016) (Figure 4). According to Alluri et al. (2018), the coasts of Gujarat and Tamil Nadu emerge as ideal sites for wind farm installations, benefiting from higher wind speeds, as indicated in Figure 5. Similar considerations are applicable to the installation of tidal energy converters at the Gulf of Kutch and the Gulf of Khambhat along the Gujarat coast (Murali and Sundar, 2017).

Hybrid energy converters

Given that hybrid energy devices in marine environments play more substantial roles compared to isolated energy devices, it is strongly recommended for the Indian coast clean energy concept. Three major hybrid classifications are considered, such as WEC with breakwater, Wind turbine with WEC, and Tidal-wind-wave hybrid system, which cover all the hybrid energy devices as explained earlier. Figure 39 illustrates the suitable site locations along India for the installation of these hybrid energy systems. WEC with a breakwater system has been proposed for all the major ports along the Indian coast, as a breakwater system is essential to any port and harbour. The hybrid system of the wind-wave devices is proposed along the Tamil Nadu and Kerala coasts according to the wind and wave energy potentials. The western and southeastern coasts of India are proposed for the hybrid tidal-wave-wind energy system, as shown in Figure 39. This hybrid system in the western location is preferred according to the tidal energy potential, as discussed in the previous section. The southeastern area is chosen due to the longshore current throughout the year.

Energy island

Energy Island is the concept of developing offshore floating structures with multiple marine energy conversion technologies on large scale aiming to supply maximum power to the land. According to Porichis (2023), the Danish energy island is considered as an integrated energy scheme for the benefit of Bornholm Island, Denmark. The Energy Island model is regarded as a workable solution that, when combined with decentralized offshore renewable energy sources, can provide low-carbon, affordable, and sustainable electricity. It also has the potential to contribute to Greek visions of future developments in the energy sector. Considering India has Islands such as Lakshadweep, this emerging concept can be adopted.

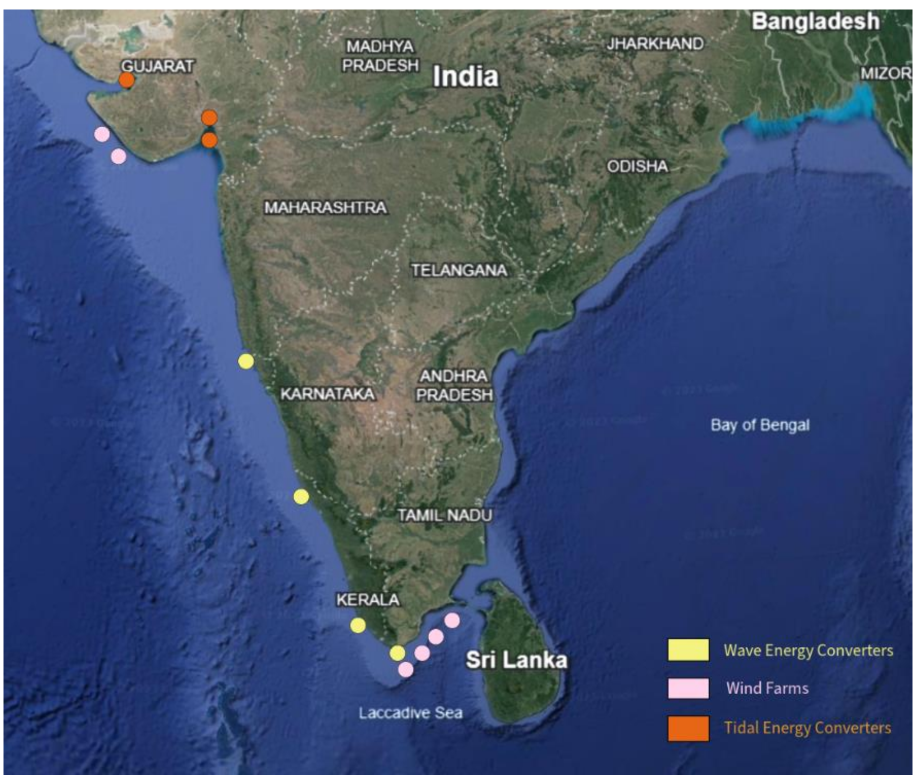


Figure 38. Different isolated energy converters along the Indian coast, based on the energy device locations decided according to Sannasiraj and Sundar (2016), Murali and Sundar (2017), and Alluri et al. (2018)

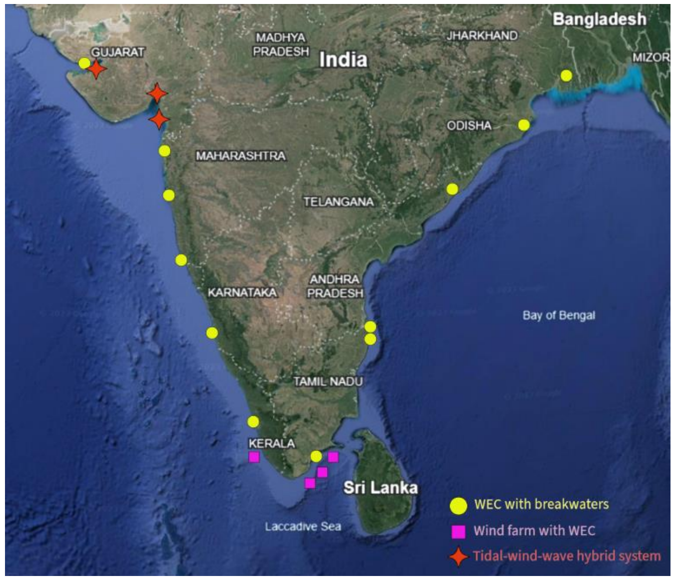


Figure 39. Different hybrid energy converters along the Indian coast. The hybrid device locations are adopted based on Sannasiraj and Sundar (2016), Murali and Sundar (2017) and Alluri et al. (2018)

SUMMARY AND CONCLUSIONS

Acknowledging the imperative for renewable energy conversion, this comprehensive review delved into various marine energy converters, exploring isolated and hybrid concepts through global case studies. While many nations have successfully executed large-scale energy projects in marine environments, it was noted that the Indian coast has yet to witness widespread implementation of energy converters for power extraction. Some pilot power plants faced setbacks, attributing the challenges to lower-than-expected power potential. Despite the existing studies indicating lesser wave energy potential along the Indian coastline compared to western counterparts, this paper contends that a hybrid energy system could surmount these challenges, enabling India to harness maximum clean energy from the marine environment. Furthermore, it is strongly recommended that research be expanded into emerging hybrid energy trends that have not been thoroughly explored on-site along the Indian coast, catering to the nation's evolving energy needs.

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Authors Credit Statement

S. Sandana Socrates: Writing original draft, literature search, selection and conceptual framework development. V. Sriram: Literature synthesis, critical review, supervision of review process and conceptual framework refinement. V. sundar: Literature synthesis and critical review, supervision of review process and conceptual framework refinement.

Data Availability

As this is a review paper, no experiments, numerical, or field data are available.

Compliance With Ethical Standards

The authors confirm that the contributions outlined above accurately reflect their respective roles in the development and writing of this review paper. The authors confirm that there are no known conflicts of interest or funding associated with this publication. All authors adhere to copyright norms

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