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HARNESSING THE BLUE TO POWER THE GREEN: OCEAN ENERGY FOR SUSTAINABILITY

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Abstract - As global energy demand escalates and the imperative for sustainable solutions intensifies marine energy is emerging as a critical frontier within diversified renewable energy portfolios. This paper presents a comprehensive analytical review of marine energy's inherent potential, its intricate\ technological evolution, and its transformative role in the broader renewable resource landscape. The analysis systematically traverses historical advancements, elucidating the progression to contemporary systems. It then highlights state-of-the-art developments across key ocean energy conversion technologies, including Ocean Thermal Energy Conversion (OTEC), advanced wave and tidal power systems, optimized oscillating water columns (OWCs), and novel hydrokinetic devices. A rigorous evaluation of their technical feasibility, economic viability, and environmental footprint specifically addressing coastal impact and ecological effects is conducted. Leveraging interdisciplinary methodologies and drawing upon pertinent global case studies, this review delineates both the opportunities and the inherent challenges associated with large-scale marine energy adoption, thereby underscoring its pivotal contribution to a sustainable energy future.

Keywords: Marine energy, renewable energy, OTEC, wave energy, tidal energy, oscillating water column, coastal impact, environmental effects.

1. INTRODUCTION

The escalating global energy crisis, driven by diminishing fossil fuel reserves and the escalating threat of climate change from greenhouse gas emissions, has profoundly amplified the imperative for sustainable power generation technologies. This pressing need has spurred substantial global investment in the research, development, and production of diverse alternative energy sources. Among these, marine energy, encompassing both tidal and wave power, stands out as a compelling and virtually inexhaustible supply of clean energy. The inherent predictability of oceanic forces, when harnessed with advanced turbine and conversion technologies, offers a significant advantage in consistent energy output compared to more intermittent renewable sources like solar and wind. With oceans covering approximately 70% of the Earth's surface, the potential for an immeasurable amount of energy in the form of tides and waves is undeniable.

The human endeavor to harness water's power dates to ancient times, with early applications in milling and irrigation. The conceptual foundations for modern marine energy began to solidify in the late 19th and early 20th centuries, notably with pioneering theories for Ocean Thermal Energy Conversion (OTEC) emerging in the 1880s, followed by initial bench-scale experiments by 1926. A pivotal acceleration in systematic research into harnessing the ocean's immense kinetic and thermal resources occurred post-1970, largely spurred by global energy crises. Today, marine energy—which broadly encompasses wave, tidal, thermal (OTEC), and salinity gradient power—is recognized as a foundational pillar for achieving a carbon-neutral future. Hundreds of megawatts of marine energy capacity are already installed globally, with optimistic projections aiming for several gigawatts by 2030. While currently in a dynamic developmental stage, ocean energy is poised for significant future prominence within the global energy industry.

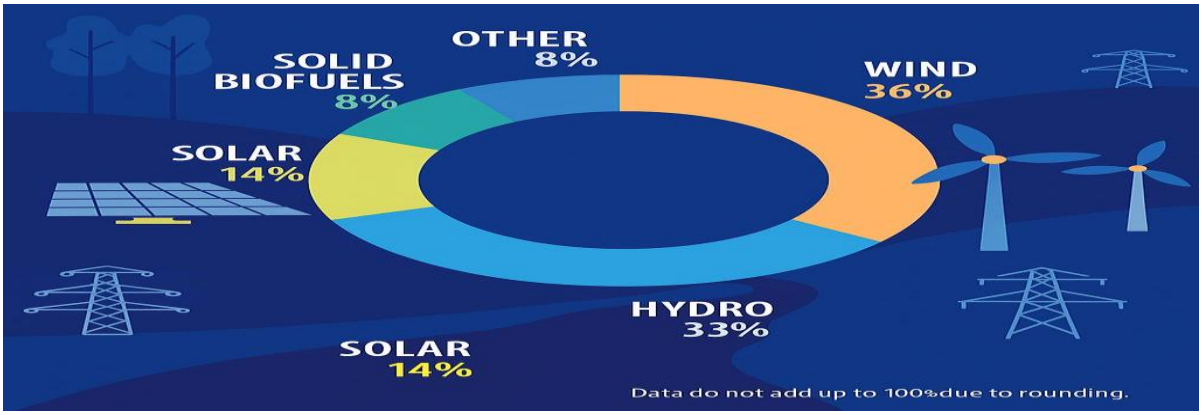

Fig. 1.1 Distribution of Renewable Energy Sources

This paper examines the fundamental principles of wave and tidal energy conversion, providing a concise review of various established and emerging technologies designed for their effective harvesting. As new technologies continually emerge, a significant diversity among devices capable of generating electricity from either waves or tides is becoming apparent. The developing industry is expected to offer a wide array of selections, optimized based on generation capacity, cost-effectiveness, and operational durability. This evolving landscape suggests a future where diverse, tailored marine energy solutions will play a pivotal role in the global energy transition.

1.1 Technical Historical Background

The lineage of marine energy traces from ancient tide mills to modern sophisticated systems. Scientific conceptualization began in the late 19th century with the Ocean Thermal Energy Conversion (OTEC) principle (1881) and early patents for wave energy converters, including the oscillating water column (OWC). A significant milestone was the 1966 commissioning of the 240 MW La Rance Tidal Power Station, the world's first large-scale tidal barrage. The 21st century has seen accelerated development, marked by the establishment of the European Marine Energy Centre (EMEC) in 2003 for open-sea testing, and the deployment of initial grid-connected tidal turbine arrays and commercial OWC wave plants (e.g., Mutriku, 2011). This era emphasizes diversification of designs, enhanced survivability, and optimized energy capture.

2. MARINE ENERGY TECHNOLOGIES

The diverse characteristics of oceanic energy resources necessitate a range of specialized technologies for their effective conversion into usable electricity. These systems are broadly categorized by the specific form of marine energy they exploit, each presenting unique engineering principles, operational advantages, and inherent deployment challenges.

2.1 Ocean Thermal Energy Conversion (OTEC)

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that leverages the natural temperature differential between warm surface seawater and cold deep-ocean water to drive a thermodynamic cycle and generate electricity. This method is primarily viable in tropical and subtropical regions where a consistent and sufficient thermal gradient, typically ≥20 ∘C (36 ∘F), exists between the surface and depths of approximately 800 to 1,000 meters. The fundamental principle relies on the Carnot cycle, though practical OTEC systems achieve lower efficiencies due to small temperature differences.

Three primary OTEC cycle configurations are recognized:

Closed-Cycle OTEC: This is the most prevalent and technologically mature configuration. A working fluid with a low boiling point (e.g., ammonia, R-134a, propane) is continuously circulated within a closed loop. Warm surface seawater (typically 25−30 ∘C) is pumped through an evaporator, vaporizing the working fluid under pressure. The expanding vapor then drives a turbine connected to an electrical generator. Subsequently, cold deep-ocean water (typically 4−8 ∘C), drawn from depths of 800-1000 meters, is circulated through a condenser, causing the working fluid vapor to condense back into a liquid, completing the cycle. Heat exchange (e.g., plate-and-frame, shell-and-tube) are critical components, requiring high efficiency and resistance to biofouling.

Open-Cycle OTEC: This system directly utilizes warm surface seawater as the working fluid. The warm seawater is flash evaporated in a vacuum chamber, creating low-pressure steam that expands to drive a turbine. The steam is then condensed by cold deep-ocean water. A significant advantage of the open-cycle is the co-production of large quantities of high-purity desalinated fresh water from the condensed steam, addressing critical freshwater scarcity in many coastal and island communities. Hybrid Cycle OTEC: This configuration combines features of both closed- and open-cycle systems. Warm seawater is flash-evaporated to produce steam, which then heats a closed-cycle working fluid. This hybrid approach aims to optimize both power generation and freshwater production.

2.1.1 OTEC offers unique and compelling Benefits

Consistent Baseload Power: Unlike intermittent renewable sources (solar, wind), OTEC plants can operate 24 hours a day, 7 days a week, providing stable and predictable baseload power to the grid, crucial for grid stability and energy security.

Desalinated Water Production: Open and hybrid cycles inherently produce potable fresh water, alleviating water stress in regions reliant on costly or energy-intensive desalination methods.

Ancillary Benefits: The large volumes of cold, nutrient-rich deep seawater discharged from OTEC plants can be utilized for various co-located industries, including cold-water aquaculture (e.g., cultivating specific fish or shellfish), district cooling for buildings (reducing electricity demand for air conditioning), and enhanced agricultural applications.

2.2 India's OTEC Potential and Initiatives

Integrated Power and Desalination India has identified a substantial OTEC potential of around 180,000 MW along its coastline, particularly in the southern coastal regions and around its island groups like Lakshadweep and

Andaman & Nicobar. The National Institute of Ocean Technology (NIOT), an autonomous institute under the Union Ministry of Earth Sciences (MoES), has been at the forefront of OTEC research and development in India.

2.2.1 Systems (LTTD-OTEC)

One of the most significant technological advancements in the Indian Ocean context is the integration of OTEC with Low Temperature Thermal Desalination (LTTD) technology. This hybrid approach offers a dual benefit: electricity generation and the production of potable water, a critical resource, especially for remote island communities.

Kavaratti OTEC-Desalination Plant (Lakshadweep): NIOT is currently establishing a 65 kW OTEC plant in Kavaratti, Lakshadweep, which will power a 100,000 liters per day LTTD plant (NIOT, 2022). This project represents a global first for utilizing indigenous OTEC technology to produce drinking water from seawater using green energy. The LTTD process leverages the same ocean thermal gradient, making it inherently environmentally friendly by avoiding chemical pre- and post-treatments common in other desalination methods.

Offshore Floating Platform Design: Building on the Kavaratti experience, NIOT has proposed a pilot-scale OTEC-desalination plant on a floating platform approximately 4 km off the Kavaratti coast, at a depth of 1000m. This platform will house a 1 lakh liters per day freshwater capacity and 165 kW gross green energy system. This move towards offshore floating platforms addresses the need for deep-water access in a more flexible and potentially scalable manner.

2.2.2 Advancements in Cold Water Pipe (CWP) Technology and Deployment

The cold-water pipe (CWP) remains a critical and historically challenging component of OTEC systems. While specific detailed research papers on recent CWP breakthroughs from NIOT are often proprietary or in various stages of peer review, the successful deployment and ongoing operation of the Kavaratti LTTD plant imply significant progress in CWP design, materials, and installation techniques suitable for the Indian Ocean's dynamic environment. Lessons learned from previous attempts are being integrated into designs for improved durability, flexibility, and resistance to biofouling and structural fatigue. Collaboration with experienced international partners likely contributes to optimizing CWP solutions.

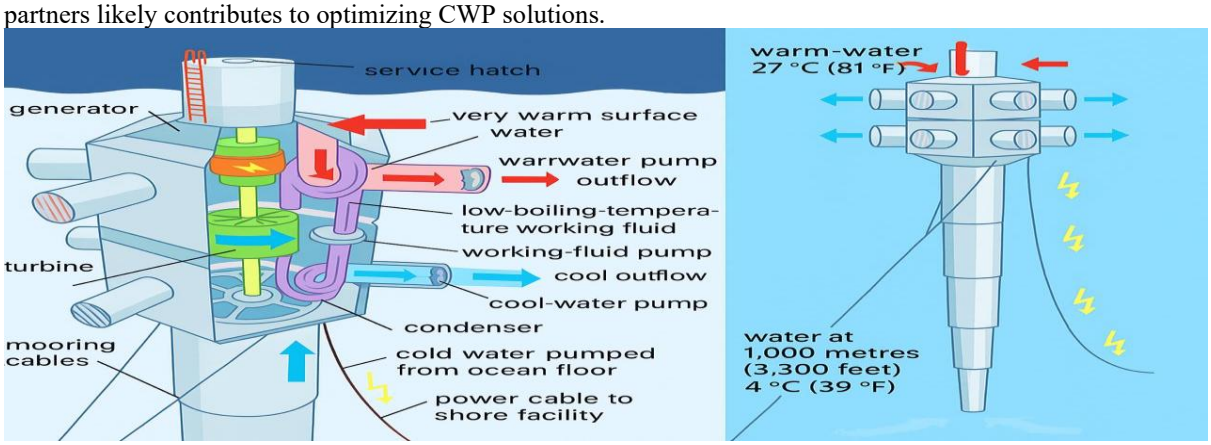

Fig. 2.1 Closed-Cycle OTEC System

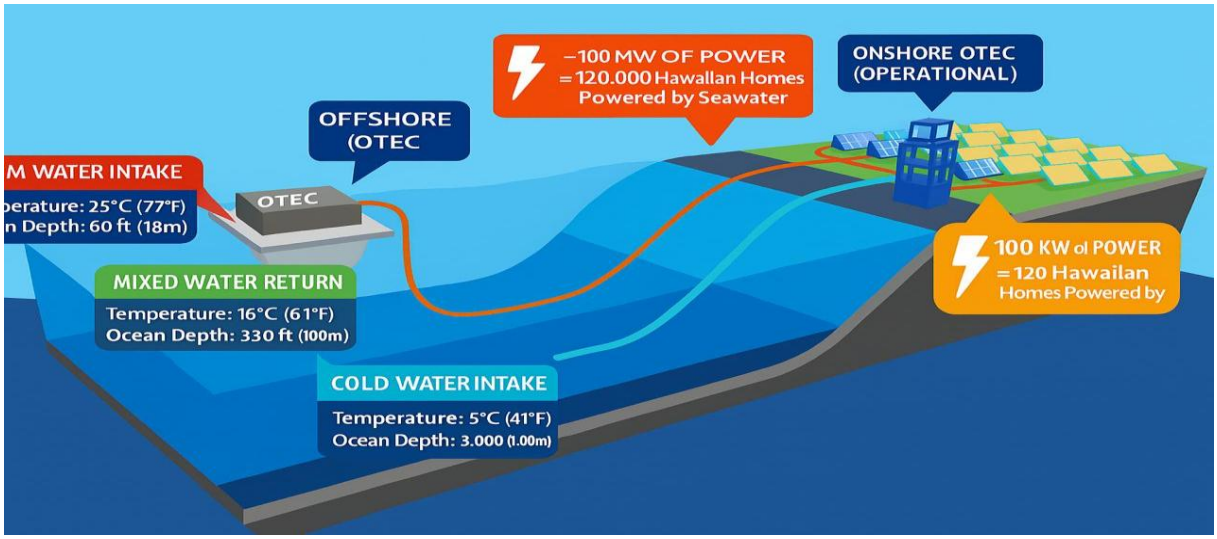

Fig. 2.2 Ocean Thermal Energy Conversion (OTEC) system

2.3 Wave Energy Converters (WECs)

Wave Energy Converters (WECs) are engineered systems designed to capture the kinetic and potential energy present in the oscillatory motion of ocean surface waves and convert it into electrical power. The energetic density of ocean waves is significantly higher than that of wind or solar insolation, making wave energy an attractive, albeit challenging, renewable resource. The stochastic and multi-directional nature of waves, coupled with extreme storm conditions, necessitates robust and adaptable designs. WECs are generally categorized by their operational principle and deployment location (onshore, nearshore, or offshore).

2.3.1 Point Absorbers

These are small, buoy-like devices designed to absorb energy from waves irrespective of their direction. They typically float on or near the water surface and convert the relative motion between an oscillating body and a fixed reference (either the seabed or another part of the device) into electricity. Power take-off (PTO) mechanisms often involve hydraulic cylinders driving generators, or direct-drive linear generators. Examples include Carnegie Clean Energy's CETO (a submerged point absorber) and CorPower Ocean's C4 (a heaving point absorber using a pneumatic system). Their omni-directional absorption capability makes them suitable for diverse wave climates.

2.3.2 Attenuators

These are elongated, multi-segmented floating structures oriented perpendicular to the dominant wave direction. They absorb energy by flexing along their length as waves propagate along the device. Each articulated section drives a hydraulic PTO system that converts the relative motion into electricity. The Pelamis Wave Energy Converter, a pioneering attenuator, demonstrated significant potential but faced challenges related to survivability and operational costs, leading to its eventual decommissioning. Lessons learned from Pelamis are informing next-generation attenuator designs focusing on improved reliability and cost-effectiveness.

2.3.3 Overtopping Devices

These WECs capture incoming waves into a reservoir positioned at an elevation above sea level, typically using a ramp structure. The potential energy of the stored water is then converted into electricity as it flows back to the sea through low-head Kaplan or Francis turbines, like run-of-river hydropower. The Wave Dragon, a floating offshore overtopping device, is a notable example, designed to be moored in deep waters. Key design considerations include optimizing the ramp profile for wave capture efficiency and ensuring the structural integrity of the reservoir.

2.3.4 Oscillating Water Columns (OWCs)

OWCs consist of a partially submerged, hollow chamber open to the sea below the waterline. As waves rise and fall outside the chamber, they cause the internal water level to oscillate, compressing and decompressing the air trapped above the water column. This bidirectional airflow drives a self-rectifying air turbine (e.g., Wells turbine, impulse turbine, or axial flow turbine) connected to a generator. OWCs can be deployed as shoreline-integrated structures (e.g., the Mutriku Wave Power Plant in Spain), fixed bottom-standing devices in nearshore environments (e.g., the Pico Plant in the Azores), or floating offshore units. Their key advantage lies in the relatively few moving parts immersed in seawater, contributing to greater robustness and lower maintenance requirements, though turbine efficiency and air leakage remain design considerations.

2.3.5 Submerged Oscillating Flaps / Surge Devices

These WECs are typically bottom-hinged or pivot-mounted flaps or panels deployed nearshore or offshore. They capture the horizontal "surge" motion of water particles as waves pass, oscillating back and forth to drive a PTO system, often hydraulic. The WaveRoller by AW-Energy is a prominent example, designed to sit on the seabed and absorb energy from subsurface wave pressure. Their submerged nature offers a reduced visual impact and enhanced protection from extreme weather.

Challenges in the commercialization of wave energy are multifaceted. Survivability in extreme storm conditions and the ability to withstand immense wave loads remain paramount. Power Take-Off (PTO) optimization is crucial for efficiently converting the irregular, low-frequency, high-force wave motion into grid-quality electricity. High capital costs for manufacturing, transport, offshore installation, and robust mooring systems contribute to a higher Levelized Cost of Energy (LCOE) compared to more mature renewables. Environmental impacts must also be carefully managed, including potential effects on marine ecosystems, acoustic emissions, altered sediment transport patterns, and visual aesthetics for surface-piercing devices. The industry is currently characterized by a diverse range of prototypes and pilot projects, with extensive testing at dedicated facilities like the European Marine Energy Centre (EMEC) aimed at identifying optimal designs and achieving cost reduction through economies of scale and learning curve effects.

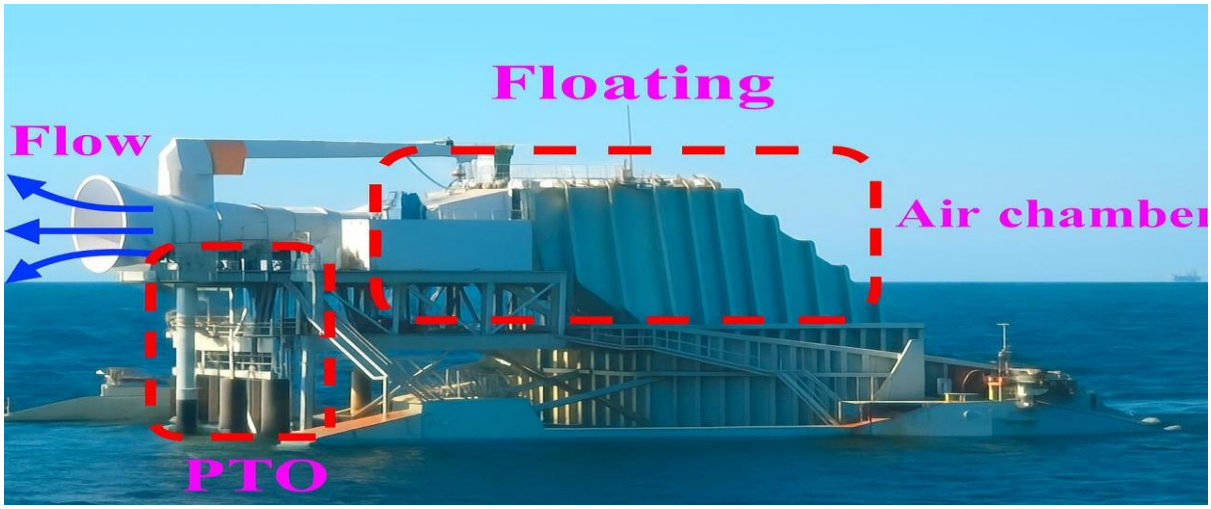

Fig. 2.3 Floating Oscillating Water Column (OWC) Wave Energy Converter

2.3 Tidal Energy Converters

Tidal energy harnesses the highly predictable, periodic movement of ocean waters driven by the gravitational forces exerted by the Moon and Sun. Its predictability, unlike wind or solar power, offers significant advantages for grid stability and resource planning. Two primary technological approaches are employed: tidal stream energy and tidal range energy.

Tidal Stream Turbines: These devices convert the kinetic energy of flowing tidal currents directly into electricity, functioning much like submerged wind turbines. They are typically deployed in areas with strong, consistent tidal currents, such as narrow straits, estuaries, or channels, where water accelerates naturally.

Horizontal-Axis Turbines (HATs): These are the most common and technologically mature design, resembling conventional wind turbines with blades rotating around a horizontal axis. They can be mounted on various subsea foundations (e.g., monopiles, gravity bases, tripods) or integrated into floating platforms. MeyGen (Scotland), featuring turbines from SIMEC Atlantis Energy, is a leading example of a multi-megawatt operational tidal array. Orbital Marine Power's O2 turbine is another prominent example of a large, floating horizontal-axis device designed for efficient installation and maintenance. Innovations include ducted turbines to accelerate flow and open-centre designs to minimize blade tip effects.

Vertical-Axis Turbines (VATs): These designs feature blades that rotate around a vertical axis, allowing them to capture flow from any direction without requiring a yaw mechanism. This can be advantageous in turbulent or bidirectional flows. Designs include Darrieus and Gorlov turbines.

2.3.1 Tidal Kites

Exemplified by Minesto's Deep Green technology, these are tethered, wing-shaped devices that "fly" dynamically through the water current in an 8-shaped trajectory. By sweeping a much larger area than their physical size, they achieve significant energy capture even in lower-velocity currents, expanding the economically viable resource base.

2.3.2 Archimedes Screw Turbines

These helical turbines are well-suited for lower-head applications and can operate efficiently in slower, more turbulent flows, often in riverine or estuarine environments.

2.3.3 Vortex-Induced Vibration Aquatic Clean Energy (VIVACE) Converters

These unconventional devices utilize the phenomenon of vortex-induced vibrations of bluff bodies in a fluid flow to generate electricity, offering potential for very low-current applications.

Challenges for tidal stream turbines include the high cost and complexity of subsea installation, grid connection, and maintenance operations in high-current, often remote, environments. Environmental concerns focus on potential interactions with marine mammals (collision risk, acoustic emissions from turbine operation) and localized impacts on sediment dynamics or benthic habitats. Extensive monitoring and modeling are crucial for sustainable deployment.

2.3.4 Tidal Range Systems (Barrages)

These are large-scale civil engineering structures that capture potential energy from the head difference created by the tide. A barrage, similar to a dam, is constructed across an estuary or bay, creating a basin.

2.3.5 Principle of Operation

As the tide rises, water flows through sluice gates into the basin. At high tide, the gates are closed, impounding the water. When the tide outside recedes, a significant head difference is created. The stored water is then released through turbines (typically bulb turbines, which are specifically designed for low head and high flow) embedded within the barrage, generating electricity. Generation can occur on the ebb tide (outflow), flood tide (inflow), or in more complex two-way systems where power is generated during both ebb and flood, sometimes utilizing multiple basins to ensure more continuous output.

The La Rance Tidal Power Station (240 MW) in France, operational since 1966, remains a global benchmark for barrage technology, demonstrating long-term reliability. The Sihwa Lake Tidal Power Station (254 MW) in South Korea, completed in 2011, is currently the largest by installed capacity.

Challenges for tidal barrages are substantial. They are characterized by extremely high capital costs and very long construction periods. Their most significant drawbacks are the profound environmental impacts, which include altering vast estuarine ecosystems, disrupting fish migration routes (necessitating complex fish-friendly turbine designs or bypass systems), changing sedimentation patterns, and affecting local flora and fauna populations. Due to these environmental concerns and high costs, the focus of new tidal energy projects has largely shifted towards tidal stream technologies.

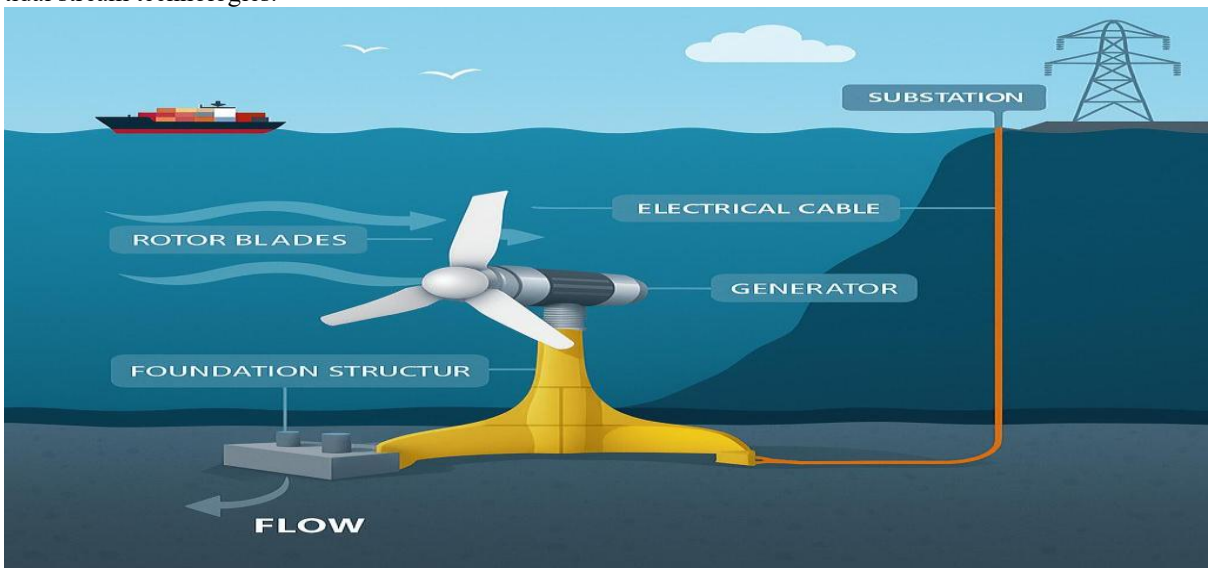

Fig. 2.4 Tidal Stream Energy Turbine System

2.4 Emerging Hydrokinetic and Water Search Devices

Beyond the primary grid-scale marine energy technologies, a dynamic area of research and development focuses on novel hydrokinetic devices and specialized "water search devices" designed for niche applications, often at lower power outputs but with high strategic value, particularly for autonomous marine operations.

2.4.1 Broader Hydrokinetic Energy

This category encompasses technologies designed to harness kinetic energy from various continuous water flows beyond just periodic tides. This includes major ocean currents (e.g., parts of the Gulf Stream, Kuroshio Current), and even harnessing energy from free-flowing rivers or man-made channels where traditional hydropower may not be feasible. These systems often employ turbine designs adapted for lower velocities or specific environmental footprints. Research in this area seeks to unlock energy from a wider array of aquatic environments.

2.4.2 Water Search Devices / Micro-Hydrokinetic Harvesters

This is a rapidly evolving segment focused on providing autonomous power solutions for remote oceanographic sensors, monitoring platforms, autonomous underwater vehicles (AUVs), and other low-power marine instrumentation. These devices reduce reliance on battery replacement or external power supply, enabling long-term, self-sustaining deployments.

2.4.3 Triboelectric Nanogenerators (TENGs)

TENGs represent a groundbreaking technology in this domain. They convert ambient mechanical energy (from wave motion, current flow, water drops, or even walking) into electrical energy through the synergistic coupling of triboelectrification (charge transfer between materials in contact) and electrostatic induction. TENGs can operate in various modes (contact-separation, sliding, single-electrode) and can be fabricated from common, flexible polymeric materials and conductive films. When water interacts with the TENGs' surfaces, it induces charge separation, leading to a voltage difference that drives current. Their advantages include simplicity, low cost, light weight, high efficiency for low-frequency motions, and robustness in harsh environments. TENGs are

exceptionally promising for self-powered sensors, remote data buoys, and distributed marine environmental monitoring networks, enabling unprecedented long-duration data collection.

2.4.4 Piezoelectric Harvesters

These devices convert mechanical strain or vibration (induced by waves or currents) directly into electrical energy via the piezoelectric effect. They are compact and durable but typically yield lower power outputs suitable for microelectronics.

2.4.5 Electromagnetic Harvesters

These systems utilize the relative motion between a magnet and a coil (or vice-versa) driven by water flow to induce an electric current. They can be integrated into various designs to capture energy from oscillating or rotational water movements.

These emerging hydrokinetic and water search technologies, while not primarily aimed at grid-scale power generation, are critical enablers for the "blue economy." They facilitate long-term, maintenance-free operation of essential oceanographic research equipment, enhance maritime security through persistent surveillance, support sustainable aquaculture operations by powering sensors and feeders, and reduce the logistical carbon footprint associated with powering remote marine assets.

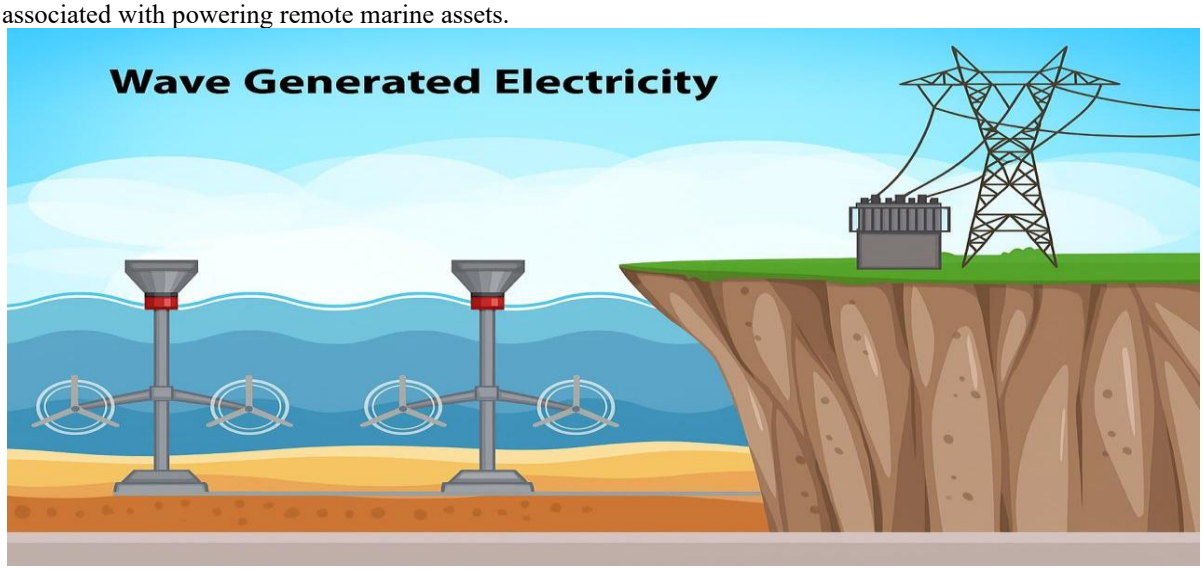

Fig. 2.5 Ocean Energy System

3. CONSIDERATIONS FOR MARINE ENERGY DEVELOPMENT

3.1 Feasibility

The technical feasibility of extracting energy from oceans is largely proven, with various prototypes and pilot projects demonstrating successful power generation from waves, tides, and thermal gradients. However, the critical challenge for broad feasibility lies in achieving sustained, reliable, and cost-effective operation over project lifespans (20+ years). This includes ensuring device survivability against extreme marine conditions (e.g., storms, corrosion, biofouling) and optimizing power take-off (PTO) systems for variable input, which currently limits widespread commercial deployment compared to more mature renewables.

3.2 Economic Aspects

Marine energy technologies currently face a high Levelized Cost of Energy (LCOE) compared to conventional energy sources and established renewables like solar and onshore wind. This is primarily driven by significant capital expenditure (CAPEX) for robust marine-grade materials and complex subsea installation, as well as high operational and maintenance (O&M) costs in challenging marine environments. Achieving economic viability requires substantial cost reductions through technological innovation, industrialization, supply chain development, and sustained policy support to foster market growth and learning-curve effects.

3.3 Significance

Marine energy holds substantial strategic significance for future energy mixes. Its inherent predictability (especially tidal) offers a valuable baseload or dispatchable power source, complementing the intermittency of solar and wind. This predictability contributes to grid stability and resilience. Furthermore, the vast, largely untapped ocean resource can significantly contribute to global decarbonization efforts, enhance energy security, and reduce reliance on fossil fuels, particularly benefiting coastal and island communities seeking energy independence.

3.4 Environmental Effects

Marine energy deployments can introduce localized environmental effects necessitating rigorous assessment and mitigation. These impacts include physical alterations to seabed habitats from foundations and mooring systems, changes in water flow patterns and sediment transport around devices, and the generation of underwater noise during construction (e.g., piling) and operation (e.g., turbine rotation, PTO systems). Electromagnetic fields (EMF) from subsea cables are another consideration, with ongoing research into their potential impacts on marine life.

3.5 Effect on Wildlife

Specific concerns regarding marine wildlife include the potential for direct collision of mobile species (e.g., fish, marine mammals, diving birds) with rotating turbine blades or moving components of wave energy converters. Acoustic disturbance from operational noise can interfere with marine mammal communication, navigation, and foraging behaviour. Furthermore, the physical presence of devices and associated infrastructure can create artificial reef effects (potentially attracting or displacing species) or act as barriers to migratory routes, requiring careful site selection and monitoring.

3.6 Ship Trafficking

The deployment of marine energy arrays can create navigational hazards and require changes to established shipping lanes and vessel traffic routes. Development sites may necessitate the establishment of exclusion zones, which must be clearly marked and communicated to maritime users. This requires careful marine spatial planning to minimize conflicts with commercial shipping, fishing activities, and other existing ocean uses, ensuring safety and efficiency of marine operations.

3.7 Impact on the View of Coastline:

The visual impact of marine energy projects on the coastal landscape and seascape is a significant public perception factor. Nearshore or surface-piercing wave energy converters, as well as visible components of tidal barrages or floating OTEC platforms, can alter the aesthetic appeal of a coastline, which is particularly sensitive in areas reliant on tourism. Submerged tidal stream turbines and far-offshore wave devices offer reduced visual impact, providing potential solutions for visually sensitive locations.

4. RESULT

This research explores how marine energy—such as Ocean Thermal Energy Conversion (OTEC), wave energy, and tidal power—can help us move toward a cleaner and more sustainable future. Oceans cover over 70% of the Earth's surface and hold a massive amount of energy that can be harnessed to generate electricity. Among the different technologies, OTEC is especially promising in tropical regions. It uses the natural temperature difference between warm surface water and cold deep-sea water to produce electricity. A major benefit of OTEC is that it can also provide fresh drinking water, which is extremely useful for island and coastal communities.

Wave and tidal energy systems are also very promising. Unlike solar and wind power, which depend on weather, waves and tides are predictable. This makes them a steady and reliable source of energy. Wave energy devices, such as point absorbers and oscillating water columns, capture the motion of ocean waves. Tidal systems, including underwater turbines, work like wind turbines but are placed in moving water. Some newer systems, like tidal kites and vertical-axis turbines, are being tested to make the technology even more efficient.

India is actively working in this field, with the National Institute of Ocean Technology (NIOT) leading OTEC and desalination projects in the Lakshadweep Islands. These efforts show real-world success in combining clean energy and freshwater production.

Despite the potential, challenges remain. Marine energy systems are expensive to build and maintain. Harsh ocean conditions and possible effects on marine life must be carefully managed. However, with ongoing research, better technology, and government support, these challenges can be overcome.

In conclusion, marine energy offers a reliable and eco-friendly power source that can support energy needs, especially in coastal areas. It can play a key role in reducing our dependence on fossil fuels and protecting the environment.

CONCLUSION

Marine energy, encompassing Ocean Thermal Energy Conversion (OTEC), diverse wave energy converters (WECs) like point absorbers and oscillating water columns, and highly predictable tidal energy systems (both stream turbines and barrages), is emerging as a critical and rapidly advancing pillar in the global transition toward a sustainable energy future. Our review highlights that the immense, largely untapped energy density and the inherent predictability of tidal resources, in particular, position marine energy as a uniquely valuable component capable of providing baseload power and enhancing grid stability. The potential for co-benefits, such as OTEC's ability to produce desalinated water and facilitate aquaculture, further underscores its multifaceted contribution to resource security.

Despite its significant promise, widespread commercialization of marine energy faces specific, yet surmountable, challenges. Economically, the Levelized Cost of Energy (LCOE) remains elevated due to the high capital expenditure (CAPEX) associated with robust marine-grade materials, complex subsea installation, and demanding operational and maintenance (O&M) activities in harsh environments. Technically, ensuring device survivability against extreme oceanic conditions and optimizing power take-off (PTO) systems for efficient energy conversion across variable sea states continues to be a primary engineering focus.

Furthermore, environmental and social considerations are paramount for responsible deployment. Potential environmental effects on marine ecosystems, including direct impacts on wildlife from collision risk and acoustic disturbance, necessitate rigorous environmental risk assessments. Careful marine spatial planning is crucial to mitigate conflicts with existing ship trafficking lanes and to manage the visual impact on coastlines for nearshore or surface-piercing devices. However, advancements in submerged technologies and strategic site selection are mitigating these concerns.

The rapid pace of innovation in this sector, exemplified by the development of sophisticated triboelectric nanogenerators (TENGs) for autonomous marine sensing, underscores the industry's dynamism. Continued investment in research, development, and demonstration (RD&D), coupled with supportive policy frameworks and a commitment to standardized, scalable solutions, will be pivotal in overcoming current hurdles. Ultimately, marine energy's unique attributes make it indispensable for coastal nations seeking to bolster energy resilience, achieve energy security, and significantly advance global decarbonization efforts.

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