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Special Issue on Energy and Water from the Ocean

Desalination plant at Kavaratti Island (India)

Hydrokinetic turbine testing by NIOT

Guest Editors
Dr. Purnima Jalihal
and
Dr. O.P. Pandey

Federation of Indian Geosciences Associations

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SPECIAL ISSUE

ON

“Energy and Water from the Ocean”

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FOREWORD

The Federation of Indian Geosciences Associations (FIGA) was established in 2014 as an umbrella organization representing various geoscientific associations and institutions throughout India. Its primary objective is to promote collaboration within the earth science community. In alignment with this mission, FIGA convened a thematic brainstorming session centered on the topic of "Energy and Water from the Ocean." It is noteworthy that the insights generated from these discussions have been meticulously compiled into a Special Issue of The Journal of Indian Geophysical Union (JIGU).

The ocean holds significant potential for energy and drinking water resources, which must be harnessed sustainably to address climate change and rising water demand. Among various methods, the ocean thermal gradient stands out as a promising source for energy and freshwater, especially in tropical areas. Additionally, offshore wind farms, benefiting from consistent sea winds, enhance clean energy production, particularly along India's extensive coastline of over 7,000 kilometers. Geothermal energy, derived from the Earth's heat, is usable for applications such as refrigeration, greenhouse cultivation, and recreational facilities, while also aiding in pollution reduction. India is expected to shift from a water-surplus state in 1947 to water-stressed by 2030, with per capita availability dropping from approximately 6,000 m^3/year to around 1,000 m^3/year. To ensure clean drinking water access, desalination, particularly via membrane technologies, will become increasingly important.

As the most populous nation, India must enhance efforts to mitigate greenhouse gas emissions by investing in clean energy. Climate change worsens water stress, and one strategy for water augmentation is desalination of seawater and brackish water. However, these systems require clean energy sources to operate without fossil fuels. In addition to wind and solar energy, exploring ocean and geothermal energy is essential. Given India's extensive coastline and vast Exclusive Economic Zone, utilizing ocean energy presents a significant opportunity.

Research efforts in India are currently underway to harness waves, tidal streams, marine currents, and the ocean thermal gradient as viable energy sources. This special issue delves into various forms of ocean energy, as well as solar energy, offshore wind, and geothermal energy. It also addresses desalination technologies and the imperative of moving operations offshore. Moreover, hybrid systems are examined. While numerous technical challenges are associated with offshore technologies, it is important to note that many of these risks are more perceptual than substantial. Thus, it is crucial to design and implement demonstration projects. These topics hold significant relevance in today's context, and readers are encouraged to persist in their endeavors in these domains to further advance the cause of green energy and clean water.

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Membrane desalination as one of the sustainable option for water needs of coastal India

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ABSTRACT

India would move to water-starved country by 2030 (per capita availability ~ 1,000 m^3/year) from water surplus (~6000 m^3/year) in 1947. To make potable water available, desalination by membrane processes will play a major role. The desalination membrane research has been carried out since 1969 at CSIR-Central Salt and Marine Chemicals Research Institute, Bhavnagar (Gujarat) with an aim to develop technology to meet the demand for clean water. The institute has given research priority on this membrane-based water desalination over the years, and now it has the capability on providing solutions as per the locational requirements. However, worldwide, a core environmental concern of desalination plants is the reject stream discharge from the plant. Zero-liquid-discharge process by rightful management of reject stream, is key towards achieving sustainable desalination.

Keywords: Membrane process, Desalination, Reject stream discharge, Environment, Sea water, Potable water

INTRODUCTION

India would move to water-starved country by 2030 as average annual per capita water availability in India is predicted to be at around 1000 m^3 only. Desalination can increase availability of potable water by converting seawater/ brackish water into potable water. Desalination by membrane processes can play a major role for providing potable water, as the process is more viable than the other processes. Besides, the membrane processes can reduce the pollution by removing undesired dissolved salts, a wide range of components ranging from suspended solids to pathogens, toxic metals, small organic compounds and other harmful ions. At CSIR-Central Salt and Marine Chemicals Research Institute (CSMCRI), (Bhavnagar, Gujarat), membrane research program was initiated in the year 1969 with an aim to develop technology to meet the demand for clean water through desalination. In the initial period during 1970-1985, RO membranes for brackish water desalination were developed. Cellulose Acetate (CA) membranes are the first generation commercial RO desalination membranes. CA membrane type is a semi-permeable membrane that allows the water containing low amount of dissolved salt to permeate through, but it retains water containing high amount of dissolved salt when operated under external pressure in excess of the osmotic pressure of the saline feed water. In this way, it is the ‘reverse osmosis’ process of forcing potable water from brackish or seawater through the membrane by applying a pressure in excess of the osmotic pressure. This is reverse to the natural process of osmosis in which solvent from dilute solution moves towards the concentrated solution across the membrane. A better membrane separation technology that allows the usage of less material, low energy consumption and permit recovery and reuse of process streams, is certainly desirable. It can be low-pressure desalination of seawater at high recovery using combinatorial approaches of advanced material preparation and integrated systems.

POTABLE WATER AVAILABILITY IN INDIA

There is acute water shortage in various regions of the world and one major aspect that a number of towns and/or cities located in such regions have in common is the lack of adequate treatment processes for producing sufficient quantities of portable drinking water. Hence, there is a significant requirement for the development of efficient and economical water treatment technologies for production of safe and portable drinking water, water for re-use for industrial, agricultural or domestic purposes or for treatment of industrial effluents to ensure safe disposal. Most water sources in India are contaminated by mixing with various industrial and sewage effluents. Although, access to drinking water has improved, significant amount of communicable diseases in India are from contaminated water. Providing safe drinking water at affordable cost is the top priority for the country as every year, millions of people suffer from water-borne disease (disease caused by microbes and pathogens). Safe water for drinking and cooking uses is an essential component of effective policy for health protection. To counter the water problems, various water treatment technologies have emerged which include physical, chemical and biological processes.

The water problem in India has been serious and it is towards water-starved country by 2030 as mentioned above as average annual per capita water availability in India is predicted as 1000 m^3 only (Figure 1). According to press release by Ministry of Jal Shakti, Government of India dated 25 MAR 2021 PIB Delhi, the average per capita per annual water availability in India is 1486 cu m which is in decrement by more than four folds from 6000 cu m of the average per capita per annual water availability in 1947 (https://pib.gov.in/PressReleaseIframe Page.aspx?PRID=1707522). The Department of Drinking Water and Sanitation, Government of India, has already taken significant steps to meet this challenge. It has made some progress in the supply of safe water to its people, but gross disparity in coverage exists across the country. The widespread occurrence of water-borne diseases resulted from poor hygiene, causing public health challenges, indicating that significant portion of the country have still inadequate sanitation and limited access of safe drinking water sources.

The National Water Policy in 1987, 2002 and 2012 by Government of India laid down principles for drinking water, irrigation, industrial and ecological environmental aspects, sanitation and treatment methods for water to make potable. The general perception on the quality of drinking water by the masses whether the water is good or bad, is on physical tests of taste, smell and looks. Bureau of Indian Standards IS 10500: 2012, has now drinking water specifications, that the drinking water should be considered safe after the acceptable specification set by BIS being the water tested by standard laboratory for all the organic and inorganic contaminants. Overall, it requires delivering potable water for the masses in aligned with Swastha Bharat and Swaccha Bharat. The Make-In-India delivering the indigenous water technologies would be better, which can link to the entrepreneurs in this sector that will save foreign exchange and can generate employments in the sector.

One of the most important water technology is desalination that can increase availability of potable water by converting seawater/ brackish water into potable water. Conventionally, it is done by thermal method, where the saline water is heated by heating system converting liquid water into water vapor, which on further condensation through a separately arranged condenser including circulation pumps, lead to separated potable water from the saline water. However, since the process involves phase change along with the multiple stages/effects and pumping systems, the overall process of thermal desalination is bulky and expensive. On the other hand, in the membrane reverse osmosis (RO) process, the saline water (seawater or brackish water) is pumped through a clarifier system operated under a lower pressure where the suspended particles, microbes and other small colloids are removed. The clarified saline water is then pumped through RO membrane system operated at a higher pressure, where excess minerals of dissolved salts are removed, giving rise to mineral balanced healthy and pathogen-free safe water. In this membrane system, there is no phase change; it only requires electrical energy to pump water through the clarifier and membrane systems. As a result, the membrane process is the most cost-effective desalination technology.

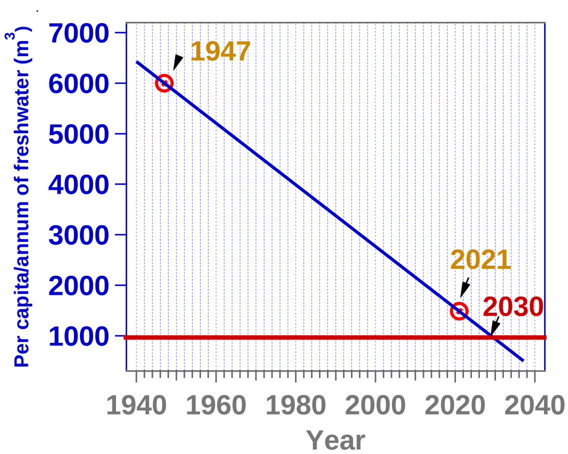

Figure 1. Declining availability of water in India with time

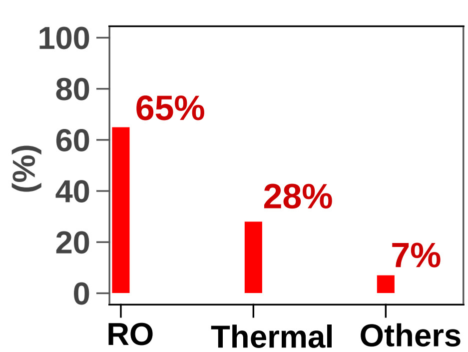

Figure 2. Total worldwide installed desalination capacity in percentage by technology (RO membrane, thermal and others)

MEMBRANE DESALINATION TECHNOLOGY

The membrane desalination process was first initiated by Sidney Loeb and Srinivasan Sourirajan (Loeb and Sourirajan, 1963) through cellulose acetate membrane. The preparation of the cellulose acetate (CA) membrane was achieved by first dissolving a desired amount of the CA in a suitable solvent to form a casting dope, followed by casting of the CA solution into the formation of the CA membrane. The CA membrane exhibits asymmetric pore structure comprising of dense skin and gradient pores underneath that acts as semi-permeable membrane allowing the water containing low amount of dissolved salt by the reversal of flow of osmosis process through the membrane.

The membrane desalination technology has been playing a major role for providing potable water, as the membrane process is more viable than the other processes (Imbrogno and Belfort, 2016; Wenten and Khoiruddin, 2016). As shown in Figure 2, the installed membrane desalination worldwide is more than twice of the installed thermal desalination (Fane, 2018). Besides, the membrane processes can reduce the pollution by removing undesired dissolved salts, a wide range of components, ranging from suspended solids to pathogens, toxic metals, small organic compounds and other harmful ions (Quist-Jensen et al., 2015; Fane et al., 2015).

MEMBRANE RESEARCH AT CSIR-CSMCRI, INDIA

At CSIR-Central Salt and Marine Chemicals Research Institute (CSMCRI), membrane research program was initiated in the year 1969. In the initial period during 1970-1985, the CA membranes for brackish water desalination were developed. The following steps were used for manufacturing of the CA membranes.

(i) Preparation of CA solution

(ii) Casting of the CA solution on a suitable support

(iii) Formation of CA membrane by immersion in a coagulating water bath.

This process results in the conversion of polymer solution on the support to a solid film with porous structure. The porous film was then separated out from the support and subjected for annealing at different temperatures for different time in hot water. This results in the creation of a membrane with an appropriate pore size for desalination. By using the CSIR-CSMCRI CA membranes, several plants (400-2000 Liters/h capacity) were set up for brackish water desalination in various part of the country during 1980-1990. The technology was highly beneficial for supplying good quality to people of coastal area of India and regions with high salinity groundwater such as Rajasthan. The desalination of seawater and high saline groundwater to the drinking quality was a noble approach for providing potable water to the common masses, provided proper maintenance was regulated and village folks was trained for the decentralized plant operation. The most satisfying moment in the CA membrane technology came in when Govt. of India gifted two CA based RO (1250 Liter/h capacity) plants to Govt. of Thailand in 1989 (Figure 3). Subsequently, Govt of Thailand had placed an order for 4000 sq. m of RO membrane. The technology for manufacturing cellulose acetate asymmetric RO membranes was licensed to BHEL, Hyderabad and Arrow Technology Pvt Ltd, Ahmedabad.

Figure 3. RO desalination installed plants based on CSIR-CSMCRI CA membranes

However, the CA membrane type has certain disadvantages because of various factors. Firstly, it is made from a single material in a single step by phase inversion process that resulted an integral membrane structure, which is asymmetrically porous comprising of top skin layer and porous sub-layer. The top skin layer is responsible for selective passing of salt and the porous sub-layer for providing mechanical support with practically negligible barrier resistance to the transport of the permeating molecule. Thinning of the top skin layer for higher water permeability was hardly possible as the structure is an integral one. Secondly, since it is natural polymer, the biological fouling is severe and tolerance in harsh environment is limited.

Both the high water permeability and salt rejection efficiency are desirable characteristics of the RO membrane as well as endurance for long life that can tolerate harsh environments and high resistant to fouling. In the pursuit, another RO membrane known as thin-film-composite (TFC) membrane was prepared in which the top selective layer is polyamide formed by interfacial polymerization by reaction between meta-phenylene diamine (MPD) and trimesoyl chloride (TMC) in the early 1980s (Cadotte, 1977, 1981; Cadotte et al., 1980, 1981).

The TFC membrane sheet is comprised of three layers such as, top selective layer of dense polyamide, middle sub-layer support of porous polymer and bottom non-woven fabric as depicted in Figure 4. It has several advantages in views of longer membrane life, mechanically high strength, high salt rejection efficiency and high water permeability and wide tolerance in pH range of 3 - 11. The TFC membrane is prepared in 2 steps. In the first step, Polymer support membrane (PSM) is prepared by a phase inversion process from polymer casting solution, prepared by dissolving a desired amount of polymer such as polysulfone in a suitable solvent. The process itself is controlled by both the thermodynamic and the kinetic factors that greatly influence on membrane morphology, surface pore size and porosity that is crucial on development of improved membranes (Singh et al., 2006; Veerababu et al, 2014).

Figure 4. TFC membrane, module and recently installed few RO desalination plants as per CSIR-CSMCRI membrane design (2020-2021).

In the second step, deposition of a dense polyamide layer over the PSM is achieved using a coating process known as interfacial polymerization (IP). The PSM is first contacted with an aqueous solution of m-phenylenediamine (MPD) to allow absorption of the MPD monomers in the PSM. The MPD absorbed support is then contacted with an organic solution of trimesoyl chloride (TMC) to allow IP process over the support. Various factors affect the properties of TFC membrane. They are the nature of the PSM, reaction condition of the IP, curing of the nascent polyamide formed after the IP, washing protocol to remove residual monomers and protective layer coating of the final TFC (Rao et al., 2003; Singh and Aswal, 2007; Jadav and Singh, 2009; Singh et al., 2011, 2012; Rangarajan et al., 2011; Agrawal and Singh, 2012). The RO desalination technology based on the TFC membrane is presently the most energy efficient of all the seawater desalination technologies (Greenlee et al., 2009; Misdan et al., 2012).

CSIR-CSMCRI developed a large-scale facility (200 m^2 per batch) for the production of such membranes and licenced the technology for commercial production of TFC membranes and modules to M/s Uniqflux Membranes LLP, Pune, Rinzai Hydratech, Ahmedabad, and OM Tech, Rajkot (Joshi et al., 2004; Shah et al., 2004, 2005; Singh et al., 2013). The institute continues to improve its RO membrane technology (Sharma et al., 2009; Bera et al., 2015; Rana et al., 2015; Gohil and Ray, 2017; Singh et al., 2020; Thummar et al., 2023), while making the plants ever more simple and robust including the use of alternative energy source such as solar or animal-powered plant. It has capability to develop water desalination tailor made RO units as per the locational requirements starting from the development of appropriate membrane to the module making by integrating customized pretreatment system and desired automation for hassle free operation. It has installed several water desalination plants across the country and abroad (Kenya, Afghanistan). The installation of RO desalination plants of various capacities in the last 25 years are shown in Figure 5. The institute also had designed and developed a mobile desalination for water desalination and purification with the key feature that the required power to operate the plant is obtained from the bus engine itself. The mobile desalination provides the potable water on spot during draught, cyclone, earth quake, or any type of national calamities. It was deployed for providing drinking water in West Bengal (North 24 Parganas) after Aila cyclone 2009, North India flood in Uttarakhand 2013, Drought in Latur in Maharashtra 2016, Cyclone Phailin in Odisha 2013, Kerala floods in 2018, Cyclone Fani in Odisha 2019, Cyclone Tauktae in Gujarat 2021, and the Konkan Floods in Maharashtra 2021.

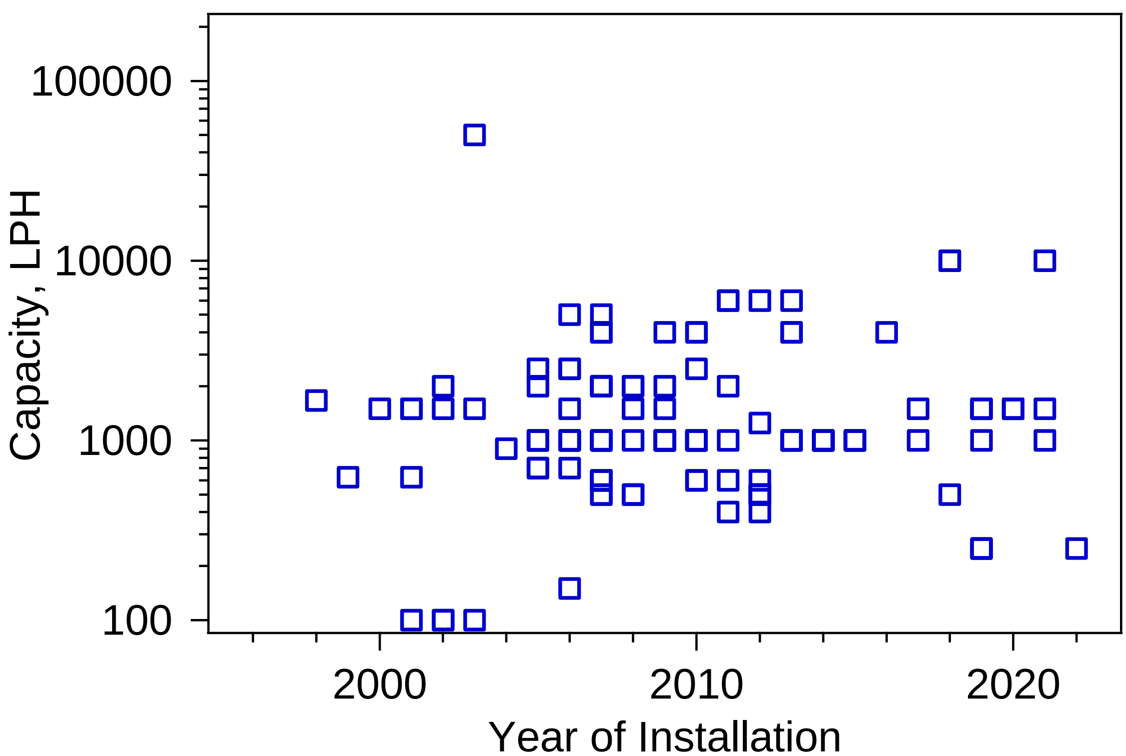

Figure 5. Installation of CSIR-CSMCRI designed RO desalination plants of various capacities in various parts of India during the last 25 years

CONCLUSIONS

CSIR-CSMCRI has given impetus on membrane-based water desalination as a research priority over the years and has capability on providing solutions as per the locational requirements by the integration of appropriate membrane modules with customized pre-treatment system for hassle free process. For India, decentralized RO plants using indigenously manufactured membrane, other consumables and capital items would reduce the overall cost. Besides, it will be of easy operation and maintenance as the service and miscellaneous items outsourced locally. Furthermore, for a medium sized seawater desalination, diffusion of about 80 m^3/h reject stream in open sea would not create any significant change in local salinity thereby no adversity in sea environment.

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Author Credit Statement

Writing original draft, review and editing, methodology and conceptualization.

Data Availability

Data will be made available on request.

Compliance with Ethical Standards

The author declares that the work reported here is in compliance with ethical standards and adhere to copyright norms

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Ocean energy technology development and demonstration activities by NIOT

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ABSTRACT

Today, the world faces several climate change-related issues due to pollution. The globe is seeing several alternate sources of renewable energy. Also, there is an acute energy crisis due to fast-depleting fossil fuel reserves on the earth, and there will be a time, when the known reserves will become extinct, or extraction from these reserves will become highly costly and technologically challenging, not forgetting the fact that this exploitation has led to adverse effects on the earth's climate. While solar, wind, biomass, and other forms are already being tapped globally, renewable energy resources that can be harnessed from the vast oceans, have now become a focus of the scientific community worldwide. The oceans offer huge spaces where new technologies can be tried and tested without affecting human settlement or the environment. Many countries have already started working towards this. In India, this development is led by the National Institute of Ocean Technology (NIOT). Extensive efforts are being made at this institute to develop technologies related to the energy extraction from ocean waves, based on the oscillating water column principle, from ocean currents using principles of hydrokinetics, and from ocean thermal gradient along the sea depth using a rankine cycle. The floating wave energy devices like backwards bent ducted buoy and wave-powered navigational buoy, cross flow hydro kinetic turbine and Open cycle ocean thermal energy conversion (OTEC), are a few of the technologies that have been developed and demonstrated. The development consists of numerical analyses, laboratory studies and open sea trials. This paper briefly discusses these developmental activities and the status of the development of ocean energy by NIOT. It also discusses all these indigenously developed ocean energy conversion systems, their performance during the testing phase, and their challenges and opportunities in India.

Keywords: Ocean energy, Wave energy, Oscillating Water Column (OWC), Hydro kinetic energy, Ocean Thermal Energy Conversion (OTEC), Renewable energy

INTRODUCTION

India has a very long coastline of about 7500 km (Dimri et al., 2023) and has very high tidal variation in specific sites (Raju and Ravindran, 1997). As a tropical country, India also possesses vast potential for OTEC resources. The ocean has approximately 8,000-80,000 TW/year of wave energy around the globe (Gunn and Stock-Williams, 2012). Locations with the most potential for wave power include the western seaboard of Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand. The north and south temperate zones have the best sites for capturing wave power (Folley and Whittaker, 2009). India is estimated to have a potential of 41GW of wave energy as per a study by the Indian Renewable Energy Development Agency Limited (IREDA) (Indian Renewable Energy, 2014). The average wave energy potential is estimated at 5-15 kW per meter of coastline. The Ministry of New and Renewable Energy (MNRE), assessed the potential of tidal energy in the country. The study indicated an estimated potential of about 8000 MW, with 7000 MW in the Gulf of Khambhat, 1200 MW in the Gulf of Kutch in Gujarat, and 100 MW in the Gangetic deltas in Sunder bans in West Bengal (Sannasiraj and Sundar, 2016). Based on the available literature, overall net power available from OTEC is around 9 to 10 TW (Ascari, 2012). A minimum temperature difference of 20^{o}C between the surface and deep-sea water is necessary for establishing an OTEC plant (Nihous, 2007). Water drawn from depths of 1000 m, will provide the above-mentioned temperature difference. Such conditions are more eminent in the country's Exclusive Economic Zone (EEZ). Theoretical estimates of the OTEC resource in India's EEZ, is around 180000 MW (Indian Renewable Energy, 2014). However, this is still under study and has to be asserted.

Further, wave-capturing devices can be installed near shore or offshore (Isaacs and Seymour, 1973; IEC, 2015) . Three fundamental methods for harnessing wave energy are, wave profile devices, oscillating water columns, and wave capture devices. Further, there are two main forms of practical tidal energy harvesting methodologies, tidal stream turbines and tidal barrages (Isaacs and Seymour, 1973). Currently, countries such as the United Kingdom, France, Canada, and China are leading in the development and deployment of tidal energy projects. The UK, in particular, has been a pioneer in this field, with the world's first tidal energy plant being established in 2016 in Scotland. With the growing interest in OTEC technology's potential to provide clean, reliable and sustainable energy, countries like Japan, India and United States are leading in OTEC research and development. OTEC works by harnessing the difference in temperature between warm surface waters and cold deep ocean waters to generate power through a heat engine (Jia et al., 2018). While OTEC is still in the early stages of development and faces challenges such as high capital costs, it has the potential to become a significant source of renewable energy for coastal communities around the world since it is a base-load source of power. With continued research and investment, we may see OTEC playing a vital role in our transition to a more sustainable future. There are three types of electricity conversion systems under OTEC: closed-cycle, open-cycle, and hybrid cycle.

A detailed study on the concept of an OTEC plant was initiated in India in 1980, and NIOT proposed to establish a 1 MW plant in 1997. In 2001, a floating closed cycle OTEC plant was constructed by NIOT, which was 40 km off the mainland in Tuticorin. Due to challenges in installation from lack of marine infrastructure for deep waters, the project could not be completed and onshore low temperature thermal desalination (LTTD) was instead attempted where cold water from comparatively shallow water depths sufficed. Successful desalinated water using ocean thermal gradient was generated at Kavaratti, Minicoy, Agatti, Kalpeni, Kadamath, Amini and Chetlat Lakshadweep Island. All these plants are continuously supplying potable water to the islanders. Various indigenous technologies developed by NIOT are discussed below as shown in Figure 1.

NIOT has been spearheading wave energy development in India. There have been three distinct developments by NIOT (a) a wave energy plant at Vizhinjam (a project started by the Indian Institute of Technology Madras and later taken over by NIOT), (b) a floating wave energy device backward bent ducted buoy to power small loads, and (c) wave-powered navigational buoy. These three developments employ oscillating water column (OWC) technique for harnessing energy in waves. All the three developments have led to successful demonstration of the wave energy conversion. NIOT has thus developed the know-how for taking wave energy conversion technology to a larger scale. This institute has been developing and demonstrating various techniques to efficiently utilize the abundant ocean waves and ocean temperature gradient available to generate energy. The progress in the development and demonstration of these techniques is shown in Figure 2. This paper discusses about the development of the power module for different energy generation methods such as wave, tidal, and OTEC energy.

METHODOLOGY

The development of ocean energy devices that took place after 2011, their operating principle, details of power module and real-time performance assessment during open sea trials are discussed here. The flow chart depicting the power module assessment for different technologies is shown in Figure 3.

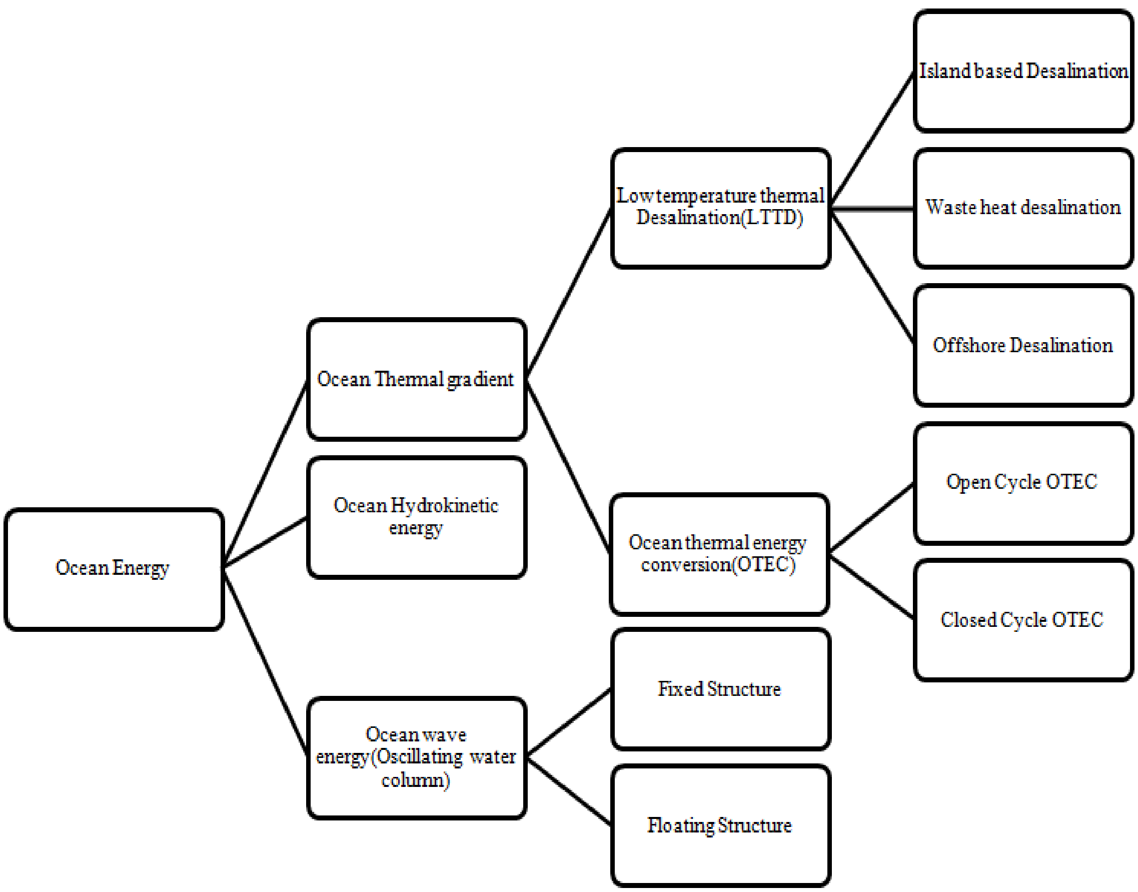

Figure 1. Various technologies used for harnessing ocean energy: Indian scenario.

Wave Energy Turbine

The BBDB is a floating type wave energy device. It consists of an interconnected vertical and horizontal duct typically 'L' shaped, which acts as the oscillating water column, sufficient buoyancy, mooring and a power module consisting of a turbine and a generator. The horizontal duct which is oriented away from the wave direction, allows enhanced movement of water in and out of chamber. This makes the water level in the vertical duct oscillate. The air above the water's surface thus is pushed out and sucked in alternately. This air drives the turbine. The BBDB fitted with a single unidirectional turbine, coupled with permanent magnet direct current (PMDC) generator, was tested in the open sea off the Chennai coast near Kamarajar port Limited (KPL). NIOT successfully carried out open sea trials on BBDB during 2011- 2015.

Figure 2. Progress in demonstration of harnessing ocean energy

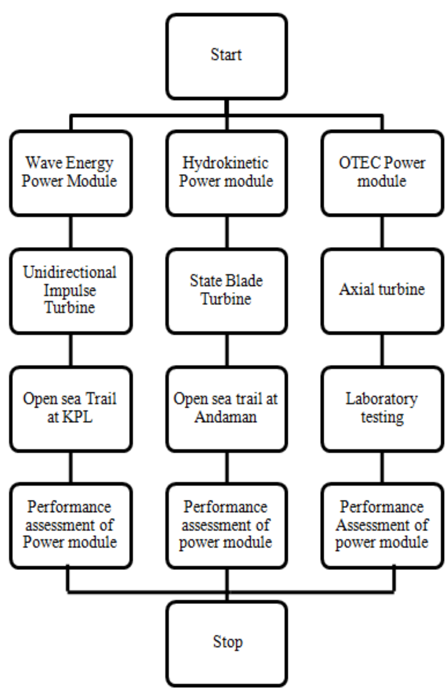

Figure 3. Power module assessment

Based on the results and understandings from this experience, a product was designed and developed that is called wave powered navigational buoy. The OWC diameter decides the discharge and pressure across the turbine and hence plays a critical role in the overall sizing of this buoy. The numerical study was carried out in RANS based CFD commercial code STAR-CCM+ (Vishwanath, 2019). Physical model experiments were also conducted on scaled down physical model of this buoy in the wave flume for the various wave conditions. The fabricated navigational buoy and the deployment location are shown in Figure 4**.** The wave-powered navigational buoy has a floating buoy in a partially submerged condition. The chamber is open to the sea below the water level so that when the wave passes over it, the water level rises, and the air gets pressurized. This pressure forces the air through an aperture at the top of the chamber and drives the turbine which is connected to the electric generator for the generation of electricity. The chamber can be shaped such that its cross-sectional area reduces towards the top, called the dome, creating a high-speed airflow required for driving the turbine from the slow-moving surface of the water. To keep the buoy in an upright position, a counterweight is attached at the bottom of the spar.

An OWC wave-powered navigational buoy using the same power module, was successfully sized and for optimized performance. The buoy was fabricated in-house, and the first prototype was tested off Ennore, Chennai, in 2018 near KPL (Pattanaik, 2018). The power module plays a significant role in the optimized generation of electricity. The wave energy power module works with the unidirectional impulse (UDI) turbine. Table 1 shows the details of the turbine developed for the wave powered navigational buoy. Once the assembly was completed, it was taken for open sea trial at KPL. Then, the performance assessment of the power module was studied. These wave buoys are solar powered and prone to vandalism. India has several ports and harbors that use navigational buoys. They can be substituted by a wave powered navigational buoy. Also, India has a well-connected network of metocean data buoys, which can be replaced with these wave powered navigational buoy as they can generate self-sustained small power demand of buoys.

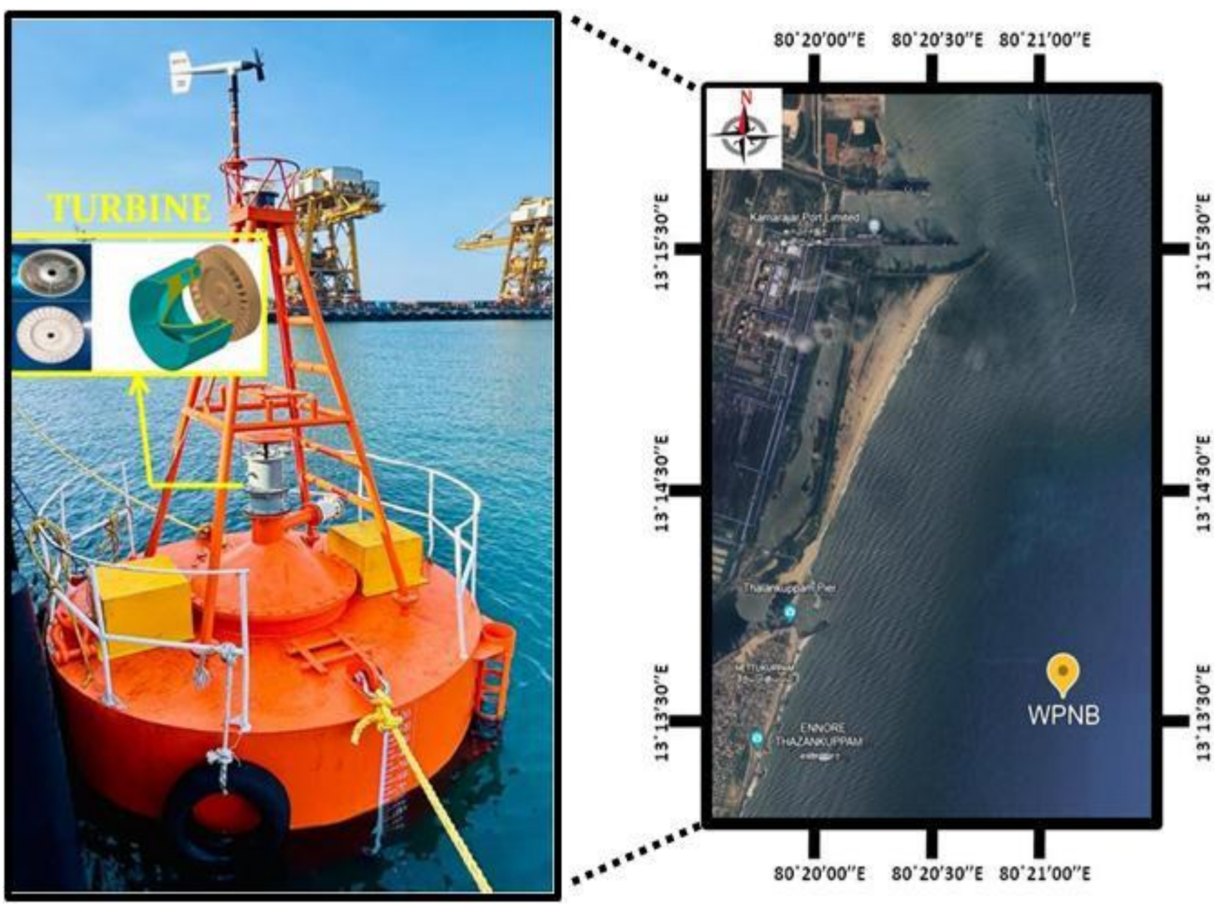

Figure 4. Wave Powered Navigational Buoy (Left) with deployed location (Right)

HYDROKINETIC TURBINE

The turbine design includes design and optimization using computational fluid dynamics (CFD) principles. Several turbines were tested in the towing tank facility at IIT Madras and a seawater channel in North Chennai. Following extensive studies, NIOT carried out successful sea trials in the Andaman and Nicobar Islands. The turbine configuration finally chosen for the hydrokinetic turbine deployment was a straight-bladed cross flow turbine, and after complete assembly, it was taken to Andaman for an open sea trial. South Andaman was chosen for the mentioned study, and Macpherson Strait region was selected for desire after measuring the depth profile and current profiles using ADCP. The location had a depth of 20 m and current speed of 1m/s to 1.8m/s. The platform was fabricated at Port Blair and towed to the desired location through tug boats which was approximately 48 km. This region was under Mahatma Gandhi National Park, so special clearance had to be obtained from the forest officials to carry out the study. After successful demonstration, studies on the power module assessment were carried out. Figure 5 shows the demonstration of the hydro kinetic (HK) turbine at Andaman and the demonstration location. In Andaman, there are several remote places where renewable sources of energy such as solar and wind cannot be used; however tidal streams are available. This technology can be used as an alternative to cater to the small power requirement of water remote places in Andaman. Table 2 describes the features of the hydro kinetic turbine.

Table 1. Turbine of wave powered navigational buoy (WPNB)

Particulars	
Medium	Air
Design for air	0.14 m^3/hr
Diameter of turbine	196 mm
No. of stator blades	26
No. of rotor blades	30
Chord length	34 mm
Material	Polycarbonate
Type of fabrication	3D printing
Type of generator	PMDC
Power module output	48V/1500 rpm

Table 2. Detailed features of hydrokinetic turbine

Particulars	
Medium	Sea water stream
Design for water speed	1.2 m/s
Diameter of turbine	0.8 m
Number of blades	3
Length of turbine	1 m
Blade material	FRP with steel reinforcement
Type of generator	Permanent magnet alternator
Power module output	60V/750 rpm

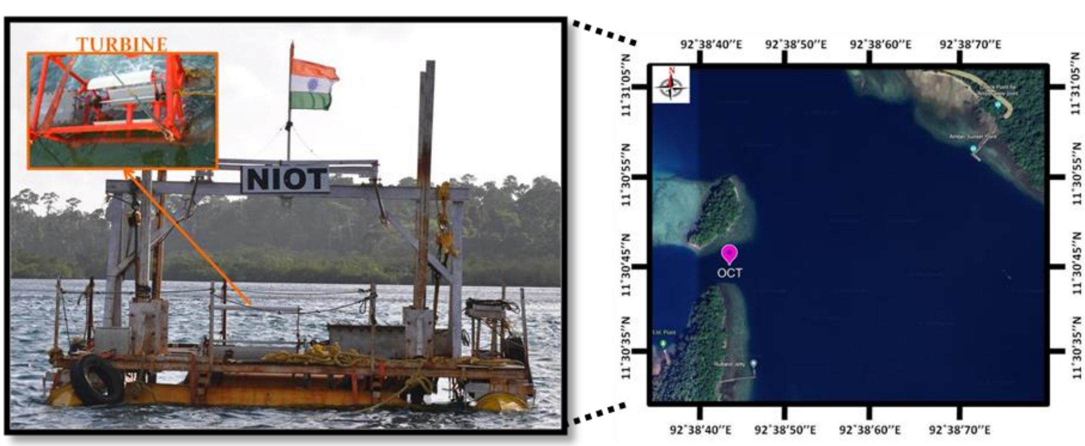

Figure 5. Demonstration of ocean current energy at Andaman (Left) with deployed location (Right)

LABORATORY SCALE OTEC OPEN CYCLE POWER MODULE

Open Cycle Ocean Thermal Energy Conversion (OC-OTEC) and Low-Temperature Thermal Desalination (LTTD) processes, utilize the temperature difference between warm surface and cold deep ocean water to generate electricity and fresh water, respectively. The warm water is supplied to a flash chamber using a warm water pump where it gets vaporized, travels through a duct, expands in a low-pressure turbo-generator to generate electricity, and condenses in a condenser using cold water. A vacuum pump maintains the OC-OTEC system at low pressure. In the lab setup, temperature of warm water is maintained with the help of a heater, and cold-water temperature is maintained using a chiller. The experiment is run for a maximum of a few minutes with full warm and cold-water flow. The test facility plant schematic is shown in Figure 6.

The axial flow turbine was developed in house, its stator and rotor were fabricated using the selective laser sintering technique of rapid prototyping. These studies are useful for understanding process parameters for the OC-OTEC- based desalination plant and for setting up large-scale OTEC and self-sustained OTEC-based desalination plants in India. This laboratory facility has been useful for studying the cycle and optimizing the plant operation. NIOT is setting up an OC-OTEC plant in Kavaratti, Lakshadweep, which will have a desalination capacity of 1 lakh litres per day. As a tropical country, India possesses a huge potential for ocean thermal energy conversion (OTEC) resources. With the sufficient availability of ocean thermal gradients in India and its islands, generating electricity from OTEC as a renewable energy source is possible.

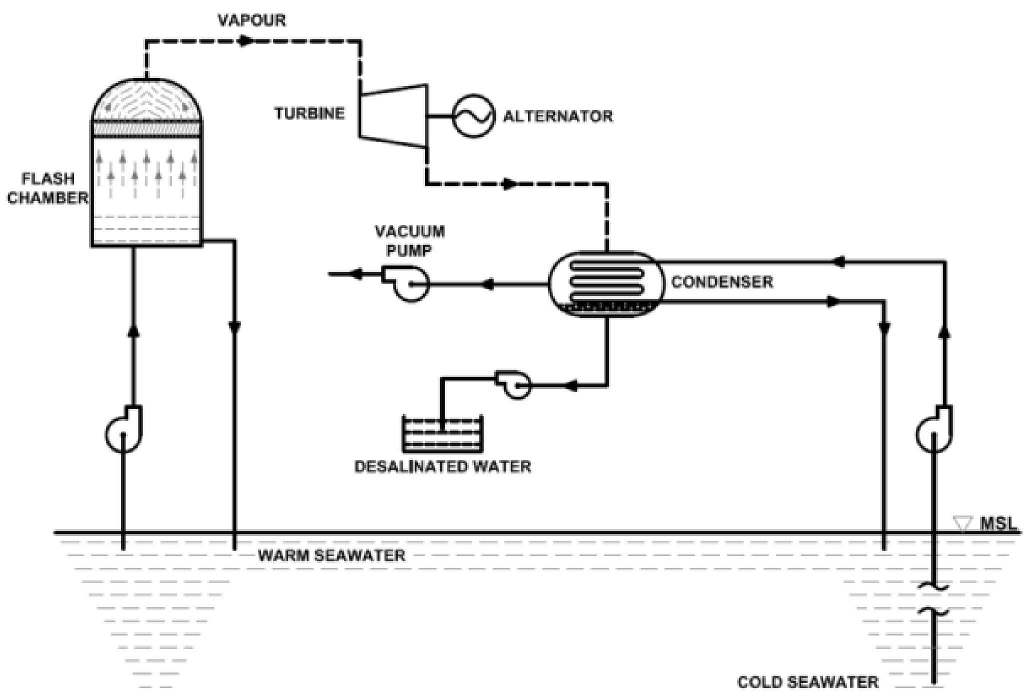

Figure 6. Schematic of open cycle - Ocean Thermal Energy Conversion plant

Table 3. Detailed feature of open cycle- Ocean Thermal Energy Conversion turbine

Particulars	
Medium	Low-pressure steam
Diameter of turbine	0.268 m
No. of stator blades	35
No. of rotor blades	70
Material	Aluminum alloy
Type of generator	BLDC
Power module output	60V/20000 rpm

In contrast to other renewable energy sources such as wind and solar, OTEC is a reliable source of renewable energy, maintaining a 90% load factor. Table 3 shows the details of the turbine developed for in-house OC-OTEC facility. Figure 7 shows the layout of the OC-OTEC facility.

RESULTS OF DEVELOPED OCEAN ENERGY DEVICES

The results of experiments on open sea trials and lab testing of wave energy, hydrokinetic energy and OTEC power module are discussed here. It can be observed from Figure 8 that the instantaneous power developed by the UDI turbine reaches a maximum of 140W. The power generation is random as waves are random in nature. The waves are generally semi-directional and vary from time to time, so depending on the wave height and the period, the power generated is not uniform. The tidal current is generally a semidiurnal tide and changes with the direction of flow, but the turbine will rotate in one direction and generate power. It can be observed from Figure 9 that power developed by the current turbine reaches a maximum of 200 W.

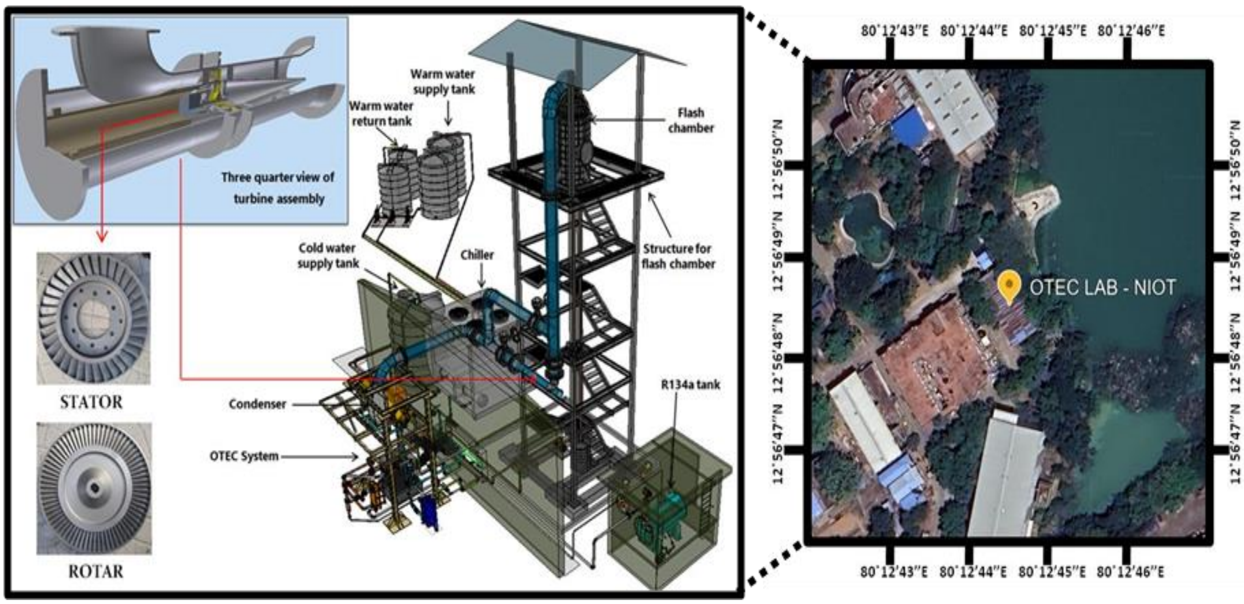

Figure 7. Location of open cycle - Ocean Thermal Energy Conversion lab setup at NIOT

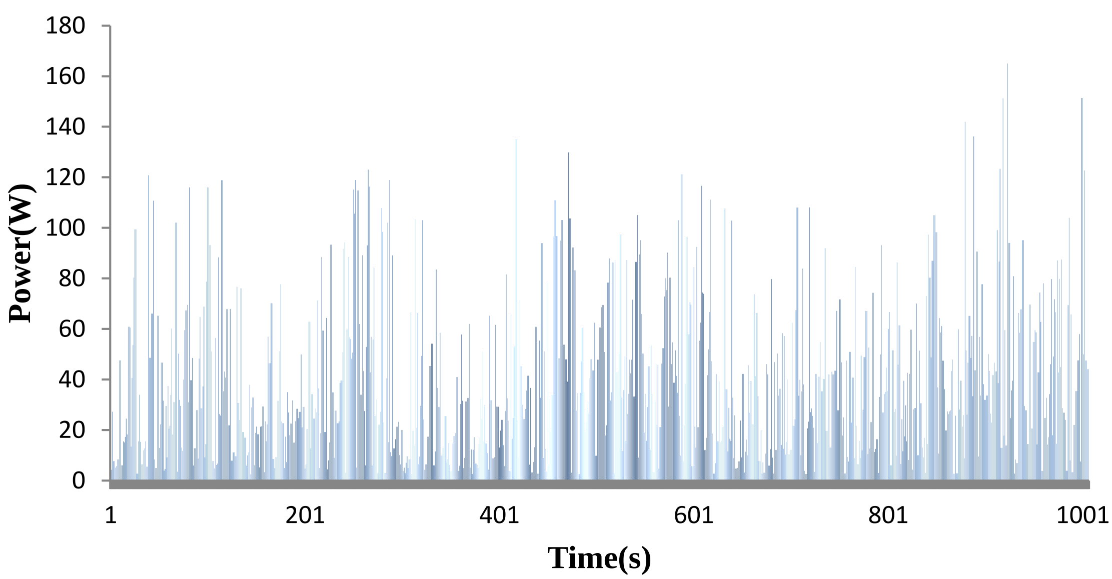

Figure 8. Unidirectional impulse turbine of wave energy power module

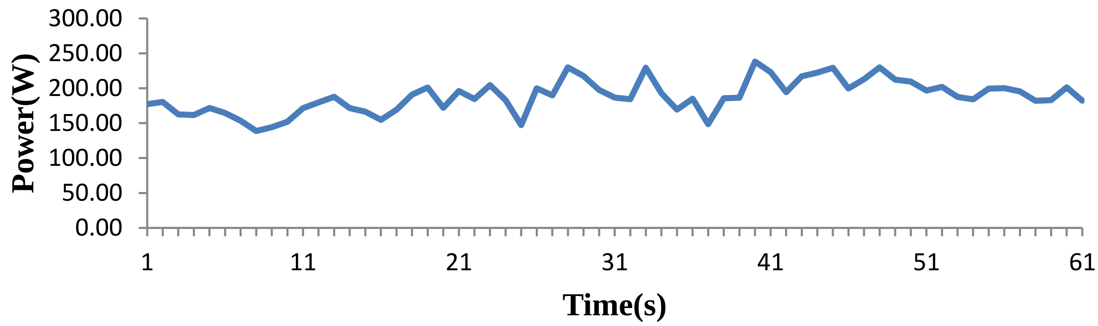

Figure 9. Current turbine power module

It is observed from Figure 10 that power developed by the OC-OTEC power module reaches a maximum of around 1400 W, and an average freshwater flow (MFW) of 0.056 kg/s is obtained. Figure 10 shows electric power generation in the primary axis and freshwater generation MFW in the secondary axis. The power generated over the period of time is steady and constant. The OTEC is an alternative source of ocean renewable energy forms that can generate electricity in remote islands for the nation.

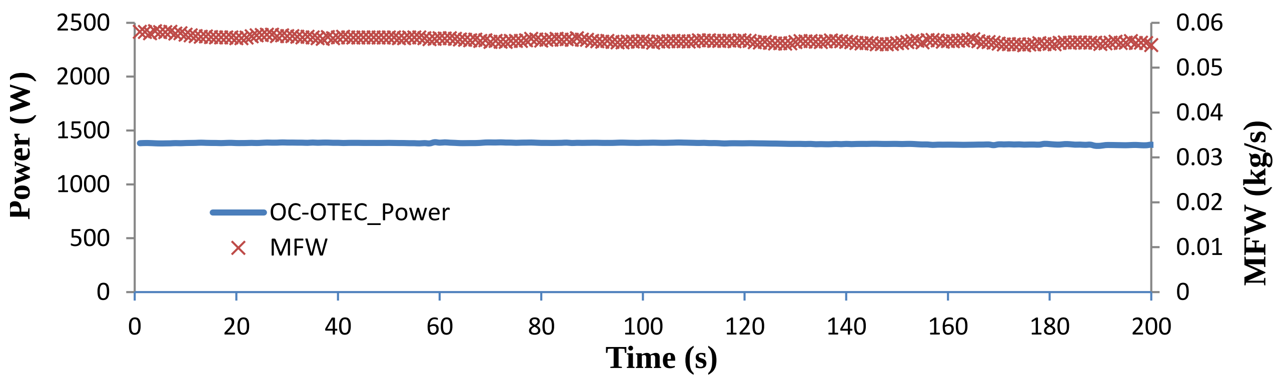

Figure 10. Open cycle Ocean Thermal Energy Conversion power module

CONCLUSIONS

The development and demonstration activities related to ocean energy technology by NIOT, are focused on exploring the potential of renewable energy resources that can be harnessed from the vast oceans. With the acute energy crisis due to fast-depleting fossil fuel reserves and the adverse effects of fossil fuel exploitation on the earth's climate, ocean energy offers a promising solution. NIOT is working to develop technologies related to energy extraction from ocean waves, ocean currents, and ocean thermal gradient. There are several possibilities for generating electricity from OTEC as a renewable energy resource in India, which has a tropical climate and sufficient availability of ocean thermal gradients. While there are still challenges and opportunities related to ocean energy development in India, NIOT's efforts in this area are promising.

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Author Credit Statement

Biren Pattanaik: Data compilation, planning and manuscript preparation. Anulekha Majumdar: formal analysis and mapping. Prasad Dudhgaonkar: Planning and interpretation to strengthen the manuscript. Purnima Jalihal: critical feedback to strengthen the manuscript.

Data Availability

Data is based on internal study. It may be made available on reasonable request.

Compliance With Ethical Standards

All the authors have read the manuscript thoroughly and confirm that it has neither been submitted to any other journal and nor been considered for publication. All authors have been actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content. Authors adhere to copyright norms.

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High capacity offshore low-temperature thermal desalination plant: A new perspective

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ABSTRACT

National Institute of Ocean Technology (NIOT) has been working on developing technologies to ameliorate the shortage of drinking water in island and other coastal areas. Towards this, various onshore desalination plants have been constructed and operated utilizing ocean thermal gradient. For high capacity ocean energy and desalination plant, going offshore is considered to be a viable option. This article discusses the experiences and work carried out for ocean thermal gradient based large capacity desalination plant. Offshore plants have their own complexities with regard to design of platform, moorings and sea water pipelines. These components were studied thoroughly and discussed in the article. The design philosophy and results have been presented for a design of 10 million liters per day (MLD) capacity desalination plant, mounted on semi-submersible platform moored in 1000 m water depth.

Keywords: Offshore thermal desalination plant, Semi-submersible, HDPE conduits, spread mooring, Kavaratti (Lakshadweep)

INTRODUCTION

Ocean is a vast source of energy and potable water, both of which need to be harnessed in a clean and green manner. Among different sources of energy from the ocean, ocean thermal gradient perhaps has the highest potential for both extraction of energy and fresh water since we are in the tropics. The process of extraction of potable water from the ocean has already reached its advanced state. Sea water desalination is attaining increasing attention of present day policy makers, especially with the growing demands that urbanization, population explosion, irregular rainfall and ground water contamination place on the fragile natural resources. Membrane and thermal desalination processes are both popular today.

Low temperature thermal desalination (LTTD) is one process that uses the availability of a temperature gradient between two water bodies or flows to evaporate the warm water at low pressure and condense the resultant vapour with cold water to obtain fresh water. The temperature difference that exists between the warm surface sea water (28^0~30^0 C) and deep sea cold water (7^0~15^0 C) could be effectively utilized to produce potable water and generate power (Rognoni et al., 2008). The advantage of using this method is that steam is not required.

National Institute of Ocean Technology (NIOT) under the Ministry of Earth Sciences (Government of India), strives to develop reliable indigenous technology to solve the various engineering problems associated with the harvesting of living and non-living resources in the Indian Exclusive Economic Zone (EEZ), which is about two-thirds of the land area of India. The LTTD process as mentioned above, which converts sea water into potable water using natural ocean thermal gradient, has been successfully demonstrated by NIOT at Kavaratti in Lakshadweep Islands for the first time ever in 2005 (Jalihal, 2022). Subsequently, this indigenized technology has been deployed in various islands of Lakshadweep recently. This technology has transformed the lives of the islanders by improving their health. NIOT has also worked on offshore based desalination plants for augmenting the freshwater requirements of mainland. The offshore plants are considered gateway for large capacity ocean thermal gradient based energy and desalination plants. Design of offshore plant is challenging due to the complexities of various offshore components such as platform, moorings, large sea water conduits, integration and installation, etc. Nonlinear time domain dynamic analyses need to be carried out for offshore components which are constantly in a dynamic environmental with wave and currents (Vishwanath et al., 2020). The article discusses those challenges, works and studies carried out by NIOT for high capacity offshore LTTD plant. It also outlines design methodology and results for the proposed 10 MLD capacity Semi-submersible mounted LTTD plant at 1000 m water depth.

OFFSHORE LTTD PLANT

The main components of the LTTD plant are: (i) Heat exchanger like shell and tube condenser, (ii) Duct that transfers vapour from the flash chamber to the condenser, (iii) Sea water pumps to supply the warm and cold sea water, (iv) Vacuum system that maintains the flash chamber, vapour duct and the vapour side of the condenser at the design vacuum, at about 26.5 mbar (abs), and (v) Pipelines to draw cold water from the required depth.The pipeline is the most challenging part of the system. In an onshore plant, as in the case of islands, the deep water is very close to the shore. This is a special feature in the Lakshadweep group of islands. Thus the pipe has been designed to be in a novel configuration with one end in shallow waters near the shore and the other end, held by a weight in deep waters. The inverted catenary configuration is possible due to the inherent buoyancy of the material of the pipeline. For the mainland application of this technology, the drawing of the cold water is the challenge since the distance to the deep water is about 40-50 km from the east coast of India. This necessitates that the plant be located on a platform which is kept in position using moorings at a deep water location. The thermal process itself is invariant. To demonstrate that this technology can work offshore, a barge mounted desalination plant with capacity of 1 million liters per day (MLD) was taken up. It was successfully demonstrated by NIOT at 40 km off Chennai coast in deep water for mainland applications in 2007. The challenges included design, installation and maintenance of plant in deep water and transport of product water to the coast. For the first time in the world, a 1 m diameter and 750 m long HDPE pipe was towed, upended and connected to the bottom of a barge to pump deep sea cold water at around 10°C. The deepest single point mooring in Asia (i.e. 1000 m water depth) was designed in house and also fabricated indigenously for mooring the 1 MLD plant. This mooring performed very well and kept the barge moored during the demonstrations trials. The barge used for the 1 MLD plant had a central moon pool through which the 1 m diameter cold water pipe was suspended vertically to draw the cold water. The one MLD offshore LTTD plant as shown in **Figure 1,** successfully generated fresh water for several weeks.

The main outcomes of this plant are following.

(i) The short demonstration of the concept of producing fresh water on a barge moored offshore and generation of excellent quality of water.

(ii) Within a year, a long 1m diameter pipe could be assembled, towed and connected many times successfully albeit with some effort due to paucity of offshore handling equipment.

(iii) Successful single point mooring in 1000 m water depth

(iv) The experience gained and success in pipe deployment and installation, is an indication that pipelines for future larger plants can be handled by NIOT, and

(v) Offshore experience derived from the efforts at deploying, connection and operation can led to capacity building for future plants.

With the gained confidence it was felt prudent to design and install a unit for 10 MLD offshore plant.

SEMI-SUBMERSIBLE MOUNTED 10 MLD OFFSHORE PLANT

The requirement for offshore desalination is a stable all weather platform like semi-submersible floating platform to house the plant, a large cold water conduit/pipeline, and station keeping /mooring for the platform and an inter-connecting mechanism between conduit and platform to withstand the differential loads.Semi submersible floating platforms are utilized in various kinds of offshore structures because of their good motion characteristics. Minkenberg and Van Sluijs (1972) studied the motion optimization of semi submersibles. Vogt et al. (2002) studied about the stability of deep water drilling semi-submersibles. Halkyard et al. (2002) developed a deep draft semi-submersible with a retractable heave plate. The system combines the advantages of a semi-submersible with the operational motion advantages of a truss spar type floater.

In a semi-submersible, the primary buoyancy members are well below the water surface so as to be relatively unaffected by the action of surface waves. This causes a decoupling of its motion from the surface wave motion and consequently, it is significantly more stable than the conventional ship hulls.

A Semi-submersible platform was chosen for accommodating the desalination plant due to several reasons. Based on the size and weight of the plant equipments, the columns and pontoon of the semi-submersible can be of rectangular shape of suitable dimension, depending on the requirements of the plant operating conditions. The deck, column and pontoon are placed and configured according to requirement of process equipments. The minimum acceptable heave natural period for the semi-submersible is above 18 sec as it is far above the encountered swell period. For the given payload conditions, a four column semi-submersible platform with interconnected pontoons was chosen for the platform configuration.

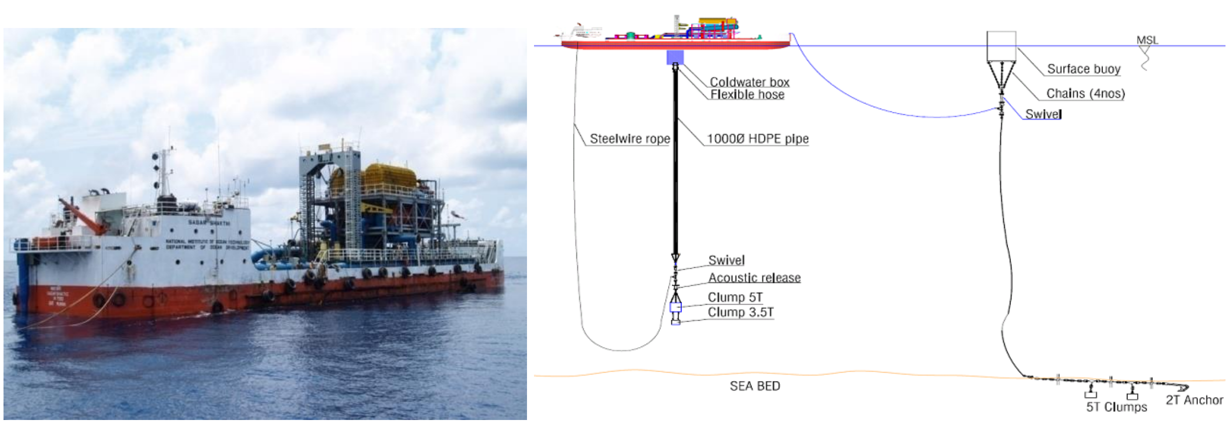

Figure 1. Barge mounted 1 MLD capacity Low temperature thermal desalination plant

The 10 MLD semi-submersible mounted plant platform, will have to be a larger displacement vessel due to the large quantities of water being handled by large plant equipment. For an all weather large platform, the design considerations are different. Several designs and analyses have been carried out with several configurations. The 10 MLD plant would have a 4 modules of 2.5 MLD units housed on this platform. Cold water supply pipelines necessarily have to be larger in size, requiring high attention in its design to suit its installation and integration with the platform. Being first of a kind in the world with no past references, several design challenges were to be addressed. Since the operational period of this offshore plant is proposed for 25 years, extremely harsh ocean environment were considered for the design. Various options and alternatives of design and the cascading effect of the changes on all discipline areas related to mechanical, pipelines, platform, moorings etc. was evaluated and final design was arrived at adopting the design spiral.

Semi-submersible hull

The platform hull is designed to support the main equipments along with the necessary utility systems in the main deck to generate 10 MLD fresh water. The sea water HDPE pipelines are connected to the deck at central position through conduit stiffening structure. **Figure 2** shows the platform with equipments on the deck. The hull consists of a square ring pontoon with four square columns at the corners. Four columns support the square truss type deck. The pontoons are subdivided into compartments for ballast water, diesel fuel oil, produced fresh water and pump rooms, and also taking into account damage stability requirements. An access tunnel runs through the pontoon providing access to various tanks and the pump rooms connecting the four columns. The pump rooms are subdivided with watertight bulkheads and doors in order to comply with damage stability requirement. The columns are subdivided by vertical and horizontal watertight bulkheads considering the damage stability requirements. The major analyses and studies that were carried out for the hull and topside design, include Platform Hull Sizing, Scantling calculations for Hull (Pontoon and Columns), Stability Analysis and Hydrodynamic Motion Analysis. Hydrostatic properties of the platform are shown Table 1.

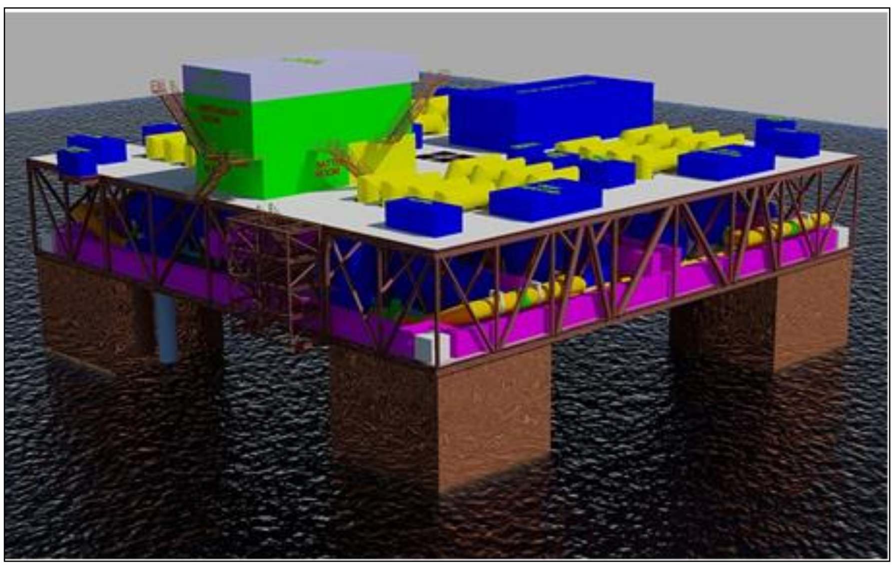

Figure 2. Arrangement of equipments on deck of the platform

Table 1. Properties of semi-submersible mounted LTTD plant

Parameter	Value
Draft (m)	18
Displacement of platform (t)	26000 (approx.)
Square ring Pontoon (m)	60x13.4x7
Column (m)	13.4x13.4x21
Position of COG from keel KG (m)	16.2
Metacentric height, GM (m)	5

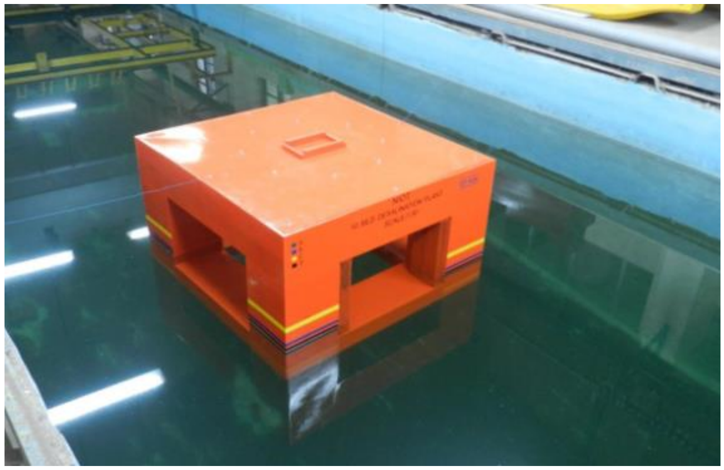

Figure 3. Physical model testing in wave flume

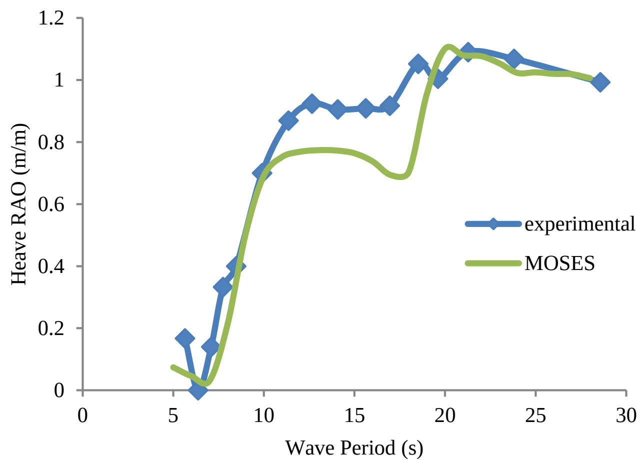

Figure 4. Comparison of RAOs with wave period

The stability of the floating platform was checked in accordance to IMO MODU (2009). The complexity of the motion response of offshore floating platform requires advanced simulation tools for the accurate assessment of the sea keeping behavior. Commercial software tools was used which is based on potential/diffraction theory for force estimation. The sizing of the water plane area, which plays a crucial role in the motion response of a floating body was done iteratively for a good response characteristic of the platform.

A 1:50 scale model of semi-submersible was prepared and tested by Ocean Engineering Department at IIT-Madras. Model tests were carried out for two conditions, free floating condition and moored condition, free floating further divided into free floating response case without considering conduit bundle, and free floating response case with central conduit bundle. Figure 3 shows the model being tested in IIT-Madras wave flume.

A comparison of heave Response Amplitude Operator (RAO) for various wave periods obtained from numerical and model tests is reported in Figure 4 for free floating operating condition without central conduit (Vishwanath and Jalihal, 2022). Peak response is observed at 20 s period. Two plots show a difference of about 15 % for mid period range (10s-18s) but are reasonable match for rest. Appropriate operating and survival environmental conditions were considered for the platform design for a life period of 25 years. The environmental conditions and the summary of extreme motions is shown in Table 2.

Mooring system

The platform is considered to be permanently moored at the location in 1000 m water depth for a design life of 25 years. The design acceptances are checked as per API RP 2 SK, 2005. The mooring system is analysed according to design criteria formulated in terms of two limit states:

(i) *Intact Condition*: A limit state to ensure that the individual mooring lines have adequate strength to withstand the load effects imposed by extreme environmental actions and.

(ii) *Damage Condition*: A limit state to ensure that the mooring system has adequate capacity to withstand the failure of one mooring line.

The hydrodynamic panel model, consisting of pontoon, four columns and the central conduit stiffening structure surrounding the supply/ discharge water conduits was used for the mooring analysis. Each mooring line is a combination of chains and polyester rope of appropriate lengths. The analysis was performed in the time domain in commercial software. Extreme values were estimated from a computer simulation time of 3 hours time period. Platform is permanently moored at 1000 m water depth. Symmetrical 8 point taut mooring arrangement is recommended as shown in Figure 5. Eight headings from 0° to 315° degrees at each 45° interval are considered for the analysis. Wind and current directions are assumed to be same as wave direction (worst case). The mooring arrangement was optimized through: (i) Mooring pattern (line arrangement and spread angle and layout), and (ii) Chain and Polyester rope grade, diameter and length of each segment of the mooring line.

Pipelines

High Density Polyethylene (HDPE) pipes are considered for deep sea cold water and warm surface water for intake and discharge pipelines. Deep sea cold water pipeline is one of the most critical components for any ocean thermal gradient based energy/desalination plant. A bundle of 4 HDPE pipeline of about 800 m long HDPE pipeline of large diameter is considered for conveying deep sea cold water of temperature less than 10^{o}C from a depth of 800 m to the semi-submersible mounted LTTD plant. Table 3 shows the HDPE properties used for cold water supply, cold water dischargeand warm water discharge pipelines. HDPE conduit group consist of total 12 conduits, 4 cold water supply conduits that go to depth of 800 m below mean sea level, 4 cold water return conduits which go to depth of 140 m below mean sea level, and another 4 warm water return conduits which go to depth of 80 m below mean sea level. Figure 6 shows the conduit bundle.

Table 2. Extreme motions of semi-submersible platform

Condition	Hs (m)	Tp range (sec)	Roll (Deg)	Pitch (Deg)	Heave (g)
Operating	5.9	8.75 – 13.30	2.365	2.360	0.089
Survival	17.3	15.0 – 23.0	7.804	7.717	0.272

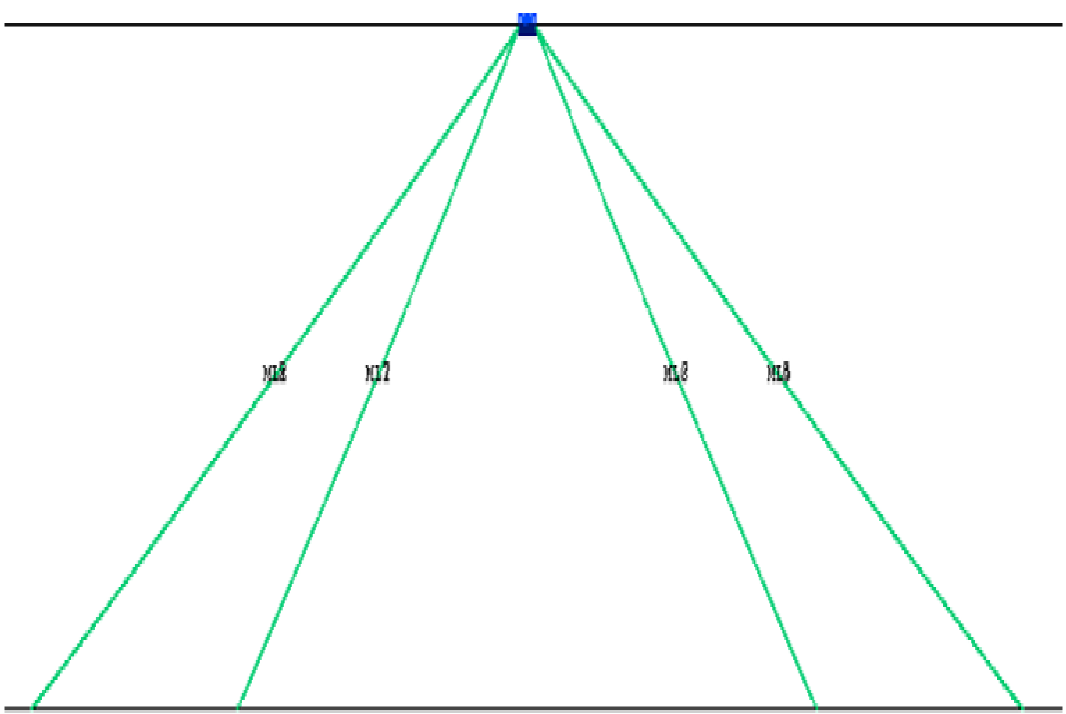

Figure 5. Spread mooring for offshore desalination plant

Table 3. Properties of HDPE pipe

Description	Value
Conduit OD (mm)	1600
Grade	PE 100
Pressure rating	PN 10
Standard dimension ratio	17
Density (kg/m^3)	930
Young's modulus (MPa)	185 (50 year life)
Yield stress (MPa)	10

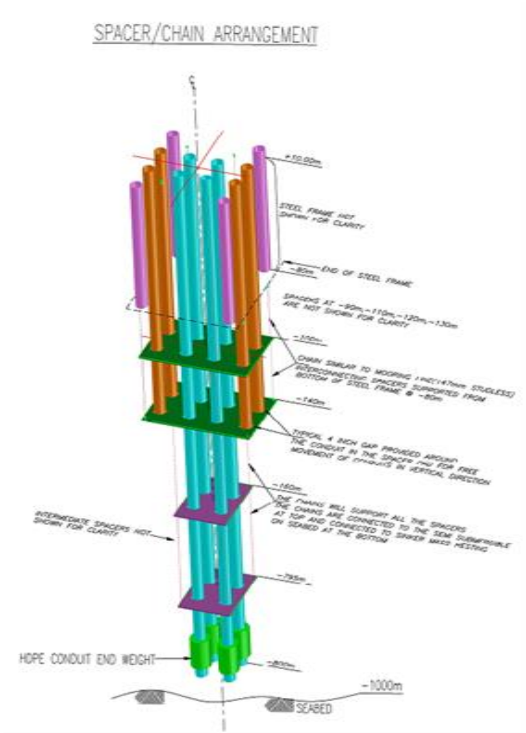

Figure 6. HDPE conduit bundle

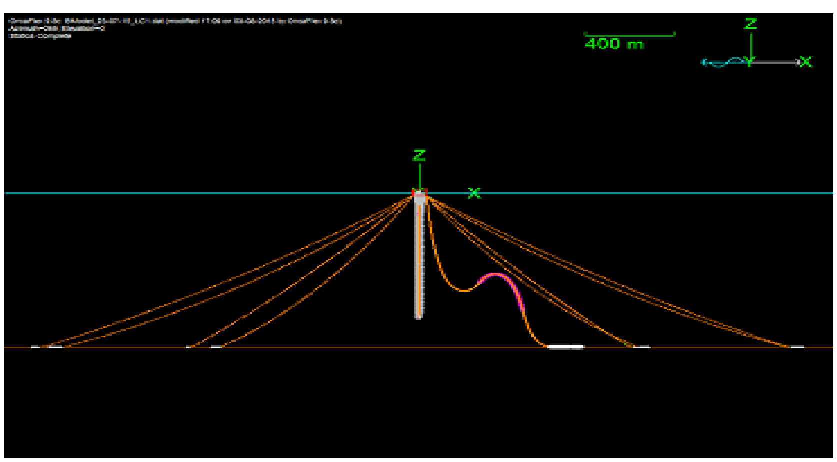

Figure 7. Snap shot of the Global In-place Model

The following major analysis and studies were carried out for the HDPE conduit and freshwater transportation pipeline design using proven commercial software's and design methods.

(i) HDPE Conduits – Global In Place Analysis

(ii) Modal / VIV / Fatigue Analysis

(iii) Loadout, Towing & Upending

(iv) Transportation of fresh water from platform to mainland using pipeline/riser configuration

(v) Design and Analysis of Connection Clamp between HDPE Conduit Bundle and Platform

The pipeline was modeled as homogenous line element with free flooding of sea water. The top end is connected to the semi-submersible and bottom end is free. Since the specific gravity of HDPE is less than 1, the pipeline overall needs to be made negatively buoyant by distributing weights along the pipe length. After the addition of weights along the length, a clump weight is added at the bottom of the pipe to eliminate compression in the pipe and also to reduce the bending stresses, arising due to the motions caused by waves and current. Several iterations were performed by varying the weights and their distribution along the length of the pipe. A configuration was achieved after various iterations. The global analysis was carried out using commercially available dynamic analysis software as shown in Figure 7. The tool performs time domain simulation for predicting the behavior of the pipeline, thus evaluating the stresses, tensions, etc. in pipeline, satisfying the allowable stresses, bending radii, tension, and other criteria. An estimated 200-ton clump weight was determined at the end of the cold-water conduit based on the analysis.

The transportation of fresh water is by combination of flexible riser from plant to seabed and rigid pipeline from there onwards to the main land for distribution. The length of the rigid pipeline is around 41km. The proposed flexible riser will pass through a tube attached to offshore LTTD Plant. The flexible riser is held in position at one end by a dead weight clamp at platform deck level and other end is connected to pipeline end manifold resting on seabed. The offshore rigid pipeline starts from the pipeline end manifold and terminates at onshore fresh water receiving terminal. Flexible pipe of 12 inch inner diameter of appropriate material for riser and 14 inch outer diameter pipe made of carbon steel is selected for the pipeline. The fresh water delivery system is designed for the functional and environment loads. For the operation phase, the system is designed for 100-year return period storm whereas for the installation phase, 1 year return period storm is considered. A detailed design was carried out for various components of thermal process, floating platform, piping, pipelines, electrical and instrumentation, costing, etc. The platform design is also CLASS certified. The design is now ready to be implemented.

CONCLUSIONS

NIOT is attempting to scale up the Low Temperature Thermal Desalination (LTTD) technology for augmenting mainland and island fresh water requirements. After successful demonstration of 1 MLD barge mounted LTTD plant, NIOT now is proposing to install a floating LTTD plant of 10 MLD capacity. Experiences gained from the earlier LTTD demonstrations, helped in design of large capacity offshore plant. Considering the large size of all components and it being the first ever such plant, and also having a major emphasis only on the offshore component, it seemed prudent to carry out detailed study of critical offshore components. A permanently moored semi- submersible platform (~26000 tons displacement) in 1000 m water depth, suitable for all weather conditions, was designed to house the LTTD plant equipment. Major emphasis on optimization of platform, moorings and critical sea water pipelines were given to come out with a viable plant design for a life span of 25 years. Various iterations were carried out to finalize layout and configuration of moorings and pipelines. The design of these components was carried out as per offshore industry practices and standards. If implemented, the 10 MLD plant will be a big boost to Indian shipping industry.

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Author Credit Statement

A Vishwanath: Data compilation, formal analysis, mapping, interpretation, and manuscript preparation; and P Jalihal: Planning, interpretation and critical feedback to strengthen the manuscript; and A Sajjan: formal analysis and manuscript preparation

Data Availability

Data is based on internal study. It may be made available on reasonable request.

Compliance with Ethical Standard

All of the authors have read the manuscript thoroughly and confirm that it has neither been submitted to any other journal and nor been considered for publication. All authors have been actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content. Authors adhere to copyright norms

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Powering desalination with renewable energy

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ABSTRACT

Today, the world is facing two challenges, water stress and climate change, for which anthropogenic causes leading to greenhouse gas emissions, are considered responsible to a large extent. One of the ways to mitigate water stress is desalination. Today, renewable energies are being taken up rapidly to reduce greenhouse gas (GHG) emissions; however, newer forms of energy, like ocean energy, need to be taken up seriously to further augment the clean energy quantum. By coupling desalination with renewable energy, we can simultaneously reduce GHG emissions and alleviate the water stress. The paper discusses the possible hybridization strategies and challenges for the same. Each type of renewable, along with the suitable type of desalination method, needs more study, and complexities for constant powering for water generation need to be addressed.

Key words: Ocean energy, Desalination, Hybrid systems, Greenhouse gas emission, Renewable energy

INTRODUCTION

Today the climate change has become a commonly used terminology referring to long term changes in temperatures and weather patterns. Over a period of time, such changes have been occurring naturally due to the sun's activity or the Earth's tectonics and volcanic activity. But in recent times, anthropogenic reasons are considered the main driver of climate change, prevailing due to the burning of fossil fuels like coal, oil and gas. Burning fossil fuels, generates Greenhouse Gas (GHG) emissions, which contribute to increased temperature levels and climate change. Thus, the need for clean and renewable energies is evident. Today, the solar and wind markets are booming because the technologies have matured and are now getting more and more inexpensive. In this context, more renewable energy forms, including ocean energies, need to play a vital role. Apart from the GHG emissions and affiliated issues, climate change is also playing a detrimental role in water-related issues. On the one hand, there is unprecedented rainfall leading to urban flooding, but in many regions, there is severe water stress. Water stress can be mitigated by augmenting water using desalination and water treatment. Desalination and water treatment systems use fossil fuels for their energy requirements. Thus, in trying to mitigate the effect of climate change, we are worsening GHG since we are increasing the use of fossil fuels. The solution to this is the use of renewable energies for powering desalination and water treatment systems. This paper discusses some hybrid solutions and issues related to realising hybridization, especially using ocean energy for desalination.

RENEWABLE ENERGY FORMS AND DESALINATION SYSTEMS

Renewable Energies

The most commonly known renewable energy forms are solar and wind. Solar PV needs large footprint on land for large powers. It is also available for only a few hours per day. Wind turbines are now installed at several locations in the country due to positive policies by MNRE. Again wind energy is intermittent and storage for standalone systems needs to be addressed. Today offshore floating solar is being studied and also attempts are being made to harness offshore wind energy.

Apart from the solar and wind energy, we need to explore other forms like ocean energy as well. Given the long coastline of India and a huge exclusive economic zone (EEZ), towards the efforts for mitigation of climate change, it is important to develop new technologies for harnessing ocean energy. Energies that can be harnessed from the ocean are wave, tidal, thermal gradient or ocean thermal energy conversion (OTEC), offshore wind and floating solar PV. The latter two forms are not considered ocean energies since the motive force is not sea water. Salinity gradient is also a possible form, but not yet viable. Today developing all of these forms is the need of the hour for coastal regions, and remote locations and islands.

Energy from ocean currents can be extracted using submerged turbines that capture energy from hydrodynamic lift and drag forces acting upon them. The Ocean Energy Systems Technology Collaboration Program under the IEA, on its website (Ocean Energy systems n.d.), gives details of tidal turbines being studied around the world. Towards developing these turbines, a small capacity unit has been indigenously developed in the National Institute of Ocean Technology (NIOT) using computational and experimental techniques. Upon successful testing of the turbine in controlled conditions of the laboratory, it was successfully tested in the MacPherson Strait, South Andaman, India, by suspending the turbine from a floating platform specially designed for this purpose (Dudhgaonkar et al., 2017). Modules of 1–5 kW ocean current turbines are in advanced stages of development since off-grid units of these ratings are of great utility in the Andaman and Nicobar Islands, India (Figure 1).

Figure 1. Hydrokinetic turbine testing at the Andaman Islands, India by NIOT

Wave energy is a prominent form of ocean energy being pursued in several countries in Europe and Asia, and again, the Ocean Energy Systems Technology Collaboration Program (Ocean Energy systems n.d.) gives information on European devices. Wave energies are high in Northern latitudes, but sustaining these systems in severe environmental conditions, is difficult. In India, the wave climate is lower in intensity; hence, design is easier. However, viability has to be addressed for scaled-up systems. For a long time, the Indian wave energy plant was one of the few working plants in the world. It was a fixed oscillating water column device (OWC) installed in the early 1980s and was generating power for a few years. The plant experience led to the development of floating wave energy devices. This was the genesis of the wave-powered navigational buoy developed by NIOT, which is being used extensively by a port off Chennai (Pattanaik et al., 2020).

While solar, wind, and wave energy are irregular, the only base load form of ocean energy is OTEC, viz., Ocean Thermal Energy Conversion. The temperature difference between the sea surface and water at deeper depths remains more or less constant throughout the year in countries like India. This difference can be used to generate power.

The sun warms the surface seawater to an extent that all the energy is captured in a region up to 100 m thickness near the surface. As we go deeper down into the ocean, the water becomes colder. A huge amount of cold water exists at depths of around 1000 m, which is due to the accumulation of ice-cold water melted from Polar Regions. The two bodies of warm water from the surface and cold water from the deep can be used to run the OTEC cycle for generating power. Essentially an OTEC device, converts a low-grade heat source into electricity using a thermodynamic cycle. For tropical countries like India, OTEC can be a good renewable source since this is a baseload source of energy. The temperature difference exists throughout the year, and hence large amounts of power can be harnessed. However, at present OTEC is still in the testing and sea trial stages in the world because of the underlying challenges.

This section has dealt with various form of ocean energy. Worldwide, ocean energy is yet to be commercialised. Small scale devices don't give much understanding of techno-commercial viability at scale. Perceived risks, huge capital costs, requirement of offshore infrastructure, grid connectivity are all issues to be dealt with for scaling up and commercialisation to happen. Hence, there have been efforts to find alternate markets like aquaculture and desalination. Both these have been studied and are available in the Ocean Energy Systems Technology Collaboration Program (Ocean energy system n.d.).

Desalination

Further, there are largely two types of desalination, viz., the thermal and membrane technologies. Some of the popular thermal technologies (Darwish and Ammar, 2004: Greenlee et al., 2009: El-Ghonemy, 2018; Jalihal and Prabhakar, 2019) include, Multi-Stage Flash (MSF), multi-effect desalination (MED) and mechanical/ thermo vapour compression (MVC/TVC). The membrane methods include, reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED) and membrane distillation (MD). These technologies have been deployed around the world and RO has a large market share today. Thermal technologies tend to be more energy-intensive, but are robust and easy to operate. Membrane methods can have environmental impacts and are hard to operate.

Desalination methods to be employed depend on the location, water to be desalinated and quantum of fresh water needed as the main factors. When the location is in the hinterland, brackish water can be desalinated which primarily is being achieved by membrane methods. Needless to say, for coastal locations, seawater desalination is the most suited. In the Indian context, RO membranes are already being manufactured indigenously, however seawater membranes are yet to be commercialized. The energy requirement for brackish water desalination, is far lower than that for the seawater. The issues in seawater desalination are far more complex due to the chemical composition, making it important to understand the quality of intake water. Corrosion is an important issue in seawater desalination systems and need to be addressed by the use of appropriate materials. NIOT has developed a technology using the ocean thermal gradient as described below.

In 2005, a 100 m^3/day land-based plant was commissioned at Kavaratti Island (Figure 2). This plant has been continuously generating freshwater for the past 19 years to meet the drinking water needs of the island community. The water is of excellent quality and has truly changed the lives of the islanders, especially the health of the people. This indigenized technology has been deployed in two more islands of Lakshadweep, namely Agatti and Minicoy, in 2011 and also in Kalpeni and Amini in 2023. The installation of LTTD plants in four other islands (Androth, Chetlat, Kadamat, and Kiltan) is now nearing completion.

In these plants, the thermal gradient between surface and deep layers of the ocean water column that provides huge reservoirs of warm and cold water, was effectively utilized for desalination (Rognoni et al., 2008; Venkatesan et al., 2015; Jalihal, 2022). Figure 3 shows a schematic diagram of the LTTD unit. When seawater at around 28°C is passed through vacuum, it can boil even at this low temperature and the vapour so generated can be condensed using the cold water siphoned from greater depths.

Figure 2. Desalination plant at Kavaratti Island, India

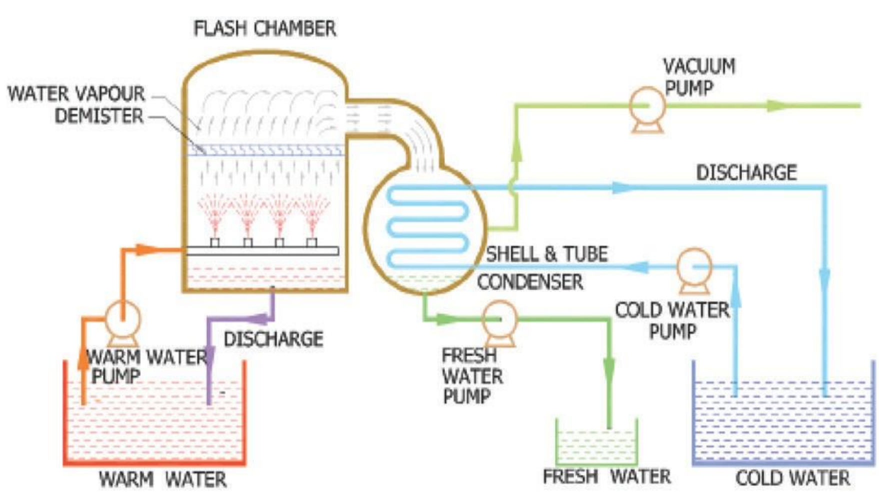

Figure 3. Schematic diagram of the low temperature thermal desalination unit

The water thus generated is of high quality and this cycle can run continuously since the thermal gradient in the ocean is nearly uniform for most of the year. The indigenous LTTD technology developed by NIOT has no requirement for membranes; therefore, has no brine formation and environmental pollution. Thus, the LTTD technology is also environmentally and ecologically safe.

These are the first ever plants in the world, from concept to commissioning, using naturally occurring temperature differences, and they have been completely designed and implemented by NIOT. However, all desalination methods, whether membrane or thermal or any other, need energy which can result in large GHG emissions. For example, CO_2 emissions from desalination using fossil fuels can range from around 2 kg/m³ to 25 kg/m³ depending on the desalination system employed (Shokri and Sanavi Fard, 2023). As can be seen, there are several types of desalination, and their applicability and energy requirements vary. Brackish water desalination is certainly low in energy consumption; however, sea water desalination consumes large amounts of energy. The types of desalination and the energy consumption thereof are location and scale dependent.

Having understood the various renewable energy forms and types of desalination, it is important to understand what can be done to hybridize to eliminate or reduce GHG emissions. Energy requirements of desalination systems, if met by renewable, can alleviate water stress while reducing GHG emissions.

HYBRID SYSTEMS

As stated earlier, treatment and desalination systems are energy-intensive, and hence, the energy-water nexus needs to be addressed. The more we desalinate or treat waste/grey water, the greater the requirement for energy. The time has come, therefore, to address this need by the use of renewable forms of energy. It is now imperative to use renewables to power the desalination and treatment processes. There have been some developments for such hybrid systems, but they are few and need further proliferation in various sectors. The use of renewable energy for desalination is set to expand to help achieve the targets set out in the Paris Climate Agreement and the 2030 Sustainable Development Agenda. Recent examples include, a PV-powered RO system producing 11 m³/day in the Philippines, deployed in 2020, and the Kwinana SWRO plant in Perth, Australia, powered by the 80 MW Emu Downs Wind Farm (Kensara et al., 2021), producing 144,000 m³/day (Ghaithan et al., 2022).

In other locations, like the Canary Islands, where there is a need for desalination as there is a heavy reliance on imported fossil fuel, there is now an increased focus on the deployment of renewable energy, particularly wind and solar, to help meet the demands of the general economy and desalination (Qiblawey et al., 2022). Some specific case studies are presented for various types of hybridized systems, which have been successfully proven and are being used for scaling-up/commercialization.

SOLAR PV–RO

Solar PV systems, connected with RO systems, have been used in several places. This is considered to be one of the best options for renewable energy-powered desalination, particularly for remote areas and the hinterland, as both PV and RO are highly modular and scalable. Using photovoltaic systems can reduce operational costs and improve environmental sustainability. A case study of designing a reverse osmosis (RO) desalination plant, using a Solar Photovoltaic (PV) system, is investigated in Kensara et al. (2021). The RO system is a desalination plant providing pure water to the Shoiaba power generation plant.

The system consists of a PV array connected to an inverter for daytime or batteries for nighttime. The paper discusses various simulations on the system, including PV modules, inverters, batteries, and pumps. The simulations indicate that the PV panels would suffice to power the desalination plant. However, this is only a theoretical study. In Ghaithan et al. (2022), the study assesses the feasibility of powering a large-scale Reverse Osmosis desalination plant using different energy supply systems, including full grid, PV-grid, PV-grid-battery storage, and PV-battery storage. In addition, the study assesses the potential of reforming the power sector in Saudi Arabia by exploring the impact of removing fuel subsidies on the cost of water. The results show that, in the case of fuel subsidies, the final cost of water desalination using PV-grid without a storage system is cheaper than full grid. Thus, there are many examples of attempts at powering RO plants using Solar PV.

Additionally, Clarke et al. (2015) dealt with a standalone energy system, which is completely powered by renewables, and the objective is to meet two external loads: (i) power generation (kWhp), and (ii) desalinated water generation (liter). Their two objectives are to minimize Net Present Cost as well as to reduce CO_2 emissions. The system consists of solar PV arrays with storage.

The power management unit (PMU) powers the RO units for desalinated water as well as the PEM electrolysers. The hydrogen generated, in turn, is used in fuel cells to power the PMU. A detailed methodology has been studied by Tsai et al. (2016), wherein a model is proposed to integrate the operation of a reservoir, hydroelectric power, desalination, and wind power. A balance between seasonal variations is taken into account for powering the desalination system by utilizing the power sources effectively

SOLAR MULTI-EFFECT DISTILLATION

In thermal desalination, solar thermal has been used in a MED system and has been successfully demonstrated. A few years ago, the Department of Science & Technology funded a project to an industry with technical support from NIOT for a Solar Multi-effect Distillation plant at Ramanathapuram in Tamil Nadu (Figure 4). This plant is considered green due to the usage of solar energy and is also safe environmentally since it is a thermal desalination system.

The solar thermal field with a sophisticated tracking system was used to generate steam, which in turn enters the MED system to generate freshwater. Here again, the lack of availability of solar energy throughout the day makes the system depend on another form of energy for augmentation.

The fluctuating and short availability of insolation makes its viability at this point questionable. The footprint for solar systems on land is also high, which is not desirable in this age of high land costs. While thermal systems can generate three times more power than PV per unit area, they need tracking systems for better efficiency.

WAVE POWERED RO

Waves are caused by winds blowing on the surface of the ocean. They are highly irregular in nature with intensities which vary with seasons and geographical location. The global distribution of wave energy indicates that there are many countries that have a coastal wave climate favourable for exploitation of this resource. The wave power devices extract energy directly from the motion of waves at the surface or from pressure fluctuations below the surface.

As far as the Indian scenario goes, for nearly two decades, research has been carried out on an oscillating water column device at a place called Vizhinjam in Kerala as shown in Figure 5. The power generated was also used to run a reverse osmosis-based desalination plant of a capacity 10,000 litres per day. This was the first ever self-sustaining system where power was generated from the sea to make fresh water out of seawater (Sharmila et al., 2004).

Such systems with intermittent power generation need batteries for charging and discharging to keep the system operational for twenty-four hours a day. Standard batteries need to be huge in size for such applications. Thus, storage is an important element for intermittent systems like solar and wave

Figure 4. Solar multi-effect desalination plant at Ramanathapuram, Tamil Nadu, India

Figure 5. Wave energy plant at Vizhinjam, Kerala, India

The need therefore is to think out of the box and explore other forms of clean energy to power desalination systems, and ocean energy is certainly one such arena. However, since wave, solar and wind are all dependent on the time of day, season and other environmental conditions, all these forms of energy need storage or augmentation with the grid power. Base load power such as OTEC does not have such restrictions. Offshore systems like floating solar and wave energy could be amenable to powering sea water desalination systems. However, hinterland brackish water systems can be more easily powered by onshore solar and wind energy systems. Off-grid devices for small powers using hydrokinetic turbines or wave energy devices can serve remote locations like islands very well as green systems to power local small desalination units.

OTEC POWERED DESALINATION

As mentioned earlier, OTEC and LTTD use the ocean thermal gradient to generate power and water, respectively. Since LTTD and OTEC utilize the same resources, it is logical that power generated by an OTEC module can also power an LTTD module from the same plant. Sharing the infrastructure for seawater handling systems, can bring down the overall cost of freshwater generation. Towards this end, NIOT has now undertaken to establish an OTEC-powered desalination plant at Kavaratti. It will be the first ever prototype plant generating power and freshwater utilizing a naturally occurring ocean thermal gradient. The main challenge with OTEC is to generate significant amount of power from a small temperature difference. However, the ocean thermal energy is clean and renewable as the heat source and heat sink possess infinite heat capacities.

The thermal desalination plant being set up in Lakshadweep, will be powered by the ocean thermal gradient. The power generation will use OTEC and desalination will be the LTTD system, eliminating the use of diesel generators. Though the plant has several complexities, it will be completely indigenous and when commissioned, it will produce 0.1 MLD of water using energy from the ocean and will be off grid during operation.

OTEC needs deep sea cold water to maintain around 20 °C as the temperature difference. This deep water is not available at all locations, and hence, for mainland requirements, we need to go offshore. Studies are currently underway to design an offshore platform-mounted OTEC-powered desalination plant to make net power as well as provide energy for the desalination process. While such systems look futuristic, we need to start work and develop appropriate technologies so we can implement viable systems in the near future.

CHALLENGES IN HYBRIDIZATION

While hybrid systems are the way forward, the actual implementation is far from easy. First, let us consider intermittent sources like solar. The solar MED plant works well but only in sunshine hours. The rest of the time, it needs augmentation with other sources of power. If solar PV is used, storage is required for continuous water generation. Similar issues arise with wind energy as well. In India, wind speeds are not very high and energy produced has low plant load factors. This can pose challenges while powering desalination systems since the latter are to be run continuously. Ocean energy resources like wave and tide are also characterised by various degrees of intermittency and these vary from site to site and season to season. This can also impact the choice of desalination technology, which the particular resource is to be hybridized with. A typical scenario with solar PV is the pumping of power to grid and the desalination plant drawing from grid directly. While the model is sufficient to increase the numbers for the renewable share, we are not making desalination emission free.

Another method for utilising wave energy is to directly generate pressure instead of electricity and run the RO membranes to produce fresh water. This method of hybridizing is being attempted in several countries; however, it is still in infancy since quantifying the pressure for different wave climates while scaling up, still poses difficulties. Using wave or tidal energy to directly pressure RO membrane could have technical issues, largely due to the fluctuation in the energy harnessed. If electricity is generated, the fluctuation can be addressed by charging or discharging batteries. When pressure is higher than the desired by the RO unit, dissipation needs to be carried out. Reduced pressure will be detrimental to operation, storage systems are challenging, unlike power equipment and other mechanical challenges also include leak tightness since the systems, including the RO units, may need to be underwater. For OTEC systems, challenges are the high capital costs and optimization of available off the shelf equipment. The biggest challenge is the cold water conduit which is needed to draw cold water from deep ocean depths. The design, installation and robustness of these pipelines are being studied internationally, and this component can be the most complex for an OTEC plant. In the case of offshore plants, power transmission along with water, is also challenging. The OTEC turbines for open and closed cycles are also complex and are yet to be manufactured anywhere. Policy makers are also unable to prioritize funding for technology development due to perceived risks, considering that offshore has severe challenges. Power storage for intermittent sources like wave, wind and solar also becomes important for the constant power requirement of desalination systems.

CONCLUSIONS

In general, there is a need to alleviate water stress today, and desalination is a good solution for the augmentation of water. To reduce GHG emissions, the way forward is using renewable energies; thus, it is important to power desalination systems using renewable energies in this context. The site location, amenable renewable solutions and choice of suitable desalination method, all need to be studied before arriving at a solution. A few researchers discussed the compatibility of different ocean energy technologies with desalination technologies, and they concluded that wave, tidal and OTEC are all amenable to being coupled to RO systems using electricity generated; however, wave and tidal may also utilize the direct pressure generation methodology. They suggest that for thermal desalination systems, OTEC may be the most amenable ocean energy source that can be coupled. In general, for actual implementation, the site selection and TRL for the energy form. will play a role in its utility for hybridization.

It appears that large-scale desalination systems, cannot be hybridized with ocean energy at this point in time. The range of opportunities depends on the cost at which ocean energy can supply power to the desalination system. But there seems to be a generic opportunity for ocean-powered systems for small and micro-scale ranges of desalination plants. If ocean-powered desalination plants can make an entry into the market for small-scale plants, it can present an opportunity for OE-powered systems to become established in a growing market. In fact, this would not only benefit overall cost reduction, but could help in the broader context of the blue economy, like in the aquaculture sector, where water and electricity are both needed at offshore locations.

Further, each type of renewable along with the suitable type of desalination method and site location, needs more study and understanding. The complexities of constant powering for water generation, necessitating storage for intermittent sources, need to be addressed. Technical and commercial viability for base load sources like OTEC, needs optimization along with industry for better components along with offshore installation strategies. Further technology development and research are necessary for a water-stress and GHG-emission-free tomorrow.

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Data Availability

Data is based on internal study. It may be made available on reasonable request.

Compliance with Ethical Standards

The author has read the manuscript thoroughly and confirms that it has neither been submitted to any other journal nor been considered for publication. The author adheres to copyright norms.

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Membrane based desalination systems for seawater

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ABSTRACT

Desalination is a necessary supplement for the already existing natural resources to meet the growing demand of fresh water. It requires energy to separate the vast resources of seawater which contains around 3.5% of dissolved salts. Several technologies have been developed in recent years, besides the century old thermal desalination processes. This article provides an overview of the membrane technologies, particularly focusing on the most used Reverse Osmosis for seawater desalination.

INTRODUCTION

Ocean is the repository of many life-sustaining requirements available tangibly or intangibly. Energy can be obtained from the ocean in many ways; from within as waves, or outside as the wind. The ocean water is spread over about two-thirds of the earth's surface (Wang and Huo, 2022) and contains virtually all the mineral salts and valuable metals albeit in a very low concentrations. With increasing population, the demand for the fresh water has increased manifold to meet the needs of several life support systems including domestic, agriculture, food processing, pharmaceuticals, power generation, metallurgical industries, refinery operations etc. Only about 3.5% of annual precipitation is available for human use in rivers, ground water and lakes. Even in this, a significant fraction is rendered unfit due to anthropogenic contaminants. With reference to India, the per capita availability of fresh water has dwindled to about 1500 m^3/annum at present, down from 5000 m^3 in 1950, indicating water stress conditions. Being aware of these constraints, already a few desalination plants have been installed in parts of Gujarat and Tamil Nadu in late nineties. Since India is blessed with a long coastline of about 7,516.6 kilometers including about 5,422.6 kilometers in mainland and 2,094 kilometers in island territories, stretching across nine states and four union territories, Government of India has established the 'Desalination Mission' to adopt desalination in larger scales towards enhancing water security (Dhakal et al., 2022). Nature has illustrated the basic concepts of desalination processes; thermal and membrane based as seen from the evaporation – condensation–precipitation cycle using the thermal energy of the sun, while the plants separate the excess water through cell membranes for its removal through transpiration. In a similar manner the desalination technologies currently in vogue are either thermal, or membrane based.

Many variations of thermal energy-based desalination processes are in practice, in tune with capacity required, and locational logistics, exhibiting varying specific energy consumptions. Based on the form of energy the specific energy for seawater desalination varies from about 3 kWh/m^3 for reverse osmosis to about 15 kWh/m^3 for electro-dialysis, with the thermal processes in the middle depending on the type. However, the selection of an appropriate desalination technology is site specific, depending on the end use, economics, opportunity and logistic costs, thus accounting for the variety of desalination technologies in use.

Among the technologies available today, reverse osmosis is the most popular, as it operates under ambient temperatures with low specific energy consumption, and has a major share, dominating over hitherto popular, century old thermal desalination. The overall cost of water is also lower per m^3 and the modularity allow variable operating capacities. Constant development in the technologies, constituting the front-end and back-end components to provide sustainable performance, have made the process more attractive. This article provides an overview of the membrane-based electro-driven, concentration-driven, thermal- driven desalination processes, with particular focus on reverse osmosis with reference to seawater desalination including design philosophy, operational characteristics, limitations, and possible opportunities.

DESALINATION PROCESSES

Desalination means separation of pure water from its solution and can be achieved either by preferentially (which form the minor constituent ~ 3.5% in seawater and still lesser in most of the other saline waters) or water from the solution. The process requires energy to achieve the separation, which can be imposed externally as in thermal desalination, and the membrane based reverse osmosis (RO), or use the internally available energy in the system as in forward osmosis (FO) and membrane distillation. Unlike thermal desalination processes, membrane processes do not involve phase change, except membrane distillation, for the purpose of desalination.

MEMBRANE PROCESSES

Membrane processes are versatile as they can be used for desalination under different energy gradients such as reverse osmosis with mechanical energy (pressure), electro-dialysis with electrical energy (electric-potential), forward osmosis with chemical potential energy (concentration), and membrane distillation with thermal energy (thermal), but with different types of membranes. Among these processes, only reverse osmosis and the electro-dialysis have been found to be suitable for large scale deployment. Reverse osmosis has become the most preferred desalination process, particularly for seawater, due to its low specific energy consumption, flexible operation, quick start-up and shutdown and the suitability of the product with minor post treatment for providing safe drinking water. On the other hand, due to higher specific energy consumption for seawater concentration, and the operational constraints in producing product water with salinities suitable for potable water supply, electro-dialysis is not a favored alternative. Improved version of ED, viz. the electro-deionization (EDI), is suitable only for low salinity water, particularly for last mile purification to produce high purity water.

Reverse osmosis

Osmosis is a natural phenomenon, which describes the flow of solvent (water) from dilute solution (lower solute concentration) to higher concentration through a semi permeable membrane. Consequent to the phenomenon, a hydraulic pressure builds up on the concentrated solution side till the attainment of equilibrium. The value of pressure at equilibrium is termed as '*Osmotic Pressure*'. When hydraulic pressure greater than the osmotic pressure is applied, pure water from the higher solute concentration side can be separated through the membrane and the process is called '*Reverse Osmosis*' as indicated in Figure 1.

One may consider the osmotic pressure as the energy required to separate pure water molecules overcoming their interactions with the solutes. Osmotic pressure is a colligative property and is a linear function of molar concentration of the species in water for dilute ideal solutions. The technology is based on the semi-permeable membrane's ability to separate pure water from its solution and transport it through the capillaries with as less a resistance as possible, providing a good water flux at reasonably low pressures (over the osmotic pressure).

Membranes

Membranes used in the reverse osmosis process are porous having pore-sizes in the order of two to five tenths of a nanometer (2–5 Angstroms). After the initial discovery of the reverse osmosis membrane in 1959, many developments have taken place leading to better separation efficiency and higher water flux at reasonably lower pressures (about 30 bar above the osmotic pressure of seawater). The membrane extensively used in desalination and water treatment applications are known as *Thin Film Composite (TFC)* membranes, which consist of a polymer formed of a diamine (m-phenylene diamine) and an acid chloride (tri-mesoyl chloride) on a porous substrate by in situ polymerization as indicated in Figure 2, which results in polymer containing neighboring groups of hydrophobic and hydrophilic substrates increasing the selectivity.

The porous substrate provides a smooth passage of water with less resistance to flow, while the top surface ensures very high selectivity (providing more than 99.4% + solute removal). Since the pores are not uniform, the membranes exhibit a distribution of pore-sizes, with some of them larger, allowing the passage of some of the solutes through the pores preventing absolute separation. Narrowing the pore-size distribution leads to better separation efficiency. Reverse osmosis phenomenon is a surface driven process and hence requires high surface area for large capacity desalination. Out of the different configurations, hollow fiber is the most compact. However, due to operating constraints related to hydrodynamic considerations, spiral wound configuration is preferred and is considered the work horse of the large capacity seawater desalination plants.

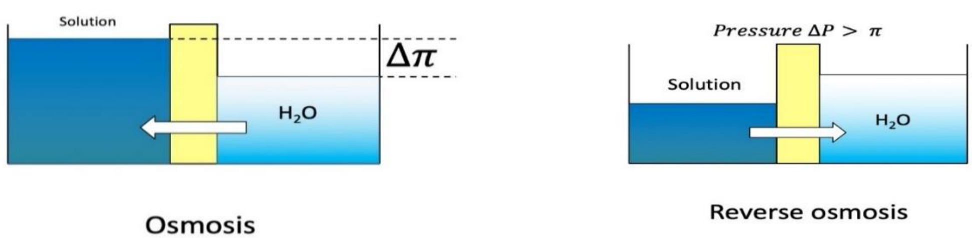

Figure 1. Principle of osmosis and reverse osmosis

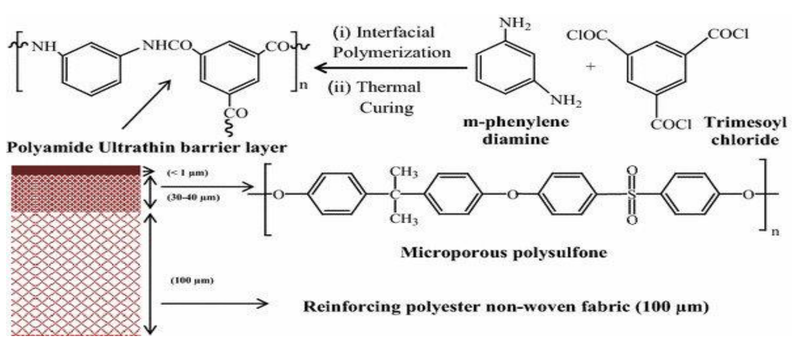

Figure 2. TFC membrane synthesis by in situ polymerization of m-phenylene- diamine and tri-mesoyl chloride over a porous support

Seawater reverse osmosis desalination plant

Typical flow diagram is shown in Figure 3. Accordingly, the feed from the source, enters the pre-treatment section. The purpose of the pre-treatment section is to ensure long service life of the membrane surface by minimizing fouling, scaling, and preventing oxidative chemical degradation. The particulate matter and micro-organisms are removed by a series of filters including ultra-filters at the end of the filtration system. Anti-scalants, and sodium-bisulfite are dosed to minimize scaling and to provide a reducing environment, to minimize the oxidative damage of the membrane surface. After monitoring the performance of the foulant removal efficiency by silt density index (SDI) and ensuring positive oxidation reduction potential (ORP) value, the feed is pressurized through high pressure pumps, and sent through a set of membrane modules arranged in parallel to meet the design capacity. Initially multi-stage centrifugal pumps were preferred, while at present positive displacement pumps compatible with the energy recovery devices are used. Each module would contain a few elements (6-8) connected in series depending on the design recovery (defined as percentage of feed recovered as product). A number of such modules are arranged in parallel to meet the design capacity. The unused pressurized feed (reject stream), is passed through the energy recovery device to recover unspent energy. Over a period, the energy recovery devices (Schunke et al., 2020) have evolved starting from a recovery efficiency of 70% in Pelton wheels to the presently popular work exchangers operating at 98%+ efficiency.

The product water is corrosive as it contains more monovalent ionic species. The product can be passivated by passing through a lime column, for domestic use and through de-ionisation using mixed-bed ion exchangers for industrial uses (boiler feed or for electronic industries) requiring high puritywater.

Seawater reverse osmosis (SWRO) plants require periodic maintenance to chemically clean the membranes. The operators have to be alert in monitoring the functioning of pre-treatment system, lest the chances of membrane failure could be high. To minimise undue damage to the membrane, the product water from the plant is allowed to flow through a (suck back) tank located at a higher elevation compared to the top module. This helps in the product water passing through the product channel of the modules, in case of sudden or temporary stoppage of the plant to avoid drying of the membrane surface. Further, osmosis will set in helping to remove the scale formed on the feed side. During planned shut down, membranes need to be protected by maintaing a reducing environment (by periodically filling them with sodium bi-sulfite solutions), to prevent oxidation of the membrane through air in leakage.

Unlike thermal desalination plants, where the product water will have a few ppm of dissolved salts (<10 ppm), the SWRO product will have a few hundreds of ppm . In order to reduce the dissolved solids content, if required, one may have to use one more reverse osmosis system, using the product water as the feed, but without any pre-treatment step and using cheaper tap water/brackish water membranes. With the use of the positive displacement pumps and the work exchangers as energy recovery device, the specific energy consumption has been found to be less than 3 kWh/m^3 (Ruiz Garcia et al., 2023).

Electrodialysis

Membrane Characteristics

Electrodialysis (ED) uses charged non-porous membranes, aiming at specifically removing the ionic solutes for producing desalinated water from the saline or seawater under an electric-potential gradient. The membranes have mobile anion and cation moieties. These membranes are akin to ion exchange resins, made of functionalized polymers with pendent groups containing replaceable sodium Na^+ or Cl^- ions such as [$SO_3^-Na^+$] or [$R_3N^+Cl^-$], known as cation exchange and anion exchange membranes, respectively.

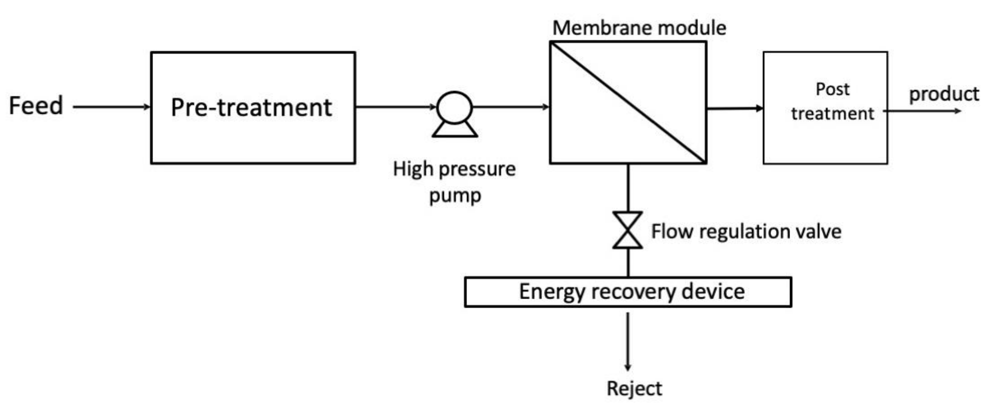

Figure 3. Flow sheet for seawater reverse osmosis desalination plant

Process description

A '*cell pair*' refers to a set of anion and a cation membranes. In an electrodialysis unit (Al-Amshawee et al., 2020), as shown in Figure 4, a number of cell pairs are arranged together between the electrodes (anode and cathode) such that cation and anion exchange membranes are alternately placed. Feed, after pre-treatment of the source water, is passed through all the compartments. Electrode rinse solutions are circulated around the electrodes to remove the gases (hydrogen at the cathode, and oxygen /chlorine at the anode). The pre-treatment involves the removal of scale forming ions such as calcium and magnesium and foulants using softeners or nanofiltration. This helps to improve the efficiency of the desalination process and prolong the life of the ED membranes.

When the electrical potential is imposed, the ions in the solution move towards their counter electrodes i.e., anions towards the cathode and the cations towards anode. The direction of the movement is fixed, due to the polarity of the electrodes. As the ions move, cations can pass through cation exchange membrane, but not through anion exchange membrane encountered in their path, and vice-versa for anions. Consequently, as the movement of ions progress, alternate compartments become depleted and concentrated with respect to the solutes, resulting in diluted water and concentrated stream. The depleted (dilute) water is collected as desalinated water, while the concentrated solutions, separately.

The operational challenge in the process, is the accumulation of ions near the membrane surface resulting in concentration polarization, attributable to the lesser diffusivity of the ions in the membrane phase compared to the solution phase, resulting in reduced current utilization efficiency. Since the energy consumption depends on the number of ions and their charge, the energy consumption for seawater desalination is high due to a higher concentration of the feed (about 35000 ppm), with significant presence of bivalent ions and the consequent concentration polarization. For brackish water with less TDS (<5000 ppm), electrodialysis, is energy efficient. ED is better suited in removing ionic components with low molecular weight, but not for neutral, high molecular weight and less mobile ionic species. At very low solute concentrations, the transport rate and the current utilization efficiency decreases. Consequently, it is difficult to obtain low concentration of product water, using electro-dialysis.

To reduce energy consumption in sea water desalination using ED, and to increase the energy utilization by circumventing the concentration polarization phenomenon, the concept of '*Electro-Dialysis Reversal* (EDR)' was introduced, by which the electrode polarities are frequently reversed to change the direction of ionic movement and hence to minimize the effect of concentration polarization. However, this concept resulted in the reversal of product and concentrate compartments resulting in contamination of the product water leading to poor product quality.

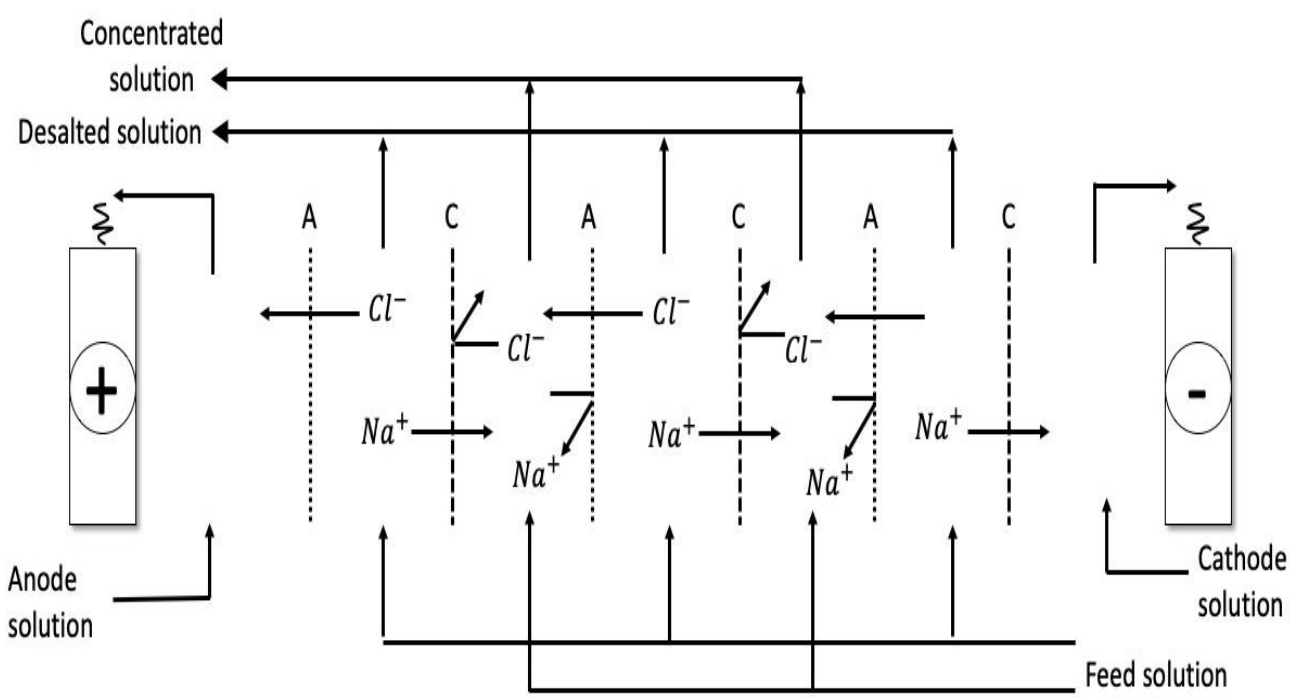

Figure 4. Working philosophy of electro-dialysis process

DEVELOPING MEMBRANE PROCESSES

Besides, reverse osmosis and electro-dialysis, a few more membrane processes have been developed for desalination operating under different energy gradients; temperature, concentration, and electric potential viz., Forward Osmosis (FO), Membrane Distillation (MD), and Electro-Deionization (EDI) respectively.

Forward Osmosis

The operating philosophy of forward osmosis (Cai and Hu, 2016) is same as osmosis i.e., water permeates through the semi permeable membrane from its higher concentration (water) to its lower concentration. In practice, a concentration difference with reference to water is imposed using a synthetic draw solution with a higher osmotic pressure than the feed stream to osmotically draw water from the feed stream. Consequently the draw solution is diluted (Mehta et al., 2014). Fresh water is then separated from the draw solution by a downstream process, using some form of energy: thermal or mechanical (pressure) as shown in Figure 5. A Variety of membranes such as thin film composites, cellulose acetate, and bio-membranes such as aquaporin etc. and draw solutes including several inorganic solutes such as ammonium bicarbonate, chlorides of magnesium, calcium and sodium, organic compounds including glycerol and high molecular weight compounds, have been investigated to decrease the reverse solute flux, improve the water flux, and the ease of recovering fresh water from downstream process. Another interesting consequence of forward osmosis namely pressure retarded osmosis, can lead to power generation, from the hydraulic pressure being developed in the draw solution side.

Membrane Distillation

Membrane distillation (Parani and Oluwafemi, 2021) uses porous membranes which are hydrophobic in nature. Unlike liquid water which exists in an associated state, water vapor does not exhibit association amongst them and behaves as hydrophobic moieties. Thus, using hydrophobic membrane, the water vapor is preferentially transported by maintaining a vapor pressure gradient created by temperature differential. Depending on the method of condensation, four different methodologies were developed as indicated in Figure 6. In direct contact membrane distillation (DCMD), the water vapor permeating through the membrane is condensed by circulating cold water in the permeate side. In vacuum membrane distillation (VMD), an appropriate vacuum is maintained on the permeate side to enable the condensation of the vapor. In the air gap membrane distillation (AGMD), the vapor is condensed on the wall of the shell, accommodating the membrane, by maintaining a cooler wall temperature by external cooling. In sweep gas membrane distillation (SGMD), the water vapor gets humidified by the gas (nitrogen or air) and recovered outside the unit. Studies on membrane distillation for seawater have been carried out using solar energy as a thermal source using vacuum for condensing the vapors (Mericq et al., 2011).

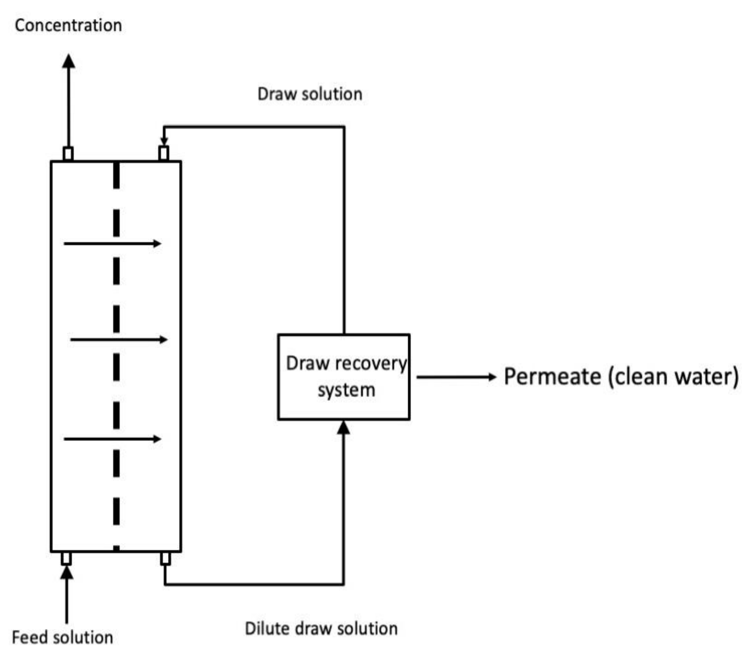

Figure 5. Working principle of forward osmosis. Feed and draw solutions are circulated on either side of the membrane during which draw solution gets diluted because of osmotic flow and clean or product water is recovered using thermal or mechanical energy.

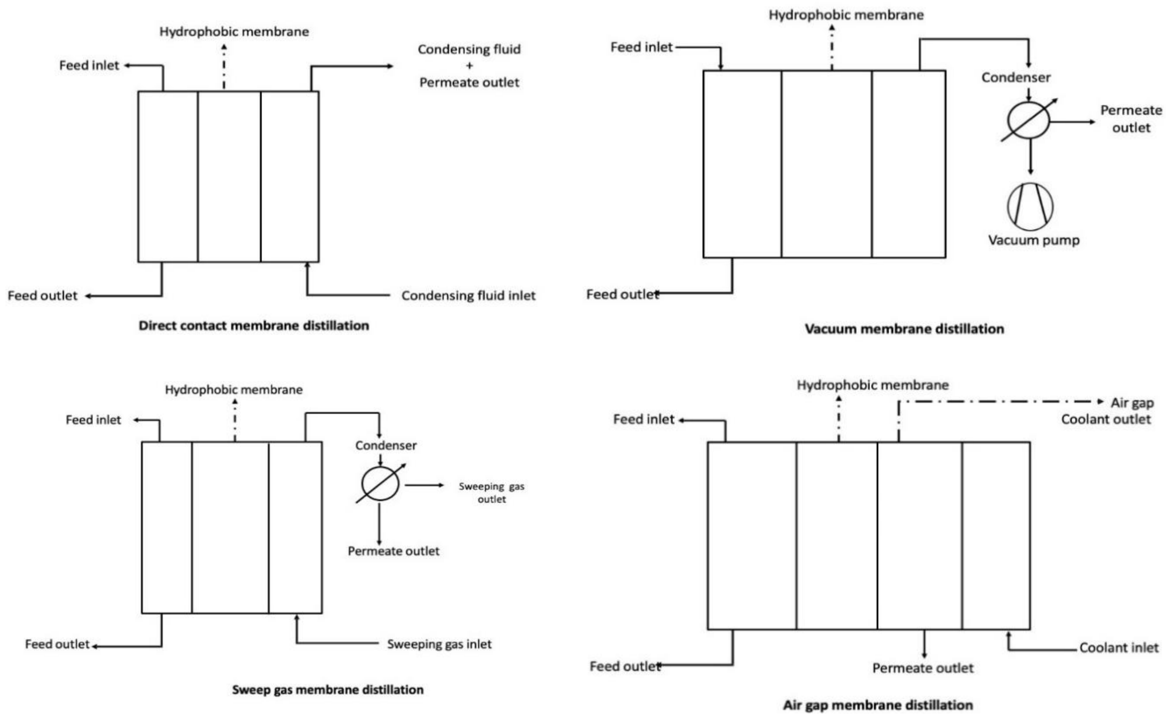

Figure 6. Different methodologies adopted for condensation of the product in membrane distillation (direct, vacuum, sweep gas and air gap).

Electro-Deionization

Electro-Deionization (EDI), like an electro-dialysis unit, consists of a number of cell pairs (a set of anion and cation exchange membrane), and is a membrane process which can be used as last mile purification process to produce de-ionized water, from the product water obtainable from any of the major desalination technologies, be it thermal, electro or pressure driven process, replacing the hitherto used mixed bed ion exchange resins. Use of the mixed bed exchangers, involve frequent regeneration following tortuous procedures and the consequent management of regenerant waste. EDI can be considered as an ion exchange bed with continuous regeneration with electrical energy. The basic difference is the presence of mixed bed exchange resins in the dilute compartment. Feed water with only a few dissolved ionic solutes, is passed through the cells under an applied electrical field. As in ED, the ions start migrating, resulting in concentrate and dilute streams in two adjacent compartments. The ions are initially bound to the resin. With the production of hydrogen and hydroxyl ions due to the high resistance of the dilute stream and consequent electrolysis of water, the resin gets regenerated, and the ions move to the adjacent concentrate compartment.

The limitations of EDI differ from conventional ion exchange, where the purity of the product is limited by the saturation of the resins, while in EDI, the purity is limited by the feed rate. However, high ionic load will overload the module. Hence mixed bed ion exchangers as well as EDI are suitable only for low concentrations of ionic solutes, except that the latter does the removal and regeneration in situ, making it ideal for last mile deionization of product water from conventional desalination processes.

CONCLUSIONS

Seawater desalination is necessary to meet the growing demand of freshwater across the globe. Amongst the commercially developed processes, reverse osmosis is a sustainable and affordable means of providing safe drinking water with many advantages such as operational flexibility because of its modular construction, with respect to capacity, availability of energy source (easily available at any location). ED has limitations in terms of feed salinity and specific energy consumption and product salinity for seawater desalination. In contrast, thermal plants barring vapor compression evaporation (VCE), requires both thermal and electrical energy and produces product with very less concentration of dissolved solids making it imperative and to have elaborate post treatment to make it potable. The basic challenge in any membrane process is the concentration polarization leading to scaling and consequent loss in productivity. The concept of EDR, which sought to alleviate the problem of polarization, resulted in poor product quality due to frequent change of product and concentrate compartments. All the membrane processes require good pretreatment to minimize scaling and fouling. Since RO is a high pressure system, the pre-treatment requirements are rigorous, while ED systems require feed pretreatment to remove hardness and species that may cause fouling and scaling on to the ion-exchange membranes (Kadhim et al., 2023), which decreases the efficiency. However, electro-dialysis can support higher concentrations of those foulants than reverse osmosis. Electro-dialysis membranes, are normally assembled in plate and frame configuration, allowing the removal of membranes and cleaning them directly. In the case of reverse osmosis, where spiral configurations are used, cleaning must be done online chemically, which has the risk of deterioration of the membrane performance. Even otherwise, the membranes deteriorate with time needing periodic replacements and considered part of operating cost rather than being a capital cost.

The greatest challenge of the membrane processes is the ultimate disposal of spent membrane elements in reverse osmosis and the charged membranes in ED, as the membranes are not bio-degradable. In the case of SWRO, the membrane elements are prepared to withstand high operating pressures and shredding them for disposal through incineration is energy intensive. Probably one may investigate the possibility using them for construction purposes. The concentrate solutions of disposed normally into the sea by slow dispersion along the coast.

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Data Availability

As such there is no data (experimental or otherwise) to share, but will be pleased to answer any queries.

Compliance with Ethical Standards

There is no conflict of interest and the contents are compliant with the ethics. Authors adhere to copyright norms

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Site feasibility for offshore wind farm development: A preliminary case study at Jakhau, Gujarat (India)

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ABSTRACT

Renewable and sustainable energy technologies have been adopted globally to meet increasing energy demands. Offshore wind farms are crucial for reducing greenhouse gas emissions and enhancing the availability of power supply. Planning offshore wind energy farm development, involves carefully considered multiple variables to identify the ideal project sites. This study assesses the feasibility of offshore wind farm development along the northern coast of Gujarat, India, which has been identified as an optimal zone for wind energy generation. This assessment was based on a long-term analysis of critical parameters, including wind speed, bathymetry and met-ocean conditions. The annual average wind speed in the study area is about 7m/s, making it feasible for offshore wind energy production. Bathymetric data show depth values ranging from 10 m to 23 m, suitable for monopile foundation structures, recommended for offshore turbines in shallow waters. The site experienced a maximum tidal fluctuation of 3 m, which affected the turbine design and placement. Wave patterns were analyzed to understand the local wave climate. This study incorporates these parameters into the site selection process, considering environmental sustainability, technical feasibility and cost-effectiveness. The results suggest that the identified location of the northern Gujarat coast provides a suitable environment for developing an offshore wind farm. This study gives valuable insights into the criteria required for the early planning stages of offshore wind projects. The findings show that the Jakhau, Gujarat has a good potential for offshore wind farm development.

Keywords: Offshore wind farm, Feasibility study, Bathymetry, Met-ocean parameters, GIS, Jakhau (Gujarat)

INTRODUCTION

Globally, fossil fuels are the most extensively utilized energy source. Historically, fossil fuels have been the primary component of energy systems in both industrialized as well as developing nations (Caetano et al., 2017). People are now forced to choose renewable energy owing to rising energy demands and the depletion of fossil fuel supplies. By the end of the 20th century, wind energy had become increasingly popular for producing electricity (Rashid and Sarkar, 2022). One of the first and most important contributions to the generation of wind energy dates back to 1941 (Kaynia, 2019). Offshore wind farms perform better than onshore wind farms because of their higher and more consistent wind speeds at the sea. India's more than 7000 km long coastline (Dimri et al., 2023), presents a significant opportunity for offshore wind energy harvesting (Rashid and Sarkar, 2022). An overview of India's offshore wind resources was provided through satellite data analysis (Nagababu et al., 2016). Subsequently, satellite data were used to assess the offshore wind potential off the western coast of India (Nagababu et al., 2017).

The feasibility of establishing offshore wind farms in the northeastern Arabian Sea was thus investigated, considering factors such as harbors, wind speed, proximity to the coast, and marine protected zones (Mani Murali et al., 2014). Soil-structure interaction (SSI) is crucial for designing wind turbines under seismic loads, influencing dynamic performance on clay with monopile foundations using p-y curves (Prowell, 2011; Bisoi and Haldar, 2014; Zuo et al., 2018). Owing to their ease of fabrication, design, and installation, monopiles are the most commonly used foundation type worldwide. Approximately 80% of the wind turbine foundations currently in use are monopiles. Other standard foundation types for offshore wind turbines include, gravity foundations, jacket foundations and floating turbine systems (IRENA, 2012). The Indian government approved Rs. 7,453 crore VGF scheme to support 1 GW offshore wind projects in Gujarat and Tamil Nadu, aiming for 37 GW capacity and long-term CO_2 reductions under the 2015 Offshore Wind Energy Policy (Press Information Bureau, 2024). Onshore wind turbines installed near the Jakhau coast in Gujarat are part of India's extensive wind-energy initiatives. This coastal region, known for its solid, steady, and consistent wind patterns, provides an ideal environment for wind energy generation. The turbines in this area contribute significantly to the state's renewable energy output, tapping into the vast wind potential of Gujarat.

The wind farms near the Jakhau coast enhances energy security and support to local economies through job creation and infrastructure development (Murthy and Atmanand, 2013), Gujarat has installed on-shore wind turbines along its coast about 5 km from the shore. As India achieves its ambitious renewable energy targets, exploring the feasibility of offshore wind farms along the Gujarat coast, becomes essential in diversifying the nation's energy portfolio and reducing its dependence on fossil fuels.

Such feasibility study encompasses various techno-economic assessments, wind resource analysis, bathymetry studies, environmental impact evaluations, and technological feasibility. This coast offers promising wind conditions, particularly in areas such as the Gulf of Khambhat and along the southern coastlines, where strong and steady winds create optimal conditions for energy generation. While the broader potential of Gujarat's coastline for offshore wind development has been acknowledged, site-specific insights, for example, wind-wave dynamics, structural feasibility, and resilience to environmental challenges remain underexplored at Jakhau. Further, several other challenges, such as complex seabed conditions, tidal variations, and potential environmental impacts on marine ecosystems and coastal communities, must also be addressed. Additionally, the study must consider logistical factors, such as the availability of port infrastructure for transporting materials and equipment, the proximity to power grid connections, and the overall installation and maintenance cost in offshore environments.

Advanced technologies, such as floating wind turbines or jacket foundations, may be required to be adapted to varying seabed depths and tidal ranges. The long-term reliability and stability of these structures under both wind and hydrodynamic forces, are vital to ensure the economic viability of the project. The present feasibility study is aimed to comprehensively understand the opportunities and challenges associated with the development of an offshore wind farm in Gujarat.

SITE DESCRIPTION

The coast of Gujarat has been favorable for wind energy projects because of its extensive coastline and steady wind conditions. The present study area, bounded between 68°19′51.13″ E, 23°11′48.76″ N and 68°36′15.35″E, 22°41′43.03″ N (Figure 1), is located off the west coast of Jakhau in Gujarat. Wind potential, bathymetry, and distance to the shoreline were considered for site selection based on the approach outlined in the Offshore Renewable Energy Conversion Platform Coordination Action [ORECCA] project (Murphy et al., 2011).

The site off the west coast near Jakhau port has been particularly chosen as the possible location for developing an offshore wind farm which experiences a tropical climate, with monsoon winds contributing to high wind energy potential. However, the region occasionally experiences extreme weather conditions, such as cyclones formed during the pre-monsoon (April-June) and post-monsoon (October-December) seasons, driven by warm ocean waters and atmospheric instability. There is already a wind farm working near Jakhau Port. The generated electricity from this wind farm is exported to Gujarat's state grid. In Turkey, such an exercise included wind potential, territorial waters, military zones, civil aviation, maritime traffic, pipelines, and underground cables (Argin and Yercy. 2015).

METHODOLOGY

The offshore wind farm development methodology, involves evaluation of critical factors. Environmental data such as water depth, wind, tide, and wave were used in this met-ocean study based on ORECCA. Long-term wind speed and direction data are analyzed to assess energy generation potential. Bathymetric studies focused on seabed depth and suitability for monopile foundations. Tidal variations are examined to account for changes in water levels and dynamic forces on the turbines. Wave patterns are analyzed to understand hydrodynamic impacts on structural stability. Geotechnical studies evaluated the seabed characteristics for foundation support. Economic assessments estimate, costs, viability and break-even periods. Logistical considerations, including proximity to Jakhau Port, are included to streamline construction, transportation, and maintenance efforts.

RESULTS AND DISCUSSION

Bathymetry

The bathymetry data was collected from GEBCO datasets (Becker et al., 2009). The bathymetry variation at the site (Figure 1), indicates a sloping seabed. This variation in depth also influences the hydrodynamic forces that act on the turbine-supporting structures, as waves, currents, and tides intensify with greater depths, pose additional challenges for installation and maintenance. Furthermore, the differing depths may suggest varying seabed sediment types, with sandy or rocky bottoms in shallower regions and softer sediments in deeper zones. These are essential factors in determining the most suitable foundation design. Understanding these bathymetric variations is necessary for optimizing the offshore wind turbine project's design, layout, and cost-effectiveness.

Wind

This site has favorable wind conditions at around 100 m above mean sea level. The wind data, spanning from 2013 to 2023, was analyzed over 11 years using hourly data on single levels to capture long-term variation and to better understand recurring patterns, which are essential for site suitability assessments. The wind rose plot for the site reveals that the predominant wind direction is from the north-northwest, which is a crucial factor when considering the placement of wind turbines to optimize energy capture. Wind speeds ranging between 7 to 15 m/s are the most frequent, occurring 40-50% of the time, which falls within the ideal operational range for modern wind turbines (Figure 2).

Additionally, wind speeds below 7 m/s occur about 20% of the time, while higher speeds above 25 m/s are relatively rare, appearing less than 2.5% of the time. These statistics indicate that extreme wind conditions, which could pose risks to turbine structures, are minimal at this location.

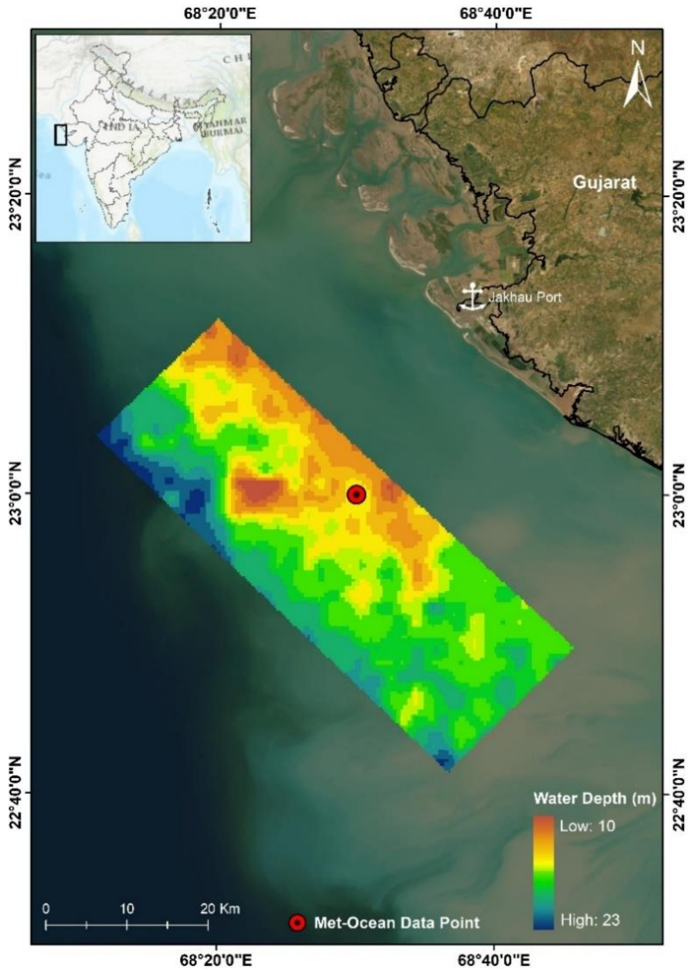

Figure 1. Site location and bathymetry variation off Jakhau coast, Gujarat (India).

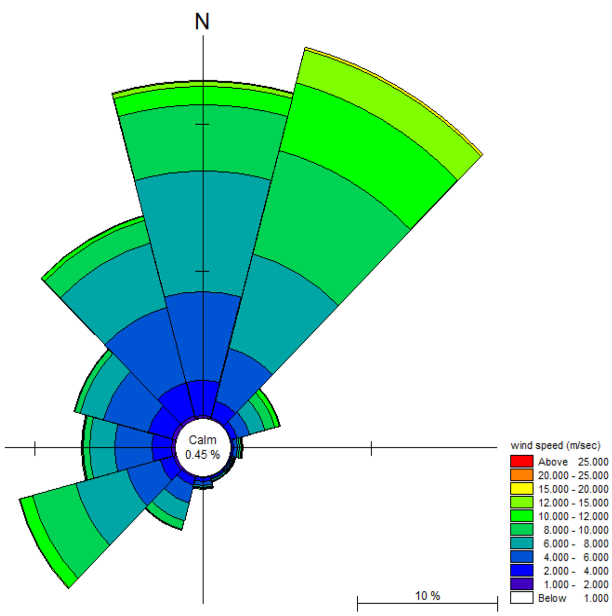

Figure 2. Wind rose plot in off Jakhau, Gujarat

Overall, the consistent presence of moderate wind speeds and the dominance of wind from a specific direction make this site an attractive candidate for offshore wind energy development. With favorable conditions occurring during a significant part of the time, this site holds considerable potential for generating a reliable and substantial amount of offshore wind energy. Studies on environmental impacts and technical factors would further confirm its feasibility for this purpose.

Tide

The tidal variation at the offshore site is based on data from a global tide model (Hart-Davis et al., 2021) for 23°N and 68.5°E, located close to Gujarat, India. Significant fluctuations in tidal elevation (-1.5 m to +1.5 m) with time, relative to the Mean Sea Level (MSL), can be seen here (Figure 3). For the present study, the data for over 18 years, spanning from 2005 to 2023, were analyzed in order to capture long-term tidal variation and recurring patterns.

The consistent variation reveals semi-diurnal tidal patterns with multiple peaks and troughs each day. This tidal range is crucial for the offshore wind turbine site study as it impacts the design of the turbine's supporting structure. The foundation must be capable of withstanding extreme tidal levels and dynamic water depths, ensuring stability during both high and low tides. Additionally, the tidal data was used to assess the hydrodynamic forces acting on the structure, which directly influences wave heights, currents, and loading conditions, including soil erosions/deposition in foundations. Understanding of the long-term tidal pattern is vital for optimizing the turbine's design, ensuring structural integrity and minimizing operational risks.

Wave

The hourly wave data from ERA5 (Hersbach et al., 2023) for over 11 years, spanning from 2013 to 2023, was analyzed to capture long-term variation and recurring patterns. Based on this data, the wave rose diagram represents the wave climate at a specific offshore wind turbine site. The dominant wave direction is southwest (SW), with wave heights primarily ranging between 2.0 and 3.5 m (Figure 4), make it the most frequent and consistent direction. Though less frequent, waves also approach from the west-southwest (WSW) and north-northeast (NNE). SW waves reach 3.5 to 4.5 m occasionally, but extreme waves above 4.5 m are rare. Calm conditions, with wave heights below 0.3 m, are infrequent, indicating that the site rarely experiences still seas. The SW direction not only produces the highest wave heights, but also the highest frequency of occurrence, dominating the wave climate. WSW and NNE waves have lesser effect on the supporting structure. The wave climate is characterized by consistent moderate wave activity with infrequent calm periods.

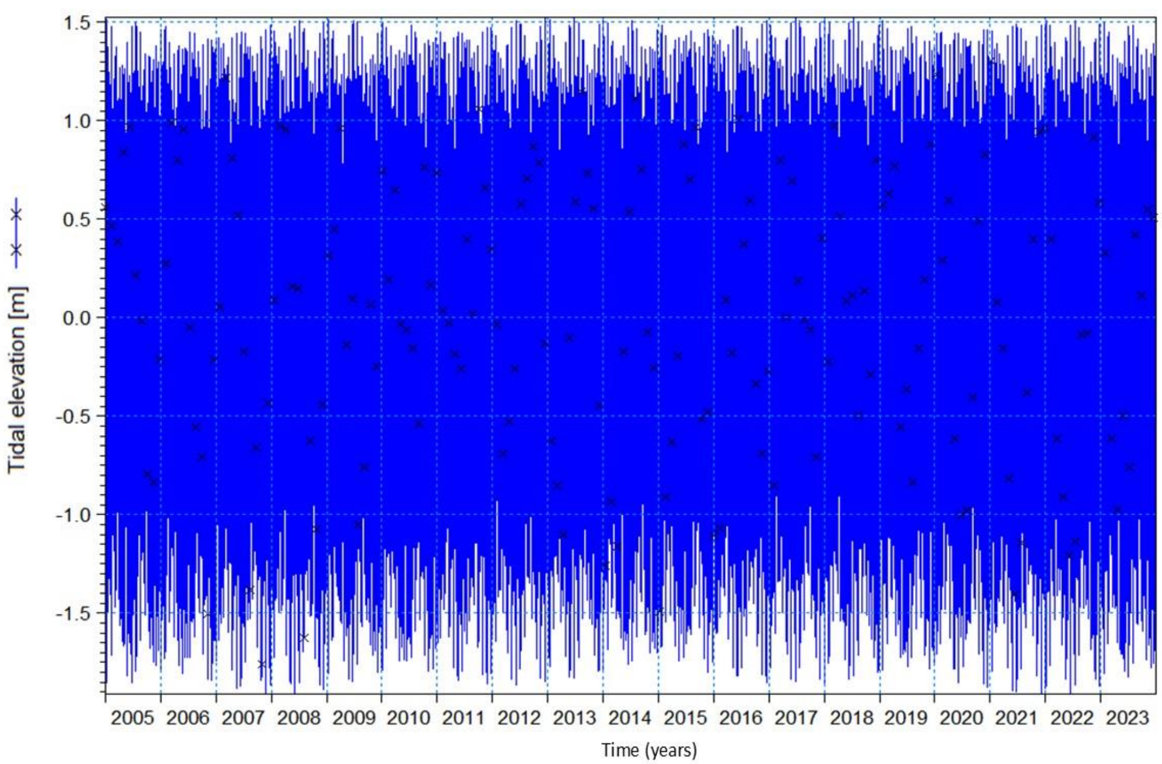

Figure 3. Tidal variation off Jakhau coast in Gujarat (India)

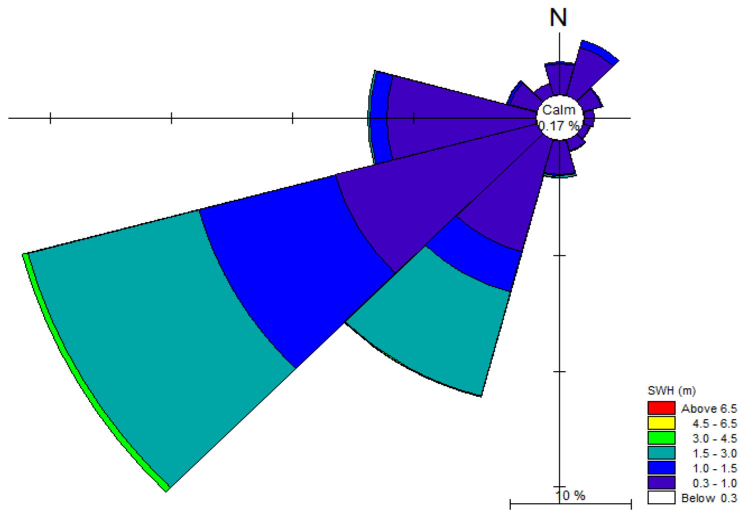

Figure 4. Significant wave height wave rose diagram off Jakhau coast, Gujarat (India)

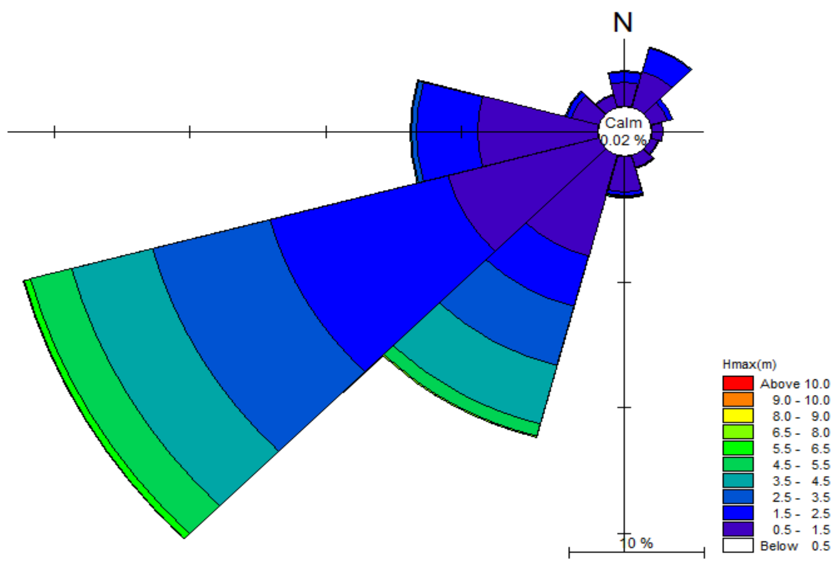

Figure 5. H_{max} wave rose diagram in off Jakhau coast, Gujarat (India)

The rose diagram (Figure 5), illustrates the maximum wave heights (H_{max}) and their corresponding mean wave direction (MWD) for an offshore wind turbine site. The dominant wave direction is southwest (SW), with additional contributions from the west-southwest (WSW) and north-northeast (NNE) directions. Most maximum wave heights range from 1.5 to 4.5 m, particularly from the SW, with occasional waves between 5.5 and 6.5 m. Calm conditions, with waves below 0.5 m, are rare. The SW direction consistently produces the highest wave activity, making it critical for wind turbine design to account for these forces. While the site experiences moderate to high-energy waves, extreme events above 10 m wave heights, are not observed, indicating that, although the site faces occasional large waves, it is not subjected to the most extreme conditions.

This wave climate analysis is essential for ensuring the structural resilience and long-term operational efficiency of offshore wind turbines. Decoupling of local winds from distant swell waves, is frequently the cause of opposing wind and wave orientations in offshore environments (Lyu et al., 2019). This phenomenon is impacted by several elements, including area meteorology, swell propagation, monsoon and geographic features (Li et al., 2023).

Site suitability analysis

The offshore wind power project site, located 37 km from Jakhau Port, Gujarat, exhibits promising conditions for wind turbine development. The wind speed at 100 m above mean sea level averages 7 m/s, which is suitable for harnessing wind energy effectively. The water depth ranges from 10 to 23 m, making it feasible to install fixed-bottom offshore wind turbines, which are cost-effective and widely used in similar depths. Additionally, the site's proximity to the Jakhau Port facilitates an advantage in logistics. With a total area of 1,284 km², this location offers ample space for large-scale wind farm development (Table 1). The short distance to Jakhau Port (37 km) further supports operational efficiency apart from ease of power evacuation, enabling convenient access for construction, transportation, and future maintenance activities.

Geotechnical study

Based on offshore subsurface information, between depths of 40 to 60 meters, the soil transitions from clay to sand, which has a submerged unit weight of 10 kN/m³. Although specific shear strength and friction angle data for the sand layer are not provided, sand typically offers higher bearing capacity and better drainage, making it an excellent base for monopile foundation support. The combined soil profile, with clay in the upper layer and the soil profile at the proposed offshore wind turbine site in Gujarat, with a monopile foundation, indicates favorable conditions for such installations. The upper 0-40 m of the seabed consists predominantly of clay, with a submerged unit weight of 7.5 kN/m³. The shear strength of the clay layer varies between 5 and 50 kPa, providing adequate resistance to lateral loads, essential for ensuring the monopile's stability (Table 2). The friction angle of 30° further supports soil-structure interaction, supporting the resistance to sliding forces. Beneath the sand at greater depths creates a balanced foundation condition for monopile installation, ensuring structural stability and efficient load distribution for the offshore wind turbines (FOWIND, 2018).

Wind resource assessment and cost estimation

The wind speeds observed at Jakhau, as depicted in the wind rose diagram, predominantly range between 7-15 m/s, with occasional higher speeds of 15-20 m/s and a small fraction below 7 m/s. This wind profile aligns effectively with the rated power range of the Siemens Gamesa 3.4-145 turbine, which achieves its maximum output of 3.4 MW at a rated wind speed of 12 m/s that operates efficiently within a wind speed range of 3-25 m/s (Figure 6). The turbine's rated power curve demonstrates a gradual increase in power output starting from the cut-in speed of 3 m/s, reaching full rated capacity at 12 m/s, and maintaining maximum power output up to the cut-out speed of 25 m/s. This performance characteristic ensures the turbine can consistently harness the available wind energy at Jakhau, where the most frequent wind speeds fall within this operational range.

3.4 MW offshore wind turbine has been taken into consideration for cost estimation based on the site's available wind potential. As a comprehensive concept, capital expenditure (CAPEX) includes direct investment costs and the financing, development and operational capital necessary to complete the project. In this study, CAPEX estimations have been made by the reported values of currently operating offshore wind farms, consistent with the methodologies suggested by Dicorato et al. (2011). The estimated cost for a 3.4 MW offshore wind turbine is Rs. 80.784 crores per turbine, which translates to a unit cost of Rs. 23.76 crores per MW.

Table 1. Parameters of the offshore site considered in for feasibility study

Average wind speed at 100 m elevation (m/s)	Water depth variation (m)	Distance to nearest coast (km)	Distance to nearest port (km)	Area (km^2)
7	10-23	34.5	37	1284

Table 2. Gujarat soil profile for spatial analysis

Depth	Soil type	Submerged unit weight (kN/m^3)	Shear strength (kPa)	Friction angle (degree)
0 - 40 m	Clay	7.5	5-50	30
40 - 60 m	Sand	10	-	-

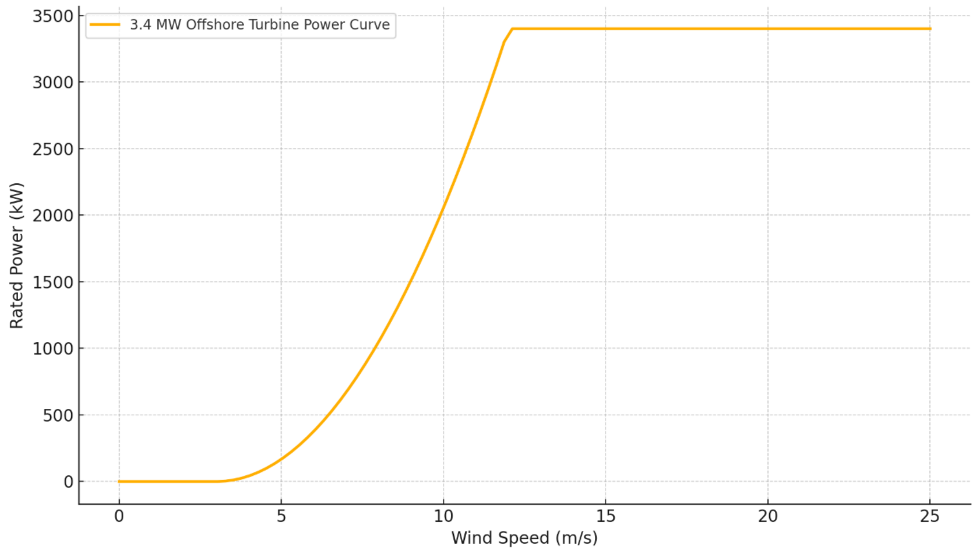

Figure 6. Typical 3.4 MW Offshore wind turbine rated power curve

Table 3. Cost estimation of a 3.4 MW capacity offshore wind turbine for a hypothetical 340 MW capacity offshore wind farm development

S. No	Category	Cost per MW (in crores)
1	Development and project management	1
2	Turbine cost	8.0
3	Balance of plant	5.5
4	Installation and commissioning	6.0
5	Operation, maintenance, and services per year	0.76
6	Decommissioning	2.5
7	Total cost	23.76
Estimated total cost for 3.4 MW offshore wind turbine = 23.76 x 3.4 = 80.784 crores/turbine		

This estimation includes several key cost components: Rs. 1 crore/MW for development and project management, Rs. 8.0 crores/MW for the turbine, Rs. 5.5 crores/MW for the balance of the plant, Rs. 6.0 crores/MW for installation and commissioning, and Rs. 2.5 crores/MW for decommissioning. Operational expenditure (OPEX), which covers operation, maintenance, and other ongoing operational expenses, is often under-reported, resulting in high uncertainty (Table 3). However, it is generally accepted that operation and maintenance (O&M) costs can account for 14–30% of the total lifecycle costs, representing around 50% of OPEX. For this analysis, an annual O&M cost of Rs. 0.76 crores/MW has been assumed based on the correlation developed by Möller et al. (2012). The economic analysis is conducted with an interest rate of 10%, a moderate value consistent with actual rates reported in the literature, and a project lifespan of 20 years, which is the consensus in wind turbine studies. These cost estimates provide a detailed financial framework, crucial for assessing the feasibility and economic sustainability of the offshore wind energy project.

The development of a 340 MW offshore wind farm using 3.4 MW turbines involves the installation of 100 turbines arranged to optimize energy capture and operational efficiency. Following industry standards, turbine spacing is approximately 8-10 times the rotor diameter (10D) along the prevailing wind direction and 3-5 times the rotor diameter (5D) in the perpendicular direction. This spacing minimizes wake effects between turbines, ensuring consistent wind flow and maximizing energy generation.

Economic analysis

The economic viability of the project, such as the installation of the 3.4 MW turbine, is strongly influenced by historical cost trends and current financial metrics like the Levelized Cost of Electricity/Energy (LCOE). The provided chart offers valuable insight into the global trend of LCOE for offshore wind energy from 2000 to 2022, measured in 2022 USD/kWh. The graph shows a clear downward trend in LCOE over the past two decades, reflecting technological advancements, increased scale of deployment, and improved project management practices in offshore wind energy. The cost reductions have been particularly significant since 2014, when the LCOE dropped sharply, making offshore wind increasingly competitive with other forms of energy generation (Figure 7).

From 2018 to 2022, the LCOE for offshore wind energy has stabilized at around $0.08 to $0.10 per kWh. This downward trend aligns with the economic analysis of a 3.4 MW offshore wind turbine in Gujarat, where the LCOE is estimated at Rs. 8.03 per kWh (Table 4). This cost is competitive within the global market, especially considering the complex logistics and environmental challenges associated with offshore wind installations.

The historical data shown in the graph further supports the economic feasibility of offshore wind projects by illustrating that as the industry matures, costs continue to decline, making such investments more attractive. This trend is a crucial factor in the long-term planning and financial forecasting for new offshore wind energy projects in Gujarat or anywhere else. The economic analysis of offshore wind energy must consider both the current LCOE estimates and the historical cost trends, as depicted in the graph, to provide a comprehensive understanding of the financial landscape of offshore wind investments.

Global perspective on offshore wind energy

Offshore wind energy roadmap (IRENA) gives significant growth ambitions, with plans to rapidly scale capacity over the following decades. The Global Wind Energy Council (GWEC) forecasts a rise in offshore wind capacity to 487 GW by 2033, driven by annual growth rates of 24%. Countries like the U.S., U.K. and China, are key players in this expansion. The United States administration has set a target of 30 GW of offshore wind by 2030, with long-term plans for 110 GW or more by 2050 (U.S. Department of the Interior). The global focus is to enhance efficiency, fast permitting processes, improving grid integration, and innovating floating wind technology to tap wind over deeper water (IRENA, 2024). In India, the government has laid a roadmap to install 30 GW of offshore wind capacity by 2030, focusing initially on Gujarat and Tamil Nadu coasts, which have significant wind potential of 36 GW and 35 GW respectively.

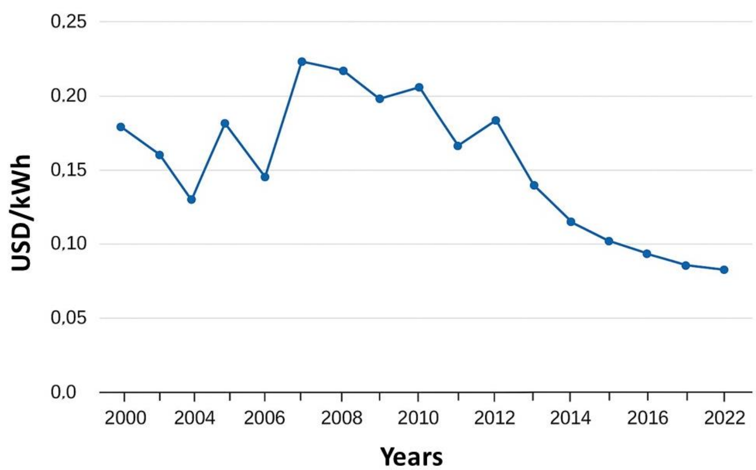

Figure 7. Weighted-average levelized cost of offshore wind generated power from 2000-2022 (IRENA, 2024)

Table 4. Levelized cost of electricity from offshore wind turbines and break-even point

S. No	Description	Value
1	Capital cost	20.50 Crores/MW
2	F O&M	0.76 Crores/MW
3	Time	20 years
4	Number of hours in a year	8760 hours
5	Capacity factor	0.45
6	Interest rate	10%
7	Tariff rate	7 Rs/kWh
LCOE		8.03 Rs/kWh
Break-even point (in years)		10.25 years

India's phased approach includes pilot projects and collaboration with international partners to enhance technical and regulatory frameworks (IRENA, 2024). Floating offshore wind technology is crucial to harness the country's deeper waters, where favorable conditions can vary based on seafloor morphology and project location. According to IRENA's latest data and analysis, in 2022, global offshore wind capacity grew to 63.2 GW, which is a positive development considering the impact that the COVID-19 pandemic had on sectoral activity. However, to comply with a 1.5˚C scenario, the global offshore wind capacity would need to increase to 494 GW by 2030 and 2465 GW by 2050, a target that will not be met with the current pace of sectoral development as well as supply chain constraints the industry has been experiencing. It is also essential to recognize that offshore wind developments have been concentrated in Europe and China. For a just and inclusive energy transition, other emerging economies must also increase their involvement in exploring offshore wind development.

CONCLUSIONS

The present study presents a comprehensive assessment of the feasibility and economic viability of offshore wind farm, developed off the west coast of Jakhau, Gujarat. Critical factors such as bathymetry, wind, tidal, wave conditions, and geotechnical characteristics were thoroughly analyzed to optimize future design and ensure structural integrity. Water depths ranging from 10 to 23 m, combined with hydrodynamic forces, highlight the need for a robust foundation design. Wind and wave analyses indicate favorable conditions for wind energy generation, with consistent wind speeds and moderate wave activity contributing to reliable and efficient power production. Wind speeds between 7 to 15 m/s, occurring 40–50% of the time, fall within the ideal operational range for modern turbines. Tidal studies emphasize the importance of designing turbines to withstand dynamic tidal forces, with fluctuations ranging from -1.5 m to +1.5 m relative to the mean sea level. Wave heights typically range from 2.0 to 3.5 m, with the southwest (SW) direction being the most frequent. The site is 34.5 km from the nearest coast and 37 km from the nearest port, offering logistical advantages. The on-site feasibility analysis confirms that an offshore wind farm at this location is viable. A conceptualized 340 MW offshore wind farm with 100 turbines spaced to industry standards, ensures optimal energy capture and operational efficiency while minimizing wake effects. Financially, the project is promising with an estimated Levelized Cost of Electricity (LCOE) at Rs.8.03 per kWh, in line with global cost-reduction trends. Break-even analysis shows that at a Rs.7 per kWh tariff, the project can break-even in 10.25 years. Given India's rising energy demand and focus on sustainable solutions, this timeline is favorable. With suitable environmental conditions and strong economic prospects, the project represents a key opportunity to support India's renewable energy goals.

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Author Credit Statement

E. Sathish Kumar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing; I. S. Judha Benhur: Conceptualization, Formal analysis, Investigation, Writing – review and editing; G. Dhinesh: Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review and editing; K.Mullai Vendhan: Investigation, Project administration, Resources, Supervision, Validation, Visualization; S. V. S. Phani Kumar: Project administration, Resources, Validation, Visualization.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request.

Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by any of the authors. The authors have followed the ethical norms of publishing. 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. The authors adhere to copyright norms.

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Geothermal energy: A multi-utility energy source

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ABSTRACT

Geothermal energy is the anomalous heat content in the interior of the earth, reported mostly along the plate boundaries, fault zones, volcanic terrains and deep seated igneous injections. Geothermal system is mainly established due to deep circulation of water through conduit zones. Hot water springs and steam emission are the main manifestations of geothermal resources. The geological investigation and exploration by drilling, helps in the development of such resources. The temperature of hot springs may vary from 30 to 97°C on surface. This hot water content is used for generation of electricity, mostly in USA, Japan, New Zealand etc. Geothermal energy being a renewable natural resource with very less carbon emission, is an environment friendly energy source. Besides electricity generation, geothermal resources can be used for direct heat uses like refrigeration, greenhouse cultivation, aquaculture, tourist attraction, spa and bath centers. It is a renewable, 24x7 source of energy, useful to control the pollution and greenhouse effects.

Key words: Hot springs, Renewable energy, Geothermal power plant, Space heating, Greenhouse

INTRODUCTION

The progress of civilization of any country depends on the social and economic growth. The economy is now directly dependent on the energy utilization, so every country is planning to produce maximum possible energy at affordable cost. Though the fossil fuels offer ready to use, convenient source of energy, there are other aspects like high emission of greenhouse gases, leading to global warming and thereby climate change. This warrants substitution of fossil fuels by renewable energy sources which are more eco-friendly. The non-conventional and renewable sources offer an alternate source of energy for power generation, which create less pollution, are user friendly and easily available for utilization.

Wind energy, solar energy, hydropower and nuclear energy have been common renewable energy sources. Besides, biomass energy, tidal energy, solar thermal and geothermal energy are upcoming energy sources which are getting acceptance. Electrical vehicles, hydrogen powered transport system are newly introduced modern energy substitutes. Systematic adoption of renewable energy will help in controlling the greenhouse gases and mitigation of climate change. Geothermal energy is an alternate renewable energy source available round the clock, having low carbon emission.

As the clean electricity supply continues to expand rapidly, the share of fossil fuels in global generation is forecasted to decline from 61% in 2023 to 54% in 2026, falling below 60% for the first time. Global CO_2 emissions from the electricity generation are expected to fall by more than 2% in 2024 after increasing by 1% in 2023. Renewables are set to provide more than one-third of total electricity generation globally by early 2025. The share of renewables in electricity generation is forecast to rise from 30% in 2023 to 37% in 2026 (IEA, 2024). The demand for energy in India is increasing very fast, with estimated demand of 243271 MW by 2024. The installed capacity of power generation is about 434195 MW in 2024 (CEA, 2024). The non-conventional energy sources in India contribute, hydropower 46928 MW, nuclear power 7480 MW, wind energy 45154 MW, solar energy 75576 MW, biomass 10262 MW, waste to energy 584 MW and small hydro 4995 MW to the power sector. The installed capacity of renewable energy sources was nearly 136570 MW in 2024, helping to reduce emission of greenhouse gases (Figure 1).

Geothermal energy is the renewable source of energy which is site specific, mostly located in hilly terrain, hence, can be utilised to fulfill the energy needs of remote areas where transmission of power is rather difficult. Considering the need to augment renewable energy sources, geothermal energy can play significant role in power supply by electricity generation as well as direct heat uses to save electricity. It is a heat source stored in the interior of the earth. The heat stored in rocks is brought to surface by the deep circulation of water moving through the rocks. It is a continuous source of energy as the heat is continuously generated in the interior of the earth and flushed to surface through hot water or steam. Considering the energy mix in power sector of India, geothermal energy has good scope to contribute to power sector in remote area and hilly terrain. Such energy sources are widely distributed along the plate boundaries and structurally disturbed areas. The igneous rocks like granite and basalt can also host geothermal energy sources. Its worldwide power production is about 16127 MW (Thinkgeoenergy, 2024) mostly located in USA, New Zealand, Iceland, Philippines, Japan, Italy, Indonesia, China, Kenya and Turkiye (Figure 2).

Besides electricity generation, upto107627 MW geothermal energy is popularly used to substitute electricity as direct heat uses, particularly in greenhouse, space heating, refrigeration, industrial uses, spa and aquaculture as shown in Figure 3 (Lund and Aniko, 2021).

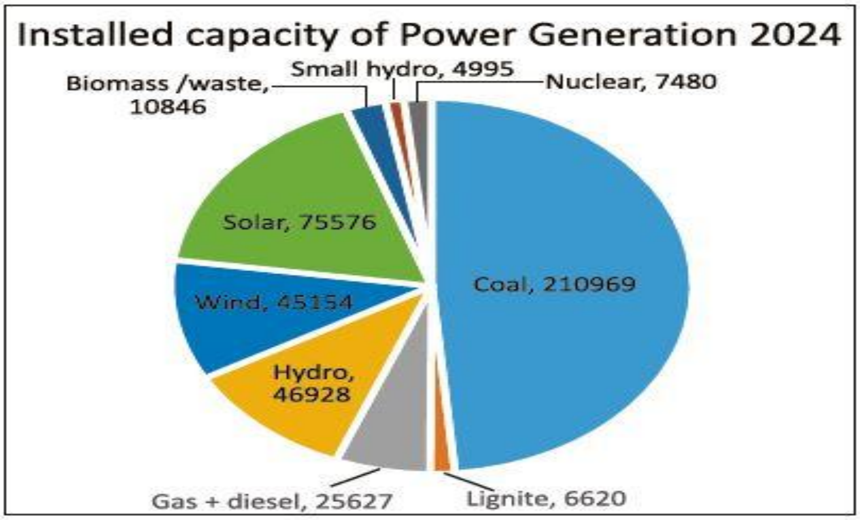

Figure 1. Installed power generation capacity in India (CEA, India)

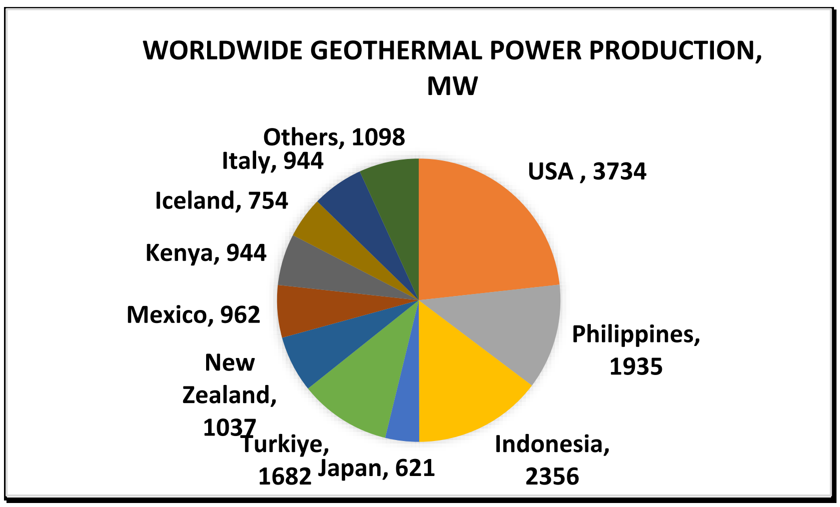

Figure 2. Main countries that are producing geothermal power (www.Thinkenergy.com)

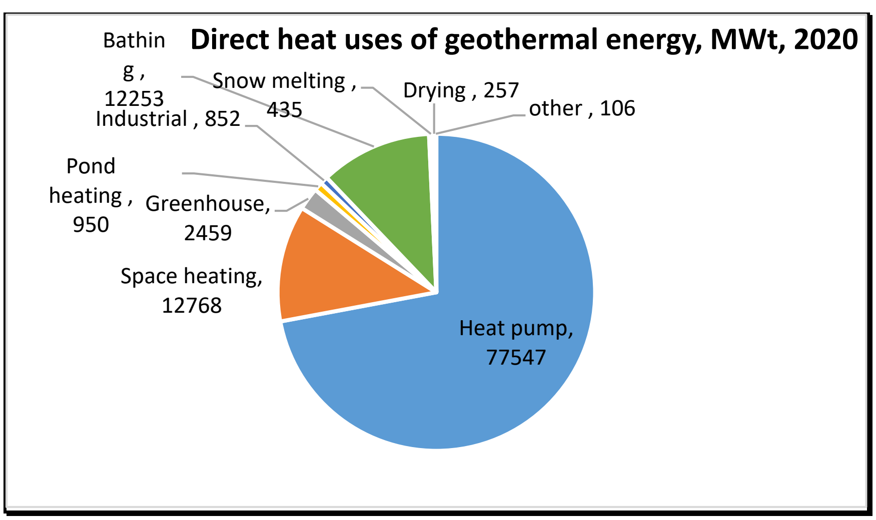

Figure 3. Direct heat utilization of geothermal energy worldwide (Lund and Aniko, 2021)

Geothermal energy is environment friendly as there is no burning of the fuel, and hence, the emission of polluting gases like CO_2, CO, NO_2, H_2S, CH_4 is in less quantity. The IPCC confirmed the environmental friendly nature of geothermal energy. The report on carbon emission of renewable energy sources and climate change mitigation by IPCC, indicated that the carbon intensity of electricity generation is around 1000 g CO_2 equivalent per unit by coal power, 840 g per unit by oil energy, 48 g per unit by solar PV and 45 - 65 g per unit by geothermal power (Figure 4).

Geothermal energy requires exploration to deep level >2000 m depth which is expensive. So the initial cost of geothermal power plant is more than the other solar or wind energy power plants. But it has very less cost on fuel and maintenance, hence in long period of time, geothermal power is also cost effective. A geothermal power plant can produce electricity 24x 7, whereas wind and solar power generation is during particular period depending on availability of the natural resource. Besides, geothermal energy saves cost of storage, as it can be transmitted directly. The estimated cost of geothermal power is around 4 cents /kWh in USA, as shown on X axis in dollars/ MWh (Figure 5). The levelised estimated cost of electricity generation depends on technology used, resource parameters and geographical conditions and it may vary from 80 to 120 US dollars/ MWh (Figure 6) (Cleantechnica, 2016).

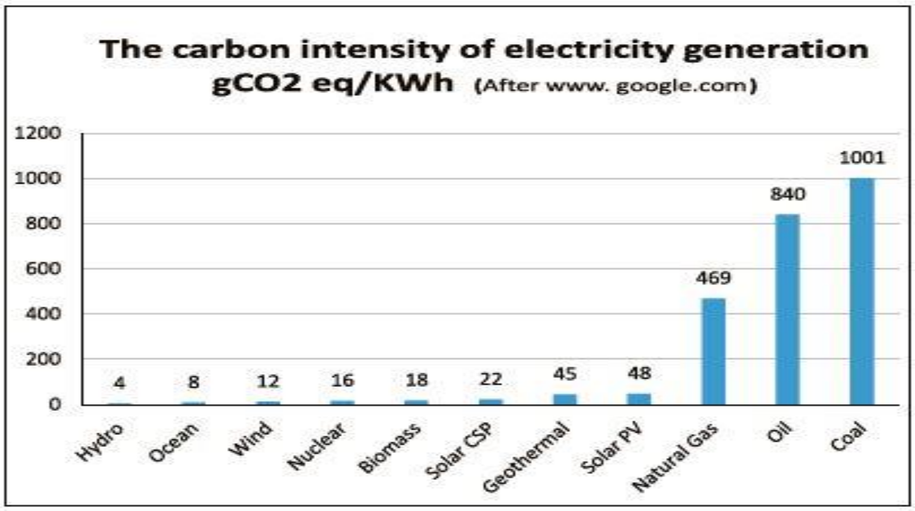

Figure 4. Carbon emission by different sources of energy

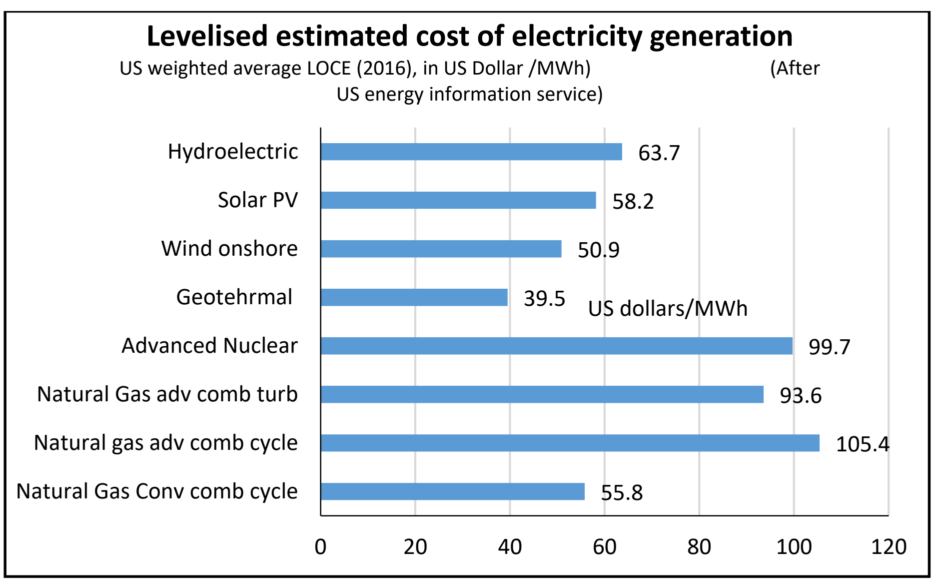

Figure 5. Levelised cost of geothermal power in USA. (US DEO, 2016)

But in India at initial stage the cost may be around 10 cents or more. The cost will substantially reduce with increase in production and availability of indigenous machinery.

The cost of power generation by different energy sources, including the renewable energy sources, indicate that the levelized cost of geothermal power is similar to nuclear energy and biomass energy. The cost of geothermal power depends on the temperature of resource, discharge capacity, method of power generation, and terrain conditions.The cost is inversely proportional to discharge, temperature of resource and capacity of powerplant. The cost of steam based power generation is less than binary cycle power geenration. (Nathwani and Mines 2015). A steam based large capacity power plant may have cost of power generation from 0.04 to 0.10 USD per unit depending on resource temperature (Nathwani and Mines 2015). Thus, geothermal power plants using proper technology and good discharge parameters are commercially viable.

For example, the geothermal power plant at Wairakei, New Zealand, is running for the last 50 years, indicating that the geothermal power is a sustainable energy source. The exploration and power generation of geothermal power resource needs investment at various stages. The general fund requirement for a 200°C resource with 30 MW flash geothermal power plant installation is suggested in Figure 7 (Nathwani and Mines, 2015). The graph on Y axis, shows variation in capital cost of geothermal power plant with base temperature by binary cycle method and flash plant and levelised cost of electricity generation (LCOE) per MWh in US dollars. This indicates that higher base temperature is required for flash plant than the binary cycle method, hence, the cost of power generation based on flash method is marginnaly less than the power generation by binary cycle method. Thus, the cost of electricty generation is controlled by the temperature of the resource and the method of power generation.

The geothermal exploration and power project installation requires funding at every stage of investigation. Geothermal exploration, field confirmation, field completion and power plant installation are main activities requiring major cost input (Nathwani and Mines, 2015). The cost component of various activities in geotehrmal power palnt development, as shown in Figure 8, indicates that the major proportion of cost input is for field devlopment and power plant installation. Hence, the production cost of a geothermal power generation depends on cost of field completion and capacity of the power plant.

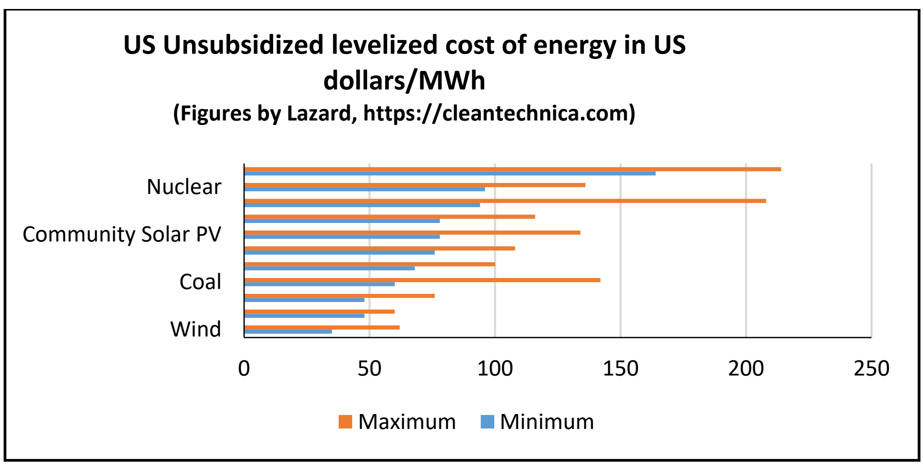

Figure 6. Estimated levelised cost of power generation (after Cleantechnica, 2016)

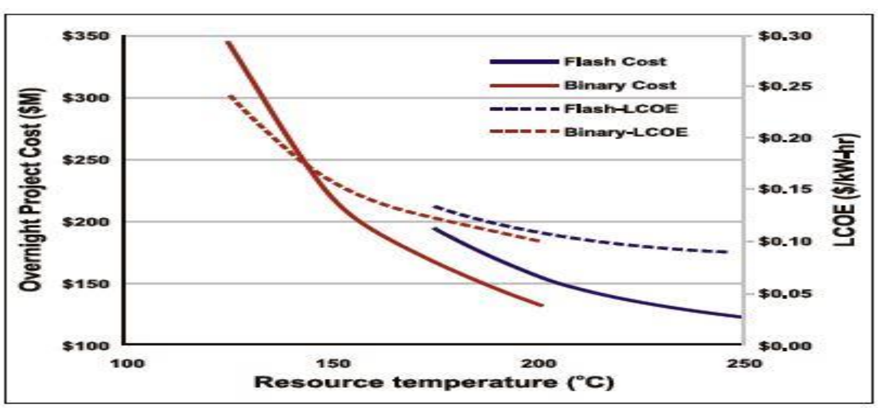

Figure 7. Cost estimation of different methods of geothermal power generation (After Nathwani and Mines, 2015)

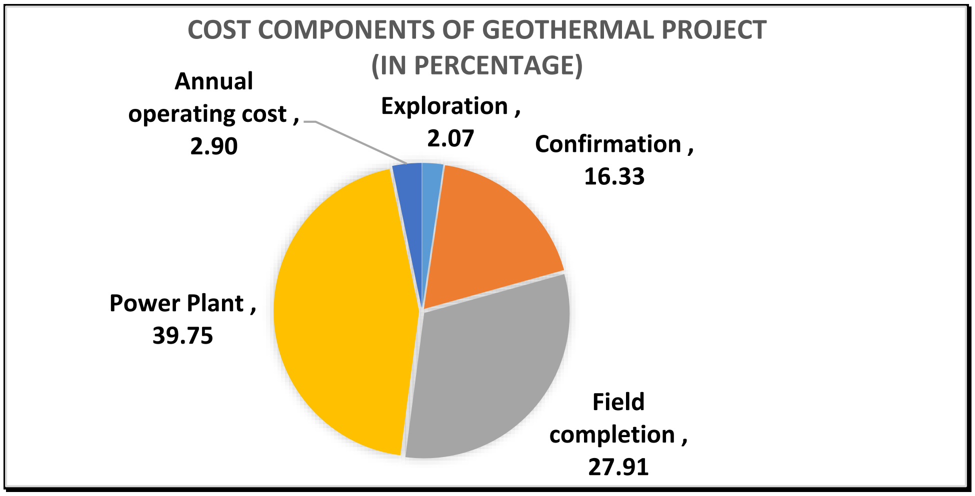

Figure 8. The percentage wise cost of various components in exploration and development (Nathwani and Mines 2015)

GEOLOGY OF A GEOTHERMAL REGION

Most of the geothermal fields are structurally controlled, located along faults, plate boundaries or near volcanoes or active volcanic zones. The rock types may vary depending on local geology. Most common geothermal basement rocks are granite, basalt and sometimes sandstone. Geothermal reservoirs are commonly reported from granites, basaltic lava, calcareous rocks and sedimentary rocks, like sandstones. A geothermal circulation cycle mostly sets in porous and permeable rocks with good inter connectivity. In places where granitic basement or volcanic rocks are present, but a hydrological recharge cycle is not developed due to lack of permeability, the geothermal system is called as hot dry rock geothermal prospect. In hot dry rock system, there is high heat flow without any hot water discharge.

An investigation for geothermal resources involves (i) Geological mapping, topographical survey, petrography, XRD and fluid inclusion study, (ii) Geochemical study, water quality and geothermometry, (iii) Geophysical surveys including MT studies, (iv) Drilling and borehole geology, and (v) hot water discharge, steam content etc. In geothermal exploration, MT method is used for detecting earth layers with different resistivity (or conductivity) of various rock materials and fluids below the Earth's surface (Subbarao et al., 2023).

GEOTHERMOMETERS

The temperature of the hot springs may vary from 30°C to 97°C while the sub-surface reservoir temperature may go 100°C to >250°C. The sub-surface temperature is estimated based on the composition of water. The solubility of quartz with temperature and the equilibrium ratio of Na- K is popularly used to infer the possible temperature of deep geothermal reservoir (Giggenbach, 1997). The content of silica in hot water and Na-K ratio are used to decipher the water temperature as suggested by Fournier (1979) and Giggenbach (1997). It is assumed that the silica content does not vary during up flow and Na- K ratio remains stable in saturated geothermal water. There are other indicators based on Ca-Mg and K-Mg ratio also. Besides this, alteration, mineral content, fluid inclusion study and gas analysis is also used to infer temperature of geothermal reservoir. The actual temperature at reservoir can be finally verified by drilling to the desired depth.

GEOPHYSICAL SURVEY

Geophysical survey is a useful tool to decipher subsurface configuration of rock types and structure which can give inference about water bodies also. Resistivity and magneto-telluric surveys are mainly used methods in geothermal investigation. Geophysical methods try to measure relative variation in following properties of the rocks.

1. Density- Gravity method
2. Magnetism- Magnetic survey
3. Seismic susceptibility- Seismic survey
4. Electrical properties- (i) Self-potential survey, (ii) Resistivity Survey, (iii) Magneto-telluric survey, and (iv) Borehole logging

RESERVOIR CONFIGURATION

The preparation of planar and 2D / 3D section of geothermal resource is part a of reservoir configuration. Geological data, lithology, structure, topography and drainage pattern, geophysical survey interpretation, temperature data, available sub-surface data are taken into consideration to prepare reservoir configuration. Based on these data, surface area of geothermal anomaly is marked, coupled with sections prepared with geophysical inferences and thermal gradient data that help in suggesting the reservoir configuration.

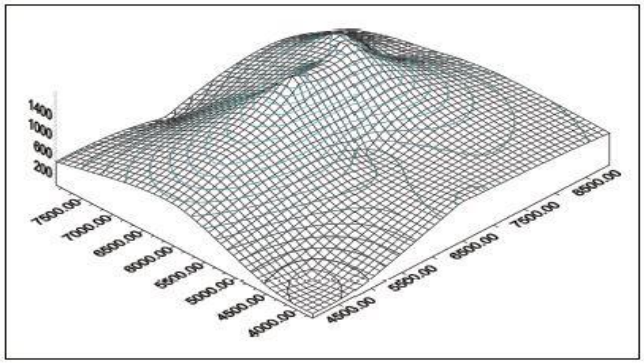

Figure 9. Surface configuration of 100°C isotherm at 1500 m depth, Tatapani geothermal field, (Chhattisgarh, India)

Figure 9, depicts a possible surface configuration of 100°C isotherm interpreted based on thermal logging and bore bole data suggesting a conical structure with peak near Tatapani village, Chhattisgarh, while the outward slope of isotherms indicate that the geothermal reservoir continues to a depth below 1500 m (Sarolkar et al., 1999). Exploration for geothermal resources is planned considering the reservoir configuration, and sub-surface characters.

POWER GENERATION METHODS

The type of power generation method is decided based on discharge temperature, steam content and flow. A plan is prepared for effluent water discharge or reinjection. A closed cycle production plan ensures good recharge of reservoir, less loss of resource and less environmental pollution. Geothermal power uses heat stored in water to generate electricity. In geothermal resource of high temperature > 200°C, the power generation is similar to steam turbine where steam separated from water is used to drive the turbine. This is called steam based geothermal power plant. In high temperature resource areas, depending on temperature, the water is flashed one or two times to separate the steam. This is called as single flash and double flash geothermal plant. The steam based geothermal plant generally has higher efficiency of power generation. When the temperature of geothermal resource is <180°C, the heat in water is used to vaporize an organic liquid of low boiling point. This organic vapour is used to drive the turbine. This method is called as Binary Cycle power plant. In binary cycle method, the efficiency of power generation is less as compared to steam turbine, and have relatively more cost of production.

FUNDING NEEDS

Geothermal exploration is an expensive activity because the drilling requires heavy machinery for drilling boreholes >2000 m deep, to control hot water flow and completion of production well. Besides cost of exploration and field preparation for steam production, the power plant costs are similar to steam based power plant while the binary cycle power plant has less output hence may require more cost of production. In geothermal power plant, the cost of hot water or steam is much less but the cost of exploration and power plant combined makes the project expensive. Considering this, initially the project looks expensive inhibiting the investors to consider it as a business proposal. Thus, funding for geothermal development is a major issue. This requires a firm policy regarding incentive for exploration and investment through public private partnership and FDI through international co-operation. (Sarolkar, 2015).

ENVIRONMENTAL ASPECTS

The best environmental policy consists in preventing the creation of pollution or nuisance, at the source rather than subsequently trying to counteract the effect. Pollution by substances which are capable of causing harm to man or any other living organism supported by the environment has to be controlled. Similarly, the greenhouse gas emission has to be checked to avoid adverse effect of climate change. Geothermal energy is clean energy as it causes much less pollution as compared to fossil fuels. The gas emission from geothermal energy comprises H_2O, CO_2, CH_4, NO_2, H_2S, H_2, Argon and Helium. CO_2 emission of geothermal power is around 65 mg /kwh compared to the CO_2 emission from 950 mg/kwh by coal based power plant (www.IPCC,ch).

Thus, use of geothermal energy is a good tool to arrest greenhouse gas emission. Besides gases, the water quality has to be monitored to avoid adverse effect on local environmental. The geothermal water contains mostly Na, K, Cl, HCO_3, SO_4, which needs to be monitored during production to avoid corrosion effect in turbine and production line. The water composition of some geothermal fields in India, given in Table 1, shows the hot water of Tatapani Chhattisgarh, Chumathang Ladakh, Manuguru Telangana, and Bakreshwar West Bengal are mostly sodium- bicarbonate type, while the Tural hot spring is sodium- chloride type. The hot water composition is suitable for industrial production purposes.

Table 1. Water composition of some geothermal fields in India

	WHO limit (Lund and Herbert, 1971)	BIS limit ppm (CPCB, 2019)	Tatapani geothermal field (Borehole 23, 1996) (Sarolkar and Mukhopadhyay, 1996)	Chhumathang geothermal field (GSI, 2022)	Manuguru geothermal field, borehole MGR-4, (Sakhare et al., 2020)	Bakreshwar Geothermal field, WB/123, (GSI, 2020)	West Coast, Tural hot spring, (GSI, 2020)
pH	6.5 to 9.2	6.5 -8.5	8.6	8.1	8. 4	7.8	7.5
Conductivity @25°C	1400	1400	642	1491	641	769	1445
CO3 ppm	-	300-600	16	76	52	NA	NA
HCO3	-	--	151	398	327	292	54
Cl	600	1000	72	95	32	86	365
SO4	400	400	65	225	15	30	70
Ca	200	200	2	16	13	67	47
Mg	150	100	1	2	5	22	2
CaCO3	500	400	8		52	262	122
Na	--	--	125	250	148	48	271
K	-	--	11	2	10	9	11
B	--	1	0.5	31	NA	NA	NA
F	1.78	1.5	16	10	1.2	0.8	2.01
As ppb	0.05ppm	.05	<10	NA	NA	NA	NA
Hg	0.002ppm	0.001	NA	NA	NA	NA	NA
SiO2	-	--	118	87	60	43	70
TDS	1500	2000	520	1010	320	385	725

The geothermal exploration and development may have some effect on terrain conditions, physiography and ground water conditions. The following effect can be observed in geothermal areas.

PHYSICAL ENVIRONMENT

Geothermal manifestations

Continuous flow from hot sprouts cause a large area into a marshy land. The marshy patches are observed near hot springs and borehole discharge create stretches of waste land showing patches of secondary deposition and sometimes hot ground.

Ground subsidence

In the hard rock area like granite, granite-gneiss and biotite gneiss, the ground is stable but in sedimentary rocks continuous production of hot water may cause ground subsidence locally. Continuous flow of the thermal water opens up the channels and fractures in the boreholes. The breccia zones cause caving and block the bore wells with loose pebbles and debris.

Drainage

Generally the geothermal plant does not require clearing of land except for power station. Hence, there is less damage to the landscape and drainage. It is necessary to monitor any effect on ground water table.

Noise

A typical noise exposure level is 85dBA for an average day of 8 hours with a peak level of 140 dBA (Cleantechnica, 2016). The noise level of the turbine and separator of effluent water may locally cause inconvenience to humans.

CHEMICAL ASPECTS OF ENVIRONMENT

The effect of pollution can be judged by the content of contaminants in the water e.g. arsenic, fluorine, mercury, calcite and silica. The damage to organism and environment may be minimized by maintaining the composition of the chemicals in water within the limit of human tolerance and industrial parameters.

Calcite scaling

Calcite scaling is a major problem in geothermal fields e.g. Kizildere, Turkiye and Te Aroha, New Zealand. Calcite or aragonite is deposited in the wells at the level of first boiling (Arnorsson, 1989) causing blockage of boreholes and large areas of white terraces near hot springs as observed in Yellow Stone Geothermal field, USA.

Silica scaling

Silica precipitation is a major problem in high temperature geothermal fields. The silica is deposited around hot springs and may also deposit in boreholes blocking the boreholes.

WATER COMPOSITION

The thermal water contains moderate amount of Cl, SO_4, Na, HCO_3, SiO_2, while K, Ca, Mg, B are low in content. Arsenic is mostly within permissible limits while fluorine content may be high. If released into a river or lake, these contaminants may cause damage to aquatic life, plants or humans, hence the need for an environmental impact assessment (Webster and Timperley, 1995). High values of TDS in geothermal water sometimes interfere with the usefulness of water as source of energy (Srivastava et al, 1996). According to the Intergovernmental Panel on Climate Change (IPCC), geothermal energy source is recognized as a competitive energy source (with a carbon footprint around 50 gCO2eq/kWh over its lifetime) compared to conventional energies such as coal or oil (with a carbon footprint around 800 g CO2 eq/kWh) (Marchand et al., 2015).

Fluorine

The fluoride content in thermal water may be high and if used for irrigation, may cause harm to the ecosystem. Fluorine content of 0.7 to 1.5 ppm is acceptable for drinking water (Deshmukh et al., 1995). Solubility experiments carried on fluorite in distilled water by Ramamohana Rao et el. (1993), revealed that addition of Ca ions to solution in contact with fluorite caused decrease in fluorine concentration.

Arsenic

Arsenic released into the river may be embedded in plants and sediments. Excess intake of arsenic is poisonous and carcinogenic to humans (Chanlett, 1973). Hence, it is desirable to remove arsenic from effluent water by bio-degradation processes.

Boron

Boron is present in geothermal water in small quantity around 1 ppm and 0.5 ppm in Tatapani, Chattisgarh. Sometimes the water contains high boron as in Puga Ladakh, which is extracted as a byproduct.

Mercury

Mercury readily combines with chloride, iodide and bromide or may be present as a mercurous ion in thermal water. Mercury may occur in steam fraction also. Hg can bind to carbon and may accumulate in the food chain. Hg has tendency to accumulate through the food chain (Webster and Timperley, 1995), hence it is necessary to monitor Hg in water.

GASEOUS CONTENTS

H_2S

H_2S occurs in a dissolved and gaseous state in thermal water. The dissolved H_2S is oxidized rapidly in the presence of oxygen to colloidal sulphur as observed in a few springs at Tatapani (Shivastava et al., 1996). The dissolved H_2S needs to be treated for extraction of native sulphur which may improve taste and odor of the water and reduce corrosion of installations.

CO_2

CO_2 is the most common gas in geothermal exhausts. Besides causing carbonate scaling in bore wells, CO_2 is highly toxic for humans and cattle. The CO_2 is colour less and odour less, heavy gas which accumulates in pits and depressions. Though less in quantity, it is essential to monitor regularly at the geothermal site to avoid the CO_2 accumulation.

UTILISATION

The most important use of geothermal energy is power generation. Besides power generation, geothermal energy is used for many other ancillary uses depending on the local conditions. The effluent water from power plant or hot water with low temperature is used for substitution of conventional energy sources for industrial purpose. The important uses of geothermal energy are discussed below (Lindal, 1973).

Binary cycle power plant (Temperature 140°C to 100°C)

In binary cycle power plant, the hot water is used to vapourize a fluid of low boiling point, which is used to generate electricity. The water and working organic liquid flow in separate closed loops so that there are no or little air emissions (US DOE, 2016). At Hussavik, geothermal heat utilization, 90 l/s hot water of 125°C with outlet temperature of 80°C, was used for generation of electricity by binary cycle power plant (Eliasson, 2001). Geothermal power plants come small (300 kW to 10 MW), medium (10 MW to 50 MW), and large (50 MW to 100 MW and higher) sizes. A geothermal power plant usually consists of two or more turbine generator ‘modules’ in one plant. Extra modules can be added as more power is needed (DOE, 2004). As such geothermal power production can be modified as per the demand.

Refrigeration and cold storage (80°C to 180°C)

This is a very popular use of geothermal water by ammonia absorption or isobutane method or using similar organic fluids. The geothermal energy is used to substitute part of the electricity required for refrigeration. Geothermal heat pumps (ground-water and ground-coupled) have become popular in the U.S. and Switzerland, used for both heating and cooling.

An example of space heating and cooling with low-to-moderate temperature geothermal energy, is the Oregon Institute of Technology in Klamath Falls, Oregon. In addition, a 541 kW (154 tons) chiller requiring up to 38 L/s of geothermal fluid used to produce 23 l/s of chilled fluid at 7°C to meet the campus cooling base load (Boyed, 1999). Dholera Swaminarayan Mandir is the first to utilize geothermal energy for air conditioning and cooking. The 50°C hot water is also used for bath (Deshgujarat.com, 2016).

Snow melting (Temperature <80°C)

The sprinkling of groundwater over roads or circulating groundwater in heating pipes embedded in the pavement are popular methods in areas which are not much cold. As for the utilization of geothermal heat, the outflow hot water from spas, has been used in the same manner as groundwater for snow melting (Morita and Togo, 2000).

Space heating (Temperature >60°C)

Space heating is most popular use of hot water. Hot water is circulated through specially designed pipes in a building for heating purpose. Geothermal energy is used in Kamath falls, USA and Tianjin,China for space/ house heating substituting large amount of electricity. Heat pump systems use groundwater aquifers and soil temperature typically in the range of 5-30°C. The extensive use of geothermal heat pumps for heating and cooling of buildings in North America and Europe is a relatively recent development (Roy and Sarolkar, 2022).

Soil warming (Temperature >40°C)

Warm water is used for soil warming in cold climate, to improve water flow and water retention in the soil. The soil warming helps in improving agricultural output. Geothermal water of low temperature, is used for soil warming and snow melting in cold terrains. The heating coils are filled with working fluid consisting of a glycol water mixture. The geothermal energy is supplied to heating system through the use of pipes, directly from circulating pipes, through a heat exchanger or by allowing water to flow directly over the pavement. The benefit of this system is that they eliminate the need for snow removal, provide greater safety for people and vehicles, and reduce the work of slush removal (Lund, 2000).

Industrial uses (Temperature 80°C-180°C)

The hot water can be used for digestion in paper mill, cement block curing, drying of vegetables, metal part cleaning, fish drying, wool processing and timber washing (Lindal, 1973), depending on the temperature. One of the first was Bloteca, a construction block factory that started using geothermal steam in curing process of concrete products. At Agrioindustrias La Lagnna, a fruit dehydration plant was set up as an experimental and demonstration project (Merida, 1999).

Aquaculture, agriculture and crocodile farming (Temperature <60°C)

The hot water is used to keep the water conditions congenial for crocodiles and fishes by regulating the temperature. Geothermal heat allows better control of pond temperature, which optimizes growth of fishes. The use of geothermal energy for raising cat-fish, shrimp, tilapia, eels, and tropical fish has produced crops faster than by conventional solar heating. Using geothermal heat allows better control of pond temperatures (Lund and Aniko, 2021). In vegetable dehydration process of onions, garlic, geothermal water flowing through heat exchanger warms the air to temperature ranging from 38°C to 104°C, which is blown over the sliced vegetables as they proceed along a conveyor belt (www.ThinkGeoenegry). In fact, the cost of dehydrating fruits by geothermal source is 15 -25% of the cost by using conventional energy (Lund and Rangel, 1995). In Utah, during winter, the geothermal water keeps the temperature in greenhouse space at about 21°C, even when outside temperature drops below freezing point. Fog cooling and ventilation system help maintain a moderate temperature during summer when outside temperature can reach 35°C (Lund and Rangel, 1995). Most greenhouse operators estimate that using geothermal resources instead of traditional energy sources, saves about 80 percent of fuel costs and about 5 to 8 percent of total operating costs (DOE, 2004). Milk pasteurization with geothermal energy has been tried at two locations, Klammath Falls, Oregon and Oradea, Romania. A geothermal water of 87°C was pumped into the building and through a 3 plate heat exchanger, to heat cold milk at 3°C to a temperature of 78°C, at the rate of 0.84 l/s (Lund, 1997). Besides electricity, geothermal heat can be utilized for dehydration of agricultural produce. Dehydrated agricultural products have a high export potential supporting the economic structure of the country as well as the rural population that depend on the agricultural income (Chandrasekharam, 2001a).

Tourism, spa and swimming pool (Temperature >40°C)

The hot water with controlled temperature is used in bathing tanks, spa and swimming pools. Bathing centers and skin care centers are popular tourist attractions. In India, geothermal water has been used for bathing purposes at Ganeshpuri, Thane, Tural, Ratnagiri, Yamunotri, Ganganani, and Badrinath in Uttarakhand. A very popular tourist place has been developed at Tatapani, Chhattisgarh and Chhumathang in Ladakh. More than 200 resorts and spas in the United States offer their guests the use of hot springs for bathing, swimming, or therapy. Geothermal water has been used for recreational purpose since long time.

Extraction of rare metals and mineral water industry (Temperature >30°C)

Geothermal water contains many rare metals like lithium, cesium and helium (Chandrasekharam, 2001b), and also borax which needs to be recovered as byproduct. Similarly, sulphur, calcite and borax are easily recovered from geothermal springs. The inert gases like nitrogen and helium are also recovered from geothermal discharge.

Desalination of water

In areas of water scarcity, the geothermal energy can be used for desalination purpose. Geothermal wells deeper than 100 m can be used for desalination, but the use of geothermal energy for thermal desalination requires cheap geothermal resource and decentralized applications focusing on small-scale water supplies in coastal regions, provided that the society is willing to pay for desalting (Goosen et al., 2010). The direct geothermal brine with temperature up to 60°C can be used in desalting by adopting membranes distillation technology (Gryta and Palczynski, 2011). The desalination of geothermal water using membrane distillation is a feasible process.

CONCLUSIONS

Geothermal energy is a natural source of non-conventional energy, useful for generation of electricity and ancillary uses. Geothermal power plant technology is a proven technology which is being utilized in developed counties like USA, Japan, New Zealand. The geothermal prospects can be used for industrial applications to substitute conventional sources of energy. The geothermal resources in India are poised for development now, contributing to the power sector in Himalayan belt, and interior parts of the country as an alternative energy to substitute the electricity in projects like cold storage, green house cultivation, aquaculture and for tourist attraction places, contributing to improve local economy. Government of India may encourage installation of demonstration geothermal power plant as a show case for feasibility of geothermal resources for utilization as a sustainable energy source.

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Author Credit Statement

Conceptualization, data collection and manuscript writing

Data Availability

No new data was generated for this study

Compliance With Ethical Standards

Author declare no conflict of interest and adhere to copyright norms

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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.

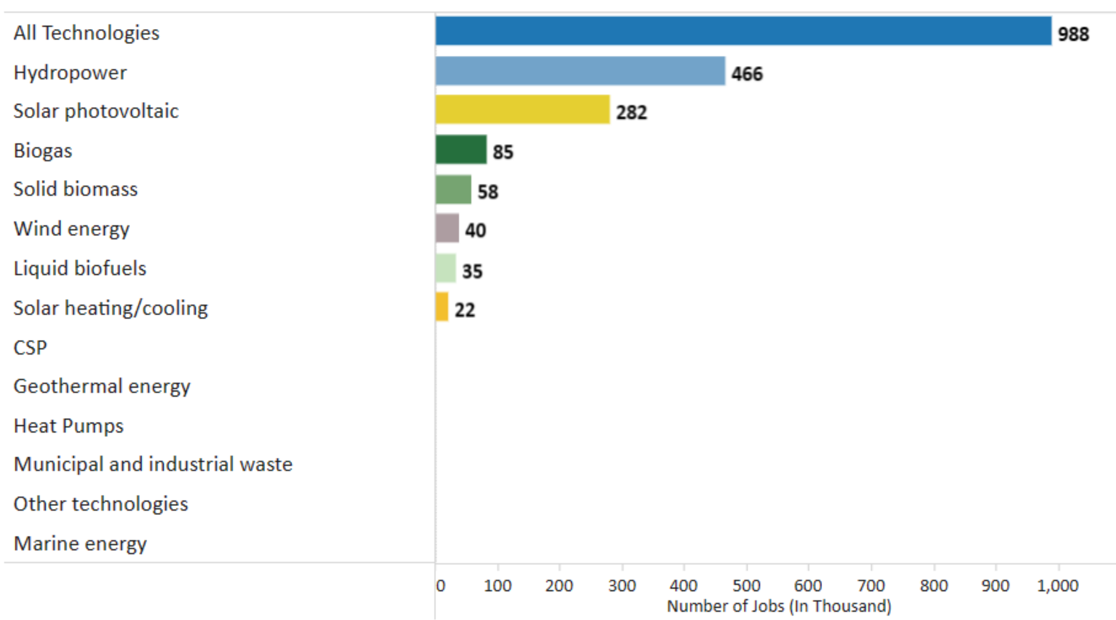


Figure 1. Renewable energy employment by technology in India in 2022 (source IRENA)

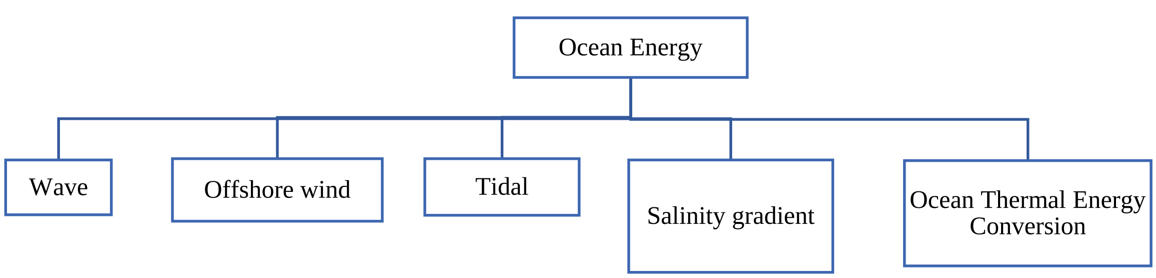


Figure 2. Different forms of Ocean energy at the global level

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

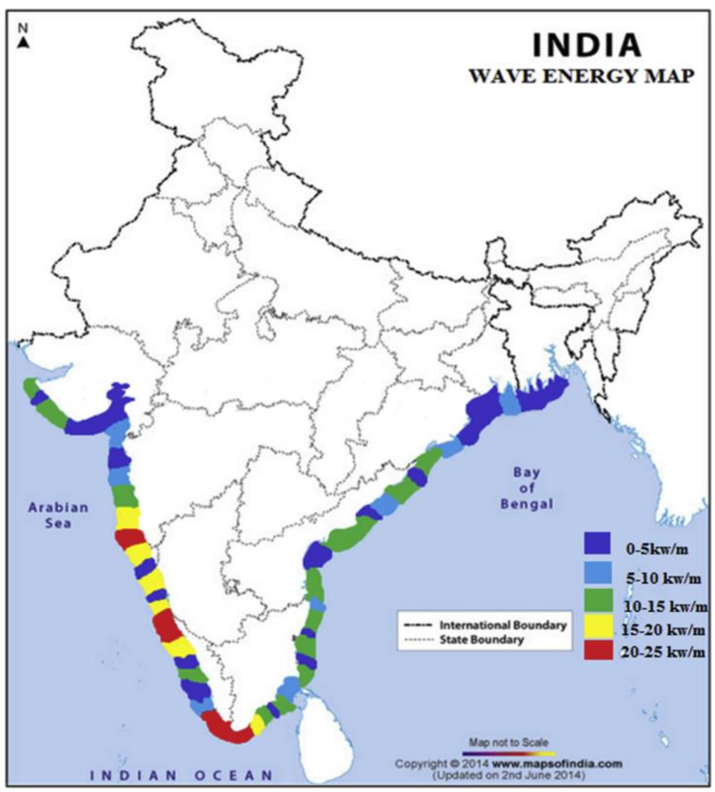


Figure 4. Wave energy map for India (Sannasiraj and Sundar, 2016)

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

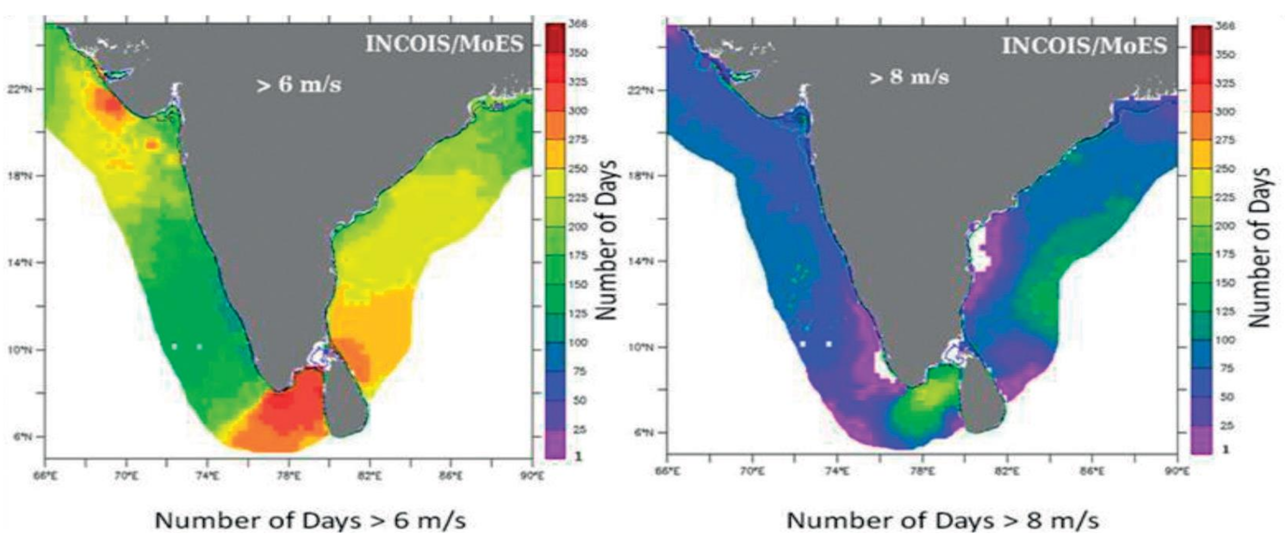


Figure 5. Offshore wind potential maps for the Indian coast (8˚4′ N to 37˚6′ N and 68˚7′E to 97˚25′E) by Earth System Science Organization (ESSO)-INCOIS (Alluri et al., 2018).

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.

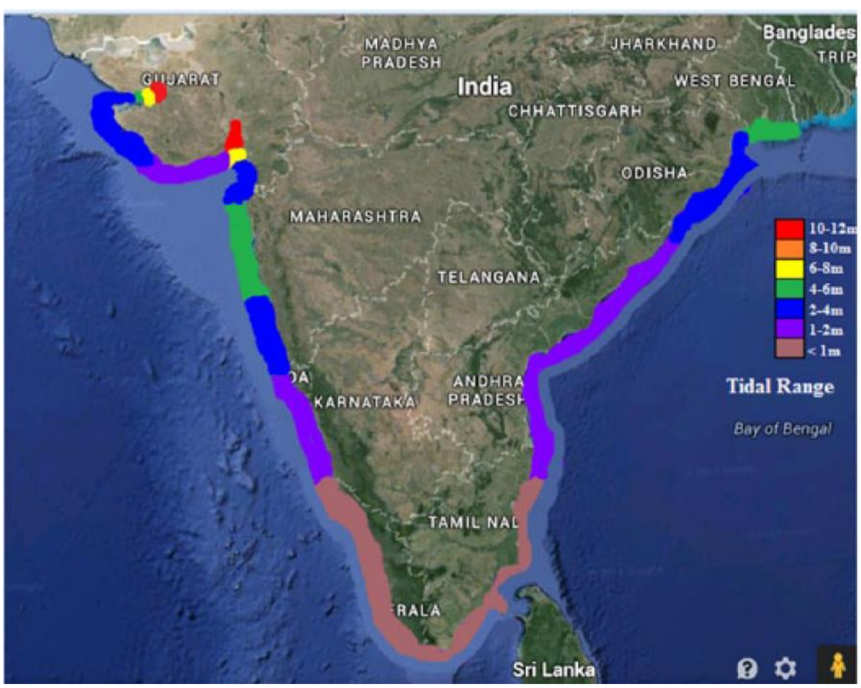


Figure 6. Potential tidal energy sites in India (Murali and Sundar, 2017)

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.

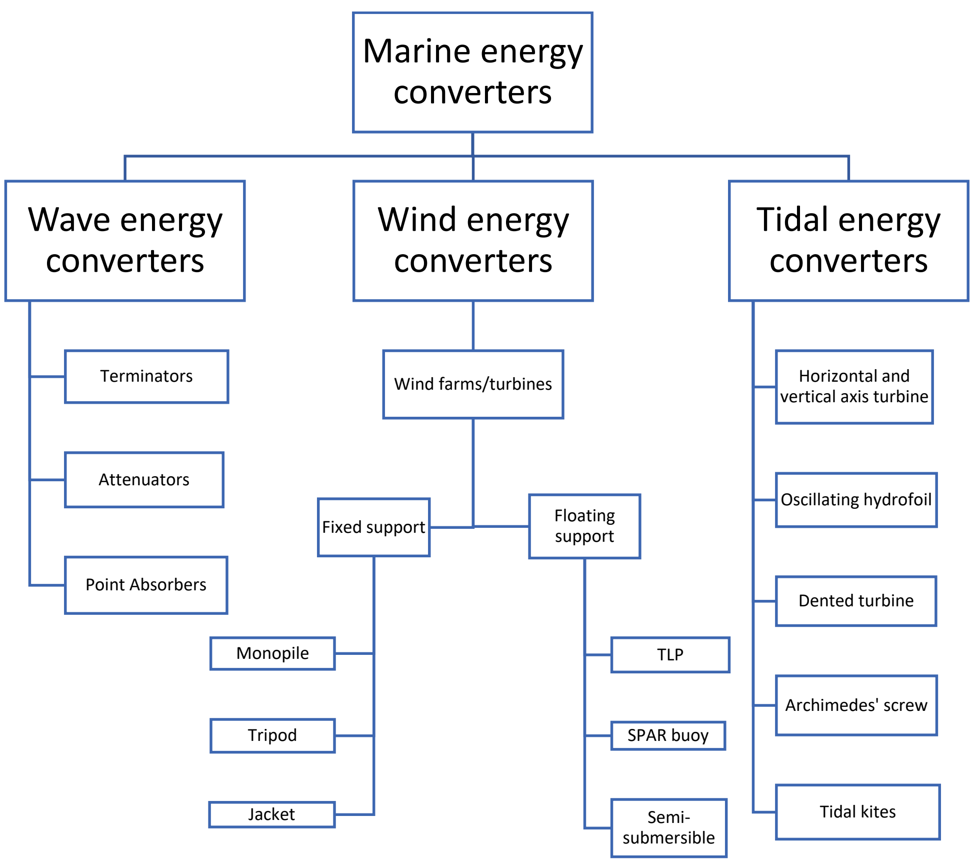
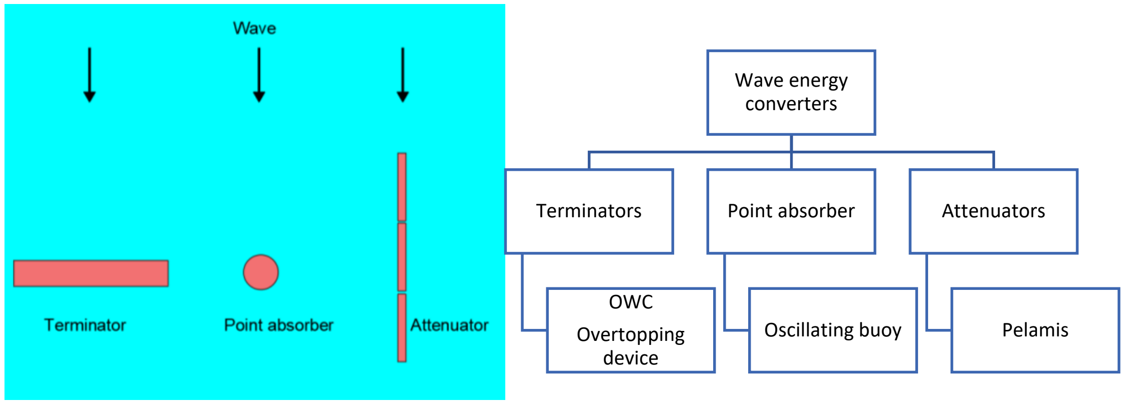


Figure7. Flow chart on different marine energy converters



(a) (b)

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)

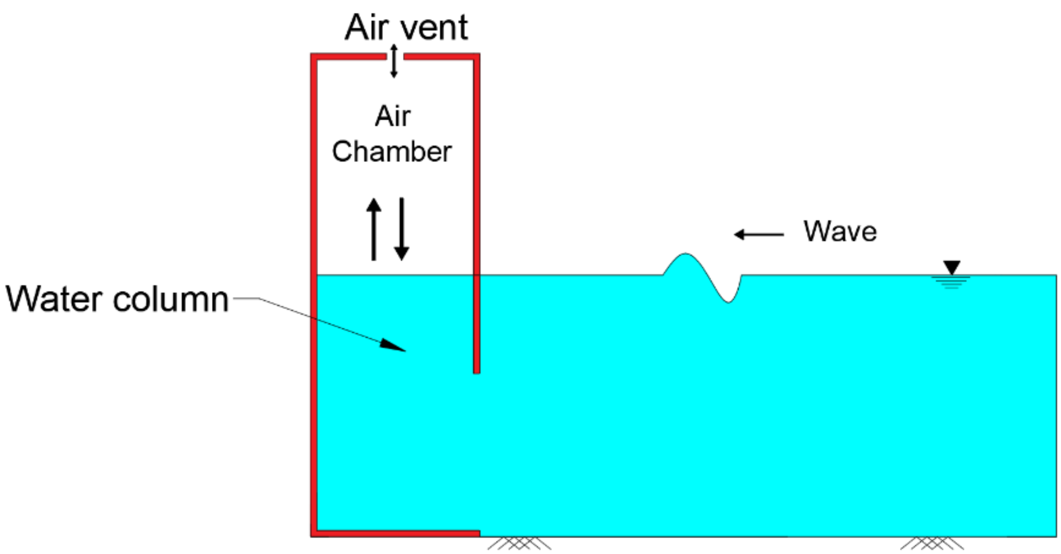
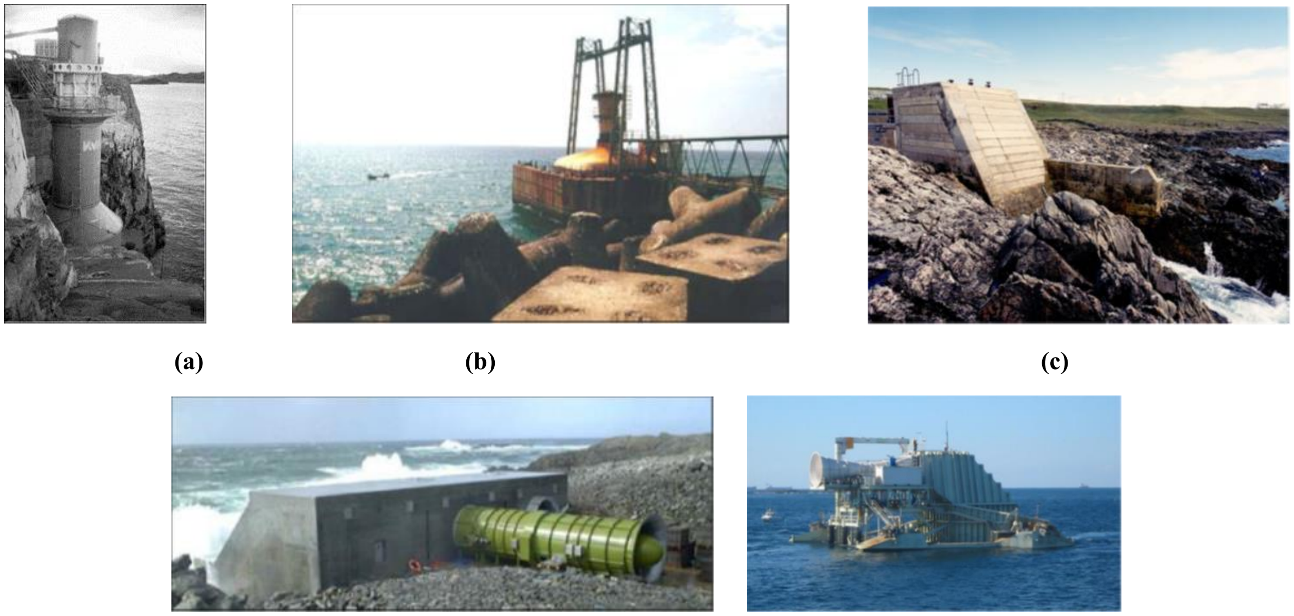


Figure 9. Principle of working of Oscillating Water Column device (OWC)

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.



(a) **(b)** **(c)**

(d) **(e)**

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

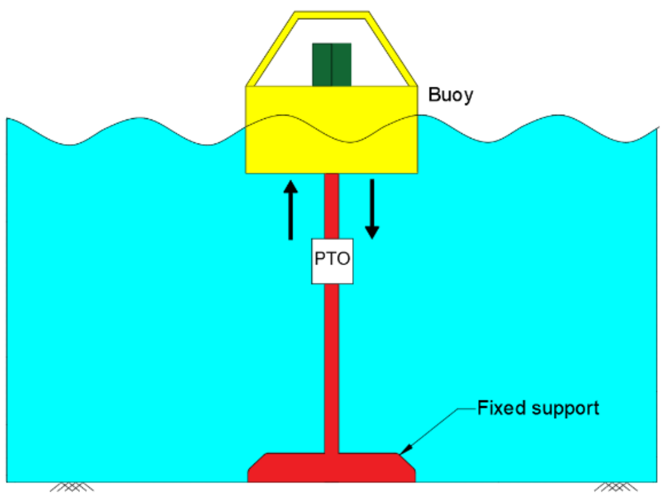


Figure 11. Point absorber/oscillating buoy

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).

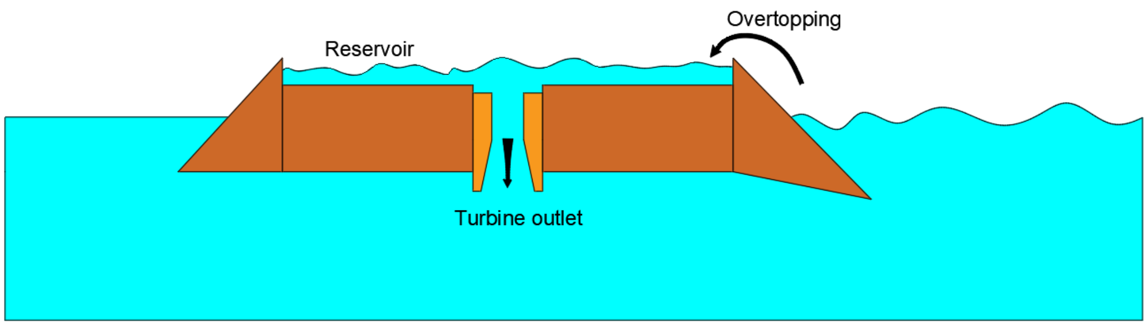


Figure 13. Overtopping device

(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.

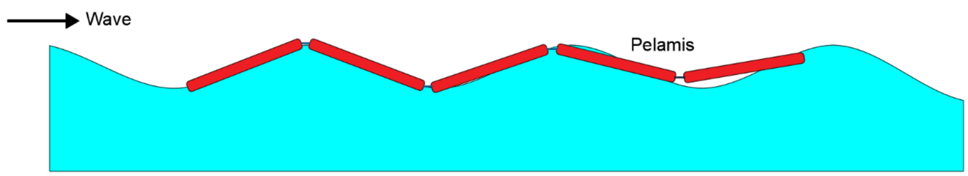


Figure 15. Pictorial view of the series of Pelamis wave energy converters on the sea surface

(a) **(b)**

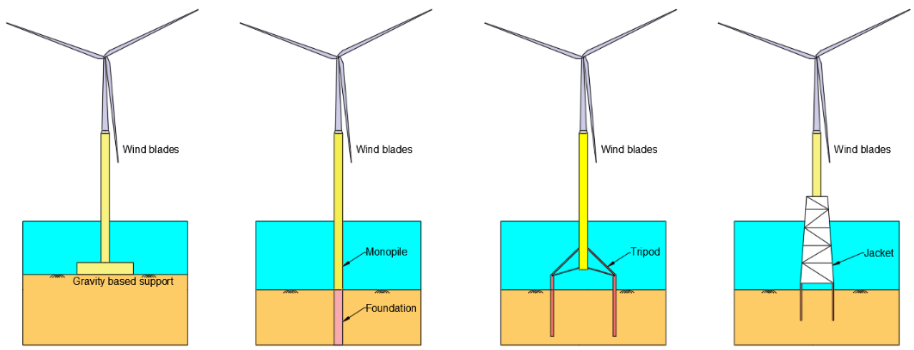
Figure 16. Case study on Pelamis WEC. **(a)** Pelamis (UK) (Bray et al., 2014). (**b**) Pelamis (UK) (Artal-Sevil et al., 2018; Zhang et al., 2021)

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

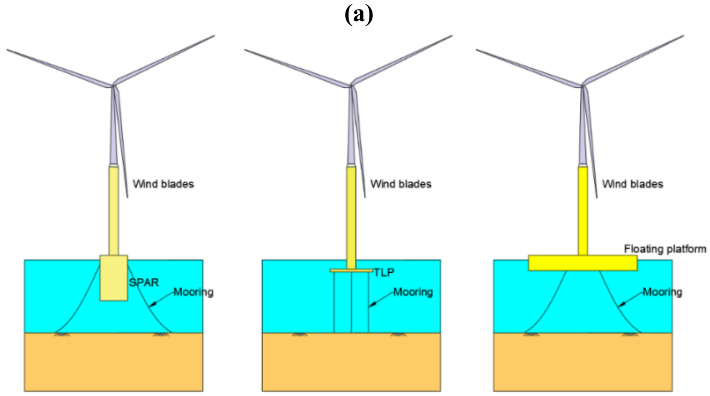
Location	Capacity (MW)	Wave height	Tidal	Technology	Cap Ex.	Status
Vizhinjam	0.15	2-4 m	0.6 m, 0.5 m/s	OWC, Horizontal axis turbine	Euro 2 million / MW	Decommissioned
BBDB	0.05	3 m	-	Floating OWC, BD turbine	-	Demonstrated
OWC integrated with coastal structures	IIT Madras has carried out several physical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

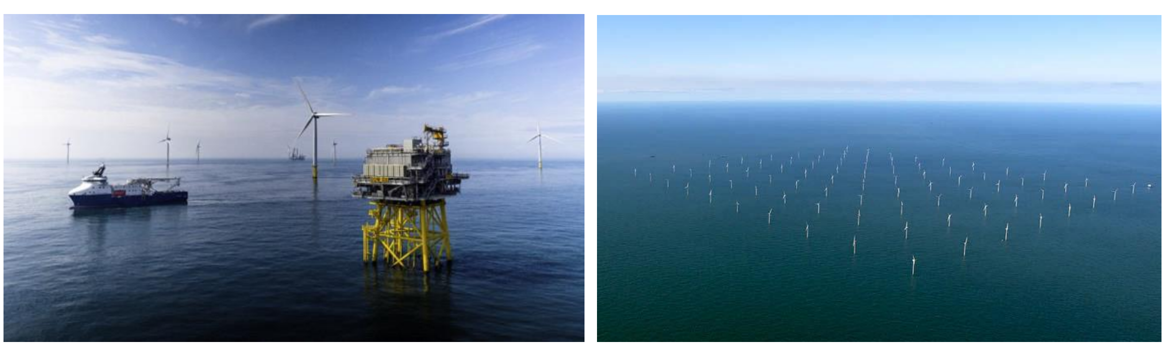


(a)



(b)

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



(a) **(b)**

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

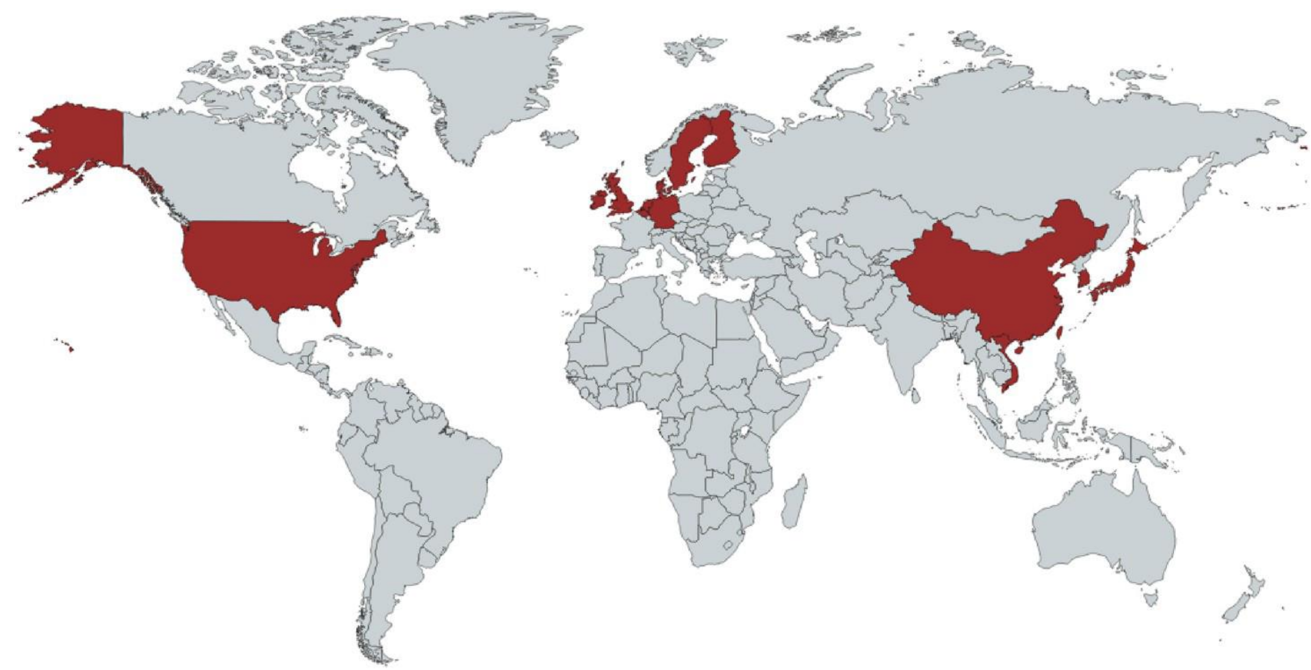


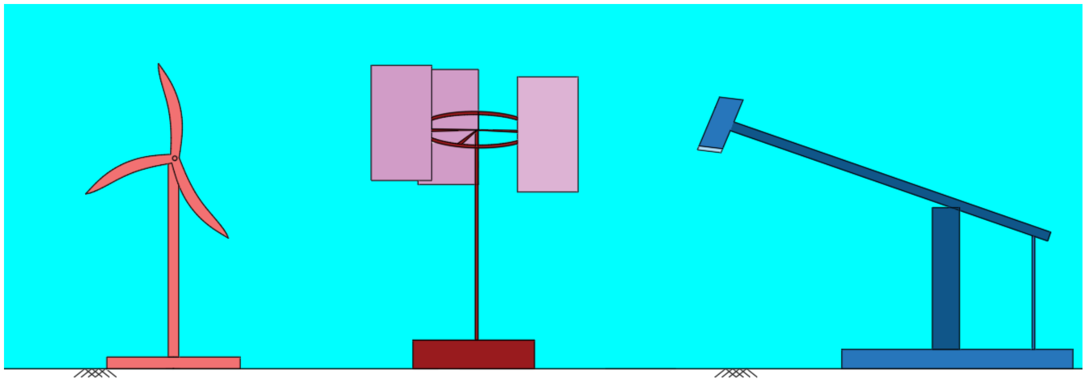
Figure 19. Global distribution of offshore wind farms by countries (Diaz and Soares, 2020)

Case study on wind farms worldwide

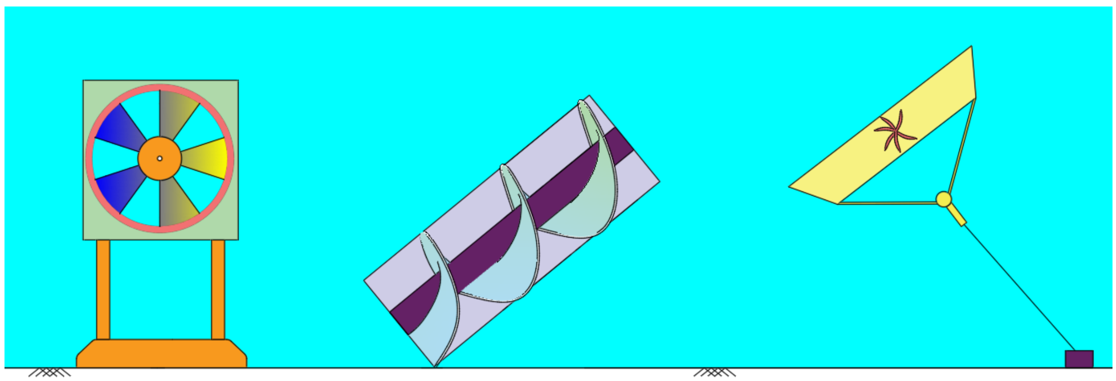
The global wind farm usage for harvesting marine energy is shown in Table 2. Diaz and Soares (2020) depicted the global distribution of offshore wind farms in Figure 19, which shows that Europe, Asia, and the American continents are focused on offshore wind energy conversion. Being a smaller coastline, 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).



(a) **(b)** **(c)**



(d) **(e)** **(f)**

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

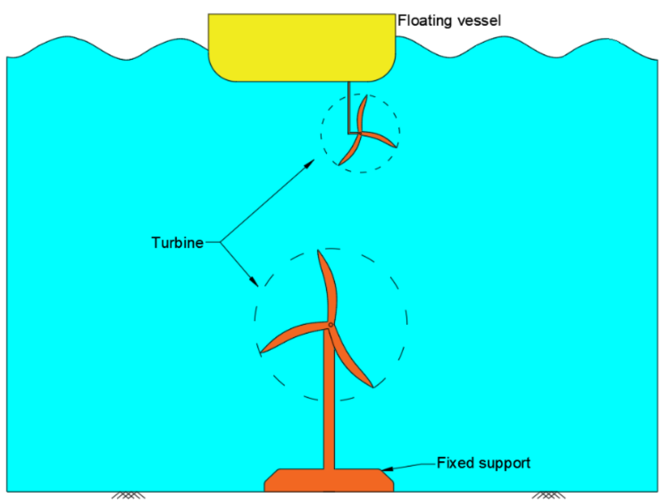
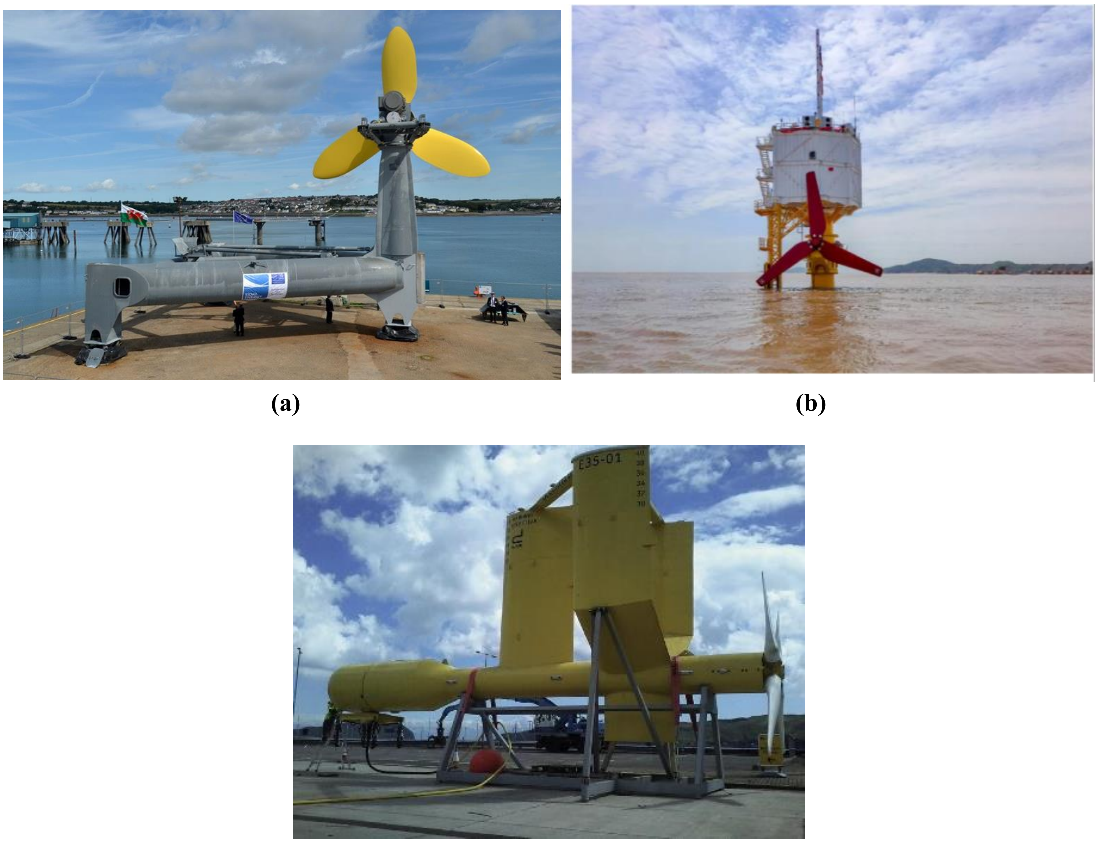


Figure 21. Seabed and surface platform-mounted turbines (Kaufmann et al., 2019)

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)

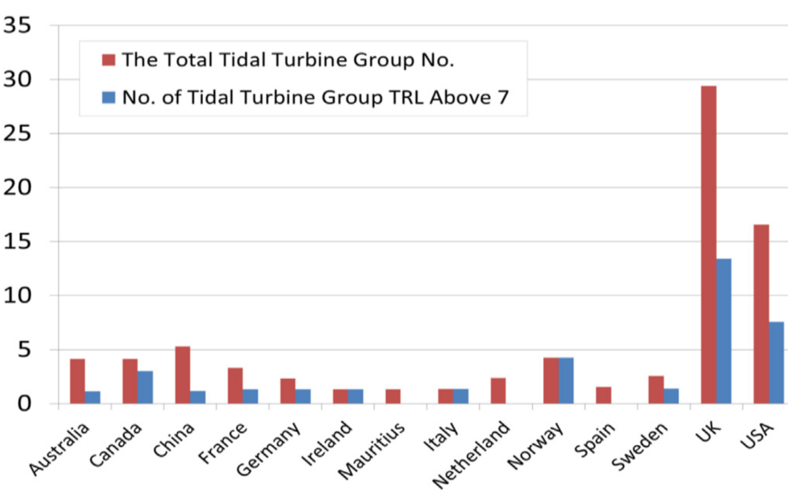


Figure 23. Technology readiness levels of the TCTs technology (Nachtane et al., 2020)

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.

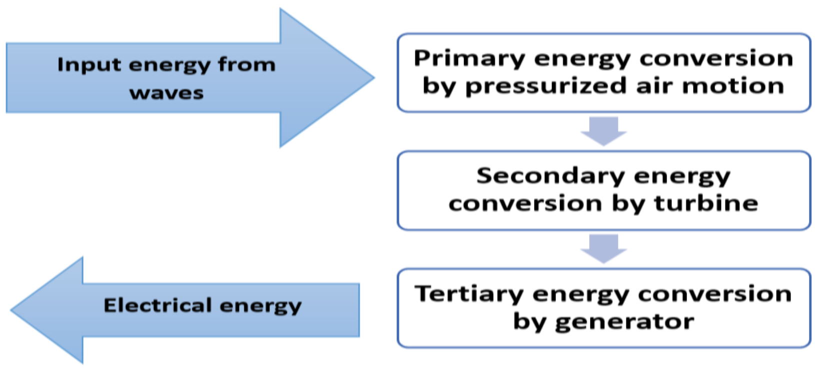


Figure 24. Stages of energy transfer from sea waves to the grid through the OWC energy converter

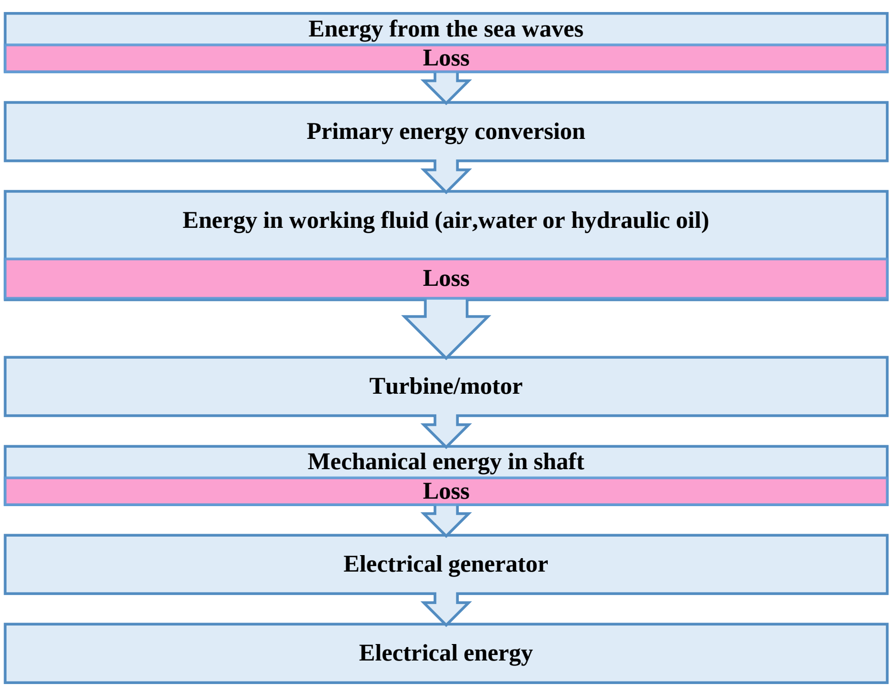


Figure 25. Flowchart for loss associated with energy transfer mechanism in OWC (Sundar and Sannasiraj, 2021)

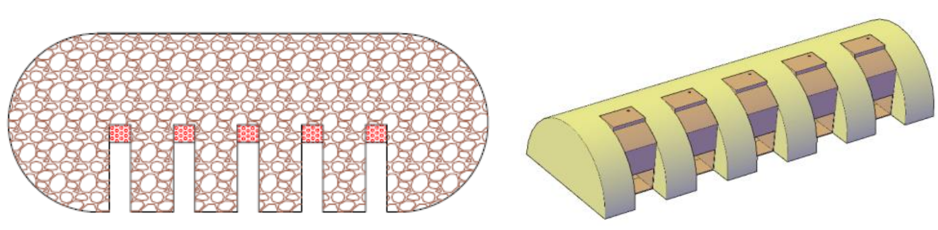
Conversely, when integrated with other structures like breakwaters or wind turbines, the need for additional support diminishes, transforming the system into a multipurpose structure. For example, integrating an OWC with a breakwater not only serves as an energy converter but also functions as a coastal 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).

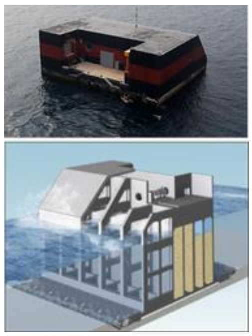
Hybrid WECs, in this context, eliminate the need for additional support foundations required in isolated conditions. Moreover, the construction of the breakwater requires less material as WECs occupy partial spaces, resulting in potential cost savings. Over the past decade, researchers at IIT Madras, 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).

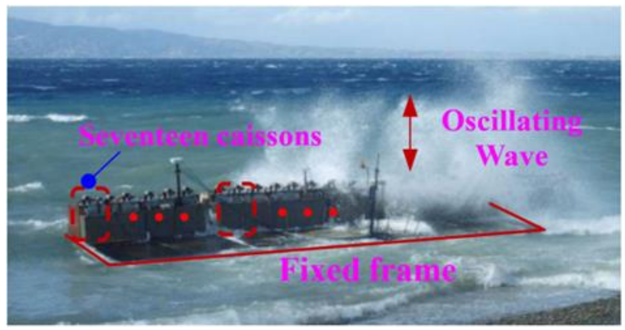


(a) (b)

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)

(**a**) (**b**)





(**c**) (**d**)

(**e**)

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.

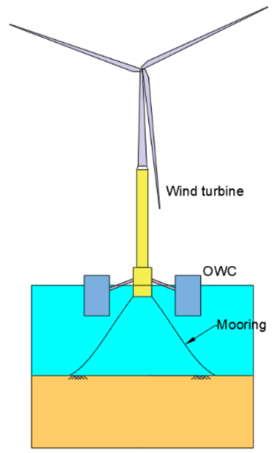
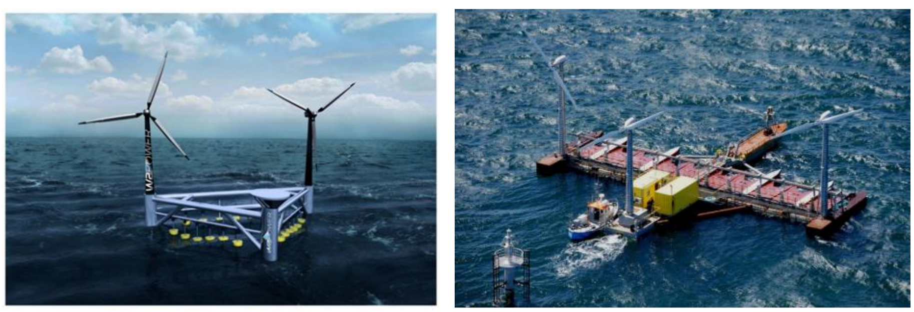


Figure 28. Multiple OWC integrated with floating wind turbine (Doyle and Aggidis, 2020; Fenu et al., 2023)



(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

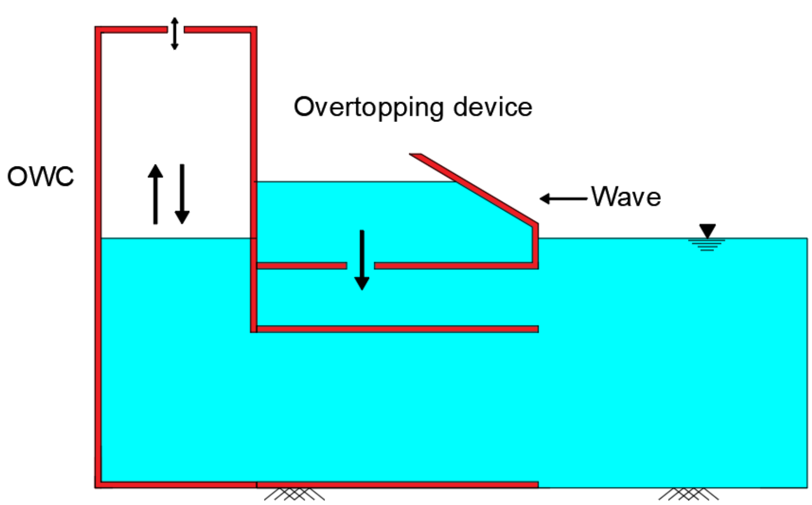


Figure 30. Overtopping device attached with OWC (Doyle and Aggidis, 2020)

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).

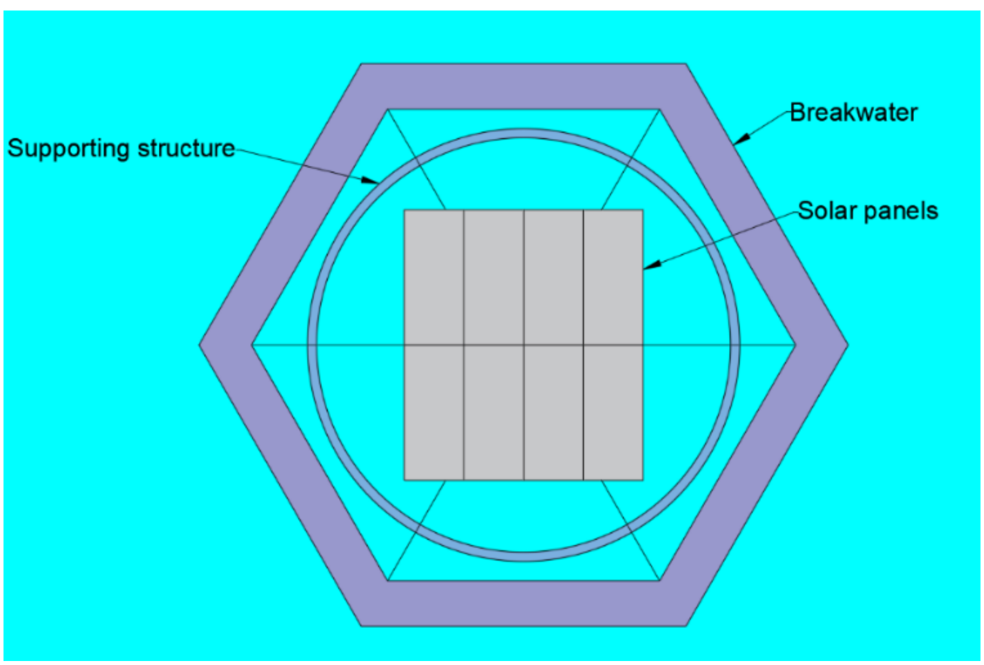
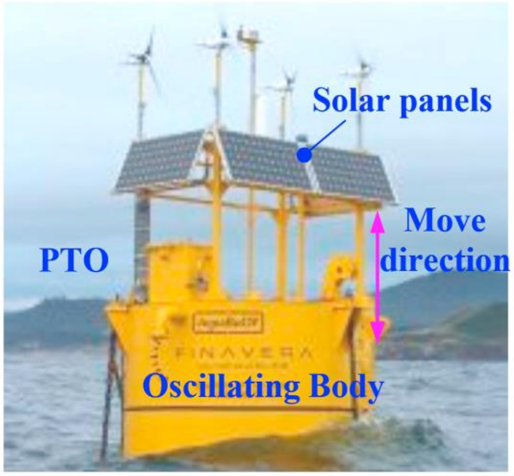
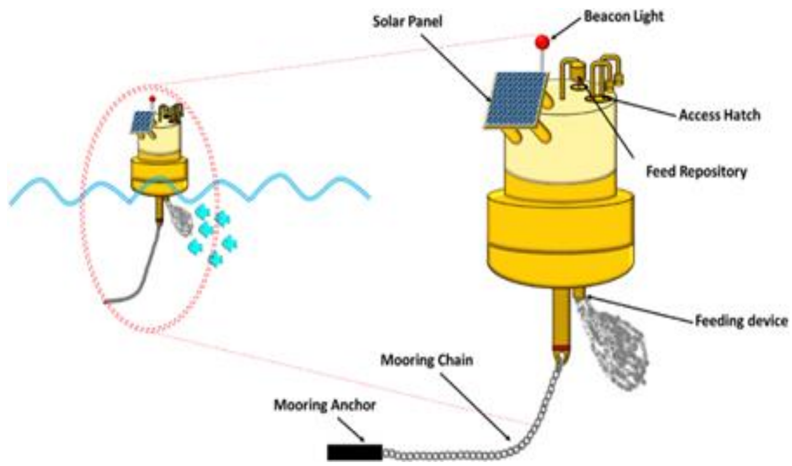


Figure 31. Top view of Solar2 Wave hybrid system (Wei et al., 2023)





(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.

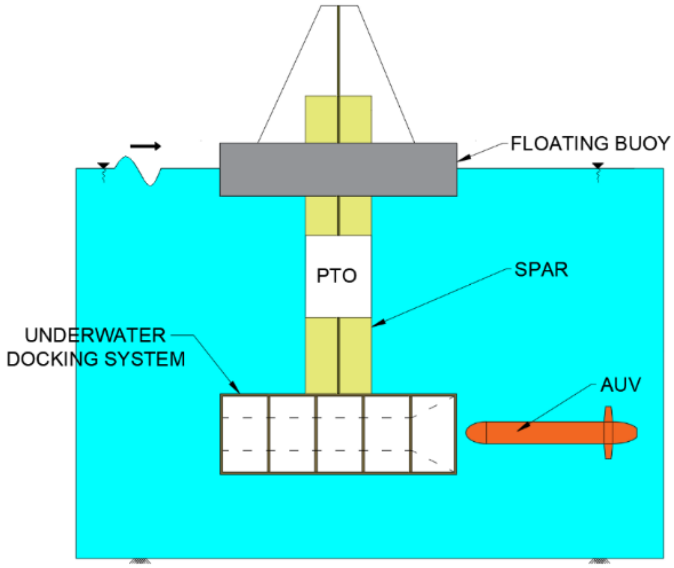
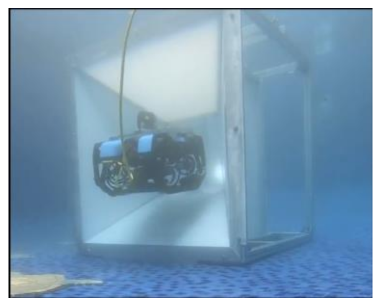


Figure 33. Integrated wave energy converter with AUV docking station



(a) **(b)**

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

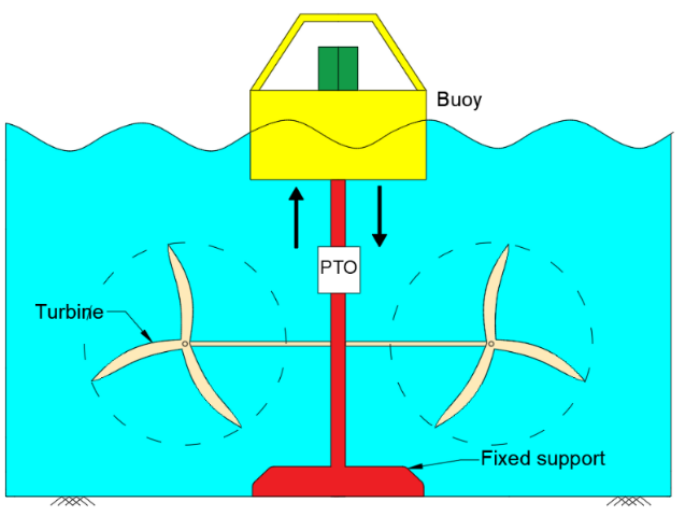


Figure 35. Horizontal axis turbine integrated with point absorber (Silva et al., 2023)

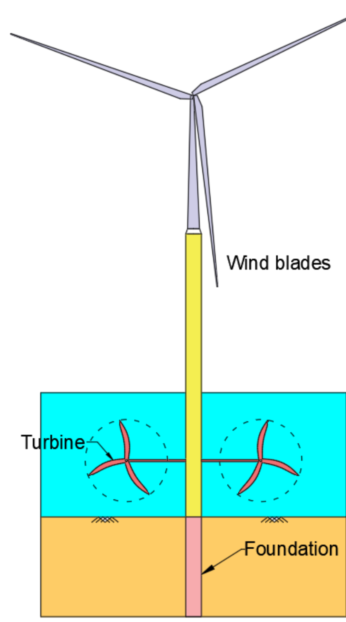


Figure 36. Tidal turbine attached to the support of wind farm (Rahman and Shirai, 2008; Da and Khaligh, 2009; Ashglaf et al., 2017)

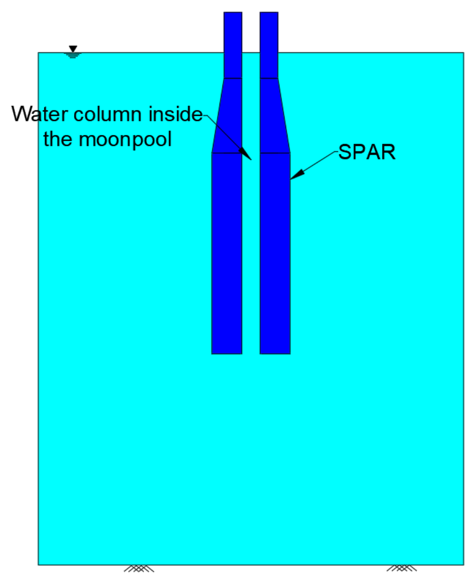


Figure 37. SPAR type offshore wind turbine with moonpool (Pham and Shin, 2019)

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.

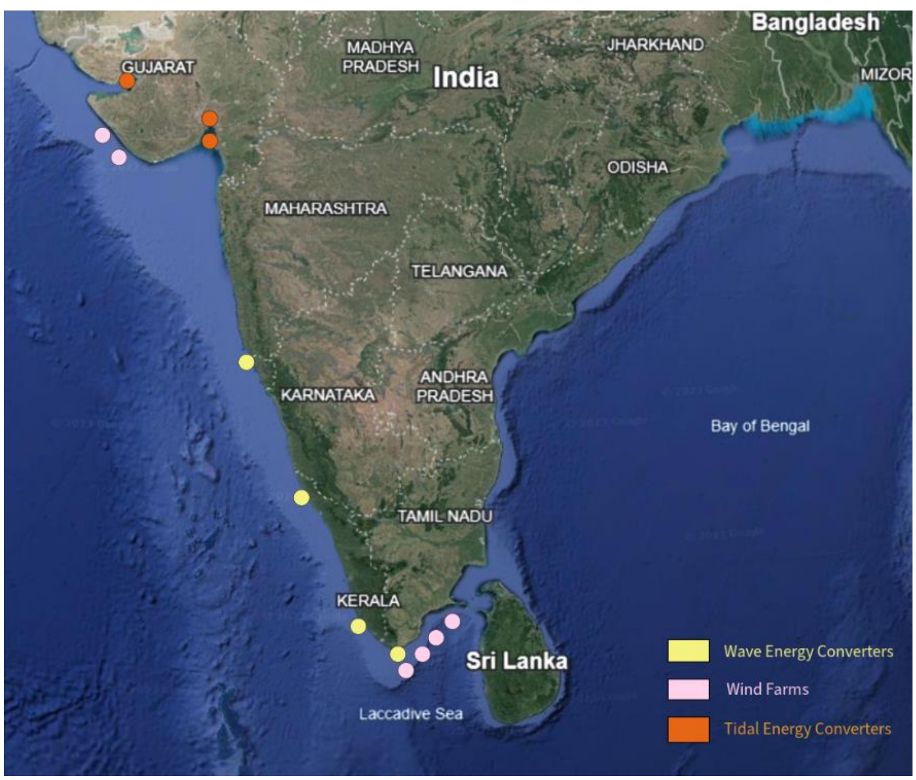


Figure 38. Different isolated energy converters along the Indian coast, based on the energy device locations decided according to Sannasiraj and Sundar (2016), Murali and Sundar (2017), and Alluri et al. (2018)

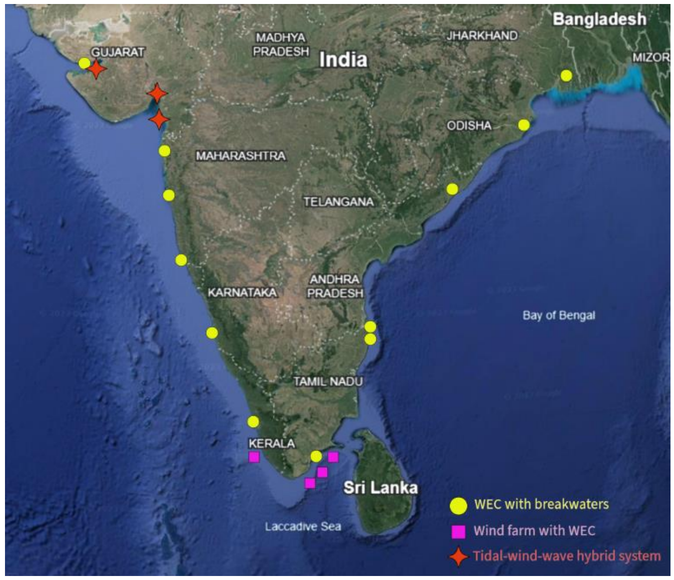


Figure 39. Different hybrid energy converters along the Indian coast. The hybrid device locations are adopted based on Sannasiraj and Sundar (2016), Murali and Sundar (2017) and Alluri et al. (2018)

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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